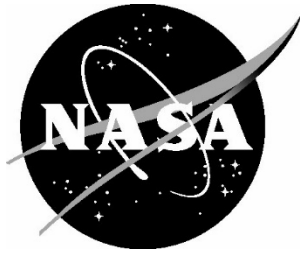


NASA/TP–20240009601



GISS Research Publications 2023

De Leon, Priscilla (Editor)

Autonomic Integra, LLC., New York, New York

Goddard Institute for Space Studies, New York, New York

Schmunk, Robert (Editor)

Autonomic Integra, LLC., New York, New York

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Mora, Josefina (Editor)

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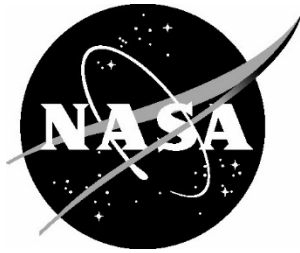
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National Aeronautics and
Space Administration

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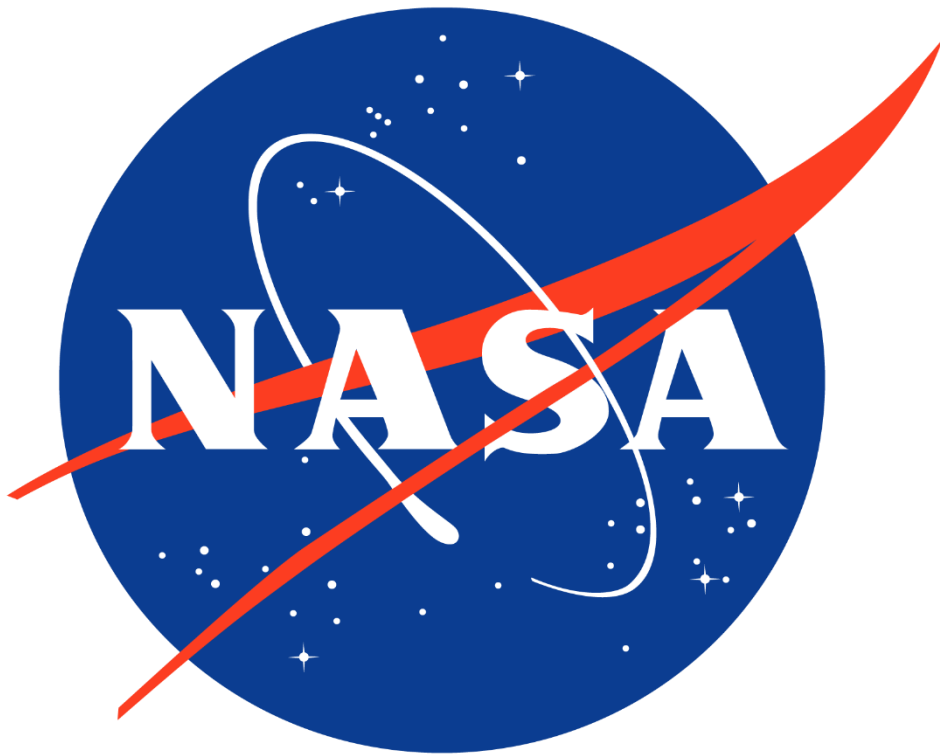
July 2024

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GISS Research Publications 2023

The GISS Research Publications document was initiated in 1992 as an annual summary of our research based on quick inexpensive reproduction of excerpts of published papers. Its aim is twofold: to communicate in and outside the GISS community what we do and how we got about it, as well as to record annual accomplishments, providing a continual basis for measuring progress.

Background

Pictured below, GISS is a laboratory of NASA's Goddard Space Flight Center (GSFC) in Goddard's Earth Sciences Division and is located at Columbia University's Armstrong Hall in New York City. GISS was established in 1961 by Dr. Robert Jastrow. Our mission is to conduct basic research in support of NASA programs. Led by Dr. James E. Hansen from 1981 to 2013, the prime objective has been improved understanding of global change. Research areas include global climate, biogeochemical cycles, planetary atmospheres, earth observations and related interdisciplinary studies. In 2014, Dr. Gavin A. Schmidt was named Chief of GISS.

Research is carried out in cooperation with the academic community, especially Columbia University, near whose campus GISS is housed, City University of New York (CUNY) and the Massachusetts Institute of Technology (MIT). Typically, about six graduate students carry out their Ph.D. thesis research under the supervision of GISS staff members at any given time. GISS is made up of approximately 150 employees including high school, undergraduate, graduate students, post-doctoral scientists, university research associates and visiting faculty, all of whom contribute to collaborative research projects.



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1. OUTREACH

A. WORLD WIDE WEB: GISS HOME PAGE

The GISS homepage on the Word Wide Web is located at the URL:

<https://www.giss.nasa.gov/>

All of the GISS website can be reached via the GISS homepage. These sites host a growing body of datasets, journal papers, preprints, software, and educational material. Sample GISS websites are depicted on the following pages including the GISS Publications main page.

The extensive GISS publications database is located at the URL:

<https://pubs.giss.nasa.gov/>

The publications website presently includes abstracts for more than 5700 GISS papers published since the institution's creation in 1961, with near complete coverage of papers published since 1990. Additionally, the publications site includes downloadable copies of about half of these papers, almost all of them in the widely used Acrobat/PDF format.

Information about GISS Research Projects and Groups can be found at:

<https://www.giss.nasa.gov/projects/>

Research at GISS emphasizes a broad study of global change, an interdisciplinary research initiative addressing natural and man-made changes in our environment which occur on various time scales from decades to millennia and which affect the habitability of our planet. The research combines analysis of comprehensive global datasets with global models of atmospheric, land surface, and oceanic processes and includes study of past events on Earth such as paleoclimate change and the study of to their planets as an aid to production of future evolution of Earth on a planetary scale.

Individual GISS projects can be accessed from the "Projects & Groups" tab on the GISS homepage. Some of these websites include:

Astrobiology — ROCKE-3D,

<https://www.giss.nasa.gov/projects/astrobio/>

Climate Impacts,

<https://www.giss.nasa.gov/projects/impacts/>

Goddard Institute Surface Temperature Analysis (GISTEMP),

<https://data.giss.nasa.gov/gistemp/>



[GISS Home](#)

[News & Features](#)

[Projects & Groups](#)

[Datasets](#)

[Publications](#)

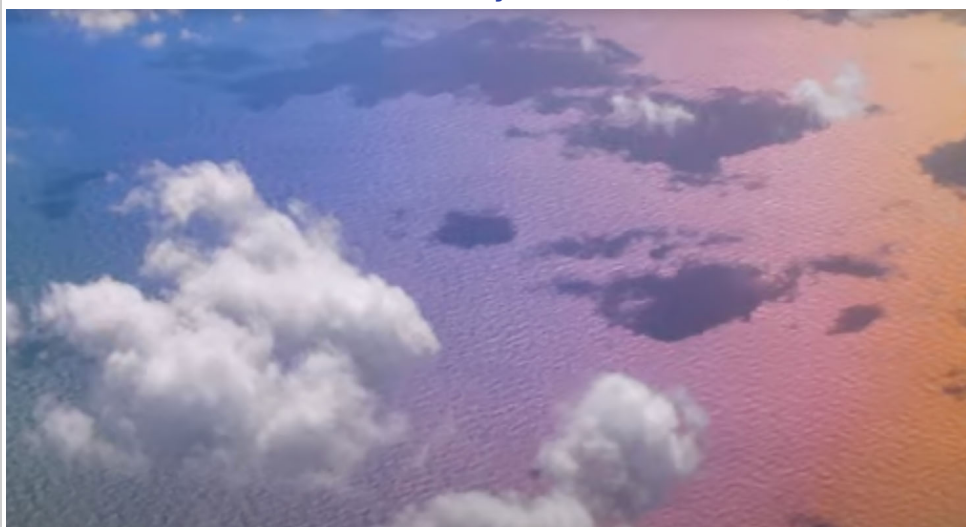
[Software](#)

[Education](#)

[Events](#)

[About GISS](#)

New NASA Satellite To Unravel Mysteries About Clouds, Aerosols



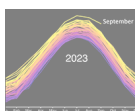
NASA's upcoming PACE mission will offer important insights on airborne particles of sea salt, smoke, human-made pollutants, and dust by observing how they interact with light. (2023-12-12)



[About PACE](#)



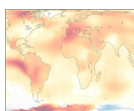
[Earth Sci 2023](#)



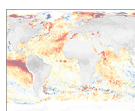
[Sept. '23 Temps](#)



[Indonesia Fires](#)



[Summer '23 Temps](#)

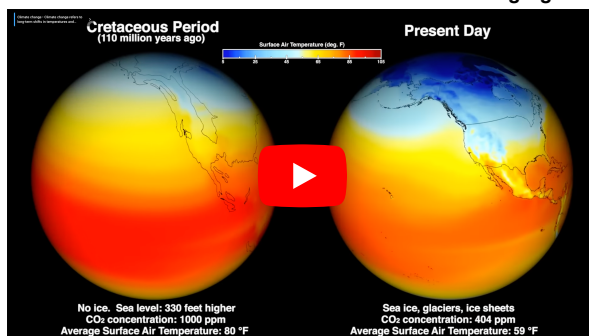


[Ocean Fever](#)

[More News & Features](#)

Featured Video

How Do We Know What Earth's Climate Was Like Long Ago?



About GISS

Research at NASA's Goddard Institute for Space Studies (GISS) emphasizes a broad study of global change, which is an interdisciplinary initiative addressing natural and man-made changes in our environment that occur on various time scales — from one-time forcings such as volcanic explosions, to seasonal and annual effects such as El Niño, and on up to the millennia of ice ages — and that affect the habitability of our planet.

GISS is located at [Columbia University](#) in [New York City](#). The institute is a laboratory in the [Earth Sciences Division](#) of NASA's [Goddard Space Flight Center](#) and is affiliated with the Columbia [Climate School](#) and [School of Engineering and Applied Science](#).

[+ More About GISS](#)

Recent Publications

Roach, L.A., K. Mankoff, A. Romanou, E. Blanchard-Wrigglesworth, T.W.N. Haine, and G.A. Schmidt, 2023: [Winds and meltwater together lead to Southern Ocean surface cooling and sea ice expansion](#). *Geophys. Res. Lett.*, **50**, no. 24, e2023GL105948, doi:10.1029/2023GL105948.

Cesana, G., A.S. Ackerman, T. Vaillant de Guélis, and D.S. Henderson, 2024: [Cloud-radiation interactions and cloud-climate feedbacks from an active-sensor satellite perspective](#). In *Clouds and Their Climatic Impact: Radiation, Circulation, and Precipitation*. S. Sullivan and C. Hoose, Eds., Geophysical Monograph Series, vol. 281, American Geophysical Union, pp. 87-102.

Barbara, J.M., R.A. West, A.D. Del Genio, and J.A. Sinclair, 2024: [A study of Jupiter's UV Great Dark Spot and tropopause to stratosphere winds in the high northern latitudes as seen by Cassini imaging](#). *Icarus*, **410**, 115913, doi:10.1016/j.icarus.2023.115913.

Schmidt, G.A., A. Romanou, L. Roach, K. Mankoff, Q. Li, C.D. Rye, M. Kelley, J.C. Marshall, and J.J.M. Busecke, 2023: [Anomalous meltwater from ice sheets and ice shelves is a historical forcing](#). *Geophys. Res. Lett.*, **50**, no. 24, e2023GL106530, doi:10.1029/2023GL106530.

[+ More Publications](#)



These database pages index more than 5900 publications authored or co-authored by NASA Goddard Institute for Space Studies scientists and colleagues since the institute was founded in 1961. Most entries are refereed journal articles, but the database also includes tech reports and tech notes, report chapters, book chapters, conference proceedings papers, doctoral dissertations, and other research publications. The database is not complete but is nearly so for the years after 1990.

Copies of some listed publications are also available here in PDF form. Otherwise, entries are citation and abstract only. Most listings also include a link to the appropriate journal website. Some include links to related news releases or non-technical science briefs describing the research.

Some complete papers provided here differ from the published form, most likely because they are post-publication versions that include typographical or other corrections. Unless otherwise indicated, the published version is the version intended by the author(s).

Recent Publications

Roach, L.A., K. Mankoff, A. Romanou, E. Blanchard-Wrigglesworth, T.W.N. Haine, and G.A. Schmidt, 2023: [Winds and meltwater together lead to Southern Ocean surface cooling and sea ice expansion](#). *Geophys. Res. Lett.*, **50**, no. 24, e2023GL105948, doi:10.1029/2023GL105948.

Leung, L.R., A. Terando, R. Joseph, G. Tselioudis, L.M. Bruhwiler, B. Cook, C. Deser, A. Hall, B.D. Hamlington, A. Hoell, F.M. Hoffman, S. Klein, V. Naik, A.G. Pendergrass, C. Tebaldi, P.A. Ullrich, and M.F. Wehner, 2023: [Chapter 3. Earth systems processes](#). In *Fifth National Climate Assessment*. A.R. Crimmins, C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds., U.S. Global Change Research Program, doi:10.7930/NCA5.2023.CH3.

Cesana, G., A.S. Ackerman, T. Vaillant de Guélis, and D.S. Henderson, 2024: [Cloud-radiation interactions and cloud-climate feedbacks from an active-sensor satellite perspective](#). In *Clouds and Their Climatic Impact: Radiation, Circulation, and Precipitation*. S. Sullivan and C. Hoose, Eds., Geophysical Monograph Series, vol. 281, American Geophysical Union, pp. 87-102, doi:10.1002/9781119700357.ch4.

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Tornow, F., A.S. Ackerman, A.M. Fridlind, G. Tselioudis, B. Cairns, D. Painemal, and G. Elsaesser, 2023: [On the impact of a dry intrusion driving cloud-regime transitions in a mid-latitude cold-air outbreak](#). *J. Atmos. Sci.*, **80**, no. 12, 2881-2896, doi:10.1175/JAS-D-23-0040.1.

Črnivec, N., G. Cesana, and R. Pincus, 2023: [Evaluating the representation of tropical stratocumulus and shallow cumulus clouds as well as their radiative effects in CMIP6 models using satellite observations](#). *J. Geophys. Res. Atmos.*, **128**, no. 23, e2022JD038437, doi:10.1029/2022JD038437.

Annual Lists

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[2024](#), [2023](#), [2022](#), [2021](#),
[2020](#), [2019](#), [2018](#), [2017](#), [2016](#),
[2015](#), [2014](#), [2013](#), [2012](#), [2011](#),
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Papers [in press](#) or [accepted](#) for publication.

Other Lists

+ [Author Bibliographies](#)
+ [Best Paper of the Year](#)
+ [Most Cited Papers](#)
+ [Doctoral Dissertations](#)

Publication Links

+ [GSFC Earth Sciences Publications](#)
+ [SAO/NASA Astrophysics Data System](#)
+ [NASA Technical Reports Server](#)
+ [DOI Resolver](#)
+ [IPCC Assessment Reports](#)

Research Projects & Groups



Following are links to some homepages for projects and groups on which GISS researchers are involved.

Astrobiology, Exoplanets and ROCKE-3D

The GISS Astrobiology and Exoplanets group is an interdisciplinary team of scientists interested in understanding our solar system through time — from the early configuration of the planets nearly 4 billion years ago to their modern state. Our focus, using the ROCKE-3D model, is on characterizing the habitability of rocky planets, extending that understanding to the climates of extrasolar planets, but also includes understanding environments as diverse as Venus, Titan and Archean Earth.

+ [Read More](#)



Climate Impacts

The Climate Impacts group at NASA GISS seeks to improve understanding of how climate affects human society through assessment of the effect of current climate variability and of potential climate change impacts caused by anthropogenic emissions of greenhouse gases and aerosols. Impacts research includes development of a framework to analyze complex interactions among biophysical and socio-economic processes.

+ [Read More](#)



Climate Modeling

The climate modeling program at GISS is primarily aimed at the development of 3D general circulation models (GCMs) and coupled atmosphere-ocean models for simulating Earth's climate system, although some research may include the use of regional climate models, 2D energy balance models, and 1D radiative-convective models. Primary emphasis is placed on investigation of climate sensitivity, including the climate system's response to forcings such as solar variability, anthropogenic and natural emissions of greenhouse gases and aerosols, etc.

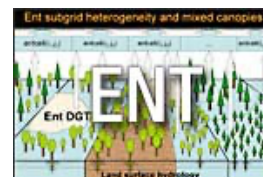
+ [Read More](#)



Ent Terrestrial Biosphere Model (Ent TBM)

The Ent model is a demographic dynamic global vegetation model developed specifically for coupling with Earth system models. Ent provides the GISS model with satellite-observed vegetation canopy structure, land surface albedo, and surface fluxes of water and carbon dioxide to the atmosphere, with canopy structure also used as boundary conditions for dust dynamics and vegetation emissions for atmospheric chemistry. Ent is also slated to serve as a lidar observation simulator of vertical canopy structure and to provide prognostic vegetation growth and decadal to century-scale alterations in vegetation cover and soil carbon and nitrogen.

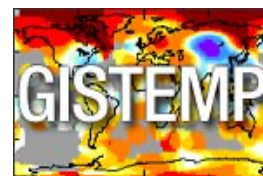
+ [Read More](#)



Goddard Institute Surface Temperature Analysis (GISTEMP)

Surface air temperature change is a primary measure of global climate change. The GISTEMP project started in the late 1970s to provide an estimate of the changing global surface air temperature which could be compared with the estimates obtained from climate models simulating the effect of changes in atmospheric carbon dioxide, volcanic aerosols, and solar irradiance. The continuing analysis updates global temperature change from the late 1800s to the present.

+ [Read More](#)



Plankton, Aerosol, Cloud, ocean Ecosystem (PACE)

PACE's data will help us better understand how the ocean and atmosphere exchange carbon dioxide. In addition, it will reveal how aerosols might fuel phytoplankton growth in the surface ocean. Novel uses of PACE data will benefit our economy and society. For example, it will help identify the extent and duration of harmful algal blooms. PACE will extend and expand NASA's long-term observations of our living planet. By doing so, it will take Earth's pulse in new ways for decades to come.

+ [Go to Website](#)



For more, see <https://www.giss.nasa.gov/projects/>

B. Global Data and Model Simulations

GISS datasets are accessible from our main datasets index at:

<https://data.giss.nasa.gov/>

This page links to introductory pages for each available dataset, which in turn link to the actual data and to sample code snippets and images. In many cases, such as model simulation datasets and the GISS global temperature analysis, the user can interactively create graphics from the data.

Ready access to our global data sets and the results of our model simulations facilitates interactions with the outside community. It is with this in mind that we are giving priority to putting these data in convenient forms. This includes data that can be downloaded directly from our web pages, larger data sets that are available via ftp, climate model simulations, and downloadable software.

This section also includes the GISS "Software Tools" homepage, which can be found at:

<https://www.giss.nasa.gov/tools/>

This page provides an index of downloadable GISS-created software applications, including three versions of the GISS climate model and other research tools. Among these are the FORTRAN source code for the new GISS ModelE coupled atmosphere-ocean model and the cross-platform Panoply netCDF data viewer.



Datasets and derived material are available from the NASA GISS websites for the following research projects:

Climate Simulations

GISS ModelE

- Earth's Energy Imbalance
- Efficacy of Climate Forcings
- Climate Simulations for 1880-2003
- Dangerous Human-Made Interference
- Transient Simulations with Beryllium-10
- Simulated Greenland Surface Mass Balance
- Desert Dust, Industrialization and Agricultural Fires

SWING2 Stable Water Isotope Intercomparisons

Climate Forcings

- Forcings in GISS Climate Model
- Dust Mineral Fractions at Emission
- Globally Uniform Mineral Dust Aerosols
- Global Land Cover Datasets
- Surface Exchange of Carbon Dioxide
- Surface Exchange of Methane

Climate Impacts

- AgMIP Climate Forcing Datasets for Agricultural Modeling
- Evolving Fragility of the Global Food System
- Global Fire Weather Database (GFWED)

Planets, Exoplanets and Astrobiology

- Simulations of Planetary Climates with ROCKE-3D
- Saturn Mean Zonal Winds and Eddy Momentum Fluxes
- Objective Classification of Saturn Cloud Features

Astrophysics

- Molecular Collision Rates Relevant to Microwave and IR Astronomy

Earth Observations

Temperature

- GISS Surface Temperature Analysis (GISTEMP)
- GISTEMP Uncertainty Quantification
- Common Sense Climate Index (CSCI)

Aerosols

- Research Scanning Polarimeter (RSP)
- Global Aerosol Climatology Project (GACP)
- Stratospheric Aerosol and Gas Experiment II (SAGE II) V6.20

Clouds

- International Satellite Cloud Climatology Project (ISCCP)
- GEWEX Cloud System Study Data Integration for Model Evaluation (GCSS-DIME)
- Cumulus And Stratocumulus Cloudsat-CALipso Dataset (CASCCAD)

Oceans

- Global Seawater Oxygen-18 Database
- Ocean Carbon States — Database and Toolbox

Precipitation

- Observed Land Surface Precipitation Data: 1850-1995

Radiative Flux

- ISCCP-FH Global Surface and Atmospheric Radiative Fluxes
- ISCCP-FH Radiative Kernels
- Surface Solar Irradiance: Datasets Produced for SeaWiFS

Storms

- Atlas of Extratropical Storm Tracks
- Observations of Extratropical Cyclones — Databases



Software Tools

```
// The partial derivatives
df1dPhi = - sinHalfLambda * sinPhi;
df1dLambda = 0.5 * onePlusCosPhi * cosHalfLambda;
df2dPhi = cosTilt * cosPhi + sinTilt * cosHalfLambda * sinPhi;
df2dLambda = 0.5 * sinTilt * (onePlusCosPhi) * sinHalfLambda;

// Equations 15 and 16.
denom = df1dPhi * df2dLambda - df2dPhi * df1dLambda;
dPhi = (f1 * df2dLambda - f2 * df1dLambda) / denom;
```

This page provides links to several self-contained, downloadable software products that have been developed by GISS personnel, either for specific research purposes or for more general analytic use.

Climate Modeling

GISS GCM - Model E

Fortran 90 source and documentation for the GISS ModelE series of coupled atmosphere-ocean models. These models have been used for our contribution to the CMIP3 and CMIP5 archives of model simulation results.

[+ Read More](#)

Exoplanets & Planetary Science

GISS GCM - ROCKE-3D

Fortran 90 source and documentation for a version of GISS modelE GCM specially adapted for planetary (non-modern-Earth) simulations.

[+ Read More](#)

Mars24

Desktop application that calculates the solar and mean time for any location on the planet Mars, presenting the data as digital readouts and in "sunclock" format. (Requires Java)

[+ Read More](#)

Radiation

T-Matrix Codes

Fortran source code for computing electromagnetic scattering by nonspherical and aggregated particles.

[+ Read More](#)

Bidirectional Reflection Codes

Fortran source code for computing bidirectional reflection function for a semi-infinite homogeneous slab composed of arbitrarily shaped, randomly oriented particles.

[+ Read More](#)

Data Visualization

Panoply

Desktop application that interactively plots georeferenced and other data encoded in netCDF, HDF and GRIB file formats. (Requires Java)

[+ Read More](#)

G.Projector

Desktop application that explores over 200 map projections, including transformation of input equirectangular map images. (Requires Java)

[+ Read More](#)

Numerical Tools

JIGSAW(GEO)

C++ package that generates variable resolution unstructured mesh grids in complex domains. It is useful for multi-resolution GCMs and climate process modeling.

[+ Read More](#)

Astrophysics

MOLSCAT

Fortran source for quantum mechanical solution of nonreactive molecular scattering, useful in astrophysical studies.

[+ Read More](#)

C. Research News and Features and Science Nuggets

The communication of research goals and results with the public is one important aspect of our research program. GISS researchers are encouraged to prepare one-page summaries of their principal publications, in language meaningful to the educated laity.

To further our communication of GISS research, this publications document also includes “News & Features,” NASA media releases about notable GISS research accomplishments. Following are copies of this year’s “NASA News and Feature Releases” and “Science Nuggets.” All belong to a larger collection of articles which are available at the GISS homepage.



Following are news releases and features posted during 2023 about research at NASA's Goddard Institute for Space Studies.

New NASA Satellite To Unravel Mysteries About Clouds, Aerosols

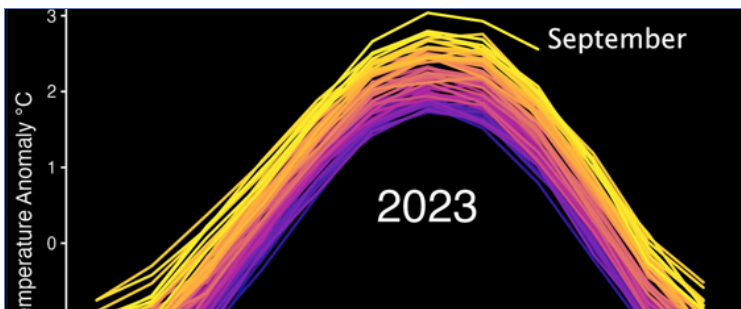


NASA's upcoming PACE mission will offer important insights on airborne particles of sea salt, smoke, human-made pollutants, and dust by observing how they interact with light.

(2023-12-12)

+ [Go to NASA Release](#)

September 2023 Temperature Data Shows Continued Record Warming

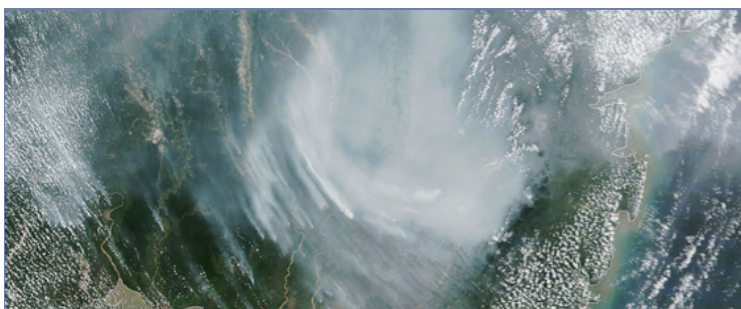


Continuing the temperature trend from this summer, September 2023 was the hottest September on record, according to scientists at NASA's Goddard Institute for Space Studies.

(2023-10-13)

+ [Go to NASA Release](#)

Indonesian Fires Return in 2023

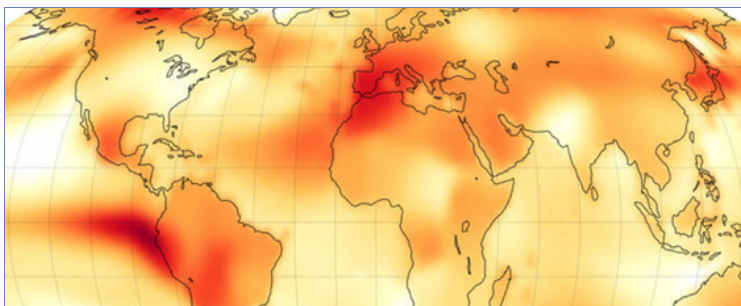


After several years of comparatively quiet fire seasons, Indonesia saw the return of intense, smoky fires in 2023. The blazes have been exacerbated by dry conditions made worse by the return of El Niño.

(2023-10-07)

+ [Go to NASA EO Feature](#)

NASA Announces Summer 2023 Hottest on Record



Summer of 2023 was Earth's hottest since global records began in 1880, according to scientists at NASA's Goddard Institute of Space Studies.

(2023-09-14)

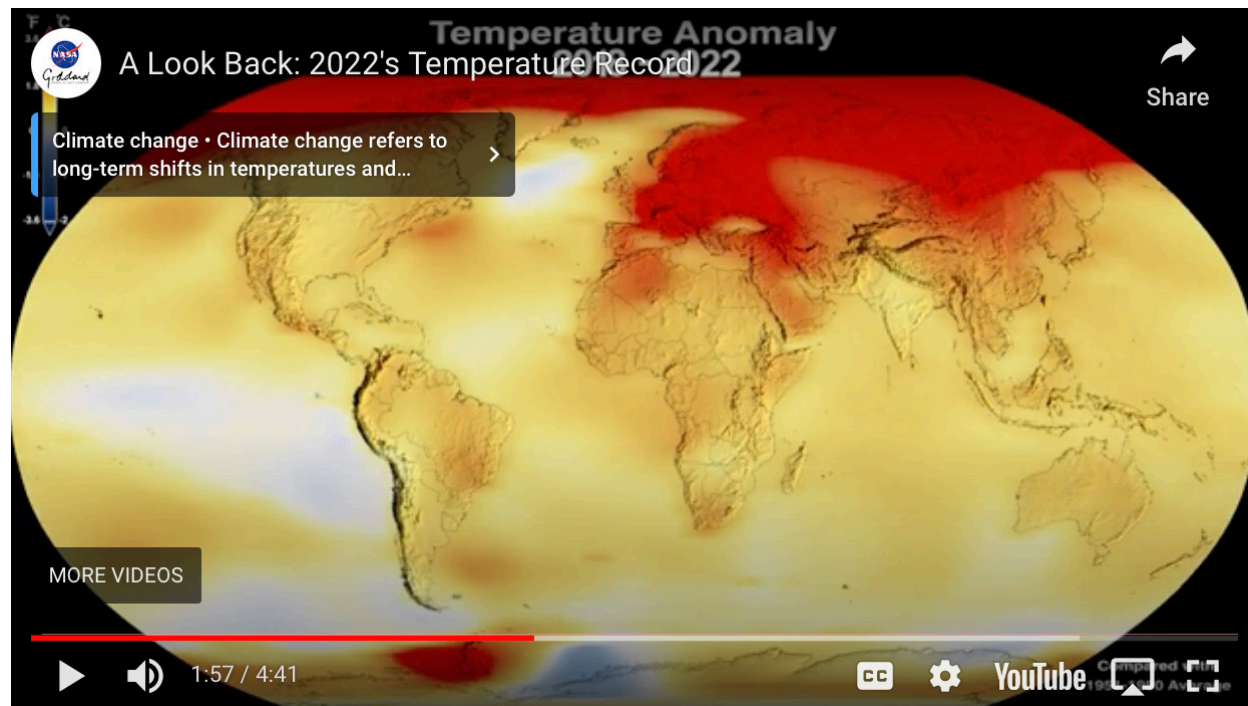
+ [Go to NASA Release](#)

For more GISS Research News & Features, see <https://www.giss.nasa.gov/research/>

NASA Says 2022 Fifth Warmest Year on Record, Warming Trend Continues

By Roxana Barden — Release 23-005 — Jan. 12, 2023

Earth's average surface temperature in 2022 tied with 2015 as the fifth warmest on record, according to an analysis by NASA. Continuing the planet's long-term warming trend, global temperatures in 2022 were 1.6 degrees Fahrenheit (0.89 degrees Celsius) above the average for NASA's baseline period (1951-1980), scientists from NASA's Goddard Institute for Space Studies (GISS) in New York reported.



2022 effectively tied for Earth's 5th warmest year since 1880, and the last 9 consecutive years have been the warmest 9 on record. NASA looks back at how heat was expressed in different ways around the world in 2022. **Video Credits:** NASA / GSFC / Kathleen Gaeta

"This warming trend is alarming," said NASA Administrator Bill Nelson. "Our warming climate is already making a mark: Forest fires are intensifying; hurricanes are getting stronger; droughts are wreaking havoc and sea levels are rising. NASA is deepening our commitment to do our part in addressing climate change. Our Earth System Observatory will provide state-of-the-art data to support our climate modeling, analysis and predictions to help humanity confront our planet's changing climate."

The past nine years have been the warmest years since modern recordkeeping began in 1880. This means Earth in 2022 was about 2 degrees Fahrenheit (or about 1.11 degrees Celsius) warmer than the late 19th century average.

"The reason for the warming trend is that human activities continue to pump enormous amounts of greenhouse gases into the atmosphere, and the long-term planetary impacts will also continue," said Gavin Schmidt, director of GISS, NASA's leading center for climate modeling.

Human-driven greenhouse gas emissions have rebounded following a [short-lived dip](#) in 2020 due to the COVID-19 pandemic. Recently, NASA scientists, as well as international scientists, determined carbon dioxide emissions were the [highest on record](#) in 2022. NASA also identified some [super-emitters](#) of methane – another powerful greenhouse gas – using the Earth Surface Mineral Dust Source Investigation instrument that launched to the International Space Station last year.

The Arctic region continues to experience the strongest warming trends – close to four times the global average – according to [GISS research](#) presented at the 2022 annual meeting of the American Geophysical Union, as well as a separate [study](#).

Communities around the world are experiencing impacts scientists see as connected to the warming atmosphere and ocean. Climate change has intensified rainfall and tropical storms, deepened the severity of droughts, and increased the impact of storm surges. Last year brought torrential monsoon rains that devastated Pakistan and a persistent [megadrought](#) in the U.S. Southwest. In September, [Hurricane Ian](#) became one of the strongest and costliest hurricanes to strike the continental U.S.

Tracking Our Changing Planet

NASA's global temperature analysis is drawn from data collected by weather stations and Antarctic research stations, as well as instruments mounted on ships and ocean buoys. NASA scientists analyze these measurements to account for uncertainties in the data and to maintain consistent methods for calculating global average surface temperature differences for every year. These ground-based measurements of surface temperature are consistent with satellite data collected since 2002 by the Atmospheric Infrared Sounder on NASA's Aqua satellite and with other estimates.

NASA uses the period from 1951-1980 as a baseline to understand how global temperatures change over time. That baseline includes climate patterns such as La Niña and El Niño, as well as unusually hot or cold years due to other factors, ensuring it encompasses natural variations in Earth's temperature.

Many factors can affect the average temperature in any given year. For example, 2022 was one of the warmest on record despite a third consecutive year of La Niña conditions in the tropical Pacific Ocean. NASA scientists estimate that La Niña's cooling influence may have lowered global temperatures slightly (about 0.11 degrees Fahrenheit or 0.06 degrees Celsius) from what the average would have been under more typical ocean conditions.

A [separate, independent analysis](#) by the National Oceanic and Atmospheric Administration (NOAA) concluded that the global surface temperature for 2022 was the sixth highest since 1880. NOAA scientists use much of the same raw temperature data in their analysis and have a different baseline period (1901-2000) and methodology. Although rankings for specific years can differ slightly between the records, they are in broad agreement and both reflect ongoing long-term warming.

NASA's [full dataset of global surface temperatures](#) through 2022, as well as full details with code of how NASA scientists conducted the analysis, are publicly available from GISS.

GISS is a NASA laboratory managed by the Earth Sciences Division of the agency's Goddard Space Flight Center in Greenbelt, Maryland. The laboratory is affiliated with Columbia University's Earth Institute and School of Engineering and Applied Science in New York.

For more information about NASA's Earth science programs, visit:

<https://www.nasa.gov/earth>

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From <https://www.nasa.gov/news-release/nasa-says-2022-fifth-warmest-year-on-record-warming-trend-continues/>

NASA News & Feature Releases

NASA Scientists & Historian Named AAAS 2022 Fellows

By Goddard Digital Team — Jan. 31, 2023

Four individuals with NASA affiliations have been named 2022 fellows by the American Association for the Advancement of Science (AAAS) in recognition of their scientifically and socially distinguished achievements in the scientific enterprise.

Election as a Fellow by the AAAS Council honors members whose efforts on behalf of the advancement of science or its applications in service to society have distinguished them among their peers and colleagues. The 2022 Fellows class includes 508 scientists, engineers, and innovators spanning 24 scientific disciplines.

Rita Sambruna from NASA's [Goddard Space Flight Center](#) in Greenbelt, Maryland, was recognized in the AAAS Section on Astronomy, and Jennifer Wiseman, also from Goddard, was recognized in the AAAS Section on Physics. Dorothy Peteet of [NASA's Goddard Institute for Space Studies \(GISS\)](#) in New York was honored in the AAAS section on Earth Science. Erik Conway of [NASA's Jet Propulsion Laboratory](#) (JPL) in southern California was honored for distinguished contributions and public outreach to the history of science and understanding of contemporary science and science policy.

Rita Sambruna

Dr. Rita Sambruna is the acting deputy director of the Science and Exploration Directorate and the deputy director of the Astrophysics Division at Goddard. She also promotes increased participation of underrepresented groups in science.

She worked with a team to position Goddard to lead the decadal top priority missions. She led a team to set into place a vision for a Multi-Messenger Astrophysics Science Support Center at Goddard, to lead the astrophysics community in reaping the most from NASA- and ground-based observations of celestial sources.

She came to Goddard in 2005 to work on multiwavelength observations of jets using the [Fermi Gamma-ray Space Telescope](#) and other NASA capabilities. From 2010 to 2020 she worked at NASA Headquarters, Washington, as a program scientist for astrophysics. Her research interests include relativistic jets, physics of compact objects, supermassive black holes in galaxies, and multiwavelength and multi-messenger astrophysics.

In December 2022, Sambruna was awarded the Honorary Fellowship of the Royal Astronomical Society (RAS) as an internationally acclaimed astrophysicist who embodies the RAS mission in promoting the advancement of science, the increased participation of historically underrepresented groups in astronomy, and a broad interest in astronomy. In 2019 she was awarded the NASA Extraordinary Achievement Medal for her leadership on the [2020 Astrophysics Decadal Survey](#) studies. She was named Fellow of the [American Physical Society](#) in 2020 and a Fellow of the American Astronomical Society in 2021.

Jennifer Wiseman

[Dr. Jennifer Wiseman is a senior astrophysicist at Goddard](#) and a [Senior Fellow](#) at Goddard, where she serves as the senior project scientist for the [Hubble Space Telescope](#). Her primary responsibility is to ensure that the Hubble mission is as scientifically productive as possible. Previously, Wiseman headed [Goddard's Laboratory for Exoplanets and Stellar Astrophysics](#). She started her career at NASA in 2003 as the program scientist for Hubble and several other astrophysics missions at NASA Headquarters.

Wiseman's scientific expertise is centered on the study of star-forming regions in our galaxy using a variety of tools, including radio, optical, and infrared telescopes. She has a particular interest in dense interstellar gas cloud cores, embedded protostars, and their related outflows as active ingredients of cosmic nurseries where stars and their planetary systems are born. In addition to research in astrophysics, Wiseman is also interested in science policy and public science outreach and engagement. She has served as a congressional science fellow of the [American Physical Society](#), an elected councilor of the [American Astronomical Society](#), and a public dialogue leader for AAAS. She enjoys giving talks on the excitement of astronomy and scientific discovery, and has appeared in many science and news venues, including The New York Times, The Washington Post, NOVA, and National Public Radio.

Dorothy Peteet

[Dr. Dorothy M. Peteet](#) is a senior research scientist at GISS and an adjunct professor at Columbia University. She directs the Paleoecology Division of the New Core Lab at Lamont Doherty Earth Observatory (LDEO) of Columbia.

In collaboration with GISS climate modelers and LDEO geochemists, she is studying conditions of the Late Pleistocene and Holocene that are archived in sediments from lakes and wetlands. Peteet documents past changes in vegetation, derived from analyses of pollen and spores, plant and animal macrofossils, carbon, and charcoal embedded in sediments. Her research provides local and regional records of ancient vegetational and climate history. One recent focus has been the sequestration of carbon in northern peatlands and coastal marshes: ecosystems that are now vulnerable to climate change and potentially substantial releases of carbon back into the atmosphere.

Peteet also has performed climate modeling experiments to test hypotheses concerning the last glacial maximum and abrupt climate change. She is interested in climate sensitivity and in how past climate changes and ecological shifts might provide insights on future climate change.



Dr. Dorothy M. Peteet. NASA

Erik Conway

[Erik Conway](#) has served as the historian at JPL since 2004. Prior to that, he was a contract historian at NASA's Langley Research Center in Hampton, Virginia. He is a historian of science and technology, and has written histories of atmospheric science, supersonic transportation, aviation infrastructure, Mars exploration, and climate change denial.

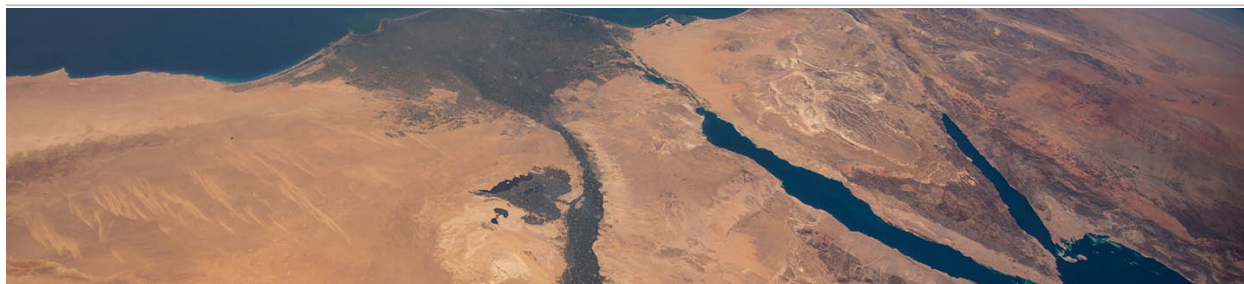
He is the author of nine books, most recently, *"A History of Near-Earth Objects Research"* (NASA, 2022), and *"The Big Myth"* (Bloomsbury, 2023). His book *"Merchants of Doubt"* with Naomi Oreskes was awarded the Helen Miles Davis and Watson Davis prize from the History of Science Society. He received a Guggenheim Fellowship in 2018 and the Athelstan Spilhaus Award from the American Geophysical Union in 2016.

AAAS noted that these honorees have gone above and beyond in their respective disciplines. They bring a broad diversity of perspectives, innovation, curiosity, and passion that will help sustain the scientific field today and into the future. Many of these individuals have broken barriers to achieve successes in their given disciplines.

AAAS is the world's largest general scientific society and publisher of the Science family of journals.

For information about NASA and agency programs, visit: <https://www.nasa.gov>

From <https://www.nasa.gov/centers-and-facilities/goddard/nasa-scientists-historian-named-aaas-2022-fellows/>



Hydroclimatic Impacts of Persistent Explosive Volcanism

Mar. 27, 2023

On June 15, 1991, Mount Pinatubo, a volcano in the Philippines, erupted, injecting approximately 18.5 million metric tons of sulfur dioxide (SO_2) into the stratosphere, creating sulfate aerosols that caused a mean global cooling of 0.5°C ($\sim 1^\circ\text{F}$) at surface for a couple of years, in one of the largest and best observed eruptions of the 20th century. Scientists examine this event to study what the potential impact might be of large eruptions in the future.

Separately, volcanic eruptions have also inspired a geoengineering idea in which the artificial injection of reflective aerosols into the upper atmosphere could provide a “solar radiation management” to mask greenhouse gas-induced global warming. However, large volcanic eruptions affect many more aspects of the Earth system beyond surface temperature. What would be the impact on human civilization? Could we adapt to changes of climate, temperatures, and even the hydrological cycle, all of which could interfere with food production and supply?

Although climate models can simulate the answer to these questions, there is only the single Mount Pinatubo example in the satellite era to inform such models. The magnitude and impact of other volcanoes must rely on simulations of atmospheric aerosols produced from past globally disruptive events, and then scientists study the resulting climate impacts in the context of history.

A real-world case of the consequences of persistent volcanic forcing appears in historical

archives of Ptolemaic Egypt (305–30 BCE; see Fig. 1). This period in Egypt was a time of cultural and scientific advancement, greatly aided by the reliable annual flood of the Nile River, which (paired with seasonal human damming of these fertile waters) allowed a large, reliable food crop to be grown. The Ptolemaic era also suffered intense power struggles with rival powers and internal revolt and unrest; 12 of these 26 Ptolemaic-era revolts began close in time to volcanic eruption dates, suggesting volcanoes disrupted this society.

How exactly does the link between eruptions and poor Nile flooding work?

Climate scientists from Columbia University and the NASA Goddard Institute for Space Studies (GISS) partnered with historians, climate scientists, and hydrologists from Ireland to California to form the [Yale Nile Initiative](#) to explore the links between explosive volcanism and hydroclimate responses across the Nile River basin during the Ptolemaic era.

Within the decade of 168 to 158 BCE, four large volcanoes erupted, and the climate impacts reverberated across the world. Although we do not know exactly where these volcanoes were, we can infer their latitude



Figure 1. A) Ancient Egyptians had a highly organized agriculture system, and this papyrus bears an administrative correspondence regarding a crop survey dated to before 190 BCE (Image credit: P. Yale I 36 (CtYBR inv. 1647)); B) A copper coin from Ptolemaic Egypt, showing the likeness of Ptolemy II, King of Egypt, 309–246 BCE, and who ruled 283–246 BCE. The coin, made of copper, was minted in Alexandria between 285–246 BCE. (Image credit: Ruth Elizabeth White Fund, Yale Art Gallery 2004.6.4054).

from “fossil” volcanic sulfate layers preserved in the polar ice caps. The first volcano was tropical in origin and about 125% the size of the 1991 Pinatubo eruption. The rest of the decade had evenly spaced eruptions of one-third the size of the 1991 Pinatubo eruption. Ptolemaic Egypt had exceptionally poor Nile flooding in 169 BCE and further failures in 166 and 161 BCE. These flooding failures and related agricultural crises (crop failures) may have laid the groundwork for internal revolts and unrest. The Ptolemaic 160s BCE decade was peppered with uprisings and power struggles, including the invasion of Seleukid King Antiochus IV during the 6th Syrian war (170 and 168 BCE) and the intervention of self-interested Romans to stop the Seleukids.

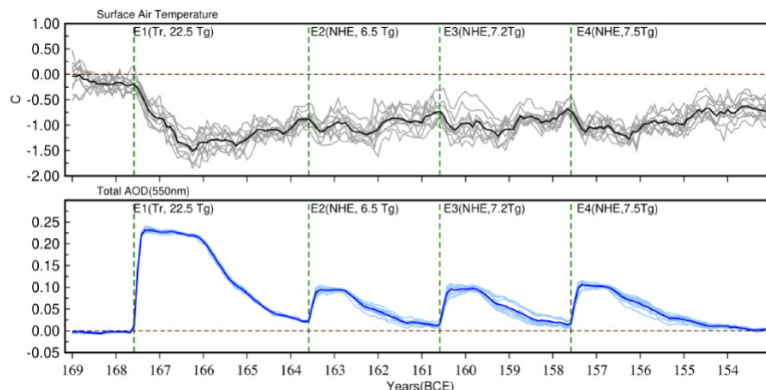


Figure 2. The blue lines in the lower panel show the simulated increases in atmospheric opacity (or aerosol optical depth, at 550nm wavelength) after the repeated injection of SO₂ from the “volcanic quartet” which caused the simulated global surface cooling shown in the top panel (see the black lines). (Image credit: Singh et al. 2023)

Could these four volcanos of the 160s BCE have caused a failure of the Nile Flood by impacting rainfall of its headwaters in Ethiopia and the Great Lakes? What other impacts did they have? What lessons can we learn?

GISS ModelE incorporates our knowledge of how the climate system works — including predictions for how aerosols interact with climate, the biosphere, the cryosphere, and the ocean. We set it to a [baseline of the Ptolemaic Era](#), then injected SO₂ into the virtual atmosphere (Fig. 2).

Persistent volcanic aerosols from the eruption quartet created a cascade of modeled impacts on temperature and rainfall of the 160s BCE, with the impacts of the initial volcanic eruption in 168 BCE being sustained for

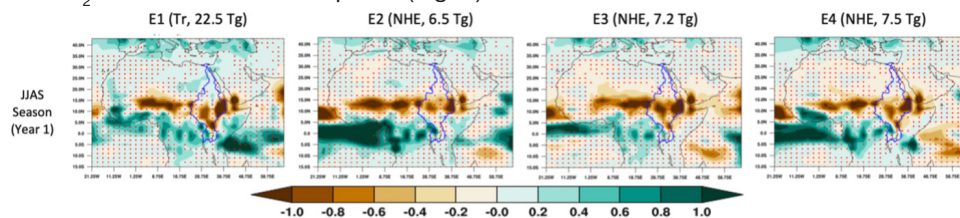


Figure 3. This graph shows the decrease in monsoon season (June to September) rainfall for the first year after each of the eruption over Africa. The blue line outlines the modern Nile River basin extent; brown colors indicate drying areas. (Image credit: Singh et al. 2023)

over a decade (Fig. 2). These aerosols hindered the northward migration of the tropical rainfall belt during the northern hemisphere summer and monsoon season over East Africa as well as the South and East Asia monsoons in the northern hemisphere, including rainfall over the Ethiopian highlands, the headwater of the Nile (Fig. 3). Annually, Nile River water flow was reduced as much as 38% after the first and largest eruption and up to 18% after the subsequent three eruptions.

This Ptolemaic “volcanic quartet” provides a natural lesson for us looking towards the future as we consider geoengineering ideas such as solar resource management. Prolonged aerosol forcing not only decreases temperature, but also causes adverse climate impacts through altering rainfall patterns, potentially diminishing food security for many nations. We did not study here the direct impact that a change from direct sunlight to scattered sunlight (diffuse radiation) might have on crop yields and regional ecosystems. However, our study points to the need for continuing research into the potential adverse impacts at regional and sub-regional scales from any deliberate effort at solar radiation management.

Reference

Singh, R., K. Tsigaridis, A.N. LeGrande, F. Ludlow, and J.G. Manning, 2023: [Investigating hydroclimatic impacts of the 168–158 BCE volcanic quartet and their relevance to the Nile River basin and Egyptian history](#), *Clim. Past*, **19**, 249–275, <https://doi.org/10.5194/cp-19-249-2023>, 2023.

NASA Center For Climate Simulation: NCCS Highlights

Simulations Probe the Impacts of Air Pollution on Premature Deaths

By Jarrett Cohen — Apr. 26, 2023

Models from Aarhus University ([AU](#)) in Denmark and the NASA Goddard Institute for Space Studies ([GISS](#)) in New York City worked in concert to study the impact of air pollution on premature mortality — both globally and regionally — under several emission and population scenarios.

The World Health Organization has ranked air pollution as the world's largest single environmental health risk. "Our primary goal was to extend our modeling capabilities to better represent highly polluted regions, such as those in Asia and Africa," said [Ulas Im](#), Senior Scientist in AU's [Department of Environmental Science](#). "The study evaluates mortality estimates based on different approaches globally and regionally and attempts to differentiate between the impacts of emissions and population dynamics."

The AU Senior Scientist collaborated with GISS Research Physical Scientist [Susanne Bauer](#), GISS/Columbia University Research Scientist [Konstantinos Tsigaridis](#), and several other AU and GISS scientists on the computational study, which was recently published in the journal *Environmental Research*.

The study combined the GISS [ModelE](#) climate model, developed on the NASA Center for Climate Simulation (NCCS) [Discover supercomputer](#), with AU's Economic Valuation of Air Pollution ([EVA](#)) model.

"NCCS resources were key for GISS model development, to which some of my co-authors contribute," Im said. "As external partners we can get the input files and other needed resources from NCCS, such as restart files of equilibrated versions of the model, to save computational time in studies like this one."

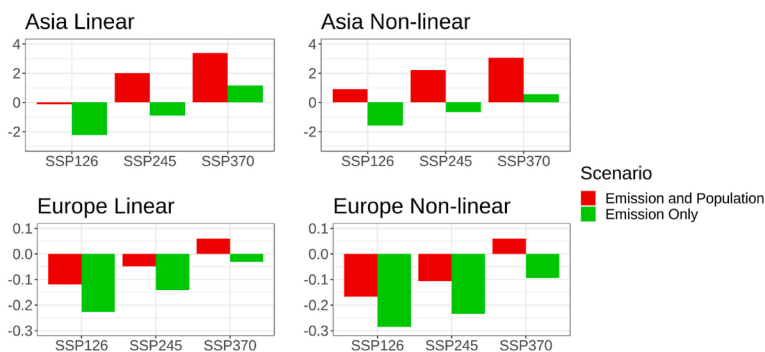
The researchers used the [GISS-E2.1-G](#) model to carry out fully coupled atmosphere-ocean climate simulations for the years 2015–2050 using three different emission scenarios from the Coupled Model Intercomparison Project Phase 6 ([CMIP6](#)). Next, surface concentrations from GISS-E2.1-G and population data served as inputs to EVA6.0 for calculating exposure to air pollution and then mortality rates. The simulations ran on high-performance computing servers in AU's Department of Environmental Science.

The simulations focused on estimating:



Buildings in New Delhi, India, are barely visible due to thick smog — typically a mixture of surface ozone, particulate matter, and other pollutants. [Photo](#) by Sumita Roy Dutta, [CC BY-SA 4.0](#), via Wikimedia Commons.

Mortality 2050-2015



The graph shows the difference in total (PM_{2.5}+O₃) premature deaths from the future (2050) compared to the present (2015) due to changes in emissions only (green) and changes in both emissions and population (red) for Asia (top panel) and Europe (lower panel), estimated using linear (left panel) and non-linear (right panel) methods. Figure from Im et al., 2023.

- Future changes in global and regional mortality from exposure to surface particulate matter (PM_{2.5}) and ozone (O₃) pollutants under emission scenarios spanning from high to low mitigation, and
- The role of population and age distribution changes in premature deaths.

“The extended version of the EVA model can use both linear and non-linear risk functions to estimate mortality,” Im said. “The linear model assumes a linear relationship between pollutant mass concentrations and mortality, while the non-linear method uses a fit between the pollutant and mortality based on epidemiological studies, where the relationship may not be linear.”

“Using a linear approach in high-pollution regions such as Asia or Africa can lead to overestimation of calculated mortality,” he added. “We saw agreement between both methods on a global basis, while, on a regional basis, there can be large differences.”

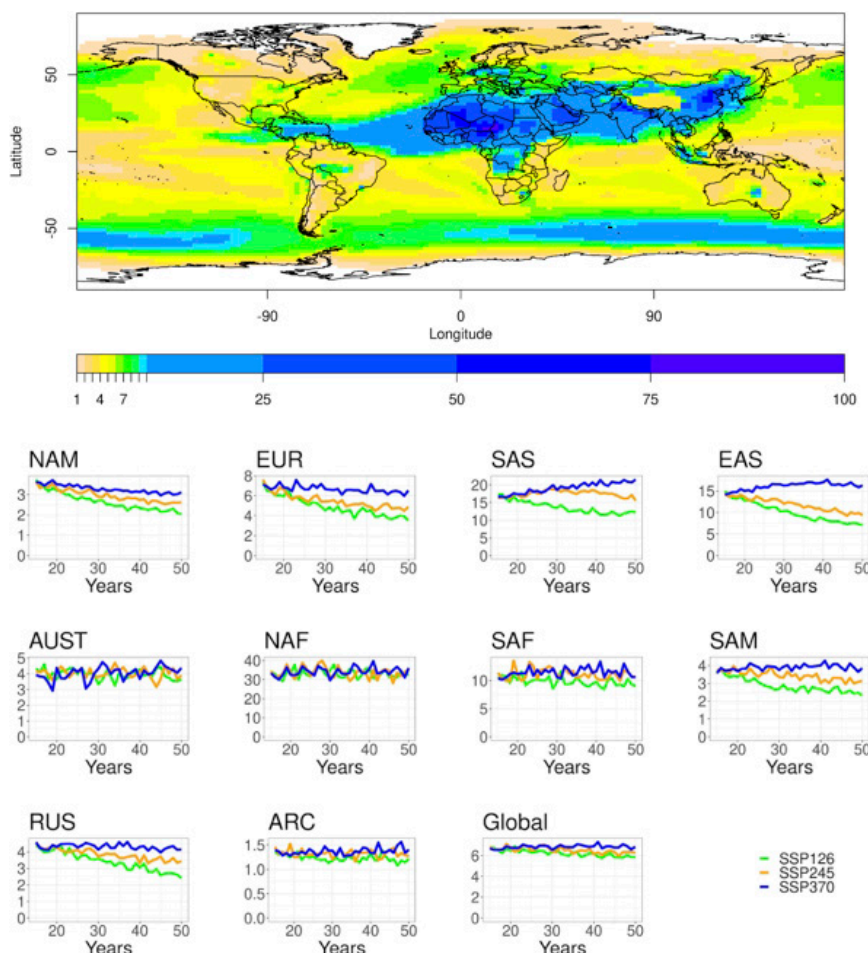
The simulation results show that surface PM_{2.5} and O₃ pollutants lead to more than 7 million premature deaths globally, with 2/3 originating in Asia. Emissions mitigation can yield up to 70% improvement by 2050 compared to today. However, in some hotspot regions an increasing and aging population can hamper this improvement, leading to an overall increase in mortality even under the most ambitious emission mitigation scenarios.

“The findings suggest that an increasing and aging population can hamper the efforts to decrease human-made emissions,” Im said. “Therefore, air quality and public health regulations should take this factor into account.”

In follow-up, Im noted that the collaboration between AU and GISS continues along several fronts. These include sometimes running simulations simultaneously on AU and NCCS supercomputers to double the computational resources and speed up the generation of output.

Reference

- Im, U., S.E. Bauer, L.M. Frohn, C. Geels, K. Tsigaridis, and J. Brandt, 2023: [Present-day and future PM_{2.5}- and O₃-related global and regional premature mortality in the EVA6.0 Health Impact Assessment Model](#). *Environmental Research*, **216**, no. 4, 114702, doi:10.1016/j.envres.2022.114702.



Top: World map showing the global distribution of annual mean surface particulate matter (PM_{2.5}) concentration ratios for the year 2015 in the medium-mitigation emission scenario SSP2-4.5. Bottom: Graphs showing regional and global changes of PM_{2.5} surface levels in the future emission projections SSP1-2.6 (high-mitigation), SSP2-4.5, and SSP3-7.0 (low-mitigation). The regions are NAM: North America, EUR: Europe, SAS: Southeast Asia, EAS: East Asia, AUST: Australia, NAF: North Africa, SAF: South Africa, SAM: South America, RUS: Russia, and ARC: Arctic. Figure from Im et al., 2023.

NASA News & Feature Releases

NASA Selects Scientific Support for Goddard Institute for Space Studies

By Jamie Adkins — Contract Release 23-001 — Feb. 8, 2023

NASA has selected Autonomic Integra of Gaithersburg, Maryland, for specialized scientific support services to the Goddard Institute for Space Studies (GISS) in New York.

This is a cost-plus fixed-fee completion contract with one base year and four one-year options to extend the contract through Feb 29, 2028. The total value of the contract, including options, is approximately \$20,875,025.

This contract will provide specialized scientific support in the following areas: scientific programming and analysis; systems programming analysis including systems programming, data handling, and data teleprocessing; computer facility operations including computer security; library and publications services; logistical support; and project management support.

GISS is a laboratory in the Earth Sciences Division of NASA's Goddard Space Flight Center in Greenbelt, Maryland, and a unit of the Columbia University Earth Institute. For more information about GISS, visit:

<http://www.giss.nasa.gov/>

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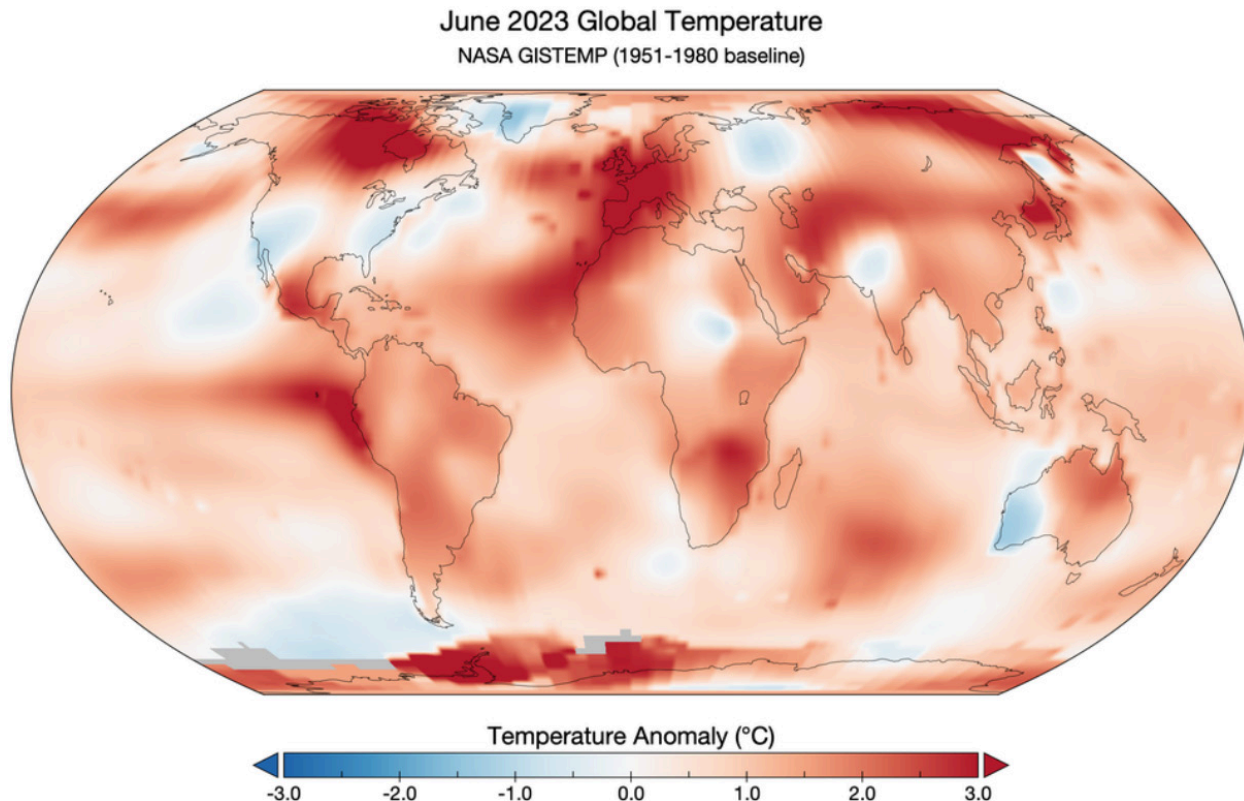


Columbia University's Armstrong Hall, home to NASA's Goddard Institute for Space Studies. Credit: NASA / GISS / Robert Schmunk

NASA Finds June 2023 Hottest on Record

By Goddard Digital Team — July 13, 2023

June 2023 was the hottest June on record according to [NASA's global temperature analysis](#).



This map shows global temperature anomalies for June 2023 according to the GISTEMP analysis by scientists at NASA's Goddard Institute for Space Studies. Temperature anomalies reflect how June 2023 compared to the average June temperature from 1951-1980. **Credits: NASA's Goddard Institute for Space Studies**

GISTEMP, NASA's global temperature analysis, is drawn from data collected by weather stations and Antarctic research stations, as well as instruments mounted on ships and ocean buoys. NASA scientists at the [Goddard Institute for Space Studies \(GISS\)](#) in New York analyze these measurements to account for uncertainties in the data and to maintain consistent methods for calculating global average surface temperature differences for every year. These ground-based measurements of surface temperature are consistent with satellite data collected since 2002 by the Atmospheric Infrared Sounder on NASA's Aqua satellite and with other estimates. NASA uses the period from 1951-1980 as a baseline to understand how global temperatures change over time.

Independent analyses by the [European Union's Copernicus Climate Change Service](#) and [NOAA's National Centers for Environmental Information](#) likewise found June 2023 to be the warmest June in their records.

NASA Center For Climate Simulation: NCCS Highlights

Oceanographer Anastasia Romanou Leads Group at GISS Studying the Interactions Between Earth's Oceans and Climate

By Sean Keefe — June 30, 2023

To honor World Ocean Month and discover how NASA scientists are helping us better understand the world's oceans in a changing climate, the NASA Center for Climate Simulation (NCCS) interviewed Anastasia Romanou, a NASA scientist who has for decades developed and used some of the most advanced models of the complex Earth system.

Current Role: I work at the NASA Goddard Institute for Space Studies (GISS) in New York City. I am interested in studying the ocean circulation, carbon exchanges between the ocean and the atmosphere, and climate change. I am a civil servant and lead a small but energetic group at GISS looking at different aspects of the interactions between Earth's oceans and climate.

Career Path to NASA: I attended college at the University of Athens, (UofA), where I completed a Bachelor of Science in Physics and a Master of Science in Oceanography. I then completed a Ph.D. in Physical Oceanography and Geophysical Fluid Dynamics at Florida State University (FSU) in Tallahassee.

After completing my graduate studies, I came to GISS as a postdoc from the Courant Institute of Mathematical Sciences at New York University.



Anastasia Romanou takes a moment in the hallway of the NASA Goddard Institute for Space Studies (GISS) in New York City. NASA photo.

When I first arrived at GISS, I knew very little about what climate models are or how to think about the Earth system as a whole. Over time, my research perspective and understanding of the Earth system has become much deeper and more holistic. I have learned that the oceans regulate Earth's climate via large-scale currents that transport heat from the equator to the poles and that they control many extreme weather phenomena.

After my post-doctoral position at GISS, I became a research scientist, and some years later a NASA civil servant. During my career at GISS, I have worked on diverse projects, from air-sea interactions, to model development and evaluation, to carbon cycle research.

Is your work done in a lab or in the field, or both? Which do you enjoy most? My work is done entirely from my office in New York City, on computers at GISS and remotely at NASA Goddard Space Flight Center. I use complex numerical models to simulate the Earth system, that is, the Earth's atmosphere, oceans, land, ice, marine life, and more. This is what I enjoy most: being able to use mathematical equations and computers to try to recreate aspects of the real world, which are indeed very close to how the real world actually is! Comparing our model output with actual field observations and finding them comparable is very satisfying and indeed gratifying.

I enjoy my work a lot. I like using mathematical models to simulate ocean currents and exchanges with the atmosphere, the land, and the ice. It astounds me that we know so much and at the same time so little, yet we keep learning more and making our models better and furthering our understanding of the world. I love my job at NASA GISS because it is much more than just work for me. I learn a lot about how nature works and how science is done and also about how policy utilizes scientific knowledge and how public opinion perceives the results of our research. I travel and meet interesting people in conferences and research campaigns.

What is the overall focus of your research? I am interested in how ocean circulation and physical and biogeochemical interactions with the rest of the Earth system change over time and how climate change can affect the oceans in small and big ways. Recent climate change is anthropogenic, caused mainly by human actions. Only a small part is due to natural variations, which, for the most part, are reversible. The ocean produces 50% of the oxygen on Earth and absorbs 90% of the heat and about 25% of the carbon added to the atmosphere through fossil fuel use and land use change.

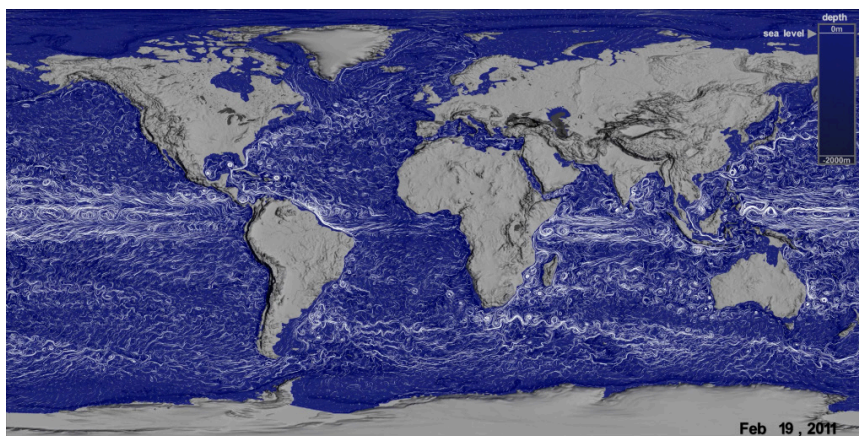
This oceanic sink of heat and carbon – a major focus of my research – is maintained by large-scale ocean circulation, those vibrant currents which include the Gulf Stream, the Kuroshio, the Antarctic Circumpolar current, and others. Some of these currents flow northward, carrying heat and carbon that sink to greater depths at high latitudes and are stored in the deep ocean for centuries. If those currents and those sinks are not maintained as we go into a much warmer world, global warming will advance faster with detrimental consequences to all of Earth's natural systems.

Where did your passion for oceans come from? I was born and grew up in Athens, Greece. My other hometown is, of course, New York City, which I love dearly. That's where I have lived and worked for the last 20 years, between the Hudson River and the North Atlantic Ocean.

Growing up along the west coast of the Aegean Sea, I always appreciated all that the sea gives us, the nutritious food, marvelous travel, recreational opportunities, and tranquility. Yet, as a child, I never knew that the oceans are important in other ways for the planetary balance and the health of the ecosystems.

I became interested in studying the oceans during my undergraduate studies at the UofA in Greece, where I studied physics. Towards the end of my studies and while considering different career paths, I came across a master's program in oceanography that included physical, biological, chemical, and geological oceanography. This was a great combination of science and real-world phenomena with my love for the sea. It was rather serendipitous that I got into this type of research, but it grew on me. And since then, I have been very fortunate because climate science came to the forefront of science due to climate change and, more recently, oceans gained even more recognition because of their critical role in Earth's climate.

Starting in college in Athens, and later, along the Gulf Coast in Tallahassee, Florida, where I completed my Ph.D., and during my many years of study, I have learned that the oceans encompass many complex phenomena. Ocean currents, waves, eddies, tides, turbulence, and exchanges with the atmosphere contain the chemical and geological records of Earth's history. Oceans nurture thousands of species, from the microscopic phytoplankton to the ultra-big fish and sea mammals.



The two scientific visualizations in the video above show the flows of ocean currents, first at sea level, then at 2,000 meters below sea level. Notice some of the differences in speed and direction of the flows between those at sea level and those at 2,000 meters below sea level. For example, the Gulf Stream off the coast of Eastern North America flows strongly towards the northeast, while at 2,000 meters below sea level, the flow is weaker and in the opposite direction. [Visualizations](#) by Greg Shirah, NASA Scientific Visualization Studio ([SVS](#)).

Interview continues at

<https://www.nccs.nasa.gov/news-events/nccs-highlights/physical-oceanographer-studies-earths-ocean-and-climate>

Reference

- Romanou, A., D.H. Rind, J.A. Jonas, R.L. Miller, M. Kelley, G.L. Russell, C. Orbe, L.S. Nazarenko, R. Latto, and G.A. Schmidt, 2023: [Stochastic bifurcation of the North Atlantic Circulation under a mid-range future climate scenario with the NASA-GISS ModelE](#). *Journal of Climate*, doi:10.1175/JCLI-D-22-0536.1.

NASA News & Feature Releases

NASA Offers Many Resources to Monitor Climate Change

By Katy Mersmann — July 20, 2023

In light of recent extreme weather events in the United States and around the world, NASA held a media roundtable July 20 from its headquarters in Washington to highlight the agency's climate work.

From wildfires raging across North America, flooding in the Northeast, heatwaves across the Southwest, and a record hot June, millions of Americans experienced the effects of extreme weather. NASA tracks it all, and shares its data.

"The data is clear: Our Earth is warming. And NASA is committed to empowering scientists, decisionmakers, and people around the world to make data-based decisions when it comes to climate, said NASA Administrator Bill Nelson. "With more than two dozen satellites, instruments aboard the International Space Station, and commercial and international partnerships, NASA uses our unique vantage point of space to observe our planet. To put it another way, NASA is bringing space down to Earth."



Dr. Kate Calvin, pictured here at the Earth Information Center ribbon cutting in June, addressed members of the media along with other NASA leadership and climate experts on July 20, 2023. **Credits: NASA/Joel Kowsky**

Other NASA experts participating in the discussion were:

- Kate Calvin, NASA chief scientist and senior climate adviser
- Karen St. Germain, director, NASA's Earth Science Division
- Gavin Schmidt, director, NASA's Goddard Institute for Space Studies
- Tom Wagner, associate director for Earth Action
- Huy Tran, aeronautics director, NASA's Ames Research Center
- Carlos Del Castillo, chief, Ocean Ecology Laboratory, NASA's Goddard Space Flight Center

The topics of discussion ranged from greenhouse gases, NASA's new Earth Information Center, the fleet of satellites the agency has observing weather-data, how NASA uses surface records to learn more about climate change, how climate change affects oceans, and more.

"NASA's vast, decades-long array of Earth, atmospheric, and solar data – which are openly and freely available to anyone – provide a comprehensive, real-time history of our dynamic and complex planet. Understanding Earth gives us the means to better protect it," said Calvin.

Audio of the full briefing is available on [NASA's Youtube channel](#).

NASA also offers a variety of resources across its websites including:

NASA GISS Resources

- [GISTEMP Global Temperature Record](#)
- [ModelE Climate Model](#)
- [Climate Impacts](#)

Agency Resources

- [Climate.NASA.gov](https://climate.nasa.gov)
- [Agency Climate Strategy Overview](#)
- [NASA Español](#)
- [JPL Center for Climate Sciences](#)
- [GSFC Global Modeling and Assimilation Office](#)
- [Langley Research Center](#)
- [Ames NASA Earth Exchange](#)

Visualization Resources

- [NASA Science Visualization Studio](#)
- [NASA Earth Observatory](#)

Social Media Resources

- [NASAEarth](#)
- [NASAClimate](#)

Climate Explainer Resources

- [Temperature Record 101: How We Know What We Know about Climate Change](#)
- [The Climate Events of 2020 Show How Excess Heat is Expressed on Earth](#)

'We Asked A NASA Scientist' Series

- [Why Does Climate Change Matter?](#)
- [Are Wildfires Getting Worse?](#)
- [Why Is Sea Level Rising?](#)
- [Are Hurricanes Getting Stronger?](#)
- [How Do We Know What The Climate Was Like Long Ago?](#)
- [Is Polar Ice Melting?](#)

Earth Action Resources

- [Earth Information Center](#)
- [NASA Earth Applied Sciences](#)
- [NASA's Cynthia Rosenzweig Receives 2022 World Food Prize](#)

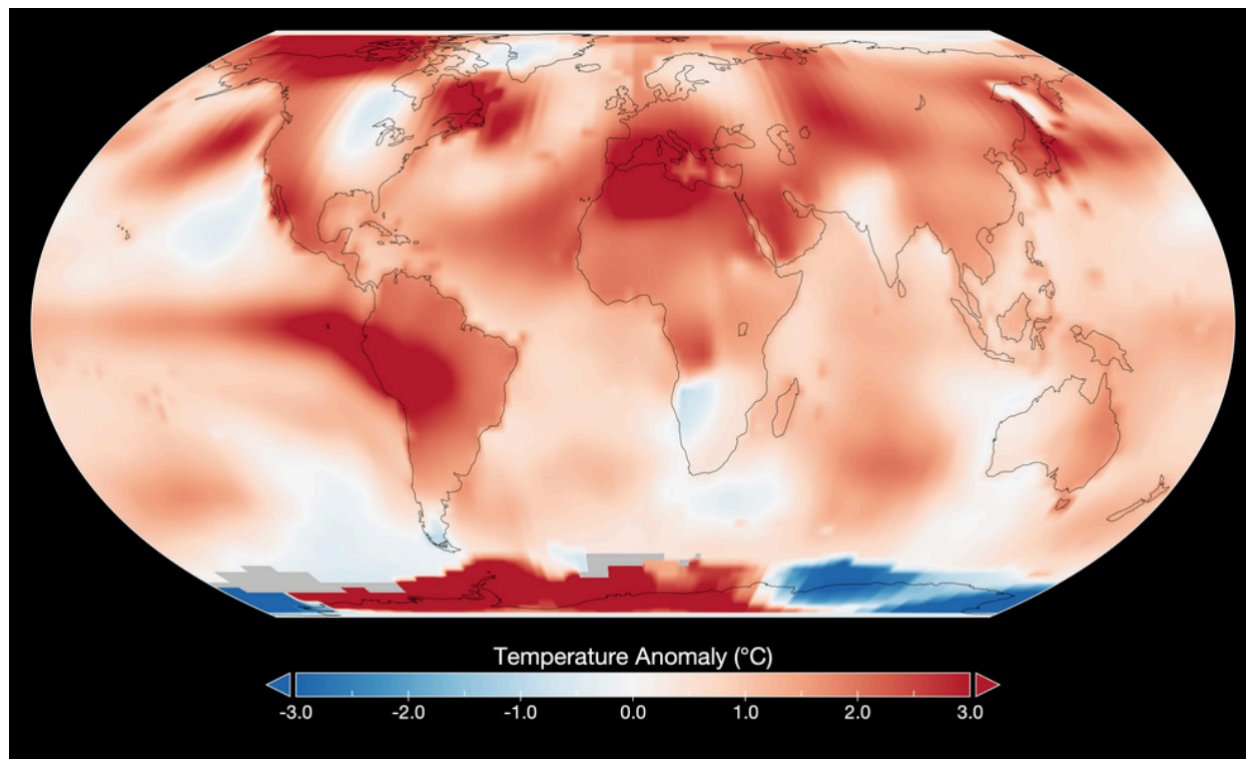
From <https://www.nasa.gov/earth/nasa-offers-many-resources-to-monitor-climate-change/>

NASA News & Feature Releases

NASA Clocks July 2023 as Hottest Month on Record Ever Since 1880

By Claire A. O'Shea — Release 23-090 — Aug. 14, 2023

According to scientists at NASA's Goddard Institute for Space Studies (GISS) in New York, July 2023 was hotter than any other month in the global temperature record.



This map shows global temperature anomalies for July 2023 according to the GISTEMP analysis by scientists at NASA's Goddard Institute for Space Studies. Temperature anomalies reflect how July 2023 compared to the average July temperature from 1951-1980. **Credits: NASA's Goddard Institute for Space Studies**

"Since day one, President Biden has treated the climate crisis as the existential threat of our time," said Ali Zaidi, White House National Climate Advisor. Against the backdrop of record high temperatures, wildfires, and floods, NASA's analysis puts into context the urgency of President Biden's unprecedented climate leadership. From securing the Inflation Reduction Act, the largest climate investment in history, to invoking the Defense Production Act to supercharge domestic clean energy manufacturing, to strengthening climate resilience in communities nationwide, President Biden is delivering on the most ambitious climate agenda in history."

Overall, July 2023 was 0.43 degrees Fahrenheit (F) (0.24 degrees Celsius (C)) warmer than any other July in NASA's record, and it was 2.1 F (1.18 C) warmer than the average July between 1951 and 1980. The primary focus of the [GISS analysis](#) are long-term temperature changes over many decades and centuries, and a fixed base period yields anomalies that are consistent over time. Temperature "normals" are defined by several decades or more – typically 30 years.

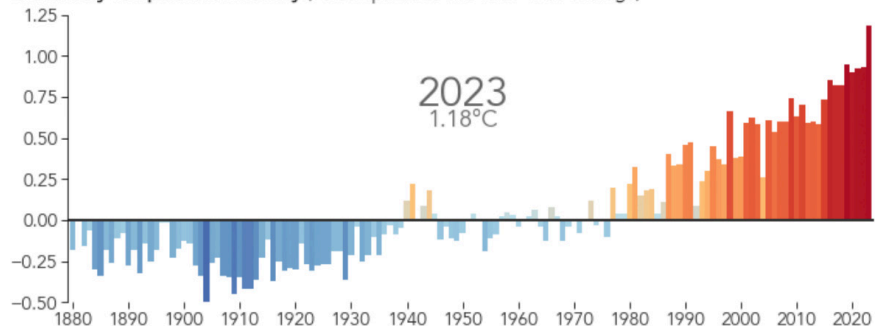
"NASA data confirms what billions around the world literally felt: temperatures in July 2023 made it the hottest month on record. In every corner of the country, Americans are right now experiencing firsthand the effects of the climate crisis, underscoring the urgency of President Biden's historic climate agenda," said NASA Administrator Bill Nelson. "The science is clear. We must act now to protect our communities and planet; it's the only one we have."

Parts of South America, North Africa, North America, and the Antarctic Peninsula were especially hot, expe-

riencing temperatures increases around 7.2 F (4 C) above average. Overall, extreme heat this summer put tens of millions of people under heat warnings and was linked to hundreds of heat-related illnesses and deaths. The record-breaking July continues a long-term trend of human-driven warming driven primarily by greenhouse gas emissions that has become evident over the past four decades. According to NASA data, the five hottest Julys since 1880 have all happened in the past five years.

July 2023 Was the Hottest Month on Record

Global July Temperature Anomaly (°C compared to the 1951-1980 average)



This chart shows global temperature anomalies for every July since the 1880s, based on NASA's GISTEMP analysis. Anomalies reflect how much the global temperature was above or below the 1951-1980 norm for July. **Credits: NASA's Goddard Institute for Space Studies**

“Climate change is impacting people and ecosystems around the world, and we expect many of these impacts to escalate with continued warming,” said Katherine Calvin, chief scientist and senior climate advisor at NASA Headquarters in Washington. “Our agency observes climate change, its impacts, and its drivers, like greenhouse gases, and we are committed providing this information to help people plan for the future.”

NASA assembles its temperature record from surface air temperature data from tens of thousands of meteorological stations, as well as sea surface temperature data acquired by ship- and buoy-based instruments. This raw data is analyzed using methods that account for the varied spacing of temperature stations around the globe and for urban heating effects that could skew the calculations.

“This July was not just warmer than any previous July – it was the warmest month in our record, which goes back to 1880,” said GISS Director Gavin Schmidt. “The science is clear this isn’t normal. Alarming warming around the world is driven primarily by human-caused greenhouse gas emissions. And that rise in average temperatures is fueling dangerous extreme heat that people are experiencing here at home and worldwide.”

High sea surface temperatures contributed to July’s record warmth. NASA’s analysis shows especially warm ocean temperatures in the eastern tropical Pacific, evidence of the El Niño that began developing in May 2023. Phenomena such as El Niño or La Niña, which warm or cool the tropical Pacific Ocean, can contribute a small amount of year-to-year variability in global temperatures. But these contributions are not typically felt when El Niño starts developing in Northern Hemisphere summer. NASA expects to see the biggest impacts of El Niño in February, March, and April 2024.

For more information on NASA’s global temperature record, visit:

<https://www.nasa.gov/feature/2023/climate-media-resources>

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NASA Selects Cross Divisional Teams for Astrobiology Research

By Tricia Talbert — July 25, 2023

NASA has announced the selection of seven new teams as part of its Interdisciplinary Consortia for Astrobiology Research (ICAR) program. The breadth and depth of the research of these teams spans the spectrum of astrobiology research, from cosmic origins to planetary system formation, origins and evolution of life, and the search for life beyond Earth.



Artist's conception of the surface and atmosphere of the Earth-size exoplanet Kepler 1649. Credit: NASA

“We’re excited to see the high level of interest in the ICAR program, and excited to see a mix of both continuing and new research programs that span astrobiology’s scientific goals,” said Stephen Rinehart, director of Planetary Research Programs at NASA Headquarters in Washington.

ICAR awards have been selected to meet the needs of the rapidly-evolving field of astrobiology. These awards facilitate large-scale scientific investigations driven by decades of research and discovery in the field. The program supports projects that use an interdisciplinary approach to address a single compelling question in astrobiology, collectively addressing the goals of the agency’s Astrobiology Strategy and ensuring that astrobiology goals are cohesively integrated with current and future NASA missions.

“We are extremely excited about the innovation and interdisciplinary nature displayed by these teams,” said Mary Voytek, senior scientist for NASA’s [Astrobiology Program](#) at NASA Headquarters.

The awarded teams are:

- **Dave Brain**, University of Colorado, Boulder: *Retention of Habitable Atmospheres in Planetary Systems*
- **Steven Desch**, Arizona State University: *Tracing Rocky Exoplanet Compositions*
- **Victoria Meadows**, University of Washington, Seattle: *The Virtual Planetary Laboratory: Advancing the Search for Life on Exoplanets*

- **Raphael Rosenzweig**, Georgia Tech Research Corporation: *Engine of Innovation: How Compartmentalization Drives Evolution of Novelty and Efficiency Across Scales*
- **Scott Sandford**, NASA Ames Research Center: *The Formation and Evolution of Prebiotic Organics in Extraterrestrial Environments: Exploring the Role of Astrochemistry in the Origin of Life*
- **Kevin Stevenson**, Johns Hopkins University: *Strange New Worlds: Characterizing Nearby M-dwarf Habitable Zone Planets*
- **Michael Way**, NASA Goddard Institute for Space Studies: *Habitability Space: Exploring a New Frontier via Climate Models and Planetary Statistics*

“These new additions to the astrobiology research portfolio will strongly contribute to the [NASA Research Coordination Networks](#) (RCNs),” said Voytek. “ICAR and the RCNs are continuing to build collaborations, advance the mission relevance of astrobiology research, and guide and develop our early career scientists.”

The goal of NASA’s Astrobiology Program is the study of the origins, evolution, and distribution of life in the Universe. The Program is central to NASA’s continued exploration of our solar system and beyond and supports research into the origin and early evolution of life, the potential of life to adapt to different environments, and the implications for life elsewhere. NASA, together with the science community, has developed an Astrobiology Strategy that describes the scientific goals and objectives of NASA’s Astrobiology Program.

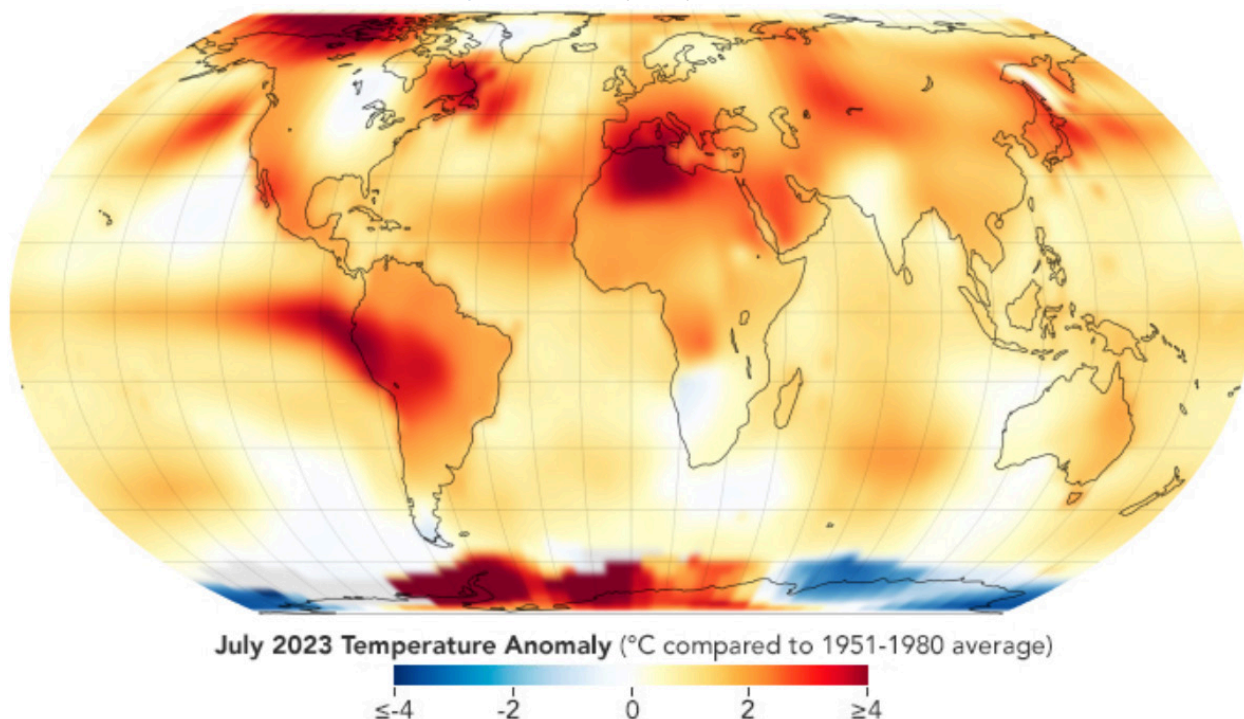
Learn more about NASA’s Astrobiology program at <https://astrobiology.nasa.gov/>

NASA Earth Observatory: Image of the Day

July 2023 Was the Hottest Month on Record

By Emily Cassidy — Aug. 15, 2023

July 2023 was hotter than any other month in the global temperature record, according to an analysis by scientists at NASA's [Goddard Institute for Space Studies](#) (GISS).



July 1 - 31, 2023

[PNG](#)

“This July was massively warmer than any previous July and any previous month on record, which goes back to 1880,” said GISS Director Gavin Schmidt. “This continues the long-term trend in dramatic warming that we have seen over the past four decades.”

The map above depicts global [temperature anomalies](#) for July 2023. It shows how much warmer or cooler the Earth was compared to the baseline average from 1951 to 1980. Note that the deepest reds are at least 4° Celsius (7° Fahrenheit) above the monthly mean.

Parts of South America, North Africa, North America, and the Antarctic Peninsula were especially hot and experienced temperature anomalies around 4°C. But it was not unusually warm everywhere. Parts of the U.S. Midwest and northern Europe saw closer to average temperatures. Overall, July 2023 was 1.18°C (2.12°F) warmer than the average July between 1951 and 1980.

The warmer-than-usual July continues a long-term trend of warming, driven primarily by human-caused greenhouse gas emissions. July 2023 was 0.24°C (0.43°F) warmer than any previous July in NASA’s record. And according to GISS temperature anomaly data, the top-five hottest Julys since 1880 have all happened in the past five years.

Extreme heat contributed to [devastating wildfires and blistering heat waves](#) in the Northern Hemisphere. “These changes that we’re seeing in global temperatures are being reflected in real heat extremes that people are experiencing locally,” Schmidt said. “We can say with some confidence now that the heat waves we are seeing in North Africa, the Middle East, the U.S. Southwest, China, and southern Europe are being directly impacted by the fact that the whole planet is warming.”

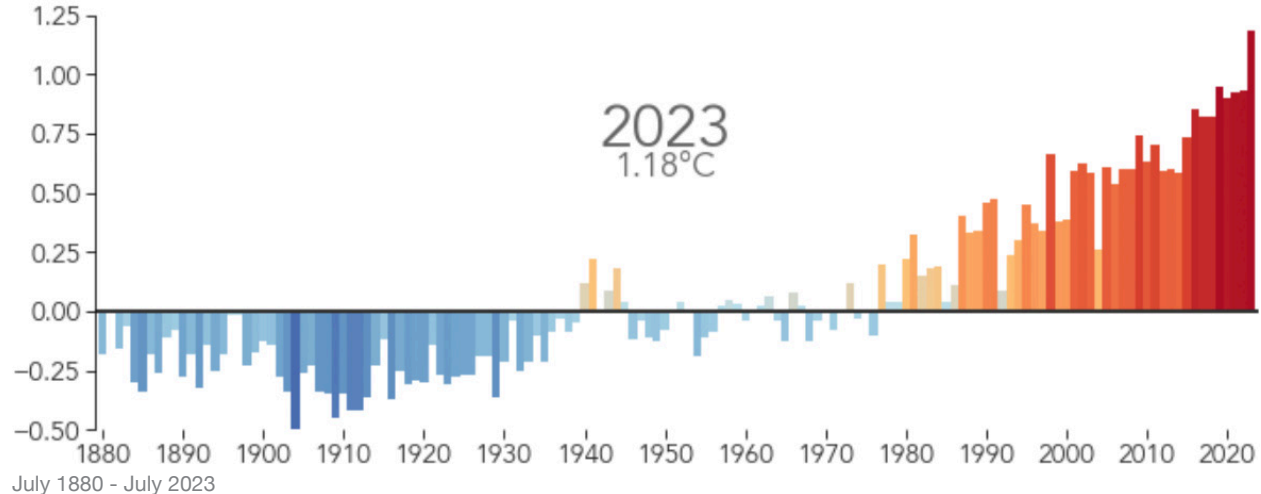
The GISS team assembles its temperature analysis from surface air temperature data from tens of thousands of metrological stations and sea surface temperature data acquired by ship- and buoy-based instruments.

This raw data is analyzed using methods that account for the varied spacing of temperature stations around the globe and for urban heating effects that could skew the calculations.

High sea surface temperatures contributed to July's record warmth. The map shows especially warm ocean temperatures in the eastern tropical Pacific, evidence of the El Niño that began developing [in May 2023](#). Phenomena such as El Niño or La Niña, which warm or cool the tropical Pacific Ocean, can contribute a small amount of year-to-year variability in global temperatures. But these contributions are not typically felt when El Niño starts developing during the Northern Hemisphere's summer.

July 2023 Was the Hottest Month on Record

Global July Temperature Anomaly (°C compared to the 1951-1980 average)



“One of the reasons this record is concerning is that the effects of El Niño on global temperatures normally have a several month lag and are felt in the winter and spring,” said Schmidt. “Even though we have an El Niño developing now, the record warmth we are seeing is not yet related to that in a significant way. We expect to see the biggest impacts of the developing El Niño in February, March, and April 2024.”

NASA's full temperature data set and the complete methodology used for the temperature calculation and its uncertainties are [available here](#).

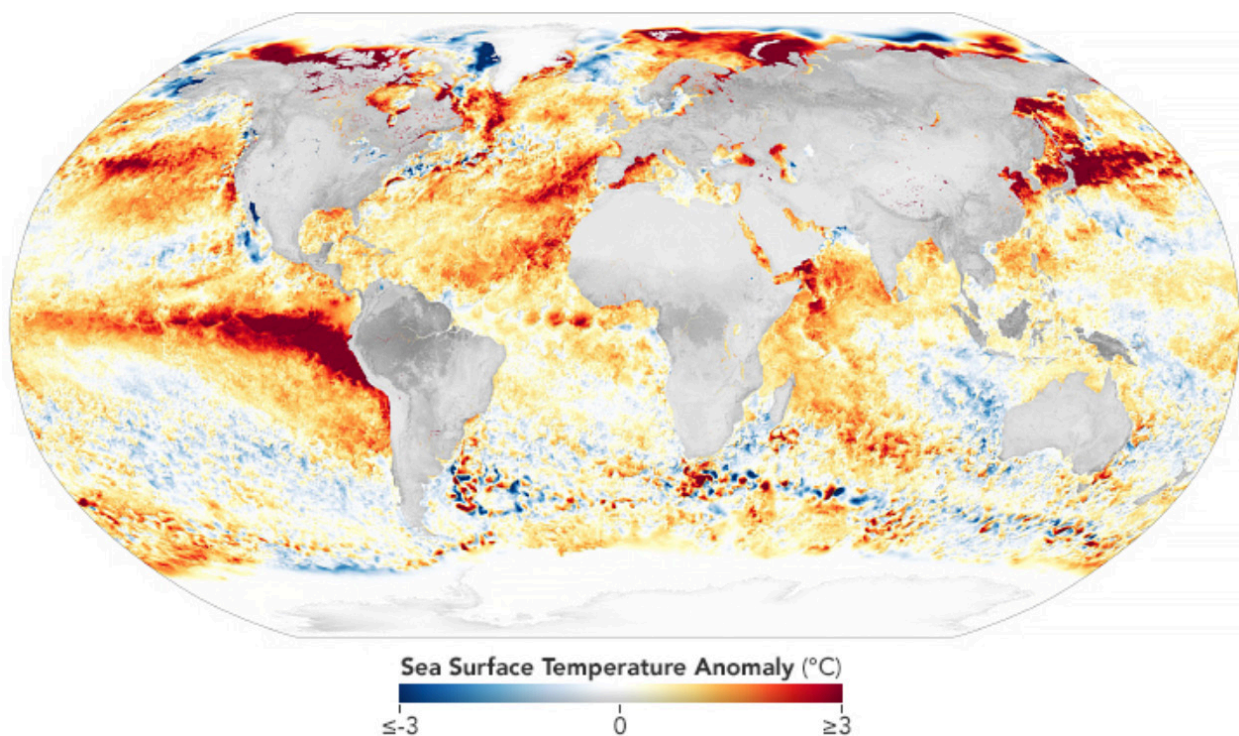
NASA Earth Observatory images by Lauren Dauphin, based on data from the NASA Goddard Institute for Space Studies. Story by Emily Cassidy.

NASA Earth Observatory: Image of the Day

The Ocean Has a Fever

By Adam Voiland — Aug. 25, 2023

In March and April 2023, some earth scientists [began to point out](#) that average sea surface temperatures had surpassed the highest levels seen in a [key data record](#) maintained by NOAA. Months later, they remain at record levels, with global sea surface temperatures [0.99°C \(1.78°F\)](#) above average in July. That was the fourth consecutive month they were at record levels.



August 21, 2023

Scientists from NASA have taken a closer look at why. “There are a lot of things that affect the world’s sea surface temperatures, but two main factors have pushed them to record heights,” said Josh Willis, an oceanographer at NASA’s Jet Propulsion Laboratory (JPL). “We have an El Niño developing in the Pacific, and that’s on top of long-term global warming that has been pushing ocean temperatures steadily upward almost everywhere for a century.”

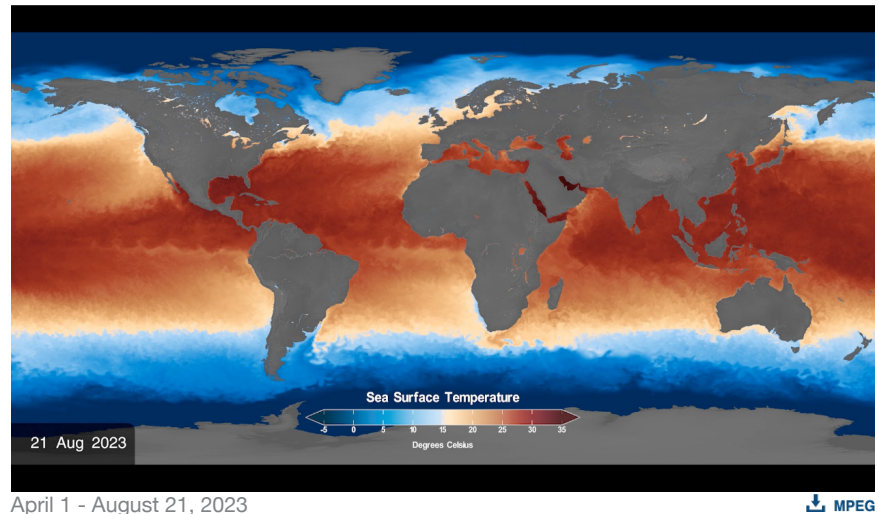
The map above shows sea surface temperature anomalies on August 21, 2023, when many areas were more than 3°C (5.4°F) warmer than normal. On that date, much of the central and eastern regions of the equatorial Pacific were unusually warm, the signature of a developing El Niño. As has been the case for weeks, large patches of warm water were also present in the Northwest Pacific near Japan and the [Northeast Pacific](#) near California and Oregon. Portions of the Indian, Southern, and Arctic Oceans also showed unusual warmth.

The map is based on data from the [Multiscale Ultrahigh Resolution Sea Surface Temperature \(MUR SST\)](#) project, a JPL effort that blends measurements of sea surface temperatures from multiple NASA, NOAA, and international satellites, as well as ship and buoy observations. Rather than showing absolute temperature, the anomaly reflects the difference between the sea surface temperature on August 21, 2023, and the 2003-2014 average for that day. The video below, also based on MUR SST data, shows global sea surface temperatures since April 1, 2023, the period when they have been at record-breaking levels. The warmest waters appear dark red.

Over the long term, we’re seeing more heat and warmer sea surface temperatures pretty much everywhere,” said Gavin Schmidt, the director of NASA’s Goddard Institute for Space Studies. “That long-term trend is

almost entirely attributable to human forcing—the fact that we’ve put such a huge amount of greenhouse gas in the atmosphere since the start of the industrial era.”

Schmidt noted that other factors—such as weather and wind patterns or the distribution of dust and [aerosols](#)—have short-term effects on sea surface temperatures in certain regions, but they generally have a minor effect on the longer-term global mean. [Previous research](#) shows that as much as [90 percent](#) of the excess heat that has occurred in recent decades due to increasing greenhouse gas emissions is absorbed by the ocean, with much of that heat stored near the surface.



The most important factor that helped push sea surface temperatures into record territory in 2023 was the [evolving El Niño](#) in the Pacific, according to Willis. He came to that conclusion by analyzing the timing and intensity of sea surface temperature anomalies in several regions and comparing them to the global trend.

“We had a big jump in global surface temperature at the beginning of April—exactly when the Pacific temperatures jumped up and also when sea levels in the eastern Pacific started to rise,” Willis said. “The heat waves in the Atlantic are important and will have serious effects on marine life and weather in Europe in the coming months. But it’s the Pacific that has taken the global mean on a wild ride this year.”

What happens in the Pacific tends to have a large influence on the global sea surface temperatures partly because of its size. The Pacific represents about half of the world’s ocean area.

[Marine heat waves](#)—defined as periods of persistent anomalously warm ocean temperatures (warmer than 90 percent of the previous observations for a given time of year)—have occurred recently in several areas. One [NOAA analysis](#) showed that 48 percent of the global oceans were in the midst of a marine heat wave in August—a larger area than for any other month since the start of the record in 1991. Particularly intense events have warmed the [North Atlantic](#) and [parts of the Caribbean](#) in recent months.

Willis expects the heat in the equatorial Pacific to have more staying power than many of the other marine heat waves simmering around the world. “Many of the marine heat waves we’re seeing are ephemeral and ‘skin’ deep, generally lasting on the order of weeks and driven by atmospheric forces,” explained Willis.

The unusually warm water in the equatorial Pacific associated with the developing El Niño [after three consecutive years of La Niña](#) is expected to weaken trade winds in ways that reinforce and amplify the warming of surface waters, fueling the El Niño further. Forecasters from NOAA say that there is a greater than [95 percent chance](#) that El Niño conditions will persist throughout the Northern Hemisphere winter. “What’s happening in the Pacific with El Niño will influence global weather patterns and sea surface temperatures well into the winter and possibly even longer,” Willis said.

To monitor sea surface temperatures, scientists at NOAA and NASA analyze observations from sensors and buoys in the oceans, ships, and several different polar-orbiting and geostationary satellites. Groups of scientists with [NOAA’s Physical Sciences Laboratory](#), [NOAA’s Coral Reef Watch](#), and [NASA’s Jet Propulsion Laboratory](#) track marine heat waves and sea surface temperature anomalies closely. You can use NASA’s [State of the Ocean Tool](#) on Worldview to monitor daily sea surface temperature anomalies.

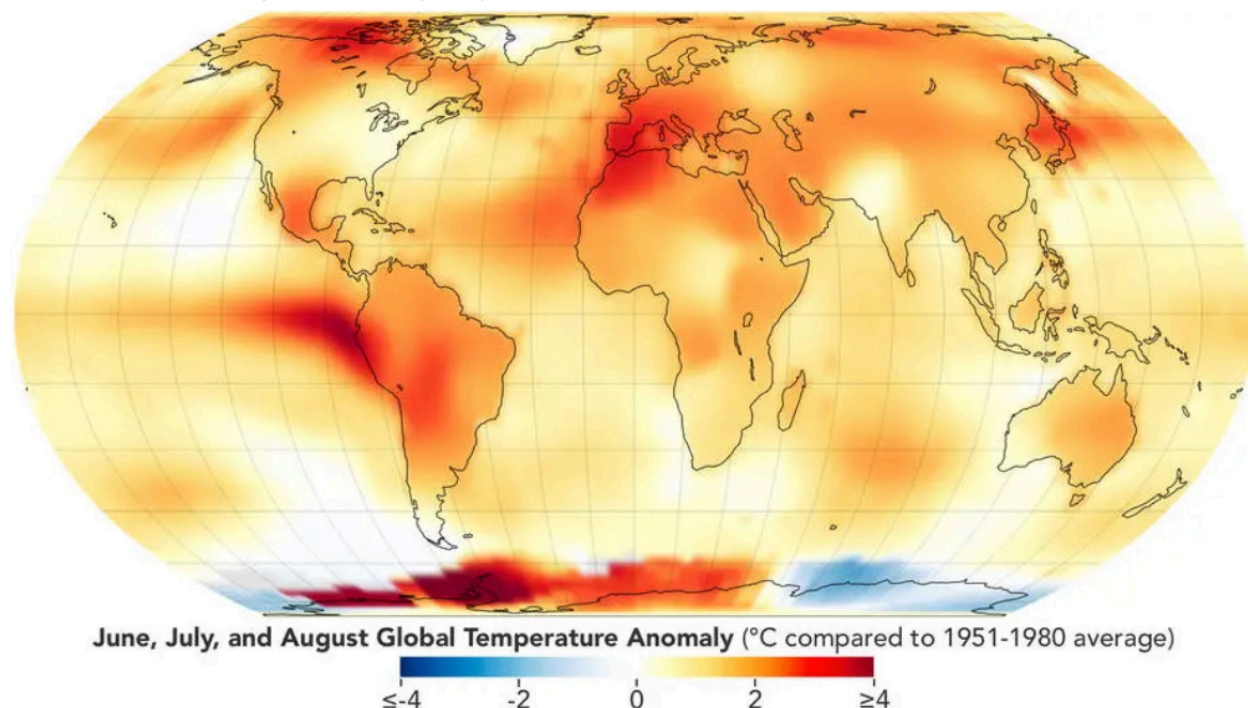
NASA Earth Observatory image by Lauren Dauphin, using data from the Multiscale Ultrahigh Resolution (MUR) project. Video by NASA’s Scientific Visualization studio, using data from the MUR project. Story by Adam Voiland.

From <https://earthobservatory.nasa.gov/images/151743/the-ocean-has-a-fever>

NASA Announces Summer 2023 Hottest on Record

Release 23-105 — Sep. 14, 2023

The summer of 2023 was Earth's hottest since global records began in 1880, according to scientists at NASA's Goddard Institute of Space Studies (GISS) in New York.



This map depicts global temperature anomalies for meteorological summer in 2023 (June, July, and August). It shows how much warmer or cooler different regions of Earth were compared to the baseline average from 1951 to 1980.

Credits: NASA Earth Observatory/Lauren Dauphin

The months of June, July, and August combined were 0.41 degrees Fahrenheit (0.23 degrees Celsius) warmer than any other summer in NASA's record, and 2.1 degrees F (1.2 C) warmer than the average summer between 1951 and 1980. August alone was 2.2 F (1.2 C) warmer than the average. June through August is considered meteorological summer in the Northern Hemisphere.

This [new record](#) comes as exceptional heat swept across much of the world, exacerbating deadly wildfires in Canada and Hawaii, and searing heat waves in South America, Japan, Europe, and the U.S., while likely contributing to severe rainfall in Italy, Greece, and Central Europe.

"Summer 2023's record-setting temperatures aren't just a set of numbers – they result in dire real-world consequences. From sweltering temperatures in Arizona and across the country, to wildfires across Canada, and extreme flooding in Europe and Asia, extreme weather is threatening lives and livelihoods around the world," said NASA Administrator Bill Nelson. "The impacts of climate change are a threat to our planet and future generations, threats that NASA and the Biden-Harris Administration are tackling head on."

NASA assembles its temperature record, known as GISTEMP, from surface air temperature data acquired by tens of thousands of meteorological stations, as well as sea surface temperature data from ship- and buoy-based instruments. This raw data is analyzed using methods that account for the varied spacing of temperature stations around the globe and for urban heating effects that could skew the calculations.

The analysis [calculates](#) temperature anomalies rather than absolute temperature. A temperature anomaly shows how far the temperature has departed from the 1951 to 1980 base average.

"Exceptionally [high sea surface temperatures](#), fueled in part by the return of El Niño, were largely responsi-

ble for the summer's record warmth," said Josh Willis, climate scientist and oceanographer at NASA's Jet Propulsion Laboratory in Southern California.

El Niño is a natural climate phenomenon characterized by warmer than normal sea surface temperatures (and higher sea levels) in the central and eastern tropical Pacific Ocean.

The record-setting summer of 2023 continues a long-term trend of warming. Scientific observations and analyses made over decades by NASA, National Oceanic and Atmospheric Administration (NOAA), and other international institutions have shown this warming has been driven primarily by human-caused greenhouse gas emissions. At the same time, natural El Niño events in the Pacific pump extra warmth into the global atmosphere and often correlate with the warmest years on record.

"With background warming and marine heat waves that have been creeping up on us for decades, this El Niño shot us over the hump for setting all kinds of records," Willis said. "The heat waves that we experience now are longer, they're hotter, and they're more punishing. The atmosphere can also hold more water now, and when it's hot and humid, it's even harder for the human body to regulate its temperature."

Willis and other scientists expect to see the biggest impacts of El Niño in February, March, and April 2024. El Niño is associated with the weakening of easterly trade winds and the movement of warm water from the western Pacific toward the western coast of the Americas. The phenomenon can have widespread effects, often bringing cooler, wetter conditions to the U.S. Southwest and drought to countries in the western Pacific, such as Indonesia and Australia.

"Unfortunately, climate change is happening. Things that we said would come to pass are coming to pass," said Gavin Schmidt, climate scientist and director of GISS. "And it will get worse if we continue to emit carbon dioxide and other greenhouse gases into our atmosphere."

NASA's [full temperature data set](#) and the complete methodology used for the temperature calculation and its uncertainties are available online.

GISS is a NASA laboratory managed by the Earth Sciences Division of the agency's Goddard Space Flight Center in Greenbelt, Maryland. The laboratory is affiliated with Columbia University's Earth Institute and School of Engineering and Applied Science in New York.

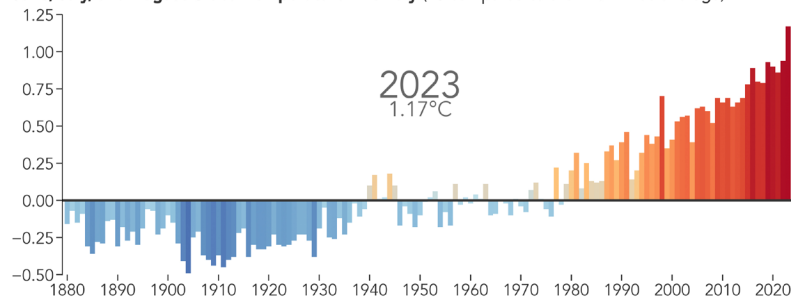
For additional figures and maps related to this announcement, visit: <https://svs.gsfc.nasa.gov/14407>

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Summer 2023 Continues Long-Term Warming Trend
June, July, and August Global Temperature Anomaly (°C compared to the 1951-1980 average)



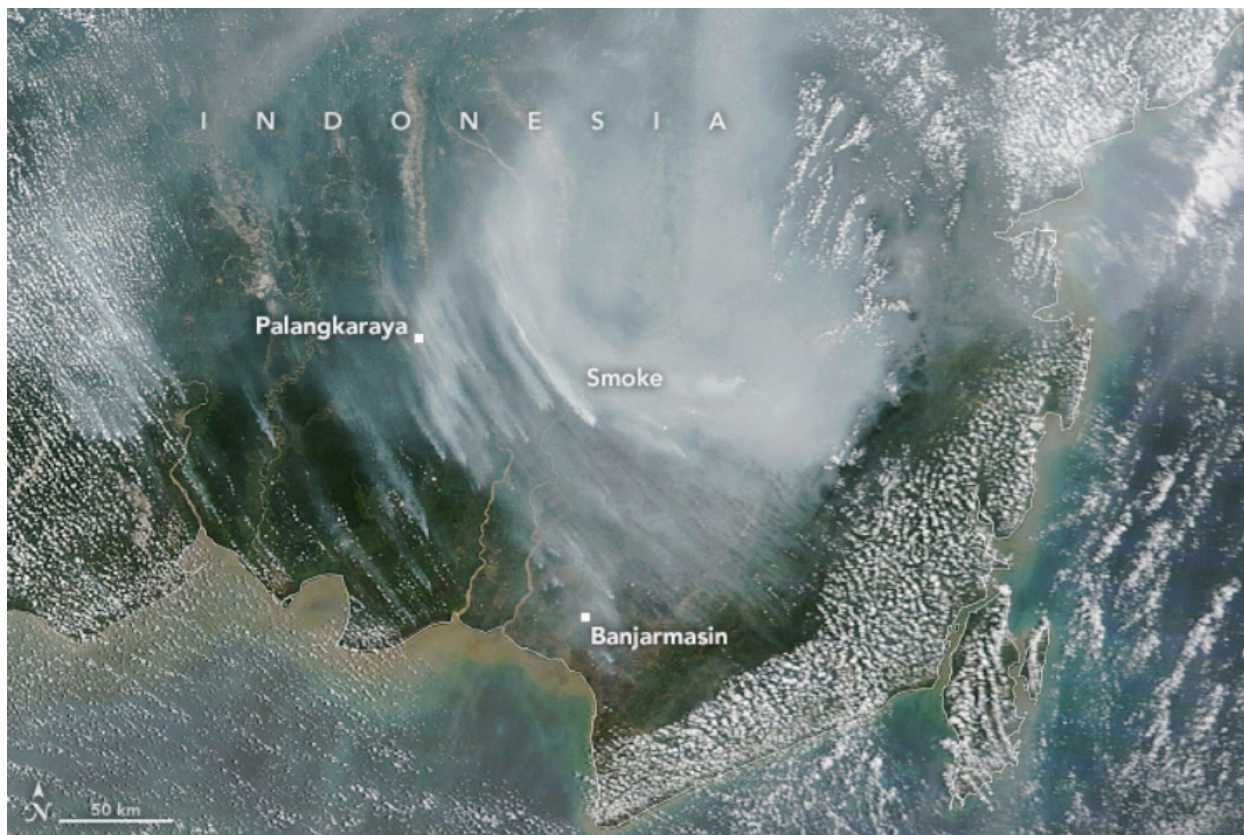
This chart shows the meteorological summer (June, July, and August) temperature anomalies each year since 1880. The warmer-than-usual summer in 2023 continues a long-term trend of warming, driven primarily by human-caused greenhouse gas emissions. **Credits: NASA Earth Observatory/Lauren Dauphin**

NASA Earth Observatory: Image of the Day

Indonesian Fires Return in 2023

By Kathryn Hansen — Oct. 7, 2023

After several years of comparatively quiet fire seasons, Indonesia saw the return of intense, smoky fires in 2023. The blazes have been exacerbated by dry conditions made worse this year by the [return of El Niño](#).



October 2, 2023

[JPEG](#)

This image shows smoke from fires burning on the island of Borneo, in the Indonesian provinces of South and Central Kalimantan. It was acquired by the [MODIS](#) (Moderate Resolution Imaging Spectroradiometer) sensor on NASA's [Terra](#) satellite on October 2, 2023. By that date, fire had burned around 267,900 hectares (662,000 acres) since the start of the year, surpassing the area burned during all of 2022, according to [news reports](#).

The image below (left) shows burn scars on the landscape near Banjarbaru, the capital city of South Kalimantan, on September 27, 2023. Most of the reds and dark browns are scars from fires that have burned so far during the 2023 fire season. Lighter browns are likely dry vegetation. For comparison, the other image (right) shows the same area on August 7, 2022. Both images are false color and were acquired by the [OLI-2](#) (Operational Land Imager-2) on [Landsat 9](#).

Burning in Indonesia often begins as farmers clear land for crops or grazing animals. Fire that escapes control in Borneo and Sumatra can become difficult to extinguish because of the islands' large deposits of peat—a soil-like mixture of partly decayed plant material that can fuel smoldering fires for months.

Fires generally correspond with Indonesia's dry season, which runs from June into December, with fire activity peaking from August into October. This year, scientists think that the natural climate phenomenon El Niño has made the landscape even drier, priming it to burn. During El Niño years, rain that is normally centered over Indonesia and the far western Pacific shifts eastward into the central Pacific, causing parts of Indonesia to experience drought.

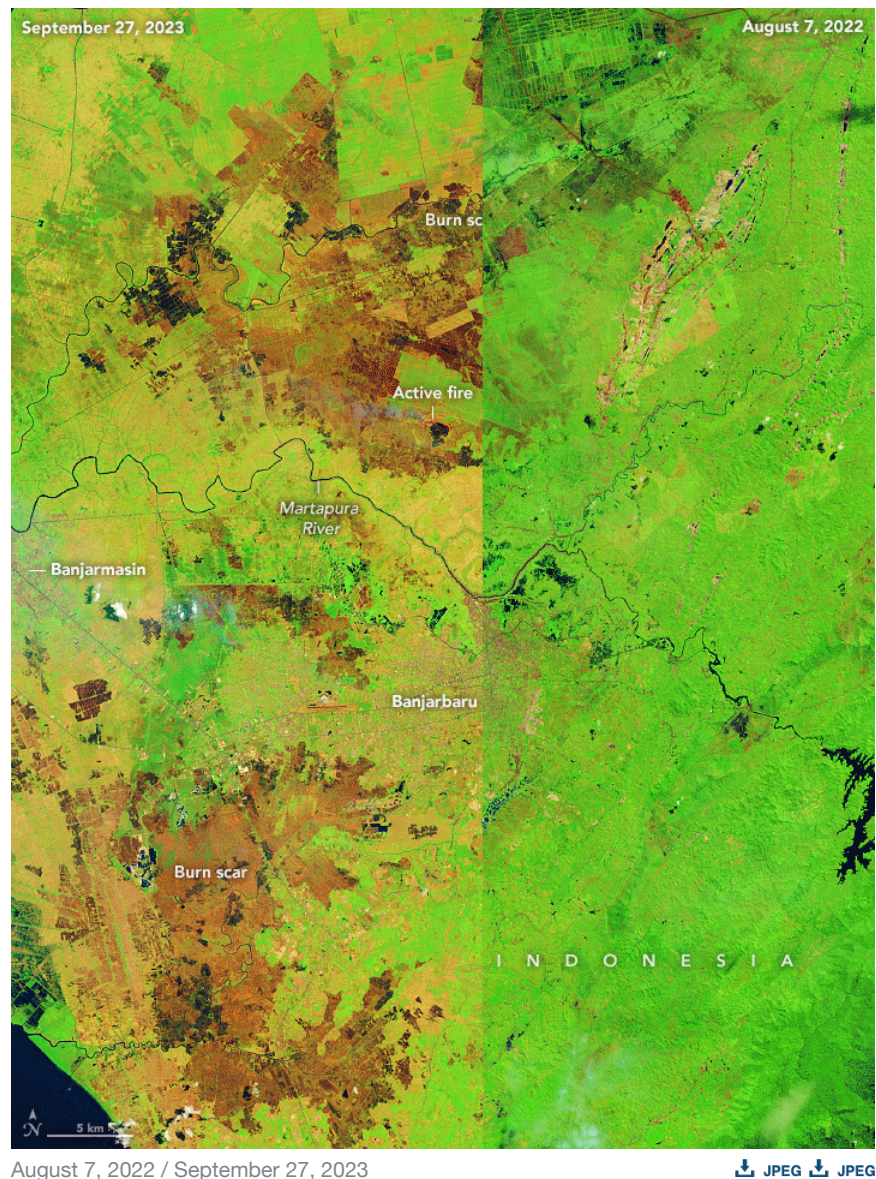
“This El Niño has maybe been delayed in drying out the main burning regions,” said NASA and Columbia University scientist Robert Field. “But it is the simplest explanation for the drying, along with a positive [Indian Ocean Dipole](#) to the west.”

Josh Willis, an oceanographer and Sentinel-6 Michael Freilich project scientist at NASA's Jet Propulsion Laboratory, agrees that El Niño is likely playing a role in the dryness this year. [Similar scenarios unfolded](#) during El Niño events that ramped up beginning in 1997 and 2015, alongside significant drought in Indonesia. Willis noted that by September of those years, El Niño was already several times stronger than the current one. But that might not matter much when it comes to fire.

“Just because it's not a huge El Niño doesn't mean it's not causing impacts, especially in the tropics,” Willis said. “Indonesia is close to the ocean regions that are the warmest in the world during a neutral or La Niña year. During an El Niño year, even a moderate one, those areas typically dry out.”

The drought is apparent in a [map from Indonesia's meteorological agency](#) provided as part of the Forest and Land Fire Warning System (SPARTAN). SPARTAN uses data from [IMERG](#) (Integrated Multi-Satellite Retrievals for GPM)—a product of the [GPM](#) (Global Precipitation Measurement) satellite mission—to track regions at high risk of burning, especially from peat fires.

NASA Earth Observatory images by Lauren Dauphin, using MODIS data from NASA EOSDIS LANCE and GIBS/Worldview and Landsat data from the U.S. Geological Survey. Story by Kathryn Hansen.



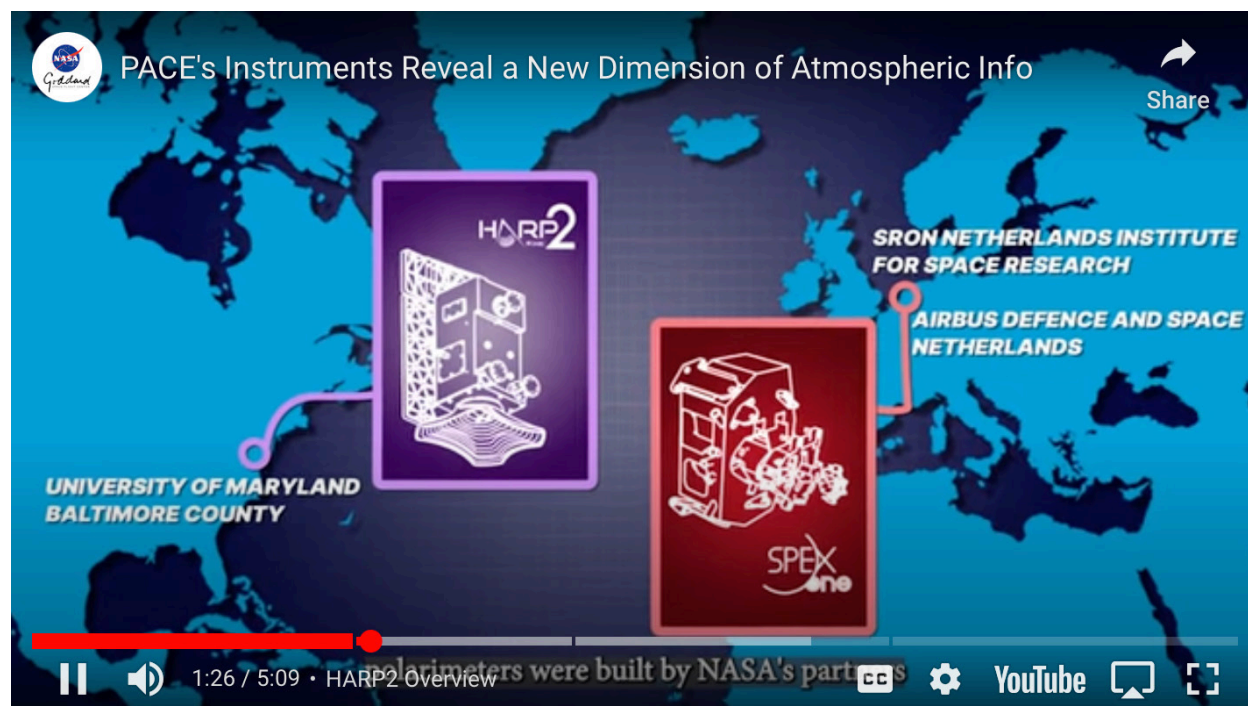
NASA News & Feature Releases

New NASA Satellite To Unravel Mysteries About Clouds, Aerosols

By Erica McNamee — Dec. 12, 2023

The summer of 2023 was Earth's hottest since global records began in 1880, according to scientists at NASA's Goddard Space Flight Center. Some of the same properties of light and optics that make the sky blue and cause rainbows can also help scientists unlock mysteries about cloud formation and the effects of tiny particles in our air.

NASA's upcoming PACE mission will offer important insights on airborne particles of sea salt, smoke, human-made pollutants, and dust – collectively called aerosols – by observing how they interact with light. With PACE data, scientists will provide better answers to key questions such as how aerosols affect cloud formation or how ice clouds and liquid clouds differ. Understanding the nature of airborne particles and clouds is crucial to deciphering how climate and air quality are changing.



Credit: NASA's Goddard Space Flight Center. Download this video in HD formats from NASA Goddard's Scientific Visualization Studio: <https://svs.gsfc.nasa.gov/14454/>

Two instruments on NASA's upcoming PACE mission will look at aerosols and clouds – the A and C in the name of the Plankton, Aerosol, Cloud, ocean Ecosystem satellite. After launch in early 2024, the PACE mission will scan the Earth and gather data on the chemical composition, movement, and interaction of aerosols and clouds through the use of two cutting-edge polarimeters – instruments that measure light properties.

There are characteristics of light that we can see with our eyes, such as color. Other characteristics are invisible to the human eye, like what scientists call polarization.

"Polarization is something that we don't have an intuitive sense for because our eyes don't see it," said Kirk Knobelspiesse, polarimetry lead for the PACE mission at NASA's Goddard Space Flight Center in Greenbelt, Maryland. "If you saw the world through eyes that could see polarization, like our sensors can, you would see rainbows everywhere."

Light leaving the Sun moves in all different directions like a wave – this is called unpolarized light, said Brian Cairns, deputy project scientist for PACE at NASA's Goddard institute for Space Studies in New York City. When it interacts with something like a cloud or an aerosol particle, however, light can oscillate more in one direction than the others: It is now polarized light. This quirk of light behavior can help scientists learn more

about the characteristics and interactions of aerosols and water droplets in the sky.

Polarimeters measure the angle at which the light is polarized, which reveals specific characteristics of whatever the light had bounced off of. With these instruments, scientists can piece together the size, composition, abundance, and other traits of the particles in the atmosphere.

The two polarimeters on PACE – HARP2 and SPEXone – make a great pair because of the complementary differences in what they measure. HARP2, built at the University of Maryland, Baltimore County, will observe four wavelengths of light from up to 60 different angles. SPEXone, built at the Netherlands Institute for Space Research (SRON) and Airbus Netherlands B.V., will peer down at a narrower swath, using five viewing angles but looking at light at hyperspectral resolution – the full range of colors in a rainbow. Together the polarimeters will offer a picture of Earth’s atmosphere in unprecedented detail.

Scientists have been observing aerosols from space for decades, though the community has not had polarimetry data for a decade, noted Otto Hasekamp, senior scientist at SRON. PACE will provide polarimeter data from multiple vantage points and, due to technological advancements in the instruments, the data will be of better quality than ever before.

“It’s exciting to see the culmination of working actively on instrument models and prototypes,” said Jeroen Rietjens, instrument scientist at SRON, “then finally seeing it end up on a real satellite.”

After PACE is launched in early 2024, the satellite will scan Earth every two days, gathering immense quantities of data on the chemical composition, movement, and interaction of aerosols and clouds.

“We want to measure properties of aerosols because aerosols affect climate,” said Hasekamp. They reflect light back into space and can also absorb it, which plays a role in how much of the Sun’s energy reaches Earth’s surface. Aerosols also affect cloud formation and properties, but the details of these relationships are not fully known to scientists. The data PACE collects will help to clarify some of these unknowns.

The new polarimetry data will also offer real-time insights on air pollution. “PACE measurements will not only answer fundamental science questions, but will also improve people’s quality of life,” said Marcela Loría-Salazar, assistant professor at the School of Meteorology at the University of Oklahoma and PACE early adopter. The [PACE Early Adopters program](#) promotes the integration of PACE data into practical applications of science.

Loría-Salazar is particularly interested in how aerosols change over time and with location, with an extra emphasis on the altitude of aerosols over the middle of the United States. There, PACE will allow scientists to identify aerosols, while also deciphering what they mean for air quality.

The measurements from PACE’s polarimeters will also help improve our understanding of Earth’s climate. By adding PACE atmospheric data to models, scientists will be able to replace the estimates now used to fill data gaps in those models with data from current measurements.

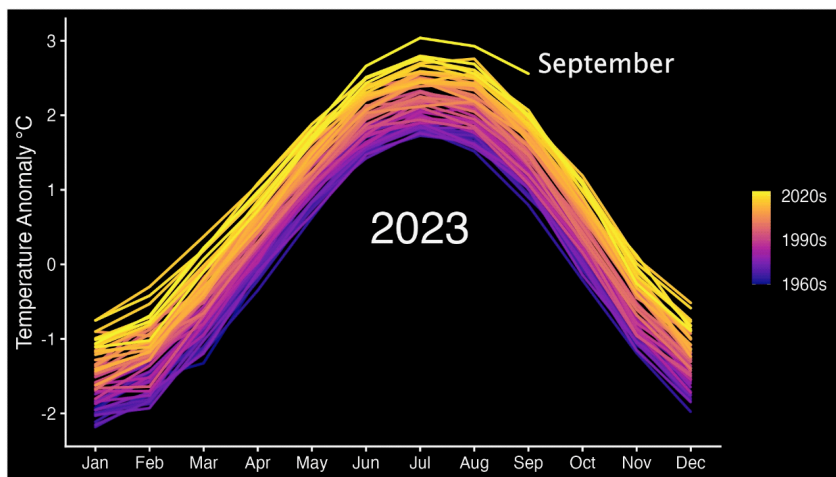
“I’m hoping to help gather the data that will reduce model uncertainty and help us make better predictions for how we expect our climate to play out in the next decades and centuries,” Knobelspiesse said.

NASA September 2023 Temperature Data Shows Continued Record Warming

By Katy Mersmann — Oct. 13, 2023

Continuing the temperature trend from this summer, September 2023 was the hottest September on record, according to scientists at NASA's Goddard Institute for Space Studies (GISS). The month also set the record for the highest temperature anomaly – the largest difference from the long-term average.

This visualization shows global temperature anomalies along with the underlying seasonal cycle. Temperatures advance from January through December left to right, rising during warmer months and falling during cooler months. The color of each line represents the year, with colder purples for the 1960s and warmer oranges and yellows for more recent years. A long-term warming trend can be seen as the height of each month increases over time, the result of human activities releasing greenhouse gases like carbon dioxide into the atmosphere.



NASA / Peter Jacobs

“What’s remarkable is that these record values are happening before the peak of the current El Nino event, whereas in 2016 the previous record values happened in the spring, after the peak,” said Gavin Schmidt, director of GISS. El Nino is the warm phase of a naturally recurring pattern of trade winds and ocean temperatures in the Eastern Tropical Pacific that influences global temperatures and precipitation patterns.

From <https://www.nasa.gov/image-article/nasa-september-2023-temperature-data-shows-continued-record-warming/>

JWST Detects Carbon Dioxide in a Centaur

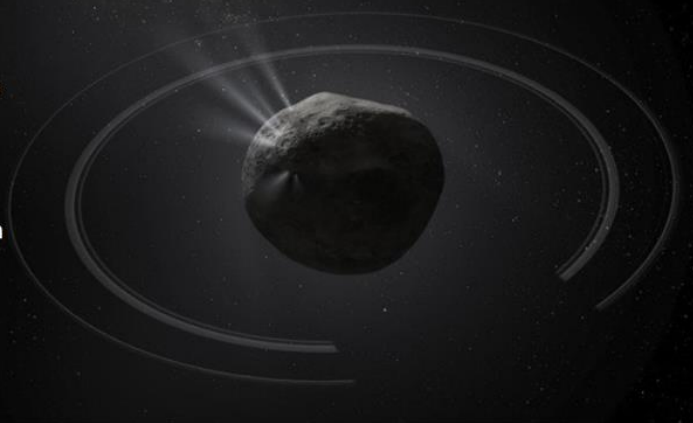


For the first time, NASA's James Webb Space Telescope (JWST) detected carbon dioxide in a Centaur, in this case the object 39P/Oterma. A Centaur is a small planetary body that orbits between Jupiter and Neptune and frequently crosses the orbits of one or more of the gas giant planets within our solar system.

The team of researchers, including planetary scientists from Goddard, used JWST's Near-Infrared Spectrograph (NIRSpec) instrument and ground-based observations from the Gemini North Observatory and Lowell Discovery Telescope to investigate the characteristics of 39P/Oterma in July 2022, as it passed the closest distance to the Sun in its orbit.

Centaurs have attributes of both asteroids and comets, but the amount of carbon dioxide detected was lower than seen in any comet. Water and carbon monoxide, gases common to Centaurs and comets, were not detected.

This discovery could mark a turning point in how scientists understand the formation, evolution, and composition of not only Centaurs, but of the early Solar System.



*Artist's illustration of the Centaur object Chiron, a comet-asteroid hybrid orbiting between Saturn and Uranus.
Image: Dan Durda, Astronomy Magazine.*

Paper: O. Pinto, M. Kelley, G. Villanueva (690), S. Faggi (693), M. DiSanti (693), et al. 2023, *Planetary Science Journal* 4, 208.

Press release: <https://www.universetoday.com/164066/jwst-detects-carbon-dioxide-in-a-centaur-for-the-first-time/>

Webb Finds Water, and a New Mystery, in Rare Main Belt Comet

A team of astronomers, including Goddard scientists Villanueva (690) and Milam (691), used Webb's Near-Infrared Spectrograph instrument (NIRSpec) to confirm the presence of water vapor around a comet in the main asteroid belt for the first time, indicating that water ice from the primordial solar system can be preserved in that region.

Sublimation of ice is what distinguishes comets from asteroids, creating their distinctive tails and hazy halos, or comas. It is especially significant for Comet 238P/Read, as it is one of 16 identified main-belt comets found in the asteroid belt, as opposed to the colder Kuiper Belt or Oort Cloud, more distant from the Sun, where most comets reside.

Strangely, carbon dioxide (CO₂), which is commonly seen in comets, was not detected in the sublimating material. This is a mystery requiring further investigation in order to get a better understanding of the role main-belt comets like 238P/Read play in the history of the Solar System.

The James Webb Space Telescope's detection of water vapor at Comet Read is a major benchmark in the study of main-belt comets and in the broader investigation of the origin of Earth's abundant water.

M. Kelley, G. Villanueva (690), S. Milam (691), et al., 2023, *Nature*, <https://doi.org/10.1038/s41586-023-06152-y>
Press release: <https://webbtelescope.org/contents/news-releases/2023/news-2023-123>



Artist's illustration of Comet 238P/Read sublimating its water ice as it approaches the Sun. Credits: NASA, ESA.

D. Science Education at GISS

Information about the GISS educational programs are available at:

<https://www.giss.nasa.gov/edu/>

GISS personnel include students and educators who participate as partners with the Institute's scientists in their research. Typically, six graduate students carry out their Ph.D. thesis research under the supervision of GISS staff members at any given time. Other participants include students and teachers from junior and senior high schools and senior colleges.

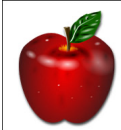
The Climate Change Research Initiative (CCRI) is a year-long STEM engagement program for educators and graduate students to work directly with NASA scientists and lead research teams in a NASA research project. Participating educators become associate researchers at NASA GISS and integrate NASA education resources and content into their classrooms while improving STEM education within their communities. During the summer session, CCRI teams add undergraduate and high school interns.

Further information about CCRI and other GISS student internship programs is available at:

<https://www.giss.nasa.gov/edu/intern/>

Education @ GISS

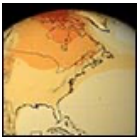
Intern and Educator Opportunities



Internships

All about high school and undergraduate student internships at NASA/GISS and its NYC-area research partners.

[+ Read More](#)



Climate Change Research Initiative

Year-round STEM engagement program allowing educators and graduate students to work directly with NASA scientists, with a summer internship program.

[+ Read More](#)

Past Programs



New York City Research Initiative

Intern and educator program in which teams affiliated university researchers. NYCRI concluded in 2014.

[+ Read More](#)



GISS Institute on Climate and Planets

A collaborative program between GISS, Columbia University, and the City University of New York. ICP concluded in 2004

[+ Go to Website](#)

More About NASA Education

[+ NASA STEM Engagement](#)

Advanced Study Programs



Columbia University Graduate Study

Study toward an advanced degree in the atmospheric sciences may be conducted at GISS through enrollment at Columbia University.

[+ Read More](#)



Postdoctoral Research Programs

Advanced programs in which early career scientists may participate in GISS research include NASA and Columbia University postdoctoral appointments.

[+ Read More](#)

Resource Materials

CCRI STEM Curriculum Modules

Instructional modules developed during the GISS Climate Change Research Initiative and NASA/SMD approved.

[+ Read More](#)

ICP Educational Materials Archive

Curriculum modules and learning tools developed during the Institute for Climate and Planets program (1994-2004) for use in classroom learning about climate and environmental research.

[+ Read More](#)

GISS Best Publication Award

Each spring/summer, scientists at NASA's Goddard Institute for Space Studies vote on the "best" paper published during the previous calendar year by a member or members of the institute. We consider this peer award to be the highest scientific honor that we bestow. The winners of this award since 1993 are listed below.

Beginning in 2023, scientists have also voted on the best paper whose first author was an early career scientist (i.e., a postdoctoral scientist or graduate student). Such papers are also included below and are prefixed by an "EC" notation.

2023

Orbe, C., D. Rind, R.L. Miller, L. Nazarenko, A. Romanou, J. Jonas, G. Russell, M. Kelley, and G. Schmidt, 2023: [Atmospheric response to a collapse of the North Atlantic circulation under a mid-range future climate scenario: A regime shift in Northern Hemisphere dynamics](#). *J. Climate*, **36**, no. 19, 6669-6693, doi:10.1175/JCLI-D-22-0841.1.

EC — Singh, R., K. Tsigaridis, A.N. LeGrande, F. Ludlow, and J.G. Manning, 2023: [Investigating hydroclimatic impacts of the 168-158 BCE volcanic quartet and their relevance to the Nile River basin and Egyptian history](#). *Clim. Past*, **19**, no. 1, 249-275, doi:10.5194/cp-19-249-2023.

2022

Bauer, S.E., K. Tsigaridis, G. Faluvegi, L. Nazarenko, R.L. Miller, M. Kelley, and G. Schmidt, 2022: [The turning point of the aerosol era](#). *J. Adv. Model. Earth Syst.*, **14**, no. 12, e2022MS003070, doi:10.1029/2022MS003070.

2021

Miller, R.L., G.A. Schmidt, L. Nazarenko, S.E. Bauer, M. Kelley, R. Ruedy, G.L. Russell, A. Ackerman, I. Aleinov, M. Bauer, R. Bleck, V. Canuto, G. Cesana, Y. Cheng, T.L. Clune, B. Cook, C.A. Cruz, A.D. Del Genio, G.S. Elsaesser, G. Faluvegi, N.Y. Kiang, D. Kim, A.A. Lacis, A. Leboissetier, A.N. LeGrande, K.K. Lo, J. Marshall, E.E. Matthews, S. McDermid, K. Mezuman, L.T. Murray, V. Oinas, C. Orbe, C. Pérez García-Pando, J.P. Perlwitz, M.J. Puma, D. Rind, A. Romanou, D.T. Shindell, S. Sun, N. Tausnev, K. Tsigaridis, G. Tselioudis, E. Weng, J. Wu, and M.-S. Yao, 2021: [CMIP6 historical simulations \(1850-2014\) with GISS-E2.1](#). *J. Adv. Model. Earth Syst.*, **13**, no. 1, e2019MS002034, doi:10.1029/2019MS002034.

2020

Kelley, M., G.A. Schmidt, L. Nazarenko, S.E. Bauer, R. Ruedy, G.L. Russell, A.S. Ackerman, I. Aleinov, M. Bauer, R. Bleck, V. Canuto, G. Cesana, Y. Cheng, T.L. Clune, B.I. Cook, C.A. Cruz, A.D. Del Genio, G.S. Elsaesser, G. Faluvegi, N.Y. Kiang, D. Kim, A.A. Lacis, A. Leboissetier, A.N. LeGrande, K.K. Lo, J. Marshall, E.E. Matthews, S. McDermid, K. Mezuman, R.L. Miller, L.T. Murray, V. Oinas, C. Orbe, C. Pérez García-Pando, J.P. Perlwitz, M.J. Puma, D. Rind, A. Romanou, D.T. Shindell, S. Sun, N. Tausnev, K. Tsigaridis, G. Tselioudis, E. Weng, J. Wu, and M.-S. Yao, 2020: [GISS-E2.1: Configurations and climatology](#). *J. Adv. Model. Earth Syst.*, **12**, no. 8, e2019MS002025, doi:10.1029/2019MS002025.

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B. Journal Papers

1. Adebisi, A.A., **Y. Huang**, B.H. Samset, and J.F. Kok, 2023: [Observations suggest that North African dust absorbs less solar radiation than models estimate](#). *Commun. Earth Environ.*, **4**, no. 1, 168, doi:10.1038/s43247-023-00825-2.....69
2. Ahsan, H., H. Wang, **J. Wu**, M. Wu, S.J. Smith, **S. Bauer**, H. Suchyta, D. Olivié, G. Myhre, H. Matsui, H. Bian, J.-F. Lamarque, K. Carslaw, L. Horowitz, L. Regayre, M. Chin, M. Schulz, R.B. Skeie, T. Takemura, and V. Naik, 2023: [The Emissions Model Intercomparison Project \(Emissions-MIP\): Quantifying model sensitivity to emission characteristics](#). *Atmos. Chem. Phys.*, **23**, no. 23, 14779-14799, doi:10.5194/acp-23-14779-2023.....70
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Observations suggest that North African dust absorbs less solar radiation than models estimate.

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Abstract. Desert dust accounts for a large fraction of shortwave radiation absorbed by aerosols, which adds to the climate warming produced by greenhouse gases. However, it remains uncertain exactly how much shortwave radiation dust absorbs. Here, we leverage in-situ measurements of dust single-scattering albedo to constrain absorption at mid-visible wavelength by North African dust, which accounts for approximately half of the global dust. We find that climate and chemical transport models overestimate North African dust absorption aerosol optical depth (AAOD) by up to a factor of two. This occurs primarily because models overestimate the dust imaginary refractive index, the effect of which is partially masked by an underestimation of large dust particles. Similar factors might contribute to an overestimation of AAOD retrieved by the Aerosol Robotic Network, which is commonly used to evaluate climate and chemical transport models. The overestimation of dust absorption by models could lead to substantial biases in simulated dust impacts on the Earth system, including warm biases in dust radiative effects.

Introduction. Most of the aerosol species in the atmosphere produce a cooling effect that opposes the warming effect produced by greenhouse gases¹. However, mineral dust is one of the three main aerosol species, in addition to black carbon and brown carbon, that absorb solar radiation and therefore could add to the warming produced by greenhouse gases^{1,2}. The exact amount of solar radiation that dust absorbs greatly affects its impact on the global climate system³. For instance, whether the net direct radiative effect of dust aerosols warms or cools the global climate system depends, in large part, on the amount of solar radiation absorbed by dust^{4,5,6}. Therefore, determining the extent of dust absorption of solar radiation is critical to determining whether future changes in atmospheric dust will slow or accelerate the projected warming of the climate system by greenhouse gases⁷. Beyond its direct radiative impacts, dust shortwave absorption also modifies atmospheric temperature profiles, thereby altering atmospheric circulations, cloud distributions, and precipitation^{8,9,10}. For example, enhanced dust shortwave absorption within the Saharan air layer can reduce the intensification of tropical cyclones over the North Atlantic Ocean by enhancing the low-level temperature inversion and increasing the vertical wind shear, which could ultimately weaken associated precipitation^{11,12}.

Despite the importance of dust shortwave absorption on weather and the climate system¹³, the exact amount of shortwave radiation absorbed by dust in the atmosphere remains highly uncertain^{14,15}. This uncertainty in estimating dust shortwave absorption is partially due to uncertainties in the microphysical properties of dust used in climate and chemical transport models (Fig. 1)^{13,16}. The amount of shortwave radiation absorbed by dust aerosols is quantified by the dust absorption aerosol optical depth (dust AAOD)—a parameter that depends on dust extinction, quantified by the dust aerosol optical depth (AOD), and the fraction of that extinction that is due to absorption, quantified by the single-scattering albedo (SSA; Fig. 1). Whereas global dust extinction scales with overall dust mass loading and has been effectively constrained using remote sensing observations^{17,18,19}, estimates of dust SSA remain very uncertain^{13,16}. This is because dust SSA primarily depends on the dust size distribution, dust shape, and the dust mineralogical composition (characterized by dust refractive index), and all these microphysical properties are poorly constrained in climate and chemical transport models (Fig. 1).

The Emissions Model Intercomparison Project (Emissions-MIP): Quantifying model sensitivity to emission characteristics.

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Abstract. Anthropogenic emissions of aerosols and precursor compounds are known to significantly affect the energy balance of the Earth-atmosphere system, alter the formation of clouds and precipitation, and have a substantial impact on human health and the environment. Global models are an essential tool for examining the impacts of these emissions. In this study, we examine the sensitivity of model results to the assumed height of SO₂ injection, seasonality of SO₂ and black carbon (BC) particulate emissions, and the assumed fraction of SO₂ emissions that is injected into the atmosphere as particulate phase sulfate (SO₄) in 11 climate and chemistry models, including both chemical transport models and the atmospheric component of Earth system models. We find large variation in atmospheric lifetime across models for SO₂, SO₄, and BC, with a particularly large relative variation for SO₂, which indicates that fundamental aspects of atmospheric sulfur chemistry remain uncertain. Of the perturbations examined in this study, the assumed height of SO₂ injection had the largest overall impacts, particularly on global mean net radiative flux (maximum difference of -0.35 W/m²), SO₂ lifetime over Northern Hemisphere land (maximum difference of 0.8 d), surface SO₂ concentration (up to 59% decrease), and surface sulfate concentration (up to 23% increase). Emitting SO₂ at height consistently increased SO₂ and SO₄ column burdens and shortwave cooling, with varying magnitudes, but had inconsistent effects across models on the sign of the change in implied cloud forcing. The assumed SO₄ emission fraction also had a significant impact on net radiative flux and surface sulfate concentration. Because these properties are not standardized across models this is a source of inter-model diversity typically neglected in model intercomparisons. These results imply a need to ensure that anthropogenic emission injection height and SO₄ emission fraction are accurately and consistently represented in global models.

Introduction. Anthropogenic emissions of aerosols or their precursors impact atmospheric energy balance, alter the formation of clouds and precipitation, and have substantial impacts on human health and the environment. Global models are an essential tool used to examine the impacts of these emissions. Model results will depend on both the actual input emissions data and the way those data are processed for use, which varies among different modeling systems. Previous work has demonstrated that the assumed injection height of anthropogenic SO₂ emissions has a large impact on modeled surface concentrations in one model (Yang et al., 2019). Here we extend these results in a multi-model sensitivity exercise (Emissions-MIP) to explore sensitivity to several aerosol-emission-related characteristics across a range of atmospheric models.

Large emission sources, such as anthropogenic point sources and large open fires (Paugam et al., 2016), inject emissions into a heated plume which rises and disperses into the atmosphere. This means that not only are those emissions effectively injected into the atmosphere at some height above the surface, but also the emissions plume may undergo chemical reactions before atmospheric dispersion. Appropriate distribution of emissions across vertical model layers is necessary to correctly reproduce the atmospheric chemistry in polluted regions (Pozzer et al., 2009).

Multi-year La Niña events and multi-season drought in the Horn of Africa.

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Abstract. One of the primary sources of predictability for seasonal hydroclimate forecasts are sea surface temperatures (SSTs) in the tropical Pacific, including El Niño–Southern Oscillation. Multiyear La Niña events in particular may be both predictable at long lead times and favor drought in the bimodal rainfall regions of East Africa. However, SST patterns in the tropical Pacific and adjacent ocean basins often differ substantially between first- and second-year La Niñas, which can change how these events affect regional climate. Here, we demonstrate that multiyear La Niña events favor drought in the Horn of Africa in three consecutive seasons [October–December (OND), March–May (MAM), OND]. But they do not tend to increase the probability of a fourth season of drought owing to the sea surface temperatures and associated atmospheric teleconnections in the MAM long rains season following second-year La Niña events. First-year La Niñas tend to have both greater subsidence over the Horn of Africa, associated with warmer waters in the west Pacific that enhance the Walker circulation, and greater cross-continental moisture transport, associated with a warm tropical Atlantic, as compared to second-year La Niñas. Both the increased subsidence and enhanced cross-continental moisture transport favors drought in the Horn of Africa. Our results provide a physical understanding of the sources and limitations of predictability for using multiyear La Niña forecasts to predict drought in the Horn of Africa.

Introduction. Drought has been a frequent trigger of acute food insecurity in the Horn of Africa (38°–53°E, 5°S–8°N) over the last decade ([Anderson et al. 2021](#); [Funk et al. 2018](#); [Maxwell and Hailey 2020](#); [Maxwell and Majid 2016](#); [Shukla et al. 2021](#)). As of February 2022, portions of the Horn of Africa are experiencing a multiseason drought in which rainfall has been below normal during the short rains (October–December) of 2020, the long rains (March–May) of 2021, and again in the short rains of 2021, which is contributing to the ongoing food security crisis in the region ([FEWS NET 2021](#)). In this context, there is considerable interest in the potential to understand and predict such multiyear drought events at lead times beyond the seasonal time scale, which would allow governments and humanitarian aid agencies to better prepare for the acute food insecurity caused by consecutive seasonal droughts.

One of the primary sources of predictability for seasonal hydroclimate forecasts are sea surface temperatures (SSTs) in the tropical Pacific, including El Niño–Southern Oscillation (ENSO) ([Lenssen et al. 2020](#); [Shukla et al. 2019](#); [Funk et al. 2018](#)). Operational seasonal forecasting systems, such as the North American Multi-Model Ensemble (NMME), demonstrate skill in predicting Niño-3.4 anomalies at leads up to 8–12 months in advance ([Barnston et al. 2019, 2012](#)). And while NMME forecasts are not available for leads longer than 12 months, machine learning-based multiyear forecasts of Niño-3.4 anomalies demonstrate skill up to 16 months in advance ([Ham et al. 2019](#)). Such forecasts of tropical Pacific SSTs are relevant for forecasting drought in East Africa during both the October–December and March–May season. Indeed, operational NMME precipitation forecasts are more skillful during strong ENSO years in East Africa ([Shukla et al. 2019](#)).

La Niña events in particular may be predictable multiple years in advance provided the correct initial conditions ([Wu et al. 2021](#); [DiNezio et al. 2017a,b](#); [Luo et al. 2017](#)). It has long been recognized that both El Niño and La Niña exhibit life cycles with predictable periods of growth and decay that are phase locked to the seasonal cycle ([Zebiak and Cane 1987](#); [Rasmusson and Carpenter 1982](#)). Recently, it has been identified that La Niñas are more likely to persist for two years as compared to El Niños ([Okumura and Deser 2010](#)).

Climate variability and simultaneous breadbasket yield shocks as observed in long-term yield records.

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Abstract. That climate variability and change can potentially force multiple simultaneous breadbasket crop yield shocks has been established. But research quantifying the mechanisms behind such simultaneous shocks has been constrained by short records of crop yields. Here we compile a dataset of subnational crop yields in 25 countries dating back to 1900 to study the frequency and trends in multiple breadbasket yield shocks and how large-scale climate anomalies on interannual timescales have affected multiple breadbasket yield shocks over the last century. We find that major simultaneous breadbasket yield shocks have occurred in at least three, four, or five of nine breadbaskets 10.3%, 2.3% and 1.1% of the time for maize and 18.4%, 4.6% and 2.3% of the time for wheat. Furthermore, we find that multiple breadbasket yield shocks decreased in frequency even as those breadbaskets experience increasingly frequent climate-related shocks. For both maize and wheat breadbaskets, there were fewer simultaneous yield shocks during the 1975–2017 time period as compared to 1931–1975. Finally, we find that interannual modes of climate variability - such as the El Niño Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), and the North Atlantic Oscillation (NAO) - have all affected the relative probability of simultaneous yield shocks in pairs of breadbaskets by up to 20–40% in both maize and wheat breadbaskets. While past literature has focused on the effects of ENSO, we find that at the global scale the NAO affects the overall number of wheat yield shocks most strongly despite only affecting northern hemisphere breadbaskets.

Introduction. In recent decades international trade has become an increasingly important part of the global food system, with a majority of people now depending on food imports to meet daily [caloric requirements](#) ([Porkka et al., 2013](#); [Puma et al., 2015](#)). Domestic food supply in heavily import-dependent countries is not always less stable than those that grow a larger fraction of their food ([Bren d'Amour and Anderson 2020](#)) as trade can either create conditions of food supply instability ([Bren d'Amour et al., 2016](#)) or lead to greater stability ([Lybbert et al., 2014](#)) depending on the context. But reliance on global food trade does present the unique risk that production shocks in remote countries can lead to reduced availability of food, which can contribute to price spikes that make food unaffordable ([Bren d'Amour et al., 2016](#), [Heslin et al., 2020](#), [Marchand et al., 2016](#), [Puma et al., 2015](#)). In this context, the possibility of multiple simultaneous breadbasket yield shocks presents a potential risk to food security by limiting options for import diversification and raising the risk of export restrictions ([Gaupp et al., 2020](#); [Gaupp et al., 2019](#); [Janetos et al., 2017](#), [Mehrabi and Ramankutty, 2019](#), [Tigchelaar et al., 2018](#), [Toreti et al., 2019](#)).

Large-scale modes of interannual [climate variability](#) - such as the [El Niño Southern Oscillation \(ENSO\)](#), the [Indian Ocean Dipole \(IOD\)](#), and the [North Atlantic Oscillation \(NAO\)](#)- are plausible mechanisms capable of affecting crop yields in multiple breadbaskets simultaneously ([Anderson et al., 2020, 2019, 2018](#); [Iizumi et al., 2014](#); [Najafi et al., 2020](#); [Singh et al., 2018](#)). ENSO, the IOD, and the NAO refer to naturally occurring modes of climate variability in the ocean and atmosphere that affect [atmospheric circulation](#), surface temperature, and precipitation on regional-to-global scales. These modes of climate variability, therefore, connect the growing conditions of distant regions and seasons to one-another ([Anderson et al., 2018](#)). While the potential for these climate modes to affect crop yields in multiple breadbaskets at once has been established using a few case studies ([Anderson et al., 2019](#); [Singh et al., 2018](#)), the importance of this mechanism to multiple breadbasket yield shocks as compared to those forced by random weather or non-climate factors is still poorly understood.

Global-to-local-to-global interactions and climate change.

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Abstract. Climate change by its very nature epitomizes the necessity and usefulness of the global-to-local-to-global (GLG) paradigm. It is a global problem with the potential to affect local communities and ecosystems. Accumulation of local impacts and responses to climate change feeds back to regional and global systems creating feedback loops. Understanding these complex impacts and interactions is key to developing more resilient adaptation measures and designing more efficient mitigation policies. To this date, however, GLG interactions have not yet been an integrative part of the decision-support toolkit. The typical approach either traces the impacts of global action on the local level or estimates the implications of local policies at the global scale. The first approach misses cumulative feedback of local responses that can have regional, national or global impacts. In the second case, one undermines a global context of the local actions most likely misrepresenting the complexity of the local decision-making process. Potential interactions across scales are further complicated by the presence of cascading impacts, connected risks and tipping points. Capturing these dimensions is not always a straightforward task and often requires a departure from conventional modeling approaches. In this paper, we review the state-of-the-art approaches to modeling GLG interactions in the context of climate change. We further identify key limitations that drive the lack of GLG coupling cases and discuss what could be done to address these challenges.

Introduction. Climate change by its very nature epitomizes the necessity and usefulness of the global-to-local-to-global (GLG) paradigm. Climate change is a global problem with the potential to affect people and their livelihoods, ecosystems and bio-diversity. No individual can escape contributing to climate change, even if there are vast differences in each individual's contribution to the problem. Because of the global significance of climate change, this is one area that almost from the beginning has been characterized by GLG-type analysis—albeit often at very different scales, and it has seen the emergence of so-called integrated assessment that captures the complex interactions between human societies and their impacts on atmospheric chemistry, energy balance and temperature, and the resulting effects on these same human societies and the bio-physical world (Weyant *et al* [1996](#), Nordhaus and Boyer [2000](#)). More recently, studies have also started to stress the importance of recognizing the GLG nature of climate change in the context of policy responses (Gupta *et al* [2007](#), Gupta [2014](#)), as well as to emphasize the value of GLG approach within other socio-economic spheres (Hertel *et al* [2019](#)).

Climate change is one of the global forces that shape the dynamics of socio-economic and biophysical systems (Tol [2018](#), Piontek *et al* [2021](#)). In combination with other global drivers, such as climate mitigation policies, changes in demographic patterns, pandemics and economic development policies, they form impact channels on the local systems (figure [1](#)). Local impacts are further shaped by the local context, such as specific biophysical and socio-economic conditions, as well as local policy responses. The latter might include climate adaptation measures, and economic or environmental policies. Interaction between global and local channels is further complicated by the presence of systemic risk (Simpson *et al* [2021](#)) and tipping points (Franzke *et al* [2022](#)). The first concept (systemic risk) tries to explain how various impacts across systems and scales can interact with each other and potentially compound leading to outcomes that were hard to anticipate under conventional (linear) assessment approaches. The concept of tipping points helps to identify cases when small perturbations generate abrupt, often irreversible changes to the future of the system (Lenton *et al* [2008](#)). Examples of tipping points in the case of climate systems include permafrost carbon feedback, the Amazon dieback and weakening of the Indian summer monsoon (Dietz *et al* [2021](#)).

An observation-based, reduced-form model for oxidation in the remote marine troposphere.

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Abstract. The hydroxyl radical (OH) fuels atmospheric chemical cycling as the main sink for methane and a driver of the formation and loss of many air pollutants, but direct OH observations are sparse. We develop and evaluate an observation-based proxy for short-term, spatial variations in OH (Proxy_{OH}) in the remote marine troposphere using comprehensive measurements from the NASA Atmospheric Tomography (ATom) airborne campaign. Proxy_{OH} is a reduced form of the OH steady-state equation representing the dominant OH production and loss pathways in the remote marine troposphere, according to box model simulations of OH constrained with ATom observations. Proxy_{OH} comprises only eight variables that are generally observed by routine ground- or satellite-based instruments. Proxy_{OH} scales linearly with in situ [OH] spatial variations along the ATom flight tracks (median $r^2 = 0.90$, interquartile range = 0.80 to 0.94 across 2-km altitude by 20° latitudinal regions). We deconstruct spatial variations in Proxy_{OH} as a first-order approximation of the sensitivity of OH variations to individual terms. Two terms modulate within-region Proxy_{OH} variations—water vapor (H₂O) and, to a lesser extent, nitric oxide (NO). This implies that a limited set of observations could offer an avenue for observation-based mapping of OH spatial variations over much of the remote marine troposphere. Both H₂O and NO are expected to change with climate, while NO also varies strongly with human activities. We also illustrate the utility of Proxy_{OH} as a process-based approach for evaluating inter-model differences in remote marine tropospheric OH.

Introduction. As the primary sink for methane, a strong greenhouse gas and air pollutant precursor, the hydroxyl radical (OH) is an influential yet poorly quantified lever on methane variations. Uncertainty in OH interannual variations is sufficiently high that it can hinder attribution of annual methane fluctuations. For example, inverse modeling analyses suggested several—sometimes conflicting—source sectors could explain the observed stabilization in methane levels from 2000 to 2005 (1–5), while uncertainty in the OH sink hinders effective trend attribution (6–8). Declining OH due to COVID-19 lockdowns has been invoked as a cause of the record-breaking increase in methane concentration observed since 2020 (9). The lack of constraints on OH also affects its representation in models that are applied to project future atmospheric composition and climate. Even when using the same emission inventories, chemistry-climate models simulate different methane lifetimes (10, 11), global mean OH (12, 13), and OH sensitivity to its drivers (13–15). Here, we develop and evaluate a proxy (Proxy_{OH}) built from OH steady-state chemistry over the remote marine troposphere. Proxy_{OH} maps spatial variations in OH and can also be deconstructed to infer the processes contributing to OH fluctuations, information that extends beyond the capacity of existing proxies.

Sharp spatiotemporal variations in OH confound the development of a representative measurement network. Interannual variability in global (16–19) or hemispheric (20) mean OH is typically inferred using the loss rate of relatively long-lived, well-mixed chemicals that react principally with OH, such as methyl chloroform (21–23). Formaldehyde, an intermediate product of methane oxidation with a lifetime of several hours, shows promise for reflecting daily OH fluctuations at the relatively small scale of a tropospheric column (24, 25). Although they offer much-needed information on OH variability, none of the existing proxies provides insight into the individual photochemical processes controlling OH.

Pre-industrial, present and future atmospheric soluble iron deposition and the role of aerosol acidity and oxalate under CMIP6 emissions

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Abstract. Atmospheric iron (Fe) deposition to the open ocean affects net primary productivity, nitrogen fixation, and carbon uptake. We investigate changes in soluble Fe (SFe) deposition from the pre-industrial period to the late 21st century using the EC-Earth3-Iron Earth System model. EC-Earth3-Iron considers various sources of Fe, including dust, fossil fuel combustion, and biomass burning, and features comprehensive atmospheric chemistry, representing atmospheric oxalate, sulfate, and Fe cycles. We show that anthropogenic activity has changed the magnitude and spatial distribution of SFe deposition by increasing combustion Fe emissions and atmospheric acidity and oxalate levels. We report that SFe deposition has doubled since the early industrial era, using the Coupled Model Intercomparison Project Phase 6 emission inventory. We highlight acidity as the main solubilization pathway for dust-Fe and oxalate-promoted processing for the solubilization of combustion-Fe. We project a global SFe deposition increase of 40% by the late 21st century relative to present day under Shared Socioeconomic Pathway (SSP) 3–7.0, which assumes weak climate change mitigation policies. Conversely, SSPs with stronger mitigation pathways (1–2.6 and 2–4.5) result in 35% and 10% global decreases, respectively. Despite these differences, SFe deposition increases over the equatorial Pacific and decreases in the Southern Ocean (SO) for all SSPs. We further observe that deposition over the equatorial Pacific and SO are highly sensitive to future changes in dust emissions from Australia and South America, as well as from North Africa. Future studies should focus on the potential impact of climate- and human-induced changes in dust and wildfires combined.

Introduction. Since the Industrial Revolution, the release of gases and aerosols into the atmosphere due to human activities has strongly increased. Consequently, atmospheric concentrations of greenhouse gases (GHGs), in particular carbon dioxide (CO₂), are now far higher than in any period over the past several hundred-thousand years (EPICA Community Members, 2004). About a quarter of the CO₂ emitted to the atmosphere since the Industrial Revolution has been absorbed and stored by the ocean (Ciais et al., 2013). The ability of the ocean to capture CO₂ depends partly on ocean net primary productivity (NPP), that is, the rate of photosynthetic carbon fixation minus the fraction of fixed carbon used for respiration and maintenance by marine biota. Ocean NPP relies upon the availability of light and nutrients, for example, nitrogen, phosphorus, iron (Fe), and silica (Behrenfeld et al., 2007). A vast area of oceanic surface waters is depleted in Fe but not in other nutrients, for example, the Southern Ocean (SO), the eastern equatorial Pacific, and the subarctic Pacific (Boyd et al., 2005). In those regions, so-called high nutrient low chlorophyll (HNLC) regions, Fe is the limiting factor for phytoplankton productivity, and thus for NPP (Jickells et al., 2005). Therefore the availability of Fe may significantly affect the ocean biological carbon export on a global scale.

The dominant Fe input to the open ocean is atmospheric aerosol deposition (Duce & Tindale, 1991). The major contributor to atmospheric Fe is mineral dust emitted from arid and semiarid regions, with an estimated present-day contribution of 95% of the total Fe aerosol burden. The remaining 5% is attributed to combustion sources, particularly anthropogenic combustion and biomass burning aerosols (Luo et al., 2008). However, not all Fe deposited to the ocean is directly bioavailable for marine biota. Much uncertainty exists about the physicochemical Fe forms that can be processed as nutrients (Baker & Croot, 2010; Jickells et al., 2005; Lis et al., 2015). It is widely assumed that soluble Fe (SFe) forms (e.g., aqueous, colloidal, or nanoparticulate) can be considered as bioavailable (Baker et al., 2006). Fe in dust (FeD) is considered to be largely insoluble at emission ($\approx 0.1\%$) (Jickells & Spokes, 2001; K. S. Johnson, 2001; Mahowald et al., 2005; Schroth et al., 2009; Sholkovitz et al., 2012).

Earth observations into action: Systemic integration of Earth observation application into national risk reduction decision structures.

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Abstract. As stated in the United Nations Global Assessment Report 2022 Concept Note, decision-makers everywhere need data and statistics that are accurate, timely, sufficiently disaggregated, relevant, accessible and easy to use. The purpose of this paper is to demonstrate scalable and replicable methods to advance and integrate the use of earth observation (EO), specifically ongoing efforts within the Group on Earth Observations (GEO) Work Programme and the Committee on Earth Observation Satellites (CEOS) Work Plan, to support risk-informed decision-making, based on documented national and subnational needs and requirements.

Introduction. Significant progress has been made specifically on developing integrated geospatial and statistical data to address the Sustainable Development Goals (SDGs) (e.g., United Nations Expert Group on the Integration of Statistical and Geospatial Information). A lesser degree of focus to date has been placed on merging the scientific earth observation (EO), global geospatial, statistical and disaster risk reduction (DRR) communities at technical and policy levels. Accelerated uptake and improved usefulness of existing and planned EOs is expected if the UN Office for Disaster Risk Reduction (UNDRR), UN Committee of Experts on Global Geospatial Information Management (UN-GGIM), Group on Earth Observations (GEO) and Committee on Earth Observation Satellites (CEOS) increase collaboration and focus on practical applications guided by high level frameworks, such as the UN-GGIM Strategic Framework on Geospatial Information and Services for Disasters.

GEO is an international partnership of governments and international organizations working on coordinated, comprehensive and sustained EOs. As a Participating Organization, i.e., a partner of GEO, CEOS and its Working Group on Disasters (WGDisasters) ensures international coordination of civil space-based EO programs and promotes exchange of data to help address global challenges, including DRR.

GEO and CEOS activities focused on DRR leverage public and private sector memberships at regional and national levels, through regionally oriented GEOs (AfriGEO, AOGE, EuroGEO and AmeriGEO) to understand requirements and work to reduce uncertainty through applications of scientific and policy developments.

Promotion of open data sharing and geospatial technology solutions that are scalable and replicable at national and subnational scales encourages accelerated implementation of successful EO applications. These solutions may also be linked to specific Sendai Framework for Disaster Risk Reduction (2015–2030) (Sendai Framework) Global Targets (E, F and G) that provide trusted answers to risk-oriented decision frameworks, as well as critical synergies between the Sendai Framework and the 2030 Agenda for Sustainable Development (SDGs).

Drought-tolerant succulent plants as an alternative crop under future global warming scenarios in sub-Saharan Africa.

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Abstract. Globally, we are facing an emerging climate crisis, with impacts to be notably felt in semiarid regions across the world. Cultivation of drought-adapted succulent plants has been suggested as a nature-based solution that could: (i) reduce land degradation, (ii) increase agricultural diversification and provide both economic and environmentally sustainable income through derived bioproducts and bioenergy, (iii) help mitigate atmospheric CO₂ emissions and (iv) increase soil sequestration of CO₂. Identifying where succulents can grow and thrive is an important prerequisite for the advent of a sustainable alternative ‘bioeconomy’. Here, we first explore the viability of succulent cultivation in Africa under future climate projections to 2100 using species distribution modelling to identify climatic parameters of greatest importance and regions of environmental suitability. Minimum temperatures and temperature variability are shown to be key controls in defining the theoretical distribution of three succulent species explored, and under both current and future SSP5 8.5 projections, the conditions required for the growth of at least one of the species are met in most parts of sub-Saharan Africa. These results are supplemented with an analysis of potentially available land for alternative succulent crop cultivation. In total, up to 1.5 billion ha could be considered ecophysiologicaly suitable and available for succulent cultivation due to projected declines in rangeland biomass and yields of traditional crops. These findings may serve to highlight new opportunities for farmers, governments and key stakeholders in the agriculture and energy sectors to invest in sustainable bioeconomic alternatives that deliver on environmental, social and economic goals.

Introduction. Dryland communities in sub-Saharan Africa (SSA) are facing a series of emerging challenges in the decades ahead. These include a continued reliance on solid fuels for daily energy requirements (Cerutti et al., 2015; IEA, 2019), increased precipitation variability caused by human-induced climatic changes (Marthews et al., 2019; Ofori et al., 2021; Otto et al., 2018) and increasingly unsustainable pastoral-based activities with a diminishing resource required to support a growing population across SSA communities (Scanes, 2018) resulting in widespread land degradation. Rangelands in particular are under increasing pressure to support sustainable livestock production; and whilst being central to the economies, social traditions and resilience of many communities (Bollig & Vehrs, 2020; Coppock et al., 2017; Godde et al., 2020; Hoffmann et al., 2014), their vegetation dynamics are highly vulnerable to climate change (trends and variability) in terms of both forage availability (Godde et al., 2020, 2021; Louhaichi et al., 2019; McCollum et al., 2017; Ouled Belgacem & Louhaichi, 2013) and feed yields (Jägermeyr et al., 2021; Rosenzweig et al., 2014).

Sustainable strategies that can tackle these challenges and provide solutions to socio-economic requirements and anticipated global warming impacts are needed. One such option is to explore the potential for alternative crops resilient to the impacts of global warming whilst simultaneously offering socio-economic gains, such as nongridded energy supplies and sustainable agricultural practices. Cultivation for bioenergy (Dahunsi et al., 2020; IRENA, 2017) and agricultural diversification (Njarui et al., 2020) have been previously explored as means by which plant-based solutions could be used to deliver benefits across the social, environmental and economic spheres. There are, however, widely differing water-usage requirements and levels of drought resilience among traditional bioenergy crops (Gasparatos et al., 2015; Gerbens-Leenes, 2018; Gerbens-Leenes et al., 2009).

Rising to the challenge: Producing and sustaining a nutrient-dense and climate-resilient food basket for all.

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Abstract. Rapidly destabilizing climatic and other biophysical conditions, competition for natural resources, geopolitical conflicts, and market pressures will continue to impose constraints and shocks to the food system, the greatest impacts of which will be felt by nutritionally vulnerable populations. Creating a just, nutritious, and sustainable food system that feeds the world requires a paradigm shift on where, what, and how we grow food while ensuring equitable channels of distribution. Moving forward, we must generate new science, reorient policies, and invest in a suite of environmental, technological, and sociocultural transformations from farm to fork.

Introduction. The current global food system is confronted with an unprecedented confluence of pressures. These challenges include meeting the increased demand for diverse and nutritious foods, adapting to climate change, mitigating greenhouse gas emissions and the other environmental costs of food systems, and maintaining the economic incentive for food system stakeholders. Each of these challenges is difficult on its own, and efforts to address them all simultaneously are further confounding.

On the supply side, the competition for water, energy, biodiversity, land, and other ecosystem resources needed for producing healthy, safe and sustainable diets for everyone will intensify as a result of climate change, particularly in lower latitudes.¹ In addition, demographic projections indicate that 68% of people will live in cities by 2050 (up from 57% in 2021), which will in turn affect agricultural productivity through labor and wage effects. On the demand side, the global population is projected to increase from nearly 7.8 billion today to 9.8 billion by 2050.³ Income growth and the nutrition transition from famine to overconsumption in developing nations will together increase the demand for diverse, safe, and nutrient-dense diets; place significant strain on the food system; and most likely exacerbate inequities.

These trends will further reinforce the need for extra resources and innovations to support the production, processing, and distribution of an optimal food basket. At the same time, cutting food loss and waste is a critical component of more sustainable food systems. Climate change, geopolitical conflicts, and market pressures will continue to impose constraints and shocks on the food system such that consumers will feel the impacts through price volatility and a reduced availability of food commodities. In this paper, we highlight the formidable challenges in generating healthy and accessible diets at scale from sustainable food systems. We also underscore the importance of science and research in generating the growing evidence base of risk and potential solutions to ensure that food systems are nutrient dense and climate resilient.

According to projections, we will require a 25%–70% increase in food production (depending on modeling scenarios and assumptions) to meet the global demand needed for attaining food security for all by 2050. However, given the recently stagnating yield trends, continuing resource depletion, and new climatic realities, achieving Sustainable Development Goal 2 (zero hunger) by 2030 remains out of reach. The latest crop modeling studies indicate that key crops are projected to face substantial pressures under unabated climate change; maize is especially affected, but soybean and rice also show declining yields in many lower-latitude systems.

Although selected crops (e.g., wheat) might see potential gains from elevated atmospheric CO₂ and moderate warming, in higher latitudes,⁸ important wheat regions (e.g., southern Canada, Pakistan, and Mexico) are projected to decline. In addition, although higher levels of atmospheric CO₂ can amplify crop growth, they will reduce the nutritional content substantially change.

Understanding model-observation discrepancies in satellite retrievals of atmospheric temperature using GISS ModelE.

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Abstract. We examine multiple factors in the representation of satellite-retrieved atmospheric temperature diagnostics in historical simulations of climate change during the satellite era (specifically 1979–2021) using GISS ModelE contributions to the Coupled Model Intercomparison Project (Phase 6) (CMIP6). The tropospheric and stratospheric trends in these diagnostics are affected by greenhouse gases (notably carbon dioxide and ozone), coupling with the ocean, volcanic aerosols, solar activity and compositional and dynamic feedbacks. We explore the impacts of internal variability, changing forcing specifications, composition interactivity, the quality of the stratospheric circulation, vertical resolution, and possible impacts of the mis-specification of volcanic aerosol optical depths. Overall temperature trends throughout the satellite period are well captured, but discrepancies at all levels exist and have multiple distinct causes. We find that stratospheric comparisons (using Stratospheric Sounding Unit (SSU) retrievals and successor instruments) are most affected by variations in the representation of ozone depletion and feedbacks, followed by the volcanic signals. Tropospheric skill (using the Microwave Sounding Unit (MSU) retrievals) is affected by the trends in ocean heat uptake and tropospheric aerosols, but also by the representation of stratospheric processes through the impact of the Brewer-Dobson circulation on the height of the tropical tropopause. We demonstrate that no single factor is the dominant cause of the discrepancies and that almost all observations lie within the broad envelope of structural uncertainty.

Introduction. The start of the satellite period (nominally 1979) marked the dawn of a new era in global multi-variate monitoring of climate. Over 40 years of data have been collected since then and has been sufficient not only to refine our knowledge of the Earth's climatology, but also to capture the trends of a changing climate. One suite of important variables is the set of vertically weighted atmospheric temperature changes seen by the Microwave Sounding Units (MSUs) (Mears et al., 2003; Spencer & Christy, 1990), Stratospheric Sounding Units (SSUs) (Thompson et al., 2012) and their successors, the Advanced Microwave Sounding Units (AMSUs).

The vertical pattern of temperature change in response to increased greenhouse gases has been recognised as a distinct fingerprint since the pioneering work of Manabe and Wetherald (1967). The surface warming enhanced tropospheric warming, and stratospheric (and above) cooling is unlike the pattern generated by increasing solar activity (which would have more uniform warming through the whole atmosphere), ozone depletion, volcanic activity, or ocean-driven internal variability. However, it wasn't until the satellite era and the development of global atmospheric retrievals using the MSU/SSU/AMSU series of instruments combined with the radiosonde record that the ability to distinguish these vertical fingerprints emerged (Ramaswamy et al., 1996; Randel & Cobb, 1994; Santer et al., 1996; Spencer & Christy, 1990).

The clear trends near the surface and in both the troposphere and stratosphere have thus long been used in detailed comparisons to climate model simulations. Those comparisons have led to the discovery of discrepancies between the satellite retrievals, surface temperatures and models, and therefore understanding them has been a major focus of scientific attention (e.g., CCSP, 2006; Christy & Spencer, 1995; Hansen et al., 1995; Jones et al., 1997; Thorne et al., 2011).

An observation-based method to assess tropical stratocumulus and shallow cumulus clouds and feedbacks in CMIP6 and CMIP5 models

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Abstract. In the Earth system models (ESMs) participating in the Coupled Models Intercomparison Project phase 6 (CMIP6), the tropical low-cloud feedback is 50% more positive than its predecessors (CMIP5) and continues to dominate the spread in simulated climate sensitivity. In the context of recent studies reporting larger feedbacks for stratocumulus (Sc) than shallow cumulus (Cu) clouds, it appears crucial to faithfully represent the geographical extent of each cloud type to simulate realistic low-cloud feedbacks. Here we use a novel observation-based method to distinguish Sc and Cu clouds together with satellite data from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) and Clouds and the Earth's Radiant Energy System (CERES) to evaluate Sc and Cu cloud fractions, cloud radiative effects and cloud feedbacks in the two latest generations of CMIP ESMs. Overall, the CMIP6 models perform better than the CMIP5 models in most aspects considered here, indicating progress. Yet the ensemble mean continues to underestimate the marine tropical low-cloud fraction, mostly attributable to Sc. Decomposition of the bias reveals that the Sc-regime cloud fraction is better represented in CMIP6, although Sc regimes occur too infrequently—even less frequently than in CMIP5. Building on our Sc and Cu discrimination method, we demonstrate that CMIP6 models also simulate more realistic low-cloud feedbacks than CMIP5 models, especially the Sc component. Finally, our results suggest that part of the CMIP6 low-cloud feedback increase can be traced back to greater cloud fraction in Sc-dominated regions.

Introduction. How clouds will respond to global warming, which is the essence of cloud feedback, continues to be a leading source of uncertainty in the two most recent Coupled Models Intercomparison Project (CMIP) generations (Zelinka et al 2016, 2020). The associated diversity of behavior impedes our ability to project the magnitude of future climate change and associated impacts (Vial et al 2013, Caldwell et al 2016, Zelinka et al 2020). More specifically, tropical low-cloud feedbacks, which are about 50% larger in CMIP6 (Cesana and del Genio 2021), remain particularly challenging because they dominate the spread among Earth system model (ESM) estimates of equilibrium climate sensitivity (ECS), a measure of the globally averaged surface air warming resulting from a doubling of CO₂ (Bony and Dufresne 2005, Andrews et al 2012, Vial et al 2013, Caldwell et al 2016).

Low clouds may be separated into two main categories: stratocumulus (Sc, including stratus clouds), typically driven by cloud-top radiative cooling, and shallow cumulus (Cu), driven by surface heat fluxes. Since these low clouds are dominated by different processes, they are typically represented by different parametrizations (i.e., turbulence for Sc and plume-like convection for Cu), and they exhibit distinct sensitivities to sea surface temperature (SST) and estimated inversion strength ([EIS]; Cesana and del Genio 2021, Myers et al 2021), the two main low-cloud controlling factors (Qu et al 2015, Klein et al 2017). As a result, Sc and Cu clouds generate distinct feedbacks that are modulated by SST and EIS patterns (e.g., Andrews and Webb 2018, Cesana and del Genio 2021). Consequently, simulating Sc or Cu clouds in the wrong places may result in unrealistic feedbacks, which explains why the issue of the Sc and Cu geographical extent emerges as being essential to estimating low-cloud feedbacks and the contribution to simulated ECS.

Efficient single-scattering look-up table for lidar and polarimeter water cloud studies.

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Abstract. Combined lidar and polarimeter retrievals of aerosol, cloud, and ocean microphysical properties involve single-scattering cloud calculations that are time consuming. We create a look-up table to speed up these calculations for water droplets in the atmosphere. In our new Lorenz–Mie look-up table we tabulate the light scattering by an ensemble of homogeneous isotropic spheres at wavelengths starting from 0.35 μm . The look-up table covers liquid water cloud particles with radii in the range of 0.001–500 μm while gaining an increase of up to 104 in computational speed. The covered complex refractive indices range from 1.25 to 1.36 for the real part and from 0 to 0.001 for the imaginary part. We show that we can precisely compute inherent optical properties for the particle size distributions ranging up to 100 μm for the effective radius and up to 0.6 for the effective variance. We test wavelengths from 0.35 to 2.3 μm and find that the elements of the normalized scattering matrix as well as the asymmetry parameter, the absorption, backscatter, extinction, and scattering coefficients are precise to within 1% for 96.7%–100% of cases depending on the inherent optical property. We also provide an example of using the look-up table with in situ measurements to determine agreement with remote sensing. The table together with C++, Fortran, MATLAB, and Python codes to interpolate the complex refractive index and apply different particle size distributions are freely available online.

Introduction. Liquid water clouds are an important radiative constituent of the Earth–atmosphere system, but microphysical processes related to clouds remain highly uncertain and poorly represented in climate models [1]. Remote sensing observations are crucial to improving our knowledge on cloud processes, but traditional methods are often biased especially in cases of broken or small clouds [2]. Furthermore, ignoring the temperature dependence of the refractive index may lead to biases in cloud remote sensing products [3]. The polarimetric cloudbow observations from NASA’s Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission will enable retrievals of cloud-top effective radius, variance, and droplet number concentration [4–6]. In addition, lidar observations contain information on cloud optical and microphysical properties [7]. NASA’s future Atmosphere Observing System (AOS) mission will likely include an imaging polarimeter and high spectral resolution lidar that will make collocated measurements further advancing cloud remote sensing capabilities. In this Letter we present a new cloud look-up table (LUT) that enables fast and precise retrievals of the microphysical properties of liquid water clouds from existing and next-generation remote sensing instruments. The LUT can also be used to compute the optical properties of clouds from airborne *in situ* droplet size distribution data. Our LUT supports a wide range of size distributions of spherical liquid water cloud droplets and derives the corresponding optical properties across the ultraviolet, visible, near-infrared, and shortwave infrared spectra.

The purpose of our LUT is to provide a fast and precise way to compute the liquid cloud inherent optical properties (IOPs) for a single-scattering case. These cases are characterized by a low value of depolarization measured by lidar and can be seen near the cloud edges [8]. The list of IOPs covered by the cloud LUT is the same as for our aerosol LUT and includes the normalized scattering matrix, the asymmetry parameter, the absorption, backscatter, extinction, and scattering coefficients [9]. Both LUTs use the same principles of work and similar unit test framework to assess the precision of estimations.

Reduced deep convection and bottom water formation due to Antarctic meltwater in a multi-model ensemble.

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Abstract. The additional water from the Antarctic ice sheet and ice shelves due to climate-induced melt can impact ocean circulation and global climate. However, the major processes driving melt are not adequately represented in Coupled Model Intercomparison Project phase 6 (CMIP6) models. Here, we analyze a novel multi-model ensemble of CMIP6 models with consistent meltwater addition to examine the robustness of the modeled response to meltwater, which has not been possible in previous single-model studies. Antarctic meltwater addition induces a substantial weakening of open-ocean deep convection. Additionally, Antarctic Bottom Water warms, its volume contracts, and the sea surface cools. However, the magnitude of the reduction varies greatly across models, with differing anomalies correlated with their respective mean-state climatology, indicating the state-dependency of the climate response to meltwater. A better representation of the Southern Ocean mean state is necessary for narrowing the inter-model spread of response to Antarctic meltwater.

Introduction. Recent observations show that the Antarctic Ice Sheet (AIS) (Forsberg et al., 2017; IMBIE, 2018; Rignot et al., 2019) and ice shelves (Adusumilli et al., 2020; Paolo et al., 2015; Scheuchl et al., 2016) are currently losing mass, which models suggest is likely to accelerate in the coming years under high emission forcing (Deconto et al., 2021; Edwards et al., 2021; Seroussi et al., 2020). The resulting meltwater discharge into the ocean influences regional and global climate (Bronse laer et al., 2018; Dong et al., 2022; Fyke et al., 2018; Purich & England, 2023; Rye et al., 2020), and has the potential to feedback onto the rate of basal ice shelf melting (Bronse laer et al., 2018; Flexas et al., 2022; Golledge et al., 2019), although this feedback is uncertain (Beadling et al., 2022; Moorman et al., 2020). However, the time-evolving interactions between the AIS, ice shelves, and the ocean are not included in Coupled Model Intercomparison Project phases 5 and 6 models (CMIP5 and CMIP6; Taylor et al., 2012; Eyring et al., 2016; Siahhan et al., 2022). These models employ specified ice sheets, where excess water from the ice/snow layer over Antarctica is rerouted to the ocean as runoff when snow depth exceeds a certain threshold. In cases where ice shelf cavities are present, the melt rates do not evolve in time (Mathiot et al., 2017). The absence of ice sheet processes and ocean–ice interactions in coupled climate models excludes potential feedbacks from meltwater discharge on regional and global climate, representing an unaccounted-for uncertainty in historical simulations and future projections (Swart et al., 2023).

The formation and recirculation of Antarctic Bottom Water (AABW) plays a crucial role in regulating the global climate by redistributing heat and carbon between the surface and deep ocean. In the real ocean, AABW is primarily formed by the sinking of dense waters on the Antarctic continental shelves (Orsi et al., 1999) with occasional contributions from open-ocean deep convection (Cheon & Gordon, 2019; Killworth, 1983). However, in most CMIP5 and CMIP6 models, AABW is formed by open-ocean deep convection (deep convection hereafter) with a large inter-model spread in the location and area of deep convection (Heuzé, 2021; Heuzé et al., 2013; Mohrmann et al., 2021). Simulated bottom water properties and transport are influenced by deep convection (Heuzé, 2021), which could be impacted by climate change. CMIP5 results suggest that Southern Ocean (SO) surface freshening caused by an enhanced hydrological cycle in a warming climate leads to a reduction in deep convection (De Lavergne et al., 2014). Additional surface freshening enhances the stratification by making surface waters less dense and thus the water column less prone to deep convection.

Diverging global dry and humid heat responses to modern irrigation.

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Abstract. The moderating influence of irrigation on dry heat extremes is well established, but the effect of irrigation on humid heat is more uncertain. Here, we study the impact of modern irrigation on both dry and humid heat-wave occurrences during the boreal summer using the NASA GISS Earth System Model (ModelE) with and without present-day irrigation. We show that the presence of modern irrigation reduces the total number of dry heat waves in most land areas, especially in arid and temperate regions. In contrast, humid heat waves occur more frequently under modern irrigation, especially in the Mediterranean Sea region, northern Africa, southern Africa, and the Middle East. Present-day irrigation reduces dry heat extremes by favoring latent heating over sensible heating and lowering surface solar radiation by increasing total cloud cover. Meanwhile, modern irrigation drives increases in humid heat through increases in specific humidity and precipitation. Notably, the reduction in dry heat is mostly localized over irrigated grid cells while humid heat increases both in locally irrigated areas and remote (non-irrigated) regions because of widespread increases in humidity associated with irrigation. Our results suggest that irrigation may amplify humid heat, even in non-irrigated areas, highlighting the importance of improving our understanding of both local and remote effects of the irrigation forcing on climate hazards.

Introduction. Heat waves are one of the most dangerous climate extremes and serve as a main contributor to weather-related morbidity and mortality ([IPCC 2021](#); [Buzan and Huber 2020](#); [Ebi et al. 2021](#); [Costello et al. 2023](#)). Heat stress has been tied to a large number of negative social issues, including increased crime, sociopolitical conflict, and decreased labor productivity, among others ([Buzan and Huber 2020](#); [Kjellstrom et al. 2009](#); [Horton et al. 2016](#)). The presence of heat stress also has significant ramifications for ecosystem health, agricultural productivity, and critical infrastructure ([Moore et al. 2021](#); [Hassan et al. 2021](#); [Teixeira et al. 2013](#); [Siebert and Ewert 2014](#); [Rübelke and Vögele 2011](#)). As our climate continues to warm, occurrences of heat stress and heat waves are expected to become more frequent and intense ([IPCC 2012](#); [Meehl and Tebaldi 2004](#); [Fischer and Knutti 2015](#)), making the study of heat events increasingly relevant in understanding and preparing for future climate risks.

While the presence of moisture has been acknowledged as a key driver of the intensity of heat stress, moist or humid heat as a phenomenon distinct from dry heat is still understudied ([Buzan and Huber 2020](#); [Matthews 2018](#)). Existing heat-wave and heat-stress literature focuses heavily on dry-bulb (or air) temperature metrics to define heat events ([Horton et al. 2015](#); [Diffenbaugh and Ashfaq 2010](#); [Mazdiyasni et al. 2017](#); [Perkins-Kirkpatrick and Lewis 2020](#)). However, the lack of inclusion of humidity causes dry heat metrics to omit a crucial component of heat when identifying and quantifying these events. Humidity has the ability to intensify heat stress and has even been shown to be more critical than temperature in driving extreme heat in regions in the United States ([Raymond et al. 2017](#); [Sherwood 2018](#)). The nonlinear nature of the relationship between humid heat and air temperature ([Matthews et al. 2017](#)) also has the potential to amplify heat-related risks to a degree not adequately conveyed by temperature alone.

Although there is a growing body of work related to humid heat ([Willett and Sherwood 2012](#); [Fischer and Knutti 2013](#); [Russo et al. 2017](#); [Raymond et al. 2017, 2020](#)), there is still much to learn with regard to the natural and anthropogenic influences on both dry and humid heat events.

Warming overwhelms the efficacy of wet conditions to moderate extreme heat and atmospheric aridity across the Central Plains

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Abstract. While the relationships between dry land surface conditions, heat, and aridity have been well-established, few studies have addressed whether global warming will affect the ability of wet conditions to moderate high temperatures and atmospheric aridity. Using Coupled Model Intercomparison Project Phase 6 models, we demonstrate that absolute changes in the monthly maximum temperature distribution during Central North American summers strongly outweigh the historical cooling effect of high precipitation and soil moisture conditions. Although wet conditions nearly always prevent concurrent extreme temperatures in the baseline period, these conditions are 40%–48% and 96%–98% less effective at 1 and 2° of global warming, respectively. However, high precipitation and soil moisture partially retain the ability to constrain concurrent high vapor pressure deficit conditions below historical thresholds at 1–2° of warming. Our results highlight the growing vulnerability of Central North America to warmer temperatures and drier atmospheric conditions, even during periods of high precipitation and soil moisture.

Introduction. Extreme temperatures cause a variety of negative impacts, including increased human mortality, and morbidity, decreased crop yields, elevated wildfire risk, and power grid failures (Abatzoglou & Williams, 2016; Deryng et al., 2014; Mazdiyasn et al., 2017; Stone et al., 2021). Vapor pressure deficit (VPD) is strongly tied to temperature, and high VPD negatively affects vegetation health and ecosystem function (Breshears et al., 2013; Ficklin & Novick, 2017; Hsiao et al., 2019; Novick et al., 2016) and is associated with elevated forest mortality and increased wildfire risk (Seager et al., 2015; Williams et al., 2013, 2014). Climate projections predict that extreme temperatures and VPD will continue increasing through the end of the 21st century in response to anthropogenic greenhouse gas emissions (Chen et al., 2021; Yuan et al., 2019), which will likely translate into even more severe impacts on socioeconomic and environmental sectors.

Historically, dry conditions have been strongly linked to the occurrence of extreme temperatures and high VPD conditions, especially in regions with significant land-atmosphere interactions (Miralles et al., 2019; Mueller & Seneviratne, 2012; Seneviratne et al., 2010; Zhou, Zhang, et al., 2019). In these regions, land surface conditions—specifically soil moisture—have been well-documented to affect the partitioning of latent and sensible heat fluxes and the exchange of energy and moisture with the overlying atmosphere (Alexander, 2011; Koster et al., 2004; Seneviratne et al., 2010). When soil moisture is abundant, latent heat fluxes dominate, promoting cloud formation, and land surface cooling (Alexander, 2011). However, during low soil moisture conditions, the ratio of sensible to latent heat flux is high, often reinforcing land surface drying with warmer and drier atmospheric conditions (Alexander, 2011). Under future warming, compound dry-hot and dry-arid events are expected to become more frequent and intense (X. Wu et al., 2021; Zhou, Zhang, et al., 2019; Zscheischler & Seneviratne, 2017). However, while the historical and future relationships between drought, heat, and aridity have previously been well-studied, there has been considerably less research done on whether rising temperatures driven by anthropogenic climate change will reduce the ability of wet conditions to constrain concurrent extreme temperatures and high VPD conditions.

Deglaciation of northwestern Greenland during Marine Isotope Stage 11.

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Abstract. Past interglacial climates with smaller ice sheets offer analogs for ice sheet response to future warming and contributions to sea level rise; however, well-dated geologic records from formerly ice-free areas are rare. Here we report that subglacial sediment from the Camp Century ice core preserves direct evidence that northwestern Greenland was ice free during the Marine Isotope Stage (MIS) 11 interglacial. Luminescence dating shows that sediment just beneath the ice sheet was deposited by flowing water in an ice-free environment 416 ± 38 thousand years ago. Provenance analyses and cosmogenic nuclide data and calculations suggest the sediment was reworked from local materials and exposed at the surface <16 thousand years before deposition. Ice sheet modeling indicates that ice-free conditions at Camp Century require at least 1.4 meters of sea level equivalent contribution from the Greenland Ice Sheet.

Introduction. Global oxygen isotopic composition of seawater ($\delta^{18}\text{O}_{\text{seawater}}$) data (1) highlight several interglacial periods since ~ 1 million years ago (Ma) with global ice volume lower than present, implying that the Greenland Ice Sheet (GrIS) and/or the Antarctic Ice Sheet were previously smaller than today. The lowest global ice volumes occurred during Marine Isotope Stage (MIS) 31 (1.08 to 1.06 Ma) and MIS 11 [424 to 374 thousand years ago (ka)]. Moderately lower ice volumes occurred during MIS 9 (337 to 300 ka), and MIS 5 (130 to 71 ka). Global mean sea level (GMSL) reconstructions indicate that the interglacials with the highest sea level were MIS 11 (+6 to 13 m) (2, 3) and MIS 5 (+1.2 to 5.3 m) (4), consistent with substantial reduction of the GrIS. However, the configuration of the GrIS, and thus its contribution to GMSL, during past interglacial periods remains poorly constrained (3).

Marine sediment archives document fluctuations in GrIS extent since ~ 1 Ma. Ice-rafted debris (IRD) in marine sediment from the North Atlantic Ocean indicates variable but persistent marine-terminating glaciation in eastern Greenland (Fig. 1) (5). Increased ^{10}Be concentrations in IRD during some intervals can be interpreted as a record of glacial erosion of landscapes exposed by smaller GrIS configurations during the Pleistocene (6). In the Labrador Sea, provenance changes in silt-sized sediment suggest that the southern GrIS retreated slightly during MIS 9 and 5 and was almost entirely absent during MIS 11 (7–9). Pollen in Labrador Sea sediment indicates that southern Greenland was inhabited by boreal forests during MIS 11 and possibly MIS 13 (533 to 478 ka), by tundra during MIS 7 (243 to 191 ka), and by fern-dominated (Pteridophyta) ecosystems during MIS 5 and perhaps MIS 9 (10). Compared to the Holocene, sea surface temperatures in the Labrador Sea were much warmer during MIS 9, 7, and 5 for brief periods [12.2, 4.4, and 9.7 thousand years (kyr), respectively] and slightly warmer during MIS 11 for a longer duration (20.7 kyr) (11, 12). Terrestrial temperatures reconstructed from leaf-wax biomarkers show that several interglacials since 600 ka were warmer than the Holocene, including brief extreme warmth during MIS 5 and prolonged moderate warmth during MIS 11 (13) (Fig. 1B).

Age constraints of Greenland ice core basal materials require substantial GrIS retreat at least once since ~ 1 Ma (Fig. 1B). Silty ice from the bottom of the Greenland Ice Core Project (GRIP) ice core suggests glacial cover in central Greenland since 950 ± 44 ka ($^{10}\text{Be}/^{36}\text{Cl}$) (14) and 970 ± 140 ka ($\delta^{40}\text{Ar}/^{38}\text{Ar}$) (15). Nearby, at the Greenland Ice Sheet Project 2 (GISP2) ice core, basal ice has $\delta^{40}\text{Ar}/^{38}\text{Ar}$ ages of >250 ka (16). Cosmogenic $^{26}\text{Al}/^{10}\text{Be}$ data from the underlying subglacial bedrock at GISP2 requires at least one episode of exposure, and thus ice-free conditions, in central Greenland after 1.1 ± 0.1 Ma (17).

A single-point modeling approach for the intercomparison and evaluation of ozone dry deposition across chemical transport models (Activity 2 of AQMEII4).

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Abstract. A primary sink of air pollutants and their precursors is dry deposition. Dry deposition estimates differ across chemical transport models, yet an understanding of the model spread is incomplete. Here, we introduce Activity 2 of the Air Quality Model Evaluation International Initiative Phase 4 (AQMEII4). We examine 18 dry deposition schemes from regional and global chemical transport models as well as standalone models used for impact assessments or process understanding. We configure the schemes as single-point models at eight Northern Hemisphere locations with observed ozone fluxes. Single-point models are driven by a common set of site-specific meteorological and environmental conditions. Five of eight sites have at least 3 years and up to 12 years of ozone fluxes. The interquartile range across models in multiyear mean ozone deposition velocities ranges from a factor of 1.2 to 1.9 annually across sites and tends to be highest during winter compared with summer. No model is within 50 % of observed multiyear averages across all sites and seasons, but some models perform well for some sites and seasons. For the first time, we demonstrate how contributions from depositional pathways vary across models. Models can disagree with respect to relative contributions from the pathways, even when they predict similar deposition velocities, or agree with respect to the relative contributions but predict different deposition velocities. Both stomatal and nonstomatal uptake contribute to the large model spread across sites. Our findings are the beginning of results from AQMEII4 Activity 2, which brings scientists who model air quality and dry deposition together with scientists who measure ozone fluxes to evaluate and improve dry deposition schemes in

Introduction. Dry deposition is a sink of many air pollutants and their precursors, removing compounds from the atmosphere after turbulence transports them to the surface and the compounds stick to or react with surfaces. Dry deposition may be a key influence on air pollution levels, including during high-pollution episodes (Vautard et al., 2005; Solberg et al., 2008; Emberson et al., 2013; Huang et al., 2016; Anav et al., 2018; Baublitz et al., 2020; Clifton et al., 2020b; Lin et al., 2020; Gong et al., 2021). Dry deposition can also harm plants when gases diffuse through stomata (Krupa, 2003; Ainsworth et al., 2012; Lombardozzi et al., 2013; Grulke and Heath, 2019; Emberson, 2020). In particular, stomatal uptake of ozone adversely impacts crop yields (Mauzerall and Wang, 2001; McGrath et al., 2015; Guarin et al., 2019; Hong et al., 2020; U.S. EPA, 2020a, b; Tai et al., 2021) and alters terrestrial carbon and water cycles (Ren et al., 2007; Sitch et al., 2007; Lombardozzi et al., 2015; Oliver et al., 2018).

Chemical transport models are key tools for research, planning, and regulatory purposes, including quantifying the influence of meteorology and emissions on air pollution. Accurate estimates of sinks like dry deposition are needed for source attribution, and simulated tropospheric and near-surface abundances of air pollutants are highly sensitive to dry deposition (Wild, 2007; Tang et al., 2011; Walker, 2014; Bela et al., 2015; Beddows et al., 2017; Hogrefe et al., 2018; Baublitz et al., 2020; Sharma et al., 2020; Ryan and Wild, 2021; Liu et al., 2022). However, chemical transport models do not always reproduce the observed variability in dry deposition nor in the near-surface abundances of air pollutants expected to be influenced strongly by dry deposition (Hardacre et al., 2015; Clifton et al., 2017; Kavassalis and Murphy, 2017; Silva and Heald, 2018; Travis and Jacob, 2019; Visser et al., 2021; Wong et al., 2022; Ye et al., 2022; Lam et al., 2023).

Influence of organized turbulence on OH reactivity at a deciduous forest.

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Abstract. Oxidation of reactive carbon fuels climate- and pollution-relevant chemistry. Deciduous forests are important sources of reactive carbon (particularly isoprene). Organization in turbulence can physically separate (“segregate”) oxidants from reactive carbon, causing oxidation to increase or decrease relative to the (ubiquitous) assumption of well-mixed conditions. We use large eddy simulation coupled to a multilayer canopy model and simplified chemistry to quantify the impact of segregation on near-canopy hydroxyl radical (OH) reactivity. Simulations mimic summer clear-sky midday and morning conditions at a homogeneous deciduous forest. OH-isoprene segregation alters OH reactivity inside the canopy by up to 9%, but the impact strongly depends on height, soil NO emissions, and sunlight. Uniquely, we identify the drivers of changes by isolating the roles of isoprene and OH. Our findings also suggest that segregation may create discrepancies between direct measurements and bottom-up estimates of OH reactivity, separate from the issue of mischaracterized or unknown OH sinks.

Introduction. The hydroxyl radical (OH) is the most important atmospheric oxidant, critical to the formation and destruction of many greenhouse gases and toxic air pollutants. OH reacts quickly with many compounds, challenging accurate OH measurements and predictive ability. Constraints on OH reactivity (OH_r) are key to better understanding of OH. Organized turbulence in the atmospheric boundary layer (ABL) may physically separate (“segregate”) OH from the compounds with which it reacts. Starting with Krol et al. (2000), a series of papers have suggested nonnegligible (e.g., 10%–40%) segregation of OH with its reactants (e.g., Butler et al., 2008; Dlugi et al., 2010; Kim et al., 2016; Patton et al., 2001). If segregation between OH and reactants is nonnegligible, then OH_r can be either slower or faster than the OH_r estimated with the (ubiquitous) assumption of well-mixed conditions. Many papers examine segregation between OH and reactants, but to our knowledge only Brosse et al. (2018) examine segregation's impact on OH_r , focusing on the influence of moist thermals in different chemical regimes. Here we also investigate segregation impacts on OH_r and changes with chemical regimes, but under very different environmental and chemical conditions and with a focus on the forest canopy.

Isoprene is emitted by vegetation, and deciduous forests are a large source of isoprene and thus oxidized reactive carbon that can lead to ozone and secondary organic aerosol formation (Carlton et al., 2009; Chameides et al., 1988; Guenther et al., 1995, 2012; Trainer et al., 1987). Previous work examines segregation between isoprene and OH using a variety of approaches (Brosse et al., 2018; Butler et al., 2008; Dlugi et al., 2010; Karl et al., 2007; Kaser et al., 2015; Kim et al., 2016; Krol et al., 2000; Li, Y. et al., 2016; Ouwersloot et al., 2011), in many cases probing the impact of clouds and land surface heterogeneity, which create large-scale organization in mixed-layer turbulence and isoprene emissions. Notably, segregation can also be important inside and right above forest canopies due to the combination of distinct organization in turbulent air motions and dynamic reactant sources and sinks that vary with height in the canopy, even across homogenous landscapes and under clear sky conditions (Clifton et al., 2022; Edburg et al., 2012; Patton et al., 2001). Specifically, in this work, we probe the impact of near-canopy isoprene-OH segregation on OH_r under clear-sky conditions at a homogeneous forest by leveraging a new version of the NCAR large eddy simulation (LES) coupled to a multilayer canopy model that simulates the broad range of scales contributing to organized turbulence over and inside canopies (Patton et al., 2016) as well as chemistry and interactive leaf-level chemical sources and sinks (Clifton et al., 2022).

Marsh archive reveals human population history and future implications for estuarine health in Long Island Sound.

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Abstract. Coastal marshes are efficient ecosystems providing a multitude of benefits for invertebrates, birds, fish and humans alike. Yet despite these benefits, wetlands are threatened by anthropogenic inputs such as human wastewater which contain high levels of nitrogen (N). Increased nitrogen loads cause [eutrophication](#) and hypoxia in estuaries leading to further degradation of these valuable ecosystems that are already stressed by [sea level rise](#) and climate change. Policies to protect wetlands via [wastewater treatments](#) are reactive rather than proactive and a growing body of research shows that characteristics associated with population health and economic activity can be identified in wastewater. Analysis of a 2-m salt marsh [sediment core](#) reveals δN^{15} signatures indicative of human population rise and connects [human impact](#) to ecosystem health. Using key X-ray fluorescence (XRF), pollen, sediment and nitrogen signatures along the core, a robust chronology was produced dating back to 1700. This result was coupled with population data to observe the relationship between δN^{15} levels and population over three centuries. There is a statistically significant positive correlation between δN^{15} and population. Other external factors such as federal government policies (regulating clean water) show a clear reduction in this association but the use of synthetic nitrogen fertilizer masks the strength of this relationship. Further research to refine the relationship between population and δN^{15} could be beneficial in predicting nitrogen loads as human population grows, which in turn would create a proactive system to protect our [coastal ecosystems](#).

Introduction. Coastal marshes are among the most productive ecosystems in the world, yet they are vulnerable, are susceptible to degradation, and have suffered enormous area loss over time ([Mitsch and Gosselink, 2000](#)). In particular, they are threatened by anthropogenic inputs of nitrogen, leading to [eutrophication](#) ([Bertness et al., 2002](#)). Globally, a minimal doubling of the annual N input to the land from anthropogenic activities compared with pre-industrial times has been documented ([Galloway, 2004](#)). These wetlands provide coastal communities protection from storm surges, are key habitats and nurseries for invertebrates, fish and birds, purify water, and are an exceptionally efficient [carbon storage](#) sinks ([Mitsch et al., 2013](#); [McLeod et al., 2011](#); [Wamsley et al., 2010](#)). Yet despite these benefits, marshes have historically been viewed as a mosquito infested, waste dumping ground or subject to backfill for coastal real estate development. Between 1780 and 1980 an estimated 74 % of wetlands have been lost in Connecticut alone ([Dahl, 1990](#)). In a more recent report, intertidal wetlands in the Northeast United States have lost 1.4 % of area between 2004 and 2009 ([Dahl, 2011](#)) and the stress of climate change, [sea level rise](#) and an increasing human footprint continues to degrade these ecosystems ([Watson et al., 2017](#)).

Protecting our vulnerable coastal areas is enhanced by a greater understanding of how development in the [Anthropocene](#) has impacted marshes historically to better inform decision makers on future protection. The US coastline has a rich history of anthropogenic development along its major waterways which create key chronological signatures in marsh cores ([Drexler et al., 2009](#), [Drexler, 2011](#), [Callaway et al., 2012](#), [Wigand et al., 2014](#), [Jones et al., 2017](#), [Peteet et al., 2018](#); [Peteet et al., 2020](#); [Pace et al., 2021](#)).

The most prevalent, but not only, but stressor on our coastal areas is also wastewater. [Human waste](#) contains high amounts of nitrogen and as populations have increased in Connecticut, higher and higher concentrations of waste have been deposited into natural environments ([Van Drecht et al., 2009](#); [Morée et al., 2013](#)).

Evaluating the representation of tropical stratocumulus and shallow cumulus clouds as well as their radiative effects in CMIP6 models using satellite observations.

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Abstract. Low clouds over tropical oceans reflect a great proportion of solar radiation back to space and thereby cool the Earth, yet this phenomenon has been poorly simulated in several previous generations of climate models. The principal aim of the present study is to employ satellite observations to evaluate the representation of marine tropical low clouds and their radiative effect at the top of the atmosphere in a subset of latest climate models participating in CMIP6. We strive for regime-oriented model validation and hence introduce a qualitative approach to discriminate stratocumulus (Sc) from shallow cumulus (Cu). The novel Sc-Cu categorization has a conceptual advantage of being based on cloud properties, rather than relying on a model response to a cloud-controlling factor. We find that CMIP6 models underestimate low-cloud cover in both Sc-regions and Cu-regions of tropical oceans. A more detailed investigation of cloud biases reveals that most CMIP6 models underestimate the relative frequency of occurrence (RFO) of Sc and overestimate RFO of Cu. We further demonstrate that tropical low cloudiness in CMIP6 models remains too bright. The regime-oriented validation represents the basis for improving parameterizations of physical processes that determine the cloud cover and radiative impact of Sc and Cu, which are still misrepresented in current climate models.

Introduction. Bright low clouds cover substantial areas of dark tropical oceans and play a critical role in regulating the Earth's radiative energy budget (Bony & Dufresne, [2005](#); Cesana & Del Genio, [2021](#); Schneider et al., [2017](#)). They reflect a substantial portion of the incoming sunlight back to space and thus exert a profound cooling effect on the Earth's climate. Climate models, however, have a longstanding problem simulating these clouds, which limits our ability to accurately predict the amount of global warming caused by rising greenhouse gas emissions (Bony & Dufresne, [2005](#); Sherwood et al., [2020](#)).

A major issue, which persisted in previous generations of climate models of the World Climate Research Programme's Coupled Model Intercomparison Project (CMIP), is known as the “too few, too bright” tropical low-cloud problem (Nam et al., [2012](#)). In brief, climate models commonly underestimated the amount of tropical and subtropical low-level clouds (e.g., Cesana & Chepfer, [2012](#); Cesana & Waliser, [2016](#); Cesana, Waliser, et al., [2019](#); Teixeira et al., [2011](#)) and simultaneously overestimated their reflectance (e.g., Karlsson et al., [2008](#); Nam et al., [2012](#); Weare, [2004](#)). In the present study, we revisit the “too few, too bright” tropical low-cloud problem in latest climate models participating in Phase 6 of CMIP (CMIP6; Eyring et al., [2016b](#)), which are currently being evaluated as a community effort (Schuddeboom & McDonald, [2021](#); Tselioudis et al., [2021](#)).

Satellite observations have been regularly exploited to assess the fidelity of climate models (e.g., Cesana & Chepfer, [2012](#); Cesana, Waliser, et al., [2019](#); Dolinar et al., [2015](#); Jiang et al., [2012](#); Pincus et al., [2008](#)), being especially valuable due to their extensive coverage. Evaluating clouds (and other fields) simulated by global climate models (GCMs) using satellite observations, however, is challenging, because satellite-borne instruments do not directly measure meteorological quantities of interest as simulated by GCMs. In order to facilitate the comparison between observed and model-simulated fields, the Cloud Feedback Model Intercomparison Project (CFMIP) community introduced the CFMIP Observation Simulator Package (COSP; Bodas-Salcedo et al., [2011](#); Swales et al., [2018](#)).

Sensitivity of the MAR regional climate model snowpack to the parameterization of the assimilation of satellite-derived wet-snow masks on the Antarctic Peninsula.

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Abstract. Both regional climate models (RCMs) and remote sensing (RS) data are essential tools in understanding the response of polar regions to climate change. RCMs can simulate how certain climate variables, such as surface melt, runoff and snowfall, are likely to change in response to different climate scenarios but are subject to biases and errors. RS data can assist in reducing and quantifying model uncertainties by providing indirect observations of the modeled variables on the present climate. In this work, we improve on an existing scheme to assimilate RS wet snow occurrence data with the “Modèle Atmosphérique Régional” (MAR) RCM and investigate the sensitivity of the RCM to the parameters of the scheme. The assimilation is performed by nudging the MAR snowpack temperature to match the presence of liquid water observed by satellites. The sensitivity of the assimilation method is tested by modifying parameters such as the depth to which the MAR snowpack is warmed or cooled, the quantity of water required to qualify a MAR pixel as “wet” (0.1 % or 0.2 % of the snowpack mass being water), and assimilating different RS datasets. Data assimilation is carried out on the Antarctic Peninsula for the 2019–2021 period. The results show an increase in meltwater production (+66.7 % on average, or +95 Gt), along with a small decrease in surface mass balance (SMB) (−4.5 % on average, or −20 Gt) for the 2019–2020 melt season after assimilation. The model is sensitive to the tested parameters, albeit with varying orders of magnitude. The prescribed warming depth has a larger impact on the resulting surface melt production than the liquid water content (LWC) threshold due to strong refreezing occurring within the top layers of the snowpack. The values tested for the LWC threshold are lower than the LWC for typical melt days (approximately 1.2 %) and impact results mainly at the beginning and end of the melting period. The assimilation method will allow for the estimation of uncertainty in MAR meltwater production and will enable the identification of potential issues in modeling near-surface snowpack processes, paving the way for more accurate simulations of snow processes in model projections.

Introduction. More than two-thirds of Earth's fresh water is held in the polar ice sheets ([Church et al., 2013](#)), with the majority of it trapped as land ice at the south pole, forming the Antarctic Ice Sheet (AIS). According to [Fretwell et al. \(2013\)](#), if all AIS ice were to melt, the global mean sea level would rise by 56 m. Currently, the AIS is primarily losing mass due to grounded ice flowing into the ocean. There, the ice is lost mainly through a combination of basal melting and calving ([The IMBIE Team, 2018](#); [Rignot et al., 2019](#); [Adusumilli et al., 2020](#)).

However, the surface melt production on the ice sheet is also important for several reasons. Even moderate surface melt over the ice shelves, the floating boundaries of the ice sheet, is thought to weaken the shelf structure and to cause ponding and hydrofracturing, leading to substantial mass loss ([Scambos et al., 2003](#); [Lai et al., 2020](#)). Additionally, surface melting is becoming a growing concern as it may increase greatly with climate change ([Trusel et al., 2015](#); [Bell et al., 2018](#); [Gilbert and Kittel, 2021](#)). Ice shelves exert a buttressing effect on the upstream ice flow, regulating the amount of ice that reaches the surrounding ocean. As they thin or collapse, this buttressing effect is reduced ([Favier and Pattyn, 2015](#); [Paolo et al., 2015](#)), and AIS ice flow velocity and mass loss are increased.

Climate models are currently one of the most useful tools in studying polar climate evolution. Some of them also include the possibility of modeling the evolution of the snowpack. A notable example is MAR (for “Modèle Atmosphérique Régional” in French), a regional climate model (RCM) specially developed to monitor the polar climate and the surface mass balance of both ice sheets.

Extreme stratospheric wave activity as harbingers of cold events over North America.

Ding, X., G. Chen, P. Zhang, D. Domeisen, and C. Orbe¹, 2023

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Abstract. Extreme cold events over North America such as the February 2021 cold wave have been suggested to be linked to stratospheric polar vortex stretching. However, it is not resolved how robustly and on which timescales the stratosphere contributes to the surface anomalies. Here we introduce a simple measure of stratospheric wave activity for re-analyses and model outputs. In contrast to the well-known surface influences of sudden stratospheric warmings (SSWs) that increase the intra-seasonal persistence of weather regimes, we show that extreme stratospheric wave events are accompanied by intra-seasonal fluctuations between warm and cold spells over North America in observations and climate models. Particularly, strong stratospheric wave events are followed by an increased risk of cold extremes over North America 5–25 days later. Idealized simulations in an atmospheric model with a well-resolved stratosphere corroborate that strong stratospheric wave activity precedes North American cold spells through vertical wave coupling. These findings potentially benefit the predictability of high-impact winter cold extremes over North America.

Introduction. As global warming is expected to reduce the frequency of severe cold spells, the causes of recent winter cold extremes in the Northern Hemisphere have attracted much public attention and scientific debate^{1,2,3,4,5,6}. Notably, the exceptional North American cold wave in February 2021 was suggested to be related to the sudden stratospheric warming (SSW) in January 2021^{7,8}, which was further proposed to be linked to Arctic sea ice loss under global warming^{3,4}. However, numerical weather forecasts for the February 2021 cold wave suggest that the January 2021 SSW event exerted only a limited influence on surface temperature^{5,9,10}. Given the disproportionate impacts of winter cold extremes on energy and society¹¹, an improved understanding of the role of the stratosphere in the predictability of surface cold spells is warranted.

There exist different types of stratospheric impacts on surface air temperature (SAT). SSWs feature an abrupt deceleration and reversal of the zonal wind in the winter stratosphere primarily due to planetary wave breaking and wave absorption, which is followed by downward propagation of negative zonal wind anomalies to the lower stratosphere on weekly to monthly timescales^{12,13,14,15,16,17,18,19,20}. The surface composite of SSWs is characterized by an anomalous high-pressure center near Greenland, with anomalous cooling over northern Eurasia and warming over eastern Canada that resemble the negative phase of the Arctic Oscillation (AO). In contrast, extreme stratospheric wave events, featuring negative meridional eddy heat flux due to planetary wave reflection, are instantaneously linked to the positive phase of the North Atlantic Oscillation (NAO) and anomalous North American cooling^{21,22,23}.

These two types of stratospheric impacts on the surface can be distinguished by the sign of lower-stratospheric meridional heat flux during the recovery stage of SSWs^{24,25}, clustering analysis^{3,26,27,28}, or empirical orthogonal function (EOF) analysis^{29,30}. Particularly, Cohen et al.³ argues that stratospheric polar vortex stretching involving planetary wave reflection is linked to North American cold spells such as the February 2021 Texas cold wave. However, the Alaskan ridge weather regime associated with widespread severe North American cold does not show a dependency on stratospheric vortex strength²⁷. Stratospheric wave reflection events are further associated with an evolution from a Pacific trough regime with surface warm anomalies over North America to an Alaskan ridge regime that favors North American cold³¹. In contrast to circulation regimes, the relevant stratosphere-troposphere coupling can be characterized as an intraseasonal variability mode³⁰.

Eye of Horus: A vision-based framework for real-time water level measurement.

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Abstract. Heavy rains and tropical storms often result in floods, which are expected to increase in frequency and intensity. Flood prediction models and inundation mapping tools provide decision-makers and emergency responders with crucial information to better prepare for these events. However, the performance of models relies on the accuracy and timeliness of data received from in situ gaging stations and remote sensing; each of these data sources has its limitations, especially when it comes to real-time monitoring of floods. This study presents a vision-based framework for measuring water levels and detecting floods using computer vision and deep learning (DL) techniques. The DL models use time-lapse images captured by surveillance cameras during storm events for the semantic segmentation of water extent in images. Three different DL-based approaches, namely PSPNet, TransUNet, and SegFormer, were applied and evaluated for semantic segmentation. The predicted masks are transformed into water level values by intersecting the extracted water edges, with the 2D representation of a point cloud generated by an Apple iPhone 13 Pro lidar sensor. The estimated water levels were compared to reference data collected by an ultrasonic sensor. The results showed that SegFormer outperformed other DL-based approaches by achieving 99.55 % and 99.81 % for intersection over union (IoU) and accuracy, respectively. Moreover, the highest correlations between reference data and the vision-based approach reached above 0.98 for both the coefficient of determination (R^2) and Nash–Sutcliffe efficiency. This study demonstrates the potential of using surveillance cameras and artificial intelligence for hydrologic monitoring and their integration with existing surveillance infrastructure.

Introduction. Flood forecasts and flood inundation mapping (FIM) can play an important role in saving human lives and reducing damage by providing timely information for evacuation planning, emergency management, and relief efforts (Gebrehiwot et al., 2019). These models and tools are designed to identify and predict inundation areas and the severity of damage caused by storm events. Two primary sources of data for these models are in situ gaging networks and remote sensing. For example, in situ stream gages, such as those operated by the United States Geological Survey (USGS) provide useful streamflow information like water height and discharge at monitoring sites (Turnipseed and Sauer, 2010). However, they cannot provide an adequate spatial resolution of streamflow characteristics (Lo et al., 2015). The limitation of in situ stream gages is further exacerbated by the lack of systematic installation along the waterways and accessibility issues (Li et al., 2018; King et al., 2018). Satellite data and remote sensing can complement in situ gage data by providing information at a larger spatial scale (Alsdorf et al., 2007). However, continuous monitoring of data for a region of interest remains to be a problem due to the limited revisit intervals of satellites, cloud cover, and systematic departures or biases (Panteras and Cervone, 2018). Crowdsourcing methods have gained attention as a potential solution but their reliability is questionable (Schnebele et al., 2014; Goodchild, 2007; Howe, 2008). To address these limitations and enhance real-time monitoring capabilities, surveillance cameras are investigated here as a new source of data for hydrologic monitoring and flood data collection. However, this requires a significant investment in computer vision (CV) and artificial intelligence (AI) techniques to develop reliable methods for detecting water in surveillance images and translating that information into numerical data.

Recent advances in CV offer new techniques for processing image data for the quantitative measurements of physical attributes from a site (Forsyth and Ponce, 2002). However, there is limited knowledge of how visual information can be used to estimate physical water parameters using CV techniques. Inspired by the principle of the float method, Tsubaki et al. (2011) used different image processing techniques to analyze images captured by closed-circuit

Vision-based texture and color analysis of waterbody images using computer vision and deep learning techniques.

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Abstract. Vision-based analysis of waterbodies can provide important information required for monitoring, analyzing, and managing water resource systems, such as visual flood detection, delineation, and mapping. Water, however, is an ornery object in image processing, as it can be found in different forms and colors in nature. This makes the detection, classification, and tracking of water in images and videos difficult for computer vision models. There are still visual differences resulting from water texture and its inherent optical properties associated with different waterbodies which can be recognized and extracted to support computer models to better analyze water images. This study aims to utilize a set of early, mid-level, and high-level vision techniques, including Gabor kernels, local binary patterns (LBPs), and deep learning (DL) models to extract and analyze water texture and color of different waterbodies in digital images. For this purpose, ATLANTIS TeXture (ATeX), an image dataset for waterbodies classification and texture analysis, was used. Models were trained for the task of classification on ATeX. Then, the performance of each model in extracting texture features was evaluated and compared. Results showed that the classification accuracy achieved by the Gabor magnitude tensor, LBP, and DL model (ShuffleNet V2 $\times$ 1.0) are 29, 35, and 92%, respectively, and thus the DL model outperforms traditional vision-based techniques. Moreover, the classification results on raw images represented by different color spaces (e.g., RGB, HSV, etc.) emphasized the importance of color information for digital image processing of water. Analyzing representative visual features and properties of different water types and waterbodies can facilitate designing a customized Convolutional Neural Networks (CNNs) for water scenes, as CNNs recognize objects through the analysis of both texture and shape clues and their relationship in the entire field of view.

Introduction. Digital images have great potential to become a new source of data due to the recent advances in Artificial Intelligence (AI) and Computer Vision (CV) ([LeCun et al. 2015](#); [Schmidhuber 2015](#)). Through calibration and estimation of camera geometry and parameters, digital images which contain water scenes can replace or complement traditional water measurement methods ([Eltner et al. 2018, 2021](#)). This requires employing Machine Learning (ML) models for analyzing and better understanding water components existing in digital images. However, training ML models to detect water in digital images is still a challenging task. The main problem which makes image processing on aquatic (eco)systems very difficult is the nature of water. Water has dynamic and inconsistent visual properties. Inherently, water is transparent, shapeless, and colorless. However, the surrounding environment, such as light reflection, flow regime, and sediments and particles can change the appearance of water in nature significantly ([Figure 1](#)).

Different constituents of the water column and their inherent optical properties have direct effects on light absorption and scattering of different water types. These particles influence the color of light that is detected by the camera sensor. For example, colored dissolved organic matter (CDOM)-rich water tends to look black because CDOM absorbs light strongly, but it does not reflect much light backward. Moreover, tidal forces cause a re-suspension of sediments, and non-algal particles (naps) making the color of water light brown. External factors such as light and temperature, as well as nutrients derive phytoplankton productivity which reflects green color possibly due to chlorophyll concentrations ([Palacios 2020](#)). These constituents, which vary from one waterbody to another, have a direct effect on the texture and color of the water.

Future climate change impacts on U.S. agricultural yields, production, and market.

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Abstract. This study provides estimates of [climate change impacts](#) on [U.S. agricultural yields](#) and the agricultural economy through the end of the 21st century, utilizing multiple climate scenarios. Results from a process-based crop model project future increases in wheat, grassland, and soybean yield due to climate change and atmospheric CO₂ change; corn and sorghum show more muted responses. Results using yields from econometric models show less positive results. Both the econometric and process-based models tend to show more positive yields by the end of the century than several other similar studies. Using the process-based model to provide future yield estimates to an integrated agricultural sector model, the welfare gain is roughly \$16B/year (2019 USD) for domestic producers and \$6.2B/year for international trade, but domestic consumers lose \$10.6B/year, resulting in a total welfare gain of \$11.7B/year. When yield projections for major crops are drawn instead from econometric models, total welfare losses of more than \$28B/year arise. Simulations using the process-based model as input to the agricultural sector model show large future production increases for soybean, wheat, and sorghum and large price reductions for corn and wheat. The most important factors are those about economic growth, [flooding](#), international trade, and the type of yield model used. Somewhat less, but not insignificant factors include adaptation, livestock productivity, and damages from surface ozone, waterlogging, and pests and diseases.

Introduction. Climate change has the potential to affect agricultural productivity and food supply through a wide array of mechanisms, as described in a large body of literature (e.g., [Rojas-Downing et al., 2017](#) and references therein, [IPCC, 2019](#)). For example, crop yields can be decreased through increases in heat stress, accelerated phenological development, insufficiency of chilling hours, higher [evapotranspiration](#) rates, increased aridity, increased climate extremes, changes in distribution of pests and diseases, [flooding](#), waterlogging, and increases in surface ozone levels. Livestock yields are also sensitive due to changes in energy for metabolic maintenance, suppressed appetite, altered fertility, lowered grass yields, shifting feedstock production, and altered feed nutrition ([Rojas-Downing et al., 2017](#)). Water demand, supply, intersectoral competition, and timing of water availability may also be impacted with agricultural implications ([Lall et al., 2018](#)). However, climate change also has the potential to benefit some crop and livestock systems through extended growing seasons (particularly in northern and western states; [Kukal and Irmak, 2018](#)) and more precipitation in some locations (particularly across the northern tier of the Pacific, Mountain, and Northern Plains states; [Marshall et al., 2015](#)). In addition, increased atmospheric CO₂ levels have been shown to increase the yields of some crops and competing weeds, while also reducing the nutritional value of some crops and forages ([Toreti et al., 2020](#), [Polley et al., 2013](#), [Ebi et al., 2021](#)). See Supplemental Electronic Material Table ESM-1 for a broader overview of these factors.

Both physical and economic models have been used to examine potential future agricultural implications of climate change for agriculture. Physical models are used to translate climate alterations to changes in crop and [livestock production](#) as well as pest-related costs and [water supplies](#). Economic models are used to translate yield, production, and pest changes into impacts on agricultural commodity prices and producer and consumer welfare, among other things (e.g., [Reilly et al., 2003](#), [von Lampe et al., 2013](#)). Globally, some economic models project a median increase of cereal prices in the 21st century due to climate change, leading to higher food prices and increased risk of food insecurity and hunger ([IPCC, 2019](#)).

The impact and estimation of uncertainty correlation for multi-angle polarimetric remote sensing of aerosols and ocean color.

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Abstract. Multi-angle polarimetric (MAP) measurements contain rich information for characterization of aerosol microphysical and optical properties that can be used to improve atmospheric correction in ocean color remote sensing. Advanced retrieval algorithms have been developed to obtain multiple geophysical parameters in the atmosphere–ocean system, although uncertainty correlation among measurements is generally ignored due to lack of knowledge on its strength and characterization. In this work, we provide a practical framework to evaluate the impact of the angular uncertainty correlation from retrieval results and a method to estimate correlation strength from retrieval fitting residuals. The Fast Multi-Angular Polarimetric Ocean coLoR (FastMAPOL) retrieval algorithm, based on neural-network forward models, is used to conduct the retrievals and uncertainty quantification. In addition, we also discuss a flexible approach to include a correlated uncertainty model in the retrieval algorithm. The impact of angular correlation on retrieval uncertainties is discussed based on synthetic Airborne Hyper-Angular Rainbow Polarimeter (AirHARP) and Hyper-Angular Rainbow Polarimeter 2 (HARP2) measurements using a Monte Carlo uncertainty estimation method. Correlation properties are estimated using autocorrelation functions based on the fitting residuals from both synthetic AirHARP and HARP2 data and real AirHARP measurement, with the resulting angular correlation parameters found to be larger than 0.9 and 0.8 for reflectance and degree of linear polarization (DoLP), respectively, which correspond to correlation angles of 10 and 5°. Although this study focuses on angular correlation from HARP instruments, the methodology to study and quantify uncertainty correlation is also applicable to other instruments with angular, spectral, or spatial correlations and can help inform laboratory calibration and characterization of the instrument uncertainty structure.

Introduction. Satellite remote sensing is important for the study of the earth system at a global scale ([National Academies of Sciences, Engineering, and Medicine, 2018](#)). Remote sensing instruments are evolving rapidly, with increasing accuracy and spatial, spectral, and angular resolutions ([Kokhanovsky et al., 2015](#); [Dubovik et al., 2019](#)). Multi-angle polarimeters (MAPs), measuring polarization states at multiple spectral bands and viewing angles, contain high information content for the study of aerosol and cloud optical and microphysical properties ([Mishchenko and Travis, 1997](#); [Chowdhary et al., 2001](#); [Hasekamp and Landgraf, 2007](#); [Knobelspiesse et al., 2012](#)). The aerosol properties derived from MAP instruments can be used to assist atmospheric correction for ocean color remote sensing ([Frouin et al., 2019](#); [Gao et al., 2020](#); [Hannadige et al., 2021](#)).

Uncertainty quantification from MAP retrievals provides information on the quality of the data products and improves our understanding of retrieval sensitivities. These uncertainties depend on the retrieval algorithm as well as the instrument characterization, including the spectral bands, viewing angles, and polarization capability and the measurement accuracy. As shown in Fig. 1 and Table 1, MAP instruments collect a large number of high-quality measurements with differing numbers of spectral bands and viewing angles ([Gao et al., 2021b](#)). The number of spectral bands are mostly within 4–14 for MAP instruments. An exception is the SPEX sensors (SPEX airborne and SPEXone, [Smit et al., 2019](#); [Hasekamp et al., 2019](#)), which acquire up to 400 spectral bands. The number of viewing angles for many instruments vary between 5 and 16 (e.g., 5 for SPEXone and 9 for SPEX airborne and MISR) but can be on the order of 100 for several hyper-angular instruments (90 for HARP2, 120 for AirHARP, 152 for RSP, and 250 for APS).

Simultaneous retrieval of aerosol and ocean properties from PACE HARP2 with uncertainty assessment using cascading neural network radiative transfer models.

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Abstract. The University of Maryland, Baltimore County (UMBC) Hyper-Angular Rainbow Polarimeter (HARP2) will be on board NASA's Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission, scheduled for launch in January 2024. In this study we systematically evaluate the retrievability and uncertainty of aerosol and ocean parameters from HARP2 multi-angle polarimeter (MAP) measurements. To reduce the computational demand of MAP-based retrievals and maximize data processing throughput, we developed improved neural network (NN) forward models for spaceborne HARP2 measurements over a coupled atmosphere and ocean system within the FastMAPOL retrieval algorithm. To this end, a cascading retrieval scheme is implemented in FastMAPOL, which leverages a series of NN models of varying size, speed, and accuracy to optimize performance. Two sets of NN models are used for reflectance and polarization, respectively. A full day of global synthetic HARP2 data was generated and used to test various retrieval parameters including aerosol microphysical and optical properties, aerosol layer height, ocean surface wind speed, and ocean chlorophyll *a* concentration. To assess retrieval quality, pixel-wise retrieval uncertainties were derived from error propagation and evaluated against the difference between the retrieval parameters and truth based on a Monte Carlo method. We found that the fine-mode aerosol properties can be retrieved well from the HARP2 data, though the coarse-mode aerosol properties are more uncertain. Larger uncertainties are associated with a reduced number of available viewing angles, which typically occur near the scan edge of the HARP2 instrument. Results of the performance assessment demonstrate that the algorithm is a viable approach for operational application to HARP2 data after the PACE launch.

Introduction. Satellite remote sensing has greatly enhanced our understanding of the Earth's environment, including the characterization of atmospheric aerosols and surface properties (Kaufman et al., 2002; Kokhanovsky et al., 2015; Kahn, 2015; Pörtner et al., 2023). Multi-angle polarimetric (MAP) remote sensing, pioneered by the Polarization and Directionality of the Earth's Reflectances (POLDER) instrument on Advanced Earth Observing Satellites (ADEOS-I; 1996–1997 and ADEOS-II; 2002–2003) and the Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL; 2004–2013) mission (Tanré et al., 2011), has emerged as a promising approach for retrieving geophysical properties from Earth observations (Mishchenko and Travis, 1997; Hasekamp and Landgraf, 2007; Knobelspiesse et al., 2012; Lacagnina et al., 2017; Dubovik et al., 2019; Hasekamp et al., 2019b; Chen et al., 2022).

This trend is set to continue with the forthcoming launch of the National Aeronautics and Space Administration (NASA) Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission in January 2024, featuring a hyperspectral scanning radiometer named the Ocean Color Instrument (OCI) (Meister et al., 2022) and two MAPs with high polarimetric accuracy: the University of Maryland, Baltimore County (UMBC) Hyper-Angular Rainbow Polarimeter (HARP2) (Martins et al., 2018; McBride et al., 2023) and the Netherlands Institute for Space Research (SRON) Spectro-Polarimeter for Planetary EXploration one (SPeXone) (Hasekamp et al., 2019a; Smit et al., 2019).

Importance of ice nucleation and precipitation on climate with the Parameterization of Unified Microphysics Across Scales version 1 (PUMASv1).

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Abstract. Cloud microphysics is critical for weather and climate prediction. In this work, we document updates and corrections to the cloud microphysical scheme used in the Community Earth System Model (CESM) and other models. These updates include a new nomenclature for the scheme, now called Parameterization of Unified Microphysics Across Scales (PUMAS), and the ability to run the scheme on graphics processing units (GPUs). The main science changes include refactoring an ice number limiter and associated changes to ice nucleation, adding vapor deposition onto snow, and introducing an implicit numerical treatment for sedimentation. We also detail the improvements in computational performance that can be achieved with GPU acceleration. We then show the impact of these scheme changes on the (a) mean state climate, (b) cloud feedback response to warming, and (c) aerosol forcing. We find that corrections are needed to the immersion freezing parameterization and that ice nucleation has important impacts on climate. We also find that the revised scheme produces less cloud liquid and ice but that this can be adjusted by changing the loss process for cloud liquid (autoconversion). Furthermore, there are few discernible effects of the PUMAS changes on cloud feedbacks but some reductions in the magnitude of aerosol–cloud interactions (ACIs). Small cloud feedback changes appear to be related to the implicit sedimentation scheme, with a number of factors affecting ACIs.

Introduction. Cloud microphysics is critical for weather and climate. In particular, supercooled liquid water (liquid at temperatures below 0 °C) and the fraction of condensate in the form of supercooled liquid at high latitudes has been shown to be important for mean state climate ([Bodas-Salcedo et al., 2019](#)) and weather ([Forbes et al., 2015](#)) biases. Supercooled liquid water is also important for understanding cloud feedbacks and climate sensitivity ([Tan et al., 2016](#); [Gettelman et al., 2019b](#); [Tan and Storelvmo, 2019](#)). For example, the Community Earth System Model version 2 (CESM2; [Danabasoglu et al., 2020](#)) has been shown to have a higher supercooled liquid fraction than observed ([Gettelman et al., 2020](#)), which has been linked to a higher climate sensitivity than previous versions ([Gettelman et al., 2019b](#)). In addition, cloud microphysics controls the formation of precipitation, which is often too light and too frequent in large-scale weather and climate models ([Stephens et al., 2010](#)). This frequency bias has been shown to be directly attributable to cloud microphysics ([Gettelman et al., 2021](#)). In this work, we describe adjustments and corrections to the ice microphysics and precipitation process in an advanced cloud microphysics scheme used in several global models and how these changes can have a significant effect on simulated climate.

The state of the art for global model cloud microphysics is the use of bulk two-moment schemes, such as the scheme developed by [Morrison and Gettelman \(2008, MG1\)](#). The CESM2 atmosphere model uses cloud microphysics described by [Gettelman and Morrison \(2015\)](#) and [Gettelman et al. \(2015\)](#), termed MG2 (Morrison–Gettelman version 2). The scheme has been updated further to include rimed ice by [Gettelman et al. \(2019a, MG3\)](#). Most two-moment bulk schemes utilize classes of hydrometeors (such as cloud liquid, cloud ice, and snow). In such schemes, number and mass are predicted for each class, and hydrometeors are treated using a size distribution with a fixed functional form. Two-moment schemes are widely used in mesoscale models (e.g., [Thompson and Eidhammer, 2014](#)) at resolutions of a few kilometers but less commonly used in global models (e.g., [Lohmann et al., 1999, 2007](#); [Michibata et al., 2019](#)).

The projected future degradation in air quality is caused by more abundant natural aerosols in a warmer world.

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Abstract. Previous studies suggest that greenhouse gas-induced warming can lead to increased fine particulate matter concentrations and degraded air quality. However, significant uncertainties remain regarding the sign and magnitude of the response to warming and the underlying mechanisms. Here, we show that thirteen models from the Coupled Model Intercomparison Project Phase 6 all project an increase in global average concentrations of fine particulate matter in response to rising carbon dioxide concentrations, but the range of increase across models is wide. The two main contributors to this increase are increased abundance of dust and secondary organic aerosols via intensified West African monsoon and enhanced emissions of biogenic volatile organic compounds, respectively. Much of the inter-model spread is related to different treatment of biogenic volatile organic compounds. Our results highlight the importance of natural aerosols in degrading air quality under current warming, while also emphasizing that improved understanding of biogenic volatile organic compounds emissions due to climate change is essential for numerically assessing future air quality.

Introduction. Air quality is an important aspect of human health¹ and of Sustainable Development Goals involving good health and well-being^{2,3}. Surface-level fine (diameter $\leq 2.5 \mu\text{m}$) particulate matter (PM_{2.5}) is a form of air pollution that is a known carcinogen^{4,5}, is tied to higher infant mortality rates^{6,7}, causes adverse respiratory affects in children⁶, and leads to a worldwide excess mortality rate of 8.8 million per year from all sources, including 5.5 million due to anthropogenic sources and 3.3 due to natural sources⁸.

Owing to multiple interactions involving emissions, chemical processes, deposition and other physical factors (e.g., temperature, precipitation and atmospheric circulation), both the sign and magnitude of PM_{2.5} changes under GHG-induced warming are uncertain^{9,10,11,12}. Several studies have emphasized the importance of altered wet removal to increased aerosol burden^{13,14,15,16}, through changes in precipitation type (large-scale versus convective) and distribution (e.g., decrease in wet-day frequency). Degraded air quality under warming will likely yield an increase in premature mortality associated with lung cancer and cardiopulmonary disease in most world regions^{17,18}. Such impacts may be exacerbated due to an increased chance of compound extreme events, including concurrent heat waves and air quality extremes^{11,19}.

GHG-induced warming will also impact the emissions of natural aerosols and precursor gases, including biogenic volatile organic compounds (BVOCs), which can oxidize into secondary organic aerosols (SOA). As the production of BVOCs requires carbon obtained from the breakdown of CO₂, BVOC production is tied to photosynthesis^{20,21}. Rising atmospheric CO₂ concentrations are likely to increase the productivity and standing biomass of plants, which allows for an increase in photosynthesis rates²², and thus an increase in the available carbon for BVOC production. An increase in atmospheric CO₂ concentrations, however, can inhibit the production of the BVOC isoprene²³. The biochemical basis for these observations is not fully resolved, but may include CO₂-mediated variations of key substrates such as pyruvate²⁴. Prior modeling studies show that taking this inhibition into account still results in a net increase in isoprene emission, and a relatively large (25%) increase in SOA under future climate change²⁵. Higher atmospheric CO₂ concentrations also promote higher global temperatures, which enhance the enzymatic activities of synthesis that produce isoprene and most other BVOCs^{20,26}. Warming also increases the atmospheric vapor pressure of certain BVOCs surrounding vegetation^{27,28}. As vapor pressure of the BVOCs rise, more can exist in the gaseous phase in the surrounding air, allowing for more oxidation to SOA.

Modeling dust mineralogical composition: sensitivity to soil mineralogy atlases and their expected climate impacts.

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Abstract. Soil dust aerosols are a key component of the climate system, as they interact with short- and long-wave radiation, alter cloud formation processes, affect atmospheric chemistry and play a role in biogeochemical cycles by providing nutrient inputs such as iron and phosphorus. The influence of dust on these processes depends on its physicochemical properties, which, far from being homogeneous, are shaped by its regionally varying mineral composition. The relative amount of minerals in dust depends on the source region and shows a large geographical variability. However, many state-of-the-art Earth system models (ESMs), upon which climate analyses and projections rely, still consider dust mineralogy to be invariant. The explicit representation of minerals in ESMs is more hindered by our limited knowledge of the global soil composition along with the resulting size-resolved airborne mineralogy than by computational constraints. In this work we introduce an explicit mineralogy representation within the state-of-the-art Multiscale Online Nonhydrostatic Atmosphere Chemistry (MONARCH) model. We review and compare two existing soil mineralogy datasets, which remain a source of uncertainty for dust mineralogy modeling and provide an evaluation of multiannual simulations against available mineralogy observations. Soil mineralogy datasets are based on measurements performed after wet sieving, which breaks the aggregates found in the parent soil. Our model predicts the emitted particle size distribution (PSD) in terms of its constituent minerals based on brittle fragmentation theory (BFT), which reconstructs the emitted mineral aggregates destroyed by wet sieving. Our simulations broadly reproduce the most abundant mineral fractions independently of the soil composition data used. Feldspars and calcite are highly sensitive to the soil mineralogy map, mainly due to the different assumptions made in each soil dataset to extrapolate a handful of soil measurements to arid and semi-arid regions worldwide. For the least abundant or more difficult-to-determine minerals, such as iron oxides, uncertainties in soil mineralogy yield differences in annual mean aerosol mass fractions of up to ~ 100 %. Although BFT restores coarse aggregates including phyllosilicates that usually break during soil analysis, we still identify an overestimation of coarse quartz mass fractions (above 2 μm in diameter). In a dedicated experiment, we estimate the fraction of dust with undetermined composition as given by a soil map, which makes up ~ 10 % of the emitted dust mass at the global scale and can be regionally larger. Changes in the underlying soil mineralogy impact our estimates of climate-relevant variables, particularly affecting the regional variability of the single-scattering albedo at solar wavelengths or the total iron deposited over oceans. All in all, this assessment represents a baseline for future model experiments including new mineralogical maps constrained by high-quality spaceborne hyperspectral measurements, such as those arising from the NASA Earth Surface Mineral Dust Source Investigation (EMIT) mission.

Introduction. Airborne dust is one of the most abundant aerosols in the atmosphere and a fundamental component of the Earth system (e.g., [Miller et al., 2014](#)). Dust scatters and absorbs short- and long-wave radiation (e.g., [Di Biagio et al., 2017, 2019](#)) and affects cloud formation processes (e.g., [Atkinson et al., 2013](#); [Harrison et al., 2019](#); [Chatziparaschos et al., 2023](#)) and atmospheric chemistry and biogeochemical cycles (e.g., [Krueger et al., 2004](#); [Jickells, 2005](#); [Kanakidou et al., 2018](#)). All these processes are sensitive to dust mineralogy, as dust is present in soils and in the atmosphere as a mixture of different minerals with varying physicochemical properties rather than as a homogeneously mixed species.

Insights into the size-resolved dust emission from field measurements in the Moroccan Sahara.

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Abstract. The particle size distribution (PSD) of mineral dust has a strong effect on the impacts of dust on climate. However, our understanding of the emitted dust PSD, including its variability and the fraction of super-coarse dust (diameter $>10\text{ }\mu\text{m}$), remains limited. Here, we provide new insights into the size-resolved dust emission process based on a field campaign performed in the Moroccan Sahara in September 2019 in the context of the Frontiers in dust minerAloGical coMposition and its Effects upoN climaTe (FRAGMENT) project. The obtained dust concentration and diffusive flux PSDs show significant dependencies upon the friction velocity (u_*), wind direction and type of event (regular events versus haboob events). For instance, the number fraction of sub-micrometre particles increases with u_* , along with a large decrease in the mass fraction of super-coarse dust. We identify dry deposition, which is modulated by u_* and fetch length, as a potential cause for this PSD variability. Using a resistance model constrained with field observations to estimate the dry deposition flux and thereby also the emitted dust flux, we show that deposition could represent up to $\sim 90\%$ of the emission of super-coarse particles ($>10\text{ }\mu\text{m}$) and up to $\sim 65\%$ of the emission of particles as small as $\sim 5\text{ }\mu\text{m}$ in diameter. Importantly, removing the deposition component significantly reduces the variability with u_* in the PSD of the emitted dust flux compared with the diffusive flux, particularly for super-coarse dust. The differences between regular and haboob event concentration and diffusive flux PSDs are suspected to result from a smaller and variable dust source fetch during the haboob events, and/or an increased resistance of soil aggregates to fragmentation associated with the observed increase in relative humidity along the haboob outflow. Finally, compared to the invariant emitted dust flux PSD estimated based on brittle fragmentation theory, we obtain a substantially higher proportion of super-micrometre particles in the dust flux. Overall, our results suggest that dry deposition needs to be adequately considered to estimate the emitted PSD, even in studies limited to the fine and coarse size ranges ($<10\text{ }\mu\text{m}$).

Introduction. Mineral dust emitted by wind erosion from arid and semi-arid regions dominates the global aerosol mass load (Textor et al., 2006) and plays a key role in the Earth system by perturbing the energy, water, iron, phosphorous, and carbon cycles (Okin et al., 2004; Bristow et al., 2010; Shao et al., 2011b; Knippertz and Stuut, 2014; Jickells and Moore, 2015). The effects of dust aerosol are controlled by its amount and physico-chemical properties, i.e. particle size distribution (PSD), mineralogy, shape, and mixing state (Tegen and Lacis, 1996; Karanasiou et al., 2012; Huang et al., 2014; Miller et al., 2014).

Despite the progress achieved over the last decades, the size-resolved emitted dust flux and its spatio-temporal variability remain as key uncertainties in the description of the dust life cycle in atmospheric and Earth system models (Kok, 2011a; Evan et al., 2014; Adebisi and Kok, 2020; Klose et al., 2021). Dust emission is complex: the most efficient release of dust particles is through saltation (Gillette, 1977; Gomes et al., 1990; Shao et al., 1993; Shao, 2008), which is – as with dust emission itself – modulated by soil properties (e.g. soil texture, mineralogical composition, presence and stability of aggregates), surface soil conditions (e.g. moisture, vegetation cover, crust, roughness), and land use (e.g. agriculture, grazing) (Tegen et al., 2002; Pierre et al., 2012; Perlwitz et al., 2015a, b; Klose et al., 2019). Current global quantitative knowledge of many of these factors is poor or nonexistent, which demands certain simplifications in model dust emission schemes.

Modulation of the seasonal cycle of the Antarctic sea ice extent by sea ice processes and feedbacks with the ocean and the atmosphere.

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Abstract. The seasonal cycle of the Antarctic sea ice extent is strongly asymmetric, with a relatively slow increase after the summer minimum followed by a more rapid decrease after the winter maximum. This cycle is intimately linked to the seasonal cycle of the insolation received at the top of the atmosphere, but sea ice processes as well as the exchanges with the atmosphere and ocean may also play a role. To quantify these contributions, a series of idealized sensitivity experiments have been performed with an eddy-permitting (°) NEMO-LIM3 (Nucleus for European Modelling of the Ocean–Louvain-la-Neuve sea ice model version 3) Southern Ocean configuration, including a representation of ice shelf cavities, in which the model was either driven by an atmospheric reanalysis or coupled to the COSMO-CLM² regional atmospheric model. In those experiments, sea ice thermodynamics and dynamics as well as the exchanges with the ocean and atmosphere are strongly perturbed. This perturbation is achieved by modifying snow and ice thermal conductivities, the vertical mixing in the ocean top layers, the effect of freshwater uptake and release upon sea ice growth and melt, ice dynamics, and surface albedo. We find that the evolution of sea ice extent during the ice advance season is largely independent of the direct effect of the perturbation and appears thus mainly controlled by initial state in summer and subsequent insolation changes. In contrast, the melting rate varies strongly between the experiments during the retreat, in particular if the surface albedo or sea ice transport are modified, demonstrating a strong contribution of those elements to the evolution of ice coverage through spring and summer. As with the advance phase, the retreat is also influenced by conditions at the beginning of the melt season in September. Atmospheric feedbacks enhance the model winter ice extent response to any of the perturbed processes, and the enhancement is strongest when the albedo is modified. The response of sea ice volume and extent to changes in entrainment of subsurface warm waters to the ocean surface is also greatly amplified by the coupling with the atmosphere.

Introduction. The sea ice extent in the Southern Ocean, defined as the ocean surface covered by at least 15 % of sea ice, displays a very pronounced seasonal cycle with a minimum in February of about 3×10^6 km² and a maximum in September of more than 18×10^6 km² on average over the last few decades (Parkinson, 2014, 2019; Handcock and Raphael, 2020) (Fig. 1). In contrast to the Arctic, where multiyear ice accounted for a significant fraction of the total ice extent – at least until the end of the 20th century – the Antarctic sea ice cover is mainly seasonal, with sea ice only present in summer in some regions close to the coast, in particular in the Weddell and Ross seas.

The seasonal cycle of Antarctic sea ice extent is highly asymmetric, with a minimum around Julian day 50 (19 February) and a maximum on average close to day 260 (18 September) (Stammerjohn et al., 2008; Massom et al., 2013; Handcock and Raphael, 2020; Raphael et al., 2020; Roach et al., 2022). The advance season, defined as the time between the minimum and maximum ice extents, is thus about 2 months longer than the retreat season, defined as the time from maximum to minimum.

New insights on the ^7Be cycle in the ocean.

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Abstract. The [cosmogenic radionuclide](#) ^7Be has been applied as a tracer of dynamical processes in the upper ocean and of [atmospheric deposition](#) of trace elements at the sea surface. These applications usually assume that ^7Be is entirely in the dissolved form, and that scavenging and downward export of ^7Be by settling particles can be neglected. In this work, we explore these assumptions and more generally assess the significance of the ^7Be activity in the particulate fraction, through the generation of vertical profiles of particulate ^7Be in the [open ocean](#). From detailed measurements obtained from low-background gamma spectrometers placed in underground facilities, we report vertical profiles of ^7Be activity in suspended particles ($^7\text{Be}_p$) collected in various oceanic regions: the Mediterranean Sea (DYFAMED station), the Indian Sector of the [Southern Ocean](#) (station A3-2 from the KEOPS2 cruise), the [Sargasso Sea](#) (OFP station), and the subpolar North Atlantic Ocean (GEOVIDE cruise).

We find that, in each oceanic region, $^7\text{Be}_p$ activities are generally higher in the mixed layer than in the [thermocline](#). They vary in the mixed layer from 3.0 dpm/m³ at DYFAMED to 33.1 dpm/m³ at GEOVIDE cross-over station 51/60, i.e., within a range consistent with previous $^7\text{Be}_p$ measurements for the open ocean. For the GEOVIDE cruise, the $^7\text{Be}_p$ activities measured on different filter types at different depths are corrected for filter offsets derived from multiple $^7\text{Be}_p$ measurements at a near-coastal station in the western Mediterranean Sea. We then combine measurements of total ^7Be activity (Shelley et al., 2017) with our measurements of $^7\text{Be}_p$ activity to estimate the solid/solution partitioning of ^7Be . On average, the particulate fraction would represent 6% of total ^7Be activity at 5-m water depth ($n = 6$), 22% at 20 m ($n = 2$) and 9% at 70 m ($n = 3$). At GEOVIDE stations, $^7\text{Be}_p$ inventories range from 5% to 19% of the total ^7Be inventories. In the Labrador Sea, the measured $^7\text{Be}_p$ inventories are lower than the dry ^7Be deposition fluxes estimated from aerosol samples collected during GEOVIDE, suggesting that a significant portion of $^7\text{Be}_p$ may be removed by sinking particles. The distribution coefficient K_d for ^7Be increases with depth, with $\log_{10}K_d$ averaging 5.2 ± 0.1 at 5 m and 6.1 ± 0.1 between 70 and 150 m, suggesting that scavenging of dissolved ^7Be by particles is more pronounced in the [thermocline](#) than in the mixed layer when differences in particle concentrations are taken into account. Overall, our study suggests that, at least in some oceanic regions, the removal of ^7Be by marine particles may be significant and that it may need to be considered in applications of ^7Be as a tracer of oceanic processes and [atmospheric deposition](#).

Introduction. Beryllium-7 (^7Be) is produced in the atmosphere by cosmic ray [spallation](#) mostly of oxygen and nitrogen nuclei ([Lal and Peters, 1967](#)). ^7Be then enters the marine and terrestrial environments via wet and [dry depositions](#) ([Feely et al., 1989](#)). The relatively short half-life of ^7Be (53.3 days; [Browne et al., 1978](#)) makes it a useful tracer of processes in the coastal ocean and the open upper ocean on seasonal and regional time-scales. In [estuaries](#) and coastal environments, ^7Be can be quickly scavenged by particles ([Aaboe et al., 1981](#); [Dibb and Rice, 1989](#); [Olsen et al., 1986](#)). Several studies have reported a significant affinity of ^7Be for particles in these environments, where the distribution coefficients K_d for ^7Be can be of the order of $10^5 \text{ cm}^3/\text{g}$, with K_d being the ratio of particulate ^7Be activity to dissolved ^7Be activity, normalized to particle concentration ([Baskaran and Santschi, 1993](#); [Dibb and Rice, 1989](#)). Consistent with this result, ^7Be has been applied in coastal and estuarine systems to study short-term variations of sediment accumulation rate and [sediment transport](#) (e.g., [Dibb and Rice, 1989](#); [Wu et al., 2018](#)).

Migration and livelihood constellations: Assessing common themes in the face of environmental change in Somalia and among Agro-Pastoral peoples.

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Abstract. Research on migration has become more challenging due to at least four factors: (1) more complex migration traditions; (2) the development of migration economies that engage many types of migrants from ever more social and cultural backgrounds; (3) increasing likelihood of climate change-driven environmental migration; and (4) increasing likelihood of conflict-based migration in some contexts. These developments have shaken economic theories of migration and have encouraged interdisciplinary, methodologically mixed, qualitative and quantitative research and analysis. From a review of the literature, we have gleaned 11 common themes about environmental, economic and conflict migration that we differentiate by process (migration behaviours that are still evolving) and patterns (migration behaviours that have become customary). We then consider how positive and negative dimensions of migration can be captured and represented with close attention to livelihood constellations (multiple economic activities combined by individuals, households and families). Finally, focusing on Somalia and agro-pastoral peoples generally, where recent environmental and conflict migration have been added to decades of economic migration and centuries of seasonal, environmental migration associated with pastoralism, we combine historical and qualitative work to demonstrate the value of a livelihood constellation perspective.

Introduction. Writing about Somalia, Lewis (1994) notes that young Somali men began working in the oil industry in the United Arab Emirates (UAEs) in the 1970s, leaving pastoralist livelihoods to the care of their kinsmen while sending remittances home for a variety of capital and consumer goods, including trucks and reservoirs for herding and watering livestock. This process was responsible “for reducing nomadic mobility and the range of grazing movements and thus encouraging partial sedentarization and the formation of small rural trading posts” (1994: 122). The emigration also caused labour shortages in Somali pastoralism, leading to opportunities for young men with few cattle who did not emigrate to work as herdsmen for migrating relatives. Paid in cash and livestock, this allowed otherwise poor members of clans to develop their own herds.

This is an example of a migration tradition embedded in a livelihood that stimulated the development of a *livelihood constellation* (Griffith, 2021). This concept derives from the literature addressing economic strategies of peoples who have multiple livelihoods, such as combining pastoralism with small-scale trading, wage labour and reproductive labour. We use the term livelihood constellation because engaging in several economic activities requires allocating time and effort to each livelihood that, in turn, influences the time and effort dedicated to others. This suggests the metaphor of constellations, where livelihoods influence one another like heavenly bodies influence one another with gravity, light, time and other physical properties. As in Somalia, livelihood constellations that incorporate migration often connect different economies, such as pastoralism and oil, and open up opportunities for others.

A high-yielding traits experiment for modeling potential production of wheat: Field experiments and AgMIP-Wheat multi-model simulations.

Guarin, J.^{1,2}, P. Martre, F. Ewert, H. Webber, S. Dueri, D. Calderini, M. Reynolds, G. Molero, D. Miralles, G. Garcia, G. Slafer, F. Giunta, D. Pequeno, T. Stella, M. Ahmed, P. Alderman, B. Basso, A. Berger, M. Bindi, G. Bracho-Mujica, D. Cammarano, Y. Chen, B. Dumont, E. Eyshi Rezaei, E. Fereres, R. Ferrise, T. Gaiser, Y. Gao, M. Garcia-Vila, S. Gayler, Z. Hochman, G. Hoogenboom, L. Hunt, K. Kersebaum, C. Nendel, J. Olesen, T. Palosuo, E. Priesack, J. Pullens, A. Rodriguez, R. Rotter, M. Ruiz Ramos, M. Semenov, N. Senapati, S. Siebert, A. Srivastava, C. Stockle, I. Supit, F. Tao, P. Thorburn, E. Wang, T. Weber, L. Xiao, Z. Zhang, C. Zhao, J. Zhao, Z. Zhao, Y. Zhu, and S. Asseng, 2023

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Abstract. Grain production must increase by 60% in the next four decades to keep up with the expected population growth and food demand. A significant part of this increase must come from the improvement of staple crop grain yield potential. Crop growth simulation models combined with field experiments and crop physiology are powerful tools to quantify the impact of traits and trait combinations on grain yield potential which helps to guide breeding towards the most effective traits and trait combinations for future wheat crosses. The dataset reported here was created to analyze the value of physiological traits identified by the International Wheat Yield Partnership (IWYP) to improve wheat potential in high-yielding environments. This dataset consists of 11 growing seasons at three high-yielding locations in Buenos Aires (Argentina), Ciudad Obregon (Mexico), and Valdivia (Chile) with the spring wheat cultivar Bacanora and a high-yielding genotype selected from a doubled haploid (DH) population developed from the cross between the Bacanora and Weebil cultivars from the International Maize and Wheat Improvement Center (CIMMYT). This dataset was used in the Agricultural Model Intercomparison and Improvement Project (AgMIP) Wheat Phase 4 to evaluate crop model performance when simulating high-yielding physiological traits and to determine the potential production of wheat using an ensemble of 29 wheat crop models. The field trials were managed for non-stress conditions with full irrigation, fertilizer application, and without biotic stress. Data include local daily weather, soil characteristics and initial soil conditions, cultivar information, and crop measurements (anthesis and maturity dates, total above-ground biomass, final grain yield, yield components, and photosynthetically active radiation interception). Simulations include both daily in-season and end-of-season results for 25 crop variables simulated by 29 wheat crop models.

Introduction. The original purpose of this dataset was to support a model inter-comparison (Guarin et al. 2022) as part of the Agricultural Model Intercomparison and Improvement Project (AgMIP, <https://agmip.org/>) (Rosenzweig et al. 2013). The field experimental data were from high-yielding trait experiments to investigate and improve wheat yield potential in high-yielding environments using improved physiological traits (Bustos et al. 2013; Garcia et al. 2013; Garcia et al. 2014). This dataset contains field measurements of selectively bred high-yielding wheat cultivars, including the highest reported wheat grain yield in the literature –16.6 t ha⁻¹ dry weight (Bustos et al. 2013; Garcia et al. 2013), for benchmarking local and regional yield improvements and model improvement against an ensemble of 29 state-of-the-art wheat crop simulation models.

Highly restricted near-surface permafrost extent during the mid-Pliocene warm period.

Guo, D., H. Wang, V.E. Romanovsky, A.M. Haywood, N. Pepin, U. Salzmann, J. Sun, Q. Yan, Z. Zhang, X. Li, B.L. Otto-Bliesner, R. Feng, G. Lohmann, C. Stepanek, A. Abe-Ouchi, W. Chan, W.R. Peltier, D. Chandan, A.S. von der Heydt, C. Contoux, **M.A. Chandler**^{1,2}, N. Tan, Q. Zhang, S.J. Hunter, and Y. Kamae, 2023

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Abstract. Accurate understanding of permafrost dynamics is critical for evaluating and mitigating impacts that may arise as permafrost degrades in the future; however, existing projections have large uncertainties. Studies of how permafrost responded historically during Earth's past warm periods are helpful in exploring potential future permafrost behavior and to evaluate the uncertainty of future permafrost change projections. Here, we combine a surface frost index model with outputs from the second phase of the Pliocene Model Intercomparison Project to simulate the near-surface (~3 to 4 m depth) permafrost state in the Northern Hemisphere during the mid-Pliocene warm period (mPWP, ~3.264 to 3.025 Ma). This period shares similarities with the projected future climate. Constrained by proxy-based surface air temperature records, our simulations demonstrate that near-surface permafrost was highly spatially restricted during the mPWP and was $93 \pm 3\%$ smaller than the preindustrial extent. Near-surface permafrost was present only in the eastern Siberian uplands, Canadian high Arctic Archipelago, and northernmost Greenland. The simulations are similar to near-surface permafrost changes projected for the end of this century under the SSP5-8.5 scenario and provide a perspective on the potential permafrost behavior that may be expected in a warmer world.

Introduction. Permafrost, that is, ground with a temperature remaining at or below 0 °C for at least two consecutive years (1), currently underlies approximately 22% of the land surface of the Northern Hemisphere (2) and stores approximately 11,000 to 37,000 km³ of ground ice (3), 1,330 to 1,580 Pg of organic carbon (4, 5), and a large pool of the harmful substance mercury (6) and various potentially harmful microorganisms (7). Both observations and model simulations indicate that permafrost will likely degrade substantially as global temperature increases (1, 8, 9). Any permafrost degradation, accompanied by melting of ground ice and release of organic carbon and harmful substances, will have considerable impacts on ecosystems (10), water resources (11), engineering infrastructure (12, 13), climate (4), and human health (7). However, the rate of projected future permafrost decline is subject to large uncertainty due to the variable climate sensitivities of climate models and differences in details of soil-related processes across different models (14–16). Thus, informed policy decisions for mitigation and adaptation are difficult.

Past Earth conditions form a useful laboratory for climate-model verification, as there is no model-independent source of information for future climate, yet model-based projections remain our only quantitative tool for research. Simulation uncertainty can be reduced through comparison of model output against available proxy-based records. To help verify models and evaluate the uncertainty of future permafrost change projections produced with these models, it is necessary to study permafrost during Earth's past (17–20). Of particular interest are past warm periods that share similarities with future conditions.

The mid-Pliocene warm period [mPWP: ~3.264 to 3.025 Ma (21)] is the most recent period of sustained (10⁴-y timescales) global warmth in geological history (22). It is characterized by land–sea distribution, topography, and greenhouse gas levels similar to the present day (21, 23) and arguably represents a natural experiment from which we can gain insights about our future climate (24).

Performance evaluation of three bio-optical models in aerosol and ocean color joint retrievals.

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Abstract. Multi-angle polarimeters (MAPs) are powerful instruments to perform remote sensing of the environment. Joint retrieval algorithms of aerosols and ocean color have been developed to extract the rich information content of MAPs. These are optimization algorithms that fit the sensor measurements with forward models, which include radiative transfer simulations of the coupled atmosphere and ocean systems (CAOSs). The forward model consists of sub-models to represent the optics of the atmosphere, ocean water surface and ocean body. The representativeness of these models for observed scenes and the number of retrieval parameters are important for retrieval success. In this study, we have evaluated the impact of three different ocean bio-optical models with one, three and seven optimization parameters on the accuracy of joint retrieval algorithms of MAPs. The Multi-Angular Polarimetric Ocean coLoR (MAPOL) joint retrieval algorithm was used to process data from the airborne Research Scanning Polarimeter (RSP) instrument acquired in different field campaigns. We performed ensemble retrievals along three RSP legs to evaluate the applicability of bio-optical models in geographically varying water of clear to turbid conditions. The average differences between the MAPOL aerosol optical depth (AOD) and spectral remote sensing reflectance ($R_{rs}(\lambda)$) retrievals and the MODerate resolution Imaging Spectroradiometer (MODIS) products were also reported. We studied the distribution of retrieval cost function values obtained for the three bio-optical models. For the one-parameter model, the spread of retrieval cost function values is narrow regardless of the type of water even if it fails to converge over coastal water. For the three- and seven-parameter models, the retrieval cost function distribution is water type dependent, showing the widest distribution over clear, open water. This suggests that caution should be used when using the spread of the cost function distribution to represent the retrieval uncertainty. We observed that the three- and seven-parameter models have similar MAP retrieval performances in all cases, though they are prone to converge at local minima over open-ocean water. It is necessary to develop a screening algorithm to divide open and coastal water before performing MAP retrievals. Given the computational efficiency and the algorithm stability requirements, we recommend the three-parameter bio-optical model as the coastal-water bio-optical model for future MAPOL studies. This study provides important practical guides on the joint retrieval algorithm development for current and future satellite missions such as NASA's Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission and ESA's Meteorological Operational-Second Generation (MetOp-SG) mission.

Introduction. The enhanced capabilities in satellite remote sensing of Earth have enabled detailed observation of the atmosphere, ocean and land, thereby improving the accurate determination of spatial and temporal distributions of the constituents of each. Satellite-borne spectroradiometers in particular have substantially advanced the way we view our home planet, and their information content will increase in the future as the technology evolves from multispectral to hyperspectral capabilities. Multi-angle polarimeters (MAPs), such as the Polarization and Directionality of the Earth's Reflectance (POLDER) (Deschamps et al., 1994), Airborne Multi-angle Spectro-Polarimetric Imager (AirMSPI) (Diner et al., 2013), Spectro-polarimeter for Planetary EXploration (SPEX) (Smit et al., 2019), Research Scanning Polarimeter (RSP) (Cairns et al., 2003), Multi-viewing Multi-Channel Multi-Polarization Imager (3MI) (Fougnie et al., 2018) and Multi-Angle Imager for Aerosols (MAIA) (Van Harten et al., 2021), have even greater information content compared to other existing single-viewing angle spectroradiometers, such as the MODerate Resolution Imaging Spectrometer (MODIS), Visible Infrared Imaging Radiometer Suite (VIIRS), and Ocean and Land Color Instrument (OLCI), owing to their ability to perform measurements at multiple viewing angles and different polarimetric states (Dubovik et al., 2019).

Global warming in the pipeline.

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Abstract. Improved knowledge of glacial-to-interglacial global temperature change yields Charney (fast-feedback) equilibrium climate sensitivity $1.2 \pm 0.3^\circ\text{C}$ (2σ) per W/m^2 , which is $4.8^\circ\text{C} \pm 1.2^\circ\text{C}$ for doubled CO_2 . Consistent analysis of temperature over the full Cenozoic era—including ‘slow’ feedbacks by ice sheets and trace gases—supports this sensitivity and implies that CO_2 was 300–350 ppm in the Pliocene and about 450 ppm at transition to a nearly ice-free planet, exposing unrealistic lethargy of ice sheet models. Equilibrium global warming for today’s GHG amount is 10°C , which is reduced to 8°C by today’s human-made aerosols. Equilibrium warming is not ‘committed’ warming; rapid phaseout of GHG emissions would prevent most equilibrium warming from occurring. However, decline of aerosol emissions since 2010 should increase the 1970–2010 global warming rate of 0.18°C per decade to a post-2010 rate of at least 0.27°C per decade. Thus, under the present geopolitical approach to GHG emissions, global warming will exceed 1.5°C in the 2020s and 2°C before 2050. Impacts on people and nature will accelerate as global warming increases hydrologic (weather) extremes. The enormity of consequences demands a return to Holocene-level global temperature. Required actions include: (1) a global increasing price on GHG emissions accompanied by development of abundant, affordable, dispatchable clean energy, (2) East-West cooperation in a way that accommodates developing world needs, and (3) intervention with Earth’s radiation imbalance to phase down today’s massive human-made ‘geo-transformation’ of Earth’s climate. Current political crises present an opportunity for reset, especially if young people can grasp their situation.

Introduction. It has been known since the 1800s that infrared-absorbing (greenhouse) gases (GHGs) warm Earth’s surface and that the abundance of GHGs changes naturally as well as from human actions [1, 2].¹ Roger Revelle wrote in 1965 that we are conducting a ‘vast geophysical experiment’ by burning fossil fuels that accumulated in Earth’s crust over hundreds of millions of years [3]. Carbon dioxide (CO_2) in the air is now increasing and already has reached levels that have not existed for millions of years, with consequences that have yet to be determined. Jule Charney led a study in 1979 by the United States National Academy of Sciences that concluded that doubling of atmospheric CO_2 was likely to cause global warming of $3 \pm 1.5^\circ\text{C}$ [4]. Charney added: ‘However, we believe it is quite possible that the capacity of the intermediate waters of the ocean to absorb heat could delay the estimated warming by several decades.’

After U.S. President Jimmy Carter signed the 1980 Energy Security Act, which included a focus on unconventional fossil fuels such as coal gasification and rock fracturing (‘fracking’) to extract shale oil and tight gas, the U.S. Congress asked the National Academy of Sciences again to assess potential climate effects. Their massive *Changing Climate* report had a measured tone on energy policy—amounting to a call for research [5]. Was not enough known to caution lawmakers against taxpayer subsidy of the most carbon-intensive fossil fuels? Perhaps the equanimity was due in part to a major error: the report assumed that the delay of global warming caused by the ocean’s thermal inertia is 15 years, independent of climate sensitivity. With that assumption, they concluded that climate sensitivity for $2 \times \text{CO}_2$ is near or below the low end of Charney’s 1.5 – 4.5°C range. If climate sensitivity was low and the lag between emissions and climate response was only 15 years, climate change would not be nearly the threat that it is.

Pliocene Model Intercomparison Project Phase 3 (PlioMIP3) — Science plan and experimental design.

Haywood, A., J. Tindall, L. Burton, **M. Chandler**^{1,2}, A. Dolan, H. Dowsett, R. Feng, T. Fletcher, K. Foley, D. Hill, S. Hunter, B. Otto-Bliesner, D. Lunt, and M. Robinson, 2023

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Abstract. The [Pliocene](#) Model Intercomparison Project (PlioMIP) was initiated in 2008. Over two phases PlioMIP has helped co-ordinate the experimental design and publication strategy of the community, which has included an increasing number of climate models and modelling groups from around the world. It has engaged with palaeoenvironmental scientists to foster new data synthesis supporting the construction of new model boundary conditions, as well as to facilitate new data-model comparisons. The work has advanced our understanding of Pliocene climates and environments, enhanced our knowledge regarding the ability of complex climate and Earth System models to accurately simulate climate change, and helped to refine our estimates of how sensitive the climate system is to forcing conditions.

In this community protocol paper, we outline the scientific plan for PlioMIP Phase 3 (PlioMIP3). This plan provides the required guidance to participating modelling groups from around the world to successfully set up and perform PlioMIP3 climate model experiments. The project is open to new participants from the scientific community (both from the climate modelling and geosciences communities).

In PlioMIP3, we retain the PlioMIP2 Core experiments (E_{oi}^{400} , E^{280}) and extend the Core requirements to include either an experiment focussed on the Early Pliocene or an alternative Late Pliocene simulation (or both). These additions (a) allow a comparison of Early and Late Pliocene warm intervals and help build research connections and synergy with the [MioMIP](#) (Miocene Model Intercomparison Project - also known as DeepMIP-Miocene) and PlioMioVAR projects (Pliocene-Miocene Variability Working Group), and (b) create an alternative time slice simulation for 3.205 Ma (MIS KM5c) through removal of some of the largest palaeogeographic differences introduced between PlioMIP1 and 2 resulting in minimal land-sea mask variations from the modern. In addition, we present ten optional experiments designed to enhance our assessment of climate sensitivity and to explore the uncertainty in greenhouse gas-related forcing. For the first time, we introduce orbital sensitivity experiments into the science plan, as well as simulations incorporating dynamic vegetation-climate feedbacks and an experiment designed to examine the potential significance of East Antarctic Ice Sheet boundary condition uncertainty. These changes enhance palaeo-to-future scientific connections and enable an exploration of the significance of palaeogeographic uncertainties on climate simulations.

Introduction. The Pliocene Model Intercomparison Project (PlioMIP) was established in 2008. The project facilitates and co-ordinates an international effort to compare multiple climate model simulations for the Pliocene Epoch ([Haywood et al., 2010](#)). The project's scientific objectives are to explore and quantify climate model variability and uncertainty, and to understand the sensitivity of the climate system to forcing in the long-term ([Haywood et al., 2016](#)). PlioMIP activities to date have occurred in two discrete phases.

PlioMIP Phase 1 (PlioMIP1; 2008-2016) consisted of atmosphere-only and coupled ocean-atmosphere climate model simulations for the mid-Piacenzian Warm Period (mPWP; ~3.3 to 3 Ma, previously referred to as the mid-Pliocene Warm Period; [Haywood et al., 2010](#), [Haywood et al., 2011](#)). These simulations used the U.S. Geological Survey (USGS) Pliocene Research Interpretation and Synoptic Mapping's third palaeoenvironmental reconstruction (PRISM3D; [Dowsett et al., 2010](#)) as required model boundary conditions.

Increased probability of hot and dry weather extremes during the growing season threatens global crop yields.

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Abstract. Although extreme weather events recur periodically everywhere, the impacts of their simultaneous occurrence on crop yields are globally unknown. In this study, we estimate the impacts of combined hot and dry extremes as well as cold and wet extremes on maize, rice, soybean, and wheat yields using gridded weather data and reported crop yield data at the global scale for 1980–2009. Our results show that co-occurring extremely hot and dry events have globally consistent negative effects on the yields of all inspected crop types. Extremely cold and wet conditions were observed to reduce crop yields globally too, although to a lesser extent and the impacts being more uncertain and inconsistent. Critically, we found that over the study period, the probability of co-occurring extreme hot and dry events during the growing season increased across all inspected crop types; wheat showing the largest, up to a six-fold, increase. Hence, our study highlights the potentially detrimental impacts that increasing climate variability can have on global food production.

Introduction. Understanding the weather signal in crop yield variations is imperative for efforts to adapt agricultural production to climate change. Historically, approximately a third of global crop yield variability can be explained by weather¹, with major impacts on food systems caused by severe extreme weather events². The sensitivity of crop yields to weather varies strongly across regions, and some globally important crop production areas such as maize in Midwestern United States and rice in Japan tend to show a greater fraction of yield variations explained by weather^{1,3,4,5}.

Typically, plants have a narrow climatic range corresponding to optimal growing conditions; outside of this range, their growth is decreased^{6,7,8,9,10} or even collapsed¹¹. Previous research has shown that excessive heat^{2,6,10,12} and drought^{13,14} consistently reduce crop yields, while the impacts of anomalously wet^{15,16} and cold¹³ weather have been more diverse. However, in regional studies, wet weather has been observed to impose major yield reductions, comparable to those of droughts^{17,18}. Worryingly, the frequency of extreme weather occurrences has increased in recent decades^{19,20,21,22}, and the trend is projected to continue in the future^{23,24}. Hence, understanding the historical trends in the co-occurrence of extreme weather events, and their related impacts on agriculture should be a global priority.

Most of the studies described above have presented the impacts of individually occurring extreme weather events^{2,7,13}. To our knowledge, previous global studies that have investigated the effects of co-occurring extremes were limited to single crop types or have utilized national level data^{15,25,26}. Here, we address this gap by utilizing sub-nationally reported and gridded global data on crop yields²⁷ to investigate how combined (in the same place at the same time) hot-dry and cold-wet extreme events have impacted wheat, maize, soybean, and rice yields at the global scale. Further, to understand whether hazards related to these co-occurring extremes have historically changed, we quantified how their probability during the growing season has developed in recent years (1980–2009).

For analysing the dependencies between climate variability and crop yield anomalies, we used growing season weather indicators calculated from daily time series of temperature²⁸, soil moisture²⁹, and precipitation²⁸ over 1980–2009 at 0.5° resolution together with annual wheat, maize, soybean, and rice yield data reported for approximately 20,000 political units and disaggregated to grid scale²⁷. Namely, we developed boosted regression tree models³⁰ with the XGBoost algorithm³¹ to quantify the relationship between co-occurring hot and dry (cold and wet) conditions and crop yield anomalies. Finally, we assessed whether the probability of these events has changed in recent history.

Observed changes in hydroclimate attributed to human forcing.

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Abstract. Observational and modeling studies indicate significant changes in the global hydroclimate in the twentieth and early twenty-first centuries due to anthropogenic climate change. In this review, we analyze the recent literature on the observed changes in hydroclimate attributable to anthropogenic forcing, the physical and biological mechanisms underlying those changes, and the advantages and limitations of current detection and attribution methods. Changes in the magnitude and spatial patterns of precipitation minus evaporation ($P-E$) are consistent with increased water vapor content driven by higher temperatures. While thermodynamics explains most of the observed changes, the contribution of dynamics is not yet well constrained, especially at regional and local scales, due to limitations in observations and climate models. Anthropogenic climate change has also increased the severity and likelihood of contemporaneous droughts in southwestern North America, southwestern South America, the Mediterranean, and the Caribbean. An increased frequency of extreme precipitation events and shifts in phenology has also been attributed to anthropogenic climate change. While considerable uncertainties persist on the role of plant physiology in modulating hydroclimate and vice versa, emerging evidence indicates that increased canopy water demand and longer growing seasons negate the water-saving effects from increased water-use efficiency.

Introduction. Water is essential for supporting life on Earth [1]. Water moves in the Earth system through the hydrologic (water) cycle maintaining the Earth's energy homeostasis [2]. Global estimates of annual total water exchanges between the atmosphere and surface (primarily precipitation and evapotranspiration) are on the order of $50 \times 10^4 \text{ km}^3$ [2]. About $40 \times 10^3 \text{ km}^3$ is transported from the ocean to land as precipitation and the same amount returns to the ocean as runoff [2]. This water exchange is critical for human well-being and development, as food security, electrical power generation, industry, and municipal water supply, amongst other socioenvironmental systems, depend on the availability and accessibility of water [3, 4]. Changes in hydroclimate (e.g., climate-driven changes in the water cycle) are one of the most impactful consequences of climate change on human society, given the importance of precipitation (seasonality and magnitude) on food security and economic development [3]. The atmospheric water balance can be expressed as the difference between precipitation (P) and evapotranspiration (E). That, in turn, equals the sum of vertically-integrated atmospheric humidity ("precipitable water," W) change (dW/dt) and horizontal moisture convergence ($\nabla \cdot \mathbf{Q}$). Since dW/dt is negligible on monthly and longer time scales [5]:

$$P - E \approx \nabla \cdot \mathbf{Q}$$

Overland, however, $P-E$ is the sum of water storage (S) change (dS/dt) and runoff (R) [5]:

$$P - E \approx \nabla \cdot \mathbf{Q} \approx R + dS/dt$$

Emissions background, climate, and season determine the impacts of past and future pandemic lockdowns on atmospheric composition and climate.

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Abstract. COVID-19 pandemic responses affected atmospheric composition and climate. These effects depend on the background emissions, climate, and season in which they occur. Although using multiple scenarios is common in explorations of long-term climate change, they are rarely used to explore atmospheric composition or climate changes in response to transient emission perturbations on the scale of COVID-19 lockdowns. We used the ModelE Earth system model to evaluate how atmospheric and climate impacts depend on the decade and season in which lockdowns occurred. Global COVID-19-related anomalies in aerosols and trace gases differed by up to an order of magnitude or more when comparing lockdowns in 1980, 2008, 2020, and 2051. Regional atmospheric composition anomalies tended to be largest when emissions were near a historical peak: 1980 in Europe and temperate North America, 2008 or 2020 in eastern Asia, and 2051 in south Asia. Regional aerosol direct effect anomalies were almost always less than 0.1 W m^{-2} during the first pandemic year, but over 0.1 W m^{-2} in Europe and exceeded 0.2 W m^{-2} in Europe and temperate North America in 1980, generally changing in tandem with regional emissions. In contrast, direct effect anomalies in Asia were positive in 1980 and negative in 2008, suggesting they may be primarily determined by exogenous emission anomalies. Shifting COVID-19 onset in 2020 by 3, 6, or 9 months also altered atmospheric composition on the order of 2%–25% globally. In all scenarios, changes in surface temperature or precipitation appeared unrelated to local atmospheric compositional changes.

Introduction. The COVID-19 pandemic has led to wide-spread measures restricting travel, industrial, and commercial activity during 2020, impacting atmospheric composition and climate (e.g., Bauwens et al., [2020](#); Field et al., [2021](#); Forster et al., [2020](#); Gettelman et al., [2021](#); Jones et al., [2021](#); Miyazaki et al., [2021](#)). Studies have documented local reductions in nitrogen dioxide (NO_2) on the order of 20%–60%, changes in ozone (O_3) on the order of 20%, 7% reductions in carbon dioxide emissions, and local or regional changes in carbon monoxide, particulate matter, and methane (Gkatzelis et al., [2021](#)).

Many of these species can affect climate—in addition to the long-lived greenhouse gases, ozone is a short-lived greenhouse gas, and aerosols affect climate directly by either absorbing or reflecting radiation or indirectly through their influence on clouds and precipitation. Global modeling studies have found either no detectable effect of COVID-19 lockdowns on global temperatures—including all models participating in the COVID Model Intercomparison Project (COVIDMIP; Jones et al., [2021](#)) or marginal warming of less than 0.1°C (Fasullo et al., [2021](#); Forster et al., [2020](#); Gettelman et al., [2021](#); Yang et al., [2020](#)).

The effects of short-term emission reductions are historically contingent—that is, they depend on the existing atmospheric composition, background emissions, season, and climate, which are undergoing substantial change. There is no reason to expect that a novel coronavirus would spread globally in 2020 specifically; the potential for emergent diseases to trigger a pandemic has long been a major public health concern, and severe outbreaks have occurred multiple times over the last century. For example, the H3N2 influenza pandemic led to an estimated 1 million deaths worldwide in 1968 (Stroup et al., [1988](#)); Severe Acute Respiratory Syndrome may have had similar pandemic potential before being contained in 2003 (Hsieh et al., [2007](#)), and the influenza pandemic of 1918–1920 killed over 20 million people (Noble, [1982](#)).

The metabolic rate of the biosphere and its components.

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Abstract. We assessed the relationship between rates of biological energy utilization and the biomass sustained by that energy utilization, at both the organism and biosphere level. We compiled a dataset comprising >10,000 basal, field, and maximum metabolic rate measurements made on >2,900 individual species, and, in parallel, we quantified rates of energy utilization, on a biomass-normalized basis, by the global biosphere and by its major marine and terrestrial components. The organism-level data, which are dominated by animal species, have a geometric mean among basal metabolic rates of $0.012 \text{ W (g C)}^{-1}$ and an overall range of more than six orders of magnitude. The biosphere as a whole uses energy at an average rate of $0.005 \text{ W (g C)}^{-1}$ but exhibits a five order of magnitude range among its components, from $0.00002 \text{ W (g C)}^{-1}$ for global marine subsurface sediments to 2.3 W (g C)^{-1} for global marine primary producers. While the average is set primarily by plants and microorganisms, and by the impact of humanity upon those populations, the extremes reflect systems populated almost exclusively by microbes. Mass-normalized energy utilization rates correlate strongly with rates of biomass carbon turnover. Based on our estimates of energy utilization rates in the biosphere, this correlation predicts global mean biomass carbon turnover rates of $\sim 2.3 \text{ y}^{-1}$ for terrestrial soil biota, $\sim 8.5 \text{ y}^{-1}$ for marine water column biota, and $\sim 1.0 \text{ y}^{-1}$ and $\sim 0.01 \text{ y}^{-1}$ for marine sediment biota in the 0 to 0.1 m and >0.1 m depth intervals, respectively.

Introduction. Energy is required by all life to fuel growth and activity, including the maintenance of viability in existing biomass. Accordingly, the availability of energy constrains the potential abundance, distribution, and productivity of life.

An extensive body of work has been devoted to quantifying rates of energy utilization by individual species and to exploring the dependence of those rates on body mass as well as extrinsic factors such as temperature. These studies reflect the range of metabolic potential—what rates of energy utilization are required, and what rates are possible—when considering a broad range of organisms. In nature, however, the relationship between biomass and energy utilization rate depends on how organisms' metabolic potential is expressed in the context of ecological interactions, life cycles, and variable if not challenging extrinsic factors that are not necessarily encompassed in measurements made on individuals.

In this study, we aim to quantify and understand the relationship between biomass and energy utilization rate—hereafter termed “mass-specific power” (MSP), with units of energy consumed per unit time per unit biomass [W (g C)^{-1} —for the biosphere overall and for its major marine and terrestrial components. We estimated rates of biological energy utilization in each of these components and combined them with existing estimates of biomass to compute MSP. In parallel, we compiled a database of >10,000 metabolic rate measurements made on >2,900 species. The results provide two fully independent but complementary assessments of MSP, with the database reflecting the scope of physiological potential in organisms, and the biosphere level calculations reflecting the expression of that potential in different environments.

QBO/Solar influences on the tropical Madden-Julian oscillation: A mechanism based on extratropical wave forcing in late fall and early winter.

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Abstract. Possible sources of the observed modulation of the tropical Madden-Julian oscillation (MJO) by the stratospheric quasi-biennial oscillation (QBO) and the 11-year solar cycle are investigated using 41 years of reanalysis data and archived climate model data. Larger upward fluxes of extratropical planetary-scale waves, leading in some cases to sudden stratospheric warmings (SSWs), are observed in late fall and early winter during the easterly phase of the QBO than during the westerly phase (the “Holton-Tan effect”). A similar but smaller increase occurs, on average, during solar minima relative to solar maxima. In addition to the warming at high latitudes, extratropical wave forcing events produce cooling and reduced static stability in the tropical lower stratosphere. Here, it is found that if SSWs occur in early winter (before ~mid-January), the reduced static stability produces, on average, a statistically significant, lagged strengthening of the MJO. This therefore represents a possible mechanism for producing, or at least enhancing, the observed QBO and solar modulations of the MJO in boreal winter. An initial analysis of archived climate model data shows that at least one model version with realistic QBO and solar forcing and with $4\times\text{CO}_2$ forcings partly simulates both of these characteristics (QBO/solar modulation of early winter wave forcing and lagged strengthening of the MJO following early winter SSWs). However, the modeled MJO is insufficiently sensitive to QBO-induced static stability reductions, precluding simulation of the QBO-MJO connection.

Introduction. The tropical Madden-Julian oscillation (MJO) is an eastward propagating, convectively coupled, tropical wave that produces the strongest of the intra-seasonal climate oscillations (e.g., Adames & Kim, [2016](#); Sobel & Maloney, [2012](#)). It generates a Rossby wave train that can be associated with high-impact weather events at northern midlatitudes (e.g., Matthews et al., [2004](#); Zhang, [2013](#)).

Recent research has found that the stratospheric quasi-biennial oscillation (QBO) (e.g., Baldwin et al., [2001](#)) modulates the occurrence rate and eastward extension of MJO episodes in boreal winter (the “QBO-MJO connection”) (e.g., Hood, [2017](#); Nishimoto & Yoden, [2017](#); Yoo & Son, [2016](#); Zhang & Zhang, [2018](#); see the reviews by Martin, Son, et al., [2021](#); Haynes et al., [2021](#)). Briefly, the modulation is such that the MJO is stronger for longer time periods, propagates more often across the Maritime Continent into the western Pacific, and is more predictable when the QBO is in its easterly phase near 50 hPa in the tropical lower stratosphere (QBOE) than when it is in its westerly phase (QBOW). Moreover, several published studies provide evidence for a significant QBO modulation of the strength of the MJO-induced Rossby wave train and associated teleconnection patterns in the extra-tropics (Hood et al., [2020](#); Toms et al., [2020](#)). As suggested by Toms et al., the latter modulation may be due in part to a QBO modulation of the tropical MJO itself and in part to the QBO modulation of the extratropical background state that affects the communication of the MJO signal to the extra-tropics.

As reviewed recently by Haynes et al. ([2021](#); their section 3.1b), Sakaeda et al. ([2020](#)) have confirmed that the QBO influence on tropical convection is limited only to the MJO and further demonstrate an increase of MJO high cloud fraction during QBOE, which provides a positive feedback on MJO activity due to cloud-radiative effects on lower stratospheric temperature (see also Giorgetta et al., [1999](#), for an original model study of cloud-radiative positive feedbacks on QBO-induced convective activity). –

pypromice: A Python package for processing automated weather station data.

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Abstract. The pypromice Python package is for processing and handling observation datasets from automated weather stations (AWS). It is primarily aimed at users of AWS data from the Geological Survey of Denmark and Greenland (GEUS), which collects and distributes in situ weather station observations to the cryospheric science research community. Functionality in pypromice is primarily handled using two key open-source Python packages, xarray (Hoyer & Hamman, 2017) and pandas (The pandas development team, 2020). A defined processing workflow is included in pypromice for transforming original AWS observations (Level 0, L0) to a usable, CF-convention-compliant dataset (Level 3, L3) (Figure 1). Intermediary processing levels (L1,L2) refer to key stages in the workflow, namely the conversion of variables to physical measurements and variable filtering (L1), cross-variable corrections and user-defined data flagging and fixing (L2), and derived variables (L3). Information regarding the station configuration is needed to perform the processing, such as instrument calibration coefficients and station type (one-boom tripod or two-boom mast station design, for example), which are held in a toml configuration file. Two example configuration files are provided with pypromice, which are also used in the package’s unit tests. More detailed documentation of the AWS design, instrumentation, and processing steps are described in Fausto et al. (2021).

Introduction. L0 data is either collected from an AWS during a station visit or is transmitted in near-real-time from each AWS via the Iridium Short Burst Data (SBD) service. An object-oriented workflow for fetching and decoding SBD messages to Level 0 data (L0 tx) is included in pypromice (Figure 2). Alongside the processing module, this workflow can be deployed for operational uses to produce L3 AWS data in near-real-time. A post-processing workflow is also included to demonstrate how near-real-time AWS data can be treated after L3 for submission to global weather forecasting models under the World Meteorological Organisation (WMO).

Statement of Need.

pypromice has four main research purposes:

1. Process and handle AWS observations
2. Document AWS data processing with transparency and reproducibility
3. Supply easy and accessible methods to handle AWS data
4. Provide opportunities to contribute to the processing and handling of AWS data in an open and collaborative manner

The pypromice software has been designed to handle and process data from AWSs located in Greenland. The compilation and processing of data from national AWS networks has historically been conducted through un-distributed, oftentimes proprietary software. Similar Python packages to pypromice have been developed to:

- Process data from historical AWS in Greenland, such as the legacy GC-Net processing workflow (K. Steffen et al., 2023; Vandecrux et al., 2020 - 2023)
- Handle data from commercial AWS, such as pywws (Easterbrook, 2008 - 2023)
- Perform post-processing steps and harmonize AWS data from different institutions, such as JAWS (Zender et al., 2017 - 2019)

Single-scattering properties of ellipsoidal dust aerosols constrained by measured dust shape distributions.

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Abstract. Most global aerosol models approximate dust as spherical particles, whereas most remote sensing retrieval algorithms approximate dust as spheroidal particles with a shape distribution that conflicts with measurements. These inconsistent and inaccurate shape assumptions generate biases in dust single-scattering properties. Here, we obtain dust single-scattering properties by approximating dust as triaxial ellipsoidal particles with observationally constrained shape distributions. We find that, relative to the ellipsoidal dust optics obtained here, the spherical dust optics used in most aerosol models underestimate dust single-scattering albedo, mass extinction efficiency, and asymmetry parameter for almost all dust sizes in both the shortwave and longwave spectra. We further find that the ellipsoidal dust optics are in substantially better agreement with observations of the scattering matrix and linear depolarization ratio than the spheroidal dust optics used in most retrieval algorithms. However, relative to observations, the ellipsoidal dust optics overestimate the lidar ratio by underestimating the backscattering intensity by a factor of ~ 2 . This occurs largely because the computational method used to simulate ellipsoidal dust optics (i.e., the improved geometric optics method) underestimates the backscattering intensity by a factor of ~ 2 relative to other computational methods (e.g., the physical geometric optics method). We conclude that the ellipsoidal dust optics with observationally constrained shape distributions can help improve global aerosol models and possibly remote sensing retrieval algorithms that do not use the backscattering signal.

Introduction. Desert dust aerosols are a key atmospheric component (Mahowald et al., 2014; Kok et al., 2021a, b; Adebisi et al., 2023). Dust impacts the Earth system by modifying the radiation budget (Ito et al., 2021; Kok et al., 2023), hydrological cycle (Miller et al., 2004, 2006), cloud microphysics (Kiselev et al., 2017), and ocean biogeochemistry (Yu et al., 2015; Ito et al., 2019). Furthermore, dust impacts anthropogenic activities by degrading air quality and visibility (Mahowald et al., 2007; Huang et al., 2019) and harming human health (Giannadaki et al., 2014). To accurately estimate these dust impacts, global aerosol models and retrieval algorithms of passive and active remote sensing products need accurate dust single-scattering properties (Dubovik et al., 2006; Winker et al., 2007; Ansmann et al., 2012; Gliß et al., 2021).

Dust single-scattering properties highly depend on dust shape (Bi et al., 2009, 2010; Lindqvist et al., 2014; Nousianen and Kandler, 2015; Saito et al., 2021; Saito and Yang, 2021; Kong et al., 2022), but global aerosol models and remote sensing retrieval algorithms use inconsistent and inaccurate dust shape quantifications (Fig. 1). Specifically, almost all global aerosol models approximate dust as spherical particles (Fig. 1a; Gliß et al., 2021), whereas most retrieval algorithms approximate dust as spheroidal particles (Fig. 1b and c) and use the length-to-height ratio to quantify dust asphericity (Dubovik et al., 2006; Hsu et al., 2019). By assuming a spherical or spheroidal dust shape, aerosol models and retrieval algorithms equate at least two of three dust perpendicular axes. However, a recent study that compiled dozens of in situ measurements of dust shape worldwide found that the three perpendicular axes differ substantially for most dust particles and thus that the triaxial ellipsoidal shape assumption (Fig. 1d) is more realistic for dust aerosols (Huang et al., 2020). In addition, relative to the compiled observations, aerosol models and retrieval algorithms substantially underestimate dust asphericity (Fig. 1e). These problematic dust shape assumptions of aerosol models and retrieval algorithms generate biases in dust single-scattering properties that further propagate into the estimated dust impacts.

Present-day and future PM_{2.5} and O₃-related global and regional premature mortality in the EVAv6.0 health impact assessment model.

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Abstract. We used the EVAv6.0 system to estimate the present (2015) and future (2015–2050) global PM_{2.5} and O₃-related premature mortalities, using simulated surface concentrations from the GISS-E2.1-G Earth system model. The PM_{2.5}-related global premature mortality is estimated to be 4.3 and 4.4 million by the non-linear and linear models, respectively. Ischemic heart diseases are found to be the leading cause of PM_{2.5}-related premature deaths, contributing by 35% globally. Both long-term and short-term O₃-related premature deaths are estimated to be around 1 million, globally. Overall, PM_{2.5} and O₃-related premature mortality leads to 5.3–5.4 million premature deaths, globally. The global burden of premature deaths is mainly driven by the Asian region, which in 2015 contributes by 75% of the total global premature deaths. An increase from 6.2% to 8% in the PM_{2.5} relative risk as recommended by the WHO leads to an increase of PM_{2.5}-related premature mortality by 28%, to 5.7 million. Finally, bias correcting the simulated PM_{2.5} concentrations in 2015 leads to an increase of up to 73% in the global PM_{2.5}-related premature mortality, leading to a total number of global premature deaths of up to 7.7 million, implying the necessity of bias correction to get more robust health burden estimates. PM_{2.5} and O₃-related premature mortality in 2050 decreases by up to 57% and 18%, respectively, due to emission reductions alone. However, the projected increase and aging of the population leads to increases of premature mortality by up to a factor of 2, showing that the population exposed to air pollution is more important than the level of [air pollutants](#), highlighting that the population dynamics should be considered when setting up health assessment systems.

Introduction. [Fine particulate matter](#) (PM_{2.5}) and ozone (O₃) are, among a range of negative health outcomes, associated with premature mortality, with large economic impacts on society. The World Health Organization (WHO), [U.S. Environmental Protection Agency](#) (EPA), and Institute for Health Metrics and Evaluation (IHME) have concluded that PM_{2.5} is associated with cardiovascular diseases such as stroke and ischemic heart disease, respiratory diseases such as chronic obstructive pulmonary disease (COPD) and lower respiratory infection, and mortality ([U.S. EPA, 2019](#); REVIHAAP, IHME). These reviews have also shown that O₃ is associated with respiratory disease, including mortality. According to the Global Burden of Disease (GBD) study of 2017, air pollution is considered the 5th leading global health risk factor, and the leading environmental and occupational health risk factor, while [WHO \(2013\)](#) ranked air pollution as the world's largest single [environmental health](#) risk.

According to [WHO \(2013\)](#), around 7 million people died prematurely in 2012 as a result of air pollution exposure from both outdoor and indoor emission sources, of which, 3.7 million premature deaths were related to exposure to [outdoor air pollution](#). Recently, [WHO \(2021\)](#) estimated 4.2 million premature deaths in 2016, globally. [Silva et al. \(2013\)](#) estimated that in 2000, 470,000 global premature respiratory deaths were associated with anthropogenic O₃ and 2.1 million deaths with anthropogenic PM_{2.5}-related cardiopulmonary diseases (93%) and lung cancer (7%). The GBD 2015 study estimated 254,000 O₃-related and 4.2 million anthropogenic PM_{2.5}-related premature deaths per year ([Cohen et al., 2017](#)). [Lelieveld et al. \(2015\)](#) estimated that outdoor air pollution led to 3.3 million premature deaths globally in 2010, suggesting that these numbers are likely to roughly double in the year 2050 assuming a business-as-usual scenario. [Silva et al. \(2016\)](#) calculated that the global mortality burden of O₃ will increase from 382,000 deaths in 2000 to between 1.09 and 2.36 million in 2100. They also estimated that the global mortality burden of PM_{2.5} will decrease from 1.70 million deaths in 2000 to between 0.95 and 1.55 million deaths in 2100.

Importance of internal variability for climate model assessment.

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Abstract. Benchmarking climate model simulations against observations of the climate is core to the process of building realistic climate models and developing accurate future projections. However, in many cases, models do not match historical observations, particularly on regional scales. If there is a mismatch between modeled and observed climate features, should we necessarily conclude that our models are deficient? Using several illustrative examples, we emphasize that internal variability can easily lead to marked differences between the basic features of the model and observed climate, even when decades of model and observed data are available. This can appear as an apparent failure of models to capture regional trends or changes in global teleconnections, or simulation of extreme events. Despite a large body of literature on the impact of internal variability on climate, this acknowledgment has not yet penetrated many model evaluation activities, particularly for regional climate. We emphasize that using a single or small ensemble of simulations to conclude that a climate model is in error can lead to premature conclusions on model fidelity. A large ensemble of multidecadal simulations is therefore needed to properly sample internal climate variability in order to robustly identify model deficiencies and convincingly demonstrate progress between generations of climate models.

Introduction. Climate models are remarkably successful in reproducing many earth-system phenomena such as atmospheric jet streams, oceanic currents, monsoons, the El Niño Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the response of global climate to external forcing^{1,2,3}. From their basis in the Navier-Stokes equations of fluid dynamics, even extreme events like heatwaves and cold snaps, floods and droughts, cyclones, and storms all appear spontaneously in climate model simulations. In some cases, models also warn us of more intense extreme events than we have yet experienced but which could plausibly occur at any time in the current climate^{4,5,6,7}. Scientists also use climate models to understand the physical mechanisms behind past changes in climate⁸, to understand and predict extreme events⁹, to project future climate change, and to inform governments and policymakers about the impacts of climate change¹⁰.

To gain confidence in model projections, the fidelity of models is assessed by comparing model simulations of the historical climate with observations. This trial of models using observations is core to identifying current model deficiencies and prioritizing areas for further development¹¹. The scientific literature presents many examples where a mismatch between model and observed climate features has been reported, such as trends in regional rainfall amount and temperature^{12,13,14}, multidecadal changes in atmospheric circulation¹⁵ and climatology¹⁶, the frequency or magnitude of extreme events^{17,18}, global teleconnections¹⁹, interaction between different modes of climate variability²⁰ or external forcing effects^{21,22}. There can be many reasons why models disagree with observations. However, even in the case of perfect models, perfect boundary conditions, and perfect observations, a lack of agreement between the modeled and observed climate can still arise simply due to chaotic internal variability^{13,23,24,25,26,27,28,29}.

Due to the inevitable presence of internal variability, each realization of climate, in both observations and models, represents only one possible realization out of many^{30,31}. When evaluating models against observations, this issue (known as sampling variability) is supposed to be handled through statistical tests, but the power of those tests relies heavily on the assumed chance process generating internal variability. This leads to a misinterpretation of significance tests, which is widespread in climate science, leading to overly lax criteria³².

Comparison between ozone column depths and methane lifetimes computed by one- and three-dimensional models at different atmospheric O₂ levels.

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Abstract. Recently, Cooke *et al.* (Cooke *et al.* 2022 *R. Soc. Open Sci.* 9, 211165. (doi:10.1098/rsos.211165)) used a three-dimensional coupled chemistry-climate model (WACCM6) to calculate ozone column depths at varied atmospheric O₂ levels. They argued that previous one-dimensional (1-D) photochemical model studies, e.g. Segura *et al.* (Segura *et al.* 2003 *Astrobiology* 3, 689–708. (doi:10.1089/153110703322736024)), may have overestimated the ozone column depth at low pO₂, and hence also overestimated the lifetime of methane. We have compared new simulations from an updated version of the Segura *et al.* model with those from WACCM6, together with some results from a second three-dimensional model. The discrepancy in ozone column depths is probably due to multiple interacting parameters, including H₂O in the upper troposphere, lower boundary conditions, vertical and meridional transport rates, and different chemical mechanisms, especially the treatment of O₂ photolysis in the Schumann–Runge (SR) bands (175–205 nm). The discrepancy in tropospheric OH concentrations and methane lifetime between WACCM6 and the 1-D model at low pO₂ is reduced when absorption from CO₂ and H₂O in this wavelength region is included in WACCM6. Including scattering in the SR bands may further reduce this difference. Resolving these issues can be accomplished by developing an accurate parametrization for O₂ photolysis in the SR bands and then repeating these calculations in the various models.

Introduction. The calculation of ozone column depth as a function of atmospheric O₂ concentration has been performed multiple times over the past 40 years using one-dimensional (1-D) photochemical models. Several of these calculations [1–3] have been done by the Kasting group. We refer to the current version of that model as the ‘standard’ 1-D model (see §2). Recently, Cooke *et al.* [4], henceforth C22, performed a similar calculation using a three-dimensional (3-D) coupled chemistry-climate model (WACCM6). They found substantially lower ozone column depths at lower pO₂ levels. For example, at 0.01 times the present atmospheric level (PAL) of O₂, Segura *et al.* [3] calculated 124 Dobson units (DU), whereas C22 [4] calculated a mean column depth of just 66 DU—almost a factor of two lower. This comparison is shown in figure 1. C22 [4] argued, correctly, that 3-D models should be able to do a better job on this problem than 1-D models because ozone column depths are affected by atmospheric transport, e.g. the Brewer–Dobson circulation in the stratosphere that blows ozone from the tropics towards the poles, as well as vertical transport that carries ozone downward from the stratosphere to the troposphere. Meridional transport is absent in 1-D models, and vertical transport is fixed, so model geometry almost certainly contributes to the observed discrepancies in ozone column depth. The 3-D model also has a variable tropopause height (higher at the equator, lower towards the poles), which is difficult to simulate in one dimension.

To complicate matters, an independent 3-D investigation of this problem by Way *et al.* [6] using the ROCKE-3D model produced results similar to the previous 1-D calculations (see C22 [4] fig. 6 and our figure 1), for example, 123 DU at 0.01 PAL O₂. Another study published in late 2022 by Jaziri *et al.* [5] shows both 1-D and 3-D calculations on the ozone column depths at low pO₂ (less than or equal to 0.005 PAL) which are much closer to WACCM6 (see black curves in figure 1). A preliminary intercomparison study between the 1-D, WACCM6 3D and ROCKE-3D models suggests that multiple factors contribute to the differences in the modelled ozone column depths.

Muted extratropical low cloud seasonal cycle is closely linked to underestimated climate sensitivity in models.

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Abstract. A large spread in model estimates of the equilibrium climate sensitivity (ECS), defined as the global mean near-surface air-temperature increase following a doubling of atmospheric CO₂ concentration, leaves us greatly disadvantaged in guiding policymaking for climate change adaptation and mitigation. In this study, we show that the projected ECS in the latest generation of climate models is highly related to seasonal variations of extratropical low-cloud fraction (LCF) in historical simulations. Marked reduction of extratropical LCF from winter to summer is found in models with ECS > 4.75 K, in accordance with the significant reduction of extratropical LCF under a warming climate in these models. In contrast, a pronounced seasonal cycle of extratropical LCF, as supported by satellite observations, is largely absent in models with ECS < 3.3 K. The distinct seasonality in extratropical LCF in climate models is ascribed to their different prevailing cloud regimes governing the extratropical LCF variability.

Introduction. Accurate projection of future climate has been an urgent need to provide scientific guidance for policy-making on climate mitigation and adaptation strategies. Global climate models (GCMs), the primary tools used for climate projection and understanding of climate systems, however, exhibit large uncertainty in depicting how Earth's climate system responds to human activity. For example, the equilibrium climate sensitivity (ECS), a quantity used to represent the change in global mean near-surface air-temperature in response to radiative forcing associated with a doubling of the atmospheric carbon dioxide concentration, significantly varies among GCMs that participated in the World Climate Research Programme (WCRP) Coupled Model Inter-comparison Project (CMIP)^{1,2}. With increased complexity in climate models, the ECS in GCMs that participated in the latest sixth phase of CMIP (CMIP6) exhibits even a larger spread of 1.8–5.6 °C than that of 2.1–4.7 °C in the CMIP5 models^{3,4,5}. The large discrepancies in ECS among GCMs have been attributed to model uncertainty in representing various feedback processes, which act to amplify (i.e., a positive feedback) or dampen (a negative feedback) the initial warming. Among them, the short-wave (SW) radiative feedback associated with low clouds, particularly over the extratropical regions of both hemispheres, has been suggested one of the largest sources of uncertainty in predicting the ECS^{4,5,6,7,8,9,10,11}. Hereafter, if not stated otherwise, the extra-tropics is referred to the latitude belts of 60–30°S and 30–60°N. All analyses in this study are conducted over ocean grid points to avoid even more complicated feedback processes over the land, and surface temperature is referred to skin temperature if not specifically defined, i.e., sea surface temperature over ocean grid cells. Low cloud fraction (LCF) in both models and observations is derived by vertical cloud fractions below 700 hPa using a maximum overlapping assumption.

As shown in Fig. 1, the strong warming by the end of the 21st century in the high ECS models (ECS greater than 4.75 K, Supplementary Table 1) from CMIP6 (Fig. 1a) is associated with reduced LCF over the extratropical oceans (Fig. 1e), which effectively reduces cloud reflection of solar radiation, indicated by a positive trend in the top-of-atmosphere (TOA) SW cloud radiative effects (SWCRE) (Fig. 1c), and generates excessive heating at the surface. This thus represents a positive cloud feedback that amplifies the surface warming over the extra-tropics. While reduced low clouds with surface warming over tropics or subtropics has been ascribed to a drying effect in the boundary layer due to enhanced vertical moisture gradient and thus mixing^{12,13,14}, processes underlying reduced extratropical low clouds under a warming climate remain poorly understood, and are highly relevant to the findings in this study. A slightly equatorward shift in the maximum TOA SWCRE changes relative to the maximum reduction of LCF is noted over 30–60°N/S (c.f. Fig. 1c,e).

Modeling sea ice albedo and transmittance measurements with a fully-coupled radiative transfer model.

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Abstract. A rigorous treatment of the sea ice medium has been incorporated in the advanced Coupled Ocean-Atmosphere Radiative Transfer (COART) model. The inherent optical properties (IOPs) of brine pockets and air bubbles over the 0.25-4.0 μm spectral region are parameterized as a function of the sea ice physical properties (temperature, salinity and density). We then test the performance of the upgraded COART model using three physically-based modeling approaches to simulate the spectral albedo and transmittance of sea ice, and compare them with measurements collected during the Impacts of Climate on the Ecosystems and Chemistry of the Arctic Pacific Environment (ICESCAPE) and the Surface Heat Budget of the Arctic Ocean (SHEBA) field campaigns. The observations are adequately simulated when at least three layers are used to represent bare ice, including a thin surface scattering layer (SSL), and two layers to represent ponded ice. Treating the SSL as a low-density ice layer yields better model-observation agreement than treating it as a snow-like layer. Sensitivity results indicate that air volume (which determines the ice density) has the largest impact on the simulated fluxes. The vertical profile of density drives the optical properties, but available measurements are scarce. The approach where the scattering coefficient for the bubbles is inferred in lieu of density leads to essentially equivalent modeling results. For ponded ice, the albedo and transmittance in the visible are mainly determined by the optical properties of the ice underlying the water layer. Possible contamination from light-absorbing impurities, such as black carbon or ice algae, is also implemented in the model and is able to effectively reduce the albedo and transmittance in the visible spectrum to further improve the model-observation agreement.

Introduction. Sea ice is a vital component of the global climate system, since it affects heat and moisture exchange within the atmosphere and ocean, and strongly impacts the surface energy budget [1–4]. A reduction in sea ice cover and its thinning lower the albedo and increases shortwave absorption in the ocean, causing more melting in a mechanism known as ice-albedo feedback [5–8], which has been quantified as the second main contributor to the Arctic amplification using climate simulations [9,10]. Many sea ice models employ simplistic parameterizations for the albedo, and typically neglect its dependence on ice physical properties such as salinity, density and their vertical distribution. Such an approach can lead to unrealistic estimates of albedo and transmittance, and therefore to large uncertainties in both present-day simulations and future climate projections in the Arctic [11–14]. An accurate description of the interaction between sea ice and solar radiation requires adequate estimations of the multiple scattering processes and the absorption rate within the ice column.

To improve our confidence in model projections of sea ice extent and thickness, it is therefore crucial to develop accurate and efficient radiative transfer models. A detailed characterization of the optical behavior of sea ice is even more important since the latter changes dramatically in response to structural variations, as a freezing water surface grows into a stable pack, to then age and undergo possible melting [15–18]. The first stages of sea-ice formation are associated with the phase transition, and are characterized by increasing salinity, viscosity and elasticity [19,20]. “Young ice” of a thickness up to 30 cm, that can still be fractured by wave motion, evolves eventually into more stable first-year ice (FYI) with thicknesses up to 2 m [21]. If FYI survives the melting season, it ages into multi-year ice (MYI) which typically exhibits a moderate increase in thickness (for a total thickness of 2-4 m), and a decrease in density and salinity mainly caused by an increase of air volume and the flushing of brine [22–24].

Structural chokepoints determine the resilience of agri-food supply chains in the United States.

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Abstract. The agricultural and food systems of the United States are critical for ensuring the stability of both domestic and global food systems. Thus, it is essential to understand the structural resilience of the country's agri-food supply chains to a suite of threats. Here we employ complex network statistics to identify the spatially resolved structural chokepoints in the agri-food supply chains of the United States. We identify seven chokepoints at county scale: Riverside CA, San Bernardino CA, Los Angeles CA, Shelby TN, Maricopa AZ, San Diego CA and Cook IL; as well as seven chokepoints at freight analysis framework scale: Los Angeles–Long Beach CA, Chicago–Naperville IL, New York–New Jersey NJ, New York–New Jersey NY, Remainder of Texas, Remainder of Pennsylvania, and San Jose–San Francisco–Oakland CA. These structural chokepoints are generally consistent through time (2007, 2012, 2017), particularly for processed food commodities. This study improves our understanding of agri-food supply-chain security and may aid policies aimed at enhancing its resilience.

Introduction. The United States plays a key role in a highly integrated global food system. The United States is a major producer and consumer of agri-food commodities and is connected to countries around the world through trades. Shocks to the US food supply chain may limit its ability to export to the rest of the world, which would restrict global supplies and raise prices, with ripple effects for the availability and affordability of staple foodstuffs. The ability of the United States to reliably move food from producers to consumers contributes to a stable, affordable and access the global food supply. Hence resilient and secure US agri-food supply chains are important for global food security.

Agricultural and food supply chains within the United States are complex, critical infrastructures that provide society with food everyday. The food services and drinking places industry underpins the US economy, according to domestic input-output tables. Importantly, disruptions to the agri-food system would probably have the largest cascading effect in the US economy of all critical infrastructure. For this reason, agricultural and food systems underpin political and economic stability, which is a key part of national security. Food system security and resilience is thus increasingly recognized as a non-traditional defense objective in the national security community, and is critical to the mission of US national defense agencies.

The Executive Order on America's Supply Chains (# 14017) calls for researchers and policy-makers to propose more resilient, diverse and secure supply chains. Other federal programmes, such as the Global Food Security Strategy and the Infrastructure Investments and Jobs Act, also aim to increase resilience in agri-food supply chains, due to their importance for both national and global security. Yet, most research on agri-food supply chains has been from the perspective of industrial firms, with a focus on firm-level logistics cost savings and resilience.

A data set of monthly freshwater fluxes from the Greenland ice sheet's marine-terminating glaciers on a glacier-basin scale 2010-2020.

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Abstract. The loss of mass from the Greenland ice sheet causes an increasing influx of freshwater to the Greenlandic fjords and the oceans. Freshwater fluxes from marine-terminating glaciers are important to understand fjord circulation and ecosystem dynamics. Here, we present a data set constructed by reformulating existing products into a shared temporal and spatial framework. We combine three publicly available data sets of solid-ice discharge (iceberg), liquid-surface runoff (runoff) and basal melt to present a cohesive overview of the flow of freshwater from marine-terminating glaciers to the Greenlandic fjords. We also calculate glacier drainage basins and compare our findings to previous studies showing that drainage-basin sizes may vary considerably depending on how they were reconstructed. The data set will be a valuable asset to oceanographic, glaciological and marine biological research activities.

Introduction. The Greenland ice sheet discharges significant volumes of freshwater into the fjords and oceans (Mankoff et al. 2020). This freshwater discharge is known to modify and influence the physical, chemical and biological properties of the fjords and coastal seas (e.g., Hopwood et al. 2020). The combined volume of freshwater that exits from marine-terminating glaciers is currently not readily available on a glacier-basin scale due to disparate data sets. This study presents a data set constructed by combining three publicly available data sets of solid-ice discharge (iceberg), liquid-surface runoff (runoff) and basal melt from the Greenland ice sheet. This new product merges disparate data sets into a product that shares spatial and temporal resolution, enabling easy comparison of mass-loss processes on glacier-basin scales. The following sections give a brief overview of the data sets that form the foundation of the product presented here.

We use the term ‘solid-ice discharge’ to describe the ice mass that is lost at the marine margin as either icebergs, bergy bits or submarine melt. While this term is traditionally reported as a mass flux in kg or Gt, we convert it to liquid water equivalents to be consistent with the other volume-loss terms. The solid-ice discharge from more than 200 flux gates situated near the front of marine-terminating glaciers was compiled and presented by Mankoff et al. (2019). Here, we give a brief overview of their methods and results and refer to the original manuscript for details. Mankoff et al. (2019; M2019 for the remainder of this manuscript) calculate ice discharge by considering the mass flow rate through predefined flux gates.

We use the term ‘solid-ice discharge’ to describe the ice mass that is lost at the marine margin as either icebergs, bergy bits or submarine melt. While this term is traditionally reported as a mass flux in kg or Gt, we convert it to liquid water equivalents to be consistent with the other volume-loss terms. The solid-ice discharge from more than 200 flux gates situated near the front of marine-terminating glaciers was compiled and presented by Mankoff et al. (2019). Here, we give a brief overview of their methods and results and refer to the original manuscript for details. Mankoff et al. (2019; M2019 for the remainder of this manuscript) calculate ice discharge by considering the mass flow rate through predefined flux gates.

The chemical characteristics of rainwater and wet atmospheric deposition fluxes at two urban sites and one rural site in Côte d'Ivoire.

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Abstract. Due to their close relationship with atmospheric chemical composition and global impacts on ecosystems, it is of crucial importance to determine rain chemical composition and quantify wet deposition. In this study, we characterized the chemical composition of precipitation at one rural and two urban sites in Côte d'Ivoire along a south-north transect. Annual and monthly Volume Weighted Mean (VWM) concentration of major ions, as well as wet deposition fluxes in rainwater samples from Abidjan, Korhogo (urban sites), and Lamto (rural site), have been calculated. We also simulated air mass back-trajectories and generated satellite maps of burnt fraction and nitrogen species emissions (NH_3 , NO_2) to better analyze our results. Results show that the dominant ion at both urban sites is Ca^{2+} , whereas NH_4^+ dominates the chemical content of the Lamto rural site. The analysis of atmospheric sources of influence shows that urban sites rains are characterized by a mixture of terrigenous continental and anthropogenic sources (39–33%), as well as a high marine contribution (34–24%) and a significant nitrogenous contribution (18–25%) mainly associated to fossil fuel from road traffic, domestic and biomass burning sources. At the rural Lamto site, marine, terrigenous, and nitrogenous contributions represent, respectively, 14%, 25%, and 30%. The average pH values are, respectively, 5.76, 5.31, and 5.57 for Abidjan, Lamto, and Korhogo, with a preponderance of mineral acidity contribution at the urban sites, while the organic acidity contribution dominates in Lamto. Neutralization factor (NF) of mineral and organic acids calculations revealed that Ca^{2+} and NH_4^+ are the most important neutralizing ions in the rain at all three sites, and we estimated that 79% to 87% of the rain acidity is neutralized by alkaline compounds.

Introduction. Atmospheric deposition represents a key mechanism in anthropogenic impacts on the environment. Atmospheric deposition includes wet and dry processes and is the major removal pathway of atmospheric pollutants and thus contributes to the earth-atmosphere biogeochemical balance [1,2,3,4]. Limiting anthropogenic impacts on atmospheric deposition is considered fundamental for addressing several sustainable development goals, such as food security, climate change, human health, and biodiversity [3,5,6]. The study of deposition processes and the determination of deposition fluxes is important for understanding the spatial and temporal evolution of the atmosphere's chemical composition and of the biogeochemical cycles of elements such as nitrogen, carbon, and sulfur. Biogeochemical cycles are strongly affected by anthropogenic activities, and atmospheric deposition can act as a source of nutrients but also as a source of toxins [7,8,9].

Wet deposition plays a key role in removing both gaseous and particulate pollutants from the atmosphere and thus influences atmospheric chemistry [7,8]. Rain chemical composition provides insights into the evolution of the chemical atmosphere composition, and it is influenced by numerous factors, including the type and strength of natural/anthropogenic sources of atmospheric compounds, long-range transport, the origin of continental air masses, as well as removal processes related to the intensity and temporal distribution of rainfall patterns [2,9,10]. Investigation of rainwater chemistry at a regional representative urban site in southern India revealed that the ionic composition of rainwater in the region is more influenced by terrestrial sources than anthropogenic and marine sources [11]. Rainwater samples were collected at five locations in the Pune region, an urban area in the southwestern part of India, from 2006 to 2009 [12]. The chemical analysis of these samples demonstrated the strong contribution of soil dust as well as an influence from marine and anthropogenic sources in that area. A long-term analysis of European precipitations from 2000 to 2017 [10] showed that the rainwater composition is mostly controlled by anthropogenic sources.

A 1D model for nucleation of ice from aerosol particles: An application to a mixed-phase Arctic stratus cloud layer.

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Abstract. Mixed-phase clouds (MPCs) have been identified as significant contributors to uncertainties in climate projections, attributable to model representation of processes controlling the formation and loss of supercooled water droplets and ice particles from the atmosphere. Arctic MPCs are commonly widespread and long-lived, with sustained ice crystal formation processes that challenge current understanding. This study examines the ice-nucleating particle (INP) reservoir dynamics governing immersion-mode heterogeneous freezing in an observed case of Arctic MPCs using a simplified 1D aerosol-cloud model. The model setup includes prescribed dynamical forcings and thermodynamic profiles and represents INPs as multicomponent and polydisperse particle size distributions. Diagnostic and prognostic approaches to immersion freezing parameterization are compared, including time-independent (singular) number- and surface area-based descriptions and a time-dependent description following classical nucleation theory (CNT). The choice of freezing parameterization defines the size of the INP reservoir. The CNT-based description yields an order of magnitude larger INP reservoir than the singular parameterizations, which is the dominant factor for sustained ice crystal formation. The efficiency of the freezing process and cloud cooling are of secondary importance. A diagnostic treatment neglecting INP loss is only accurate when the INP reservoir size is large and INP depletion weak. Since a larger INP reservoir sustains ice crystal formation substantially longer, and ice water path scales with ice crystal concentrations for the conditions considered, resolving the source of differences in INP reservoir dynamics due to model implementation is a high priority for advancing climate model physics.

Introduction. Current climate modeling efforts aim to constrain the uncertainty of the mean equilibrium surface air warming from a doubling of carbon dioxide, termed the equilibrium climate sensitivity (ECS). A dominant cause of the predicted range in ECS among models has been identified as differing shallow extratropical cloud responses to warming for both liquid-phase (“warm”) clouds and mixed-phase clouds (MPCs) in which supercooled liquid droplets and ice crystals coexist (Cesana & Del Genio, 2021; McCoy et al., 2022; Zelinka et al., 2020). MPCs are ubiquitous in the polar regions (Shupe, 2011), which warm more rapidly than other parts of the globe, as exemplified by so-called Arctic amplification (Hahn et al., 2021). Assessing the climate feedback of shallow MPCs is complicated by model difficulties properly reproducing the supercooled cloud fraction that impacts cloud radiative forcing (Storelvmo, 2017). The shortwave cloud feedback, which is directly related to the ratio of supercooled water droplets and ice crystals has been identified as one key factor of uncertainty in the ECS predicted by global climate models (GCMs) (McCoy et al., 2022). Additionally, the rate at which moisture is depleted by precipitation processes in MPCs has been recognized as a source of ECS differences between models (McCoy et al., 2020). Lastly, Arctic MPCs can be long-lived, sustaining droplets and ice crystals over many hours, a phenomenon generally not skillfully captured by models, further indicating an insufficient understanding of the microphysical cloud processes (Fridlind & Ackerman, 2018). Hence, improving the parameterization of MPC processes, specifically those affecting ice crystal formation, is crucial to reducing uncertainties in extratropical cloud feedbacks. Here we introduce an analysis of the available ice-nucleating particle (INP) reservoir within a simplified column model to illustrate how commonly used immersion freezing parameterizations divergently impact sustained ice crystal formation in long-lived MPCs. This sensitivity analysis provides crucial information for scaling immersion freezing parameterizations to larger scale models.

Planetary boundary layer (PBL) Arctic MPCs (de Boer et al., 2011; Fridlind & Ackerman, 2018; Fridlind et al., 2012; McFarquhar et al., 2011; Savre & Ekman, 2015) are commonly found at temperatures greater than about -20°C and to the extent that such clouds contain ice by definition, that ice quickly grows and precipitates, consistent with the so-called cold rain process (Silber et al., 2021).

The compound risk of heat and COVID-19 in New York City: Risksapes, physical and social factors, and interventions.

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Abstract. Climate change is disrupting the fundamental conditions of human life and exacerbating existing inequity by placing further burdens on communities that are already vulnerable. Risk exposure varies by where people live and work. In this article, we examine the spatial overlap of the compound risks of COVID-19 and extreme heat in New York City. We assess the relationship between socio-demographic and natural, built and social environmental characteristics, and the spatial correspondence of COVID-19 daily case rates across three pandemic waves. We use these data to create a compound risk index combining heat, COVID-19, density and social vulnerability. Our findings demonstrate that the compound risk of COVID-19 and heat are public health and equity challenges. Heat and COVID-19 exposure are influenced by natural, built, and social environmental factors, including access to mitigation infrastructure. Socio-demographic characteristics are significant indicators of COVID-19 and heat exposure and of where compound vulnerability exists. Using GIS mapping, we illustrate how COVID-19 risk geographies change across the three waves of the pandemic and the particular impact of vaccinations before the onset of the third wave. We, then, use our compound risk index to assess heat interventions undertaken by the city, identify neighborhoods of both adequate and inadequate coverage and provide recommendations for future interventions.

Introduction. Climate change and the COVID-19 pandemic are disrupting the fundamental conditions of human life and exacerbating existing inequities by placing further burdens on communities that are already vulnerable. Some are better positioned and resourced to adapt to or avoid the worst impacts of climate change, while others find their homes becoming uninhabitable, their livelihoods vanishing and their health and security threatened (Islam and Winkel [Citation2017](#); King and Harrington [Citation2018](#); Oppenheimer et al. [Citation2022](#)). The overlapping nature and multiplicity of risks associated with climate change are captured in the concept of “risksapes”, a term that calls attention to interactions among risks, or potential dangers and harms, such as exposure to natural environmental harms like extreme heat and flooding, built and social environmental risks such as inadequate or crowded housing and social risk, such as lack of access to social support and economic opportunity (Neisser and Müller-Mahn [Citation2017](#); Davies et al. [Citation2020](#)). Vulnerable neighbourhoods are disproportionately exposed to elevated risks and cumulative impact across several dimensions of human life and the biophysical environment (Liévanos [Citation2020](#); Renn [Citation2008](#)).

Exposure to risk varies by where people live, work and the multiplicity of other contexts in which they engage in social interaction. Too often, however, these risks have been studied in isolation. For example, heightened environmental exposure is studied separately from elevated exposure to crime, elevated exposure to health risks is studied without concern for heightened economic risks and so forth (Müller-Mahn, Everts, and Stephan [Citation2018](#)). Studying risksapes enables an understanding of the origins, interdependencies and spillovers between risk clusters that operate on multiple spatial scales from the local to the global as well as the factors that sustain risk (Beck [Citation2012](#); Renn [Citation2008](#)).

Risks of synchronized low yields are underestimated in climate and crop model projections.

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Abstract. Simultaneous harvest failures across major crop-producing regions are a threat to global food security. Concurrent weather extremes driven by a strongly meandering jet stream could trigger such events, but so far this has not been quantified. Specifically, the ability of state-of-the-art crop and climate models to adequately reproduce such high impact events is a crucial component for estimating risks to global food security. Here we find an increased likelihood of concurrent low yields during summers featuring meandering jets in observations and models. While climate models accurately simulate atmospheric patterns, associated surface weather anomalies and negative effects on crop responses are mostly underestimated in bias-adjusted simulations. Given the identified model biases, future assessments of regional and concurrent crop losses from meandering jet states remain highly uncertain. Our results suggest that model-blind spots for such high-impact but deeply-uncertain hazards have to be anticipated and accounted for in meaningful climate risk assessments.

Introduction. Extreme weather events like heatwaves, droughts and extreme precipitation can adversely impact crop production¹ and food security^{2,3}. Global warming is increasing the frequency and intensity^{4,5,6,7} of weather extremes and the likelihood of their simultaneous occurrence globally^{8,9,10}. Extremes occurring in close temporal vicinity^{11,12,13} can lead to outsized societal impacts, often beyond the sum of each extreme occurring in isolation¹⁴. In particular, synchronized crop failures due to simultaneous weather extremes across multiple breadbasket regions pose a risk to global food security and food system supply chains^{15,16}, with potential disproportional impacts for import-dependent regions^{2,3}.

Risks of synchronized breadbasket failures have been assessed on a purely statistical basis^{17,18} and in relation to dominant modes of climate variability¹⁶ that act on annual and seasonal timescales. In the mid-latitudes, however, concurrent weather extremes are to a large degree driven by the jet stream, the fast flowing winds in the upper tropospheric mid-latitude circulation^{19,20,21}. Specific summertime circulation regimes in the jet stream act as circumglobal teleconnections^{22,23,24}, promoting simultaneous heat^{9,25} and rainfall^{20,26} extremes with adverse effects on agricultural production across the mid-latitudes¹⁹. In Northern Hemisphere (NH) summer, recurrent patterns have been identified as quasi-stationary Rossby waves with wavenumbers 5 and 7 (wave-5 and wave-7 from hereon), where the wavenumber refers to the number of ridges and troughs observed within the mid-latitudes, whenever their amplitude is high. Such high amplitude waves have been observed during major NH summer weather extremes recently^{25,27,28}.

While earlier analyses have shown the importance of atmospheric wave patterns for local²⁹ or coinciding^{19,30} extreme weather events, their impact on yield anomalies has to date only been quantified on a regional basis. The effect of such wave patterns on yield co-variability between pairs of regions remains unquantified in observations as well as in model experiments. Purely model based risk assessments require both crop models that show skill in reproducing observed extreme weather yield responses with sufficient accuracy and climate models that reproduce observed relationships between wave patterns and extreme weather. A recent analysis by Luo et al.³¹ shows that the surface imprint of wave patterns is largely underestimated in three climate models, while their phase position is reasonably well depicted.

The drivers and impacts of Amazon forest degradation.

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Abstract. Approximately 2.5×10^6 square kilometers of the Amazon Forest are currently degraded by fire, edge effects, timber extraction, and/or extreme drought, representing 38% of all remaining forests in the region. Carbon emissions from this degradation total up to 0.2 petagrams of carbon per year (Pg C year^{-1}), which is equivalent to, if not greater than, the emissions from Amazon deforestation (0.06 to $0.21 \text{ Pg C year}^{-1}$). Amazon forest degradation can reduce dry-season evapotranspiration by up to 34% and cause as much biodiversity loss as deforestation in human-modified landscapes, generating uneven socioeconomic burdens, mainly to forest dwellers. Projections indicate that degradation will remain a dominant source of carbon emissions independent of deforestation rates. Policies to tackle degradation should be integrated with efforts to curb deforestation and complemented with innovative measures addressing the disturbances that degrade the Amazon Forest.

Introduction. Tropical forests are critical for Earth's climate, biodiversity, local well-being and livelihoods, and humanity at large (1). They are also a hotspot for CO_2 emissions to the atmosphere, largely as a result of deforestation and other anthropogenic disturbances (2). Most analyses of land-use and land-cover changes in tropical forests have focused on the causes and effects of deforestation (3–5). However, other, less-well-studied anthropogenic disturbances also threaten the future of tropical forests. These disturbances include edge effects, selective logging, fire, and extreme drought, which have been intensified by human-induced climate change.

In the Amazon forest, the extent and long-term effects of such anthropogenic disturbances on the terrestrial carbon cycle, ecosystem functioning, and livelihoods of local populations are beginning to be understood and differentiated from deforestation impacts (6). These disturbances often co-occur and repeat multiple times and greatly increase the impact on forest condition and biodiversity (7). Many of the effects of these disturbances also occur over longer time scales. For instance, ongoing tree mortality after disturbance means that forests can continue to emit more carbon for decades after the disturbance (8, 9), such that current estimates of the total carbon loss tied to degradation are comparable to, if not greater than, carbon loss from deforestation (10–16). Moreover, the reduced provision of ecosystem services resulting from such anthropogenic disturbances appears to disproportionately affect local livelihoods (17–19).

A recent study of the Amazon showed that only 14% of degraded forests were later deforested over a period of 22 years (11), suggesting that these are partially independent processes. Understanding and representing degradation as a process separate from deforestation is thus critical for improving observation networks, climate change and conservation policies, as well as modeling the resilience of the Amazon forest and its human populations, in light of ongoing land-cover and land-use changes and increased frequency of climate extremes.

Arctic tropospheric ozone trends.

Law, K.S., J.L. Hjorth, J.B. Pernov, C. Whaley, H. Skov, M. Collaud Coen, J. Langner, S.R. Arnold, D.W. Tarasick, J. Christensen, M. Deushi, P. Effertz, **G. Faluvegi**^{1,2}, M. Gauss, U. Im, N. Oshima, I. Petropavlovskikh, D. Plummer, **K. Tsigaridis**^{1,2}, S. Tsyro, S. Solberg, and S.T. Turnock, 2023

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Abstract. Observed trends in tropospheric ozone, an important air pollutant and short-lived climate forcer (SLCF), are estimated using available surface and ozonesonde profile data for 1993–2019, using a coherent methodology, and compared to modeled trends (1995–2015) from the Arctic Monitoring Assessment Program SLCF 2021 assessment. Increases in observed surface ozone at Arctic coastal sites, notably during winter, and concurrent decreasing trends in surface carbon monoxide, are generally captured by multi-model median trends. Wintertime increases are also estimated in the free troposphere at most Arctic sites, with decreases during spring months. Winter trends tend to be overestimated by the multi-model medians. Springtime surface ozone increases in northern coastal Alaska are not simulated while negative springtime trends in northern Scandinavia are not always reproduced. Possible reasons for observed changes and model performance are discussed including decreasing precursor emissions, changing ozone dry deposition, and variability in large-scale meteorology.

Introduction. Tropospheric ozone (O_3) is a short-lived climate forcer (SLCF) contributing to global and Arctic warming (AMAP, 2015; Sand et al., 2016; von Salzen et al., 2022), and a critical secondary air pollutant, detrimental to human health (Anenberg et al., 2010) and ecosystems (Arnold et al., 2018). The Arctic tropospheric O_3 budget is complex, as recently discussed in a companion paper, Whaley et al. (2023). It originates from photochemical production of anthropogenic or natural emissions of O_3 precursors, including nitrogen oxides (NO_x), carbon monoxide (CO) and methane (CH_4), in the Arctic, or following air mass transport from mid-latitudes, as well as transport of O_3 from the stratosphere (Law et al., 2014; Schmale et al., 2018). Sinks include photochemical destruction, including reactions involving halogens leading to so-called ozone depletion events (ODEs) (Barrie, et al., 1988; Simpson et al., 2007), and surface dry deposition (Clifton et al., 2020). Growth in anthropogenic emissions since pre-industrial times has led to increases in tropospheric O_3 throughout the Northern Hemisphere (NH) (Cooper et al., 2020; Gaudel et al., 2018; Tarasick et al., 2019; Turnock et al., 2020) contributing to observed global and Arctic warming over the past century (e.g., Griffiths et al., 2021; Szopa et al., 2021). Since the mid-1990s, a mix of relatively weak positive and negative trends (+1 to −1 parts per billion by volume (ppbv) per decade) have been reported in the NH at the surface and in the free troposphere (FT), with largest increases over south and eastern Asia, associated with increasing anthropogenic emissions (Cooper et al., 2020; H. Wang et al., 2022).

To date, only a few studies have focused on assessing tropospheric O_3 trends in the Arctic. While positive O_3 trends were diagnosed at several surface sites, results do not always have high certainty, and both positive and negative trends were reported at some Canadian sites (Cooper et al., 2020; Sharma et al., 2019; Tarasick et al., 2016). In the Arctic FT, studies found significant positive trends (B. Christiansen et al., 2017; H. Wang et al., 2022), no trends (Tarasick et al., 2016), or mixed trends in different seasons (Bahramvash Shams et al., 2019). Differences in the periods analyzed, sign or magnitude of trends, based on different methodologies, data averaging, etc. emphasizes the need to further examine trends using the same methodology. Coherent estimation of observed trends, and evaluation of modeled trends, is needed to better understand O_3 changes and impacts on Arctic climate that are sensitive to the altitude where O_3 perturbations occur (Rap et al., 2015). This study assesses annual/decadal and monthly trends, together with possible evolution in seasonal cycles, of Arctic tropospheric O_3 over the last 20–30 years. Observed changes are also compared to results from atmospheric chemistry-climate models run as part of the recent Arctic Monitoring and Assessment Programme (AMAP) SLCF assessment (AMAP, 2021; Whaley et al., 2022; von Salzen et al., 2022), taking into account reported model deficiencies (Whaley et al., 2023). Results are discussed in light of possible changes in sources and sinks of Arctic tropospheric O_3 .

Use of Lidar aerosol extinction and backscatter coefficients to estimate cloud condensation nuclei (CCN) concentrations in the Southeast Atlantic.

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Abstract. Accurately capturing cloud condensation nuclei (CCN) concentrations is key to understanding the aerosol–cloud interactions that continue to feature the highest uncertainty amongst numerous climate forcings. In situ CCN observations are sparse, and most non-polarimetric passive remote sensing techniques are limited to providing column effective CCN proxies such as total aerosol optical depth (AOD). Lidar measurements, on the other hand, resolve profiles of aerosol extinction and/or backscatter coefficients that are better suited for constraining vertically resolved aerosol optical and microphysical properties. Here we present relationships between aerosol backscatter and extinction coefficients measured by the airborne High Spectral Resolution Lidar 2 (HSRL-2) and in situ measurements of CCN concentrations. The data were obtained during three deployments in the NASA ObseRvations of Aerosols above CLouds and their intERactionS (ORACLES) project, which took place over the southeast Atlantic (SEA) during September 2016, August 2017, and September–October 2018.

Our analysis of spatiotemporally collocated in situ CCN concentrations and HSRL-2 measurements indicates strong linear relationships between both data sets. The correlation is strongest for supersaturations (S) greater than 0.25 % and dry ambient conditions above the stratocumulus deck, where relative humidity (RH) is less than 50 %. We find CCN–HSRL-2 Pearson correlation coefficients between 0.95–0.97 for different parts of the seasonal burning cycle that suggest fundamental similarities in biomass burning aerosol (BBA) microphysical properties. We find that ORACLES campaign-average values of in situ CCN and in situ extinction coefficients are qualitatively similar to those from other regions and aerosol types, demonstrating overall representativeness of our data set. We compute CCN–backscatter and CCN–extinction regressions that can be used to resolve vertical CCN concentrations across entire above-cloud lidar curtains. These lidar-derived CCN concentrations can be used to evaluate model performance, which we illustrate using an example CCN concentration curtain from the Weather Research and Forecasting Model coupled with physics packages from the Community Atmosphere Model version 5 (WRF-CAM5). These results demonstrate the utility of deriving vertically resolved CCN concentrations from lidar observations to expand the spatiotemporal coverage of limited or unavailable in situ observations.

Introduction. One of the most pressing environmental questions is how Earth's climate will respond to anthropogenic emissions and associated radiative forcings. Natural and anthropogenic aerosols and their interactions with radiation and clouds play a key role in climate change and its uncertainty. Effective radiative forcing due to direct aerosol–radiation interactions (ERF_{dir}) includes scattering and absorption of incoming solar radiation, while effective radiative forcing due to interactions between aerosols and clouds (ERF_{ind}) is defined by the way that aerosols interact with clouds and, consequently, how clouds interact with radiation (Lohmann and Feichter, 2005; Andreae and Rosenfeld, 2008). These indirect effects include changes in cloud albedo and cloud lifetime, whose impacts on incoming solar energy can be significant in terms of temperature change at the surface and in the atmosphere (Budyko, 1969; Twomey, 1974; Albrecht, 1989; Andreae, 2009). Such aerosol–cloud interactions may have a large, but highly uncertain, cooling effect, as defined by the Intergovernmental Panel on Climate Change (IPCC) (Forster et al., 2021).

Comparisons of simulated radiation, surface wind stress and SST fields over tropical Pacific by the GISS CMIP6 versions of global climate models with observations.

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Abstract. This study compares the overall performance between versions 2.1 and 3 of National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS) global climate models (referred to as GISS-E2.1 and GISS-E3, respectively), in simulating the present-day Pacific climate using the CMIP6 protocol. Model physical representations and configurations are extensively changed from GISS-E2.1 to GISS-E3, which result in greatly reduced discrepancies, including ice water path (IWP), ice water content (IWC), radiative fluxes, surface wind stress (TAU), sea surface temperature (SST), precipitation (PR) and column water vapor (PRW), relative to satellite-based observational products over south Pacific oceans. Cloud only IWP (CIWP) shows the largest change, decreasing biases from $\sim 400 \text{ g kg}^{-1}$ in GISS-E2.1 to $10\text{--}20 \text{ g kg}^{-1}$ in GISS-E3. The combination of improved CIWP and the inclusion of snow in GISS-E3 may play roles on reducing overestimated outgoing longwave radiation, overestimated reflected shortwave at the top of atmosphere, and underestimated surface downward shortwave in GISS-E2.1. Both models' intertropical convergence zones (ITCZs) are, however, located far too north of the equator, as found in radiative fluxes, PR and PRW but not in SST relative to observations. This introduces biases in TAU, PR and PRW over north flank of the equator and north Pacific. Over south Pacific, especially the trade wind regions, the improvements of radiation fluxes, SST, PR and PRW appear to be due to improved TAU associated with inclusion of snow-radiative effects. In particular, GISS-E3 reduces a longstanding too warm SST bias over trade-wind regions, from 4 K in GISS-E2.1 to within 0.5 K, and too cold SST bias over north Pacific Ocean. Although GISS-E3 shows improved geographic patterns of the simulated fields in particular over south Pacific oceans compared to GISS-E2.1, our results suggest that the location of ITCZ needs to be further improved.

Introduction. Recently, the climate modeling group at the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS) decided to freeze one of the four configurations of the latest version of the NASA GISS ModelE version 3 global climate model (GCM), referred as GISS-E3, (Cesana *et al* [2019](#), [2021](#)), following the previous generation (GISS-E2.1, Kelley *et al* [2020](#)), which is already submitted to the Coupled Model Intercomparison Project phase 6 (CMIP6) (Eyring *et al* [2016](#)). GISS-E3 has major modifications in particular in cloud microphysics and convective schemes with multiple hydrometeor species considered prognostically along with improved radiation scheme and planetary boundary layer (PBL) clouds in GISS-E3. For details, refer to Cesana *et al* ([2019](#)). The uniqueness of the newest GISS-E3 is the implementation of more realistic representations of hydrometeors-radiation interactions by adding radiative effects of stratiform snow and in particular, convective snow and rain (see model description in section [2](#)) that are not considered in other CMIP GCMs to our knowledge (Li *et al* [2014b](#), [2015](#), Michibata *et al* [2019](#)). This is also the first model that implements prognostic convective snow + ice rather than diagnostic convective ice radiation interactions in other GCMs such as Community Earth System Model version 1 (CESM1). The impacts of inclusion of radiatively active stratiform snow in a GCM have been found critical important for improving tropical climate in many fully-coupled GCMs (Gettelman and Morrison [2015](#), Gettelman *et al* [2010](#), [2015](#), Michibata *et al* [2019](#), Li *et al* [2020a](#)), for example, CESM1-CAM5 and MIROC6.

The optimization of model ensemble composition and size can enhance the robustness of crop yield projections.

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Abstract. Linked climate and crop simulation models are widely used to assess the impact of climate change on agriculture. However, it is unclear how ensemble configurations (model composition and size) influence crop yield projections and uncertainty. Here, we investigate the influences of ensemble configurations on crop yield projections and modeling uncertainty from Global Gridded Crop Models and Global Climate Models under future climate change. We performed a cluster analysis to identify distinct groups of ensemble members based on their projected outcomes, revealing unique patterns in crop yield projections and corresponding uncertainty levels, particularly for wheat and soybean. Furthermore, our findings suggest that approximately six Global Gridded Crop Models and 10 Global Climate Models are sufficient to capture modeling uncertainty, while a cluster-based selection of 3-4 Global Gridded Crop Models effectively represents the full ensemble. The contribution of individual Global Gridded Crop Models to overall uncertainty varies depending on region and crop type, emphasizing the importance of considering the impact of specific models when selecting models for local-scale applications. Our results emphasize the importance of model composition and ensemble size in identifying the primary sources of uncertainty in crop yield projections, offering valuable guidance for optimizing ensemble configurations in climate-crop modeling studies tailored to specific applications.

Introduction. Climate change associated with increasing atmospheric greenhouse gas concentrations affects many agricultural regions and threatens global crop production and food security^{1,2,3,4}. In recent years, climate change has increased the risks of simultaneous failure of major crops for breadbaskets across the globe⁵ and projected climate change may push one-third of food production areas outside a “safe” climatic space⁶. Coincident with these factors, increasing population and food demand increase the difficulty of achieving the UN’s Sustainable Development Goal target of hunger eradication by 2030^{7,8} and other health and environmental targets⁹.

Process-based biophysical crop models driven by climate data downscaled from multiple global climate models (GCMs) are often used to project crop yield changes and aid strategic decision-making for agriculture^{10,11,12}. The Agricultural Model Intercomparison and Improvement Project (AgMIP)’s Global Gridded Crop Model Intercomparison (GGCMI) provides the essential data products needed to analyze global crop yield in response to climate change at global scales^{13,14,15}. Projections based on the latest generation of GCMs, those contributing to the Coupled Model Intercomparison Project phase 6 (CMIP6)¹⁶, show climate change having a largely negative impact on crop yield in many breadbasket regions but also indicate some positive changes for individual crops, especially across higher latitudes³. However, there are large uncertainties in GCM–GGCM yield projections, both for the breadbasket regions^{2,17} and at the global gridded scale^{18,19}. These include modeling uncertainty related to the structure and parameters of the GCMs and crop models^{20,21,22}. Recent analyses of uncertainty due to GCM and GGCM at a global scale for different crops have been conducted^{3,23}. These studies reported that GGCMs are often the dominant source of uncertainty in quantifying relative changes in crop yield, even though the GGCM-induced variance decreased in the latest CMIP6-based projections³ compared with an earlier GGCM ensemble-driven with CMIP5 climate projections¹⁸. Note that Müller et al.²³ also found that the overall variance of a crop-model emulator ensemble increases when driven by CMIP6 in comparison with being driven by the previous CMIP5 generation of GCM climate projections, but the relative shares of GGCM-induced variance were similar between the CMIP5 and CMIP6 ensembles.

Global climate impacts of Greenland and Antarctic meltwater: A comparative study.

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Abstract. Both the Greenland and Antarctic ice sheets have been melting at an accelerating rate over recent decades. Meltwater from Greenland might be expected to initiate a climate response that is distinct, and perhaps different from, that associated with Antarctic meltwater. Which one might elicit a greater climate response, and what mechanisms are involved? To explore these questions, we apply climate response functions (CRFs) to guide a series of meltwater-perturbation experiments using a fully coupled climate model. In both hemispheres, meltwater drives atmospheric cooling, sea ice expansion, and strengthened Hadley and Ferrel cells. Greenland meltwater induces a slowdown of the Atlantic meridional overturning circulation (AMOC) and a cooling of the subsurface ocean in the northern high latitudes. Antarctic meltwater, instead, induces a slowdown of the Antarctic Bottom Water formation and a warming of the subsurface ocean around Antarctica. For melt rates up to 2000 Gt yr⁻¹, the climate response is rather linear. However, as melt rates increase to 5000 Gt yr⁻¹, the climate response becomes nonlinear. Due to a collapsed AMOC, the climate response is superlinear at high Greenland melt rates. Instead, the climate response is sublinear at high Antarctic melt rates, due to the halting of the northward expansion of Antarctic sea ice by warm surface waters. Finally, in the linear limit, we use CRFs and linear convolution theory to make projections of important climate parameters in response to meltwater scenarios, which suggest that Antarctic meltwater will become a major driver of climate change, dominating that of Greenland meltwater, as the current century proceeds.

Introduction. The Greenland and Antarctic ice sheets represent the largest land store of freshwater over the globe, which, should they completely melt and flow into the ocean, could contribute a total of 7.5 and 58 m to global-mean sea level, respectively (Morlighem et al. 2017; Fretwell et al. 2013). Recent observations have shown that these ice sheets are melting at an accelerating rate (Paolo et al. 2015; Rignot et al. 2019; Mouginot et al. 2019; Shepherd et al. 2018, 2020; King et al. 2020). Between the periods of 1992–2011 and 2012–17, the rate of ice-mass loss has risen from roughly 100 to 250 Gt yr⁻¹ in Greenland (Shepherd et al. 2020) and from 75 Gt yr⁻¹ to roughly 200 Gt yr⁻¹ in Antarctica (Shepherd et al. 2018). Since the 1990s, their combined contribution to global-mean sea level has been 18 mm, of which 10 mm came from Greenland (Shepherd et al. 2020) and 8 mm from Antarctica (Shepherd et al. 2018). The Greenland ice mass loss is ice-sheet-wide owing to rapidly increasing surface melting and ice dynamical imbalances (King et al. 2020). The Antarctic ice sheet retreat is largely due to ice-shelf basal melt and iceberg calving in roughly equal magnitude along the periphery, primarily in the Amundsen–Bellingshausen Sea sectors (West Antarctica), Wilkes Land (East Antarctica), and the West and Northeast Peninsula (Rignot et al. 2019). Twenty-first-century simulations of the Greenland and Antarctic ice sheets forced with time-evolving ocean and climate fields derived from a high-emissions scenario suggest that the projected melt rates would exceed 500 and 5000 Gt yr⁻¹, respectively, by 2100, leading to a total sea level rise in excess of 250 mm with meltwater feedback (Golledge et al. 2019).

Meltwater from Greenland and Antarctica contributes not only to sea level but also initiates climate change through its effect, for example, on sea ice extent and the ocean's overturning circulation. One might expect the impacts of Greenland meltwater to be different from that of Antarctic meltwater because they act in different hemispheres and perturb different parts of the climate system. For example, it is thought that Antarctic meltwater spreading to the proximal ocean initiates surface cooling and freshening trends across the Southern Ocean (Bronselaer et al. 2018; Rye et al. 2020).

Large-eddy simulations of marine boundary layer clouds associated with cold-air outbreaks during the ACTIVATE Campaign. Part II: Aerosol-meteorology-cloud interaction.

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Abstract. Aerosol effects on micro/macrophysical properties of marine stratocumulus clouds over the western North Atlantic Ocean (WNAO) are investigated using in situ measurements and large-eddy simulations (LES) for two cold-air outbreak (CAO) cases (28 February and 1 March 2020) during the Aerosol Cloud Meteorology Interactions over the Western Atlantic Experiment (ACTIVATE). The LES is able to reproduce the vertical profiles of liquid water content (LWC), effective radius r_{eff} and cloud droplet number concentration N_c from fast cloud droplet probe (FCDP) in situ measurements for both cases. Furthermore, we show that aerosols affect cloud properties (N_c , r_{eff} , and LWC) via the prescribed bulk hygroscopicity of aerosols ($\bar{\kappa}$) and aerosol size distribution characteristics. N_c , r_{eff} , and liquid water path (LWP) are positively correlated to $\bar{\kappa}$ and aerosol number concentration (N_a) while cloud fractional cover (CFC) is insensitive to $\bar{\kappa}$ and aerosol size distributions for the two cases. The realistic changes to aerosol size distribution (number concentration, width, and the geometrical diameter) with the same meteorology state allow us to investigate aerosol effects on cloud properties without meteorological feedback. We also use the LES results to evaluate cloud properties from two reanalysis products, ERA5 and MERRA-2. Compared to LES, the ERA5 is able to capture the time evolution of LWP and total cloud coverage within the study domain during both CAO cases while MERRA-2 underestimates them.

Introduction. Aerosols and clouds pose the largest uncertainty in climate projection since they mediate the radiative forcing of Earth's atmosphere ([Seinfeld et al. 2016](#)). An increased loading of aerosols in the atmosphere reflects more incoming solar energy to space and consequently cools the Earth system. The increased aerosol number concentration N_a in an environment with constant liquid water content (LWC) leads to cloud droplets with smaller size and larger number concentration N_c , which makes the cloud more reflective, often called the first indirect effect, aka the Twomey effect ([Twomey 1977](#)). Reduced droplet sizes can also result in less precipitation and longer cloud lifetime. The latter effect is known as the second indirect effect ([Albrecht 1989](#)). Cloud radiative properties are determined by both the cloud macrophysical properties, such as the liquid water path (LWP) and cloud fractional coverage (CFC), and by the cloud microphysical properties, such as N_c and the effective radius r_{eff} . Global mean change in radiative forcing due to anthropogenic aerosols, relative to preindustrial era (before year 1850), is roughly estimated to be between -1.6 and -0.6 W m^{-2} with a 68% confidence interval in the years 2005–15 ([Bellouin et al. 2020](#)). However, how the anthropogenic aerosols affect LWC and CFC remains unclear ([Bellouin et al. 2020](#); [McCoy et al. 2020](#)), which is due to the fact that LWC and CFC are predominantly determined by meteorology states but also modulated by changes in N_c through precipitation ([Stevens and Feingold 2009](#)). This is the aerosol–meteorology–cloud-interaction (AMCI) problem that encompasses a wide range of spatial–temporal scales from nm-sized aerosol particles to large-scale atmospheric circulations [O(100)km]. Global Earth system models and even cloud-resolving models suffer from coarse resolutions such that vital cloud macro/microprocesses in the marine boundary layer cannot be physically represented.

Mean state AMOC affects AMOC weakening through subsurface warming in the Labrador Sea.

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Abstract. While most models agree that the Atlantic meridional overturning circulation (AMOC) becomes weaker under greenhouse gas emission and is likely to weaken over the twenty-first century, they disagree on the projected magnitudes of AMOC weakening. In this work, CMIP6 models with stronger climatological AMOC are shown to project stronger AMOC weakening in both 1% ramping CO₂ and abrupt CO₂ quadrupling simulations. A physical interpretation of this result is developed. For models with stronger mean state AMOC, stratification in the upper Labrador Sea is weaker, allowing for stronger mixing of the surface buoyancy flux. In response to CO₂ increase, surface warming is mixed to the deeper Labrador Sea in models with stronger upper-ocean mixing. This subsurface warming and corresponding density decrease drives AMOC weakening through advection from the Labrador Sea to the subtropics via the deep western boundary current. Time series analysis shows that most CMIP6 models agree that the decrease in subsurface Labrador Sea density leads AMOC weakening in the subtropics by several years. Also, idealized experiments conducted in an ocean-only model show that the subsurface warming over 500–1500 m in the Labrador Sea leads to stronger AMOC weakening several years later, while the warming that is too shallow (<500 m) or too deep (>1500 m) in the Labrador Sea causes little AMOC weakening. These results suggest that a better representation of mean state AMOC is necessary for narrowing the inter-model uncertainty of AMOC weakening to greenhouse gas emission and its corresponding impacts on future warming projections.

Introduction. The Atlantic meridional overturning circulation (AMOC) is a global ocean circulation that generally transports warm and salty upper waters northward, releasing heat to the atmosphere to form the cold, deep waters flowing southward. The AMOC varies over broad time scales, and these AMOC variations shape global and regional climate through the transport of heat, salt, and biochemical substances ([Jackson et al. 2015](#); [Liu et al. 2020](#); [Zhang et al. 2019](#)). The climate impacts associated with the time-evolving AMOC include changes in sea surface temperature ([Knight et al. 2005](#); [Muir and Fedorov 2015](#)), shifts in tropical precipitation ([Moreno-Chamorro et al. 2019](#); [Parsons et al. 2014](#)), the extent of the Arctic sea ice ([Liu and Fedorov 2019](#); [Mahajan et al. 2011](#)), and projections of sea level rise ([Gregory et al. 2016](#); [Little et al. 2019](#)).

Since the AMOC plays a vital role in modifying the global climate, scientists have been focusing on the driving mechanisms of the AMOC variations on multiple time scales. On seasonal to interannual time scale, wind stress curl can drive the Ekman transport that corresponds to meridional Sverdrup flow ([Eden and Willebrand 2001](#); [Köhl 2005](#)). At the same time, surface wind forcing might trigger Rossby waves that modify the basinwide east–west density gradient ([Hirschi et al. 2007](#)). Both account for the higher-frequency AMOC fluctuations ([Zhao and Johns 2014](#)). On interannual to decadal time scale, buoyancy flux plays a major role in determining the AMOC variations ([Yeager and Robson 2017](#)). Studies have found that the North Atlantic Oscillation (NAO) may be responsible for the decadal buoyancy forcing in the subpolar region ([Delworth and Zeng 2016](#); [Eden and Jung 2001](#); [Lohmann et al. 2009](#)), and the transport of the buoyancy anomalies involves multiple processes including mean ocean advection and propagation via boundary waves ([Buckley and Marshall 2016](#); [Zhang 2010](#)). On centennial to millennial time scales, water flux and the associated salinity anomalies become dominant in changing the AMOC strength ([Delworth and Zeng 2012](#); [Menary et al. 2012](#)).

AgMIP-Wheat multi-model simulations on climate change impact and adaptation for global wheat.

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Abstract. The climate change impact and adaptation simulations from the Agricultural Model Intercomparison and Improvement Project (AgMIP) for wheat provide a unique dataset of multi-model ensemble simulations for 60 representative global locations covering all global wheat mega environments. The multi-model ensemble reported here has been thoroughly benchmarked against a large number of experimental data, including different locations, growing season temperatures, atmospheric CO₂ concentration, heat stress scenarios, and their interactions. In this paper, we describe the main characteristics of this global simulation dataset. Detailed cultivar, crop management, and soil datasets were compiled for all locations to drive 32 wheat growth models. The dataset consists of 30-year simulated data including 25 output variables for nine climate scenarios, including Baseline (1980-2010) with 360 or 550 ppm CO₂, Baseline +2oC or +4oC with 360 or 550 ppm CO₂, a mid-century climate change scenario (RCP8.5, 571 ppm CO₂), and 1.5°C (423 ppm CO₂) and 2.0oC (487 ppm CO₂) warming above the pre-industrial period (HAPPI). This global simulation dataset can be used as a benchmark from a well-tested multi-model ensemble in future analyses of global wheat. Also, resource use efficiency (e.g., for radiation, water, and nitrogen use) and uncertainty analyses under different climate scenario can be explored at different scales. The DOI for the dataset is 10.5281/zenodo.4027033 (AgMIP-Wheat, 2020), and all the data are available on the data repository of Zenodo (doi: 10.5281/zenodo.4027033) Two scientific publications have been published based on some of these data here.

Introduction. As one of the largest staple crops, wheat (*Triticum aestivum*L.) plays an important role in ensuring global food security. Global wheat production, which covers tremendously diverse environments, is facing unprecedented climate change challenges (Lobell et al., 2011). Quantifying potential climate change impacts on global and regional crop production (including quantity and quality) Liuet al. 2023, Open Data Journal for Agricultural Research, vol. 9, p. 10-25.12 accurately can provide valuable support for policymaking in mitigating climate change and for adapting local wheat production for future scenarios (IPCC, 2014). Daily wheat development and growth dynamic at 60 global locations during a 30-year period were simulated as part of the Agricultural Model Intercomparison and Improvement Project (AgMIP;Rosenzweig et al., 2013) for wheat under different climate change scenarios with 32 wheat growth models. The multi-model ensemble reported here has been thoroughly benchmarked against a large number of experimental data, including different locations, growing season temperatures, atmospheric CO₂ concentration, heat stress scenarios, and their interactions (Asseng et al., 2015; Asseng et al., 2013; Asseng et al., 2019; Martre et al., 2015). The 60 global locations covered contrasting conditions across all global wheat mega environments and included 30 high-rainfall or irrigated wheat-growing locations and 30 low-rainfall wheat-growing locations (Reynolds and Braun, 2013). Each location represents an important wheat-growing area worldwide (Fig. 1).

Silver lining to a climate crisis in multiple prospects for alleviating crop waterlogging under future climates.

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Abstract. Extreme weather events threaten food security, yet global assessments of impacts caused by crop waterlogging are rare. Here we first develop a paradigm that distils common stress patterns across environments, genotypes and climate horizons. Second, we embed improved process-based understanding into a farming systems model to discern changes in global crop waterlogging under future climates. Third, we develop avenues for adapting cropping systems to waterlogging contextualised by environment. We find that yield penalties caused by waterlogging increase from 3–11% historically to 10–20% by 2080, with penalties reflecting a trade-off between the duration of waterlogging and the timing of waterlogging relative to crop stage. We document greater potential for waterlogging-tolerant genotypes in environments with longer temperate growing seasons (e.g., UK, France, Russia, China), compared with environments with higher annualised ratios of evapotranspiration to precipitation (e.g., Australia). Under future climates, altering sowing time and adoption of waterlogging-tolerant genotypes reduces yield penalties by 18%, while earlier sowing of winter genotypes alleviates waterlogging by 8%. We highlight the serendipitous outcome wherein waterlogging stress patterns under present conditions are likely to be similar to those in the future, suggesting that adaptations for future climates could be designed using stress patterns realised today.

Introduction. Increasingly frequent and compound extreme weather events driven by the intensification of the global water cycle threaten the sustainability and consistency of agri-food production^{1,2,3}. Coupled with global population growth and a burgeoning demand for food, exposure to weather extremes demand the development of new knowledge, technologies and practices that enable scalable, sustainable intensification^{4,5}.

Robust projections of climate impacts on crop growth underpinned by process-based models^{6,7} are fundamental in the quest to design effective and credible systems-based adaptations that minimise downside risk associated with future climate^{8,9,10}. Application of such models enables consideration of nonlinear, integrated crop responses to environmental, genetic and management conditions^{7,11}, supporting the development of socially-acceptable and profitable climate change adaptation and/or greenhouse gas emissions mitigation strategies^{12,13,14}. However, while the overwhelming majority of previous climate change assessments have used a lens focused on either drought, heat or gradual climate change^{1,3,15,16,17}, our knowledge of the impacts of soil waterlogging on crop growth is very much in its infancy^{18,19,20,21}.

Globally, around 27% of cultivated lands are impacted by flooding each year, with annual costs of flood damage over the last half-century reaching a headline value of US\$19 billion^{22,23,24,25}. Intensification of the global water cycle called forth by the climate crisis would appear to be driving a higher prevalence of waterlogging, placing pressure on the use-efficiency of economic, natural and social capital²⁰. While genotype (G) × environment (E) × management (M) studies pertaining to climate change adaptation abound^{26,27,28,29,30,31}, such work is often not conducted in a way that facilitates scaling to other regions or transferability from other studies. Here, we develop a new approach for assimilating manifold results from crop models into common, discrete sets of groups.

The statistical emulators of GGCM phase 2: Responses of year-to-year variation of crop yield to CO₂, temperature, water and nitrogen perturbations.

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Abstract. Understanding the impact of climate change on year-to-year variation of crop yield is critical to global food stability and security. While crop model emulators are believed to be lightweight tools to replace the models, few emulators have been developed to capture such interannual variation of crop yield in response to climate variability. In this study, we developed a statistical emulator with a machine learning algorithm to reproduce the response of year-to-year variation of four crop yields to CO₂ (C), temperature (T), water (W), and nitrogen (N) perturbations defined in the Global Gridded Crop Model Intercomparison Project (GGCM) phase 2. The emulators were able to explain more than 52 % of the variance of simulated yield and performed well in capturing the year-to-year variation of global average and gridded crop yield over current croplands in the baseline. With the changes in CO₂–temperature–water–nitrogen (CTWN) perturbations, the emulators could reproduce the year-to-year variation of crop yield well over most current cropland. The variation of R and the mean absolute error was small under the single CTWN perturbations and dual-factor perturbations. These emulators thus provide statistical response surfaces of yield, including both its mean and interannual variability, to climate factors. They could facilitate spatiotemporal downscaling of crop model simulation, projecting the changes in crop yield variability in the future and serving as a lightweight tool for multi-model ensemble simulation. The emulators enhanced the flexibility of crop yield estimates and expanded the application of large-ensemble simulations of crop yield under climate change.

Introduction. The impact of climate change on crop yield is an increasing concern related to global food security (Kinnunen et al., 2020). Two distinct approaches have been used to evaluate the impact of climate change on crop yield, process-based crop models and statistical models. Process-based crop models are reliable tools to project crop yields under future climate change but are computationally expensive (Jones et al., 2017). In contrast, statistical models are lightweight tools that can fit yield response to historical climate change (Li et al., 2019b), but the relationship between climate factors and crop yield is based on the historical climate conditions and their effects on crop yields, which can hardly be used for future projection with new, unprecedented climate conditions. Therefore, it is promising to develop tools that can reduce the expense of computation and increase capacity for flexible future projections (Franke et al., 2020a).

Earlier studies have developed statistical emulators of process-based crop model results to balance the advantages and disadvantages of process-based crop models and statistical models. Those statistical emulators were initially developed with “entire scenario” (simultaneous changes in climate factors) simulation during historical or future periods. Emulators have been developed for process-based crop models, like APSIM (Shahhosseini et al., 2019), GEPIC (Folberth et al., 2019), GWG (Xu et al., 2021), GAZE (Raimondo et al., 2021), and WOFOST (Tartarini et al., 2021), and used to estimate historical crop yield. As an emulator trained by historical simulations cannot project the crop yield in the future, multiple crop model ensemble simulations in future climate scenarios have been used to calibrate emulators (Blanc, 2017, 2020; Blanc and Sultan, 2015; Mistry et al., 2017; Ostberg et al., 2018). However, scenario-based future crop yield projection is not a systematic perturbation of climate factors (Franke et al., 2020a). For instance, scenario-based yield projection can only provide the simulated crop yield driven by simultaneous changes in climate factors. The dependency of temperature and precipitation will be kept in scenarios such that the impact of temperature and precipitation cannot be clearly separated.

Greenland and Canadian Arctic ice temperature profiles database.

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Abstract. Here, we present a compilation of 95 ice temperature profiles from 85 boreholes from the Greenland ice sheet and peripheral ice caps, as well as local ice caps in the Canadian Arctic. Profiles from only 31 boreholes (36 %) were previously available in open-access data repositories. The remaining 54 borehole profiles (64 %) are being made digitally available here for the first time. These newly available profiles, which are associated with pre-2010 boreholes, have been submitted by community members or digitized from published graphics and/or data tables. All 95 profiles are now made available in both absolute (meters) and normalized (0 to 1 ice thickness) depth scales and are accompanied by extensive metadata. These metadata include a transparent description of data provenance. The ice temperature profiles span 70 years, with the earliest profile being from 1950 at Camp VI, West Greenland. To highlight the value of this database in evaluating ice flow simulations, we compare the ice temperature profiles from the Greenland ice sheet with an ice flow simulation by the Parallel Ice Sheet Model (PISM). We find a cold bias in modeled near-surface ice temperatures within the ablation area, a warm bias in modeled basal ice temperatures at inland cold-bedded sites, and an apparent underestimation of deformational heating in high-strain settings. These biases provide process level insight on simulated ice temperatures.

Introduction. With the tremendous social implications of sea level change, the past decade has seen a proliferation of simulations of the current and future geometry and dynamics of the Greenland ice sheet (Bindshadler et al., 2013; Goelzer et al., 2020; Aschwanden et al., 2021). These present-day complex ice flow models build upon the legacy of simpler past thermomechanical models (Létréguilly et al., 1991; Huybrechts et al., 1991; Funk et al., 1994; Calov and Hutter, 1996). Due to the high sensitivity of ice viscosity to ice temperature, the thermal state of the ice sheet is a critical element of these simulations (Colgan et al., 2015). At present, however, the englacial temperature fields of even cutting-edge ice sheet simulations remain largely unevaluated against observed temperatures (Aschwanden et al., 2019). While recent studies show potential for deriving internal ice temperatures from satellite or airborne data (Macelloni et al., 2019; Jezek et al., 2022), these techniques are not yet widely employed. There are consequently diverse opinions on Greenland's basal thermal state across the current generation of thermomechanical ice flow models (MacGregor et al., 2016, 2022).

Several different methods for measuring ice temperatures have been used on the Greenland ice sheet and in the Canadian Arctic. The methods include the following: borehole logging, where a temperature sensor is moved up or down the borehole, measuring either “continuously” as the probe moves or stopping to measure at every depth (known as “stop-and-go”; Johnsen et al., 1995; Clow, 2008); sensor strings (this term includes both digital and analog), where thermistors are frozen into the ice, and ice temperatures are recorded at various depths at the same time (Iken et al., 1993; Ryser et al., 2014); and fiber optic distributed temperature sensing (DTS), where the ice temperature is measured near-continuously along the full cable length (Law et al., 2021). We summarize the methods and their advantages and disadvantages in Table 1.

The j and k dependencies of the line coupling and line mixing effects: Theoretical studies of the relaxation matrices of N₂-broadened CH₃D.

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Abstract. Line coupling and line mixing effects in parallel and perpendicular bands of CH₃D perturbed by N₂ have been studied. The work focuses on exhibiting the j and k dependencies of these two processes. The calculations were based on a previously reported anisotropic [intermolecular potential](#) including both the long-range [multipole](#), induction, and dispersion forces and a short-range atom-atom model. It is shown that components with $L_I = 3$ of the atom-atom model are dominant contributions to the diffusion operator. As a consequence, in comparison with other molecular systems such as the CH₃Cl-N₂ and CH₃I-N₂, theoretically predicted line coupling and line mixing effects exhibit completely new j and k dependencies. In general, the theoretically calculated halfwidths and intra-doublets' off-diagonal elements of the relaxation matrix are in reasonable agreement with measurements.

Introduction. Accurate lineshape parameters of monodeuterated methane CH₃D are crucial for quantitative analyses of the [spectral signatures](#) of this molecule in the terrestrial and other [planetary atmospheres](#) (see Ref. [1] and references therein). This is the reason why numerous studies have been devoted both experimentally and theoretically to the halfwidths (HWHM) and shifts of air- as well as self- broadened lines in various vibrational bands (a complete review can be found in [2], [3], [4], [5]).

From the theoretical point of view, which concerns us most directly, the most recent calculations of N₂ broadened halfwidths of CH₃D lines have been performed by Predoi-Cross et al. [4,5] based on the Robert-Bonamy (RB) formalism [6] using exact trajectories and a potential model including an atom-atom potential model.

In recent papers devoted to N₂-broadening of symmetric top molecules [7], [8], [9], we have shown that the isolated line approximation severely limits the validity of the RB model. As outlined previously by Cherkasov [10], the S_2 operator is not diagonal in the linespace, contrary to the isolated line assumption adopted in the RB model [11]. Ignoring this fact (called by us as Line Coupling (LC)) leads to neglecting any coupling between transition lines and a failure in calculating the relaxation matrix. For symmetric tops with k-degeneracy, LC will have an additional consequence: transitions between [rotational states](#) labeled by $k \neq 0$ should be considered as doublets. For each doublet, its two components are coupled through the line mixing (LM) process. For degenerated doublets (i.e. not resolved by the A₁-A₂ splitting), the LM process may significantly reduce theoretically calculated halfwidths of the doublet.

The present work is devoted to the CH₃D-N₂ system. For its degenerate doublets, we have found that the intra-doublet's coupling does play a major role in the calculation of the halfwidths. However, for CH₃D a significant A₁-A₂ splitting exists (for states in the fundamental [vibrational state](#), with $k = 3n$, $n = 1, 2, 3, \dots$). Consequently, the degeneracy of the corresponding doublets can be resolved, providing an opportunity to directly measure the intra-doublet's off-diagonal elements of the relaxation matrix. Then, the latter can be compared with the theoretical predictions.

Tree growth enhancement drives a persistent biomass gain in unmanaged temperate forests.

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Abstract. While enhanced tree growth over the last decades has been reported in forests across the globe, it remains unclear whether it drives persistent biomass increases of forest stands, particularly in mature forests. Enhanced tree growth and stand-level biomass are often linked with a simultaneous increase in density-driven mortality and a reduction in tree longevity. Identifying empirical evidence regarding the balance between these processes is challenging due to the confounding effects of stand history, management, and environmental changes. Here, we investigate the link between growth and biomass via the negative relationship between average tree size and stand density (tree number per area). We find increasing stand density for a given mean tree size in unmanaged closed-canopy forests in Switzerland over the past six decades and a positive relationship between tree growth and stand density across forest plots—qualitatively consistent with our simulations using a mechanistic, cohort-resolving ecosystem model (BiomeE). Model simulations show that, in the absence of other disturbances, enhanced tree growth persistently increases biomass stocks despite simultaneous decreases in carbon residence time and tree longevity. However, the magnitude of simulated biomass changes for a given growth enhancement critically depends on the shape of the mortality functions. Our analyses reconcile reports of growth-induced reductions of tree longevity with model predictions of persistent biomass increases, and with our finding of trends toward denser forests in response to growth—also in mature stands.

Introduction. Forest demographic processes, namely growth, recruitment, and mortality, are being altered by global environmental change (McDowell et al., 2020). Enhanced tree growth over the last decades has been widely reported (Brienen et al., 2015; Cole et al., 2009; Fang et al., 2014; McMahon et al., 2010; Wu et al., 2014). Trends in forest stand growth have been attributed to increased nutrient inputs by atmospheric deposition, rising temperatures and extended growing seasons (Anderegg et al., 2015; Pretzsch et al., 2014), and elevated atmospheric carbon dioxide (eCO₂) (Huang et al., 2007; Hubau et al., 2020; Lewis et al., 2009; Phillips et al., 2009; Walker et al., 2019). Also, biomass stocks have been reported to have increased in forests around the globe (Pan et al., 2011), unless logging, large-scale disturbances, and extreme events reversed long-term trends (Wang et al., 2021). However, it remains unclear to what extent increased biomass stocks are a consequence of accelerated tree growth in response to environmental change or of recovery from past disturbances and land use (Frelich, 2002; Gloor et al., 2009). Disturbance history and stand age are dominant factors determining forest biomass stocks (Bradford et al., 2008) and can mask the effects of environmental change. This limits our understanding and poses an observational challenge for attributing the observed forest carbon (C) sink (Pan et al., 2011) to anthropogenic versus environmental drivers, and for answering the question of whether accelerated tree growth, induced by environmental change, leads to persistent increases in forest biomass stocks. Understanding the relationship between growth and biomass is thus key also for the role of CO₂ fertilization of photosynthesis and growth in driving the observed terrestrial C sink (Walker et al., 2021).

Direct evidence for environmental change effects on tree growth and biomass comes from ecosystem manipulation experiments. Free Air CO₂ Enrichment (FACE) experiments have identified increases in biomass production in response to enhanced CO₂ (Ainsworth & Long, 2005; Hovenden et al., 2019; Jiang et al., 2020; Norby et al., 2005; Walker et al., 2021). However, positive effects on biomass stocks have been argued to be transitory (Brienen et al., 2020; Bugmann & Bigler, 2011; Büntgen et al., 2019; Fatichi et al., 2019; Fleischer et al., 2019) without long-term increases in carbon storage (Körner, 2006, 2009), or limited to young forests (Norby & Zak, 2011).

The lack of a QBO-MJO connection in climate models with a nudged stratosphere.

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Abstract. The observed stratospheric quasi-biennial oscillation (QBO) and the tropospheric Madden-Julian oscillation (MJO) are strongly connected in boreal winter, with stronger MJO activity when lower-stratospheric winds are easterly. However, the current generation of climate models with internally generated representations of the QBO and MJO do not simulate the observed QBO-MJO connection, for reasons that remain unclear. This study builds on prior work exploring the QBO-MJO link in climate models whose stratospheric winds are relaxed toward reanalysis, reducing stratospheric biases in the model and imposing a realistic QBO. A series of ensemble experiments are performed using four state-of-the-art climate models capable of representing the MJO over the period 1980–2015, each with similar nudging in the stratosphere. In these four models, nudging leads to a good representation of QBO wind and temperature signals, however no model simulates the observed QBO-MJO relationship. Biases in MJO vertical structure and cloud-radiative feedbacks are investigated, but no conclusive model bias or mechanism is identified that explains the lack of a QBO-MJO connection.

Introduction. The quasi-biennial oscillation (QBO; Baldwin et al., 2001; Ebdon, 1960; Reed et al., 1961)—a descending, ~28 months reversal in the tropical stratospheric zonal wind—is the most significant mode of interannual variability in the tropical stratosphere. While QBO signals are strongest in the tropical stratosphere, through teleconnections the QBO modulates climate processes outside the tropics and below the stratosphere (Anstey et al., 2022; Camargo & Sobel, 2010; Garfinkel & Hartmann, 2011; Gray et al., 2018; Holton & Tan, 1980). In particular, a strong connection has recently been observed between the QBO and the Madden-Julian oscillation (MJO; Madden & Julian, 1971, 1972), a subseasonal, eastward propagating envelope with strong coupling of tropical convection and circulation. During boreal winter, MJO activity and strength is significantly enhanced when the QBO is in the easterly phase relative to the westerly phase (Martin, Son, et al., 2021; Son et al., 2017; Yoo & Son, 2016). This QBO-MJO connection modulates MJO predictability and its teleconnections (Feng & Lin, 2019; Kim et al., 2019; Lim et al., 2019; Marshall et al., 2017; Mayer & Barnes, 2020; Toms et al., 2020; Wang et al., 2018, 2019). Yet despite these far-reaching impacts, the QBO-MJO connection remains theoretically difficult to explain (Martin, Son, et al., 2021).

Challenges in understanding the physics behind the QBO-MJO connection are in large part hampered by the inability of climate models to capture the connection. While convection-permitting models (Back et al., 2020; Martin et al., 2019) and subseasonal forecast models (Abhik & Hendon, 2019; Martin et al., 2020) have shown some indication of a QBO-MJO link, model signals in both frameworks are weaker-than-observed and difficult to confidently detect or interpret. Free-running global climate models (GCMs) present an alternative framework in which to examine this problem, which is attractive given that many GCMs are now capable of internally simulating both a QBO and an MJO (e.g., Ahn et al., 2020; Kim et al., 2020; Richter et al., 2020; Orbe, Van Roekel, et al., 2020). However, GCMs have repeatedly failed to show any QBO-MJO link (Kim et al., 2020; Lee & Klingaman, 2018; Lim & Son, 2020; Martin, Orbe, et al., 2021).

Changing nature of high-impact snowfall events in Eastern North America.

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Abstract. Snowstorms cause substantial disruption in the eastern United States and Canada each winter. While reductions in annual snowfall are projected over most of this region due to anthropogenic global warming, daily snowfall extremes that have the greatest impact may not decrease in the same manner. We examine changes to two extreme snowfall metrics: the 95th percentile of daily snowfall (SF95, cm) and the number of events during which 10% of the mean annual snowfall is exceeded during a single day (TC10, events yr⁻¹). We explore changes to these metrics in two ensembles of the fifth-generation Canadian Regional Climate Model, including four 0.22° (≈25 km) simulations driven by different coupled general circulation models as well as the higher-resolution (0.11°, ≈12 km) ClimEx ensemble, driven by 50 members of a large initial-condition ensemble of one global model. We find that while mean annual snowfall is projected to decrease over our domain, SF95 is projected to remain relatively constant, suggesting that the most extreme daily snowfalls currently observed are likely to occur even in a warmer future climate. The region of the largest TC10 values exhibits a northward shift, with a larger percentage of annual snowfall occurring during a few large events along the U.S.-Canada border. These projected changes to the nature of snowfall events may have important socioeconomic consequences in this densely populated region of North America.

Introduction. Snowstorms can have severe socioeconomic effects on the highly populated regions of the eastern United States and Canada (e.g., Kocin & Uccellini, [2004](#)). Heavy snowfall can make surface and air transportation difficult or impossible as a result of slippery surfaces. Wet snow can weigh down and break trees and power lines, and shoveling this heavy snow can lead to health risks. Heavy snow loads can also result in roof and building collapse. Changnon and Changnon ([2006](#)) estimated that from 1949 to 2000, snowstorms caused \$21.6 billion (year 2000 U.S. dollars) in insured property losses in the U.S. with the greatest losses occurring in the Northeast (\$7.3 billion) and Southeast (\$4.1 billion) regions. Several severe snowstorms have impacted this region in recent years. For example, a January 2016 blizzard prompted Washington, D.C. and New York City to implement driving bans and shut down public transportation (Glenza, [2016](#)). In December 2022, a historic lake-effect snow event produced more than 50 in. (≈130 cm) of snow over a 4-day period in Buffalo, New York, stranding motorists and resulting in fatalities (Kilgannon et al., [2022](#)).

The definition of a “snowstorm” may vary between regions—while substantial disruption may require large snowfall amounts over northernmost regions such as southeastern Canada, areas that are less accustomed to heavy snowfalls may be paralyzed by only a few centimeters of snow. One example is the January 2014 snow event, during which ≈2 in. (≈5 cm) of snow resulted in thousands of flight cancellations and traffic crashes that stranded motorists for up to 20 hr in Atlanta and surrounding regions (Burns, [2014](#); Samenow, [2014](#); Severson, [2014](#)).

Future snowfall changes may be driven by several, sometimes competing, factors. First, with continued anthropogenic greenhouse gas emissions, additional warming may decrease snowfall and increase the percentage of precipitation falling as rain. On the other hand, in regions where temperatures remain sufficiently cold for snow, increased precipitation due to higher atmospheric water vapor content and greater precipitation intensity may result in increased snowfall.

Irrigation in the Earth system.

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Abstract. Irrigation accounts for ~70% of global freshwater withdrawals and ~90% of consumptive water use, driving myriad Earth system impacts. In this Review, we summarize how irrigation currently impacts key components of the Earth system. Estimates suggest that more than 3.6 million km² of currently irrigated land, with hot spots in the intensively cultivated US High Plains, California Central Valley, Indo-Gangetic Basin and northern China. Process-based models estimate that $\sim 2,700 \pm 540$ km³ irrigation water is withdrawn globally each year, broadly consistent with country-reported values despite these estimates embedding substantial uncertainties. Expansive irrigation has modified surface energy balance and biogeochemical cycling. A shift from sensible to latent heat fluxes, and resulting land–atmosphere feedbacks, generally reduce regional growing season surface temperatures by $\sim 1\text{--}3$ °C. Irrigation can ameliorate temperature extremes in some regions, but conversely exacerbates moist heat stress. Modelled precipitation responses are more varied, with some intensive cropping regions exhibiting suppressed local precipitation but enhanced precipitation downstream owing to atmospheric circulation interactions. Additionally, irrigation could enhance cropland carbon uptake; however, it can also contribute to elevated methane fluxes in rice systems and mobilize nitrogen loading to groundwater. Cross-disciplinary, integrative research efforts can help advance understanding of these irrigation–Earth system interactions, and identify and reduce uncertainties, biases and limitations.

Introduction. Irrigation is a critical component of land and water resource management, accounting for ~70% of freshwater withdrawals, that is, water abstracted from a ground or surface freshwater reservoir and conveyed to a place of use. Additionally, irrigation is responsible for 84–90% of annual global freshwater consumption (withdrawn water that is evaporated, transpired, incorporated into products or crops, or consumed by humans or livestock), or $\sim 1,200$ km³ of water, with ~ 545 km³ being sourced from groundwater. Irrigated fields cover ~20% (~ 3.5 million km²) of global croplands, and these areas produce ~40% of the world's food (according to the United Nations Food and Agriculture Organization (UN FAO)). Irrigation is also a complex driver of regional environmental change, which has consequences for process-based modelling. Although irrigated lands occupy only ~2.5% of global land area, irrigation drives groundwater depletion⁹, enhanced soil salinity and nutrient leaching in agricultural systems, among myriad other environmental impacts. Furthermore, rising irrigation demand has intensified water management over the twentieth century, partly driving increased construction of water reservoirs and diversions that also have downstream hydrological impacts. Applied irrigation water also impacts regional hydroclimates both locally, through feedbacks on temperature, humidity and precipitation, and remotely through complex interactions between altered temperature and moisture gradients and larger-scale processes such as atmospheric circulation and wave activity. These changes can even affect heat extremes in both agricultural and urban areas and biogeochemical cycling. Demand for irrigation will continue to rise throughout the twenty-first century, primarily for agriculture but increasingly for urban landscapes as well. These trends, alongside climate change-induced water disruptions, put pressure on existing irrigation water supplies and might drive some regions into water scarcity.

On the links between ice nucleation, cloud phase, and climate sensitivity in CESM2.

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Abstract. Ice nucleation in mixed-phase clouds has been identified as a critical factor in projections of future climate. Here we explore how this process influences climate sensitivity using the Community Earth System Model 2 (CESM2). We find that ice nucleation affects simulated cloud feedbacks over most regions and levels of the troposphere, not just extratropical low clouds. However, with present-day global mean cloud phase adjusted to replicate satellite retrievals, similar total cloud feedback is attained whether ice nucleation is simulated as aerosol-sensitive, insensitive, or absent. These model experiments all result in a strongly positive total cloud feedback, as in the default CESM2. A microphysics update from CESM1 to CESM2 had substantially weakened ice nucleation, due partly to a model issue. Our findings indicate that this update reduced global cloud phase bias, with CESM2's high climate sensitivity reflecting improved mixed-phase cloud representation.

Introduction. Mixed-phase clouds, which exist at temperatures where either liquid droplets or ice crystals may form (roughly -38°C – 0°C), are a major source of uncertainty in climate projections (Forster et al., 2021; Storelvmo et al., 2015). These clouds are governed by complex microphysical interactions between water's three thermodynamic phases (vapor, liquid, and ice) (Korolev et al., 2017). The importance of these processes has been brought to light by a number of studies (Frey & Kay, 2018; Tan & Storelvmo, 2016; Zhu et al., 2022) that uncovered major changes to projected climate after altering mixed-phase clouds in global simulations. These studies reported strong impacts on the global mean surface air temperature change that ultimately develops following a doubling of carbon dioxide in the atmosphere, a central metric in climate science known as equilibrium climate sensitivity (ECS).

The established link between mixed-phase clouds and ECS is the *cloud phase feedback* (Mitchell et al., 1989), wherein warming ice clouds reduce global climate change by deglaciating into liquid clouds. Since cloud droplets tend to be smaller than ice crystals, deglaciation results in more exposed surface area per unit mass (i.e., optically thicker clouds), hence more reflection of sunlight and reduced ECS. This negative feedback has been most associated with near-surface clouds at high latitudes, especially over the Southern Ocean. Climate model estimates of ECS have likely overestimated this feedback, implying underestimated global warming (Tan et al., 2016). This is linked to a deficiency of cloud liquid relative to total cloud condensate (supercooled liquid fraction, or SLF) in these models compared to satellite retrievals (Komurcu et al., 2014), leaving simulated clouds with excessive ability to deglaciade with warming. Effort to correct this bias has been proposed as a major reason that an unprecedented proportion of contemporary climate models have high ($>4.5^{\circ}\text{C}$) climate sensitivity (Zelinka et al., 2020).

Multiple realizations of microphysical processes may result in similar global mean SLF (Tan et al., 2016). It is unknown which microphysical processes most account for the present-day proportion of ice, and to what degree each process will affect ECS by responding to warming. New ice crystals may form within mixed-phase clouds, primarily through *immersion freezing*, whereby cloud droplets freeze with the aid of embedded aerosols acting as *ice nucleating particles* (INPs) (Kanji et al., 2017). Alternatively, ice crystals may fall from overlying cirrus or be detrained from deep convective cores. Once ice crystals are present in mixed-phase clouds, the crystals may grow by depleting surrounding liquid droplets via the Wegener-Bergeron-Findeisen (WBF) vapor deposition process (Storelvmo & Tan, 2015).

Connections between upper tropospheric and lower stratospheric circulation responses to increased CO₂.

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Abstract. There are myriad ways atmospheric circulation responds to increased CO₂. In the troposphere, the region of the tropical upwelling narrows, the Hadley cells expand, and the upper-level subtropical zonal winds that comprise the subtropical jet strengthen. In the stratosphere, the tropical upwelling narrows and strengthens, enhancing the Brewer–Dobson circulation. Despite the robustness of these projections, dynamical coupling between the features remains unclear. In this study, we analyze output from the NASA Goddard Institute for Space Studies (GISS) ModelE coupled climate model to examine any connection between the upper tropospheric and lower stratospheric circulation by considering the features’ seasonality, hemispheric asymmetry, scaling, and transient response to a broad range of CO₂ forcings. We find that a narrowing and strengthening of upper tropospheric upwelling occurs with a strengthening of the subtropical jet. There is also a narrowing and strengthening of lower stratospheric upwelling that is related to an equatorward shift in critical latitude for wave breaking and the associated strengthening of the subtropical lower stratosphere’s zonal winds. However, the stratospheric responses display different seasonal, hemispheric, and transient patterns than those in the troposphere, indicating independent circulation changes between the two domains.

Introduction. A wide range of changes in zonal-mean atmospheric circulation have been reported as a response to increased atmospheric CO₂. In the troposphere, this includes a widening of the Hadley cell (HC) ([Seidel et al. 2008](#); [Birner et al. 2014](#)), poleward shift of the eddy-driven jet (EDJ) ([Barnes and Polvani 2013](#); [Kushner et al. 2001](#)), strengthening and upward shift of the subtropical jet (STJ) ([Shaw and Tan 2018](#); [Singh and O’Gorman 2012](#)), and a narrowing of the intertropical convergence zone (ITCZ) ([Lau and Kim 2015](#); [Byrne et al. 2018](#)). Likewise, models show that the lower stratospheric circulation also responds to increased CO₂ with a narrowing and acceleration of the Brewer–Dobson circulation (BDC) ([Lin and Fu 2013](#); [Butchart et al. 2006](#); [Eichelberger and Hartmann 2005](#)).

However, there remains uncertainty in the mechanisms of these changes, and it is not well known how tightly coupled features are to one another. For example, there has been interest over the last decade in diagnosing tropical widening, but results are dependent on the metrics used to define tropical width ([Seidel et al. 2008](#); [Davis and Birner 2017](#)). It has recently been determined that the HC edge is strongly linked to eddy momentum flux convergence such that a poleward shift of the EDJ is associated with HC expansion ([Chemke and Polvani 2019](#); [Waugh et al. 2018](#)). In contrast, the strength of the STJ has a contradictory relationship with the HC edge. While a poleward HC is associated with a weaker STJ interannually, the STJ strengthens in response to CO₂ as the HC widens ([Menzel et al. 2019](#)). Yet, STJ behavior is still related to HC dynamics as the circulation’s poleward advection of angular momentum is an important contribution to STJ strength.

The uncertainty in coupling between different features is especially true between the troposphere and stratosphere. The acceleration of the BDC has been linked to the strengthening of the zonal winds in the subtropical upper troposphere and lower stratosphere (UTLS) via enhanced wave propagation ([Garcia and Randel 2008](#); [Shepherd and McLandress 2011](#)). One hypothesis arising from those studies is that the lower stratospheric upwelling inducing the BDC is impacted by the upper tropospheric upwelling through changes in the STJ. It is believed that in addition to the STJ’s coupling to the upper tropospheric upwelling through HC dynamics, it is also coupled to the BDC as an extension of the UTLS subtropical winds that moderate wave propagation into the lower stratosphere. [Li et al. \(2010\)](#) note a narrowing of the HC’s upwelling branch in the twenty-first century in addition to the enhanced lower stratospheric upwelling, and suggested changes in eddy forcing could be playing a role in both trends.

StratoFIRE: Modeling wildfire smoke in the stratosphere.

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Abstract. The most extreme manifestation of a fire–weather interaction is the formation of pyrocumulonimbus (pyroCb) thunderstorms, triggered by super-heated updrafts, which can eject smoke at altitudes exceeding 20 Km. In this study, we investigated climate-related impacts from the most intensive pyroCb-triggered injection of smoke in the stratosphere: the Australian New Year wildfires in 2019/2020. We first provide a general overview of the vision and objectives of the StratoFIRE project. With the aid of the global chemistry-climate model EMAC, we then simulate radiative and chemical perturbations in the stratosphere in relation to 0.9 Tg smoke in the stratosphere assuming different injection heights, from 13 to 16 Km. The simulation of stratospheric optical depth perturbations were found to be sensitive to the assumed injection height, with a maximum height at 16 Km showing the best agreement with the GLOSSAC and SAGE-ISS aerosol extinction observations.

Introduction. Large-scale wildfires have been making global headlines over the recent years, highlighting the importance of fire and its feedback within the Earth system. The most extreme manifestation of a fire–weather interaction is the formation of pyrocumulonimbus (pyroCb) clouds. PyroCbs are thunderstorm-like clouds developed by powerful wildfires under favorable meteorological conditions. Observations over the last years highlight that: (a) pyroCbs are surprisingly frequent in the mid-latitude summer, (b) pyroCbs can inject as much smoke, water, and reactive gases into the stratosphere as volcanic eruptions, (c) without fast removal in the stratosphere, the smoke flies high for months and spreads over the globe, and (d) a warming climate favors more frequent and severe smoke injections [1,2,3]. PyroCb firestorms have thus emerged as new semi-seasonal source of aerosols in the stratosphere. Smoke is largely composed of organic and black carbon, numerous reactive gases, and other aerosol precursors. Black carbon (BC) is of particular interest as it is the strongest absorber of shortwave light. Absorption by BC heats the plume causing shelf-lofting to higher altitudes, which prolongs the smoke lifetime and amplifies radiative and chemical perturbations [3,4]. The global and regional radiative effects and feedbacks associated with stratospheric smoke are uncertain, partly because smoke aging in the stratosphere is not well constrained. Apart from radiative perturbations, smoke may also accelerate ozone destruction via (a) heterogeneous chlorine chemistry, (b) moistened stratosphere and water vapor photolysis, (c) chlorine activation on polar stratospheric clouds (PSCs), and (d) changes in circulation [5]. These mechanisms are known from studies of volcanic aerosols, but their chemical reactivity might differ for smoke, given the different nature of smoke aerosols.

These recent developments call for a comprehensive characterization of the multi-faced role of smoke to the variability of the lower stratosphere and the global climate. StratoFIRE is aiming exactly at reducing some of those uncertainties. StratoFIRE is an ELIDEK project running from 2022 to 2025 to provide evidence that the lower stratosphere may act as a mediator connecting extreme wildfires, smoke, and global climate. In the three years of this project, we aim to (i) monitor stratospheric smoke with a variety of ground-based and space-borne instruments, with particular emphasis given to continuous measurements at the PANGAEA observatory (PANhellenic GEophysical Observatory of Antikythera), (ii) develop novel methodologies to infer emissions, optical properties and lifetime of smoke and quantify its corresponding radiative forcing, and (iii) apply this new information to global climate models to assess the climatic relevance of the stratospheric smoke intrusions.

The largest known stratospheric smoke injection was associated with the fierce Australian wildfires in the New Year of 2019/2020 (ANY hereafter). Many pyroCbs injected over 1 million tons of smoke particles into the stratosphere, reaching altitudes up to 35 Km. The mass and reach of this aerosol injection exceeded all volcanic aerosol injections over the last 30 years.

Non-monotonic feedback dependence under abrupt CO₂ forcing due to a North Atlantic pattern effect.

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Abstract. Effective climate sensitivity (EffCS), commonly estimated from model simulations with abrupt 4×CO₂ for 150 years, has been shown to depend on the CO₂ forcing level. To understand this dependency systematically, we performed a series of simulations with a range of abrupt CO₂ forcing in two climate models. Our results indicate that normalized EffCS values in these simulations are a non-monotonic function of the CO₂ forcing, decreasing between 3× and 4×CO₂ in CESM1-LE (2× and 3×CO₂ in GISS-E2.1-G) and increasing at higher CO₂ levels. The minimum EffCS value, caused by anomalously negative radiative feedbacks, arises mainly from sea-surface temperature (SST) relative cooling in the tropical and subtropical North Atlantic. This cooling is associated with the formation of the North Atlantic Warming Hole and Atlantic Meridional Overturning Circulation collapse under CO₂ forcing. Our findings imply that understanding changes in North Atlantic SST patterns is important for constraining near-future and equilibrium global warming.

Introduction. Equilibrium climate sensitivity (ECS), the equilibrium global-mean surface air temperature response to a doubling of atmospheric CO₂ relative to pre-industrial (PI) levels, is one of the most important metrics in climate science. The Charney 1979 report (Charney et al., [1979](#)) estimated a “likely” ECS range of 1.5–4.5K; most recently, a tighter range of ECS values between 2.6 and 3.9K was established using a Bayesian framework that combines multiple lines of evidence (Sherwood et al., [2020](#)).

When evaluated from climate models, ECS is often approximated with an effective climate sensitivity (EffCS), estimated from 150-year abrupt CO₂ quadrupling simulations within coupled global climate models (GCMs), with an underlying assumption that EffCS remains constant with different CO₂ doublings and over time. However, previous modeling (Bloch-Johnson et al., [2021](#); Mauritsen et al., [2019](#); Meraner et al., [2013](#); Mitevski et al., [2021](#); Sherwood et al., [2020](#); Zhu & Poulsen, [2020](#)) and paleoclimate studies (Anagnostou et al., [2016](#), [2020](#); Farnsworth et al., [2019](#); Friedrich et al., [2016](#); Shaffer et al., [2016](#); Zhu et al., [2019](#)) have shown that EffCS may not be linear with each successive CO₂ doubling. It tends to increase at higher CO₂ values primarily due to a nonlinear temperature dependence of the radiative feedbacks (λ), referred to as the state-dependence of feedbacks (Bloch-Johnson et al., [2021](#); Sherwood et al., [2015](#)), with minor contributions from nonlinear CO₂ dependence of radiative forcing (Mitevski et al., [2022](#)).

However, previous attempts to study the state dependence have been limited to CO₂-doubling scenarios (2×, 4×, 8×CO₂) (Good et al., [2016](#); Rugenstein et al., [2019](#)), whereas the shared socioeconomic pathway for the highest emission scenarios (SSP5-8.5) projects a transient increase of greenhouse gas forcing up to 8×CO₂ at the year 2300 (Meinshausen et al., [2020](#)) passing through all the intermediate states of $n\times\text{CO}_2$ ($n = 2, 3, 4, 5, 6, 7, 8$). Moreover, previous studies on state dependence have been focused on how EffCS and feedbacks vary in response to changes in global-mean temperatures under different CO₂ forcing (Bloch-Johnson et al., [2021](#); Caballero & Huber, [2013](#); Meraner et al., [2013](#)). Additionally, there has been enormous attention on the dependence of EffCS and feedbacks on the spatial patterns of surface warming (e.g., Andrews et al. ([2015](#)); Andrews et al. ([2022](#)); Zhou et al. ([2016](#)); Rugenstein et al. ([2016](#), [2020](#))). Here, we systematically examine the dependence of EffCS on the level of abrupt CO₂ forcing, as well as its connection to the spatial patterns of surface warming and climate feedbacks. To accomplish this, we conduct and analyze GCM experiments with a range of abrupt CO₂ forcings including 2×, 3×, 4×, 5×, 6×, 7×, and 8×CO₂ relative to PI level (hereafter denoted as abrupt $n\times\text{CO}_2$ experiments).

The CO₂ profile and analytical model for the Pioneer Venus Large Probe neutral mass spectrometer.

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Abstract. We present a significantly updated CO₂ altitude profile for Venus (64.2–0.9 km) and provide support for a potential deep lower atmospheric haze of particles (≤ 17 km). We extracted this information by developing a new analytical model for [mass spectra](#) obtained by the Pioneer Venus Large Probe (PVLVP) Neutral [Mass Spectrometer](#) (LNMS). Our model accounts for changes in LNMS configuration and output during descent and enables the disentanglement of isobaric species *via* a data fitting routine that adjusts for mass-dependent changes in peak shape. The model yields CO₂ in units of density (kg m^{-3}), [isotope ratios](#) for ¹³C/¹²C and ¹⁸O/¹⁶O, and 14 measures of CO₂ density across 55.4–0.9 km, which represents the most complete altitude profile for CO₂ at ≤ 60 km to date. The CO₂ density profile is also consistent with the pressure, temperature, and volumetric gas measurements from the PVLVP and VeNeRa spacecraft. Nominal and low-noise operations for the LNMS mass analyzer are supported by the behaviors (*e.g.*, ionization yields, fragmentation yields, and peak shapes) of several internal standards (*e.g.*, CH₃⁺, CH₄⁺, ⁴⁰Ar⁺, ¹³⁶Xe²⁺, and ¹³⁶Xe⁺), which were tracked across the descent. Lastly, our review of the CO₂ profile and LNMS spectra reveals hitherto unreported partial and rapidly clearing clogs of the inlet in the [lower atmosphere](#), along with several ensuing data spikes at multiple masses. Together, these observations suggest that atmospheric intake was impacted by particles at ≤ 17 km and that rapid particle degradation at the inlet yielded a temporary influx of mass signals into the LNMS.

Introduction. Venus is again emerging as an exciting target for planetary exploration with multiple upcoming missions including DAVINCI and VERITAS from NASA ([Garvin et al., 2022](#); [Smrekar et al., 2022](#)), EnVision from ESA ([Ghail, 2021](#)), Shukrayaan-1 from the Indian [Space Research](#) Organization (ISRO) ([Antonita et al., 2022](#); [Sundararajan, 2021](#)), and a potential orbiter mission from the China National Space Administration (CNSA). Likewise, [astrobiology](#) considerations for Venus have a gained substantial interest with the 2023–2032 Decadal Report highlighting that “Venus’ atmosphere has been suggested as a prospective abode for life” with a potential [habitable zone](#) in the middle clouds.

The clouds and lower atmosphere of Venus were initially studied by descent probes as part of the Pioneer Venus (1978), VeGa (1984), and VeNeRa (1961–1984) programs. The clouds and lower atmosphere are also subjects of the upcoming DAVINCI mission, which is scheduled to launch in 2029. Hence, in the projected ~ 45 years between launches to Venus, the roles of archival data analysis, remote observations, ground-based testing, and computational approaches remain as the drivers for Venus science today.

In this context, we present a new analysis and interpretation of the [mass spectra](#) obtained by the Pioneer Venus (PV) Large Probe Neutral Mass Spectrometer (LNMS), which descended through Venus’ atmosphere as an instrument on board the Pioneer Venus Large Probe (PVLVP) on December 9, 1978. Results from the LNMS were first reported in [Hoffman et al., 1979a](#), [Hoffman et al., 1979b](#), [Hoffman et al., 1979c](#), while the mixing ratios for major and minor [atmospheric gases](#) (based on ³⁶Ar), and the associated analytical strategies, were described in [Hoffman et al., 1979a](#), [Hoffman et al., 1979b](#), [Hoffman et al., 1979c](#) and [Hoffman et al. \(1980a\)](#). Design of the LNMS and selected control experiments were briefly described in [Hoffman et al., 1979a](#), [Hoffman et al., 1979b](#), [Hoffman et al., 1979c](#) and [Hoffman et al. \(1980b\)](#), while a majority of the associated engineering, pre-flight testing, and in-flight diagnostic information remain in restricted documents in the PV mission archive at the NASA Ames Research Center (ARC).

Deriving new mixing ratios for gases in Venus' atmosphere using data acquired by the Pioneer Venus Large Probe Neutral Mass Spectrometer.

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Abstract. We present the first published method to convert data obtained by the Pioneer Venus Large Probe Neutral Mass Spectrometer (LNMS) into units of mixing ratio (ppm) and volume percent (v%) against CO₂ and N₂, the dominant Venus atmospheric gases, including conversion to density (kg m⁻³). These unit conversions are key to unlocking the untapped potential of the data, which represents a significant challenge given the scant calibration data in the literature. Herein, we show that our data treatments and conversions yield mixing ratios and volume percent values for H₂O, N₂, and SO₂ that are within error to those reported for the gas chromatograph (LGC) on the Pioneer Venus Large Probe (PVLP). For the noble gases, we developed strategies to correct for instrument biases by treating the data as a relative scale and using PVLP and Venera-based measurements as calibration points. Together, these methods, conversions, calibrations, and comparisons afford novel unit conversions for the LNMS data and yield unified measures for Venus' atmosphere from the LNMS and LGC on the PVLP.

Introduction. We present a new methodological procedure to convert data obtained by the Pioneer Venus Large Probe Neutral Mass Spectrometer (LNMS) into units of atmospheric mixing ratio (ppm) and volume percent (v%) against CO₂ and N₂, the dominant Venus atmospheric gases, including conversion to density (kg m⁻³). These units were not published in the original LNMS investigations, which spanned 1979–1993 and described the instrument [1,2], initial results [3], [4], [5], and ensuing data analyses [6], [7], [8], [9]. Hence, our study represents a significant advance towards unlocking the untapped potential of the LNMS mass spectral data. For example, in Mogul *et al.* 2021 [10], we extracted novel chemical trends from the LNMS data that are suggestive of redox disequilibria within the cloud deck. In Mogul *et al.* 2023 [11], we extracted the most detailed altitude profile for CO₂, to date, and supported the potential presence of a near-surface particle haze layer. In this report, we detail means to enact the unit conversions to mixing ratio (ppm), volume percent (v%), and density (kg m⁻³), which represent significant challenges given the absence of detailed calibration data regarding ionization, ion transmission, and ion conductance rates in the LNMS.

The Large Probe Neutral Mass Spectrometer (LNMS) was a magnetic sector and electron ionization mass spectrometer onboard the NASA Pioneer Venus Large Probe (PVLP), which descended through Venus' atmosphere in 1978 [1,2,5]. Upon entry into Venus' atmosphere, the LNMS obtained a total of 56 spectra, which included 4 background spectra obtained just prior to atmospheric sampling (pre-sampling spectra; ~200–64 km), and 52 spectra obtained during atmospheric sampling between the altitudes of 64.2–0.2 km (descent profile). The LNMS operations also included a pre-programmed Isotope Ratio Measuring (IRM) sequence for noble gases, which involved the collection of atmospheric samples at ~62 km, scrubbing of the active gases, and analysis of the partly purified noble gases between ~48–45 km [1,5]. During sampling, electron ionizations were conducted at 70 eV (46 spectra) with additional pre-programmed ionizations at 30 eV (3 spectra) and 22 eV (3 spectra) during descent through the clouds (~54–53 km) and lower atmosphere (~30–28 and 9–8 km). Pre-sampling spectra were obtained at 70 eV. Positive ions produced from the respective electron ionizations were detected through use of separate low mass (m/z 1–16) and high mass (m/z 16–208) electron multiplier-counter channels¹, which afforded high sensitivity across a broad detectable mass range of m/z (1–208 u).

Uncertainty in land-use adaptation persists despite crop model projections showing lower impacts under high warming.

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Abstract. Climate change is expected to impact crop yields and alter resource availability. However, the understanding of the potential of agricultural land-use adaptation and its costs under climate warming is limited. Here, we use a global land system model to assess land-use-based adaptation and its cost under a set of crop model projections, including CO₂ fertilization, based on climate model outputs. In our simulations of a low-emissions scenario, the land system responds through slight changes in cropland area in 2100, with costs close to zero. For a high emissions scenario and impacts uncertainty, the response tends toward cropland area changes and investments in technology, with average adaptation costs between −1.5 and +19 US\$05 per ton of dry matter per year. Land-use adaptation can reduce adverse climate effects and use favorable changes, like local gains in crop yields. However, variance among high-emissions impact projections creates challenges for effective adaptation planning.

Introduction. The land system undergoes continuous adjustments due to the strong dependence of agricultural production on the long and short-term variability of climatic and socioeconomic conditions. However, the increasing greenhouse gas (GHG) concentrations are expected to generate unprecedented changes in average local temperatures, precipitation, and recurrence of extreme weather events¹, impacting biophysical factors relevant to crop production^{2,3,4}. Effective adaptation measures, in the form of adjustments to changing ecological and socioeconomic conditions, are therefore key to capitalize on possible opportunities effectively and minimize negative impacts^{5,6,7,8,9,10}.

Different measures at different system levels can ratchet up agricultural adaptation to climate change. On the farm scale, incremental adjustments in irrigation^{11,12}, the use of climate-resilient cultivars¹³, modifications in planting dates¹⁴, Nitrogen Input¹², and changes in other management practices can improve the resilience of the agroecosystem¹⁵. To further maximize the benefits of adaptation, a change of production patterns can be introduced at the land-use system scale in the form of transformations between land-use types (e.g., expansion of irrigated and rainfed cropland¹⁶) or a shift in crop types and cultivation zones within existing crop areas, investments in technological enhancements^{10,17}, and changes in trade flows¹⁸, among others. Due to the uneven spatial distribution of climate change impacts, a location-specific combination of these measures is required. Additionally, socioeconomic dynamics (e.g., capital allocation) play an essential role in decision-making since they determine relationships between the different levels of adaptation and could slow down the rate at which adjustments are adopted¹⁹.

Most global land system models intrinsically consider various autonomous adaptation measures and their overall effect on food prices, economic welfare, and costs. However, agro-economic climate change adaptation studies have mainly focused on the analysis of particular adaptation measures (e.g., trade^{20,21,22,23}, cropland expansion^{24,25,26}, and investments in research and development (R&D)²⁷).

The sensitivity of primary productivity in Disko Bay, a coastal Arctic ecosystem, to changes in freshwater discharge and sea ice cover.

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Abstract. The Greenland ice sheet is melting, and the rate of ice loss has increased 6-fold since the 1980s. At the same time, the Arctic sea ice extent is decreasing. Meltwater runoff and sea ice reduction both influence light and nutrient availability in the coastal ocean, with implications for the timing, distribution, and magnitude of phytoplankton production. However, the integrated effect of both glacial and sea ice melt is highly variable in time and space, making it challenging to quantify. In this study, we evaluate the relative importance of these processes for the primary productivity of Disko Bay, west Greenland, one of the most important areas for biodiversity and fisheries around Greenland. We use a high-resolution 3D coupled hydrodynamic–biogeochemical model for 2004–2018 validated against in situ observations and remote sensing products. The model-estimated net primary production (NPP) varied between 90–147 gC m⁻² yr⁻¹ during 2004–2018, a period with variable freshwater discharges and sea ice cover. NPP correlated negatively with sea ice cover and positively with freshwater discharge. Freshwater discharge had a strong local effect within ~ 25 km of the source-sustaining productive hot spots during summer. When considering the annual NPP at bay scale, sea ice cover was the most important controlling factor. In scenarios with no sea ice in spring, the model predicted a ~ 30 % increase in annual production compared to a situation with high sea ice cover. Our study indicates that decreasing ice cover and more freshwater discharge can work synergistically and will likely increase primary productivity of the coastal ocean around Greenland.

Introduction. The warming of the Arctic (Cohen et al., 2020) has a strong impact on the regional sea ice. Over the past few decades, the sea ice melt season has lengthened (Stroeve et al., 2014), summer extent has declined, and the ice is getting thinner (Meier et al., 2014). This has an immediate effect on the primary producers of the ocean. The photosynthetic production is constrained by the annual radiative cycle, and the sea ice reduces the availability of light and thereby the development of the sea ice algae and the pelagic phytoplankton communities (Ardyna et al., 2020). An extended open-water period will affect the phenology of primary producers and potentially lead to an earlier spring bloom (Ji et al., 2013; Leu et al., 2015) and may also increase the potential for autumn blooms (Ardyna et al., 2014). In the Arctic coastal ocean, there are additional impacts of a warming climate. As the freshwater discharge increases due to the melt of snow and ice on land and due to higher precipitation (Kjeldsen et al., 2015; Mankoff et al., 2020a, 2021), the land–ocean coupling along the extensive Arctic coastline is intensified (Hernes et al., 2021). The summer inflow of meltwater has complex biogeochemical impacts on the coastal ecosystem and combines with changes in sea ice cover to affect the magnitude and phenology of marine primary production. In areas dominated by glaciated catchments such as Greenland, the increase in meltwater discharge has been substantial, and the rate of ice mass loss has increased 6-fold since the 1980s (Mankoff et al., 2020b; Mouginot et al., 2019).

The changes in sea ice cover and freshwater discharge will affect the marine primary production through the complex interactions of changes in stratification, light, and nutrient availability (Arrigo and van Dijken, 2015; Hopwood et al., 2020). The individual processes are relatively well described, but the interactions between them and their temporal and spatial importance in relation to different Arctic physical regimes are less well understood. A lower extent of sea ice cover may also increase the wind-induced mixing of the water column and deepen or weaken the stratification. Therefore, the potential for the phytoplankton to stay and grow in the illuminated surface layer is reduced.

Global droughts connected by linkages between drought hubs.

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Abstract. Quantifying the spatial and interconnected structure of regional to continental scale droughts is one of the unsolved global hydrology problems, which is important for understanding the looming risk of mega-scale droughts and the resulting water and food scarcity and their cascading impact on the worldwide economy. Using a Complex Network analysis, this study explores the topological characteristics of global drought events based on the self-calibrated Palmer Drought Severity Index. Event Synchronization is used to measure the strength of association between the onset of droughts at different spatial locations within the time lag of 1-3 months. The network coefficients derived from the synchronization network indicate a highly heterogeneous connectivity structure underlying global drought events. Drought hotspot regions such as Southern Europe, Northeast Brazil, Australia, and Northwest USA behave as drought hubs that synchronize regionally and with other hubs at inter-continental or even inter-hemispheric scale. This observed affinity among drought hubs is equivalent to the ‘rich-club phenomenon’ in Network Theory, where ‘rich’ nodes (here, drought hubs) are tightly interconnected to form a club, implicating the possibility of simultaneous large-scale droughts over multiple continents.

Introduction. Droughts significantly impact water resources, agriculture, energy production, and a host of socio-economic activities¹. By far, droughts are among the costliest natural disasters². Compared to other hydroclimatic extremes, droughts occur at larger spatiotemporal scales^{3,4}, typically spreading over hundreds to thousands of kilometers and often lasting for months to years^{1,3}. The impact of drought on different sectors (e.g., water, energy, and agriculture) varies by region and continent depending on the adaptation strategies and resilience of the systems¹, leading to contrasting biophysical and social consequences⁵.

Recently, spatially compounding droughts have gained prominence due to their detrimental cascading impact on food, water, and energy security^{6,7,8}. Such mega-scale droughts ($>10^6$ km²) simultaneously occurring across multiple continents can trigger international food price hikes⁹, disruption of trade infrastructure, political instability^{9,10}, and even unsound human migration^{11,12}. The risk of such synchronous drought conditions across multiple kinds of wheat, maize, and soybean-producing regions has increased in the last four decades⁶. Furthermore, the projected increase in dry spell length and drought frequency¹³ may amplify the possibility of synchronous drought conditions over multiple croplands and pastures⁶. Climate change has already increased drought all over the globe^{13,14}. Therefore, understanding the global synchronization (or teleconnection) structure of drought events is critical to quantifying the likelihood of spatially compounding droughts under changing dynamic and thermodynamic conditions. Notably, understanding synchronous drought occurrences over several continents may be the key to regionalizing and quantifying the looming risks of simultaneous bread-basket failures in the future⁷.

Many studies have investigated the role of teleconnections and large-scale circulation in driving synchronous large-scale drought occurrences over different continents^{7,15,16,17,18}. For example, a few studies have considered the influence of individual climate modes on droughts at regional to continental scale⁷, focusing primarily on atmospheric teleconnections and how they may drive drought conditions. Studies analyzing droughts’ spatial and temporal structure typically use empirical orthogonal function (EOF) or coupled pattern analysis. However, EOFs and related methods lack the ability to explore the complexity of the higher-order statistical interrelationships in climatological data¹⁹, which is critically important to study the synchronization (teleconnection) of global drought events. Furthermore, previous studies have focused on specific objects, processes, or spatiotemporal scale²⁰, without explicit considerations of all possible interactions/dependencies (or covariates)²¹.

Temperature of the Villarrica lava lake from 1963 to 2015 constrained by phase-equilibrium and a new glass geothermometer for basaltic andesites.

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Abstract. Magma/lava temperature is one of the most basic and critical parameters in volcanology. Yet at many active volcanoes, including during eruptions, this parameter remains poorly constrained due to vent accessibility, with estimates from different geothermometers commonly varying by several tens to more than a hundred degrees. One such volcano is Villarrica, one of the most active and hazardous volcanoes in South America and whose crater hosts a persistent lava lake. Here, we use experimentally determined phase equilibria to constrain the temperature of the Villarrica lava lake. The experiments were all performed at ambient pressure (i.e. 0.1 MPa), ranged in temperature from 1000°C to 1250°C and in oxygen fugacity from QFM + 1 to QFM–1 (where QFM stands for the quartz-fayalite-magnetite redox buffer). Within the investigated range, fO_2 was found to have little to no effect on the phase equilibria and hence the lava lake fO_2 could not be constrained. The temperature range explored, however, did bracket the entire liquidus to solidus assemblage evolution. On the basis of these experiments, two empirical geothermometers calibrated strictly between 1050°C and 1200°C (i.e. not to be used outside this range) were developed for the Villarrica lava lake based on its matrix glass composition and modal proportion. The 2015 state of the natural system was experimentally reproduced at temperatures around 1141°C. In detail, the lava lake melt composition in the period 1963 to 2015 indicates a cooling trend from $1186 \pm 19^\circ\text{C}$ in 1963 to $1153 \pm 8^\circ\text{C}$ in 1999–2000 and $1149 \pm 28^\circ\text{C}$ in 2015. A generic glass geothermometer was also developed for any Basaltic Andesite composition from the compilation of 175 phase equilibria experiments giving the relation: $\text{elt Temperature } (^\circ\text{C}) = 12.43 \times \text{Al}_2\text{O}_3 + 10.73 \times \text{MgO} + 8.51 \times \text{CaO} + 591 \times (\text{Na}_2\text{O} + \text{K}_2\text{O})$ with all oxides in wt.% normalized. The geothermometers we have developed can be used to follow future temperature evolutions of the Villarrica lava lake or to estimate the lava temperature at any basaltic andesite eruption. Their application is simple, requiring only petrographic observations (to quantify the melt proportion) or analysis of the melt composition.

Introduction. With 40 observed eruptions between 1900 and 2022 (Smithsonian Global Volcanism Program), Villarrica is often considered Chile's most active volcano (e.g. [Petit-Breuilh, 1994](#); [Petit-Breuilh & Lobato, 1994](#); [Moreno, 1998](#); [Moreno & Clavero Ribes, 2006](#)). Located within the Central Southern Volcanic Zone of the southern Andes, Villarrica (39.42°S, 71.93°W; 2847 m a.s.l) shares with a handful of other active volcanoes on Earth, such as Erebus, Erta 'Ale, Nyiragongo, Masaya and Kilauea, the characteristic of hosting a persistently degassing lava lake in its crater. The lava lake has been active since 1985, its composition is basaltic to basaltic-andesite (e.g. [Witter et al., 2004](#); [Pizarro et al., 2019](#); [Boschetti et al., 2022](#)), its size and level varies widely (e.g. [Marzeki, 2010](#); [Goto & Johnson, 2011](#); [Richardson et al., 2014](#); [Johnson et al., 2018](#)), in January 2016 it had surface dimensions of 32 x 22 m and its surface was located ~140 m below the outer crater rim ([Moussallam et al., 2016](#)). The lava lake activity is characterized by continuous bubble bursting, occasionally perturbed by Strombolian eruptions and fountaining (e.g. [Calder et al., 2004](#); [Shinohara & Witter, 2005](#); [Gurioli et al., 2008](#); [Palma et al., 2008](#); [Moussallam et al., 2016](#); [Lehr & Rabbel, 2021](#)). In March 2015, an eruption at Villarrica produced a 1.5 km-high lava fountain, followed by a 6–8 km-high sustained eruptive column producing intense tephra fallout, agglutinate spatter flows, mixed (ice/snow and scoria) debris avalanches and a 20 km long lahar with a total volume of erupted tephra estimated at 1.4×10^9 kg with a mass eruption rate of 1.5×10^6 kg/s (e.g. [Bertin et al., 2015](#); [Johnson & Palma, 2015](#); [Rivadeneira & Palma, 2017](#); [Romero et al., 2018](#)).

Sucrose transport inside the phloem: Bridging hydrodynamics and geometric characteristics.

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Abstract. In plants, the delivery of the products of photosynthesis is achieved through a hydraulic system labeled as phloem. This semi-permeable plant tissue consists of living cells that contract and expand in response to fluid pressure and flow velocity fluctuations. The Münch pressure flow theory, which is based on osmosis providing the necessary pressure gradient to drive the mass flow of carbohydrates, is currently the most accepted model for such sucrose transport. When this hypothesis is combined with the conservation of fluid mass and momentum as well as sucrose mass, many simplifications must be invoked to mathematically close the problem and to resolve the flow. This study revisits such osmotically driven flows by developing a new two-dimensional numerical model in cylindrical coordinates for an elastic membrane and a concentration-dependent viscosity. It is demonstrated that the interaction between the hydrodynamic and externally supplied geometrical characteristic of the phloem has a significant effect on the front speed of sucrose transport. These results offer a novel perspective about the evolutionary adaptation of plant hydraulic traits to optimize phloem soluble compounds transport efficiency.

Introduction. The transport of soluble organic compounds within plants from production sites made during photosynthesis (i.e., leaves) to where sucrose consumption occurs (e.g., stems and roots) is receiving renewed attention in plant physiology, eco-hydrology, and earth systems models. The phloem provides the necessary pathway for this transport mechanism. Its structure and function have been conjectured to be optimized for efficient transport of photosynthates. The implications of efficient sucrose transport range from local impact on plant mortality under extreme weather conditions, such as drought,¹ to ecosystem-scale effects on carbon and water cycling because of the link between photosynthesis and sucrose transport.^{2,3} Many models for phloem transport and their possible deficiencies have been formulated and discussed.⁴⁻¹¹ The most accepted hypothesis of which most of these models rely on is the so-called pressure-flow hypothesis, commonly known as the Münch mechanism.⁴ In the pressure-flow hypothesis, the difference between the osmotic potential at the source and the sink leads to a pressure gradient along the phloem pathway necessary to drive the flow. The water reservoir needed for osmosis is provided by the xylem system, which is the other hydraulic network delivering water from roots to leaves under tension.¹²

Experimental challenges in measuring mass fluxes and pressure within the phloem^{13,14} have led to reliance on theoretical approaches to predict sucrose transport. However, due to geometrical and hydrodynamic complexities of the phloem tissues, many simplifications have been used to allow mathematical tractability.^{2,10,15} These simplifications have resulted in models that link the effects of a CO₂ enriched climate to plant growth^{3,16} and the effect of environmental factors on plant hydraulic failure.^{12,17-22} Nevertheless, such models remain silent on why measured leaf sugar concentrations are comparable to or even higher in shot crops than in tall trees.²³ Another critique is the presence of sieve plates throughout the phloem that appear to have no obvious advantage when viewed from the perspective of the Münch mechanism. Rather, the sieve plates seem to increase the flow resistance leading to increased pressure gradients to drive the flow that may not match the measured sugar concentrations in the leaves suggesting that phloem transport in tall trees is either a “miracle” or other mechanisms and adaptations are needed to compensate for the increased flow resistance.¹⁷

Toward a realistic representation of sucrose transport in the phloem of plants.

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Abstract. The significance of phloem hydrodynamics to plant mortality and survival, which impacts ecosystem-scale carbon and water cycling, is not in dispute. The phloem provides the conduits for products of photosynthesis to be transported to different parts of the plant for consumption or storage. The Münch pressure flow hypothesis (PFH) is the leading framework to mathematically represent this transport. It assumes that osmosis provides the necessary pressure differences to drive water and sucrose within the phloem. Mathematical models utilizing the PFH approximate the phloem by a relatively rigid slender semi-permeable tube. However, the phloem consists of living cells that contract and expand in response to pressure fluctuations. The effect of membrane elasticity on osmotically driven sucrose front speed has rarely been considered and frames the scope here. Laboratory experiments were conducted to elucidate the elastic-to-plastic pressure-deformation relation in membranes and their effect on sucrose front speeds. It is demonstrated that membrane elasticity acts to retard the sucrose front speed. The retardation emerges because of two effects: (a) part of the osmotic pressure is diverted to perform mechanical work to expand the membrane instead of pressurizing water, and (b) expansion of the membrane reduces the sucrose concentration driving osmotic potential due to volume increases and concomitant dilution effects. These results offer a novel perspective about the much-discussed presence of sieve plates throughout the phloem acting as structural expansion dampers.

Introduction. A variety of fluid transport phenomena in plants do not require active pumping or externally imposed pressure difference to move solutes and fluids. Instead, they rely on osmotic pressure, a passive transport process, to move loaded solutes and water simultaneously. A prototypical example is sucrose transport in the phloem of plants formulated in the 1930s by Ernst Münch and is now labeled as the pressure-flow hypothesis (Münch, 1930) or pressure flow hypothesis (PFH) (van Bel, 2003). The PFH is routinely used to describe the transport of photosynthates from production sites (leaves) to areas of consumption or storage (growing tissues and roots). This mechanism has been used to explain aspects of plant mortality under extreme weather conditions (Sevanto et al., 2014) and ecosystem-scale impacts on carbon and water cycling (Nikinmaa et al., 2013), which is why it continues to be a subject of active research in eco-hydrology (Fatichi et al., 2019; Hölttä et al., 2009; Huang et al., 2018; Konrad et al., 2018; Salmon et al., 2019).

Many models for phloem transport have been formulated and discussed (Cabrita et al., 2013; Jensen et al., 2009; Nakad et al., 2021, 2022b; Phillips & Dungan, 1993; Sevanto, 2014; Thompson & Holbrook, 2003). One of the simplifications used in these models is that phloem is presented as a long cylindrical and relatively rigid slender tube with semi-permeable walls that enable water but not sugar to be exchanged between the tube and its surroundings (xylem). Since the phloem (e.g., sieve cells in gymnosperms, sieve tube members in angiosperms and parenchyma cells) is composed of living cells that are not lignified (Sevanto et al., 2018), the rigid tube assumption may not be appropriate. Tube wall rigidity can impact sucrose transport rates through a number of mechanisms that remain to be uncovered (Tateshima et al., 2010). One latent mechanism is the dilution effect. Membrane expansion and consequent tube volume increase decreases the osmotic potential (i.e., the main driving mechanism) by volumetrically increasing water storage within the tube without altering the number of sugar molecules. In case of a rigid (or weakly elastic) tube, any inflow of water is balanced by an equivalent outflow of water (due to conservation of water mass) leading to a negligible water storage within the tube and thus no dilution effects. Prior mathematical models estimated the impact of tube wall rigidity by assuming that volume expansion linearly relates to hydrostatic pressure within the phloem (Thompson & Holbrook, 2003). The model calculations suggest that when using typical values for the phloem's Young modulus of elasticity, phloem elasticity had minimal impact on transport timescale.

Linking the water and carbon economies of plants in a drying and warming climate.

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Abstract. Harsher abiotic conditions are projected for many woodland areas, especially in already arid and semi-arid climates such as the Southwestern USA. Stomatal regulation of their aperture is one of the ways plants cope with drought. Interestingly, the dominant species in the Southwest USA, like in many other ecosystems, have different stomatal behaviors to regulate water loss ranging from isohydric (e.g., piñon pine) to anisohydric (e.g., juniper) conditions suggesting a possible niche separation or different but comparable strategies of coping with stress. The relatively isohydric piñon pine is usually presumed to be more sensitive to drought or less desiccation tolerant compared to the anisohydric juniper although both species close their stomata under drought to avoid hydraulic failure, and the mortality of one species (mostly piñon) over the other in the recent droughts can be attributed to insect outbreaks rather than drought sensitivity alone. Furthermore, no clear evidence exists demonstrating that iso- or anisohydric strategy increases water use efficiency over the other consistently. How these different stomatal regulatory tactics enable woody species to withstand harsh abiotic conditions remains a subject of inquiry to be covered in this review.

Introduction. Climate change is expected to increase the frequency and severity of both drought and heatwaves, especially in the temperate, semi-arid, and arid zones. Shifts in plant functioning and in turn in the tree and ecosystem-level water, carbon, and energy balances in association with drought and Sanna Sevanto and Jean-global biomes [1, 2]. As the climate warms, the evaporative demand will increase due to a higher vapor pressure deficit, leading to a greater loss of water from the soil and vegetation [3, 4], which will make these regions even more susceptible to drought. The fate of the current vegetation in these areas will depend on the ability of the species to tolerate and adapt to unprecedented conditions where higher temperatures leading to increased evaporative demand and “atmospheric drought” will coincide with a lack of precipitation and more frequent and severe “soil drought.” Generally, plants can adapt to new environments both structurally and functionally. Structural adaptations, such as increased root growth to improve access to water and development of different leaf forms [5] and surface structures such as smooth or seriated leaves bearing waxy cuticles in conifers [6], or thick and hairy leaves with trichomes in angiosperms [7] to conserve water or reflect excess sunlight or reduction in xylem conduit diameter [8–10] as a response to increased solar irradiation and drought occur at time scales of years to decades [11]. Functional acclimation, such as biochemical changes in leaves to reduce photodamage under increased irradiation, on the other hand, can occur at time scales of several hours to days [12]. While adaptation and acclimation both contribute to plant survival in unprecedented conditions, the severity and time scale at which environmental changes occur will determine what amount of plasticity and at what time scale is required for survival.

Stomatal control of water loss is one of the main ways plants use to protect themselves from environmental stress such as drought. While stomatal closure is an effective mechanism to conserve water during drought, it comes with a cost of loss in photosynthetic productivity as stomatal closure prevents both exit of water vapor and entry of CO₂ for photosynthesis. This coupling of exit of water vapor and entry of CO₂ at stomatal level is the basis for the carbon-water economy coupling in plants. Different types of plants are known to vary in the sensitivity of stomatal conductance g to drought (soil drought) and heat (atmospheric drought) with consequences for their survival and growth [13]. Due to the rapid changes in leaf-to-air vapor pressure deficit, one of the key regulatory roles played by stomata is to limit transpiration induced leaf water deficit.

Cloud and precipitation in low-latitude extratropical cyclones conditionally sorted on CYGNSS surface latent and sensible heat fluxes.

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Abstract. Extratropical cyclones are the primary cause of midlatitude winds, precipitation, and clouds. Surface latent and sensible heat fluxes from the ocean impact cyclone intensity, but their role in moisture transport leading to cloud and precipitation is still under investigation. While numerical simulations can help establish such links, evaluating and constraining these simulations require observations. To this end, satellite-based observations of cloud and precipitation in low-latitude extratropical cyclones are examined for four distinct classifications based on the Cyclone Global Navigation Satellite System (CYGNSS) latent and sensible heat fluxes, averaged in the post-cold-frontal or warm-sector areas of the cyclones. Using a cyclone compositing approach, contrasts in cloud and precipitation in strong- versus weak-surface-flux conditions are examined. In the post-cold-frontal region, stronger latent or sensible heat fluxes are associated with lower precipitation rates and higher cloud opacity, indicating more vigorous shallow convection. However, larger sensible heat flux cases display larger cloud fraction, while larger latent heat flux cases exhibit lower cloud fraction, which could indicate differing cloud morphologies. In the comma region of the cyclones, clouds and precipitation depend on both cyclone strength and moisture availability. Consistent with this, larger cloud amount and precipitation are found for strong fluxes in the post-cold-frontal region, and weak or negative sensible heat fluxes, indicative of poleward warm advection, in the warm sector. The strong regional differences in the surface heat flux–cloud and precipitation relationships highlight the need for further investigation into moisture supply and transport in cyclones, while providing guidance for future work.

Introduction. In the midlatitude ocean regions, extratropical cyclones play an important role for the poleward transfer of heat and moisture, the production of precipitation and clouds, and the planet’s radiative balance (e.g., [Tselioudis et al. 2000](#)). The moist processes, such as latent heating within the cyclone warm sector, are themselves dependent on the energy exchange between the ocean and the atmosphere (e.g., [Booth et al. 2012](#)). As such, surface latent and sensible heat fluxes are important for the genesis of extratropical cyclones (e.g., [Mak 1998](#)), their development (e.g., [Kuo et al. 1991](#)), and their intensification (e.g., [Hirata et al. 2019](#); [Tsopouridis et al. 2021](#)). Most of the previous work that has aimed to understand the role of the surface fluxes on cyclone intensification has used numerical models to separate the effect the cyclone itself has on the fluxes from the effect the fluxes have on the cyclone (e.g., [Kuo et al. 1991](#); [Booth et al. 2012](#); [Haualand and Spengler 2020](#)). These experiments, however, have some limitations: they can only be performed for a small number of cases or for a specific region, and have to rely on how well the model represents various aspects of the atmosphere and, more specifically, moist processes. Therefore, an observational benchmark to evaluate simulations that is focused on the interplay between surface heat fluxes, cyclone strength, and precipitation (e.g., [Demirdjian et al. 2022](#)) would be useful.

Satellite observations have proven to be a reliable tool for characterizing cloud or precipitation in cyclones. Satellite-based surface heat flux products are also being developed, which, together, allow a large-scale, large-sample-size, long-term examination of the relationships between moist variables and surface fluxes in cyclones. Unlike with models, it is not possible to determine how the surface heat fluxes are directly interacting with the precipitation and cloud processes within cyclones. However, it is possible to analyze relationships from a purely observational standpoint and contrast them with conclusions drawn from controlled simulations.

Automated identification of occluded sectors in midlatitude cyclones: Method and some climatological applications.

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Abstract. A novel automated scheme for identifying occluded mid-latitude cyclones from gridded datasets is described and employed to construct a limited climatology of such storms as well as composites of their thermodynamic and kinematic structures. The climatology (2006–2017) is derived from the MERRA-2 reanalysis and reveals differences in the distribution of occlusions between the hemispheres. Northern Hemisphere occlusions are most frequent in winter (DJF) and are found poleward of the mean tropopause-level jets in both the Atlantic and Pacific basins. In the Southern Hemisphere, however, occlusions are most frequent during autumn (MAM) and are almost never found equatorward of 40°S. Using the identification scheme, wintertime occlusions are stratified based upon the value of 700 hPa θ_e (equivalent potential temperature) in their characteristic thickness ridges. Composites of six groups of occlusions, based upon this distinction, are constructed for each hemisphere. The composites reveal notable differences in the thermodynamic structures among these six groups with more poleward (lower θ_e or “colder”) storms exhibiting shallower, less developed thermal structures as compared to their lower-latitude (higher θ_e or “warmer”) counterparts. These differences are attended by contrasts in the intensity of upward vertical motions in the occluded sectors of the various composite storms implying that “warm” storms are associated with greater latent heat release than “colder” storms. It is suggested that these coincident differences between “cold” and “warm” storms provide further evidence of the fundamental importance of latent heat release to the development of occluded thermal structures.

Introduction. In their conceptual model of the mid-latitude cyclone, Bjerknes and Solberg (1922) were the first to suggest a relationship between the three-dimensional (3D) thermal structure of the storm and its associated distribution of clouds and precipitation. The model, which has come to be known as the Norwegian Cyclone Model (NCM), described how the amplification of the nascent cyclone distorted the polar front, the globe-girdling boundary separating polar air to the north from the tropical air to the south into the cold and warm fronts of the storm structure. The so-called warm sector, a region of homogeneously warm air between the two fronts, extended downward to the surface. The thermal evolution of such cyclones involves changes in both the vigor of the individual frontal zones and in their orientation with respect to one another. The dynamical processes that control this evolution are also responsible for producing the secondary circulations to which the characteristic cloud and precipitation distribution in cyclones – linear bands of varying widths along the cold and warm fronts and a cloud head poleward and westward of the storm center – can be accurately attributed.

Namias (1939) was among the first to examine the 3D airflow through cyclones and relate it to the attendant distribution of clouds and precipitation. He identified an ascending airstream, originating in the warm-sector boundary layer, that bifurcated into two separate streams – one turning cyclonically to the west and the other turning anticyclonically to the east. More recent studies by Browning and Harrold (1969), Harrold (1973), Carlson (1980), Young *et al.* (1987) and Browning (1990) have christened the latter as the warm conveyor belt. This feature has garnered considerable research attention in the ensuing 30 years (e.g., Berman and Torn, 2019; Eckhardt *et al.*, 2004; Madonna *et al.*, 2014; Martínez-Alvarado *et al.*, 2014; Schäfler and Harnisch, 2015; Wernli and Davies, 1997; Wernli, 1997). The cyclonically turning airstream has also been noted by Atkinson and Smithson (1974) as well as Iskenderian (1988), Kurz (1988), Mass and Schultz (1993), Schultz and Mass (1993) and Reed *et al.* (1994).

Dominant cloud controlling factors for low-level cloud fraction: Subtropical versus extratropical oceans.

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Abstract. To improve cloud feedback understanding and simulation, observations have been used to quantify the rate of change of cloud radiative properties as a function of specific environmental metrics (or cloud controlling factors; CCFs). The study focuses on low-level cloud dominated regions during 2006–2010. For each ocean gridpoint, Spearman's rank correlation coefficients of daily mean observed cloud fraction versus (a) 10-m wind, (b) sensible heat flux (SHF), (c) sea surface temperature, (d) estimated inversion strength (EIS), (e) 850 hPa vertical velocity, and (f) the M parameter ($\Delta\theta_{\text{skin}}^{800\text{hPa}}$) are sorted to identify the dominant CCFs in both extratropics (30°–60°N/S) and subtropics (30°S–30°N). A novel map for visualizing dominant CCFs for low-level cloud fraction reveals that: $\Delta\theta_{\text{skin}}^{800\text{hPa}}$ dominates in the subtropical stratocumulus regions while 10-m winds dominate in shallow cumulus regions but in the extratropics, a different inversion structure diagnostic (EIS) dominates, while SHF dominates in western boundary current areas.

Introduction. Low-level clouds are ubiquitous (Mace et al., 2009) and reflect solar radiation (Figure 1), thus collectively they play an important role in Earth's radiation balance (Sherwood et al., 2020, and references therein). Because these clouds are notoriously difficult to accurately represent in general circulation models, it remains difficult to estimate the extent of their feedback effect (Brient & Schneider, 2016; Zelinka et al., 2020). One workaround has been proposed by estimating the change in these cloud properties given a change in some salient environmental metrics or “cloud controlling factors” (CCFs; Stevens & Brenguier, 2009). With this approach, observations can be used to quantify the sensitivity of low cloud properties to metrics that are physically known to matter for clouds (Cesana & Del Genio, 2021; Scott et al., 2020). While an exhaustive examination of such metrics for tropical clouds was conducted by Klein et al. (2017), it is unclear at present whether the same metrics and relationships still hold in the dynamically different extratropics (30°–60° N/S). As illustrated in Figure 1, low-level clouds are found in the wake of extratropical cyclones, where the dynamical conditions are different from what typically occurs in the tropical oceans.

To address this gap in knowledge, we examine the relationship between global, gridded, daily mean satellite-based cloud fraction and a number of environmental metrics. The initial environmental metrics chosen for their potential impact on cloud fraction, and their established use in the literature, are:

1. Sea surface temperature (SST): as described in Klein et al. (2017) and references therein, an increase in SST leads to an upward expansion and warming of the boundary layer, which works to hinder both cloud formation and persistence, leading to a decrease in cloud fraction.
2. Estimate Inversion Strength (EIS; Wood & Bretherton, 2006): this parameter was introduced as a means to characterize the strength of the inversion at the top of the boundary layer using coarse resolution fields. By definition, it is a function of the potential temperature (θ) contrast between 700 hPa and the surface but corrected for the effect of the moist adiabat above the lifting condensation level. Its expression is:

$$\text{EIS} = \theta_{700\text{hPa}} - \theta_{\text{surf}} - \Gamma_m^{850\text{hPa}}(Z_{700} - \text{LCL})$$

A cloud detection neural network for above-aircraft clouds using airborne cameras.

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Abstract. For aerosol, cloud, land, and ocean remote sensing, the development of accurate cloud detection methods, or cloud masks, is extremely important. For airborne passive remote sensing, it is also important to identify when clouds are above the aircraft since their presence contaminates the measurements of nadir-viewing passive sensors. We describe the development of a camera-based approach to detecting clouds above the aircraft *via* a convolutional neural network called the cloud detection neural network (CDNN). We quantify the performance of this CDNN using human-labeled validation data where we report 96% accuracy in detecting clouds in testing datasets for both zenith viewing and forward-viewing models. We present results from the CDNN based on airborne imagery from the NASA Aerosol Cloud meteorology Interactions oVer the western Atlantic Experiment (ACTIVATE) and the Clouds, Aerosol, and Monsoon Processes Philippines Experiment (CAMP2Ex). We quantify the ability of the CDNN to identify the presence of clouds above the aircraft using a forward-looking camera mounted inside the aircraft cockpit compared to the use of an all-sky upward-looking camera that is mounted outside the fuselage on top of the aircraft. We assess our performance by comparing the flight-averaged cloud fraction of zenith and forward CDNN retrievals with that of the prototype hyperspectral total-diffuse Sunshine Pyranometer (SPN-S) instrument's cloud optical depth data. A comparison of the CDNN with the SPN-S on time-specific intervals resulted in 93% accuracy for the zenith viewing CDNN and 84% for the forward-viewing CDNN. The comparison of the CDNNs with the SPN-S on flight-averaged cloud fraction resulted in an agreement of .15 for the forward CDNN and .07 for the zenith CDNN. For CAMP2Ex, 53% of flight dates had above-aircraft cloud fraction above 50%, while for ACTIVATE, 52% and 54% of flight dates observed above-aircraft cloud fraction above 50% for 2020 and 2021, respectively. The CDNN enables cost-effective detection of clouds above the aircraft using an inexpensive camera installed in the cockpit for airborne science research flights where there are no dedicated upward-looking instruments for cloud detection, the installation of which requires time-consuming and expensive aircraft modifications, in addition to added mission cost and complexity of operating additional instruments.

Introduction. For passive remote sensing of aerosols from aircraft, the importance of detecting and masking for clouds below the aircraft is well-known, but the impact of high-level clouds above the aircraft is often ignored. In fact, above-aircraft cloud contamination by thin cirrus or supercooled liquid water clouds can significantly impact aerosol optical and microphysical property retrievals ([Stamnes et al., 2018](#)). For airborne passive remote sensing of aerosol, cloud, and surface properties, it is critical to carry instruments on the aircraft that can detect the presence of above-aircraft clouds. A recent study reveals that below-cloud aerosols share properties similar to those without overlying clouds, but the large fraction of below-cloud aerosols indicates a likely significant impact of above-aircraft cirrus on the aerosol direct radiative effect. This significant impact is due to 50% of the total aerosols being located below thin-cirrus clouds ([Hong and Di Girolamo, 2022](#)). Our paper studies the possibilities of detecting such above-aircraft clouds from upward-looking cameras mounted in the cockpit and on top of the aircraft by processing the images using convolutional neural networks.

The extreme 2016 wheat yield failure in France.

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Abstract. France suffered, in 2016, the most extreme wheat yield decline in recent history, with some districts losing 55% yield. To attribute causes, we combined the largest coherent detailed wheat field experimental dataset with statistical and crop model techniques, climate information, and yield physiology. The 2016 yield was composed of up to 40% fewer grains that were up to 30% lighter than expected across eight research stations in France. The flowering stage was affected by prolonged cloud cover and heavy rainfall when 31% of the loss in grain yield was incurred from reduced solar radiation and 19% from floret damage. Grain filling was also affected as 26% of grain yield loss was caused by soil anoxia, 11% by fungal foliar diseases, and 10% by ear blight. Compounding climate effects caused the extreme yield decline. The likelihood of these compound factors recurring under future climate change is estimated to change with a higher frequency of extremely low wheat yields.

Introduction. The production of wheat, the most important source of food for humans (Igrejas & Branlard, [2020](#)), is increasingly variable due to climatic extremes, which threatens to disrupt global efforts toward abolishing poverty and ensuring food security and peace (Nóia Júnior et al., [2021](#); Perez, [2013](#); Shew et al., [2020](#)). Europe is responsible for 35% of global wheat production (FAO stat, [2022](#)). Drought and heatwaves are the main causes of the historical crop failures widespread across the breadbasket regions of the continent, as experienced by northern European countries in 2018 (Beillouin et al., [2020](#); Webber et al., [2020](#)). Such adverse weather conditions will become more pronounced and widespread with climate change (Battisti & Naylor, [2009](#); IPCC, [2021](#); Trnka et al., [2014](#)). For example, in 2010, Russia suffered from the worst heatwave on record according to the Warm Spell Duration Index (Hoag, [2014](#)). Initial attempts have been made to identify the future risk posed by heat and drought to local agriculture (Bailey et al., [2015](#); Rosenzweig et al., [2013](#)). Several wheat crop modeling approaches have been developed and improved to estimate wheat yield responses to extreme weather conditions (Ceglar et al., [2019](#); Jägermeyr et al., [2021](#); Lischeid et al., [2022](#); Martre et al., [2015](#); Rötter et al., [2018](#); Wang et al., [2017](#); Webber et al., [2017](#)). These studies have helped to identify future regional risks to national and global wheat production directly caused by extreme weather disasters (Asseng et al., [2011](#); Liu et al., [2019](#); Webber et al., [2018](#)), and have been incorporated into wheat yield forecast systems to anticipate seasonal food shortages (Bussay et al., [2015](#); Lecerf et al., [2019](#); van der Velde & Nisini, [2019](#)).

A major wheat production decline occurred in 2016 in Western Europe, centered around France, the fourth largest wheat-exporting country in the world (Ben-Ari et al., [2018](#)). The national wheat yield of France dropped by 27% in 2016. This was the most extreme wheat yield decline in France since 1960 causing a shortfall of about 2.3 billion USD in the country's trade balance (Ben-Ari et al., [2018](#)). The public European forecasting system failed to anticipate the magnitude of this wheat yield loss until shortly before harvest (van der Velde et al., [2020](#)), which has been explained by the complexity (sequence, timing, or connectedness) of likely yield-determining events in 2016. Indeed, the 2016 yield failure was not caused by a single event. Winter wheat usually remains dormant during the cold of winter, flowering in the drier, warmer spring weather. However, the combination of a warm, wet winter and an extended period of precipitation in the spring of 2016 led to a number of simultaneous or consecutive yield-reducing factors, including heavy rainfall, crop diseases, low solar radiation, and anoxia, affecting both grain set and grain filling (Ben-Ari et al., [2018](#)). Temporal and multivariate compound events (Bevacqua et al., [2021](#); Zscheischler et al., [2020](#)) caused the extreme 2016 wheat yield failure. Most crop modeling approaches only consider seasonal water shortage and heat stress, thus neglecting the connected or compound nature of many extreme climate- (Lischeid et al., [2022](#); Raymond et al., [2020](#)) and weather-related events on crop growth and development.

Venus, the planet: Introduction to the evolution of Earth's sister planet.

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Abstract. Venus is the planet in the Solar System most similar to Earth in terms of size and (probably) bulk composition. Until the mid-20th century, scientists thought that Venus was a verdant world—inspiring science-fictional stories of heroes battling megafauna in sprawling jungles. At the start of the Space Age, people learned that Venus actually has a hellish surface, baked by the greenhouse effect under a thick, CO₂-rich atmosphere. In popular culture, Venus was demoted from a jungly playground to (at best) a metaphor for the redemptive potential of extreme adversity. However, whether Venus was much different in the past than it is today remains unknown. In this review, we show how now-popular models for the evolution of Venus mirror how the scientific understanding of modern Venus has changed over time. Billions of years ago, Venus could have had a clement surface with water oceans. Venus perhaps then underwent at least one dramatic transition in atmospheric, surface, and interior conditions before present day. This review kicks off a topical collection about all aspects of Venus's evolution and how understanding Venus can teach us about other planets, including exoplanets. Here we provide the general background and motivation required to delve into the other manuscripts in this collection. Finally, we discuss how our ignorance about the evolution of Venus motivated the prioritization of new spacecraft missions that will rediscover Earth's nearest planetary neighbor—beginning a new age of Venus exploration.

Introduction. Venus is so hot right now. Literally, its massive, CO₂-rich atmosphere creates a greenhouse effect that makes its surface the hottest in the Solar System on average. Figuratively, Venus is heating up in popularity following recent announcements that NASA and the European Space Agency (ESA) will send three new missions to Earth's sister planet. These capable missions—VERITAS, DAVINCI, and EnVision—will help end a thirty-year drought when visits to Venus were rare—a historical anomaly. Overall, more than forty missions have been launched with Venus on their itinerary (e.g., Taylor et al. [2018](#))—virtually the same total number that have been sent towards Mars. However, the last NASA-led mission to Venus (Magellan) death-spiraled into the atmosphere in 1994 after finishing its successful radar mapping campaign. Since then, Venus has been relatively lonely, hosting only three flybys (MESSENGER, Galileo, and Cassini) and two orbiters (Venus Express and Akatsuki, which is still operating as of 2023). In the last three decades, spacecraft data from Venus helped illuminate the workings of its modern atmosphere and hinted at its past. New missions will let us better address the profound question: How has Venus evolved over time?

Scientists can tell an alluring story about the evolution of Venus that is impossible to prove or disprove using available data (Fig. [1](#)). According to this “habitable hypothesis,” a time traveler could visit two clement worlds with oceans early in the Solar System's history. Venus and Earth likely accreted with similar bulk inventories of volatiles (e.g., Chambers [2001](#); Rubie et al. [2015](#)). Both planets were probably born hot with a steam atmosphere above a magma ocean (e.g., Matsui and Abe [1986](#); Zahnle et al. [1988](#); Elkins-Tanton [2008](#)). If Venus shed more heat to space than it absorbed from the Sun, then its magma ocean could solidify within ~10 Myr while its atmosphere cooled enough for the remaining steam to condense onto the surface (e.g., Hamano et al. [2013](#)). Clouds on the dayside of Venus may have kept surface temperatures Earth-like even as the Sun brightened over time (e.g., Yang et al. [2014](#); Way et al. [2016](#); Way and Del Genio [2020](#)). Eventually, perhaps as recently as half a billion years ago, increasing solar input and huge amounts of volcanism caused a climatic catastrophe that led to the current, caustic conditions (e.g., Strom et al. [1994](#); Weller and Kiefer [2020](#); Krissansen-Totton et al. [2021](#); Way et al. [2022a](#)).



Atmospheric response to a collapse of the North Atlantic circulation under a mid-range future climate scenario: A regime shift in Northern Hemisphere dynamics.

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Abstract. Climate models project a future weakening of the Atlantic meridional overturning circulation (AMOC), but the impacts of this weakening on climate remain highly uncertain. A key challenge in quantifying the impact of an AMOC decline is in isolating its influence on climate, relative to other changes associated with increased greenhouse gases. Here we isolate the climate impacts of a weakened AMOC in the broader context of a warming climate using a unique ensemble of Shared Socioeconomic Pathway (SSP) 2–4.5 integrations that was performed using the Climate Model Intercomparison Project phase 6 (CMIP6) version of the NASA Goddard Institute for Space Studies ModelE (E2.1). In these runs internal variability alone results in a spontaneous bifurcation of the ocean flow, wherein 2 out of 10 ensemble members exhibit an entire AMOC collapse, while the other 8 members recover at various stages despite identical forcing of each ensemble member and with no externally prescribed freshwater perturbation. We show that an AMOC collapse results in an abrupt northward shift and strengthening of the Northern Hemisphere (NH) Hadley cell (HC) and intensification of the northern midlatitude eddy-driven jet. We then use a set of coupled atmosphere–ocean abrupt CO₂ experiments spanning the range 1 times to 5 times CO₂ (1x to 5xCO₂) to show that this response to an AMOC collapse results in a nonlinear shift in the NH circulation moving from 2xCO₂ to 3xCO₂. Slab-ocean versions of these experiments, by comparison, do not capture this nonlinear behavior. Our results suggest that changes in ocean heat flux convergences associated with an AMOC collapse—while highly uncertain—can result in profound changes in the NH circulation and continued efforts to constrain the AMOC response to future climate change are needed.

Introduction. Future projections of the atmospheric circulation remain highly uncertain and reflect uncertainties in the direct radiative response to CO₂ forcing (Deser and Phillips 2009; Grise and Polvani 2014; Shaw and Voigt 2015; Cessi et al. 2018), as well as both the (direct) response to changes in sea surface temperatures (SSTs) and the (indirect) response to changes in eddy feedbacks (see Shepherd 2014 and references therein). Uncertainties in SST projections over the subpolar North Atlantic are particularly consequential, as they strongly influence the location and strength of the North Atlantic storm track, with profound downstream impacts on precipitation and wintertime weather over Europe and parts of Africa (e.g., Zhang and Delworth 2006; Smith et al. 2010; Woollings et al. 2012; O'Reilly et al. 2016). In particular, while increases in greenhouse gases over the twenty-first century are expected to result in substantial warming over much of the North Atlantic, climate models project considerable cooling over midlatitudes resulting in a so-called North Atlantic warming hole (NAWH) (e.g., Josey et al. 2018; Driethout et al. 2012; Robson et al. 2016; Caesar et al. 2018). While the drivers of this NAWH have been under considerable debate, recent detection–attribution analysis suggests that the anthropogenic signal of the NAWH has emerged from internal climate variability and, moreover, that this cooling can be attributed to declining northward oceanic heat flux over recent decades related to increased greenhouse gas emissions (Chemke et al. 2022).

Trends and seasonal variability in ammonia across major biomes in western and central Africa inferred from long-term series of ground-based and satellite measurements.

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Abstract. Ammonia (NH₃) is the most abundant alkaline component in the atmosphere. Changes in NH₃ concentrations have important implications for atmospheric chemistry, air quality, and ecosystem integrity. We present a long-term ammonia (NH₃) assessment in the western and central African regions within the framework of the International Network to study Deposition and Atmospheric chemistry in Africa (INDAAF) programme. We analyse seasonal variations and trends in NH₃ concentrations and total column densities along an African ecosystem transect spanning dry savannas in Banizoumbou, Niger, and Katibougou, Mali; wet savannas in Djougou, Benin, and Lamto, Côte d'Ivoire; and forests in Bomassa, Republic of the Congo, and Zoétélé, Cameroon. We use a 21-year record of observations (1998–2018) from INDAAF passive samplers and an 11-year record of observations (2008–2018) of atmospheric vertical column densities from the Infrared Atmospheric Sounding Interferometer (IASI) to evaluate NH₃ ground-based concentrations and total column densities, respectively. Climatic data (air temperature, rainfall amount, and leaf area index), as well as ammonia emission data of biomass combustion from the fourth version of the Global Fire Emissions Database (GFED4) and anthropogenic sources from the Community Emissions Data System (CEDS), were compared with total NH₃ concentrations and total columns over the same periods. Annual mean ground-based NH₃ concentrations are around 5.7–5.8 ppb in dry savannas, 3.5–4.7 ppb in wet savannas, and 3.4–5.6 ppb in forests. Annual IASI NH₃ total column densities are $10.0\text{--}10.7 \times 10^{15}$ molec. cm^{−2} in dry savanna, $16.0\text{--}20.9 \times 10^{15}$ molec. cm^{−2} in wet savanna, and $12.4\text{--}13.8 \times 10^{15}$ molec. cm^{−2} in forest stations. Non-parametric statistical Mann–Kendall trend tests applied to annual data show that ground-based NH₃ concentrations increase at Bomassa (+2.56 % yr^{−1}) but decrease at Zoétélé (−2.95 % yr^{−1}) over the 21-year period. The 11-year period of IASI NH₃ total column density measurements show yearly increasing trends at Katibougou (+3.46 % yr^{−1}), Djougou (+2.24 % yr^{−1}), and Zoétélé (+3.42 % yr^{−1}). From the outcome of our investigation, we conclude that air temperature, leaf area index, and rainfall combined with biomass burning, agricultural, and residential activities are the key drivers of atmospheric NH₃ in the INDAAF stations. The results also show that the drivers of trends are (1) agriculture in the dry savanna of Katibougou; (2) air temperature and agriculture in the wet savanna of Djougou and Lamto; and (3) leaf area index, air temperature, residential, and agriculture in the forest of Bomassa.

Introduction. Atmospheric nitrogen (N) compounds play an important role in all compartments of the critical zone (biosphere–atmosphere–hydrosphere) at the global scale. Since 2002, Bouwman et al. (2002a) have claimed that in the future, both acidification and eutrophication risks due to excess of N could significantly increase in Asia, Africa and South America but decrease in North America and western Europe. Reactive nitrogen (Nr) in the atmosphere, either reduced (NH_x = NH₃ and NH) or oxidized (NO_x) forms, has a very different role. Ammonia (NH₃), the inorganic form of Nr typically produced through the deprotonation of NH, is the most abundant alkaline component in the atmosphere (Behera et al., 2013). In the atmosphere, NH₃ influences the abundance and chemical composition of sulfate particles, primarily from dimethyl sulfide (DMS) emissions arising from planktonic algae (Bouwman and Van Der Hoek, 1997). In the lower troposphere, NH₃ neutralizes a great portion of the acids produced by oxides of sulfur and nitrogen (Adon et al., 2010) and forms fine particulate matter (PM_{2.5}) (Malm et al., 2004). Through wet or dry deposition to the surface, NH₃ can be detrimental over time due to an increased toxicity toward sensitive species of plants (Behera et al., 2013; Galloway et al., 2004), ecosystems (Erisman et al., 2013), and soils (Stevens et al., 2018).

Wintertime synoptic patterns of midlatitude boundary layer clouds over the western North Atlantic: Climatology and insights from in-situ ACTIVATE observations.

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Abstract. The winter synoptic evolution of the western North Atlantic and its influence on the atmospheric boundary layer is described by means of a regime classification based on Self-Organizing Maps applied to 12 years of data (2009–2020). The regimes are classified into categories according to daily 600-hPa geopotential height: dominant ridge, trough to ridge eastward transition (trough-ridge), dominant trough, and ridge to trough eastward transition (ridge-trough). A fifth synoptic regime resembles the winter climatological mean. Coherent changes in sea-level pressure and large-scale winds are in concert with the synoptic regimes: (a) the ridge regime is associated with a well-developed anticyclone; (b) the trough-ridge gives rise to a low-pressure center over the ocean, ascents, and northerly winds over the coastal zone; (c) trough is associated with the eastward displacement of a cyclone, coastal subsidence, and northerly winds, all representative characteristics of cold-air outbreaks; and (d) the ridge-trough regime features the development of an anticyclone and weak coastal winds. Low clouds are characteristic of the trough regime, with both trough and trough-ridge featuring synoptic maxima in cloud droplet number concentration (N_d). The N_d increase is primarily observed near the coast, concomitant with strong surface heat fluxes exceeding by more than 400 W m^{-2} compared to fluxes further east. Five consecutive days of aircraft observations collected during the ACTIVATE campaign corroborates the climatological characterization, confirming the occurrence of high N_d for days identified as trough. This study emphasizes the role of boundary-layer dynamics and aerosol activation and their roles in modulating cloud microphysics.

Introduction. Marine boundary layer (MBL) clouds have been a topic of active research during recent decades owing to their central role in the Earth's energy budget (Hartmann et al., 1992). Their occurrence is preferentially over the global ocean, with distinct local maxima in cloud coverage located off the western edge of the continents in the subtropics and in the baroclinic zonal bands of the extratropics (Wood, 2012). While low-altitude clouds in the extratropics are generally less persistent, broad stratiform cloud fields are easily identified in satellite imagery, in connection with midlatitude weather systems (e.g., Naud et al., 2014) and associated with rapid transitions in large-scale wind, surface fluxes, and temperature advection. Indeed, satellite climatologies reveal extensive cloud decks over the Southern Ocean as well as the midlatitude Pacific and Atlantic Oceans. Extratropical low clouds have recently drawn attention of the climate community due to their contribution to global cloud feedback in the Coupled Model Intercomparison Project Phase 6 (CMIP6) models, with stronger feedback in the extratropics than in the tropics (Zelinka et al., 2020). As processes that control extratropical MBL cloud variability remain to some degree unexplored, the mechanisms that need to be refined in climate models for achieving a more faithful representation of low clouds, regionally and globally, are not well known. For instance, Naud et al. (2019) found a climate model underestimation of low-cloud cover in the postfrontal region in the Southern Ocean, which also extends to underestimations of Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2) and ERA-Interim reanalyses relative to satellite data (Naud et al., 2014). Challenges in simulating boundary layer clouds by climate models are also documented for the western North Atlantic Ocean (WNAO), where four climate models developed by U.S. research centers simulate a broad range in cloud cover and liquid water path (LWP) that differ from satellite climatologies (Painemal, Corral, et al., 2021).

Drivers and impacts of Eastern African rainfall variability.

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Abstract. Eastern Africa exhibits bimodal rainfall consisting of long rains (March–May) and short rains (October–December), changes in which have profound socioeconomic and environmental impacts. In this Review, we examine the drivers and corresponding impacts of Eastern African rainfall variability. Remote teleconnections, namely the El Niño–Southern Oscillation and the Indian Ocean Dipole, exert a dominant influence on interannual variability. From the mid-1980s to 2010, the long rains have tended toward a drier state (trends of -0.65 to -2.95 mm season⁻¹ year⁻¹), with some recovery thereafter, while the short rains have become wetter since the mid-1980s (1.44 to 2.36 mm season⁻¹ year⁻¹). These trends, overlain by substantial year-to-year variations, affect the severity and frequency of extreme flooding and droughts, the stability of food and energy systems, the susceptibility to water-borne and vector-borne diseases, and ecosystem stability. Climate model projections of rainfall changes differ, but there is some consensus that the short rains will deliver more rainfall than the long rains by 2030–2040, with implications for sustaining agricultural yields and triggering climate-related public health emergencies. Mitigating the impacts of future Eastern African climate requires continued investments in agriculture, clean water, medical and emergency infrastructures, and development and adoption of adaptation strategies, as well as targeted early-warning systems driven by improved meteorological observations.

Introduction. Seasonal rainfall is integral to the 457 million people living across Eastern Africa, a region including Burundi, Djibouti, Eritrea, Ethiopia, Kenya, Rwanda, Somalia, South Sudan, Sudan, Tanzania and Uganda (Box 1). The number, duration and timing of these rainfall seasons varies, driven principally by the movement of the intertropical convergence zone (ITCZ)1. For instance, the most northerly and southerly regions (northern Ethiopia, Eritrea, Sudan, South Sudan and southern Tanzania) experience a single summer wet season for their respective hemispheres. In contrast, countries between these latitudinal extremes (encompassing Kenya, Uganda, Somalia, Burundi, Rwanda and parts of northern Tanzania and southern Ethiopia) experience two wet seasons. These two wet seasons occur during boreal spring (typically March–May, MAM; the more intense long rains) and autumn (typically October–December, OND; the less intense short rains), although there are substantial regional variations in these timings.

This seasonal rainfall is vital to the health and economic prosperity of the region. For example, long rains support agricultural production and thus national food security. Rain-fed agriculture, in turn, has a substantial role in the economy of many Eastern African countries. Agriculture employs 67% of people in Ethiopia, 80% in Somalia, 54% in Kenya, 63% in Eritrea and 38% in Sudan2. Agriculture also represents an extensive contribution to the annual multibillion-dollar export of goods such as sugar, tea, coffee, tobacco, nuts and seeds, cut flowers and vegetables3. Moreover, rainfall is pivotal to energy production, particularly given that hydropower represents a large fraction of electricity generation in Eastern Africa4. Aquifer recharge from rainfall5,6 also provides a sustainable reservoir of groundwater for potable water (and irrigation) during periods of drought5, demonstrating the importance of rainfall for water security, especially when looking to the future7.

Herbarium records provide reliable phenology estimates in the understudied tropics.

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Abstract.

1. Plant phenology has been shifting dramatically in response to climate change, a shift that may have significant and widespread ecological consequences. Of particular concern are tropical biomes, which represent the most biodiverse and imperilled regions of the world. However, compared to temperate floras, we know little about phenological responses of tropical plants because long-term observational datasets from the tropics are sparse.
2. Herbarium specimens have greatly increased our phenological knowledge in temperate regions, but similar data have been underutilized in the tropics and their suitability for this purpose has not been broadly validated. Here, we compare phenological estimates derived from field observational data (i.e. plot surveys) and herbarium specimens at various spatial and taxonomic scales to determine whether specimens can provide accurate estimations of reproductive timing and its spatial variation.
3. Here, we demonstrate that phenological estimates from field observations and herbarium specimens coincide well. Fewer than 5% of the species exhibited significant differences between flowering periods inferred from field observations versus specimens regardless of spatial aggregation. In contrast to studies based on field records, herbarium specimens sampled much larger geographic and climatic ranges, as has been documented previously for temperate plants, and effectively captured phenological responses across varied environments.
4. *Synthesis.* Herbarium specimens are verified to be a vital resource for closing the gap in our phenological knowledge of tropical systems. Tropical plant reproductive phenology inferred from herbarium records is widely congruent with field observations, suggesting that they can and should be used to investigate phenological variation and their associated environmental cues more broadly across tropical biomes.

Introduction. Shifts in plant phenology—the timing of life-history events—are among the most iconic biological responses to climatic change and have widespread consequences for individual taxa and critical ecosystem processes (Keenan et al., 2014; Polgar & Primack, 2011; Richardson et al., 2013; Willis et al., 2008). Of particular concern are tropical biomes, which represent the most biodiverse and imperilled regions of the world (Jenkins et al., 2013; Kreft & Jetz, 2007; Mora et al., 2013; Raven et al., 2020). However, there is comparatively little information on the phenological responses of tropical plants to climate (Abernethy et al., 2018; Cook et al., 2012; Davis & Ellison, 2018; Davis, Lyra, Park, Asprino, et al., 2022; Pau et al., 2011). Along these lines, most of our knowledge regarding the patterns, cues and mechanisms of plant phenology derives from temperate biomes in North America, western Europe and northeast Asia (Davis, Lyra, Park, Asprino, et al., 2022; Wolkovich et al., 2014). Our understanding of tropical plant phenology has been especially limited by the overall paucity of long-term observational data and the overwhelming diversity of tropical species and their varied phenological behaviours (Abernethy et al., 2018; Davis & Ellison, 2018; Davis, Lyra, Park, Asprino, et al., 2022). Tropical systems comprise diverse climates, from aseasonal rainforests to seasonally dry forests and grasslands. Moreover, various reproductive phenological strategies coexist in the tropics, including near complete synchrony and total asynchrony; sub- and supra-annual flowering; and short bursts of activity as well as continuous reproduction (Augsburger, 1983; Bronstein & Patel, 1992; Frankie et al., 1974; Galetto et al., 2000; Medway, 1972; Newstrom et al., 1994; Sakai, 2002; Van Schaik et al., 1993).

Geophysical uncertainties in air pollution exposure and benefits of emissions reductions for global health.

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Abstract. Exposure to fine particulate matter (PM_{2.5}) air pollution is associated with large-scale health consequences, but the ranges in estimates of global air pollution exposure and PM_{2.5}-related global premature mortality remain understudied. Using four model/observation-based PM_{2.5} data sets and six Coupled Model Intercomparison Project Phase 6 (CMIP6) climate models, we compare ranges in current PM_{2.5}-related mortality estimates based on model/observation combinations to the range of projected emissions reductions and the resulting impacts on global health from CMIP6 models. Although estimates of current mortality are sensitive to the PM_{2.5} data set (6.54–9.23 million/year using the central estimate from the Global Exposure Mortality Model), the projected near-term benefits of emissions reductions for reduced mortality are much more certain. Specifically, until the middle of the century, uncertainty ranges in projected avoided deaths are less than the magnitude of ranges in present-day mortality estimates, even when projected future changing socio-demographic factors are considered. Under a low-emissions scenario, avoided cumulative early deaths could reach 275 million (range: 243–351 million) by 2100, assuming no future socio-demographic changes. Avoided cumulative deaths could reach 124 million (range: 74–246 million) if changing future socio-demographic factors are considered. As the global population ages and becomes more sensitive to breathing polluted air, there will be an increasing need for policies that both reduce air pollution and improve public health.

Introduction. Exposure to ambient fine particulate matter (PM_{2.5}) air pollution is a major global health issue (Liang et al., 2018; Murray et al., 2020). Specifically, exposure to elevated levels of PM_{2.5} is associated with an increased risk of childhood respiratory problems and heart and lung problems in adults, among other outcomes (Murray et al., 2020; Thurston et al., 2017). Due to the negative impact of poor air quality on global health, in September of 2021 the World Health Organization (WHO) updated its Global Air Quality Guidelines (AQG) from annual mean PM_{2.5} concentrations of 10 µg/m³ to concentrations of 5 µg/m³. Previous work has suggested that 95% of the world's population is exposed to outdoor ambient PM_{2.5} concentrations of at least 10 µg/m³ (Shaddick et al., 2018). PM_{2.5}-associated premature deaths could be as high as ~9–10 million/year (Burnett et al., 2018; Lelieveld et al., 2019; Vohra et al., 2021), and air pollution-associated global welfare losses are estimated to be US\$4.6 trillion per year (Landrigan et al., 2018).

Despite the negative impacts of ambient PM_{2.5} exposure on human health and well-being, a comparison of global PM_{2.5} exposure and mortality estimates (e.g., Farrow et al., 2020) using different global observation-based estimates (e.g., Alvarado et al., 2019) has not been conducted. Furthermore, although air quality outcomes across Shared Socioeconomic Pathways (SSPs) have been examined using a simplified global air quality model (Rao et al., 2017) and using one climate model (Im et al., 2023; Yang et al., 2022), future global air pollution exposure and associated consequences (Allen et al., 2021; Shindell et al., 2021; Silva et al., 2016; Vandyck et al., 2018) under high- and low-emissions scenarios in a suite of the latest climate models have not been addressed. Previous assessments have focused on epidemiological uncertainties related to differences in exposure/concentration response functions (ERFs/CRFs) or background baseline mortality data (e.g., Giani et al., 2020; McDuffie et al., 2021), but here we focus on ranges of estimates of global premature mortality for the present day calculated using different observation-based estimates and projected modeled air pollution to better account for geophysical uncertainties. Assessing often-neglected geophysical sources of uncertainty can be important in health impacts analyses because geophysical uncertainties can be comparable to or larger than other sources of uncertainty (e.g., Giani et al., 2020; Liang et al., 2018; Vanos et al., 2020).

A new multi-method assessment of stratospheric sulfur load from the Okmok II caldera-forming eruption of 43 BCE.

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Abstract. The 43 BCE eruption of Okmok Volcano has been proposed to have had a significant climate cooling impact in the Northern Hemisphere. In this study, we quantify the climate cooling potential of the Okmok II eruption by measuring sulfur concentration in melt inclusions (up to 1,606 ppm) and matrix glasses and estimate a total of 62 ± 16 Tg S released. The proportion reaching the stratosphere (2.5%–25%, i.e., 1.5–15.5 Tg S) was constrained by physical modeling of the caldera-collapse eruption. Using the NASA Goddard Institute for Space Studies E2.2 climate model we found a linear response between cooling and stratospheric sulfur load (0.05–0.08°C/Tg S). Thus, the 1–2°C of cooling derived from proxy records would require 16–32 Tg sulfur injection. This study underscores the importance of combining approaches to estimate stratospheric S load. For Okmok II, we find all methods are consistent with a range of 15–16 Tg S.

Introduction. What will be the climate impact of the next major volcanic eruption? The answer to this question lies in our understanding of past notable events. Here we explore the volcanic drivers and climatic response of the Okmok II eruption, Alaska. This eruption was recently recognized by McConnell et al. (2020) as the source of Greenland ice core sulfate peaks at 43 BCE and implicated as the cause for regional temperature and precipitation anomalies that may have led to social unrest in the late Roman Republic and Ptolemaic Kingdom.

Okmok II consisted of two eruptive phases, the first producing ~ 0.85 km³ bulk (0.6 km³ DRE) of Plinian rhyodacite and subsequent andesite fall deposits across Umnak Island, and the second major caldera-forming phase producing ~ 50 km³ bulk (29 km³ DRE) of pyroclastic density current (PDC) deposits (Burgisser, 2005; Larsen et al., 2007; Wolfe, 2001). The composition of the tephra recovered from the GISP2 ice core aligns best with the material erupted as basaltic andesite PDCs (McConnell et al., 2020 and see below). This suggests that the PDC material was lofted high enough to be dispersed to the opposite side of the Northern Hemisphere, prompting further study of pyroclastic-associated plumes and caldera collapse via physical modeling (Burgisser et al., 2023).

The primary goal of this study is to provide the first petrological measurements of the total amount of sulfur released by Okmok II magma. The other goal is to estimate the fraction of this load injected to the stratosphere, critical to determining its climate impact. This quantity is challenging to determine by any one method, and the novelty of our study is that we employ three independent methods and data sets for estimating stratospheric sulfur: (a) ice sheet deposition and sulfur isotopes, (b) global climate model and climate proxy data, and (c) total petrologic sulfur load and eruption dynamics modeling for stratospheric injection.

Materials and Methods. Okmok II PDC and andesite fall samples were selected for melt inclusion study (Figure 1a, Table S3 in Supporting Information S1). Polished crystals and matrix glasses from four samples were measured by electron microprobe for major element composition and sulfur concentration. Selected melt inclusions and matrix glasses were then measured for water and sulfur content by ion microprobe (Figure 1d; Texts S3 and S4 in Supporting Information S1).

Rapidly evolving aerosol emissions are a dangerous omission from near-term climate risk assessments.

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Abstract. Anthropogenic aerosol emissions are expected to change rapidly over the coming decades, driving strong, spatially complex trends in temperature, hydroclimate, and extreme events both near and far from emission sources. Under-resourced, highly populated regions often bear the brunt of aerosols' climate and air quality effects, amplifying risk through heightened exposure and vulnerability. However, many policy-facing evaluations of near-term climate risk, including those in the latest Intergovernmental Panel on Climate Change assessment report, underrepresent aerosols' complex and regionally diverse climate effects, reducing them to a globally averaged offset to greenhouse gas warming. We argue that this constitutes a major missing element in society's ability to prepare for future climate change. We outline a pathway towards progress and call for greater interaction between the aerosol research, impact modeling, scenario development, and risk assessment communities.

Introduction. Anthropogenic aerosols as a unique driver of climate change. Anthropogenic aerosols—the particulate air pollutants that make up a major component of atmospheric haze—play an important role in the evolution of both air quality and global climate change. Anthropogenic emissions of aerosols and their precursors have continuously changed through the historical era and are expected to continue to rapidly evolve over the coming decades (figure 1). Currently, the net effect of aerosols cools the Earth's surface by around 0.4° C, offsetting part of the global warming due to increased atmospheric concentrations of greenhouse gases (GHGs). Since the 1970s, however, the geographical distribution of emissions has shifted substantially: transitioning from a locus over North America and Europe to one over Asia [1]. In the last decade, emissions from China have slowed markedly, bringing improvements in air quality and human health [2]. However, China and India both remain major emitters. Aerosol emissions in many low and middle-income countries, including much of Africa and Southeast Asia, are projected to increase with future industrialization, depending on socio-economic factors and technology choices [3]. The range of potential global trajectories of anthropogenic aerosol emissions by the mid-21st century, as captured by the shared socioeconomic pathways (SSPs) future emissions scenarios employed in the current generation of climate model projections, is comparable to the growth of emissions over the entire industrial era (figure 1). Future aerosol induced climate forcing, therefore, constitutes a major source of uncertainty in near-term climate change—globally and regionally.

The global and regional implications of anthropogenic aerosol changes are known to be distinct from those of GHGs. For instance, the global hydrological sensitivity—i.e. the precipitation change per unit of temperature change—to aerosol emissions (3%/K for sulfate and −3%/K for black carbon) is twice as large as the sensitivity to CO₂ (1.5%/K) [4, 5], due to their differing interactions with short- and longwave radiation and with clouds and circulation. Temperature and precipitation extremes have also recently been recognized to be more sensitive to changes in aerosol forcing than to an equivalent change in GHG forcing [6–8].

Summer atmospheric circulation over Greenland in response to Arctic amplification and diminished spring snow cover.

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Abstract. The exceptional atmospheric conditions that have accelerated Greenland Ice Sheet mass loss in recent decades have been repeatedly recognized as a possible dynamical response to Arctic amplification. Here, we present evidence of two potentially synergistic mechanisms linking high latitude warming to the observed increase in Greenland blocking. Consistent with a prominent hypothesis associating Arctic amplification and persistent weather extremes, we show that the summer atmospheric circulation over the North Atlantic has become wavier and link this wavier flow to more prevalent Greenland blocking. While a concomitant decline in terrestrial snow cover has likely contributed to this mechanism by further amplifying warming at high latitudes, we also show that there is a direct stationary Rossby wave response to low spring North American snow cover that enforces an anomalous anticyclone over Greenland, thus helping to anchor the ridge over Greenland in this wavier atmospheric state.

Introduction. Summer atmospheric circulation in the Northern Hemisphere has undergone a pronounced shift in recent decades. Nowhere has this been more apparent than over the North Atlantic. Observations have revealed a more prevalent negative phase of the North Atlantic Oscillation (NAO) since the turn of the century and a coincident increase in the frequency of anomalous quasi-stationary anticyclonic conditions—known as atmospheric blocking—over Greenland^{1,2,3}.

Greenland blocking episodes transport warm, moist air from lower latitudes, which promotes widespread melt of the Greenland Ice Sheet (GrIS) through a spatially variable surface energy balance response and consequent positive feedback mechanisms^{4,5,6,7}. Indeed, this dynamical forcing of the GrIS has been a primary cause of accelerating surface runoff in recent decades^{1,2,8,9} and it has been estimated that a continuation of these more frequent anticyclonic conditions would result in approximately twice the surface mass loss projected by global climate models¹⁰, which collectively fail to capture the observed shift in atmospheric circulation over Greenland^{2,11,12}. This bias has clear far-reaching implications, as it has caused even the upper range of climate projections to underestimate the contribution of GrIS surface runoff to global sea-level rise¹³. Therefore, it is of critical importance to understand whether these observed changes are merely a temporary manifestation of internal variability or a continuing consequence of anthropogenic climate change.

One active area of research aims to determine whether Arctic Amplification (AA)—i.e., an elevated rate of warming at high latitudes relative to low latitudes under global climate change—causes more frequent persistent weather extremes, including both winter cold spells¹⁴ and summer heatwaves¹⁵. A prominent hypothesis underlying this area of research contends that the reduced meridional temperature gradient caused by AA results in weaker westerlies, as dictated by the thermal wind relation, and a higher amplitude—or wavier—jet that propagates downstream more slowly, thus favoring persistent extremes such as those associated with atmospheric blocking¹⁶. While immediate follow-up studies argued that initial results supporting this hypothesis were likely an artificial byproduct of methodology^{17,18}, subsequent efforts have applied more robust measures of waviness, yielding statistically significant positive trends over regional domains spanning North America in summer^{19,20}, and the North Atlantic in both summer and winter²¹. However, previous studies have not focused on Greenland, as the regions examined have tended to dissect Greenland itself.

Arctic warming in response to regional aerosol emissions reductions.

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Abstract. This study examines the Arctic surface air temperature response to regional aerosol emissions reductions using three fully coupled chemistry–climate models: National Center for Atmospheric Research–Community Earth System Model version 1, Geophysical Fluid Dynamics Laboratory–Coupled Climate Model version 3 (GFDL-CM3) and Goddard Institute for Space Studies–ModelE version 2. Each of these models was used to perform a series of aerosol perturbation experiments, in which emissions of different aerosol types (sulfate, black carbon (BC), and organic carbon) in different northern mid-latitude source regions, and of biomass burning aerosol over South America and Africa, were substantially reduced or eliminated. We find that the Arctic warms in nearly every experiment, the only exceptions being the U.S. and Europe BC experiments in GFDL-CM3 in which there is a weak and insignificant cooling. The Arctic warming is generally larger than the global mean warming (i.e., Arctic amplification occurs), particularly during non-summer months. The models agree that changes in the poleward atmospheric moisture transport are the most important factor explaining the spread in Arctic warming across experiments: the largest warming tends to coincide with the largest increases in moisture transport into the Arctic. In contrast, there is an inconsistent relationship (correlation) across experiments between the local radiative forcing over the Arctic and the simulated Arctic warming, with this relationship being positive in one model (GFDL-CM3) and negative in the other two. Our results thus highlight the prominent role of poleward energy transport in driving Arctic warming and amplification and suggest that the relative importance of poleward energy transport and local forcing/feedbacks is likely to be model dependent.

Introduction. The Arctic has experienced rapid warming over recent decades (Gulev *et al* 2021), with this warming occurring about four times faster than the global mean warming since 1979 (Chylek *et al* 2022, Rantanen *et al* 2022). While the dominant role of anthropogenic greenhouse gases (GHGs) in driving the recent Arctic warming is well established (e.g. Najafi *et al* 2015, Polvani *et al* 2020, England 2021, Aizawa *et al* 2022), other anthropogenic forcings—notably, aerosols—may have contributed as well. England (2021) found that anthropogenic aerosol forcing warmed the Arctic at a rate of 0.18 °C/decade during 1975–2019 (compared with a warming of 0.59 °C/decade during this period from GHGs). This aerosol-induced warming is a result of reductions in aerosol (and aerosol precursor) emissions from the United States and Europe (Acosta Navarro *et al* 2016, Wang *et al* 2018). In contrast, increases in aerosol emissions from Asia in recent decades have likely contributed to Arctic cooling (Yang *et al* 2014, Wang *et al* 2018), thus opposing the observed warming. These increases in Asian emissions are not expected to continue, however, as efforts to improve air quality are likely to result in decreases in anthropogenic aerosol emissions from Asia over the next several decades (Lund *et al* 2019). These decreases in Asian emissions could contribute significantly to Arctic warming and sea-ice loss (Wang *et al* 2018, Merikanto *et al* 2021), thus enhancing the effects of rising GHGs.

Motivated by these potential impacts of anthropogenic aerosol forcing on Arctic climate, we here examine the Arctic climate response to several different regional aerosol emissions reductions using three coupled chemistry–climate models: the Community Earth System Model version 1 (CESM1) which was run at the National Center for Atmospheric Research (NCAR-CESM1), the Geophysical Fluid Dynamics Laboratory (GFDL) Coupled Climate Model version 3 (GFDL-CM3), and the Goddard Institute for Space Studies (GISS) ModelE version 2 (GISS-E2-R).

Little change in apparent hydrological sensitivity at large CO₂ forcing.

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Abstract. Apparent hydrological sensitivity (η_a), the change in the global mean precipitation per degree K of global surface warming, is a key aspect of the climate system's response to increasing CO₂ forcing. To determine whether η_a depends on the forcing amplitude we analyze idealized experiments over a broad range of abrupt CO₂ forcing, from 2× to 8× preindustrial values, with two distinct climate models. We find little change in η_a between 2× and 4×CO₂, and almost no change beyond 5×CO₂. We validate this finding under transient CO₂ forcing at 1%-per-year, up to 8×CO₂. We further corroborate this result by analyzing the 1%-per-year output of more than 15 CMIP5/6 models. Lastly, we examine the 1,000-year long LongrunMIP model output, and again find little change in η_a . This wealth of results demonstrates that η_a is a very weak function of CO₂ forcing.

Introduction. Equilibrium Climate Sensitivity (ECS) is the global mean change in surface temperature for a doubling of CO₂ from the pre-industrial (PI) value. ECS is one of the key metrics used in assessing future global warming, and therefore plays a very important role in climate change related policy-making. One important question in this regard is how ECS changes in a warmer world. Several studies found that ECS increases at higher CO₂ concentrations (e.g., Bloch-Johnson et al., 2021; Colman & McAvaney, 2009; Gregory et al., 2015; Meraner et al., 2013). And, more recently, Mitevski et al. (2021) found a non-linear and non-monotonic dependence of ECS on CO₂ concentrations.

In addition to the surface temperature response, the precipitation response is another critical aspect of climate change. To evaluate precipitation changes, the key metric used is Hydrological Sensitivity (HS). HS is defined as the difference in global mean precipitation per one degree of global mean temperature change from the PI control state. Previous studies have explored the response of the hydrological cycle to global warming by examining HS in terms of the global energy budget, and have described the mechanisms affecting it (e.g., Allen & Ingram, 2002; Held & Soden, 2006; Jeevanjee & Romps, 2018; O'Gorman et al., 2011). The fact that HS is energetically constrained means that the precipitation response can be separated into fast and slow components. The fast response depends only on the CO₂ concentrations in the atmosphere, before the surface temperature has time to warm, and results in a decrease in precipitation. The slow response, in contrast, is associated with surface warming, and results in an increase in precipitation (Andrews et al., 2010).

One might ask if ECS and HS are related. Watanabe et al. (2018) suggested an anti-correlation between ECS and HS due to the low cloud response in a warmer world. More recently, however, Pendergrass (2020) revisited this connection using Phase 6 of the Coupled Model Intercomparison Project (CMIP6, Eyring et al. (2016)) and found no correlation between ECS and HS. Nonetheless, since ECS was found to be strongly affected by the magnitude of CO₂ forcing, one might ask if HS, as another aspect of the climate response, could also be affected in the same way, even if ECS and HS are not related.

We are aware of only one study which explored this subject (Good et al., 2012), which reported that HS decreases at higher CO₂ concentrations. However, that finding was obtained with a single climate model. Furthermore, the range of CO₂ forcing explored in that study was limited, as the authors only considered three values of CO₂ (0.5×, 2×, and 4×CO₂). Whether the finding of Good et al. (2012) can be confirmed with different climate models and over a broader range of CO₂, remains to be determined.

Approaching a thermal tipping point in the Eurasian boreal forest at its southern margin.

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Abstract. Climate change is increasing the intensity and frequency of extreme heat events. Ecological responses to extreme heat will depend on vegetation physiology and thermal tolerance. Here we report that *Larix sibirica*, a foundation species across boreal Eurasia, is vulnerable to extreme heat at its southern range margin due to its low thermal tolerance (T_{crit} of photosynthesis: $\sim 37\text{--}48\text{ }^{\circ}\text{C}$). Projections from CMIP6 Earth System Models (ESMs) suggest that leaf temperatures might exceed the 25th percentile of *Larix sibirica*'s T_{crit} by two to three days per year within the next two to three decades (by 2050) under high emission scenarios (SSP3-7.0 and SSP5-8.5). This degree of warming will threaten the biome's continued ability to assimilate and sequester carbon. This work highlights that under high emission trajectories we may approach an abrupt ecological tipping point in southern boreal Eurasian forests substantially sooner than ESM estimates that do not consider plant thermal tolerance traits.

Introduction. The circumpolar boreal forest is the most extensive biome covering ~ 15 million km^2 and accounts for nearly a third of the 450Gt terrestrial carbon stock^{1,2,3}. Boreal carbon resides in three major pools: peatlands, soils and forest biomass⁴. All pools are sensitive to rising temperatures from human-caused climate change due to direct impacts of warming and indirect impacts such as permafrost thaw, increased wildfire, and insect activity^{3,4,5}. Two-thirds of the circumpolar boreal biome lies in Eurasia and North Mongolia, defined here as a ~ 1 million km^2 region between $95\text{--}114^{\circ}\text{E}$ and $46\text{--}52^{\circ}\text{N}$, is located at the southern margin of the Eurasian boreal biome (Fig. 1a). The presence of boreal forest in North Mongolia can be attributed to its relatively cool mesic climate with mean annual precipitation generally exceeding 350 mm/year and mean annual temperatures between -5 and $0\text{ }^{\circ}\text{C}$ (Fig. 1b and Supplementary Fig. 1a)^{6,7}. Further south, the dominant ecosystem rapidly transitions into grassland-steppe due to warmer and drier climate conditions⁸.

Boreal regions can host stable but competing forest, shrub, and grassland-steppe ecosystems as a result of various land-atmosphere feedbacks such as albedo, fire, and insects^{6,7,9,10}. Over the past four decades since the mid-1980s, accelerated warming and associated drying have decreased forest productivity and shifted the southern boreal forest margin northward, consistent with early stages of a projected ecosystem transition towards grass and shrublands^{11,12}. Under continued global change, many Earth System Models (ESMs) predict the exceedance of a 'tipping point' in the southern boreal forest, a critical threshold at which a small perturbation in forcing (e.g., temperature) can fundamentally and irreversibly alter the ecosystem state at regional to sub-continental spatial scales (order of several hundred kilometres) over human timescales¹³. ESMs forecast synchronised southern margin boreal forest dieback to commence at $\sim 1.5\text{ }^{\circ}\text{C}$ of global warming, become widespread by $\sim 3.5\text{ }^{\circ}\text{C}$, and exceed a biome-wide tipping point at $\sim 4\text{ }^{\circ}\text{C}$ of global warming relative to 1850 C.E pre-industrial levels⁹. Upon crossing this tipping point, southern boreal forest dieback is projected to occur over $\sim 50\text{--}100$ year timescales and result in up to $\sim 52\text{GtC}$ of potential emissions^{9,13}. Notably, North Mongolia and the circumpolar boreal forest have already warmed three times faster than global temperature due to Arctic amplification^{10,14,15,16,17,18} (Fig. 1c, d and Supplementary Fig. 2), with negative impacts on high-elevation Altai permafrost, tree growth¹⁹, and pastoral nomadic herding, the latter a traditional source of livelihood for a third of all Mongolians^{8,20,21,22}. ESMs participating in the sixth phase of the Coupled Model Intercomparison Project (CMIP6²³) suggest that warming will persist and intensify through the 21st century without compensating increases in precipitation (Fig. 1c, d and Supplementary Figs. 2, 3).

The coupling between tropical meteorology, aerosol lifecycle, convection, and radiation, during the Cloud, Aerosol and Monsoon Processes Philippines Experiment (CAMP²Ex).

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Abstract. The NASA Cloud, Aerosol, and Monsoon Processes Philippines Experiment (CAMP²Ex) employed the NASA P-3, Stratton Park Engineering Company (SPEC) Learjet 35, and a host of satellites and surface sensors to characterize the coupling of aerosol processes, cloud physics, and atmospheric radiation within the Maritime Continent's complex southwest monsoonal environment. Conducted in the late summer of 2019 from Luzon, Philippines, in conjunction with the Office of Naval Research Propagation of Intra-seasonal Tropical Oscillations (PISTON) experiment with its R/V *Sally Ride* stationed in the northwestern tropical Pacific, CAMP²Ex documented diverse biomass burning, industrial and natural aerosol populations, and their interactions with small to congestus convection. The 2019 season exhibited El Niño conditions and associated drought, high biomass burning emissions, and an early monsoon transition allowing for observation of pristine to massively polluted environments as they advected through intricate diurnal mesoscale and radiative environments into the monsoonal trough. CAMP²Ex's preliminary results indicate 1) increasing aerosol loadings tend to invigorate congestus convection in height and increase liquid water paths; 2) lidar, polarimetry, and geostationary Advanced Himawari Imager remote sensing sensors have skill in quantifying diverse aerosol and cloud properties and their interaction; and 3) high-resolution remote sensing technologies are able to greatly improve our ability to evaluate the radiation budget in complex cloud systems. Through the development of innovative informatics technologies, CAMP²Ex provides a benchmark dataset of an environment of extremes for the study of aerosol, cloud, and radiation processes as well as a crucible for the design of future observing systems.

Introduction. The Maritime Continent (MC) of Southeast Asia, comprising the archipelago of islands from the Malay Peninsula through Indonesian New Guinea and the Philippines, hosts some of the world's most complex aerosol, cloud, and coupled ocean–terrestrial–atmospheric systems. With its steep topography situated in the Pacific warm pool, the MC is an important contributor to Earth's moisture, energy, and vertical transport budgets far outside its tropical latitude range (e.g., [Ramage 1968](#); [Jin and Hoskins 1995](#); [Neale and Slingo 2003](#); [Carminati et al. 2014](#)). High levels of pollution and biomass burning emissions contrast with natural marine and biogenic aerosol sources. Burning for agriculture and urbanization occurs at significant rates ([Miettinen et al. 2016](#)).

The hydrological cycle and ocean circulation of the Maritime Continent in the mid-Pliocene: Results from PlioMIP2.

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Abstract. The Maritime Continent (MC) forms the western boundary of the tropical Pacific Ocean, and relatively small changes in this region can impact the climate locally and remotely. In the mid-Piacenzian warm period of the Pliocene (mPWP; 3.264 to 3.025 Ma) atmospheric CO₂ concentrations were ~ 400 ppm, and the subaerial Sunda and Sahul shelves made the land–sea distribution of the MC different to today. Topographic changes and elevated levels of CO₂, combined with other forcings, are therefore expected to have driven a substantial climate signal in the MC region at this time. By using the results from the Pliocene Model Intercomparison Project Phase 2 (PlioMIP2), we study the mean climatic features of the MC in the mPWP and changes in Indonesian Throughflow (ITF) with respect to the preindustrial. Results show a warmer and wetter mPWP climate of the MC and lower sea surface salinity in the surrounding ocean compared with the preindustrial. Furthermore, we quantify the volume transfer through the ITF; although the ITF may be expected to be hindered by the subaerial shelves, 10 out of 15 models show an increased volume transport compared with the preindustrial.

In order to avoid undue influence from closely related models that are present in the PlioMIP2 ensemble, we introduce a new metric, the multi-cluster mean (MCM), which is based on cluster analysis of the individual models. We study the effect that the choice of MCM versus the more traditional analysis of multi-model mean (MMM) and individual models has on the discrepancy between model results and data. We find that models, which reproduce modern MC climate well, are not always good at simulating the mPWP climate anomaly of the MC. By comparing with individual models, the MMM and MCM reproduce the preindustrial sea surface temperature (SST) of the reanalysis better than most individual models and produce less discrepancy with reconstructed sea surface temperature anomalies (SSTA) than most individual models in the MC. In addition, the clusters reveal spatial signals that are not captured by the MMM, so that the MCM provides us with a new way to explore the results from model ensembles that include similar models.

Introduction. The Maritime Continent (MC; 20° N–10° S and 90–150° E) consists of more than 22 000 islands and lies in the warmest ocean region of the west Pacific Warm Pool (WPWP; [Ramage, 1968](#); [Yoneyama and Zhang, 2020](#)). The near-surface air temperature in most areas of the MC is higher than 27 °C throughout the year ([Li et al., 2018a](#)). High sea surface temperature (SST) leads to substantial moisture flux into the atmosphere. High levels of moisture and energy characterise the unstable climate in this region and make it “the world's strongest atmospheric convection center” ([Yoneyama and Zhang, 2020](#)). Based on satellite data, it has been established that the MC is the region that produces the largest amount of precipitation in the world ([Adler et al., 2017](#); [Yamanaka et al., 2018](#)). A large amount of rainfall releases vast quantities of latent heat into the atmosphere (1 mm yr^{−1} equals 0.08 W m^{−2}), which is an important driver of global atmospheric circulation ([Trenberth et al., 2009](#); [Yamanaka et al., 2018](#)). According to these characteristics, the MC has been recognised as the “boiler box” of the global climate system ([Ramage, 1968](#); [Neale and Slingo, 2003](#)).

Deformation lines in Arctic sea ice: Intersection angle distribution and mechanical properties.

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Abstract. Despite its relevance for the Arctic climate and ecosystem, modeling sea-ice deformation, i.e., the opening, shearing, and ridging of sea ice, along linear kinematic features (LKFs) remains challenging, as the mechanical properties of sea ice are not yet fully understood. The intersection angles between LKFs provide valuable information on the internal mechanical properties, as they are linked to them. Currently, the LKFs emerging from sea-ice rheological models do not reproduce the observed LKF intersection angles, pointing to a gap in the model physics. We aim to obtain an intersection angle distribution (IAD) from observational data to serve as a reference for high-resolution sea-ice models and to infer the mechanical properties of the sea-ice cover. We use the sea-ice vorticity to discriminate between acute and obtuse LKF intersection angles within two sea-ice deformation datasets: the RADARSAT Geophysical Processor System (RGPS) and a new dataset from the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) drift experiment. Acute angles dominate the IAD, with single peaks at $48^\circ \pm 2$ and $45^\circ \pm 7$. The IAD agrees well between both datasets, despite the difference in scale, time period, and geographical location. The divergence and shear rates of the LKFs also have the same distribution. The dilatancy angle (the ratio of shear and divergence) is not correlated with the intersection angle. Using the IAD, we infer two important mechanical properties of the sea ice: we found an internal angle of friction in sea ice of $\mu_1 = 0.66 \pm 0.02$ and $\mu_1 = 0.75 \pm 0.05$. The shape of the yield curve or the plastic potential derived from the observed IAD resembles a teardrop or a Mohr-Coulomb shape. With these new insights, sea-ice rheologies used in models can be adapted or redesigned to improve the representation of sea-ice deformation.

Introduction. Sea-ice deformation is a crucial process for the polar climate. It creates areas of open water that allow enhanced heat and gas exchange, and it also forms ridges that serve as a habitat for biota and provide barriers against winds and ocean currents. The deformation patterns of sea ice in the Arctic Ocean are dominated by narrow lines where deformation concentrates ([Schall and van Hecke, 2010](#)); these lines are known as linear kinematic features (LKFs), failure lines, or shear bands ([Kwok, 2001](#)). LKFs play a primary role in the mass and energy budget of the Arctic Ocean. First, the creation of thicker ice (ridges) or open water (leads), where sea-ice growth is enhanced in winter, takes place along LKFs ([Stern et al., 1995](#); [Hopkins, 1994](#); [von Albedyll et al., 2020, 2022](#)). Second, shear motion and sea-ice growth along LKFs influence the halocline through pycnocline upwelling and brine injection, respectively ([McPhee et al., 2005](#); [Itkin et al., 2015](#); [Nguyen et al., 2012](#)). Finally, despite their small total area, open leads govern the polar ocean–atmosphere heat and moisture exchange ([Maykut, 1978](#); [Untersteiner, 1961](#); [Tetzlaff et al., 2015](#)). Thus, LKFs are an essential component of the Arctic climate system and need to be accurately represented in regional models for reliable regional weather predictions, navigation charts, and services to Arctic communities.

LKFs emerge from the mechanical properties of sea ice. Sea ice is often described as a granular material ([Overland et al., 1998](#); [Tremblay and Mysak, 1997](#); [Feltham, 2005](#)) that exhibits brittle properties ([Schulson, 2002](#); [Dansereau et al., 2016](#)). Important mechanical properties of sea ice are imprinted in the orientation of the failure lines relative to the stress direction.

Teardrop and parabolic lens yield curves for viscous-plastic sea ice models: New constitutive equations and failure angles.

Ringeisen, D.^{1,2,3,4}, M. Losch², and B. Tremblay⁴, 2023

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Abstract. Most viscous-plastic sea ice models use the elliptical yield curve. This yield curve has a fundamental flaw: it excludes acute angles between deformation features at high resolution. Conceptually, the teardrop (TD) and parabolic lens (PL) yield curves offer an attractive alternative. These yield curves feature a non-symmetrical shape, a Coulombic behavior for the low-medium compressive stress, and a continuous transition to the ridging-dominant mode, but their published formulation leads to negative or zero bulk and shear viscosities and, consequently, poor numerical convergence with stress states at times outside the yield curve. These issues are a consequence of the original assumption that the constitutive equations of the commonly used elliptical yield curve are also applicable to non-symmetrical yield curves and yield curves with tensile strength. We derive a corrected formulation for the constitutive relations of the TD and PL yield curves. Results from simple uni-axial loading experiments show that with the new formulation the numerical convergence of the solver improves and much smaller nonlinear residuals after a smaller number of total solver iterations can be reached, resulting in significant improvements in numerical efficiency and representation of the stress and deformation fields. The TD and PL yield curves lead to smaller angles of failure that better agree with observations. They are promising candidates to replace the elliptical yield curve in high-resolution pan-Arctic sea ice simulations.

Introduction. Sea ice dynamical models are an integral part of the CMIP6 models (Notz & Community, 2020). Recent increases in computational power allow for increased spatial resolution in sea ice dynamical model and representation of narrow bands of high deformation, referred to as Linear Kinematic Features or LKFs (Hutchings et al., 2005; Hutter et al., 2019; Kwok, 2001). Divergence (lead opening) or convergence (ridging) can be present along LKFs where significant heat and matter transfer between atmosphere and ocean takes place (Maykut, 1978). It is therefore crucial to represent LKFs adequately in sea ice models.

The capacity of a sea ice dynamical model to represent LKFs explicitly depends mainly on its spatial resolution (Bouchat et al., 2022; Hutter et al., 2022). In turn, the angle between conjugate pairs of LKFs, at least in principle, depends on its rheological model, which parameterizes sea ice physical properties and relates stresses and strain rates. Multiple sea-ice rheological models have been proposed in the community: Elastic-Plastic (EP, Coon et al., 1974), Viscous-Plastic (VP, Hibler, 1977), Elastic-Anisotropic-Plastic (EAP, Tsamados et al., 2013), Maxwell-Elasto-Brittle (MEB, Dansereau et al., 2016), or Bingham-Brittle-Maxwell (BBM, Ólason et al., 2022). To this day, the VP rheological model is the most common because of its simplicity and the fact that it performs well compared to observations and other rheologies (Bouchat et al., 2022; Hutter et al., 2022), especially at high resolution—despite the fact that the VP model has many shortcomings (Coon et al., 2007). The creation process of LKFs is not entirely clear. LKF formation as a consequence of ill-posedness of the VP model (Gray, 1999; Gray & Killworth, 1995) can probably be ruled out as the VP equations in fact well-posed (Brandt et al., 2022; Liu et al., 2022). Sharp gradients of ice strength may act as nucleation points for LKFs, but rheology is still important (see also Figure 9 in Ringeisen et al. (2019)). It appears that only a few ingredients, chiefly, a sharp transition from large to small deformation, are necessary to match deformation statistics.

Asymmetry in the seasonal cycle of zonal-mean surface air temperature.

Roach, L.A.^{1,2,3}, I. Eisenman, T. Wagner, and A. Donohoe, 2023

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Abstract. At most latitudes, the seasonal cycle of zonal-mean surface air temperature is notably asymmetric: the length of the warming season is not equal to the length of the cooling season. The asymmetry varies spatially, with the cooling season being ~40 days shorter than the warming season in the subtropics and the warming season being ~100 days shorter than the cooling season at the poles. Furthermore, the asymmetry differs between the Northern Hemisphere and the Southern Hemisphere. Here, we show that these observed features are broadly captured in a simple model for the evolution of temperature forced by realistic insolation. The model suggests that Earth's orbital eccentricity largely determines the hemispheric contrast, and obliquity broadly dictates the meridional structure. Clouds, atmospheric heat flux convergence, and time-invariant effective surface heat capacity have minimal impacts on seasonal asymmetry. This simple, first-order picture has been absent from previous discussions of the surface temperature seasonal cycle.

Introduction. The seasonal cycle in surface air temperature is a fundamental feature of Earth's climate system, governing many aspects of human and ecological behavior. Qualitatively, it is understood that the seasonal cycle in temperature is driven by the seasonal cycle in insolation and moderated primarily by the effective heat capacity of the surface, which damps the amplitude of the seasonal cycle over the ocean more than over the land. Seasonal variations in atmospheric circulation and spatial variations in radiative feedbacks also contribute to the seasonal evolution of temperature, and may provide an analog to the spatial pattern of warming expected in response to anthropogenic forcing (McKinnon et al., [2013](#)). Quantitative understanding of the seasonal cycle in surface temperature and its changes under global warming has been developed through previous analyses that focus on the phase and amplitude of the annual harmonic (e.g., Donohoe & Battisti, [2013](#); Dwyer et al., [2012](#); Stine & Huybers, [2012](#); Stine et al., [2009](#)).

However, as highlighted by Donohoe, Dawson et al. ([2020](#)), there are substantial departures in the surface air temperature from its annual harmonic that vary across the globe. These departures can be described using the difference in length between the periods of seasonal warming and cooling as a measure of asymmetry. Donohoe, Dawson et al. ([2020](#)) propose several candidate mechanisms that may explain asymmetry in various locations, including the atmospheric versus oceanic contrast in seasonal boundary layer depth in response to solar heating, the phase differences between surface insolation and top-of-atmosphere insolation due to clouds, and the impact of seasonally evolving atmospheric circulations such as the monsoon and stationary waves. Donohoe, Dawson et al. ([2020](#)) stress that their analysis is exploratory, and the authors find no single mechanism that adequately explains the broad-scale features of the asymmetry.

Here, we consider asymmetry in the seasonal cycle of zonal-mean surface air temperature, and in particular we focus on latitudinal variations in asymmetry (i.e., the meridional structure of the asymmetry). We show that the meridional structure of the asymmetry is consistent with idealized model results that describe the local thermodynamic response to the seasonal cycle in insolation, which features substantial departures from the annual harmonic in the high latitudes and subtropics. This model is cast as a simple ordinary differential equation (ODE) forced by realistic insolation; it is adopted from Roach et al. ([2022](#)) and applied here to a different question. The predicted asymmetry is found to be mostly insensitive to the inclusion of seasonally varying clouds, atmospheric circulation, and the specification of radiative feedbacks.

Winds and meltwater together lead to Southern Ocean surface cooling and sea ice expansion.

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Abstract. Southern Ocean surface cooling and Antarctic sea ice expansion from 1979 through 2015 have been linked both to changing atmospheric circulation and melting of Antarctica's grounded ice and ice shelves. However, climate models have largely been unable to reproduce this behavior. Here we examine the contribution of observed wind variability and Antarctic meltwater to Southern Ocean sea surface temperature (SST) and Antarctic sea ice. The free-running, CMIP6-class GISS-E2.1-G climate model can simulate regional cooling and neutral sea ice trends due to internal variability, but they are unlikely. Constraining the model to observed winds and meltwater fluxes from 1990 through 2021 gives SST variability and trends consistent with observations. Meltwater and winds contribute a similar amount to the SST trend, and winds contribute more to the sea ice trend than meltwater. However, while the constrained model captures much of the observed sea ice variability, it only partially captures the post-2015 sea ice reduction.

Introduction. The Southern Ocean is of critical importance for global climate. Connecting three major ocean basins, it plays a key role in global ocean circulation via sea ice formation (Abernathey et al., [2016](#)) and is responsible for a large majority of global ocean heat and carbon uptake (Frölicher et al., [2015](#)). It drives melt of the Antarctic ice sheet (AIS), impacting global and regional sea level rise (Rignot et al., [2019](#))—a major threat to societies around the world. Changes in the Southern Ocean may also impact the climate of other regions via atmospheric teleconnections (Kim et al., [2022](#)). Besides these physical climate impacts, the subpolar Southern Ocean provides nutrients that shape global biological productivity (Sarmiento et al., [2004](#)).

While most of the globe has warmed in recent decades as greenhouse gas concentrations have increased, the Southern Ocean has cooled on average at the surface, with cooling strongest in the Pacific. Concurrently, the areal coverage of Antarctic sea ice shows a negligible overall trend, consisting of a weak expansion from 1979 through 2015 and strong lows thereafter. The Southern Ocean surface cooling and associated freshening enhance upper ocean stratification, leading to greater subsurface and abyssal warming (Purkey & Johnson, [2013](#); N. C. Swart et al., [2018](#)).

The latest generation of coupled climate models in the Climate Model Intercomparison Project Phase 6 (CMIP6; Eyring et al., [2016](#)) generally does not capture the observed Southern Ocean cooling nor Antarctic sea ice expansion over the recent historical period (Beadling et al., [2020](#); Roach et al., [2020](#); Wills et al., [2022](#)), leading to large uncertainty in projections of future Antarctic and Southern Ocean change (Fox-Kemper et al., [2021](#)). Southern Ocean SSTs and Antarctic sea ice are tightly coupled (Blanchard-Wrigglesworth et al., [2021](#); X. Zhang et al., [2021](#)). In CMIP6 models, the Southern Ocean is typically biased warm and fresh relative to observations, with some models being exceptionally warm (Beadling et al., [2020](#)). Models are broadly unable to capture the observed SST trends over the Southern Ocean, even when considering the internal variability in large ensembles (Wills et al., [2022](#)). Many models simulate strong declines in Antarctic sea ice, unlike the observations, and none capture the observed spatial distribution of sea ice trends (Roach et al., [2020](#)). It has been unclear to what extent the mismatch is due to biases in the forced response versus an underestimation of natural variability (Chung et al., [2022](#); Roach et al., [2020](#)). The observed behavior into externally forced changes and internal variability, and to improve future projections.

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Abstract. A 10-member ensemble simulation with the NASA GISS-E2-1-G climate model shows a clear bifurcation in the Atlantic meridional overturning circulation (AMOC) strength under the SSP2–4.5 extended scenario. At 26°N, the bifurcation leads to 8 strong AMOC and 2 much weaker AMOC states, while at 48°N, it leads to 8 stable AMOC-on and 2 nearly AMOC-off states, the latter lasting approximately 800 years. A variety of fully coupled models have demonstrated tipping points in AMOC through hosing experiments, i.e., prescribing sufficient freshwater inputs in the subpolar North Atlantic. In the GISS simulations, there are no external freshwater perturbations. The bifurcation arises freely in the coupled system and is the result of stochastic variability (noise-induced bifurcation) associated with sea ice transport and melting in the Irminger Sea after a slowing of the greenhouse gas forcing. While the AMOC strength follows the near shutdown of the Labrador Sea deep convection initially, the Irminger Sea salinity and deep mixing determine the timing of the AMOC recovery or near collapse at 48°N, which varies widely across the ensemble members. Other feedbacks such as ice-albedo, ice-evaporation, $E - P$, and the overturning salt-advection feedback play a secondary role that may enhance or reduce the primary mechanism which is ice melt. We believe this is the first time that a coupled climate model has shown such a bifurcation across an initial condition ensemble and might imply that there is a chance for significant and prolonged AMOC slow down due to internal variability of the system.

Introduction. The Atlantic meridional overturning circulation (AMOC) is a distinct pattern of the large-scale oceanic circulation, associated with northward transport of warm and salty waters and the concomitant release of heat to the atmosphere as this water cools and eventually subducts in the North Atlantic Subpolar Gyre and the Nordic seas. Through this process, the AMOC regulates climate locally and regionally in the Northern Hemisphere over seasonal, interannual, and decadal scales, and globally over centennial scales (Buckley and Marshall 2016). At the same time, the AMOC is considered one of the tipping elements of the climate system (Lenton et al. 2008), with low probability of a collapse occurring in the twenty-first century but with high impact, according to the latest two Assessment Reports (AR5 and AR6) of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2013, 2021).

This paper investigates the AMOC bistability in the NASA Goddard Institute for Space Studies (GISS) version E2.1 climate model (GISS-E2-1-G) model simulations under surface warming conditions consistent with middle-of-the-road projections of anthropogenic greenhouse gas (GHG) emissions, prescribed in the Shared Socioeconomic Pathway (SSP) 2–4.5 projection. In a 10-member ensemble scenario, the overturning circulation at 48°N in the Atlantic nearly collapses [reaches 0.7 ± 0.05 Sv (1 Sv $\equiv 106$ m³ s^{−1}) over the course of approximately 400 years] in 2 members and recovers in the rest at different times (Fig. 1). Eventually, the AMOC of those two ensemble members will recover after 800 years of simulations).

The possibility that the AMOC can have multiple equilibrium states and how it may transition between them has been a central theme of AMOC stability analyses since the 1960s (Stommel 1961; Bryan 1986; Manabe and Stouffer 1988; Rahmstorf 1996; de Vries and Weber 2005; Drijfhout et al. 2011; Jackson and Wood 2018; Weijer et al. 2020; Hirschi et al. 2020).

Magma ocean, water, and the early atmosphere of Venus.

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Abstract. The current state and surface conditions of the Earth and its twin planet Venus are drastically different. Whether these differences are directly inherited from the earliest stages of planetary evolution, when the interior was molten, or arose later during the long-term evolution is still unclear. Yet, it is clear that water, its abundance, state, and distribution between the different planetary reservoirs, which are intimately related to the solidification and outgassing of the early magma ocean, are key components regarding past and present-day habitability, planetary evolution, and the different pathways leading to various surface conditions.

In this chapter we start by reviewing the outcomes of the accretion sequence, with particular emphasis on the sources and timing of water delivery in light of available constraints, and the initial thermal state of Venus at the end of the main accretion. Then, we detail the processes at play during the early thermo-chemical evolution of molten terrestrial planets, and how they can affect the abundance and distribution of water within the different planetary reservoirs. Namely, we focus on the magma ocean cooling, solidification, and concurrent formation of the outgassed atmosphere. Accounting for the possible range of parameters for early Venus and based on the mechanisms and feedbacks described, we provide an overview of the likely evolutionary pathways leading to diverse surface conditions, from a temperate to a hellish early Venus. The implications of the resulting surface conditions and habitability are discussed in the context of the subsequent long-term interior and atmospheric evolution. Future research directions and observations are proposed to constrain the different scenarios in order to reconcile Venus' early evolution with its current state, while deciphering which path it followed.

Introduction. Water is not only an essential element for the chemical and biological processes responsible for the emergence and development of life and living organisms (e.g., Westall and Brack 2018; Hoehler et al. 2018). Its abundance and distribution within and between the different reservoirs of a rocky planet, from the deep interior to the exosphere, is also of fundamental importance in controlling their properties and thus the physical and chemical processes at play within and between these reservoirs, making it a crucial factor in setting the conditions suitable for the development of life and for the overall planetary evolution (e.g., Kasting and Catling 2003; Hirschmann 2006; Karato 2015; Foley and Driscoll 2016; Korenaga et al. 2017; Ohtani 2020). Understanding the mechanisms shaping the water budget within the planets and how they evolve through time is thus required to build a consistent picture of planetary evolution and characterize the potential habitability of terrestrial planets (classically defined as the ability of a planet to sustain liquid water at its surface; e.g., Kasting et al. 1993b).

From that perspective, the early stages of planetary evolution appear to be of first importance. Indeed, during this relatively short but intense period of time, the combination of different heat sources, in particular the energy delivered by successive collisions of planetary building-blocks during planetary accretion and growth, is believed to substantially melt the planetary body (e.g., Safronov 1978; Kaula 1979; Tonks and Melosh 1993; Nakajima et al. 2021), resulting in the creation of a so-called “magma ocean” (“MO”): a possibly global, from mantle-thick to near-surface shell of magma of low, water-like viscosity (hence “ocean”; e.g., Warren 1985). During this magma ocean stage, because of the molten surface, the absence of a thick, long-lasting boundary layer between the planetary interior and the atmosphere allows for free and extremely efficient thermal and chemical exchanges between these reservoirs.

The CHROMA cloud top pressure retrieval algorithm for the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) satellite mission.

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Abstract. This paper provides the theoretical basis and simulated retrievals for the Cloud Height Retrieval from O₂ Molecular Absorption (CHROMA) algorithm. Simulations are performed for the Ocean Color Instrument (OCI), which is the primary payload on the forthcoming NASA Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission, and the Ocean Land Colour Instrument (OLCI) currently flying on the Sentinel 3 satellites. CHROMA is a Bayesian approach which simultaneously retrieves cloud optical thickness (COT), cloud-top pressure and height (CTP and CTH respectively), and (with a significant prior constraint) surface albedo. Simulated retrievals suggest that the sensor and algorithm should be able to meet the PACE mission goal for CTP error, which is ± 60 mb for 65 % of opaque ($COT \geq 3$) single-layer clouds on global average. CHROMA will provide pixel-level uncertainty estimates, which are demonstrated to have skill at telling low-error situations from high-error ones. CTP uncertainty estimates are well-calibrated in magnitude, although COT uncertainty is overestimated relative to observed errors. OLCI performance is found to be slightly better than OCI overall, demonstrating that it is a suitable proxy for the latter in advance of PACE's launch. CTP error is only weakly sensitive to correct cloud phase identification or assumed ice crystal habit/roughness. As with other similar algorithms, for simulated retrievals of multi-layer systems consisting of optically thin cirrus clouds above liquid clouds, retrieved height tends to be underestimated because the satellite signal is dominated by the optically thicker lower layer. Total (liquid plus ice) COT also becomes underestimated in these situations. However, retrieved CTP becomes closer to that of the upper ice layer for ice $COT \approx 3$ or higher.

Introduction. The NASA Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission (<https://pace.gsfc.nasa.gov>, last access: 10 February 2023) is expected to launch in January 2024. As its name suggests, it will extend and improve upon various key satellite-based Earth system data records in the atmospheric and ocean colour disciplines ([Werdell et al., 2019](#)). PACE will host three sensors; the primary payload is the Ocean Color Instrument (OCI), a broad-swath passive imaging radiometer with continuous spectral coverage from the ultraviolet to near-infrared (NIR), as well as seven discrete channels in the NIR and short-wave infrared (SWIR). It will also carry two CubeSat-sized multi-angle polarimeters, namely the Hyper-Angle Rainbow Polarimeter 2 (HARP2; [Martins et al., 2018](#)) and Spectro-Polarimeter for planetary EXploration (SPEXone; [van Amerongen et al., 2019](#)).

Mission success requires routine production of various geophysical data sets from OCI measurements. These “required” data products represent a minimal set of those which it is envisioned the mission will be able to produce, and in most cases the at-launch algorithms are expected to be adaptations of existing heritage retrieval codes. Due to differences in sensor capabilities, some algorithms require more adaptation than others. For clouds, the required products include a cloud mask, cloud optical thickness (COT) at mid-visible wavelengths, cloud effective radius (CER), cloud-top pressure (CTP), and cloud phase (i.e. liquid droplets or ice crystals). Together COT, CER, and phase will also be used to calculate cloud water path (CWP). CTP can be transformed to cloud-top height or temperature (CTH and CTT respectively); in this paper “altitude” is used to refer to these three coordinate systems generically. These are the same cloud properties in operational production from NASA's MODerate resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS) sensors ([Platnick et al., 2003](#)), among others

Comment on "Advanced testing of low, medium, and high ECS CMIP6 GCM simulations versus ERA5-T2m" by N. Scafetta (2022).

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Abstract. Scafetta (2022, <https://doi.org/10.1029/2022gl097716>) purports to test Coupled Model Intercomparison Project Phase 6 (CMIP6) climate models through a comparison of temperature changes over three decades. Unfortunately, the paper contains numerous conceptual and statistical errors that undermine all of the conclusions. First, no uncertainty is given for the observational temperature difference, making it impossible to assess compatibility with any model result. Second, the CMIP6 data are the ensemble means for each model, but the metric being tested is sensitive to the internal variability and so the full ensemble for each model must be used. When this is corrected, the conclusion that “all models with ECS > 3.0°C overestimate the observed global surface warming” is not sustained. Third, the statistical test in Section 2 would reject all models even in a perfect model setup given sufficient ensemble members, thus the second conclusion “that spatial *t*-statistics rejects the data-model agreement” is also not sustainable.

Introduction. The Coupled Model Intercomparison Project Phase 6 (CMIP6) archive is a publicly available collation of climate model experiments performed by multiple groups around the world (Eyring et al., 2016). It includes simulations of the recent historical past, possible futures, and other idealized numerical experiments. The key characteristics of the archive is that there is (a) structural variability across models, (b) a quantification of initial condition uncertainty (since different initial conditions will give rise to different weather realizations), and (c) some exploration of forcing uncertainty and parametric uncertainty for some models. The historical hindcasts are run for 1850–2014, and are continued using the Shared Socioeconomic Pathways scenarios (2015–2100). For the purposes of this comment, we use the historical simulations paired with the SSP2-4.5 scenario.

We use CMIP6 simulations from the same source as Scafetta (2022), the Climate Explorer (ClimExp) from Koninkrijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute) (KNMI). There are at present 175 individual simulations available from this portal that have historical and ssp245 continuations, from 36 models plus one physics variant which we treat as an independent model. One model listed in Scafetta (2022) does not have any ssp245 data available through ClimExp (note this is a limited subset of the full archive available through the Earth System Grid Federation). ClimExp offers multiple options for downloading the model data for instance, one simulation per model variant, or the ensemble mean per model variant—when more than one initial condition set is available, or a single simulation. In their Section 3, Scafetta (2022) claims to be examining single simulations from each model, however our replication shows that the results in their Table 1 are the ensemble means. We downloaded all the available simulations so that we could examine the impact of internal variability within each model. One model (FIO-ESM-2) does not have a documented climate sensitivity, so its 3 simulations are not used in our analysis (as with Scafetta (2022)), leaving 172 useable simulations. We take the Equilibrium Climate Sensitivity (ECS) values from Zelinka et al. (2020) (plus recent updates and corrections, (Hausfather et al., 2022)).

We downloaded the global mean surface air temperature (SAT) from the European Centre for Medium Range Weather Forecasts Re-Analysis (version 5) (ERA5) (Hersbach et al., 2020; Simmons et al., 2021) directly from the Copernicus data store. We calculate the temperature difference between the two full 11-year periods 1980–1990 and 2011–2021. We note that this is not substantively different from the period used in Scafetta (2022) (January 2011–June 2021). We compare the same period in the models, again noting that this is not substantively different from the average of the 2011–2020 and 2011–2021 periods used in Scafetta (2022).

CERESMIP: A climate modeling protocol to investigate recent trends in the Earth's energy imbalance.

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Abstract. The Clouds and the Earth's Radiant Energy System (CERES) project has now produced over two decades of observed data on the Earth's Energy Imbalance (EEI) and has revealed substantive trends in both the reflected shortwave and outgoing longwave top-of-atmosphere radiation components. Available climate model simulations suggest that these trends are incompatible with purely internal variability, but that the full magnitude and breakdown of the trends are outside of the model ranges. Unfortunately, the Coupled Model Intercomparison Project (Phase 6) (CMIP6) protocol only uses observed forcings to 2014 (and Shared Socioeconomic Pathways (SSP) projections thereafter), and furthermore, many of the 'observed' drivers have been updated substantially since the CMIP6 inputs were defined. Most notably, the sea surface temperature (SST) estimates have been revised and now show up to 50% greater trends since 1979, particularly in the southern hemisphere. Additionally, estimates of short-lived aerosol and gas-phase emissions have been substantially updated. These revisions will likely have material impacts on the model-simulated EEI. We therefore propose a new, relatively low-cost, model intercomparison, CERESMIP, that would target the CERES period (2000-present), with updated forcings to at least the end of 2021. The focus will be on atmosphere-only simulations, using updated SST, forcings and emissions from 1990 to 2021. The key metrics of interest will be the EEI and atmospheric feedbacks, and so the analysis will benefit from output from satellite cloud observation simulators. The Tier 1 request would consist only of an ensemble of AMIP-style simulations, while the Tier 2 request would encompass uncertainties in the applied forcing, atmospheric composition, single and all-but-one forcing responses. We present some preliminary results and invite participation from a wide group of models.

Introduction. The Earth's Energy Imbalance (EEI) refers to an imbalance between how much solar radiant energy is absorbed by Earth and how much thermal infrared radiation is emitted to space (Stephens et al., 2012; Trenberth and Cheng, 2022; von Schuckmann et al., 2023). Assuming constant atmospheric composition, a positive EEI would imply increasing global mean temperature, sea level rise, further heating within the ocean and land, and melting of snow and sea ice (Masson-Delmotte et al., 2021). As such, EEI is a key metric for detecting ongoing anthropogenic climate change and assessing the causes (e.g., Hansen et al., 1988, 2005). Climate models have long predicted that the increases in well-mixed greenhouse gases would cause an increasing net energy imbalance for the planet, a prediction that was borne out with the observed increases in ocean heat content (e.g., Levitus et al., 2001; Meehl et al., 2005; Donohoe et al., 2014; von Schuckmann et al., 2016; Hakuba et al., 2021; Cheng et al., 2022). Over the period 1970–2020, the EEI is estimated to have been $0.48 \pm 0.1 \text{ W m}^{-2}$ (von Schuckmann et al., 2023), with a clear acceleration seen over the last two decades (Figure 1).

In effect, EEI represents the net heating acting on the climate system—it is the difference between total climate forcing and the climate system's response to the forcing (Hansen et al., 2011). The EEI is driven by increasing CO₂ and other GHGs as well as changes in aerosols and feedbacks associated with temperature, water vapor, cloud, and surface albedo changes. Continued increases in greenhouse gases and a reversal in recent aerosol forcing trends has led to an acceleration of the forcing of climate change (Quaas et al., 2022). In principle, accelerated climate forcing should increase EEI, but over decadal and shorter timescales appreciable internal climatic variations potentially offset or augment the anthropogenic forcing impacts.

Anomalous meltwater from ice sheets and ice shelves is a historical forcing.

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Abstract. Recent mass loss from ice sheets and ice shelves is now persistent and prolonged enough that it impacts downstream oceanographic conditions. To demonstrate this, we use an ensemble of coupled GISS-E2.1-G simulations forced with historical estimates of anomalous freshwater, in addition to other climate forcings, from 1990 through 2019. There are detectable differences in zonal-mean sea surface temperatures (SST) and sea ice in the Southern Ocean, and in regional sea level around Antarctica and in the western North Atlantic. These impacts mostly improve the model's representation of historical changes, including reversing the forced trends in Antarctic sea ice. The changes in SST may have implications for estimates of the SST pattern effect on climate sensitivity and for cloud feedbacks. We conclude that the changes are sufficiently large that model groups should strive to include more accurate estimates of these drivers in all-forcing historical simulations in future coupled model intercomparisons.

Introduction. While coupled climate models have skillfully predicted global mean sea surface temperature (SST) trends since the 1970s (Hausfather et al., [2020](#)), and successfully represented them in hindcasts over the historical period (e.g., Miller et al., [2021](#)), there are nonetheless persistent regional biases. Notably, cooling trends since the 1980s in the Eastern Tropical Pacific and in the Southern Oceans are significantly different from the expectations drawn from the Coupled Model Intercomparison Project, Phase 6 (CMIP6) multi-model ensemble (Eyring et al., [2021](#)) (Figure [1](#)) even when the models are screened for the likely range of Transient Climate Response (TCR) (Hausfather et al., [2022](#)). Whether these departures from the expected forced pattern derived from a multi-model mean are due to internal variability, unrepresented or poorly represented climate feedbacks, or mis-specifications or incompleteness of the forcings, is a subject of much current research (Dong et al., [2022](#); Kang et al., [2023](#); Wills et al., [2022](#)).

Additionally, trends in Antarctic sea ice have been anomalous with respect to the multi-model ensembles (Roach et al., [2020](#)). From 1979 to 2014, Antarctic trends were in fact slightly positive, in contrast to the situation in the Arctic and to the expectations of the CMIP5/CMIP6 models (Roach et al., [2020](#); Rye et al., [2020](#)). Internal variability in the region is however high, and in recent years (2015 onward), Antarctic sea ice anomalies have been significantly negative, with 2022/2023 being the lowest austral summer sea ice amounts on record (Gautier, [2023](#)).

Many explanations have been proposed for the departures in the Southern Ocean - such as impacts of changes in the Southern Annular Mode (driven by ozone depletion and rising greenhouse gases (Hartmann, [2022](#); Kostov et al., [2017](#), [2018](#); Miller et al., [2006](#))), problems associated with coarse resolution in ocean models that don't permit or resolve eddies (Rackow et al., [2022](#); Yeager et al., [2023](#)), and/or errors in Southern Ocean cloud feedbacks (Dong et al., [2022](#); Kim et al., [2022](#)). One specific forcing that was not included in the CMIP5/6 models is the freshwater from historical changes in the mass balance of the Antarctic ice sheet and surrounding ice shelves (Bintanja et al., [2013](#)). Note that for models without a representation of the dynamics of ice sheets and ice shelves, which includes all of the models in the standard CMIP6 historical ensemble, anomalous freshwater or ice inputs from the ice sheets can be regarded as a forcing, even if in the fully coupled ice-sheet climate system those fluxes might arise as a response to ongoing climate changes. Hereafter, we therefore refer to the freshwater as a forcing in this context.

Understanding CMIP6 biases in the representation of the greater Horn of Africa long and short rains.

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Abstract. The societies of the Greater Horn of Africa (GHA) are vulnerable to variability in two distinct rainy seasons, the March–May ‘long’ rains and the October–December ‘short’ rains. Recent trends in both rainy seasons, possibly related to patterns of low-frequency variability, have increased interest in future climate projections from General Circulation Models (GCMs). However, previous generations of GCMs historically have poorly simulated the regional hydroclimate. This study conducts a process-based evaluation of simulations of the long and short rains in CMIP6, the latest generation of GCMs. Key biases in CMIP5 remain or are worsened, including long rains that are too short and weak and short rains that are too long and strong. Model biases are driven by a complex set of related oceanic and atmospheric factors, including simulations of the Walker Circulation. Biased wet short rains in models are connected with Indian Ocean zonal sea surface temperature (SST) gradients that are too warm in the west and convection that is too deep. Models connect equatorial African winds with the strength of the short rains, though in observations a robust connection is primarily found in the long rains. Model mean state biases in the timing of the western Indian Ocean SST seasonal cycle are associated with certain rainfall timing biases, though both biases may be due to a common source. Simulations driven by historical SSTs (AMIP runs) often have larger biases than fully coupled runs. A path towards using biases to better understand uncertainty in projections of GHA rainfall is suggested.

Introduction. The Greater Horn of Africa (GHA), comprising eleven countries in East Africa, is a region of both climatic extremes and related societal vulnerability. It comprises the driest area of the tropics, while its societies are heavily dependent on the rainfall cycle. Around 75% of the population in Ethiopia, Kenya, and Tanzania are smallholder farmers primarily working on rainfed lands (Salami et al. [2019](#); Biazin et al. [2012](#)), and around 60% of the Somali population practice pastoralism in arid and semi-arid water-stressed regions (UNDP [2019](#)). Consequently, droughts are often associated with threats to food security—for example, the 2011 East African Drought led to the United Nations declaring a famine in southern Somalia, where 2.8 million people needed ‘life-saving assistance’ (NASA Earth Observatory [2011](#)).

A notable characteristic of the regional climate is the presence of two distinct rainy seasons in the coastal plains of Ethiopia, Somalia, Kenya, and Tanzania: the stronger ‘long’ rains, known locally as the *gu* in Somali or *masika* in Swahili, occur in the boreal spring, and the generally weaker but more variable ‘short’ rains, known locally as the *deyr* in Somali or *vuli* in Swahili, occur in the boreal fall (these will be referred to as the ‘long’ and ‘short’ rains, respectively, throughout this paper). Drought extremes that contribute to famines often result from a mistiming or a complete loss of a rainy season such as during the fall 2010 drought (FEWSNET [2011](#)), in which the short rains largely failed. Conversely, particularly wet seasons can cause destructive flooding, such as during the record short rains associated with the 1997–1998 El Niño, which resulted in over 1300 deaths and 270,000 displacements in Somalia alone (IRIN [97](#)).

Recent trends in the observational records in both rainy seasons have heightened concerns about the impact of climate change on rainfall variability in the GHA region. Declines in total annual rainfall since 1983 and specifically during the long rains have been found in studies examining satellite data, station records, satellite-station hybrid datasets, and in farmer recollections (Diem et al. [2014](#), [2019](#); Ssentongo et al. [2018](#); Cattani et al. [2018](#); Salerno et al. [2019](#)). These changes are associated with a decrease in the rainy season length, with both later onsets and earlier demises (Wainwright et al. [2019](#)).

Design and performance of the Hotrod melt-tip ice-drilling system.

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Abstract. We introduce the design and performance of an electrothermal ice-drilling system designed to insert a temperature sensor cable into ice. The melt tip is relatively simple and low-cost, designed for a one-way trip to the ice–bed interface. The drilling system consists of a melt tip, umbilical cable, winch, interface, power supply, and support items. The melt tip and the winch are the most novel elements of the drilling system, and we make the hardware and electrical designs of these components available open-access. Tests conducted in a laboratory indicate that the melt tip has an electrical energy to forward melting heat transfer efficiency of ~35 % with a theoretical maximum penetration rate of ~12 m h⁻¹ at maximum 6.0 kW power. In contrast, ice-sheet testing suggests the melt tip has an analogous heat transfer efficiency of ~15 % with a theoretical maximum penetration rate of ~6 m h⁻¹. We expect the efficiency gap between laboratory and field performance to decrease with increasing operator experience. Umbilical freeze-in due to borehole refreezing is the primary depth-limiting factor of the drilling system. Enthalpy-based borehole refreezing assessments predict refreezing below critical umbilical diameter in ~4 h at –20 °C ice temperatures and ~20 h at –2 °C. This corresponds to a theoretical depth limit of up to ~200 m, depending on firn thickness, ice temperature, and operator experience.

Introduction. The thermal state of the ice–bed interface is a critical boundary condition for understanding the form and flow of an ice sheet. Geothermal heat flow provides the basal boundary condition for the thermodynamics in an ice-sheet model. The presence or absence of basal sliding similarly provides the basal boundary condition for the continuum mechanics in an ice-sheet model. Presently, however, there is poor scientific agreement over whether the ice–bed interface is at, or below, pressure-melting-point temperature beneath an estimated one-third of the Greenland Ice Sheet (MacGregor et al., 2022). There is also substantial disagreement between regional models of geothermal heat flow across Greenland, which approaches 100 % relative disagreement in southern Greenland (Colgan et al., 2021).

While many boreholes have been drilled around the ice-sheet periphery, basal temperature and geothermal heat flow have only been directly sampled in the ice-sheet interior at six sites in the last 6 decades (Løkkegaard et al., 2022). These six sites denote the locations of the deep Greenland ice cores: Camp Century (1966), DYE-3 (1981), GISP2 (1993), GRIP (1998), NGRIP (2003), and NEEM (2010). Retrieving each of these invaluable ice core records represents a tremendous multi-annual logistical and scientific undertaking (Langeway, 2008). At these sites, ice samples are collected and analyzed as the primary data. Basal temperature and geothermal heat flow are generally measured as secondary data. Demand for increasingly detailed prognostic simulations of ice-sheet form and flow, however, now provides a strong impetus to drill deep boreholes for the primary purpose of measuring basal thermal state (Siegert et al., 2020).

Here, we describe the design and performance of a high-power electrothermal ice-drilling system that has the sole purpose of rapidly deploying thermistor strings to the ice–bed interface with minimum logistical support. The fundamental concept is to pull a thermistor cable into the ice sheet behind a compact and inexpensive melt tip on a one-way trip to the ice–bed interface. We describe the laboratory and field testing of this ice-drilling system. We also discuss the efficiency and applicability of our drilling system.

The important role of African emissions reductions in projected local rainfall changes.

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Abstract. Africa is highly vulnerable to climate change but emits a small portion of global greenhouse gases. Additionally, decarbonization might lead to a ‘climate penalty’ whereby reductions in cooling aerosols offset temperature benefits from CO₂ reductions for several decades. However, climate change impacts conditions other than temperatures, including precipitation. Using the NASA Goddard Institute for Space Studies climate model, we find that although African emissions cuts have weak impacts on projected African temperatures, they significantly impact rainfall. Whereas business-as-usual increasing emissions lead to substantial drying over tropical Northern Hemisphere Africa during local summer, that drying is essentially eliminated under a sustainable development pathway. The reduction in cooling aerosols is responsible for ~33–90% of the avoided drying in our model, with the remainder largely attributable to reduced absorbing aerosols. African policy choices may therefore greatly reduce regional African summer drying, giving parts of Africa substantial leverage over their own climate and air quality future.

Introduction. Africa is developing rapidly, with rapid population growth, economic growth, and urbanization¹. The African Union’s Agenda 2063, the ‘Africa We Want’, articulates a vision for development where people have improved and sustainable livelihoods, live in clean environments with low air pollution, and where Africa ensures that it is climate resilient. Though African countries aim to play their role in limiting global climate change, as evidenced by their latest NDC submissions, the perception is that local efforts to address climate change are almost entirely about adaptation. This is because local mitigation is expected to have little impact on African climate change given that Africa emits less than 4% of global (2020) CO₂ emissions from fossil fuels and industry².

Cooling aerosols, including sulfates, ammonium, nitrates, and organic carbon, contribute to local air pollution and currently mask a portion of the warming from increased greenhouse gases (GHGs). Removal of these aerosols, either due to policies to improve air quality or to mitigate climate change, can thus have both beneficial and detrimental effects on society via changes in both air quality and climate. There is a large body of literature on the so-called ‘climate penalty’ attributable to reductions in cooling aerosols that unmask greenhouse gas warming^{3,4,5}. For example, aerosol reductions that were implemented for the sake of air quality have contributed to observed local warming in the US⁶, Europe⁷ and China⁸. Although an instantaneous, global removal of all cooling aerosols would lead to a sharp rise in global warming³, a realistic phaseout of fossil fuel usage would only lead to a modest (~0.02–0.10 °C) warming⁹. The knowledge that climate mitigation can lead to near-term warming has led some to a focus on strategies that prioritize the rapid reduction in emissions of short-lived climate pollutants (SLCPs), the strategy promoted by the Climate and Clean Air Coalition. Adoption of both sustainable development and SLCP reduction strategies provides a pathway for near-term mitigation of both warming and drying^{10,11}.

The climate scientific community continues to highlight the temperature penalty associated with the aerosol decreases that accompany GHG reductions. For instance, the latest Intergovernmental Panel on Climate Change (IPCC) report’s Summary for Policy Makers highlights this ‘climate penalty’, stating that “In the low and very low GHG emissions scenarios, assumed reductions in anthropogenic aerosol emissions lead to a net warming”¹². Similarly, that report’s Frequently Asked Question 6.2 shows how emission reductions lead to one or more of four outcome categories: climate benefit, crop benefit, health benefit, and climate penalty, with reductions in cooling aerosols leading to health benefit and climate penalty impacts only. As Africa has a particularly large ratio of aerosol to CO₂ emissions, the climate penalty in response to African decarbonization might be expected to be especially large.

The life and death of a subglacial lake in West Antarctica.

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Abstract. Over the past 50 years, the discovery and initial investigation of subglacial lakes in Antarctica have highlighted the paleo-glaciological information that may be recorded in sediments at their beds. In December 2018, we accessed Mercer Subglacial Lake, West Antarctica, and recovered the first *in situ* subglacial lake-sediment record—120 mm of finely laminated mud. We combined geophysical observations, image analysis, and quantitative stratigraphy techniques to estimate long-term mean lake sedimentation rates (SRs) between $0.49 \pm 0.12 \text{ mm a}^{-1}$ and $2.3 \pm 0.2 \text{ mm a}^{-1}$, with a most likely SR of $0.68 \pm 0.08 \text{ mm a}^{-1}$. These estimates suggest that this lake formed between 53 and 260 a before core recovery (BCR), with a most likely age of $180 \pm 20 \text{ a BCR}$ —coincident with the stagnation of the nearby Kamb Ice Stream. Our work demonstrates that interconnected subglacial lake systems are fundamentally linked to larger-scale ice dynamics and highlights that subglacial sediment archives contain powerful, century-scale records of ice history and provide a modern process-based analogue for interpreting paleo-subglacial lake facies.

Introduction. More than 600 subglacial lakes have been identified beneath the Antarctic ice sheet, including 140 “active” lakes that fill and drain, modulating subglacial meltwater transport from the continental interior to coastal ocean ([Livingstone et al., 2022](#)). Geophysical evidence shows that sediment deposition occurs at beds of subglacial lakes (e.g., [Peters et al., 2008](#); [Smith et al., 2018](#)); this sediment record has been hypothesized to provide a record of subglacial processes and ice-sheet history ([Bentley et al., 2011](#); [Yan et al., 2022](#)). However, Antarctic subglacial lakes are among the least accessible features on Earth, leaving this hypothesis largely untested: the only documented subglacial lake sediment cores were retrieved from Whillans Subglacial Lake (SLW) and consisted of structureless diamict indistinguishable from those retrieved from non-lacustrine subglacial environments ([Kamb, 2001](#)).

We present unequivocal evidence that lake sediment deposition occurs in Mercer Subglacial Lake (SLM), located 63 km south of SLW beneath the West Antarctic Ice Sheet. We demonstrate a tight coupling between the initiation of deposition in SLM and regional ice-stream variability, wherein stagnation of Kamb Ice Stream reorganized ice flow of adjacent ice streams ([Catania et al., 2012](#)) and led to SLM formation $180 \pm 20 \text{ a}$ before core recovery (BCR) based on our most likely sedimentation rate (SR) estimate. Subglacial lakes modulate ice-flow velocity (e.g., [Stearns et al., 2008](#)), impact location and timing of freshwater and nutrient-rich discharge into the Southern Ocean ([Carter and Fricker, 2012](#)), and interact with deeper, more expansive subglacial groundwater systems ([Gustafson et al., 2022](#)). Therefore, establishing the life cycle of these features remains crucial for quantifying transport of carbon ([Vick-Majors et al., 2020](#)), nutrients ([Hawkings et al., 2020](#)), and dissolved gases ([Michaud et al., 2017](#)) within and beyond the subglacial system.

The downstream confluence of Mercer and Whillans Ice Streams hosts a widespread, active subglacial hydrologic network ([Fricker et al., 2007](#)). Interconnected chains of subglacial lakes, including SLM and SLW ([Fig. 1A](#)), temporarily store water for months to decades before episodic drainage events release water downstream (e.g., [Smith et al., 2009](#)). Based on updated lake surface-elevation time series, SLM completes a fill-drain cycle every 4–6 a ([Fig. 1B](#)) with a clear connection to the activity of two lakes upstream: Conway Subglacial Lake (SLC) and Upper Conway Subglacial Lake (USLC) ([Fig. 1C](#); [Carter et al., 2013](#)).

Long-term variability of Jupiter's mid-infrared auroral CH₄ emissions.

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Abstract. We present a study of the long-term variability of Jupiter's mid-infrared CH₄ auroral emissions. 7.7–7.9 μm images of Jupiter recorded by NASA's [Infrared Telescope](#) Facility, Subaru and Gemini-South over the last three decades were collated in order to quantify the magnitude and timescales over which the northern auroral hotspot's CH₄ emission varies. These emissions predominantly sound the 10- to 1-mbar pressure range and therefore highlight the temporal variability of lower-stratospheric auroral-related heating. We find that the ratio of the radiance of the poleward northern auroral emissions to a lower-latitude zonal-mean, henceforth 'Relative Poleward Radiance' or RPR, exhibits variability over a 37% range and over a range of apparent timescales. We searched for patterns of variability in order to test whether seasonally varying solar insolation, the 11-year solar cycle, or short-term solar wind variability at Jupiter's [magnetopause](#) could explain the observed evolution. The variability of the RPR exhibits a weak ($r < 0.2$) correlation with both the instantaneous and phase-lagged solar insolation received at Jupiter's high-northern latitudes. This rules out the hypothesis suggested in previous work (e.g. Sinclair et al. 2017a, 2018) that shortwave solar heating of aurorally produced haze particles is the dominant auroral-related heating mechanism in the lower [stratosphere](#). We also find the variability exhibits negligible ($r < 0.18$) correlation with both the instantaneous and phase-lagged monthly-mean [sunspot number](#), which therefore rules out a long-term variability associated with the solar cycle. On shorter timescales, we find moderate correlations of the RPR with solar wind conditions at Jupiter in the preceding days before images were recorded. For example, we find correlations of $r = 0.45$ and $r = 0.51$ of the RPR with the mean and standard deviation solar wind dynamical pressure in the preceding 7 days. The moderate correlation suggests that either: (1) only a subset of solar wind compressions lead to brighter, poleward CH₄ emissions and/or (2) a subset of CH₄ emission brightening events are driven by internal magnetospheric processes (e.g., Io activity) and independent of solar wind enhancements.

Introduction. Auroral processes on Jupiter represent an extreme example of space weather due to the planet's large magnetic field and the internal plasma source in the form of Io's volcanism. Solar wind perturbations to the magnetosphere and internal magnetospheric dynamics accelerate energetic ions and electrons into Jupiter's polar atmosphere producing auroral emissions over a large range of the electromagnetic spectrum (e.g., Dunn et al., 2017, Hue et al., 2021, O'Donoghue et al., 2021). A significant amount of energy is ultimately deposited as deep as Jupiter's lower stratosphere (~ 1 mbar), heating the atmosphere (e.g. Drossart et al., 1993, Sinclair et al., 2018), enriching the abundances of higher-order hydrocarbons (e.g. Sinclair et al., 2017a, Sinclair et al., 2019b), thereby producing enhanced mid-infrared emission features of stratospheric CH₄ and its photochemical by-products species (e.g. Caldwell et al., 1980, Kim et al., 1985, Kostiuk et al., 1993, Flasar et al., 2004).

The auroral hotspots in both auroral regions have been observed using both Earth-based (e.g., Kostiuk et al., 1993, Drossart et al., 1993, Livengood et al., 1993, Kim et al., 2014, Sinclair et al., 2018) and spacecraft instrumentation (Flasar et al., 2004, Sinclair et al., 2017a, Sinclair et al., 2019a). Generally, the strongest mid-infrared auroral emissions, commonly termed the 'auroral hotspot', are observed spatially coincident with the 'poleward' ultraviolet auroral emissions: enclosed within or magnetospherically poleward of the main auroral oval (e.g. Grodent et al. 2015). Anecdotally, the auroral hotspots have been observed to vary in brightness, disappear and re-emerge but the mechanisms driving this variability have remained uncertain. This is demonstrated in Fig. 1, which shows examples where the northern auroral hotspot is absent and another where it is present.

Causes, impacts, and mitigation strategies of urban pluvial floods in India: A systematic review.

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Abstract. Urban pluvial floods or rainfall-driven floods are often misrepresented as nuisance floods and tend to receive limited attention. In [India](#), recent urban pluvial floods have affected population displacement, damaged infrastructure, and impacted means of livelihood. In this paper, we describe the current state of rainfall-driven flood research in India, focusing on how the scholarly community approaches the causes, impacts, and mitigation strategies in urban settings. This [systematic literature review](#) of academic databases SCOPUS, Web of Science, Science Direct, and Google Scholar asks: 1) In the context of India, how do we define urban pluvial [flooding](#)? 2) What factors cause urban pluvial [flooding](#) in India? 3) What are the impacts of urban pluvial flooding in India? and 4) What mitigation strategies should be adopted to cope with urban pluvial floods? Our close review of 62 articles finds that urban pluvial floods in India are attributed to extreme rainfall (n = 51), urban development (n = 44), topography (n = 34), drainage (n = 33), waste (n = 13), management (n = 11), and soil type (n = 7). We categorize the reported impacts of such floods as direct (n = 31) and indirect (n = 14) and the suggested mitigation strategies to cope with pluvial urban floods as proactive (n = 57), reactive (n = 6), and recovery (n = 10). This review provides a summary of urban pluvial floods in India and suggests new directions for future research.

Introduction. The Intergovernmental Panel on Climate Change (IPCC) stated with high confidence that over 20 million people per year have been displaced by extreme weather events such as storms and floods since 2008 [\[1\]](#). Flood hazards can be difficult to escape, due to the onset speed and interruption of [evacuation](#) routes, particularly for low-income households. Recent research suggests that 1.81 billion people (23% of the world population) live in areas at risk of 1-in-100-year floods, with the vast majority (89%) living in low- and middle-income countries [\[2\]](#). Since the early 2000s, flood frequency and duration has increased at a global scale [\[3\]](#). It is also a trend likely to continue. The IPCC, with ‘medium confidence,’ found that the likelihood of floods will increase in many regions due to rising temperatures making heavy rain events more frequent [\[1\]](#).

Urban floods are a growing issue of concern for both developed and developing nations [\[4\]](#). [Rapid population growth](#) in urban areas increases exposure to floods. Flood risk is further compounded by unequal social vulnerability, increased runoff, and inadequate infiltration [\[5,6\]](#). In the past decade, researchers have assessed the impacts of [flooding](#) through holistic frameworks of flood risk management. These frameworks consider risks beyond physical processes and include associated probabilities of socioeconomic consequences, ecological frameworks, and technological dimensions [\[7, 8, 9, 10\]](#). Such holistic frameworks can alleviate the complex nature of urban [flooding](#) and provide a [risk analysis](#) system that prepares a community to incorporate sustainable mitigation strategies. Urban floods are not constrained to the growing number of megacities; billions live in small and intermediate cities which typically have fewer resources to mitigate and respond to floods [\[4,11\]](#). Most urban flood research is focused on areas susceptible to coastal storm surges, dam outbursts, or fluvial (river-based) floods [\[12, 13, 14\]](#). However, less work has considered the direct risk to urban areas from ‘pluvial’ (rainfall-runoff) floods, despite several studies indicating that excessive surface runoff is likely to pose a threat to human-environment systems [\[15, 16, 17\]](#). Recent advances in urban pluvial research include expansion of [global navigation satellite systems](#), hydrological forecasts through [data assimilation](#), and radar station technologies that have allowed finer scale monitoring of such floods; progress in achieving better computational capabilities with hopes to improve models for real-time applications; and an interdisciplinary understanding of pluvial flood risks and opportunities to achieve [urban resilience](#) [\[18, 19, 20\]](#).

Anthropogenic aerosols delay the emergence of GHGs-forced wetting of South Asian rainy seasons under a fossil-fuel intensive pathway.

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Abstract. With continued fossil-fuel dependence, anthropogenic aerosols over South Asia are projected to increase until the mid-21st century along with greenhouse gases (GHGs). Using the Community Earth System Model (CESM1) Large Ensemble, we quantify the influence of aerosols and GHGs on South Asian seasonal precipitation patterns over the 21st century under a very high-emissions (RCP 8.5) trajectory. We find that increasing local aerosol concentrations could continue to suppress precipitation over South Asia in the near-term, delaying the emergence of precipitation increases in response to GHGs by several decades in the monsoon season and a decade in the post-monsoon season. Emergence of this wetting signal is expected in both seasons by the mid-21st century. Our results demonstrate that the trajectory of local aerosols together with GHGs will shape near-future precipitation patterns over South Asia. Therefore, constraining precipitation response to different trajectories of both forcings is critical for informing near-term adaptation efforts.

Introduction. Anthropogenic aerosols have affected multiple aspects of the Earth's climate system by modulating the Earth's energy budget and influencing cloud properties (Sato & Suzuki, 2019; Szopa et al., 2021). Their effects are particularly strong over East and South Asia, where their current concentrations are among the highest worldwide (Samset et al., 2019; Singh et al., 2019). In fact, anthropogenic aerosols have been identified as a stronger driver of historical changes in South Asian monsoon precipitation than greenhouse gases (GHGs) (Z. Li et al., 2016; Singh et al., 2019). In contrast to most other regions, aerosol concentrations are projected to increase over South Asia for the next few decades even with moderate air-quality policies (Lund et al., 2019; Samset et al., 2019; Figure S1 in Supporting Information S1). Few studies examine how the trajectory of aerosols is likely to influence future precipitation patterns over South Asia and most risk assessments rely on the climate response to GHGs (Persad et al., 2022).

Aerosols influence climate through various processes including modification of the radiation budget, tropospheric lapse rates, and cloud microphysical properties, and altering thermal and moisture gradients that govern the large-scale circulation (J. Li et al., 2022; Szopa et al., 2021). High aerosol concentrations across the Northern Hemisphere (NH) have shifted the Intertropical Convergence Zone (ITCZ) southward, weakening the NH monsoon circulation and suppressing monsoonal precipitation (Z. Li et al., 2016). The effect of aerosols on South Asia precipitation depends on their composition, spatial distribution, emission sources, meteorology, and cooling efficacies (Persad & Caldeira, 2018; Westervelt et al., 2020). Black carbon from fossil fuel combustion and biomass burning dominates aerosol loading during the pre-monsoon (March–May) and post-monsoon (October–December) seasons, while a mix of anthropogenic aerosols, mineral dust, and sea salt aerosols occur in the monsoon (June–September) season (Z. Li et al., 2016; Westervelt et al., 2020). Anthropogenic aerosols have suppressed ~30–50% of the global mean warming caused by GHGs since the mid-twentieth century (Szopa et al., 2021; Persad et al., 2022), offsetting warming-driven intensification of rain-producing systems such as atmospheric rivers (Baek & Lora, 2021) and the Asian monsoons (Ayantika et al., 2021; Singh et al., 2019).



Early Career Winner

Investigating hydroclimatic impacts of the 168-158 BCE volcanic quartet and their relevance to the Nile River basin and Egyptian history.

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Abstract. The Ptolemaic era (305–30 BCE) is an important period of Ancient Egyptian history known for its material and scientific advances, but also intermittent political and social unrest in the form of (sometimes widespread) revolts against the Ptolemaic elites. While the role of environmental pressures has long been overlooked in this period of Egyptian history, ice-core-based volcanic histories have identified the period as experiencing multiple notable eruptions, and a repeated temporal association between explosive volcanism and revolt has recently been noted. Here we analyze the global and regional (Nile River basin) hydroclimatic response to a unique historical sequence of four large and closely timed volcanic eruptions (first a tropical one, followed by three extratropical northern hemispheric events) between 168 and 158 BCE, a particularly troubled period in Ptolemaic history for which we now provide a more detailed hydroclimatic context. The NASA (National Aeronautics and Space Administration) GISS (Goddard Institute for Space Studies) ModelE2.1 Earth system model simulates a strong radiative response with a radiative forcing (top of atmosphere) of -7.5 W m^{-2} (following the first eruption) and -2.5 W m^{-2} (after each of the three remaining eruptions) at a global scale. Associated with this, we observe a global surface cooling of the order of $1.5 \text{ }^{\circ}\text{C}$ following the first (tropical) eruption, with the following three extratropical eruptions extending the cooling period for more than 15 years. Consequently, this series of eruptions is observed to constrain the northward migration of the inter-tropical convergence zone (ITCZ) during the Northern Hemisphere summer monsoon season, and major monsoon zones (African, South Asian, and East Asian) were seen to experience a suppression of rainfall of $>1 \text{ mm d}^{-1}$ during the monsoon (JJAS) season averaged for 2 years after each eruption. A substantial suppression of the Indian and North African summer monsoon (over the Nile River headwater region) was seen to strongly affect the modeled river flow in the catchment and discharge at river mouth. River mass flow over the basin was observed to decrease by 29 % and 38 % relative to an unperturbed (non-volcanic) annual mean flow in the first and second year, respectively, after the first (i.e., tropical) eruption. A moderate decrease ranging between 5 % and 18 % was observed after the third and fourth (extratropical) eruptions. These results indicate, in sum, that the first eruption likely produced a strong hydroclimate response, with the following extratropical eruptions prolonging this. These results also support the recently hypothesized association between ice-core-based signals of explosive volcanism and hydroclimatic variability during the Ptolemaic era, including the suppression of the agriculturally critical Nile summer flooding.

Introduction. Explosive volcanic eruptions that result in high-altitude sulfate aerosol distribution across one or both hemispheres can diminish insolation with global and regional climatic impacts (e.g., Robock, 2000; Toohey et al., 2019). The sulfate aerosols resulting from (for example) the 1991 Mt. Pinatubo eruption of $\sim 18 \text{ Tg SO}_2$ increased the aerosol optical depth of the stratosphere up to ~ 0.15 (from <https://data.giss.nasa.gov/modelforce/strataer/>, last access: 17 January 2023) and was associated with surface cooling of $0.5 \text{ }^{\circ}\text{C}$ (Robock and Mao, 1995; Parker et al., 1996). Volcanically induced cooling can also reduce net evaporation and hence precipitation over large areas (Lui et al., 2016; Iles et al., 2013), while also potentially producing a near-global dynamical suppression of the northward migration of the inter-tropical convergence zone (ITCZ) during the boreal summer, as the convergence follows the surface area of maximum temperature (Peterson et al., 2000; Chiang and Bitz, 2005; Broccoli et al., 2006; Colose et al., 2016). These changes can impact river outflow (Oman et al., 2006; Sabzevari et al., 2015; Kostić et al., 2016), with implications for civilizations from antiquity to the present-day. The Nile River, upon which Egyptian agriculture was heavily dependent, is a key example.

Evaluating Greenland surface-mass-balance and firn-densification data using ICESat-2 altimetry.

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Abstract. Surface-mass-balance (SMB) and firn-densification (FD) models are widely used in altimetry studies as a tool to separate atmospheric-driven from ice-dynamics-driven ice-sheet mass changes and to partition observed volume changes into ice-mass changes and firn-air-content changes. Until now, SMB models have been principally validated based on comparison with ice core and weather station data or comparison with widely separated flight radar-survey flight lines. Firn-densification models have been primarily validated based on their ability to match net densification over decades, as recorded in firn cores, and the short-term time-dependent component of densification has rarely been evaluated at all. The advent of systematic ice-sheet-wide repeated ice-surface-height measurements from ICESat-2 (the Ice Cloud, and land Elevation Satellite, 2) allows us to measure the net surface-height change of the Greenland ice sheet at quarterly resolution and compare the measured surface-height differences directly with those predicted by three FD–SMB models: MARv3.5.11 (Modèle Atmosphérique Régional version 3.5.11) and GSFCv1.1 and GSFCv1.2 (the Goddard Space Flight Center FD–SMB models version 1.1 and 1.2). By segregating the data by season and elevation, and based on the timing and magnitude of modelled processes in areas where we expect minimal ice-dynamics-driven height changes, we investigate the models' accuracy in predicting atmospherically driven height changes. We find that while all three models do well in predicting the large seasonal changes in the low-elevation parts of the ice sheet where melt rates are highest, two of the models (MARv3.5.11 and GSFCv1.1) systematically overpredict, by around a factor of 2, the magnitude of height changes in the high-elevation parts of the ice sheet, particularly those associated with melt events. This overprediction seems to be associated with the melt sensitivity of the models in the high-elevation part of the ice sheet. The third model, GSFCv1.2, which has an updated high-elevation melt parameterization, avoids this overprediction.

Introduction. Ice-sheet surface heights vary on timescales from hours (Amory et al., 2021; Lai et al., 2021) to millennia (Khan et al., 2016; NEEM Community Members, 2013). Repeated altimetry measurements can provide estimates of ice-sheet mass changes (Shepherd et al., 2020) and thus their contribution to sea-level change, providing clues to the mechanisms driving mass loss (Smith et al., 2020; Catania et al., 2020) based on spatial patterns and timing of the changes. On an ice sheet in steady state, whose volume and mass are constant in time, snow accumulation and ice ablation at the surface are balanced by ice-flux divergence in the ice–snow column (e.g. thinning of the ice column related to horizontal stretching of the ice) and by snow and firn compaction in the near-surface layers. Any deviation of the rate of one of these processes from its steady-state rate will result in a non-zero rate of surface-height change. We expect to see large variations in the net surface mass balance over the course of a year, and, over most of the ice sheet, we expect to see much slower, annual-to-decadal variations in the rate of ice-flux divergence driven by evolution of the local stress balance of the ice. Thus, even in a part of the ice sheet where the climatological mean surface mass balance exactly compensates for ice flow, we expect to see seasonal surface-height variations. Secular trends in the local net ice-sheet mass balance, such as thickening due to net annual SMB that exceeds the local flux divergence or thinning due to increased ice-flow speeds that are not balanced by additional snowfall, are superimposed on these seasonal signals.

Time series of ice surface height measured by altimeters cannot, by themselves, distinguish between the effects of surface-mass-balance changes and those of variations in ice flow or between surface-height variations caused by changes in the average firn density (e.g., due to imbalances between snowfall and compaction) and those caused by changes in the ice-column mass.

A governance framework to manage the food-environment-livelihood trilemma of alternative proteins.

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Abstract. Global food systems are closely interconnected with contemporary challenges such as food security, environmental crises, and inclusive development. Protein production, in particular, is strongly associated with these issues, as the resource-intensive predominant production models can lead to environmental pressures and food inequity. Alternative proteins (APs) have been proposed as part of the solution to meeting future global protein demand while keeping modes of production and consumption within planetary boundaries. Here, we stress that the potential of APs to address this crucial food-environment-livelihoods trilemma hinges on collective social choices made early in the sociotechnical transition. We therefore call for a managed and socially embedded transition in which public agents together with civil society and private actors work to ensure balanced outcomes, with global and domestic food inequities in mind. Our emphasis on AP adoption as an open-ended process highlights the underlying political economy of food systems transitions and technological development.

Introduction. Accelerating ecological crises have placed issues related to food production and consumption at the center of the global sustainability agenda. Proteins are key in this respect, as they provide essential macronutrients but are also commonly characterized by resource-intensive modes of production. Debates about how to guarantee sustainable future proteins have frequently highlighted the need to limit the consumption of animal-source (AS) protein. The contributions of AS protein to climate change have often been stressed, either in the form of emissions directly produced as part of the production processor through land-use change due to pasture expansion or feed production. Beyond climate-related emissions, large-scale AS protein production systems have also been found to negatively affect biodiversity and phosphorus and nitrogen cycles, as well as bacterial and zoonotic virus risks.

In response to contemporary and, notably, future sustainability challenges related to AS production, alternative proteins (APs) have been highlighted as a potential solution. The notion of APs refers to a broad category of foodstuffs rich in amino acids, frequently proposed as a substitution for AS proteins, to mitigate negative environmental externalities from meat production. Some AP products are already available for consumers, such as plant-based meat substitutes and precision-fermented products (e.g., mycoproteins and algae). Others, such as cultured meat and insect-based products are still at a more incipient stage of development. In recent years, both public and scientific interest in APs has grown substantially. Beyond the food-environment nexus, much research has thus far tended to focus on issues such as technological maturity and consumer acceptance.

While this approach may be relevant to understanding the challenges in the development and dissemination of AP products, much less attention has been directed at the wider socioeconomic reverberations of this process. A move toward increased AP consumption invariably entails a range of trade-offs and dilemmas related to the technological trajectories and potential societal disruptions that characterize sociotechnical transitions. Outcomes within critical areas such as food security, social development, and environmental sustainability often follow a path-dependent logic, being defined by collective social choices early in the process. A failure to properly address this challenge could not only compromise the purported sustainability goals of AP adoption but maybe even lead to adverse outcomes in terms of nutrition, livelihoods, and resource use. We, therefore, heed calls to take a step backwards and examine the role of APs within future global food systems from a socioeconomic perspective to understand the wider reverberations of a potential socio-institutional change toward meat alternatives.

Spatially-coordinated airborne data and complementary products for aerosol, gas, cloud, and meteorological studies: The NASA ACTIVATE dataset.

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Abstract. The NASA Aerosol Cloud meTeorology Interactions oVer the western ATlantic Experiment (ACTIVATE) produced a unique dataset for research into aerosol–cloud–meteorology interactions, with applications extending from process-based studies to multi-scale model intercomparison and improvement as well as to remote-sensing algorithm assessments and advancements. ACTIVATE used two NASA Langley Research Center aircraft, a HU-25 Falcon and King Air, to conduct systematic and spatially coordinated flights over the northwest Atlantic Ocean, resulting in 162 joint flights and 17 other single-aircraft flights between 2020 and 2022 across all seasons. Data cover 574 and 592 cumulative flights hours for the HU-25 Falcon and King Air, respectively. The HU-25 Falcon conducted profiling at different level legs below, in, and just above boundary layer clouds (< 3 km) and obtained in situ measurements of trace gases, aerosol particles, clouds, and atmospheric state parameters. Under cloud-free conditions, the HU-25 Falcon similarly conducted profiling at different level legs within and immediately above the boundary layer. The King Air (the high-flying aircraft) flew at approximately ~ 9 km and conducted remote sensing with a lidar and polarimeter while also launching dropsondes (785 in total). Collectively, simultaneous data from both aircraft help to characterize the same vertical column of the atmosphere. In addition to individual instrument files, data from the HU-25 Falcon aircraft are combined into “merge files” on the publicly available data archive that are created at different time resolutions of interest (e.g., 1, 5, 10, 15, 30, 60 s, or matching an individual data product's start and stop times). This paper describes the ACTIVATE flight strategy, instrument and complementary dataset products, data access and usage details, and data application notes. The data are publicly accessible through <https://doi.org/10.5067/SUBORBITAL/ACTIVATE/DATA001> (ACTIVATE Science Team, 2020).

Introduction. Aerosol–cloud interactions are responsible for the largest uncertainty in estimates of total anthropogenic radiative forcing (Bellouin et al., 2020). This uncertainty stems partly from the difficulty in experimentally characterizing such interactions in the atmosphere due to the need for methods such as the use of airborne platforms. Furthermore, it is challenging to isolate the relative influence of different factors that impact the life cycle and properties of clouds, including meteorology and aerosol particles. Decades of airborne field studies focused on aerosol–cloud interactions have been limited in terms of the data volume and number of variables measured, the diversity of aerosol and weather conditions, and the vertical data coverage.

The PACE-MAPP algorithm: Simultaneous aerosol and ocean polarimeter products using coupled atmosphere-ocean vector radiative transfer.

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Abstract. We describe the PACE-MAPP algorithm that simultaneously retrieves aerosol and ocean optical parameters using multiangle and multispectral polarimeter measurements from the SPEXone, Hyper-Angular Rainbow Polarimeter 2 (HARP2), and Ocean Color Instrument (OCI) instruments onboard the NASA Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) observing system. PACE-MAPP is adapted from the Research Scanning Polarimeter (RSP) Microphysical Aerosol Properties from Polarimetry (RSP-MAPP) algorithm. The PACE-MAPP algorithm uses a coupled vector radiative transfer model such that the atmosphere and ocean are always considered together as one system. Consequently, this physically consistent treatment of the system across the ultraviolet, (UV: 300–400 nm), visible (VIS: 400–700 nm), near-infrared (NIR: 700–1100 nm), and shortwave infrared (SWIR: 1100–2400 nm) spectral bands ensures that negative water-leaving radiances do not occur. PACE-MAPP uses optimal estimation to simultaneously characterize the optical and microphysical properties of the atmosphere's aerosol and ocean constituents, find the optimal solution, and evaluate the uncertainties of each parameter. This coupled approach, together with multiangle, multispectral polarimeter measurements, enables retrievals of aerosol and water properties across the Earth's oceans. The PACE-MAPP algorithm provides aerosol and ocean products for both the open ocean and coastal areas and is designed to be accurate, modular, and efficient by using fast neural networks that replace the time-consuming vector radiative transfer calculations in the forward model. We provide an overview of the PACE-MAPP framework and quantify its expected retrieval performance on simulated PACE-like data using a bimodal aerosol model for observations of fine-mode absorbing aerosols and coarse-mode sea salt particles. We also quantify its performance for observations over the ocean of dust-laden scenes using a trimodal aerosol model that incorporates non-spherical coarse-mode dust particles. Lastly, PACE-MAPP's modular capabilities are described, and we discuss plans to implement a new ocean bio-optical model that uses a mixture of coated and uncoated particles, as well as a thin cirrus model for detecting and correcting for sub-visual ice clouds.

Introduction. Aerosols constitute the number one source of uncertainty in passive ocean remote sensing products (Gordon, 1997). Legacy atmospheric correction procedures can lead to the retrieval of negative water-leaving radiances in coastal waters where the ocean sub-surface is not completely absorbing in the near-infrared (NIR). But if the atmosphere-ocean system is correctly modeled as a coupled system, then retrieval of negative water-leaving radiances is physically impossible (Stamnes et al., 2003). Retrieval using a coupled atmosphere-ocean system is the best way to reliably and accurately retrieve ocean products in complex coastal zones, particularly in the presence of absorbing aerosol. Therefore, a key feature of the PACE-MAPP algorithm is that the atmosphere and ocean are considered together as one coupled system from a vector radiative transfer perspective. This physically consistent treatment of the atmosphere-ocean system across all spectral bands ensures that negative water-leaving radiances, which can otherwise occur above bright waters such as coastal areas, are avoided. And by simultaneously solving for the aerosol and ocean products, we can determine the optimal solution, together with a full accounting of the uncertainties of each parameter. The PACE-MAPP algorithm, with its coupled atmosphere-ocean vector radiative transfer approach, which is operationally fast due to the use of neural networks, is expected to be capable of providing aerosol and ocean products for both the global ocean and in coastal areas.

Earth-system-model evaluation of cloud and precipitation occurrence for supercooled and warm clouds over the Southern Ocean's Macquarie Island.

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Abstract. Over the remote Southern Ocean (SO), cloud feedbacks contribute substantially to Earth system model (ESM) radiative biases. The evolution of low Southern Ocean clouds (cloud-top heights $< \sim 3$ km) is strongly modulated by precipitation and/or evaporation, which act as the primary sink of cloud condensate. Constraining precipitation processes in ESMs requires robust observations suitable for process-level evaluations. A year-long subset (April 2016–March 2017) of ground-based profiling instrumentation deployed during the Macquarie Island Cloud and Radiation Experiment (MICRE) field campaign (54.5° S, 158.9° E) combines a 95 GHz (W-band) Doppler cloud radar, two lidar ceilometers, and balloon-borne soundings to quantify the occurrence frequency of precipitation from the liquid-phase cloud base. Liquid-based clouds at Macquarie Island precipitate ~ 70 % of the time, with deeper and colder clouds precipitating more frequently and at a higher intensity compared to thinner and warmer clouds. Supercooled cloud layers precipitate more readily than layers with cloud-top temperatures > 0 °C, regardless of the geometric thickness of the layer, and also evaporate more frequently. We further demonstrate an approach to employ these observational constraints for evaluation of a 9-year GISS-ModelE3 ESM simulation. Model output is processed through the Earth Model Column Collaboratory (EMC²) radar and lidar instrument simulator with the same instrument specifications as those deployed during MICRE, therefore accounting for instrument sensitivities and ensuring a coherent comparison. Relative to MICRE observations, the ESM produces a smaller cloud occurrence frequency, smaller precipitation occurrence frequency, and greater sub-cloud evaporation. The lower precipitation occurrence frequency by the ESM relative to MICRE contrasts with numerous studies that suggest a ubiquitous bias by ESMs to precipitate too frequently over the SO when compared with satellite-based observations, likely owing to sensitivity limitations of spaceborne instrumentation and different sampling methodologies for ground- versus space-based observations. Despite these deficiencies, the ESM reproduces the observed tendency for deeper and colder clouds to precipitate more frequently and at a higher intensity. The ESM also reproduces specific cloud regimes, including near-surface clouds that account for ~ 25 % of liquid-based clouds during MICRE and optically thin, non-precipitating clouds that account for ~ 27 % of clouds with bases higher than 250 m. We suggest that the demonstrated framework, which merges observations with appropriately constrained model output, is a valuable approach to evaluate processes responsible for cloud radiative feedbacks in ESMs.

Introduction. Extratropical shortwave (SW) radiation cloud feedbacks are a significant source of uncertainty in Earth system model (ESM) projections of a perturbed climate (e.g., [Caldwell et al., 2016](#); [McCoy et al., 2020](#)). In particular, ESMs in phase 5 of the Coupled Model Intercomparison Project (CMIP5; [Taylor et al., 2012](#)) exhibit high-biased SW absorption due to a deficit in low- and mid-level cloudiness over the Southern Ocean (SO) ([Bodas-Salcedo et al., 2014, 2016](#); [Naud et al., 2014](#)). CMIP6 models improved this bias to some degree (e.g., [Schuddeboom and McDonald, 2021](#); [Cesana et al., 2022](#)), but low- and mid-level clouds at latitudes higher than 55° S were found to still produce a low bias in reflected SW radiation compared to satellite observations (e.g., [Mallet et al., 2023](#)), likely due to poor phase representation in the dominant supercooled-liquid-cloud regime ([Cesana et al., 2022](#)). Furthermore, the equilibrium climate sensitivity (ECS) has increased from CMIP5 to CMIP6 generations, primarily due to stronger positive low-cloud feedbacks ([Zelinka et al., 2020](#)) that may contribute to increased high-biased sea surface temperatures in CMIP6 compared to CMIP5 ([Zhang et al., 2023](#)).

Wheat crop traits conferring high yield potential may also improve yield stability under climate change.

Stella, T., H. Webber, E.E. Rezaei, S. Asseng, P. Martre, S. Dueri, **J.R. Guarín**^{1,2,3}, D. Pequeno, D.F. Calderini, G. Slafer, G. Molero, D. Miralles, G. Garcia, F. Giunta, Y.-U. Kim, C. Wang, **A.C. Ruane**¹, and F. Ewert, 2023

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Abstract. Increasing genetic wheat yield potential is considered by many as critical to increasing global wheat yields and production, barring major changes in consumption patterns. Climate change challenges breeding by making target environments less predictable, altering regional productivity and potentially increasing yield variability. Here we used a crop simulation model solution in the SIMPLACE framework to explore yield sensitivity to select trait characteristics (radiation use efficiency [RUE], fruiting efficiency and light extinction coefficient) across 34 locations representing the world's wheat-producing environments, determining their relationship to increasing yields, yield variability and cultivar performance. The magnitude of the yield increase was trait-dependent and differed between irrigated and rainfed environments. RUE had the most prominent marginal effect on yield, which increased by about 45 % and 33 % in irrigated and rainfed sites, respectively, between the minimum and maximum value of the trait. Altered values of light extinction coefficient had the least effect on yield levels. Higher yields from improved traits were generally associated with increased inter-annual yield variability (measured by standard deviation), but the relative yield variability (as coefficient of variation) remained largely unchanged between base and improved genotypes. This was true under both current and future climate scenarios. In this context, our study suggests higher wheat yields from these traits would not increase climate risk for farmers and the adoption of cultivars with these traits would not be associated with increased yield variability.

Introduction. Recent decades have seen wheat yields ([Hochman et al. 2017](#); [Schauberger et al. 2018](#); [Reynolds and Braun 2022](#)) and harvested area ([FAO 2022](#)) stagnate globally. Current rates of yield increase associated with genetic improvement ($<1\%$ year⁻¹, [Dreisigacker et al. 2021](#)) are not sufficient to meet the increase in wheat grain demand expected by 2050 particularly considering expected demand growth in Asia ([Erenstein et al. 2022](#)), challenging effort to achieve food security. Evidence for on-farm conditions suggest that the rate of genetic improvement is even less optimistic when actual farm production conditions are considered ([Rife et al. 2019](#)). Nevertheless, increasing the genetic yield potential (YP) is considered by many as a cornerstone for an integrated strategy to increase wheat productivity ([Foulkes et al. 2022](#)). In this context, understanding crop yield physiology can support conventional breeding approaches and increase the current rates of genetic gains ([Reynolds and Langridge 2016](#); [Richards et al. 2019](#)). While climate change is projected to increase mean wheat yields in many environments due to CO₂ fertilization effects ([Webber et al. 2018](#); [Jägermeyr et al. 2021](#)), it challenges breeding by making target environments less predictable ([Zheng et al. 2016](#)), altering crop productivity ([Abberton et al. 2016](#); [Atlin et al. 2017](#); [Webber et al. 2018](#)), and potentially increasing yield variability ([Hernandez-Ochoa et al. 2018](#); [Yang et al. 2019](#)). Ensuring continuity in yield gains thus requires genotypic adaptation, that is the design and development of novel cultivars with enhanced productivity and stability under future climates ([Ramirez-Villegas et al. 2020](#)).

Increasing average YP through genetic improvement can be achieved through increasing light interception (LI), radiation use efficiency (RUE) and/or harvest index (HI) ([Reynolds et al. 2012](#)). The contribution of breeding on the improvement of LI is uncertain ([Richards et al. 2019](#)), with studies reporting contrasting trends in LI among modern cultivars ([Acreche et al. 2009](#); [Yang et al. 2021](#)). Despite the generally high LI for wheat canopies, there might be scope for further optimizing in-canopy light characteristics via a modified canopy architecture ([Richards et al. 2019](#); [Slafer et al. 2021](#)).

The Southern Ocean Freshwater Input from Antarctica (SOFIA) Initiative: Scientific objectives and experimental design.

Swart, N.C., T. Martin, R. Beadling, J.-J. Chen, C. Danek, M.H. England, R. Farneti, S.M. Griffies, T. Hattermann, J. Hauck, F.A. Haumann, A. Jüling, Q. Li, **J. Marshall**^{1,2}, M. Muilwijk, A.G. Pauling, A. Purich, I.J. Smith, and M. Thomas, 2023

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Abstract. As the climate warms, the grounded ice sheet and floating ice shelves surrounding Antarctica are melting and releasing additional freshwater into the Southern Ocean. Nonetheless, almost all existing coupled climate models have fixed ice sheets and lack the physics required to represent the dominant sources of Antarctic melt. These missing ice dynamics represent a key uncertainty that is typically unaccounted for in current global climate change projections. Previous modelling studies that have imposed additional Antarctic meltwater have demonstrated regional impacts on Southern Ocean stratification, circulation, and sea ice, as well as remote changes in atmospheric circulation, tropical precipitation, and global temperature. However, these previous studies have used widely varying rates of freshwater forcing, have been conducted using different climate models and configurations, and have reached differing conclusions on the magnitude of meltwater–climate feedbacks. The Southern Ocean Freshwater Input from Antarctica (SOFIA) initiative brings together a team of scientists to quantify the climate system response to Antarctic meltwater input along with key aspects of the uncertainty. In this paper, we summarize the state of knowledge on meltwater discharge from the Antarctic ice sheet and ice shelves to the Southern Ocean and explain the scientific objectives of our initiative. We propose a series of coupled and ocean–sea ice model experiments, including idealized meltwater experiments, historical experiments with observationally consistent meltwater input, and future scenarios driven by meltwater inputs derived from stand-alone ice sheet models. Through coordinating a multi-model ensemble of simulations using a common experimental design, open data archiving, and facilitating scientific collaboration, SOFIA aims to move the community toward better constraining our understanding of the climate system response to Antarctic melt.

Introduction. As the largest relative contributor to the oceanic sink of both anthropogenic heat and carbon, processes at work in the Southern Ocean directly modulate the rate of global change ([Roemmich et al., 2015](#); [Khatiwala et al., 2009](#); [Frölicher et al., 2015](#); [Gruber et al., 2019](#); [Meredith et al., 2019](#)). The Southern Ocean also exerts a direct influence on sea level rise, as interactions with the warming ocean are the primary driver of the observed melting of ice shelves around West Antarctica that in turn leads to mass loss from the grounded Antarctic ice sheet (AIS) ([Fox-Kemper et al., 2021](#); [DeConto and Pollard, 2016](#); [Pritchard et al., 2012](#)). Observations over recent decades show that mass loss from Antarctica is accelerating in regions of rapid ice shelf melt ([Shepherd et al., 2018](#); [Rignot et al., 2019](#)). Standalone ice sheet models project that this mass loss will continue to accelerate in the future, with the resulting freshwater input to the Southern Ocean becoming a primary contributor to global sea level rise in coming decades and centuries ([Fox-Kemper et al., 2021](#)). This freshwater input from melting of the grounded ice sheet and the fringing floating ice shelves is expected to have significant impacts that feedback onto the global climate system and influence the trajectory of global climate change ([Fyke et al., 2018](#); [Bronselaer et al., 2018](#); [Golledge et al., 2019](#); [Sadai et al., 2020](#); [Dong et al., 2022](#)). However, interactive ice sheets and shelves have generally not been included in coupled climate model simulations, including those used in the latest generation of the Coupled Model Intercomparison Project (CMIP6; [Eyring et al., 2016](#)).

The hazard components of representative key risks. The physical climate perspective.

Tebaldi, C., G. Aðalgeirsdóttir, S. Drijfhout, J. Dunne, T.L. Edwards, E. Fischer, J.C. Fyfe, R. Jones, R.E. Kopp, C. Koven, G. Krinner, F. Otto, **A.C. Ruane**¹, S.I. Seneviratne, J. Sillmann, S. Szopa, and Z. Prodimos, 2023

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Abstract. The framework of Representative Key Risks (RKR) has been adopted by the Intergovernmental Panel on Climate Change Working Group II (WGII) to categorize, assess and communicate a wide range of regional and sectoral key risks from climate change. These are risks expected to become severe due to the potentially detrimental convergence of changing climate conditions with the exposure and vulnerability of human and natural systems. Other papers in this special issue treat each of eight RKRs holistically by assessing their current status and future evolution as a result of this convergence. However, in these papers, such assessment cannot always be organized according to a systematic gradation of climatic changes. Often the big-picture evolution of risk has to be extrapolated from either qualitative effects of “low”, “medium” and “high” warming, or limited/focused analysis of the consequences of particular mitigation choices (e.g., benefits of limiting warming to 1.5 or 2C), together with consideration of the socio-economic context and possible adaptation choices.

In this study we offer a representation – as systematic as possible given current literature and assessments – of the future evolution of the hazard components of RKRs.

We identify the relevant hazards for each RKR, based upon the WGII authors’ assessment, and we report on their current state and expected future changes in magnitude, intensity and/or frequency, linking these changes to [Global Warming Levels](#) (GWLs) to the extent possible. We draw on the assessment of changes in climatic impact-drivers relevant to RKRs described in the 6th Assessment Report by Working Group I supplemented when needed by more recent literature.

For some of these quantities - like regional trends in oceanic and atmospheric temperature and precipitation, some heat and precipitation extremes, [permafrost](#) thaw and Northern Hemisphere snow cover - a strong and quantitative relationship with increasing GWLs has been identified. For others - like frequency and intensity of [tropical cyclones](#) and extra-tropical storms, and fire weather - that link can only be described qualitatively. For some processes - like the behavior of ice sheets, or changes in [circulation dynamics](#) - large uncertainties about the effects of different GWLs remain, and for a few others - like ocean pH and air pollution - the composition of the scenario of anthropogenic emissions is most relevant, rather than the warming reached. In almost all cases, however, the basic message remains that every small increment in CO₂ concentration in the atmosphere and associated warming will bring changes in climate phenomena that will contribute to increasing risk of impacts on human and natural systems, in the absence of compensating changes in these systems’ exposure and vulnerability, and in the absence of effective adaptation. Our picture of the evolution of RKR-relevant climatic impact-drivers complements and enriches the treatment of RKRs in the other papers in at least two ways: by filling in their often only cursory or limited representation of the physical climate aspects driving impacts, and by providing a fuller representation of their future potential evolution, an important component – if never the only one – of the future evolution of risk severity.

Introduction. The Intergovernmental Panel on Climate Change (IPCC)’s Working Group II (WGII) – tasked with the assessment of Impacts, Adaption and Vulnerability – has used the concept of representative key risk (RKR) as an organizing label to categorize a large number of sectoral and regional risks identified as becoming potentially severe with climate change ([Oppenheimer et al., 2014](#), [O’Neill et al., 2022](#)). In the latest report, Chapter 16 of the WGII contribution to the IPCC Sixth Assessment Report (AR6) ([O’Neill et al., 2022](#)) clusters more than 100 key risks identified through the assessment of the regional and sectoral chapters of the same report into eight RKRs.

A computationally efficient statistically downscaled 100 m resolution Greenland product from the regional climate model MAR.

Tedesco, M.^{1,2}, P. Colosio, X. Fettweis, and G. Cervone, 2023

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Abstract. The Greenland Ice Sheet (GrIS) has been contributing directly to sea level rise, and this contribution is projected to accelerate over the next decades. A crucial tool for studying the evolution of surface mass loss (e.g., surface mass balance, SMB) consists of regional climate models (RCMs), which can provide current estimates and future projections of sea level rise associated with such losses. However, one of the main limitations of RCMs is the relatively coarse horizontal spatial resolution at which outputs are currently generated. Here, we report results concerning the statistical downscaling of the SMB modeled by the Modèle Atmosphérique Régional (MAR) RCM from the original spatial resolution of 6 km to 100 m building on the relationship between elevation and mass losses in Greenland. To this goal, we developed a geospatial framework that allows the parallelization of the downscaling process, a crucial aspect to increase the computational efficiency of the algorithm. Using the results obtained in the case of the SMB, surface and air temperature are assessed through the comparison of the modeled outputs with in situ and satellite measurement. The downscaled products show a considerable improvement in the case of the downscaled product with respect to the original coarse output, with the coefficient of determination (R^2) increasing from 0.868 for the original MAR output to 0.935 for the SMB downscaled product. Moreover, the value of the slope and intercept of the linear regression fitting modeled and measured SMB values shifts from 0.865 for the original MAR to 1.015 for the downscaled product in the case of the slope and from the value $-235 \text{ mm w.e. yr}^{-1}$ (original) to $-57 \text{ mm w.e. yr}^{-1}$ (downscaled) in the case of the intercept, considerably improving upon results previously published in the literature.

Introduction. The Greenland Ice Sheet (GrIS) has been contributing directly to sea level rise since the beginning of the century through meltwater runoff and ice mass loss. Hörhold et al. (2022) found that modern temperatures over northern and central Greenland are 1.5°C warmer than the 20th century and that meltwater run off, a major contributor to sea level rise, has been consequently enhanced. The duration of surface melting and melt extent have also been increasing since 1979, as measured by passive microwave satellite observations (e.g., Tedesco et al., 2013; Colosio et al., 2021). Moreover, Hanna et al. (2021) found that over the 1972–2018 period each 1°C of summer warming corresponds to 116 Gt of surface mass loss and 26 Gt of solid-ice discharge increase. A key tool for studying the evolution of surface mass loss (e.g., surface mass balance, SMB) over the GrIS is represented by (polar) regional climate models (RCMs), which, in contrast to remote sensing observations (that can provide information about surface height changes but are unable to attribute height change to a mass change without more information about snow and firn compaction, e.g., Smith et al., 2023), can provide information on the mass loss and represent an irreplaceable tool to provide future projections of such losses. A widely used model in this regard is the Modèle Atmosphérique Régional (MAR, Fettweis et al., 2013, 2017, 2020; Tedesco et al., 2013), a coupled surface–atmospheric model forced at its boundaries with reanalysis data. However, one of the limitations of MAR (and of RCMs in general) lies in the horizontal spatial resolution at which outputs can be generated. This is due to computational considerations and to the physics behind the models. Currently, MAR simulations over Greenland are generated at a horizontal spatial resolution of 6 km (e.g., Colosio et al., 2021). Such spatial resolution does not allow capturing fine-scale processes occurring in areas characterized by complex topography (e.g., glaciers terminating in fjords) or small glaciated surface (e.g., ice caps). Moreover, the knowledge of mass loss at a horizontal spatial resolution higher than the one currently available (e.g., hundreds of meters) might allow a better characterization of the spatial inputs of runoff and freshwater to the surrounding oceans.

On the remote impacts of mid-Holocene Saharan vegetation on South American hydroclimate: A modelling intercomparison.

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Abstract. Proxy reconstructions from the mid-Holocene (MH: 6,000 years ago) indicate an intensification of the West African Monsoon and a weakening of the South American Monsoon, primarily resulting from orbitally-driven insolation changes. However, model studies that account for MH orbital configurations and greenhouse gas concentrations can only partially reproduce these changes. Most model studies do not account for the remarkable vegetation changes that occurred during the MH, in particular over the Sahara, precluding realistic simulations of the period. Here, we study precipitation changes over northern Africa and South America using four fully coupled global climate models by accounting for the Saharan greening. Incorporating the Green Sahara amplifies orbitally-driven changes over both regions, and leads to an improvement in proxy-model agreement. Our work highlights the local and remote impacts of vegetation and the importance of considering vegetation changes in the Sahara when studying and modeling global climate.

Introduction. Vegetation cover is known to impact regional climate variability, but the magnitude and global implications of vegetation changes are not well constrained due to the limited variability over the historical period. The Paleoclimate Modeling Intercomparison Project (PMIP) coordinates experiments to determine consistent responses across models that, when constrained against proxy reconstructions, can provide for a deeper understanding of how the climate system operates (Braconnot et al., [2012](#); Kageyama et al., [2018](#); Otto-Bliesner et al., [2017](#)). A key interval for study is the mid-Holocene (MH), which refers to the time-slice around 6,000 years ago. The MH was characterized by paleogeographic and ice-sheet distributions comparable to today, but the orbital configuration and greenhouse gas (GHG) composition differed. Most notably, the perihelion occurred during boreal autumn as opposed to boreal winter today, enhancing Northern Hemisphere seasonality. The Northern (Southern) Hemisphere received greater (lesser) summer insolation relative to the present day. In addition, carbon dioxide and methane compositions were lower by ~7% and ~26% respectively, relative to the pre-industrial (PI) period (Otto-Bliesner et al., [2017](#)). These differences are prescribed in the coordinated PMIP4 *midHolocene* experiments. The PMIP4 MH simulations indicate stronger monsoons in the Northern Hemisphere, especially over northern Africa (Brierley et al., [2020](#)). This is supported by multi-proxy reconstructions from various archives such as organic biomarkers (Collins et al., [2017](#); Shanahan et al., [2015](#); Tierney et al., [2017](#)), dust (McGee et al., [2013](#); Palchan & Torfstein, [2019](#)), pollen (Bartlein et al., [2011](#); Hély et al., [2014](#)), speleothems (Sha et al., [2019](#)) and paleohydrological records (Gasse, F., [2000](#); Lézine et al., [2011](#)). However, proxy-model comparisons indicate that climate models generally under-estimate the magnitude of African precipitation change with too little rainfall to support the proxy reconstructed vegetation (Braconnot et al., [2012](#); Brierley et al., [2020](#); Tierney et al., [2017](#)).

The proxy-model discrepancy over northern Africa may be resolved to great extent through the incorporation of appropriate vegetation in climate models. There is considerable evidence that there were large-scale vegetation changes throughout the world during the MH (Bartlein et al., [2011](#)). Most notably, the expansion of grasslands and shrubs into the current desert region of the Sahara (the so-called “Green Sahara”; e.g., Hély et al., [2014](#)) led to significant amplification of the orbital-driven strengthening of the West African monsoon (WAM) through positive nonlinear feedbacks such as vegetation, dust and albedo feedbacks (Pausata et al., [2020](#); Swann et al., [2014](#)).

On the impact of a dry intrusion driving cloud-regime transitions in a mid-latitude cold-air outbreak.

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Abstract. Marine cold-air outbreaks (CAOs) occur in the postfrontal sector of midlatitude storms, usually accompanied by dry intrusions (DIs) shaping the free-tropospheric (FT) air aloft. Substantial rain initiates overcast to broken regime transitions in marine boundary layer (MBL) cloud decks that form where cold air first meets relatively high sea surface temperatures. An exemplary CAO in the northwest Atlantic shows earlier transitions (corresponding to reduced extents of overcast clouds) closer to the low pressure center. We hypothesize that gradients in the meteorological pattern imposed by the prevailing DI induced a variability in substantial rain onset and thereby transition. We compile satellite observations, reanalysis fields, and Lagrangian large-eddy simulations (LES) translating along MBL trajectories to show that postfrontal trajectories closer to the low-pressure center are more favorable to rain formation (and thereby cloud transitions) because of 1) weaker FT subsidence rates, 2) greater FT humidity, 3) stronger MBL winds, and 4) a colder MBL with reduced lower-tropospheric stability. LES confirms the observed variability in transitions, with substantial rain appearing earlier where there is swifter reduction of cloud condensation nucleus (CCN) concentration and increase of liquid water path (LWP). Prior to substantial rain, CCN budgets indicate dominant loss terms from FT entrainment and hydrometeor collisions. LWP-enhancing cloud thickness increases more rapidly for weaker large-scale subsidence that enables faster MBL deepening. Mere MBL warming and moistening cannot explain cloud thickness increases. The generality of such a DI-imposed cloud transition pattern merits further investigation with more cases that may additionally be convoluted by onshore aerosol gradients.

Introduction. Cold-air outbreaks (CAOs) lead to marine boundary layer (MBL) clouds that commonly undergo rain-initiated overcast to broken cloud regime transitions that can drastically impact reflected solar radiation. We aim to better understand what mechanisms control these transitions. For a CAO event in the northwest Atlantic that shows earlier transitions closer to the low-pressure center, we find the transition timing to be largely governed by the coinciding dry intrusion that imposes an inhomogeneous large-scale meteorological pattern onto the overlying free troposphere and thereby affects MBL rain formation. Our findings update conceptual understanding of extratropical cyclones and motivate analyzing observations and conducting simulations for more postfrontal cases through a Lagrangian perspective as done here for one case, to assess the generality of our findings.

The fate of nitrogen during agricultural intensification in East Africa: Nitrogen budgets in contrasting agroecosystems.

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Abstract. The intensification of agricultural systems in sub-Saharan Africa (SSA) is necessary to reduce poverty and improve food security, but increased nutrient applications in smallholder systems could have negative consequences for water quality, greenhouse gas emissions, and air quality. We tracked nitrogen (N) inputs and measured maize (*Zea mays*) biomass, grain yields, N leaching, and nitric oxide (NO) and nitrous oxide fluxes from a clayey soil in Yala, Kenya and a sandy soil in Tumbi, Tanzania, with application rates of 0, 50, 75, 100, 150, and 200 kg N ha⁻¹ yr⁻¹ over two cropping seasons. Maize yields were 4.5 times higher in Yala than Tumbi, but yields plateaued at both sites with fertilizer applications at or above 100 kg N ha⁻¹ yr⁻¹. Partial N budgets in Yala were typically negative, meaning more N was exported in maize biomass plus grain or lost from the system than was added in fertilizer. In Tumbi, N budgets were negative at lower fertilizer levels but positive at higher fertilizer levels. At both sites most (96%) of the N was lost through maize biomass/grain removal and N leaching. Fertilizer additions at or less than 50 kg N ha⁻¹ yr⁻¹ on these two contrasting sites resulted in minor gaseous N losses, and fertilizer additions less than 200 kg N ha⁻¹ yr⁻¹ caused relatively little change to N leaching losses. This indicates that the modest increases in fertilizer use required to improve maize yields will not greatly increase cropland N losses.

Introduction. The technological transformations of smallholder agricultural systems that took place as part of the Green Revolution in Asia and Latin America in the second half of the twentieth century have been slow to take hold in sub-Saharan Africa (SSA). A history of low fertilizer use in SSA has led to widespread depletion of soil nitrogen (N) and other nutrients (Cobo et al., 2010; Vitousek et al., 2009), limiting crop productivity and contributing to the inability of many smallholders to break out of poverty (Barrett & Bevis, 2015). New efforts at agricultural intensification became a focus of international development and national policy in multiple African countries during the 2000s (Jayne & Rashid, 2013; Jayne & Sanchez, 2021). Many agricultural development practitioners have focused on restoring soil nutrients, increasing productivity, and alleviating poverty through the intensification of smallholder agriculture (AGRA, 2009). Although there is some debate about the ability of smallholder agricultural intensification to alleviate poverty in SSA, it is widely seen as critical for reducing food insecurity (Dawson et al., 2016; Denning et al., 2009; Harris & Orr, 2014; Larson et al., 2018; Ollenburger et al., 2019). Potential obstacles to smallholder intensification include the cost and availability of fertilizer or improved seed and small or inconsistent yield responses to fertilizer (Burke et al., 2016; Denning et al., 2009; Roobroeck et al., 2021). The initial goal of the Abuja Declaration on Participatory Development (1989) was to increase mean fertilizer inputs to 50 kg nutrients ha⁻¹ by 2015 (UN ECA, 1990). This goal was not met (Masso et al., 2017). However, nutrient inputs have increased, and although mineral fertilizer use remains less than 10 kg N ha⁻¹ in most countries in SSA, it has increased to >50 kg N ha⁻¹ in some countries (Jayne & Sanchez, 2021) while inputs from biological N fixation have increased in several others (Elrys et al., 2019).

Intensification of agriculture with increased fertilizer N inputs almost inevitably results in greater losses of N. In temperate croplands, only about half of added N is taken up by crops (Conant et al., 2013). Losses of fertilizer N can have cascading effects on ecosystems including emissions of the greenhouse gas nitrous oxide (N₂O), emissions of the air pollutant precursors nitric oxide (NO) and ammonia (NH₃), and leaching of nitrate (NO₃⁻) to groundwater, with negative impacts on soils, water, and biodiversity (Galloway et al., 2003; Tilman et al., 2002).

The historical Greenland Climate Network (GC-Net) curated and augmented Level 1 dataset.

Vandecrux, B., J.E. Box, A.P. Ahlstrøm, S.B. Andersen, N. Bayou, W.T. Colgan, N.J. Cullen, R.S. Fausto, D. Haas-Artho, A. Heilig, D.A. Houtz, P. How, I. Iosifescu Enescu, N.B. Karlsson, R. Kurup Buchholz, **K.D. Mankoff**^{1,2}, D. McGrath, N.P. Molotch, B. Perren, M.K. Revheim, A. Rutishauser, K. Sampson, M. Schneebeli, S. Starkweather, S. Steffen, J. Weber, P.J. Wright, H.J. Zwally, and K. Steffen, 2023

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Abstract. The Greenland Climate Network (GC-Net) consists of 31 automatic weather stations (AWSs) at 30 sites across the Greenland Ice Sheet. The first site was initiated in 1990, and the project has operated almost continuously since 1995 under the leadership of the late Konrad Steffen. The GC-Net AWS measured air temperature, relative humidity, wind speed, atmospheric pressure, downward and reflected shortwave irradiance, net radiation, and ice and firn temperatures. The majority of the GC-Net sites were located in the ice sheet accumulation area (17 AWSs), while 11 AWSs were located in the ablation area, and two sites (three AWSs) were located close to the equilibrium line altitude. Additionally, three AWSs of similar design to the GC-Net AWS were installed by Konrad Steffen's team on the Larsen C ice shelf, Antarctica. After more than 3 decades of operation, the GC-Net AWSs are being decommissioned and replaced by new AWSs operated by the Geological Survey of Denmark and Greenland (GEUS). Therefore, making a reassessment of the historical GC-Net AWS data is necessary. We present a full reprocessing of the historical GC-Net AWS dataset with increased attention to the filtering of erroneous measurements, data correction and derivation of additional variables: continuous surface height, instrument heights, surface albedo, turbulent heat fluxes, and 10 m ice and firn temperatures. This new augmented GC-Net level-1 (L1) AWS dataset is now available at <https://doi.org/10.22008/FK2/VVXGUT> (Steffen et al., 2023) and will continue to be refined. The processing scripts, latest data and a data user forum are available at <https://github.com/GEUS-Glaciology-and-Climate/GC-Net-level-1-data-processing> (last access: 30 November 2023). In addition to the AWS data, a comprehensive compilation of valuable metadata is provided: maintenance reports, yearly pictures of the stations and the station positions through time. This unique dataset provides more than 320 station years of high-quality atmospheric data and is available following FAIR (findable, accessible, interoperable, reusable) data and code practices.

Introduction. The Greenland Ice Sheet plays a substantial role in the global climate system. As a low-temperature topographic obstacle, the ice sheet exerts important influences on regional atmospheric circulation (Bromwich et al., 1993; Hahn et al., 2020). Additionally, the majority of the ice sheet is covered with a highly reflective perennial snow cover and an overall negative net radiation budget, which makes the ice sheet a net cooling element in the global climate system (e.g., Toniazzi et al., 2004; Ridley et al., 2005). Recently, however, ice discharge via marine-terminating outlet glaciers and seasonal melting of the ice sheet have both been increasing (e.g., The IMBIE Team, 2020; Mankoff et al., 2021). This has increased the freshwater flux into the North Atlantic, impacting ecosystems (e.g., Oksman et al., 2022), influencing ocean circulation (e.g., He and Clark, 2022) and contributing to global sea level rise (Nerem et al., 2018). In spite of the development of remote sensing techniques and weather modeling, the in-situ measurement of ice sheet surface climate variables remains paramount to improving our understanding of the Greenland Ice Sheet response to climate variability.

The Greenland Climate Network (GC-Net) of automated weather stations (AWSs) adds to a long history of meteorological observation on the Greenland Ice Sheet. The study of the Greenland Ice Sheet's meteorology began with overland expeditions during the late 19th and early 20th centuries. After the Second World War, purpose-built mechanized vehicles made it possible to transport the personnel and equipment required to maintain staffed stations on the ice sheet.

Exploring climate with obliquity in a variable-eccentricity Earth-like world.

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Abstract. Exploring planetary systems similar to our solar system can provide a means to explore a large range of possibly temperate climates on Earth-like worlds. Rather than run hundreds of simulations with different eccentricities at fixed obliquities, our variable-eccentricity approach provides a means to cover an incredibly large parameter space. Herein Jupiter's orbital radius is moved substantially inward in two different scenarios, causing a forcing on Earth's eccentricity. In one case, the eccentricity of Earth varies from 0 to 0.27 over ~ 7000 yr for three different fixed obliquities (0° , 23° , and 45°). In another case, the eccentricity varies from 0 to 0.53 over ~ 9400 yr in a single case with zero obliquity. In all cases, we find that the climate remains stable, but regional habitability changes through time in unique ways. At the same time, the moist greenhouse state is approached but only when at the highest eccentricities.

Introduction. Since the discovery of the first exoplanet nearly three decades ago, another 5000+ exoplanets have been found. These planets have been found in a variety of systems (single-star, multi-stellar, multi-planet) and orbital architectures. The search for a habitable planet in one of these systems is a key goal within the scientific community. This question has become more relevant since the detection of planets with masses and sizes similar to those of Earth is now common. In addition, some of these planets (e.g., Gillon et al. [2016](#); Gilbert et al. [2020](#), [2023](#); Kossakowski et al. [2023](#)) are found in the habitable zone of their host stars.

Planetary habitability is a multifaceted problem that requires an understanding of several properties and characteristics of the host star, the planet, the planetary system it belongs to, and its location within its host galaxy (e.g., see Meadows & Barnes [2018](#) for a review). In our solar system, the orbits of the planets are almost circular and coplanar. Mercury has the highest eccentricity of around 0.2 and an orbital inclination of about 7° . Some exoplanets have been found to move on highly eccentric orbits with HD20782b being the most eccentric exoplanet discovered thus far at $e = 0.97$ (Stassun et al. [2017](#)). *an* 514b is a potentially habitable planet with a 3σ upper limit eccentricity of 0.9 (Damasso et al. [2022](#)). A number of systems have also been discovered to have noncoplanar orbits (e.g., McArthur et al. [2010](#)). The eccentricity of the planetary orbit is an important factor as it affects the instellation the planet receives from its host star. In planetary systems with more than two bodies, the eccentricity may oscillate on various timescales and with significant amplitudes, while the semimajor axis shows little to almost no variation (e.g., see Georgakarakos [2003](#); Georgakarakos & Eggl [2015](#)). This behavior of the planetary orbit may affect the potential of a planet to retain liquid water on its surface (e.g., Way & Georgakarakos [2017](#); Georgakarakos et al. [2018](#)). _____

The planetary obliquity, i.e., the angle between the planetary spin axis and the normal of its orbital plane, is another important factor that may affect the climate of the planet. It has been the subject of many investigations either at the purely dynamical level, i.e., how it evolves under the gravitational perturbations of other bodies in the system (e.g., Atobe et al. [2004](#); Saillenfest et al. [2019](#)) or with respect to habitability and climate evolution. An example of the latter type of work is Williams & Kasting ([1997](#)), who simulated the climate of Earth at different obliquities using a 1D energy balance model. Williams & Kasting ([1997](#)) and Spiegel et al. ([2009](#)) used the same model to investigate the climate of a terrestrial planet at various obliquities. By using a 3D atmospheric general circulation model (GCM), Wang et al. ([2016](#)) studied the effect of obliquity on the habitability of planets around around M dwarf stars but with a lower-complexity thermodynamic 50 m slab ocean with zero horizontal heat transport. Additional studies have examined the relationship between obliquity and planetary climate (e.g., Ferreira et al. [2014](#); Kilic et al. [2017](#); Rose et al. [2017](#); Colose et al. [2019](#)).

Synergies between Venus and exoplanetary observations: Venus and its extrasolar siblings.

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Abstract. Here we examine how our knowledge of present-day Venus can inform terrestrial exoplanetary science and how exoplanetary science can inform our study of Venus. In a superficial way the contrasts in knowledge appear stark. We have been looking at Venus for millennia and studying it via telescopic observations for centuries. Spacecraft observations began with Mariner 2 in 1962 when we confirmed that Venus was a hothouse planet, rather than the tropical paradise science fiction pictured. As long as our level of exploration and understanding of Venus remains far below that of Mars, major questions will endure. On the other hand, exoplanetary science has grown leaps and bounds since the discovery of Pegasus 51b in 1995, not too long after the golden years of Venus spacecraft missions came to an end with the Magellan Mission in 1994. Multi-million to billion dollar/euro exoplanet focused spacecraft missions such as JWST, and its successors will be flown in the coming decades. At the same time, excitement about Venus exploration is blooming again with a number of confirmed and proposed missions in the coming decades from India, Russia, Japan, the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA). Here we review what is known and what we may discover tomorrow in complementary studies of Venus and its exoplanetary cousins.

Introduction. It may sound preposterous to propose that terrestrial exoplanets, which are far from being explored in-situ, and which present challenges even to detection of their atmospheres, can in any way inform Venus' evolutionary history. Yet exoplanetary science has already provided a means to put ancient Venus 4.2 billion years ago within the habitable zone (Yang et al. [2014](#); Way et al. [2016](#)). Initial studies of Venus' early climate by Ingersoll ([1969](#)), Pollack ([1971](#)), Kasting et al. ([1984](#)), and others laid out the challenges for Venus having temperate surface conditions in its early history, given the ~40% higher incident solar radiation it received 4.2 Ga compared with modern-day Earth. However, Pollack ([1971](#)) demonstrated that temperate conditions were possible if Venus had 100% cloud cover, providing an albedo sufficiently high to block enough incoming sunlight to reduce surface temperatures to less than 300 K. Yet he provided no rationale for his choice of 100% cloud cover. Moving 40+ years into the future exoplanet researchers were beginning to look at large parameter sweeps using 3-D General Circulation Models (GCMs) to investigate how insolation and rotation rate influence climate (e.g. Yang et al. [2014](#)). This effort was driven in part by the discovery of a large number of planets orbiting M-dwarf and K-dwarf stars – many in their habitable zones. One of the first of these exoplanet studies by Leconte et al. ([2013](#)) used the Laboratoire de Météorologie Dynamique (LMD)^{[Footnote1](#)} GCM to demonstrate that temperate conditions were possible for the tidally locked world HD 85512 b, which orbits a K-dwarf star with a 58-day period. A year later, using the National Center for Atmospheric Research (NCAR)^{[Footnote2](#)} Community Atmosphere Model (CAM) GCM, Yang et al. ([2014](#)) demonstrated that slowly rotating worlds (not necessarily tidally locked) with modern Earth-like atmospheres could in fact host temperate surface conditions with mean surface temperatures <300 K at stellar insulations approaching 2.5 times what Earth receives today. This was due to large scale contiguous high albedo tropospheric clouds located in the substellar region. These were a byproduct of the extended single-hemisphere-sized Hadley cells from a weakened Coriolis force due to the slower rotation rate. This exoplanet related discovery had confirmed Pollack's proposed 100% cloud cover 43 years later. The Yang et al. ([2014](#)) work prompted a number of similar studies (Way et al. [2016](#), [2018](#)) that confirmed the original result with a completely different 3-D GCM known as ROCKE-3D (Resolving Orbital Keys of Earth and Extraterrestrial Environments with Dynamics)^{[Footnote3](#)} (Way et al. [2017](#)).

The impact of background ENSO and NAO conditions and anomalies on the modeled response to Pinatubo-sized volcanic forcing.

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Abstract. Strong, strato-volcanic eruptions are a substantial, intermittent source of natural climate variability. Initial atmospheric and oceanic conditions, such as El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), also naturally impact climate on interannual timescales. We examine how initial conditions of ENSO and NAO contribute to the evolution of climate in the period following a Pinatubo-type eruption using a large (81-member) ensemble of model simulations in GISS model E2.1-G. Simulations are initialized from sampled conditions of ENSO and NAO using the protocol of the coordinated CMIP6 Volcanic Model Intercomparison Project (VolMIP) – where aerosols are forced with respect to time, latitude, and height. We analyze paired anomalous variations (perturbed – control) to understand changes in global and regional climate responses under positive, negative, and neutral ENSO and NAO conditions. In particular, we find that for paired anomalies there is a high probability of strong (~ 1.5 °C) warming of northern Eurasia surface air temperature in the first winter after the volcanic eruption for negative NAO ensembles coincident with decreased lower stratospheric temperature at the poles, decreased geopotential height, and strengthening of the stratospheric polar vortex. Climate anomalies (relative to average conditions across the control period), however, show no mean warming and suggest that the strength of this response is impacted by conditions present in the selected period of the control run. Again using paired anomalies, we also observe that under both +ENSO and –ENSO ensembles sea surface temperature decreases in the first post-eruptive boreal winter coinciding with surface cooling from volcanic aerosols. Neutral ENSO ensembles, on the other hand, show variability in their response with no clear trend in post-eruptive warming or cooling. In general, paired anomalies from unperturbed simulations give insight into the evolution of the climate response to volcanic forcing; however, when compared with anomalies from climatological conditions, it is clear that paired anomalies are significantly affected by sampled initial conditions occurring at the time of the volcanic eruption.

Introduction. Strong, explosive volcanic eruptions are an intermittent, natural source of climate variability acting on both interannual and decadal scales. Explosive volcanic eruptions eject sulfur dioxide, halogens, ash, and water vapor into the stratosphere, where the particles are converted into sulfate aerosols ([LeGrande et al., 2016](#)). The loading of stratospheric aerosols increases aerosol optical depth of the atmosphere ([Lacis, 2015](#)), thus imposing a radiative forcing via scattering of shortwave radiation and absorption of longwave radiation in the stratosphere ([Zanchettin et al., 2013](#)).

The impact that a strong volcanic eruption has on the climate system depends on many factors including size, ejection height, and location of the eruption. These factors impact the amount, location, and dynamics of how aerosols are loaded in the atmosphere ([Timmreck et al., 2010](#); [LeGrande and Anchukaitis, 2015](#)). Mount Pinatubo is an example of one such strong volcanic eruption which occurred in the Philippines in June 1991, ejecting 18 Tg of SO₂ into the atmosphere at a height of 20 km ([Stenchikov et al., 1998](#)). The Pinatubo eruption is widely studied as it is one of the largest volcanic eruptions since 1991, thus providing well-constrained satellite observations to run climate model simulations ([McCormick et al., 1995](#); [Bluth et al., 1992](#); [Stenchikov et al., 1998](#)).

Unraveling the mechanisms and implications of a stronger mid-Pliocene AMOC in PlioMIP2.

Weiffenbach, J.E., M.L.J. Baatsen, H.A. Dijkstra, A.S. von der Heydt, A. Abe-Ouchi, E.C. Brady, W.-L. Chan, D. Chandan, **M.A. Chandler**^{1,2}, C. Contoux, R. Feng, C. Guo, Z. Han, A.M. Haywood, Q. Li, X. Li, G. Lohmann, D.J. Lunt, K.H. Nisancioglu, B.L. Otto-Bliesner, W.R. Peltier, G. Ramstein, **L.E. Sohl**^{1,2}, C. Stepanek, N. Tan, J.C. Tindall, C.J.R. Williams, Q. Zhang, and Z. Zhang, 2023

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Abstract. The mid-Pliocene warm period (3.264–3.025 Ma) is the most recent geological period in which the atmospheric CO₂ concentration was approximately equal to the concentration we measure today (ca. 400 ppm). Sea surface temperature (SST) proxies indicate above-average warming over the North Atlantic in the mid-Pliocene with respect to the pre-industrial period, which may be linked to an intensified Atlantic Meridional Overturning Circulation (AMOC). Earlier results from the Pliocene Model Intercomparison Project Phase 2 (PlioMIP2) show that the ensemble simulates a stronger AMOC in the mid-Pliocene than in the pre-industrial. However, no consistent relationship between the stronger mid-Pliocene AMOC and either the Atlantic northward ocean heat transport (OHT) or average North Atlantic SSTs has been found. In this study, we look further into the drivers and consequences of a stronger AMOC in mid-Pliocene compared to pre-industrial simulations in PlioMIP2. We find that all model simulations with a closed Bering Strait and Canadian Archipelago show reduced freshwater transport from the Arctic Ocean into the North Atlantic. This contributes to an increase in salinity in the subpolar North Atlantic and Labrador Sea that can be linked to the stronger AMOC in the mid-Pliocene. To investigate the dynamics behind the ensemble's variable response of the total Atlantic OHT to the stronger AMOC, we separate the Atlantic OHT into two components associated with either the overturning circulation or the wind-driven gyre circulation. While the ensemble mean of the overturning component is increased significantly in magnitude in the mid-Pliocene, it is partly compensated by a reduction in the gyre component in the northern subtropical gyre region. This indicates that the lack of relationship between the total OHT and AMOC is due to changes in OHT by the subtropical gyre. The overturning and gyre components should therefore be considered separately to gain a more complete understanding of the OHT response to a stronger mid-Pliocene AMOC. In addition, we show that the AMOC exerts a stronger influence on North Atlantic SSTs in the mid-Pliocene than in the pre-industrial, providing a possible explanation for the improved agreement of the PlioMIP2 ensemble mean SSTs with reconstructions in the North Atlantic.

Introduction. At a CO₂ concentration similar to today (ca. 400 ppm) ([Seki et al., 2010](#); [Pagani et al., 2010](#); [Badger et al., 2013](#); [Haywood et al., 2016](#); [de la Vega et al., 2020](#)), the mid-Pliocene warm period (mPWP; 3.264–3.025 Ma) is the most recent geological period of sustained warmth. The mid-Pliocene climate features global surface temperatures that were roughly 3 °C higher than in the pre-industrial, substantially smaller ice sheets and a reduced meridional temperature gradient ([Haywood et al., 2013b, 2020](#)). Many mid-Pliocene boundary conditions, such as the geographic position of the continents and oceans, were similar to the present day. Studying the mid-Pliocene climate can therefore provide us with knowledge that is highly relevant to understanding climate dynamics in a near-future greenhouse climate ([Burke et al., 2018](#); [Tierney et al., 2019](#)).

One component of the mid-Pliocene climate system that is of particular interest is the Atlantic Meridional Overturning Circulation (AMOC). The AMOC is an essential mechanism of poleward heat transport and has a profound impact on the global climate system. It has been linked to many other components of the climate system, such as precipitation, average Northern Hemisphere temperatures and North Atlantic storm tracks ([Jackson et al., 2015](#)). Future projections predict a decline in the AMOC as a transient response to 21st-century global warming and a possible recovery on longer timescales ([Weijer et al., 2019, 2020](#)), changes that would inevitably impact the European and North American climate ([Jackson et al., 2015](#); [Haarsma et al., 2015](#)).

The habitability of Venus.

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Abstract. Venus today is inhospitable at the surface, its average temperature of 750 K being incompatible to the existence of life as we know it. However, the potential for past surface habitability and upper atmosphere (cloud) habitability at the present day is hotly debated, as the ongoing discussion regarding a possible phosphine signature coming from the clouds shows. We review current understanding about the evolution of Venus with special attention to scenarios where the planet may have been capable of hosting microbial life. We compare the possibility of past habitability on Venus to the case of Earth by reviewing the various hypotheses put forth concerning the origin of habitable conditions and the emergence and evolution of plate tectonics on both planets. Life emerged on Earth during the Hadean when the planet was dominated by higher mantle temperatures (by about 200 °C), an uncertain tectonic regime that likely included squishy lid/plume-lid and plate tectonics, and proto continents. Despite the lack of well-preserved crust dating from the Hadean and Paleoproterozoic, we attempt to review current understanding of the environmental conditions during this critical period based on zircon crystals and geochemical signatures from this period, as well as studies of younger, relatively well-preserved rocks from the Paleoproterozoic. For these early, primitive life forms, the tectonic regime was not critical, but it became an important means of nutrient recycling, with possible consequences on the global environment in the long-term, that was essential to the continuation of habitability and the evolution of life. For early Venus, the question of stable surface water is closely related to tectonics. We discuss potential transitions between stagnant lid and (episodic) tectonics with crustal recycling, as well as consequences for volatile cycling between Venus' interior and atmosphere. In particular, we review insights into Venus' early climate and examine critical questions about early rotation speed, reflective clouds, and silicate weathering, and summarize implications for Venus' long-term habitability. Finally, the state of knowledge of the Venusian clouds and the proposed detection of phosphine is covered.

Introduction. With an average temperature of ~750 K, today the surface of Venus is far from environmental conditions suitable for life as we know it. However, billions of years ago, when the Sun was much fainter (Sagan and Mullen 1972; Hart 1979; Gough 1981; Claire et al. 2012), Venus was located in the middle of the classical habitable zone around our sun (Kasting 1993; Kopparapu et al. 2013), thus fueling speculations about the early habitability of the planet (Pollack 1971; Grinspoon and Bullock 2007; Way et al. 2016). Important preconditions for habitability at the surface of Venus include a temperature range allowing the existence of liquid water; surface geochemistry with available chemical energy and appropriate elemental and molecular constituents, such as active water/rock interfaces; and protection from lethal solar radiation. The latter could have been provided by liquid water, as well as by a large reflective cloud cover resulting from the presence of liquid water. Surface thermochemical conditions would have ultimately been controlled by Venus' tectonic activity, although different models suggest different scenarios. Venus' convection regime may have changed over the course of the planet's history and at least some models suggest that Venus could have maintained temperate surface conditions until as recently as 0.7 Ga (Way et al. 2016). Lastly, although the early Sun was fainter, Venus' more sunward position means that solar incident insolation during its early history was still 40% higher than for present-day Earth (Lammer et al. 2008). Even if the overall radiation environment at the surface (as determined by absorption in Venus' early atmosphere) was clement, it may have affected conditions for early life potentially inhabiting water on exposed landmasses or subsea environments, such as hydrothermal vents. Increasing solar luminosity, continuous degassing of CO₂ from Venus' mantle into the atmosphere, or large-scale volcanic eruptions (Way et al. 2022) may have brought an end to a potential early habitable period.

Arctic tropospheric ozone: Assessment of current knowledge and model performance.

Whaley, C.H., K.S. Law, J.L. Hjorth, H. Skov, S.R. Arnold, J. Langner, J.B. Pernov, R.-Y. Chien, J.H. Christensen, M. Deushi, X. Dong, **G. Faluvegi**^{1,2}, M. Flanner, J.S. Fu, M. Gauss, U. Im, L. Marelle, T. Onishi, N. Oshima, D.A. Plummer, L. Pozzoli, J.-C. Raut, R. Skeie, M.A. Thomas, **K. Tsigaridis**^{1,2}, S. Tsyro, S.T. Turnock, K. von Salzen, and D.W. Tarasick, 2023

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Abstract. As the third most important greenhouse gas (GHG) after carbon dioxide (CO₂) and methane (CH₄), tropospheric ozone (O₃) is also an air pollutant causing damage to human health and ecosystems. This study brings together recent research on observations and modeling of tropospheric O₃ in the Arctic, a rapidly warming and sensitive environment. At different locations in the Arctic, the observed surface O₃ seasonal cycles are quite different. Coastal Arctic locations, for example, have a minimum in the springtime due to O₃ depletion events resulting from surface bromine chemistry. In contrast, other Arctic locations have a maximum in the spring. The 12 state-of-the-art models used in this study lack the surface halogen chemistry needed to simulate coastal Arctic surface O₃ depletion in the springtime; however, the multi-model median (MMM) has accurate seasonal cycles at non-coastal Arctic locations. There is a large amount of variability among models, which has been previously reported, and we show that there continues to be no convergence among models or improved accuracy in simulating tropospheric O₃ and its precursor species. The MMM underestimates Arctic surface O₃ by 5 % to 15 % depending on the location. The vertical distribution of tropospheric O₃ is studied from recent ozonesonde measurements and the models. The models are highly variable, simulating free-tropospheric O₃ within a range of ± 50 % depending on the model and the altitude. The MMM performs best, within ± 8 % for most locations and seasons. However, nearly all models overestimate O₃ near the tropopause (~ 300 hPa or ~ 8 km), likely due to ongoing issues with underestimating the altitude of the tropopause and excessive downward transport of stratospheric O₃ at high latitudes. For example, the MMM is biased high by about 20 % at Eureka. Observed and simulated O₃ precursors (CO, NO_x, and reservoir PAN) are evaluated throughout the troposphere. Models underestimate wintertime CO everywhere, likely due to a combination of underestimating CO emissions and possibly overestimating OH. Throughout the vertical profile (compared to aircraft measurements), the MMM underestimates both CO and NO_x but overestimates PAN. Perhaps as a result of competing deficiencies, the MMM O₃ matches the observed O₃ reasonably well. Our findings suggest that despite model updates over the last decade, model results are as highly variable as ever and have not increased in accuracy for representing Arctic tropospheric O₃.

Introduction. Tropospheric ozone (O₃) is the third most important greenhouse gas (GHG) after CO₂ and methane (IPCC, 2021), and it is an air pollutant causing damage to human health (World Health Organization (WHO), 2021). It also causes damage to vegetation following dry deposition to the surface (U.S. EPA, 2013). However, our knowledge about the sources and sinks of tropospheric O₃ is still uncertain (AMAP, 2015, 2022; Gaudel et al., 2018), in particular in regions where fewer observations exist and where our understanding of key processes is still evolving. The Arctic is one such region where few long-term measurements of O₃ exist and measurements of compounds that are important for producing and destroying O₃ in the atmosphere are scarce at the surface and even more so in the free troposphere. Progress has been made recently in terms of our understanding of certain processes, and a picture is emerging about the distribution of Arctic tropospheric O₃ as well as seasonal cycles and trends at different locations (e.g., Young et al., 2018; Tarasick et al., 2019b). In particular, the connection between surface O₃ depletion episodes and halogens is now well-established (e.g., Simpson et al., 2007; Abbatt et al., 2012).

Venus evolution through time: Key science questions, selected mission concepts and future investigations.

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Abstract. In this work we discuss various selected mission concepts addressing Venus evolution through time. More specifically, we address investigations and payload instrument concepts supporting scientific goals and open questions presented in the companion articles of this volume. Also included are their related investigations (observations & modeling) and discussion of which measurements and future data products are needed to better constrain Venus' atmosphere, climate, surface, interior and habitability evolution through time. A new fleet of Venus missions has been selected, and new mission concepts will continue to be considered for future selections. Missions under development include radar-equipped ESA-led EnVision M5 orbiter mission (European Space Agency [2021](#)), NASA-JPL's VERITAS orbiter mission (Smrekar et al. [2022a](#)), NASA-GSFC's DAVINCI entry probe/flyby mission (Garvin et al. [2022a](#)). The data acquired with the VERITAS, DAVINCI, and EnVision from the end of this decade will fundamentally improve our understanding of the planet's long term history, current activity and evolutionary path. We further describe future mission concepts and measurements beyond the current framework of selected missions, as well as the synergies between these mission concepts, ground-based and space-based observatories and facilities, laboratory measurements, and future algorithmic or modeling activities that pave the way for the development of a Venus program that extends into the 2040s (Wilson et al. [2022](#)).

Introduction. Each of the companion articles in this collection has identified key open questions about the evolution of Venus' atmosphere, climate, surface, interior and habitability through time, as well as the measurements or approaches that are needed to address them. To capture the wide variety of scientific domains and fields covered in this collection, and before describing current and future investigations to address these questions, we provide a summary of their conclusions as well as open questions regarding the dynamical properties and various processes of the present-day atmosphere.

VERITAS (Smrekar et al. [2022a](#)), DAVINCI (Garvin et al. [2022a](#)), and EnVision (European Space Agency [2021](#)) will greatly advance our understanding and lead to new questions about the evolution of Venus through time. Key advances will come from new types of data to better constrain the interior, such as improved crustal thickness and structure, mantle viscosity/temperature from seismology, lithospheric thickness from electromagnetic sounding, in-situ heat flow to constrain thermal lithospheric thickness and radiogenic heat budget and distribution. Over the next 15 years, these three missions will work together to answer many of the outstanding questions in Venus science and rocky planet evolution described above (Fig. [2](#); Table [1](#)).

Accounting for herbaceous communities in process-based models will advance our understanding of "grassy" ecosystems.

Wilcox, K.R., A. Chen, M.L. Avolio, E.E. Butler, S. Collins, R. Fisher, T. Keenan, **N.Y. Kiang**¹, A.K. Knapp, S.E. Koerner, L. Kueppers, G. Liang, E. Lieungh, M. Loik, Y. Luo, B. Poulter², P. Reich, K. Renwick, M.D. Smith, A. Walker, **E. Weng**^{1,3}, and K.J. Komatsu, 2023:

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Abstract. Grassland and other herbaceous communities cover significant portions of Earth's terrestrial surface and provide many critical services, such as carbon sequestration, wildlife habitat, and food production. Forecasts of global change impacts on these services will require predictive tools, such as process-based dynamic vegetation models. Yet, model representation of herbaceous communities and ecosystems lags substantially behind that of tree communities and forests. The limited representation of herbaceous communities within models arises from two important knowledge gaps: first, our empirical understanding of the principles governing herbaceous vegetation dynamics is either incomplete or does not provide mechanistic information necessary to drive herbaceous community processes with models; second, current model structure and parameterization of grass and other herbaceous plant functional types limits the ability of models to predict outcomes of competition and growth for herbaceous vegetation. In this review, we provide direction for addressing these gaps by: (1) presenting a brief history of how vegetation dynamics have been developed and incorporated into earth system models, (2) reporting on a model simulation activity to evaluate current model capability to represent herbaceous vegetation dynamics and ecosystem function, and (3) detailing several ecological properties and phenomena that should be a focus for both empiricists and modelers to improve representation of herbaceous vegetation in models. Together, empiricists and modelers can improve representation of herbaceous ecosystem processes within models. In so doing, we will greatly enhance our ability to forecast future states of the earth system, which is of high importance given the rapid rate of environmental change on our planet.

Introduction. Herbaceous and grass-dominated ecosystems are critical components of Earth's land surface (Faber-Langendoen et al., [2016](#)), occupying a large proportion of Earth's ice-free terrestrial surface (Dixon et al., [2014](#); White et al., [2000](#)) and providing many important ecosystem services such as carbon sequestration, livestock grazing, and wildlife habitat (Bai & Cotrufo, [2022](#); Gibson, [2009](#)). Examples of these "grassy" ecosystems are grasslands, shrublands, tundra, open tree savannas, and woodlands. Human impacts, such as land use change, suppression or ignition of fire, and climate change, are changing herbaceous ecosystems rapidly (e.g., Bowd et al., [2018](#); Dieleman, [2016](#); Harrison, [2020](#); Komatsu et al., [2019](#); Myers-Smith & Hik, [2018](#)). Such changes not only alter local and regional ecosystem functioning provided by these ecosystems (Smith et al., [2009](#)), but they may also feed back to the climate system to impact ecosystem processes and services beyond their geographical boundaries (Cook et al., [2009](#); Zhou et al., [2019](#)). To capture this broad range of ecosystem changes and their impacts on human and climate systems, it is necessary to develop and improve models that provide detailed representations of herbaceous ecosystem processes. With these models, it is also possible to evaluate mechanisms underlying ecological patterns at scales that are difficult to measure empirically (e.g., Luo & Reynolds, [1999](#); Walker et al., [2015](#)), and to make predictions for novel environmental conditions without the need for spatial extrapolation (Evans et al., [2013](#)). This is particularly important as global change and human demand for natural resources are pushing many herbaceous ecosystems beyond historical boundaries (Alexander et al., [2015](#); Easterling et al., [2000](#); IPBES, [2019](#); IPCC, [2021](#); Wang et al., [2022](#)).

The Regional Aerosol Model Intercomparison Project (RAMIP).

Wilcox, L.J., R.J. Allen, B.H. Samset, M.A. Bollasina, P.T. Griffiths, J.M. Keeble, M.T. Lund, R. Makkonen, J. Merikanto, D. O'Donnell, D.J. Paynter, G.G. Persad, S.T. Rumbold, T. Takemura, **K. Tsigaridis**^{1,2}, S. Undorf, and **D.M. Westervelt**^{1,3}, 2023

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Abstract. Changes in anthropogenic aerosol emissions have strongly contributed to global and regional trends in temperature, precipitation, and other climate characteristics and have been one of the dominant drivers of decadal trends in Asian and African precipitation. These and other influences on regional climate from changes in aerosol emissions are expected to continue and potentially strengthen in the coming decades. However, a combination of large uncertainties in emission pathways, radiative forcing, and the dynamical response to forcing makes anthropogenic aerosol a key factor in the spread of near-term climate projections, particularly on regional scales, and therefore an important one to constrain. For example, in terms of future emission pathways, the uncertainty in future global aerosol and precursor gas emissions by 2050 is as large as the total increase in emissions since 1850. In terms of aerosol effective radiative forcing, which remains the largest source of uncertainty in future climate change projections, CMIP6 models span a factor of 5, from -0.3 to -1.5 W m^{-2} . Both of these sources of uncertainty are exacerbated on regional scales.

The Regional Aerosol Model Intercomparison Project (RAMIP) will deliver experiments designed to quantify the role of regional aerosol emissions changes in near-term projections. This is unlike any prior MIP, where the focus has been on changes in global emissions and/or very idealised aerosol experiments. Perturbing regional emissions makes RAMIP novel from a scientific standpoint and links the intended analyses more directly to mitigation and adaptation policy issues. From a science perspective, there is limited information on how realistic regional aerosol emissions impact local as well as remote climate conditions. Here, RAMIP will enable an evaluation of the full range of potential influences of realistic and regionally varied aerosol emission changes on near-future climate. From the policy perspective, RAMIP addresses the burning question of how local and remote decisions affecting emissions of aerosols influence climate change in any given region. Here, RAMIP will provide the information needed to make direct links between regional climate policies and regional climate change.

RAMIP experiments are designed to explore sensitivities to aerosol type and location and provide improved constraints on uncertainties driven by aerosol radiative forcing and the dynamical response to aerosol changes. The core experiments will assess the effects of differences in future global and regional (Africa and the Middle East, East Asia, North America and Europe, and South Asia) aerosol emission trajectories through 2051, while optional experiments will test the nonlinear effects of varying emission locations and aerosol types along this future trajectory. All experiments are based on the shared socioeconomic pathways and are intended to be performed with 6th Climate Model Intercomparison Project (CMIP6) generation models, initialised from the CMIP6 historical experiments, to facilitate comparisons with existing projections. Requested outputs will enable the analysis of the role of aerosol in near-future changes in, for example, temperature and precipitation means and extremes, storms, and air quality.

Introduction. Aerosols emitted from natural and anthropogenic sources exert strong influences on the Earth's climate. At the global mean scale, anthropogenic emissions of aerosols, such as black carbon (BC) from incomplete combustion, and of aerosol precursor gases, such as SO_2 that leads to the formation of sulfate particles, currently induce a net, global annual mean cooling of around $0.4 \text{ }^\circ\text{C}$ ([Masson-Delmotte et al., 2021](#)).

AMORE-Isoprene v1.0: A new reduced mechanism for gas-phase isoprene oxidation.

Wiser, F., B. Place, S. Sen, H.O.T. Pye, B. Yang², **D.M. Westervelt**^{1,2}, D.K. Henze, A.M. Fiore, and V.F. McNeill, 2023

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Abstract. Gas-phase oxidation of isoprene by ozone (O₃) and the hydroxyl (OH) and nitrate (NO₃) radicals significantly impacts tropospheric oxidant levels and secondary organic aerosol formation. The most comprehensive and up-to-date chemical mechanism for isoprene oxidation consists of several hundred species and over 800 reactions. Therefore, the computational expense of including the entire mechanism in large-scale atmospheric chemical transport models is usually prohibitive, and most models employ reduced isoprene mechanisms ranging in size from ~ 10 to ~ 200 species. We have developed a new reduced isoprene oxidation mechanism using a directed-graph path-based automated model reduction approach, with minimal manual adjustment of the output mechanism. The approach takes as inputs a full isoprene oxidation mechanism, the environmental parameter space, and a list of priority species which are protected from elimination during the reduction process. Our reduced mechanism, AMORE-Isoprene (where AMORE stands for Automated Model Reduction), consists of 12 species which are unique to the isoprene mechanism as well as 22 reactions. We demonstrate its performance in a box model in comparison with experimental data from the literature and other current isoprene oxidation mechanisms. AMORE-Isoprene's performance with respect to predicting the time evolution of isoprene oxidation products, including isoprene epoxydiols (IEPOX) and formaldehyde, is favorable compared with other similarly sized mechanisms. When AMORE-Isoprene is included in the Community Regional Atmospheric Chemistry Multiphase Mechanism 1.0 (CRACMM1AMORE) in the Community Multiscale Air Quality Model (CMAQ, v5.3.3), O₃ and formaldehyde agreement with Environmental Protection Agency (EPA) Air Quality System observations is improved. O₃ bias is reduced by 3.4 ppb under daytime conditions for O₃ concentrations over 50 ppb. Formaldehyde bias is reduced by 0.26 ppb on average for all formaldehyde measurements compared with the base CRACMM1. There was no significant change in computation time between CRACMM1AMORE and the base CRACMM. AMORE-Isoprene shows a 35 % improvement in agreement between simulated IEPOX concentrations and chamber data over the base CRACMM1 mechanism when compared in the Framework for 0-D Atmospheric Modeling (F0AM) box model framework. This work demonstrates a new highly reduced isoprene mechanism and shows the potential value of automated model reduction for complex reaction systems.

Introduction. Isoprene is the most abundant non-methane hydrocarbon in the atmosphere. It has a major impact on tropospheric oxidant levels ([Butler et al., 2008](#)) and contributes to secondary organic aerosol (SOA) formation (and therefore fine particulate matter, PM_{2.5}) in many parts of the US and the world ([Kroll et al., 2006](#); [Henze and Seinfeld, 2006](#); [Farmer et al., 2010](#); [Liu et al., 2016](#); [Fu et al., 2009](#)). During the warm season, isoprene emissions enhance both regional and hemispheric ozone abundances at northern midlatitudes ([Fiore et al., 2011](#); [Guo et al., 2018](#)). Isoprene oxidation chemistry contributes to natural background ozone and particulate matter over much of the US during the warm season ([Fiore et al., 2014](#)). Different representations of isoprene chemistry lead to uncertainty in air pollutant responses to anthropogenic emission reductions ([Carlton et al., 2009](#)) and to differences in model estimates of the background versus anthropogenic fractions ([Fiore et al., 2005, 2014](#)).

Knowledge of the isoprene oxidation reaction mechanism, including key pathways for both ozone and aerosol formation, has advanced rapidly over the last 2 decades ([Wennberg et al., 2018](#)). The full chemical mechanism for isoprene oxidation, as it is currently understood, consists of several hundred species (up to 602 in the Master Chemical Mechanism, MCM, v3.3.1; [Jenkin et al., 2015](#)) and ~ 1000 reactions (see Table 1).

Heat stress to jeopardize crop production in the US Corn Belt based on downscaled CMIP5 projections.

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Abstract. Global food security [faces](#) increasing challenges from the changing climate. Changes of agricultural output from some of the most productive regions such as the US [Corn Belt](#) can largely affect the world's food market. Developing predictive understanding of the agricultural risk of [climate change](#) and potential mitigation strategies is critical for the global food security.

The objective of this study is to assess the responses of maize and soybean yield to projected climate changes in the Corn Belt, identify the shifting environment stressors on crop yield, and tackle potential climate adaptation strategies.

We drive a process-based model, the Decision Support System for Agrotechnology Transfer, with high-resolution statistically downscaled and bias-corrected historical and future climates from ten CMIP5 models in the MACA-2 database.

The multi-model ensemble mean suggests a 12% decrease of maize yield by mid-century and 40% by late century, with a high degree of model consensus in the direction of changes: for individual models, the projected decrease of maize yield by late century ranges from <5% to over 80%, with the worst crop outcome corresponding to the most sensitive climate models. Soybean yield is projected to increase by midcentury with a high degree of model consensus, but such consensus is lost by late century as some projections shift to significant decreases. Crop yield in the Corn Belt is currently limited by water stress but is projected to be increasingly limited by heat stress as well after the midcentury. The mounting heat stress will drive the most productive zone for maize to shift from central to northern part of the Corn Belt, but the projected increase in the northern states cannot fully compensate for the decrease in the south, causing the total production to decrease if agricultural practice stays the same. Earlier planting can alleviate only a small fraction of the heat-induced crop loss in a warmer climate. Climate change will (at least partially) offset the yield boost caused by agricultural technology and intensification.

This study advances our predictive understanding of crop yield responses to [climate change](#), and suggests that a multitude of strategies will be needed to address the climate change challenges for the U.S. [agriculture](#).

Introduction. Agriculture is the foundation for fighting against global hunger and malnutrition (FAO et al., 2020), and also plays a critical role in boosting regional economy and promoting social stability (Hsiang et al., 2013; Wang et al., 2015). As the world's leading producer for maize and soybean, the United States is responsible for 37% of the world's maize production and 34% of soybean, of which approximately 14% and 52% respectively are exported to other countries (Ortiz-Bobea et al., 2019; USDA, 2020). Nearly 90% of the U.S. maize and soybean are produced in the Midwest region known as the Corn Belt (Wang et al., 2020a). However, with an irrigation rate <20%, crops in this region are vulnerable to the increasingly frequent environmental stressors such as drought and heat waves (Green et al., 2018; Lobell et al., 2014, Lobell et al., 2020; Ortiz-Bobea et al., 2019; Wang et al., 2015). For example, the 2011–2014 U.S. droughts and the associated heat drove international crop prices to a record high.

Water stress dominates the projected maize yield changes in Ethiopia.

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Abstract. In Ethiopia, a highly food-insecure nation, traditional agriculture faces significant climate change challenges. Long-term food security planning and famine prevention efforts require a comprehensive assessment of how crop yield might change in the future across the whole Ethiopia at a spatial scale usable and useful for local decision-making. In this study we aimed to assess future climate-induced maize yield changes in Ethiopia and identify the primary stress factor that limit regional agricultural productivity using a high-resolution process-based crop model (DSSAT) forced by multiple regional climate projections from CORDEX-Africa under the Representative Concentration Pathway 8.5. The climate projections were statistically downscaled and bias-corrected for local relevance before used as input to the crop model. It was found that without technology advancement and management practice changes, climate change would cause the Ethiopian maize yield to decrease from ~1400 kg/ha in present day climate to ~900 kg/ha by late century, primarily due to increased water stress during critical growth stages caused by changing precipitation patterns and rising temperatures. While the most productive regions may suffer significant yield losses, some less productive areas might become more suitable for maize cultivation, indicating a possible spatial shift in agricultural productivity. These findings should be considered in developing climate adaptation strategies at the individual farming communities, national, and international levels. Climate change will offset at least some of the yield boosting power of agricultural technologies in Ethiopia and challenge the future food security of a growing population.

Introduction. According to the Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR5), it is unequivocal that the Earth's climate is warming ([Masson-Delmotte et al., 2018](#)). Climate change poses great risks to regional and global food security ([Lobell and Field, 2007](#); [Vogel et al., 2019](#)). The rising temperature, extreme precipitation, long-lasting drought and other extreme events resulting from a more variable climate will inevitably threaten the current agricultural systems, especially in developing countries with poor resilience to environmental shocks and uncertainties ([Serdeczny et al., 2017](#)). In the past three decades, climate change has already led to a decrease of global agricultural production at a rate of 1–5% per decade, with particularly negative impacts on cereal crops such as maize in tropical areas ([Lesk et al., 2021](#); [Ortiz-Bobea et al., 2021](#); [Porter et al., 2014](#)). The recent warming trend is highly likely to continue in this century ([Brown and Caldeira, 2017](#); [Hansen et al., 2000](#); [Liang et al., 2020](#)), which would further alter regional water resources and crop production.

As one of the most food-insecure tropical countries, Ethiopia's traditional rain-fed agriculture system is particularly vulnerable to environmental changes. Crops in Ethiopia have already shown a sign of being affected by recent changes in climate ([Yang et al., 2020](#)). Understanding and evaluating how further climate change may influence crop yield in the future will inform long-term planning efforts to combat the potential climate-induced crop loss and optimize allocation of resources in Ethiopia. So far, past studies have mostly focused on assessing the future [climate change impact](#) on site level crop yield ([Abera et al., 2018](#); [Araya et al., 2015](#); [Mohammed et al., 2022](#)), which cannot account for the vast variations related to topographic and climate gradients. Moreover, many past studies focused on the impact of one climate variable at a time (e.g., by prescribing a uniform temperature increase) ([Maitah et al., 2021](#); [Wang et al., 2020b](#); [Zhu et al., 2019](#)), missing the interactions of multiple climate variables and their spatial variability. Comprehensive, spatially explicit assessment of crop yield response to more realistic pattern of climate change is needed to inform decision makers at regional and national levels.

Seasonal prediction of crop yields in Ethiopia using an analog approach.

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Abstract. As Ethiopia's population grows, crop yield predictions are becoming increasingly important for national food security. Accurate, easy-to-implement, and computationally efficient forecast approaches are desirable for broad applications in emerging regimes like Ethiopia. In this study, we develop and test an analog approach for pre-season crop yield prediction conditioned on antecedent precipitation and planting time soil moisture content indices to guide cultivation decision making. Historical planting time soil moisture at four selected sites were simulated using the Coupled Routing and Excess Storage (CREST) hydrological model and classified into five levels. Likewise, a historical crop yield database for each of the five classes of planting time soil moisture were constructed using the Decision Support System for Agrotechnology Transfer (DSSAT) agricultural model. Adopting maize as a representative crop, analog models based on different indexes or predictors with various lead times were constructed and used to conduct hindcasts during 1979–2014 and real-time forecast in 2018 and 2019. Both the hindcast and real-time forecasts were then evaluated against yield observations. To verify the applicability at locations with various environments, the analog models were then applied in different Agroecological Zones. The analog models were shown to be accurate and easy to implement, which may incentivize adoption by local extension agents and regional agricultural agencies to inform farmers' crop choices.

Introduction. Crop yield predictions are increasingly important to every sector of public and private agricultural systems and the supply chain, in terms of aiding crop selections, optimizing management practices, and anticipating market fluctuations ([Lecerf et al., 2019](#); [Macdonald and Hall, 1980](#)). Historically, farmers make crop yield predictions following the instructions of local experts who provide their forecast mainly by evaluating the crop status throughout the [growing season](#) ([Basso et al., 2013](#)). Yet, advanced data collection techniques and increased computational capacity have facilitated the development of a wide variety of crop yield forecast methods in recent decades. Recent studies utilize statistical models, process-based models, [remote sensing](#), machine learning and the hybrid of these technologies to generate crop yield predictions at various spatiotemporal scales ([Basso et al., 2013](#); [Bolton and Friedl, 2013](#); [Chlingaryan et al., 2018](#); [Kang et al., 2009](#); [Lobell et al., 2009](#)). However, great data demand, high model complexity, and high computational expense have limited their application especially in areas with scarce data, labor, education, and economic resources ([Basso et al., 2013](#); [Filippi et al., 2019](#)).

Season-ahead prediction of crop yield is particularly important in countries prone to climate-driven food insecurity, such as Ethiopia, where the agricultural sector comprises over 50% of the country's GDP ([FSIN, 2019](#); [Welteji, 2018](#)). However, large rural populations and highly fragmented farmland result in a [farming system](#) dominated by [smallholders](#) in Ethiopia with limited access to modern farm technologies and irrigation infrastructure ([Mellander et al., 2013](#); [Passarelli et al., 2018](#); [Welteji, 2018](#)). Crop production in the country depends highly on precipitation and other climate factors, with less than 5% of the cropland in Ethiopia under irrigation ([Passarelli et al., 2018](#)). Pre-season yield prediction may facilitate farmers' [decision making](#) to maximize output by adjusting crop choices. As [climate variability](#) in Ethiopia is shown to affect crop yields and the national economy, seasonal predictions are critical for developing adaptation capacity and building resilience to climate shocks ([Block et al., 2008](#); [Lala et al., 2020](#); [Lewis, 2017](#); [MacLeod, 2019](#)). Studies also found that preseason soil moisture has a significant impact on crop yields and can act as a key index in forecasting the total seasonal yield ([Mjelde and Keplinger, 1998](#); [Yang et al., 2021](#)).

Detailing cloud property feedbacks with a regime-based decomposition.

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Abstract. Diagnosing the root causes of cloud feedback in climate models and reasons for inter-model disagreement is a necessary first step in understanding their wide variation in climate sensitivities. Here we bring together two analysis techniques that illuminate complementary aspects of cloud feedback. The first quantifies feedbacks from changes in cloud amount, altitude, and optical depth, while the second separates feedbacks due to cloud property changes within specific cloud regimes from those due to regime occurrence frequency changes. We find that in the global mean, shortwave cloud feedback averaged across ten models comes solely from a positive within-regime cloud amount feedback countered slightly by a negative within-regime optical depth feedback. These within-regime feedbacks are highly uniform: In nearly all regimes, locations, and models, cloud amount decreases, and cloud albedo increases with warming. In contrast, global-mean across-regime components vary widely across models but are very small on average. This component, however, is dominant in setting the geographic structure of the shortwave cloud feedback: Thicker, more extensive cloud types increase at the expense of thinner, less extensive cloud types in the extratropics, and vice versa at low latitudes. The prominent negative extratropical optical depth feedback has contributions from both within- and across-regime components, suggesting that thermodynamic processes affecting cloud properties as well as dynamical processes that favor thicker cloud regimes are important. The feedback breakdown presented herein may provide additional targets for observational constraints by isolating cloud property feedbacks within specific regimes without the obfuscating effects of changing dynamics that may differ across timescales.

Introduction. The responses of clouds to planetary warming—cloud feedbacks—are the primary cause of uncertainties in future warming for a given increase in greenhouse gas concentration. This stems from the large role of clouds in modifying the flow of heat into and out of the Earth system and the challenge of observing, understanding, and modeling cloud processes at scales ranging from microscopic to global for the wide variety of cloud types and responses to warming that together make up the cloud feedback.

Recent work using cloud radiative kernels (Zelinka et al. [2012a](#), [b](#), [2013](#), [2016](#)) has advanced our ability to diagnose cloud feedbacks, providing new insights into robust features simulated by all models, their linkage to the physical processes driving them, and their sources of inter-model spread. For example, it is now clear that models systematically simulate positive feedbacks from decreases in low-cloud amount, positive feedbacks from rising high-cloud top altitude, and negative feedbacks from increases in low-cloud optical depth.

However, as noted in Zelinka et al. ([2012a](#)), there remains ambiguity regarding the actual causes of the cloud changes that drive some of these components. For example, climate models robustly simulate negative feedback from increased optical depth of (primarily) low-level extratropical clouds. This feedback could have contributions from both changes in the relative frequency of occurrence of optically thin versus thick cloud types as well as from changes in the optical properties of clouds of a given morphology. In the former case, it is possible that transitions from relatively thin boundary layer clouds to thicker frontal clouds, perhaps associated with a storm-track shift, are leading to the overall increase in cloud albedo. This would imply that a better understanding of changes in meteorology and large-scale dynamics would be necessary to constrain this feedback. In the latter case, optical properties of the cloud types that are already present are changing (e.g., thin boundary layer clouds becoming thicker), suggesting a greater role for thermodynamic processes that increase cloud liquid water content or decrease particle size.

Dependence of Northern Hemisphere tropospheric transport on the midlatitude jet under abrupt CO₂ increase.

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Abstract. Understanding how the transport of gases and aerosols responds to climate change is necessary for policy making and emission controls. There is considerable spread in model projections of tracer transport in climate change simulations, largely because of the substantial uncertainty in projected changes in the large-scale atmospheric circulation. In particular, a relationship between the response of tropospheric transport into the high latitudes and a shift of the midlatitude jet has been previously established in an idealized modeling study. To test the robustness of this relationship, we analyze the response of a passive tracer of northern midlatitude surface origin to abrupt 2xCO₂ and 4xCO₂ in a comprehensive climate model (Goddard Institute for Space Studies E2.2-G). We show that a poleward shift of the northern midlatitude jet and enhanced eddy mixing along isentropes on the poleward flank of the jet result in decreased tracer concentrations over the midlatitudes and increased concentrations over the Arctic. This mechanism is robust in abrupt 2xCO₂ and 4xCO₂ simulations, the nonlinearity to CO₂ forcing, and two versions of the model with different atmospheric chemistry. Preliminary analysis of realistic chemical tracers suggests that the same mechanism can be used to provide insights into the climate change response of anthropogenic pollutants.

Introduction. The long-range transport of trace gases and aerosols from the surface throughout the troposphere plays a key role in determining the composition of the atmosphere, climate change, and air quality. It is therefore important to know the processes controlling this transport and how the transport will change with climate. Previous studies comparing simulations of real and idealized tracers show a large spread among models (Monks et al., [2015](#); Orbe et al., [2017](#), [2018](#); Shindell et al., [2008](#); Yang et al., [2019](#)). Furthermore, there remain large uncertainties in the role of different processes in causing changes, such as the relative role of changes in the large-scale circulation, isentropic mixing, and convection (e.g., Orbe et al., [2018](#); Yang et al., [2019](#)). In addition, there is a large spread among model projections of transport in climate change simulations (e.g., Doherty et al., [2017](#)).

This uncertainty in future changes in tracer transport is not surprising as there is substantial uncertainty in projections of the atmospheric circulation response to increasing greenhouse gas concentrations (e.g., Shepherd, [2014](#)). For example, while models generally predict a poleward shift in the westerly jet (which has been linked to changes in transport, e.g., Orbe et al., [2013](#), [2015](#)), there is a large spread among models in the magnitude of this shift (e.g., Grise & Polvani, [2016](#); Oudar et al., [2020](#); Vallis et al., [2015](#)) and this spread is not correlated with the level of global warming in the models (Grise & Polvani, [2016](#)).

Using a dry dynamical core model and air-mass fraction tagging, Orbe et al. ([2013](#)) analyzed changes in tropospheric transport to idealized warming. They found an increase in the fraction of air originating from the northern hemisphere (NH) extratropical (north of 33°N) boundary layer in the high-latitude upper troposphere. They attributed this increase to a poleward shift of the NH midlatitude jet resulting in enhanced eddy kinetic energy (EKE) that stirs more air out of the midlatitude boundary layer in a warmer climate. We are motivated to test the robustness of the relationship between midlatitude jet/EKE responses and changes in tropospheric transport.

The climate change response in Orbe et al. ([2013](#)) features upper tropospheric warming, which is a known mechanism to drive a poleward shift of the midlatitude jet via strengthened meridional temperature gradients. However, comprehensive climate models also simulate NH high latitude warming associated with Arctic amplification that weakens the meridional temperature gradient. The resulting NH jet shift represents a “tug-of-war” between the two opposing temperature responses (Shaw, [2019](#); Shaw et al., [2016](#)).

Comparison of clouds and cloud feedback between AMIP5 to AMIP6.

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Abstract. We examine the changes in clouds and cloud feedback between Phase 5 (AMIP5) and Phase 6 (AMIP6) of the Atmospheric Model Intercomparison Project. Each model is perturbed by uniformly increasing the sea surface temperature by 4 K. The simulated cloud fraction, the perturbed states and cloud radiative kernels are used to derive cloud feedback in the shortwave (SW), longwave (LW) and their sum (Net). Compared to AMIP5, the cloud fraction in AMIP6 increases by 9.1%, while the perturbation leads to a 0.25% decrease. The Net cloud feedback at the top of the atmosphere (TOA) is almost double (174%). Statistical tests support that this change is mainly due to an increase in the surface SW cloud feedback caused by optically thick, middle and low clouds. The contribution of the atmospheric Net component (12%) stems from the increase in the atmospheric LW cloud feedback, likely to play a role in weakening (strengthening) the northward (southward) meridional atmospheric energy transport, while the opposite is true for the surface LW and Net cloud feedback in the meridional oceanic energy transport. The substantial increase in cloud feedback at the TOA primarily contributes to the higher climate sensitivity. The cloud feedback spread in AMIP6 is comparable to that in AMIP5.

Introduction. In the last three decades, both observations and General Circulation Models (GCMs) have indicated that the largest uncertainty in climate simulations resides within cloud feedback [1]. In climate modeling, cloud feedback indeed exhibits the largest intermodel spread of all feedbacks, and is highly correlated with the equilibrium/effective climate sensitivity (ECS), an important indicator of future climate trends [2]. The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) was recently finalized [3]. It concluded that improved knowledge of climate processes, paleoclimate evidence and the response of the climate system to increasing radiative forcing gives a best estimate of ECS of 3 °C, with a very likely range of 2 °C to 5 °C. The likely range (2.5–4 °C) is narrower than that in AR5 (1.5–4.5 °C) [4,5], but some of the Coupled Model Intercomparison Project Phase 6 (CMIP6) climate models have either high (>5 °C) or low (<2 °C) ECS, which also simulate past global surface temperature changes outside the range of proxy-based reconstructions for the coldest and warmest reference periods. The ensemble-mean global surface temperature change obtained from the CMIP6 historical simulations assessed in AR6 is within 0.2 °C of the observations over most of the historical periods. Additionally, the observed warming is within the very likely range of the CMIP6 ensemble, but some models simulate warming that is either above or below the assessed, very likely range of observed warming [4,5]. The AR6 differs from previous reports because it does not directly use climate model estimates of ECS (and transient climate response, TCR) in the assessed ranges of climate sensitivity. Indeed, the AR6 uses “observational constraints” to select a subset of CMIP6 for its warming projections (i.e., the projection is not entirely based on CMIP6 projection). Zelinka et al. [2] show that ECS > 5 K for 4 of the 27 CMIP6 models and ECS < 2 K for one model only. In comparison, none of the 28 Coupled Model Intercomparison Project Phase 5 (CMIP5) models have such excessive ECS values. Forster et al. [6] concluded that one-third of the CMIP6 models exhibit a higher ECS than did the CMIP5 models, and those with CMIP6 models showing the highest warming are unlikely to be representative of real-world conditions. Additionally, it is reported that CMIP6 projections of global surface temperature should not be exclusively relied on for policy-relevant decisions. Scafetta [7] argued that the real ECS could lie between 1 and 2 °C, which implies moderate warming for the next decades. Subsequently [8], he identified a subset of seventeen best-performing CMIP6 GCMs for which the ECS ranges between 1.8 and 3.0 °C and the TCR between 1.2 and 1.8 °C.

Global radiative flux profile dataset: Revised and extended.

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Abstract. The third generation of the radiative flux profile data product, called ISCCP-FH, is described. The revisions over the previous generation (called ISCCP-FD) include improvements in the radiative model representation of gaseous and aerosol effects, as well as a refined statistical model of cloud vertical layer variations with cloud types and increased spatial resolution. The new product benefits from the changes in the new H-version of the ISCCP cloud products (called ISCCP-H): higher spatial resolution, revised radiance calibration and treatment of ice clouds, treatment of aerosol effects, and revision of all the ancillary atmosphere and surface property products. The ISCCP-FH product is evaluated against more direct measurements from the Clouds and the Earth's Radiant Energy System and the Baseline Surface Radiation Network products, showing some small, overall reductions in average flux uncertainties; but the main results are similar to ISCCP-FD: the ISCCP-FH uncertainties remain $\lesssim 10 \text{ Wm}^{-2}$ at the top-of-atmosphere (TOA) and $\lesssim 15 \text{ Wm}^{-2}$ at surface for monthly, regional averages. The long-term variations of TOA, surface and in-atmosphere net fluxes are documented and the possible transient cloud feedback implications of a long-term change of clouds are investigated. The cloud and flux variations from 1998 to 2012 suggest positive cloud-radiative feedback on the oceanic circulation and negative feedback on the atmospheric circulation. This example demonstrates that the ISCCP-FH product can provide useful diagnostic information about weather-to-interannual scale variations of radiation induced by changes in cloudiness as well as atmospheric and surface properties.

Introduction. Earth's climate is determined by a long-term, global balance of energy exchanges in the form of radiative fluxes, water phase changes, surface-atmosphere exchanges, and transports by the oceanic and atmospheric circulations; but the circulations and their transports are modified by the short-term, local imbalances of the energy and water exchanges. The atmospheric circulations (weather) produce water phase changes in the form of clouds and precipitation that feedback on all of these exchanges and circulation transports. The early focus of weather studies was on the precipitation produced from clouds. The early focus of climate studies was on the modulation of the top-of-atmosphere (TOA) radiative fluxes by cloud variations, usually the global average changes that are associated with global mean surface temperature changes. However, the global mean temperature is not simply related to the average energy balance because changes in the atmospheric and oceanic circulation redistribute the energy, complicated by induced cloud feedbacks on these circulations. Hence, fully diagnosing cloud-radiative feedbacks on weather and climate requires decomposing the space-time variations of TOA fluxes into surface (SRF) net fluxes that affect the ocean circulation and atmospheric (ATM) net flux profiles that affect the atmospheric motions and cloud (and precipitation) formation. Since the solar (shortwave (SW)) fluxes act primarily on the surface and the terrestrial (longwave (LW)) fluxes act primarily on the atmosphere, these have to be diagnosed separately. This diagnosis has to be done across a range of space-time scales to establish the coupling at different scales of atmosphere-ocean motions. Obtaining global observations that directly resolve bulk-cloud-process-scale variations of surface fluxes and atmospheric profiles of radiation is infeasible, so another approach is to measure the space-time-resolved variations of the properties of the clouds, atmosphere and the surface and then calculate the radiative fluxes with a detailed radiative transfer model. Atmospheric radiative transfer is sufficiently advanced that the accuracy of such calculations is primarily limited by the accuracy and completeness of the description of the cloud, atmosphere and surface properties input to the model. The knowledge and accuracy of this information has increased over the past few decades so that such calculations can improve to reliably reveal more detailed radiative exchanges and their variations. The advantage of the flux-calculation analysis is that determining the causes of flux variations is direct. The success of this approach depends on assessment of the accuracy of the input quantities against independent measurements and verification of the output fluxes against direct measurements.

Automated machine learning to evaluate the information content of tropospheric trace gas columns for fine particle estimates over India: A modeling testbed.

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Abstract. India is largely devoid of high-quality and reliable on-the-ground measurements of fine particulate matter (PM_{2.5}). Ground-level PM_{2.5} concentrations are estimated from publicly available satellite Aerosol Optical Depth (AOD) products combined with other information. Prior research has largely overlooked the possibility of gaining additional accuracy and insights into the sources of PM using satellite retrievals of tropospheric trace gas columns. We evaluate the information content of tropospheric trace gas columns for PM_{2.5} estimates over India within a modeling testbed using an Automated Machine Learning (AutoML) approach, which selects from a menu of different machine learning tools based on the data set. We then quantify the relative information content of tropospheric trace gas columns, AOD, meteorological fields, and emissions for estimating PM_{2.5} over four Indian sub-regions on daily and monthly time scales. Our findings suggest that, regardless of the specific machine learning model assumptions, incorporating trace gas modeled columns improves PM_{2.5} estimates. We use the ranking scores produced from the AutoML algorithm and Spearman's rank correlation to infer or link the possible relative importance of primary versus secondary sources of PM_{2.5} as a first step toward estimating particle composition. Our comparison of AutoML-derived models to selected baseline machine learning models demonstrates that AutoML is at least as good as user-chosen models. The idealized pseudo-observations (chemical-transport model simulations) used in this work lay the groundwork for applying satellite retrievals of tropospheric trace gases to estimate fine particle concentrations in India and serve to illustrate the promise of AutoML applications in atmospheric and environmental research.

Introduction. High levels of ambient fine particles (known as PM_{2.5}, particles 2.5 μm in diameter or smaller) pose a major environmental issue in India. As estimated by Chowdhury et al. (2019), nearly the entire population (99.9%) in India is exposed to annual PM_{2.5} exceeding the previous World Health Organization (WHO) guideline of 10 $\mu\text{g}/\text{m}^3$. The latest WHO Global Air Quality Guidelines (AQG) announced on 22 September 2021, lowered the annual AQG level of PM_{2.5} to 5 $\mu\text{g}/\text{m}^3$ (World Health Organization, 2021). To tackle the issue of air pollution, the Government of India launched the National Clean Air Program in January 2019, aimed at reducing particulate pollution by 20%–30% relative to 2017 levels by 2024. Monitoring air quality and understanding pollutant sources are critical to implementing effective air quality management plans, but India mostly lacks long-term, publicly accessible, reliable (i.e., quality controlled) measurements of particle composition that enable source attribution (Bali et al., 2021; Brauer et al., 2019). Although the Central Pollution Control Board (CPCB) has maintained a routine monitoring network for total PM_{2.5} mass (composition unknown) and certain gas-phase species since 2008, the density of India's monitoring network (~ 0.14 monitors/million persons) is lower than other developing countries such as China (1.2 monitors/million persons) and developed countries such as USA (3.4 monitors/million persons), and leaves the majority of rural India entirely unmonitored (Bali et al., 2021; Brauer et al., 2019; Karambelas et al., 2018; Ravishankara et al., 2020).

Threefold reduction of modeled uncertainty in direct radiative effects by constraining absorbing aerosols over biomass burning regions.

Zhong, Q., N. Schutgens, G.R. van der Werf, T. Takemura, T. van Noije, T. Mielonen, R. Checa-Garcia, U. Lohmann, A. Kirkevåg, D.J.L. Olivié, H. Kokkola, H. Matsui, Z. Kipling, P. Ginoux, P. Le Sager, S. Rémy, H. Bian¹, M. Chin¹, K. Zhang, **K. Tsigaridis**^{2,3}, and **S. Bauer**^{2,3}, 2023

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Abstract. Absorbing aerosols emitted from biomass burning (BB) greatly affect the radiation balance, cloudiness, and circulation over tropical regions. Assessments of these impacts rely heavily on the modeled aerosol absorption from poorly constrained global models and thus exhibit large uncertainties. By combining the AeroCom model ensemble with satellite and in situ observations, we provide constraints on the aerosol absorption optical depth (AAOD) over the Amazon and Africa. Our approach enables identification of error contributions from emission, lifetime, and MAC (mass absorption coefficient) per model, with MAC and emission dominating the AAOD errors over Amazon and Africa, respectively. In addition to primary emissions, our analysis suggests substantial formation of secondary organic aerosols over the Amazon but not over Africa. Furthermore, we find that differences in direct aerosol radiative effects between models decrease by threefold over the BB source and outflow regions after correcting the identified errors. This highlights the potential to greatly reduce the uncertainty in the most uncertain radiative forcing agent.

Introduction. Biomass burning (BB) is a leading contributor to global emissions of carbonaceous aerosols that can potentially exacerbate climate warming by absorbing solar radiation at visible to ultraviolet (UV) wavelengths [i.e., black carbon (BC) and organic aerosol (OA), the absorbing component of OA is also referred to as brown carbon] (1, 2). Therefore, these absorbing BB aerosols (BBAs) can essentially affect radiation balance (2, 3), cloud formation and properties (4, 5), precipitation (6, 7), and regional circulation patterns (8, 9). To better understand these impacts, recent flight campaigns have paid particular attention to the BBA over tropical regions where large amounts of BBA are injected into the atmosphere every year (10–13).

Despite the recent progress in airborne measurements of BBA, large-scale and long-term assessments of the climate impacts of BBA have far relied on global aerosol models (14, 15). However, models have shown substantial discrepancies and errors regarding BBA absorption (16–19), which remains a key obstacle to reliable climate assessments because BBA absorption can simultaneously contribute to direct, semidirect, and indirect aerosol effects (9, 20). Comparisons between models and satellite observations suggest that global models generally underestimate the overall warming impacts of BBA, as indicated by a substantial underestimation of the aerosol absorption optical depth (AAOD) (21) in combination with an overestimation of the single-scattering albedo (SSA) (20). These findings are supported by flight campaign measurements (22, 23) such as the ObseRvations of Aerosols above CLouds and their intERactionS (ORACLES) project (22), suggesting that the overall warming caused by BBA plumes is greater than previously considered, particularly in tropical regions. However, when considering the aerosol composition, global models tend to produce stronger absorption than observed from field and laboratory measurements for a given BC mass mixing ratio (24). The contradiction between the underestimated overall warming and overestimated absorbing capability per unit of BC mass highlights important errors in the emission, composition, and optical properties of absorbing BBA. Although there have been discussions regarding the possible reasons for these model errors [e.g., particle size distribution, vertical profiles, mixing states, and refractive index (24–28)], a quantitative evaluation of how these factors contribute to the overall errors is still missing. This poses a fundamental challenge to the aerosol modeling community, which hinders reliable climate assessments over tropical regions.

C. Chapters, Conferences, Workshops, other Publications

1. Crespo, J.A., S. Asharaf, D.J. Posselt, **C.M. Naud**, and A. Cobb, 2023: [CYGNSS Ocean Surface Heat Flux Product development, updates, and applications with extratropical cyclones and atmospheric rivers](#). In *IGARSS 2023 — 2023 IEEE International Geoscience and Remote Sensing Symposium, Pasadena, CA, USA*, pp. 845-847, doi:10.1109/IGARSS52108.2023.10282114.....229
2. Gliese, U., Z. Rhodes, K. Squire, K.S. Jepsen, **B. Cairns**, B.L. Clemons, J. Cook, R. Esplin, R.H. Estep, Jr., E.T. Gorman, E. Kan, G. Meister, W. Lu, D.B. Mott, F.S. Patt, J. Peterson, and R.G. Schnurr, 2023: [Pulse response of the shortwave infrared detection system of the ocean color instrument for the NASA PACE Mission](#). In *Sensors, Systems, and Next-Generation Satellites XXVII, 19 Oct. 2023, Amsterdam, Netherlands*. S.R. Babu, A. Hélière, and T. Kimura, Eds., Proc. SPIE, vol. 12729, p. 127290O, doi:10.1117/12.2684367.....230
3. Green, R.O., N. Mahowald, D.R. Thompson, C. Ung, P. Brodrick, R. Pollock, M. Bennett, S. Lundeen, M. Joyce, W. Olson-Duvall, B. Oaida, C. Bradley, E. Diaz, R. Clark, S. Vannan, G. Swayze, R. Kokaly, P. Ginoux, **R.L. Miller**, G. Okin, C. Pérez García-Pando, B. Ehlmann, O. Kalashnikova, T.H. Painter, V. Realmuto, D. Chadwick, E. Ben-Dor, D.H. Pearlshtien, L. Guanter, B. Phillips, K. Reath, A. Thorpe, L. Shaw, A. Keebler, F. Ochoa, K. Grant, A. Sen, R. Duren, **V. Obiso**, M. Gonçalves-Ageitos, and **Y. Huang**, 2023: [Performance and early results from the Earth Surface Mineral Dust Source Investigation \(EMIT\) imaging spectroscopy mission](#). In *2023 IEEE Aerospace Conference*, IEEE, on-line, doi:10.1109/AERO55745.2023.10115851.....231
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CYGNSS Ocean Surface Heat Flux Product development, updates, and applications with extratropical cyclones and atmospheric rivers

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Abstract. Latent and sensible ocean surface heat fluxes (LHF and SHF, respectively) can significantly impact the genesis and evolution of climate and weather systems. As heat fluxes increase within the boundary layer, static stability decreases, leading to a lower lifted condensation level, which could lead to dry and moist convection development in various weather systems. The energy transported through LHF and SHF between the ocean surface and boundary layer can influence weather systems at the microscale, mesoscale, and synoptic scale, including, but not limited to, tropical and extratropical cyclones, convection, and large-scale waves such as the Madden-Julian Oscillation.

Introduction. Latent and sensible ocean surface heat fluxes (LHF and SHF, respectively) can significantly impact the genesis and evolution of climate and weather systems. As heat fluxes increase within the boundary layer, static stability decreases, leading to a lower lifted condensation level, which could lead to dry and moist convection development in various weather systems [1]-[2]. The energy transported through LHF and SHF between the ocean surface and boundary layer can influence weather systems at the microscale, mesoscale, and synoptic scale, including, but not limited to, tropical and extratropical cyclones, convection, and large-scale waves such as the Madden-Julian Oscillation [3]-[6].

SHF and LHF are estimated as functions of surface wind speeds and air-sea temperature and humidity differences when direct observations of these fluxes are unavailable. Routine and widespread measurements of ocean surface heat fluxes and their components are necessary with their impacts on weather systems at multiple scales and their rapid spatial and temporal variations. While in-situ observations of LHF and SHF, and their components, from flux towers, buoys, and autonomous sailing drones are preferable, they are often limited spatially and temporally. Space-borne instruments can fill in these gaps by measuring wind speed, temperature, and humidity over the open oceans but have limitations as their signals attenuate with heavy precipitation. Additionally, many of these instruments, especially those in polar orbits, may miss large spatial areas and have infrequent sampling over the tropical and subtropical oceans. To help fill the gaps left by existing in-situ and remote sensing platforms, we have developed the Level-2 Ocean Surface Heat Flux Product for the Cyclone Global Navigation Satellite System (CYGNSS), which features rapid revisits over the tropical and subtropical oceans and can offer observations of ocean surface wind speeds in the presence of heavy precipitation [7].

By combining CYGNSS surface wind speed observations with temperature and humidity observations from reanalysis datasets, such as MERRA-2 and ERA5, one can estimate LHF and SHF over the tropical and subtropical oceans in nearly all-weather conditions with daily coverage over most of the tropical and subtropical oceans [8] (Figure 1). Since the CYGNSS Ocean Surface Heat Flux Product was initially released, updates have included renewed CYGNSS wind speed products and changes to the thermodynamic inputs, such as a recent change from MERRA-2 to ERA5. While CYGNSS is primarily a tropical mission, its orbit inclination allows it to observe significant surface heat fluxes occurring in the lower midlatitudes in both hemispheres where high surface wind speeds interact with areas of air-sea temperature and humidity differences, usually around western boundary currents [9]. Surface heat fluxes along these western boundary currents, such as the Gulf Stream and Kuroshio Current, can impact the formation of developing extratropical cyclones (ETCs) [10]-[11].

Pulse response of the shortwave infrared detection system of the ocean color instrument for the NASA PACE Mission.

Gliese, U., Z. Rhodes, K. Squire, K.S. Jepsen, **B. Cairns**¹, B.L. Clemons, J. Cook, R. Esplin, R.H. Estep, Jr., E.T. Gorman, E. Kan, G. Meister, W. Lu, D.B. Mott, F.S. Patt, J. Peterson, and R.G. Schnurr, 2023

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Abstract. The Ocean Color Instrument (OCI) on NASA's Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission is a hyperspectral Earth imager with a spatial resolution of $1 \text{ km} \times 1 \text{ km}$ and a spectral resolution of 5 nm in 2.5 nm steps over 342-887 nm. In addition, OCI provides seven discrete bands in the 940 nm to 2260 nm Short-Wave InfraRed (SWIR) range. The front-end optical imager is a rotating mirror-based system that images the ground scene onto a slit with an instantaneous field of view of $16 \text{ km} \times 1 \text{ km}$. For the SWIR bands, the slit-image is re-imaged onto a 161 micro-lens array that effectively acts as the focal plane since each lens element is fiber coupled to wavelength filtered InGaAs and HgCdTe Photo Diodes (PDs). The pulse response of the detection system is critical to OCI SWIR performance. We find that PDs introduce an inherent slow tail in the pulse response due to slow diffusion moving carriers in their n and p regions. We show that this introduces response errors ranging from 1 down to 0.01 % for up to tens of science pixels after the pulse depending on the PD design and materials. It is shown that the response is distinctly different for the InGaAs and HgCdTe PDs. We explain how the front-end design can further increase this error. Finally, we detail the cause of the slow pulse response tail, how to model it, its impact on OCI performance and how it is characterized and corrected to meet OCI requirements.

Introduction. The Ocean Color Instrument (OCI) on NASA's Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission is a hyperspectral imager that collects images of Earth with a 2-day global coverage, a spatial resolution of $1 \text{ km} \times 1 \text{ km}$ and a spectral resolution of 5 nm in 2.5 nm steps in the 342-887 nm wavelength range [1]-[3]. As detailed in [3], [4], it does this with high Signal-to-Noise Ratio (SNR), large Dynamic Range (DR), excellent radiometric gain stability and very low spatial image striping artifact level. In comparison, previous ocean imagers [1], [5] such as SeaWiFS [6], VIIRS [7] and MODIS [8] have only provided discrete bands. With its hyperspectral capability and high performance, OCI provides a significant technological advancement enabling quantitative evaluation of separate plankton species from space for the first time. In addition to its hyperspectral imaging system, OCI provides 7 discrete Short-Wave InfraRed (SWIR) bands in the 940-2260 nm wavelength range.

The SWIR imaging and detection system is based on fiber-coupled band-filtered InGaAs and HgCdTe PhotoDiodes (PDs) as described in detail in Section 2.1. Each PD is used to detect the photons, after filtering, coming out of the fibers from each $1 \text{ km} \times 1 \text{ km}$ ground scene imaged by OCI. The pulse response of the detection system to a ground scene, in the following called a Science Pixel (SP), is critical to the OCI SWIR Modulation Transfer Function (MTF) and high contrast performance. The simulated and measured pulse response of the SWIR system is presented in Section 2.2. We find the pulse response to be slower than expected with a long decay. As discussed in this paper, the slow response is caused by two effects. The first is a slow pulse response of the flight PDs. As detailed in Section 3, PDs introduce an inherent slow tail in the pulse response due to slow diffusion moving carriers in their n and p regions [9], [10]. We show that this introduces varying response errors for up to tens of SPs after the pulse peak depending on the PD design and materials. Because of this, the response is different for the InGaAs and HgCdTe PDs. As shown, the slow PD response can be successfully modeled using a more detailed equivalent circuit diagram for the PDs. The second effect is the pulse response of the implemented Front-End Electronics (FEE). The impact is caused by the use of a tuned transimpedance amplifier in the FEE chosen to enable a very high gain while achieving FEE stability.

Performance and early results from the Earth Surface Mineral Dust Source Investigation (EMIT) imaging spectroscopy mission.

Green, R.O.¹, N. Mahowald, D.R. Thompson¹, C. Ung, P¹. Brodrick¹, R. Pollock¹, M. Bennett¹, S. Lundeen¹, M. Joyce, W. Olson-Duvall¹, B. Oaida¹, C. Bradley, E. Diaz¹, R. Clark¹, S. Vannan¹, G. Swayze, R. Kokaly, P. Ginoux, **R.L. Miller**², G. Okin, C. Pérez García-Pando, B. Ehlmann, O. Kalashnikova¹, T.H. Painter, V. Realmuto¹, D. Chadwick¹, E. Ben-Dor, D.H. Pearlshtien, L. Guanter, B. Phillips³, K. Reath³, A. Thorpe¹, L. Shaw¹, A. Keebler, F. Ochoa, K. Grant, A. Sen¹, R. Duren¹, **V. Obiso**², M. Gonçalves-Ageitos, and **Y. Huang**^{2,4}, 2023

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Abstract. The Earth Surface Mineral Dust Source Investigation (EMIT) acquires new observations of the Earth from a state-of-the-art, optically fast F/1.8 visible to short wavelength infrared imaging spectrometer with high signal-to-noise ratio and excellent spectroscopic uniformity. EMIT was launched to the International Space Station from Cape Canaveral, Florida, on July 14, 2022, local time. The EMIT instrument is the latest in a series of more than 30 imaging spectrometers and testbeds developed at the Jet Propulsion Laboratory, beginning with the Airborne Imaging Spectrometer that first flew in 1982. EMIT's science objectives use the spectral signatures of minerals observed across the Earth's arid and semi-arid lands containing dust sources to update the soil composition of advanced Earth System Models (ESMs) to better understand and reduce uncertainties in mineral dust aerosol radiative forcing at the local, regional, and global scale, now and in the future. EMIT has begun to collect and deliver high-quality mineral composition determinations for the arid land regions of our planet. Over 1 billion high-quality mineral determinations are expected over the course of the one-year nominal science mission. Currently, detailed knowledge of the composition of the Earth's mineral dust source regions is uncertain and traced to less than 5,000 surface sample mineralogical analyses. The development of the EMIT imaging spectrometer instrumentation was completed successfully, despite the severe impacts of the COVID-19 pandemic. The EMIT Science Data System is complete and running with the full set of algorithms required. These tested algorithms are open source and will be made available to the broader community. These include calibration to measured radiance, atmospheric correction to surface reflectance, mineral composition determination, aggregation to ESM resolution, and ESM runs to address the science objectives. In this paper, the instrument characteristics, ground calibration, in-orbit performance, and early science results are reported.

Introduction. The Earth Surface Mineral Dust Source Investigation (EMIT) is a Class C, NASA Earth Venture Instrument project that was selected in 2018 [1]. The EMIT instrument collects imaging spectroscopy measurements of the Earth's surface below the International Space Station (ISS) to determine the mineral composition of the Earth's mineral dust-producing source regions and adjacent lands to address a current gap in our knowledge of direct radiative forcing from mineral dust at the local, regional, and global scales [2]–[8]. The two science objectives of EMIT are as follows:

1. Constrain the sign and magnitude of dust-related direct radiative forcing at regional and global scales. EMIT achieves this objective by acquiring, validating, and delivering updates of surface mineralogy used to specify soil composition in Earth System Models (ESMs).
2. Predict the increase or decrease of available dust sources under future climate scenarios. EMIT achieves this objective by providing forecast models with the mineralogy of soils exposed within at-risk lands bordering arid and semi-arid dust source regions.

Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Lee, H., K. Calvin, D. Dasgupta, G. Krinner, A. Mukherji, P. Thorne, C. Trisos, J. Romero, P. Aldunce, K. Barrett, G. Blanco, W.W.L. Cheung, S.L. Connors, F. Denton, A. Diongue-Niang, D. Dodman, M. Garschagen, O. Geden, B. Hayward, C. Jones, F. Jotzo, T. Krug, R. Lasco, J.-Y. Lee, V. Masson-Delmotte, M. Meinshausen, K. Mintenbeck, A. Mokssit, F.E.L. Otto, M. Pathak, A. Pirani, E. Poloczanska, H.-O. Pörtner, A. Revi, D.C. Roberts, J. Roy, **A.C. Ruane**¹, J. Skea, P.R. Shukla, R. Slade, A. Slangen, Y. Sokona, A.A. Sörensson, M. Tignor, D. van Vuuren, Y.-M. Wei, H. Winkler, P. Zhai, and Z. Zommers, 2023

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Introduction. This Synthesis Report (SYR) of the IPCC Sixth Assessment Report (AR6) summarizes the state of knowledge of climate change, its widespread impacts and risks, and climate change mitigation and adaptation, based on the peer-reviewed scientific, technical and socio-economic literature since the publication of the IPCC's Fifth Assessment Report (AR5) in 2014.

The assessment is undertaken within the context of the evolving international landscape, in particular, developments in the UN Framework Convention on Climate Change (UNFCCC) process, including the outcomes of the Kyoto Protocol and the adoption of the Paris Agreement. It reflects the increasing diversity of those involved in climate action.

This report integrates the main findings of the AR6 Working Group reports and the three AR6 Special Reports. It recognizes the interdependence of climate, ecosystems and biodiversity, and human societies; the value of diverse forms of knowledge; and the close linkages between climate change adaptation, mitigation, ecosystem health, human well-being and sustainable development. Building on multiple analytical frameworks, including those from the physical and social sciences, this report identifies opportunities for transformative action which are effective, feasible, just and equitable using concepts of systems transitions and resilient development pathways. Different regional classification schemes are used for physical, social and economic aspects, reflecting the underlying literature.

After this introduction, Section 2, '*Current Status and Trends*', opens with the assessment of observational evidence for our changing climate, historical and current drivers of human-induced climate change, and its impacts. It assesses the current implementation of adaptation and mitigation response options. Section 3, '*Long-Term Climate and Development Futures*', provides a long-term assessment of climate change to 2100 and beyond in a broad range of socio-economic futures. It considers long-term characteristics, impacts, risks and costs in adaptation and mitigation pathways in the context of sustainable development. Section 4, '*Near-Term Responses in a Changing Climate*', assesses opportunities for scaling up effective action in the period up to 2040, in the context of climate pledges, and commitments, and the pursuit of sustainable development.

Based on scientific understanding, key findings can be formulated as statements of fact or associated with an assessed level of confidence using the IPCC calibrated language. The scientific findings are drawn from the underlying reports and arise from their Summary for Policymakers (hereafter SPM), Technical Summary (hereafter TS), and underlying chapters and are indicated by {} brackets. Figure 1.1 shows the Synthesis Report Figures Key, a guide to visual icons that are used across multiple figures within this report.

Chapter 3. Earth systems processes.

Leung, L.R., A. Terando, R. Joseph, **G. Tselioudis**¹, L.M. Bruhwiler, **B. Cook**¹, C. Deser, A. Hall, B.D. Hamlington², A. Hoell, F.M. Hoffman, S. Klein, V. Naik, A.G. Pendergrass, C. Tebaldi, P.A. Ullrich, and M.F. Wehner, 2023

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Abstract. Human activities have unequivocally caused the global warming observed over the industrial era, altering the intensity, frequency, and duration of many weather and climate extremes, including extreme heat, extreme precipitation and flooding, drought, and wildfire. Recent scientific developments have enabled deeper understanding of climate processes and their responses to human influence.

Introduction. The Earth system consists of the atmosphere, land, oceans, and cryosphere, which interact and cycle energy, water, and essential elements of life such as carbon, nitrogen, and phosphorus. Powered by the sun, these interactions and cycles determine Earth's climate, which naturally varies at a broad range of timescales from days to millennia through diverse Earth system processes.

Since industrialization, human activities have dramatically altered atmospheric composition and land cover, with consequential impacts on climate. Human-caused emissions of greenhouse gases have warmed the planet by trapping more outgoing energy, leading to a change in the net energy balance at the top of the atmosphere. The net increase in energy input warms the surface and the air and increases moisture in the lower atmosphere, resulting in significant changes in Earth system processes, including changes in atmospheric and oceanic circulations, clouds, and precipitation and melting of sea ice, glaciers, and ice sheets. The increase in energy input also provides fuel for increasing the frequency and intensity of extreme weather events such as heatwaves and convective storms.

In recent years, advances have been made in understanding the changes that have already occurred, attributing changes to human influence, and projecting future changes. These advances are facilitated by new and diverse observations, improved models and experiments, and the combination of observations and models to support multiple lines of evidence and inquiry. Building on previous scientific assessments, these advances have enabled scientists to unequivocally attribute the observed global warming to human activities and to narrow by 50% the range of estimated global warming that would be caused by a doubling of atmospheric carbon dioxide concentration. Complementary to Chapter 2, which focuses on past and future climate trends, particularly in the US, this chapter discusses more generally how Earth system processes respond to the drivers of climate change. It begins by introducing the natural and human (anthropogenic) drivers of climate change (KM 3.1). Next, it addresses our understanding of the climate response to those drivers, including the sensitivity of the climate to changing greenhouse gas concentrations and the feedback processes that can amplify or partially counteract the influences of human activities (KM 3.2). Recent advances in observations, modeling, and attribution of climate change are then discussed (KM 3.3). Lastly, changes in Earth system processes that underpin the many facets of global and regional climate change (KM 3.4) and changes in extreme events (KM 3.5) are discussed.

Customized positional encoding to combine static and time-varying data in robust representation learning for crop yield prediction.

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Abstract. Accurate prediction of crop yield under the conditions of climate change is crucial to ensure food security. Transformers have shown remarkable success in modeling sequential data and hold the potential for improving crop yield prediction. To understand how weather and meteorological sequence variables affect crop yield, the positional encoding used in Transformers is typically shared across different sample sequences. We argue that it is necessary and beneficial to differentiate the positional encoding for distinct samples based on time-invariant properties of the sequences. Particularly, the sequence variables influencing crop yield vary according to static variables such as geographical locations. Sample data from southern areas may benefit from more tailored positional encoding different from that for northern areas. We propose a novel transformer-based architecture for accurate and robust crop yield prediction, by introducing a Customized Positional Encoding (CPE) that encodes a sequence adaptively according to static information associated with the sequence. Empirical studies demonstrate the effectiveness of the proposed novel architecture and show that partially linearized attention better captures the bias introduced by side information than softmax re-weighting. The resultant crop yield prediction model is robust to climate change, with mean-absolute-error reduced by up to 26% compared to the best baseline model in extreme drought years.

Introduction. Climate change is anticipated to exacerbate extreme weather events, including heat waves and droughts, which pose significant risks to global food security. To mitigate these effects, it is essential to accurately estimate and predict regional and global crop productivity in response to climate variability, changes, and extremes. Such estimates are crucial for developing agricultural policies, prioritizing international food aid, forecasting and analyzing global trade trends, and identifying effective strategies for climate change adaptation.

Agriculture is the mainstay of Ethiopia's economy, contributing 46% of its gross national product, employing 85% of the population, and accounting for almost all commodity exports [Yang et al., 2021]. Despite this, Ethiopia is among the most severely food-insecure countries in the world. In 2022, approximately 23.6 million people, equivalent to 23.1 %of its total population, were facing high levels of acute food insecurity [FSIN and GRFC, 2023]. Food security remains a significant challenge in Ethiopia. The country's smallholder, rain-fed agriculture system is highly susceptible to climate variability and extremes, exacerbating the vulnerability of its food production system. [Yang et al., 2020]

Crop yield prediction based on seasonal meteorological forcing and soil properties is an effective approach. Machine learning methods have been used to create predictive models [Zhang et al., 2019; Jiang et al., 2020; Sun et al., 2019. Khaki et al., 2020; Liu et al., 2022a]. Recently, Transformers have demonstrated exceptional success for natural language processing and computer vision tasks and have been tested in crop yield prediction using the Informer model [Liu et al., 2022b]. However, the Informer only considers longitudinal variables, and does not consider non-sequential side information, such as soil and fertilization data. The side information can be critical, as evidenced by the impact of the synthetic fertilizers import ban in May 2021, which caused a 20% drop in rice production in the following 6 months and led to an 80% increase in the rice price in Sri Lanka. Leveraging this type of side information in Transformers should further improve the prediction performance.

Chapter 7: Food Systems.

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Introduction. Food systems — including food production, distribution, consumption, and waste disposal — are critical to sustaining livelihoods and delivering nutrition worldwide. However, food systems contribute significantly to the climate crisis, accounting for over 30 percent of human-caused global greenhouse gas emissions (e.g., methane, carbon dioxide, and nitrous oxide). Climate change, in turn, has a significant and growing impact on food systems. Climate change increases heat stress and can lead to deteriorating soil health, for example, slowing agricultural productivity and reducing the nutritional content of crops and livestock. The cascading impacts of climate extremes on agricultural production are likely to destabilize global food security, endangering the livelihoods of billions of people and threatening public health.

A. Food system greenhouse gas emissions

All parts of the food system – from land use change to waste disposal – result in greenhouse gas emissions.

- (i) **Land-use change.** The conversion³ of natural ecosystems such as forests, marshes and grasslands into land for agriculture. Eighty percent of deforestation and land degradation is due to land-use change intended for agricultural production. This is a significant contributor⁴ to carbon dioxide and nitrous oxide emissions. Sustainable intensification can spare land from conversion and take land out of agricultural production. Well-designed land-use management strategies⁵ —such as agroforestry, cover cropping and reductions in tillage—can preserve soil health and enhance carbon sequestration in working lands.
- (ii) **Production:** The inputs and operations needed to produce food with agriculture. For example, existing agricultural practices⁶ contribute to copious⁷ methane production (e.g., through flooded rice fields and enteric fermentation in livestock) and nitrous oxide production (e.g., over-application of synthetic fertilizers). Improving livestock management, including rotational grazing and optimized feed, and implementing precision agriculture techniques to reduce fertilizer and pesticide use can help lower total emissions.
- (iii) **Supply chains:** The processing, distribution, storage, trade, marketing and handling of food following production and before consumption. Food-system supply chains have considerable potential to employ more sustainable strategies, from increasing penetration of renewable energy into food cold chains⁸ and decreasing energy expenditures across all steps of the food supply chain via improved logistics and reductions in post-harvest food loss.
- (iv) **Consumption and Waste:** Processes related to consumer food preparation and to the disposal of food waste. Substantial carbon dioxide emissions occur⁹ in the production and combustion of biomass and fossil fuels for cooking. The disposal of food waste in landfills emits significant amounts of methane¹⁰ globally. Food waste and consequent emissions also occur during food production, storage, and transportation.

Calibration and preliminary performance of an in-water integrated total scattering and backscattering sensor.

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Abstract. The design and the calibration of the Beam-attenuation, b and bb Laser Underwater Environment Sensor (4BLUES), which borrows from advanced designs developed by the authors' individual groups in the course of the last two decades. The sensor features unparalleled accuracy in determining the optical scattering and backscattering coefficients, which are critical parameters for the remote sensing of water constituents and in-water bio-optical applications. Calibration procedures performed in the laboratory with spheres of known properties are presented together with an assessment of the performance in two field experiments in coastal waters. The more complex calibration of the scattering channel includes a novel inversion approach, which accounts for scattering and absorption losses along the laser-beam path. Strong agreement was observed with current advanced sensors for extinction and the backscattering measurement for one of the field experiments. Total scattering comparison with the current state of the art showed reasonable agreement (within 25%) for all stations except one, where the interpretation for the higher discrepancies is unresolved. These preliminary results suggest further assessment is warranted.

Introduction. The light field incident in seawater is altered through processes controlled by the inherent optical properties (IOPs) including absorption, scattering, and fluorescence, which are in turn controlled by constituents such as suspended biological organisms, minerals and organic detritus, aggregates, air bubbles, and water molecules.¹ Current remote sensing methods resolving characteristics of particle populations in the ocean are almost entirely optically based.^{2, 3} Direct in-water measurements of IOPs form the link between remote sensing methods and the seawater biogeochemical properties of interest to the oceanography community.

Scattering measurements can serve as an essential proxy for characterizing particle fields in seawater. From an overall biogeochemical perspective, absorption, a [m^{-1}], and fluorescence can be linked to the abundance of phytoplankton pigments and (potentially) to the presence of different phytoplankton groups and particulates. Nevertheless, far more detailed information about particle populations is encoded in the angular distribution of the scattered light field, described via the Volume Scattering Function (VSF), β [$\text{m}^{-1} \text{sr}^{-1}$], and its polarization signatures (i.e., the plane of vibration of the electromagnetic wave), which depend on particle concentration, internal composition, shape, and size.^{4, 5} The 4π integration of the VSF yields the total scattering coefficient, b [m^{-1}], which has been correlated through models and (limited) measurements to total-volume and total-mass concentration.^{2, 6, 7} The backscattering coefficient bb [m^{-1}], i.e. the component of b in the backward hemisphere, has been used to infer particulate organic carbon (POC), total suspended matter (TSM) and biological productivity.^{8–15} From a remote sensing perspective, since the inception of the satellite era, the ratio of b_b to $(a + bb)$ has been widely used [e.g., 16] in analytical approximations of radiative transfer theory as a link to the so-called remote sensing reflectance, defined as the spectral distribution of water-leaving radiance normalized to the downwelling solar irradiance.

Unfortunately, the interpretation of b and bb measurements is rather challenging because (i) describing light scattering from very diverse particle fields requires complex models; and (ii) purely empirical relationships constructed to describe such relationships assume the composition of the particle population remains approximately constant. Because of the considerable temporal and spatial variability of natural particle populations, particularly in coastal regions, the latter assumption is rarely valid. A significant hindrance in advancing our understanding of scattering as a particle biogeochemical proxy is a lack of rigorous, direct, in-water sensing approaches to quantify b and bb .

Integrated climate change assessments on selected farming systems in India, Pakistan, Bangladesh, and Viet Nam.

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Introduction. Early work on climate change and agriculture was often limited to site-based crop modeling without addressing farming systems at regional scales and socio-economic outcomes to fill these gaps, the Agricultural Model Intercomparison and Improvement Project (AgMIP) was founded in 2010. AgMIP has built a network of 1,200+ transdisciplinary scientists and decision-makers and developed a portfolio of climate, biophysical, and socioeconomic models and assessments to understand and respond to current and future challenges in agriculture and food security.

There is a further gap with regard to the evidence base required by policy makers to adopt agricultural adaptation policies and undertake resilience programs for the agricultural sector. To fill this gap, AgMIP is developing tools and methods that help decision-makers, and policy makers create multiple-scale interventions and policies to offset the negative impacts of climate change. The AgMIP tools and methods can aid in the more equitable implementation of agricultural development strategies to ensure that all farmers will benefit.

Finally, there is a large gap or "siloization" of responses between mitigation and adaptation actions by countries. As many countries are now seeking to implement strategies for both climate change mitigation and adaptation as part of their Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs), interventions in farming systems can address both reductions in greenhouse gas (GHG) emissions and improvement in resilience. AgMIP projects are addressing this siloization in Bangladesh, Viet Nam, and India by testing the co-benefits and trade-offs between mitigation and adaptation in regard to elements of the sustainable rice intensification management system, including alternate wetting and drying (AWD).

AgMIP has developed protocols for regional integrated assessments (RIAs) that bring together climate, biophysical, and economic modelers to work together on farming system scales. The purpose of this chapter is to synthesize and evaluate the results of RIAs that have been done at subnational scales in India and Pakistan, to present crop modeling results from Viet Nam, and illustrate a pilot study in Bangladesh on combined mitigation and adaptation.

In this chapter, we share examples from AgMIP regional integrated assessment studies in South Asia, illustrate the AgMIP mitigation and adaptation co-benefits protocols with an example from Bangladesh, and present major overall findings (Rosenzweig, Mutter, and Mencos Contreras 2021). We then build on the AgMIP project results to formulate policy recommendations for development pathways in Asia and the Pacific region, as well as implications for global food supplies and food security.

An operational fire danger rating system for Thailand and Lower Mekong Region: Development, utilization, and experiences.

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Abstract. This study describes development, utilization, and experiences of implementing a fire danger rating forecast system for Thailand and Upper ASEAN, or the Lower Mekong River Region, which is referred to as "FR-Mek (short for Fire Danger Rating System for Lower Mekong River Region)". It was developed within the widely used framework of the Canadian Fire Danger Rating System which has been adopted in equatorial Southeast Asia. Following its development, FR-Mek has been transferred to and officially operated since 2015 by the Department of National Parks, Wildlife and Plant Conservation and since 2020 by Royal Forest Department. The system uses two fire danger indices: the FPMC (Fine Fuel Moisture Code) and FWI (Fire Weather Index), representing how easy a fire would be ignited and how dangerous an ignited fire would be in terms of spread and intensity respectively. To adapt the system for the regional fire environment, fires over Upper ASEAN or the Lower Mekong River Region were studied using Terra/Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) and their relationship with fire weather was investigated. The FPMC and FWI were calibrated to four fire danger levels from low to high. A suite of computer programs were developed as FR-Mek for a daily forecast operation capable of forecasting fire danger at grid resolutions of 3-9 km over six days (current day and next five days). The daily FWI value is used to adjust FWI signs placed in front of 305 forest fire suppression stations throughout Thailand. Beyond this direct public data sharing, more intensive operational use is still evolving. During the 2021 fire season, its use has increased and become a part of daily operation of forest fire, open burning and smoke haze control and management for 17 northern provinces of Thailand.

Introduction. Fires and smoke haze have become an annual hazard in Thailand and the Upper ASEAN (or Lower Mekong River Region) during the dry season, particularly in Upper North Thailand (UNT) and most of the Lower Mekong River Region (LMR), which is the study area of interest. The LMR geographically includes Thailand, Myanmar, Lao PDR, Cambodia, and Vietnam. For the region, the dry season typically lasts six months (November–April), while the wet season includes the remaining months. In the early part of the dry season, the northeast monsoon prevails and brings cool, dry continental air from mid-latitudes. In the later part, the monsoon weakens and is replaced by warm lows. Although the air becomes warmer and more humid, the moisture availability needs to be higher to produce considerable rain. These conditions are favorable to vegetation fires. In addition to climate, most of the fires in Southeast Asia are attributed to human factors (Biswas et al. 2015; Alabar et al. 2018; Hayasaka and Sepriando 2018; Lasko and Vadrevu 2018; Saharjo and Yungan 2018; Syaufina and Maulana 2021; Vadrevu et al. 2021a,b). Agricultural burning usually intensifies in this period due to land clearing and preparation for crop farming in the forthcoming wet season (Oanh et al. 2018). Fires can cause many impacts. They are an environmental disturbance that may alter the richness of forest ecology and biodiversity. Severe fires can seriously threaten firefighters and people within affected areas. It also emits a large amount of air pollutants and greenhouse gasses into the atmosphere, potentially resulting in degraded air quality due to smoke haze and, in turn, negatively affecting tourism, business, air, and land transportation, and, importantly, public health (Manomaiphiboon et al. 2009 and 2017; Phairuang 2021; Lam and Roy 2021; Adam and Balasubramanian 2021; Park and Takeuchi 2021; Lee and Wang 2021; Uranishiet al. 2021).

TRACER Lightning Mapping Array Field Campaign Report.

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Introduction. Our observational contribution to the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) user facility's Tracking Aerosol Convection Interactions Experiment (TRACER) was the deployment of additional Lightning Mapping Array sensors to provide enhanced capability to the Houston Lightning Mapping Array (HLMA) during the TRACER intensive operational period. To that end, the Texas Tech University personnel (Professor Bruning and Dr. Brunner, and graduate students Jessica Souza, David Singewald, Stephanie Weiss, and Matthew Miller) deployed two portable LMA antennae at locations G and B shown in the map below. The map also shows the predicted lightning flash detection efficiency in black contours, as well as color-shaded very-high-frequency (VHF) source detection efficiency, which roughly corresponds to the sensitivity to lightning channel detail.

Feeds from these sensors were integrated in the HLMA processing in real-time and in post-processing, partially leveraging National Science Foundation support through the TRACER campaign that supported the core HLMA, operated by Timothy Logan.

2.0 Results. Processing of HLMA data confirms the enhanced ability of HLMA to detect lightning – excluding these sensors results in lower source counts, and decreased range of minimum sensitivity, as illustrated by the following plots.

3.0 Publications and References. Bruning, EC, K Brunner, J Souza, M van Lier-Walqui, and T Logan. 2022. “Observations of mixed-phase microphysics and lightning for the 2022 TRACER/ESCAPE field campaigns.” Presented at the Fifth Texas Weather Conference. van Lier-Walqui, M, K Brunner, EC Bruning, T Matsui, T Iguchi, D Hernandez-Deckers, and A Fridlind. 2022. “Tracking isolated thunderstorms in Houston TX with polarimetric radar and the lightning mapping array.” Presented at the European Conference on Radar Meteorology. Locarno, Switzerland. Bruning, EC, T Logan, K Brunner, M van Lier-Walqui, and JCS Souza. 2022. “Houston Lightning Mapping Array Observations during ESCAPE.” Presented at the ESCAPE Science Meeting. Norman, Oklahoma.

Bruning, EC, K Brunner, M van Lier-Walqui, T Logan, M Miller, JCS Souza, D Singewald, and S Weiss. 2022. “Radar polarimetry and flash rate variability in varying thermodynamic and aerosol environments in Houston, Texas.” Presented at the American Geophysical Union Fall Meeting. van Lier-Walqui, M, EC Bruning, K Brunner, T Matsui, T Iguchi, A Fridlind, V Chandra, and T Logan. 2023. “Lagrangian analysis of isolated cells during TRACER: comparison of cell lifetime-relative polarimetric radar and lightning.” Presented at the TRACER/ACPC workshop. Houston, Texas.

4.0 Lessons Learned. LMAs are reliable, continuous-monitoring technology for lightning, and can be supplemented with additional stations to optimize detection efficiency at locations of interest. Integration of stations into a network requires some expert configuration of each station and care to ensure data are incorporated properly into post-processed data. Note that the distributed nature of LMA sites is somewhat unusual for an ARM campaign. University partners are able to deploy in such a mode, typically with handshake agreements with local landowners since the sites only require 1 square meter of land and are self-contained on solar power.

D. PhD Theses

1. **Mitevski, I.**, 2023: [Asymmetric and Non-monotonic Response of the Climate System to Idealized CO2 Forcing](#). Ph.D. thesis. Columbia University, doi:10.7916/18qg-2y74.....241

Asymmetric and Non-monotonic Response of the Climate System to Idealized CO₂ Forcing.

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In this thesis, I explore the climate system's response to symmetric abrupt and transient CO₂ forcing across a range of concentrations, from 1/8× to 8×CO₂, relative to pre-industrial levels. I use two CMIP6 class models: the CESM Large Ensemble (CESM-LE) model configuration and the NASA Goddard Institute for Space Studies Model E2.1-G (GISS-E2.1-G). I use a hierarchy of (1) fully coupled atmosphere-ocean-sea-ice-land, (2) slab ocean, and (3) prescribed sea surface temperature simulations to analyze and support the findings.

First, I find an asymmetric response in global mean surface air temperature (ΔT_s) and effective climate sensitivity (EffCS) between colder and warmer experiments. The ΔT_s response at 8×CO₂ is more than a third larger than the corresponding cooling at 1/8×CO₂. I attribute this asymmetry primarily due to the non-logarithmic CO₂ forcing, not to changes in the radiative feedbacks.

Second, I identify a non-monotonic response of EffCS in the warmer scenarios, with a minimum occurring at 4×CO₂ (3×CO₂) in CESM-LE (GISS-E2.1-G). This minimum in the warming simulations is associated with a non-monotonicity in the radiative feedback. Similar non-monotonic responses in Northern Hemisphere sea-ice, precipitation, the latitude of zero precipitation-minus-evaporation, and the strength of the Hadley cell are also identified. Comparing the climate response over the same CO₂ range between fully coupled and slab-ocean versions of the same models, I demonstrate that the climate system's non-monotonic response is linked to changes in ocean dynamics, associated with a collapse of the Atlantic Meridional Overturning Circulation (AMOC).

Third, to establish the significance of North Atlantic cooling in driving the non-monotonic changes in the radiative feedback, I conducted additional atmosphere-only (AMIP) simulations using the same models but with prescribed sea surface temperatures (SSTs) restricted to different regions. Through these simulations, I uncovered that the minimum EffCS value, characterized by notably negative radiative feedbacks, primarily originates from relative cooling of the sea surface temperature (SST) in the tropical and subtropical North Atlantic. This cooling of SSTs contributes to an increase in low-level cloud content in the eastern region of the North Atlantic, subsequently leading to a pronounced negative (stabilizing) feedback response.

Furthermore, I investigated the state dependence of the effective radiative forcing (ERF) from 1/16× to 16×CO₂. I found that ERF increases with CO₂ concentration due to the increase in Instantaneous Radiative Forcing (IRF). Specifically, the IRF increases at higher CO₂ values primarily due to stronger stratospheric cooling induced by CO₂ forcing. On the other hand, the radiative adjustments counteract the IRF increase, causing the ERF to rise at a slower pace compared to the corresponding increase in IRF induced by higher CO₂ concentrations.

Lastly, I studied the winter storm tracks in the Southern Hemisphere, focusing on experiments up to 8×CO₂. Through this analysis, I identified a non-linear response in the low latitude storm tracks. It is projected that the storm tracks will experience an intensification by the end of the century. However, my findings reveal that this intensification does not scale linearly with CO₂ forcing. In fact, the storm tracks shift poleward, including a reduction of the storm tracks at low-mid latitudes and intensification at mid-high latitudes.

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