National Aeronautics and Space Administration

NASA's High-Resolution GEOS Forecasting and Reanalysis Products: A Unified Tool from Local to Global Scales

K. Emma Knowland

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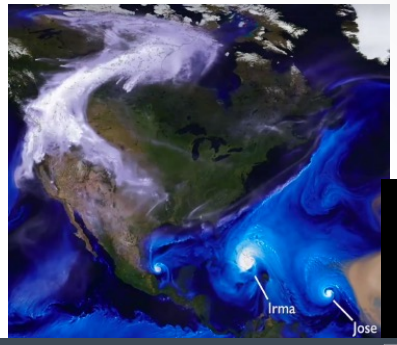
NASA Global Modeling and Assimilation Office (GMAO)

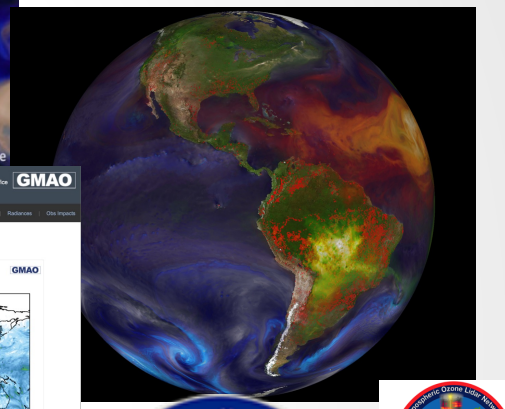
In collaboration with many scientists from GMAO and other labs at NASA Goddard Space Flight Center

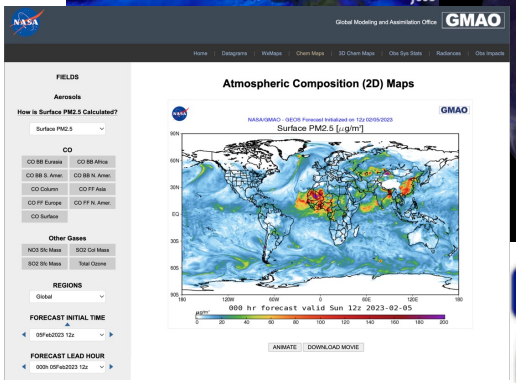
National Aeronautics and Space Administration

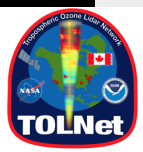
OUTLINE

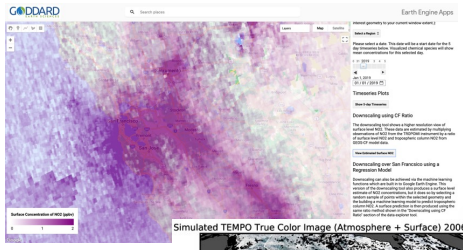
1. Overview of GEOS current capabilities
   - Numerical Weather Prediction
   - Aerosol and Constituent data assimilation systems
   - Composition Forecasting
2. How to access GEOS “big data” for research scientists and engaged community members
3. Applications
4. Future Direction

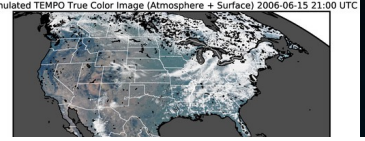


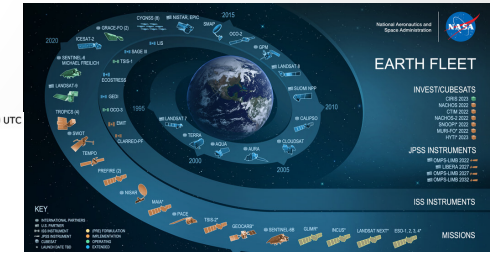












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GMAO's core mission is to enhance the value of NASA's observations to understand, analyze and predict changes in the physics, chemistry and biology of the Earth system

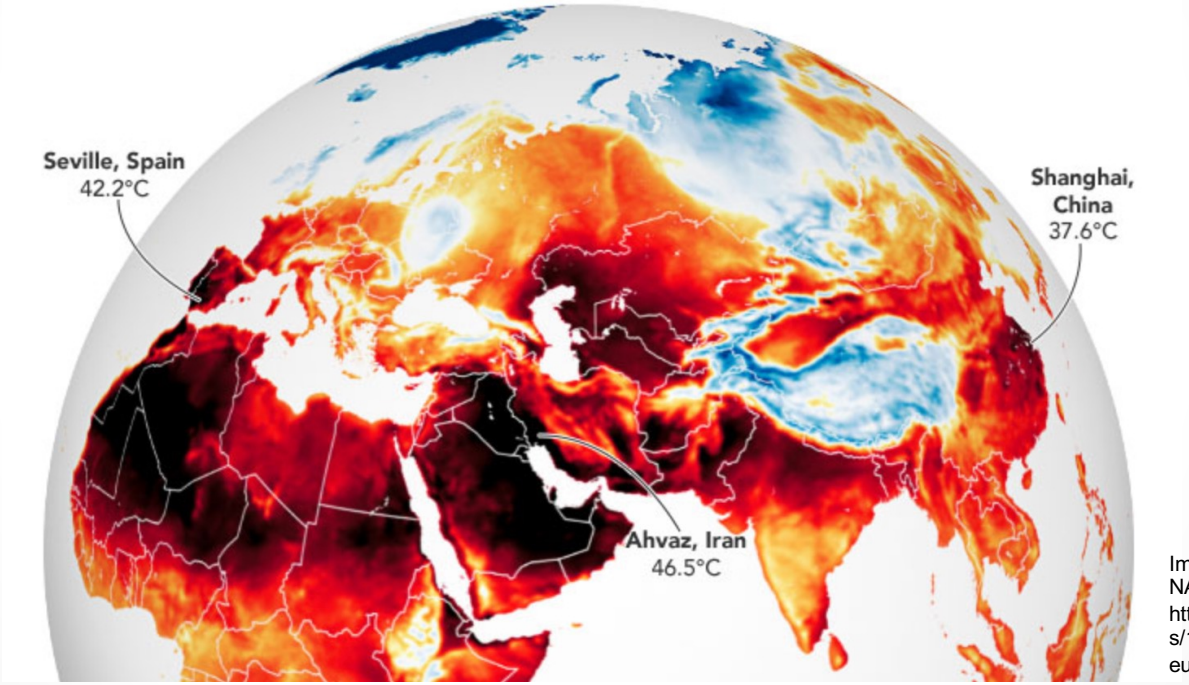

Image by Joshua Stevens,
NASA Earth Observatory
https://earthobservatory.nasa.gov/images/150083/heatwaves-and-fires-scorch-europe-africa-and-asia

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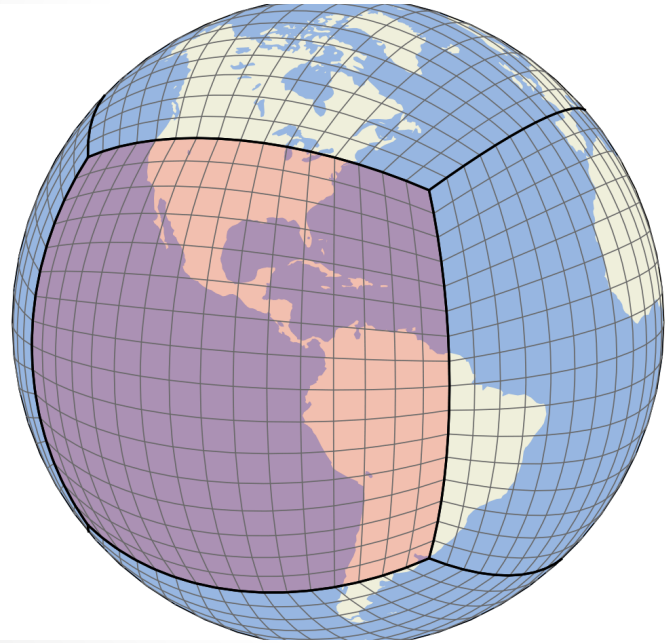
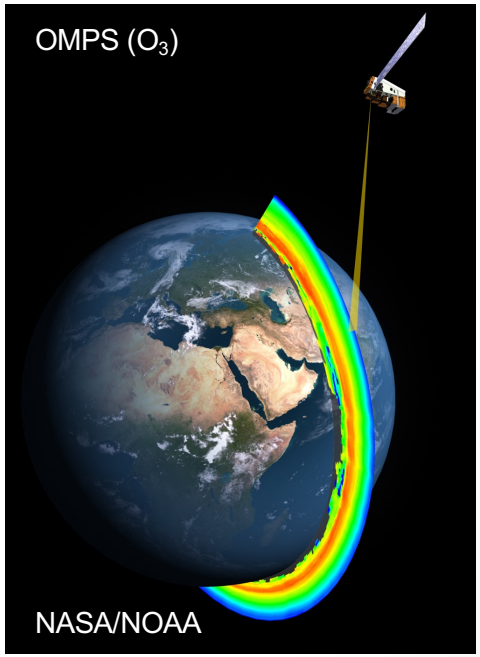
NASA GMAO global meteorology and chemistry products

GEOS



Bindle et al., 2021 GMD



www.nasa.gov

NASA GMAO global meteorology and chemistry products

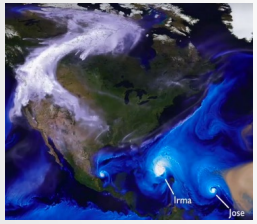
GEOS

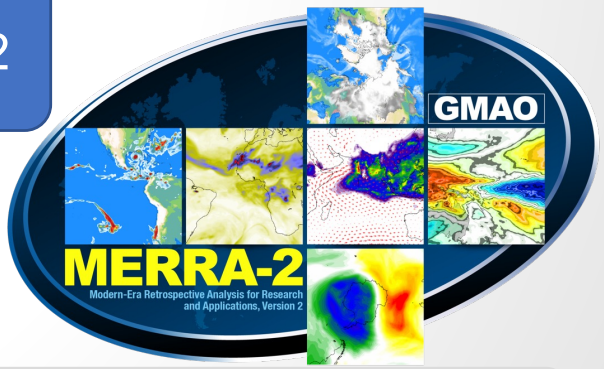
Forecasting

Reanalysis

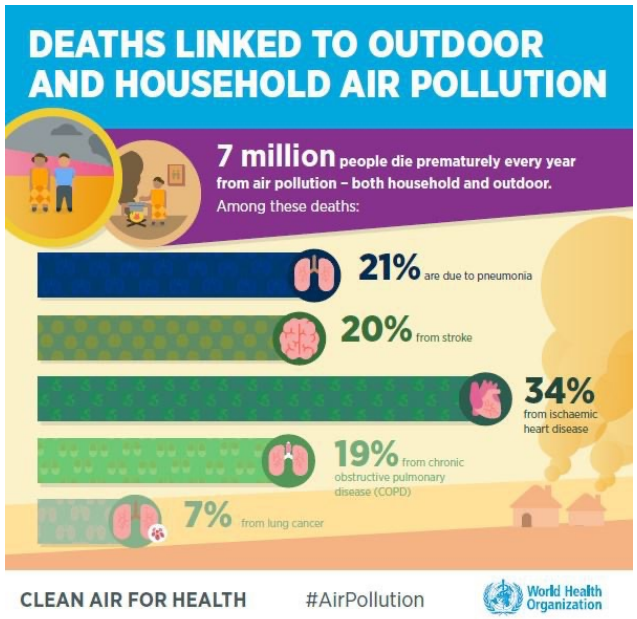
GEOS FP

MERRA-2

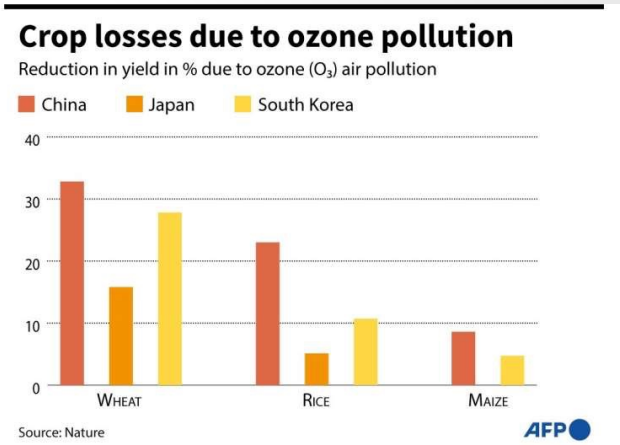




Air pollution is harmful for human health and crops



https://www.ccacoalition.org/en/news/world-health-organization-releases-new-global-air-pollution-data



https://phys.org/news/2022-01-ozone-pollution-asia-billions-lost.html

https://airquality.gsfc.nasa.gov/ozone-bioindicator-garden

- 1 of every 9 death is related to air pollution (WHO)
- $5 Trillion in welfare losses every year (World Bank)
- Locally up to 50% crop loss due to ozone

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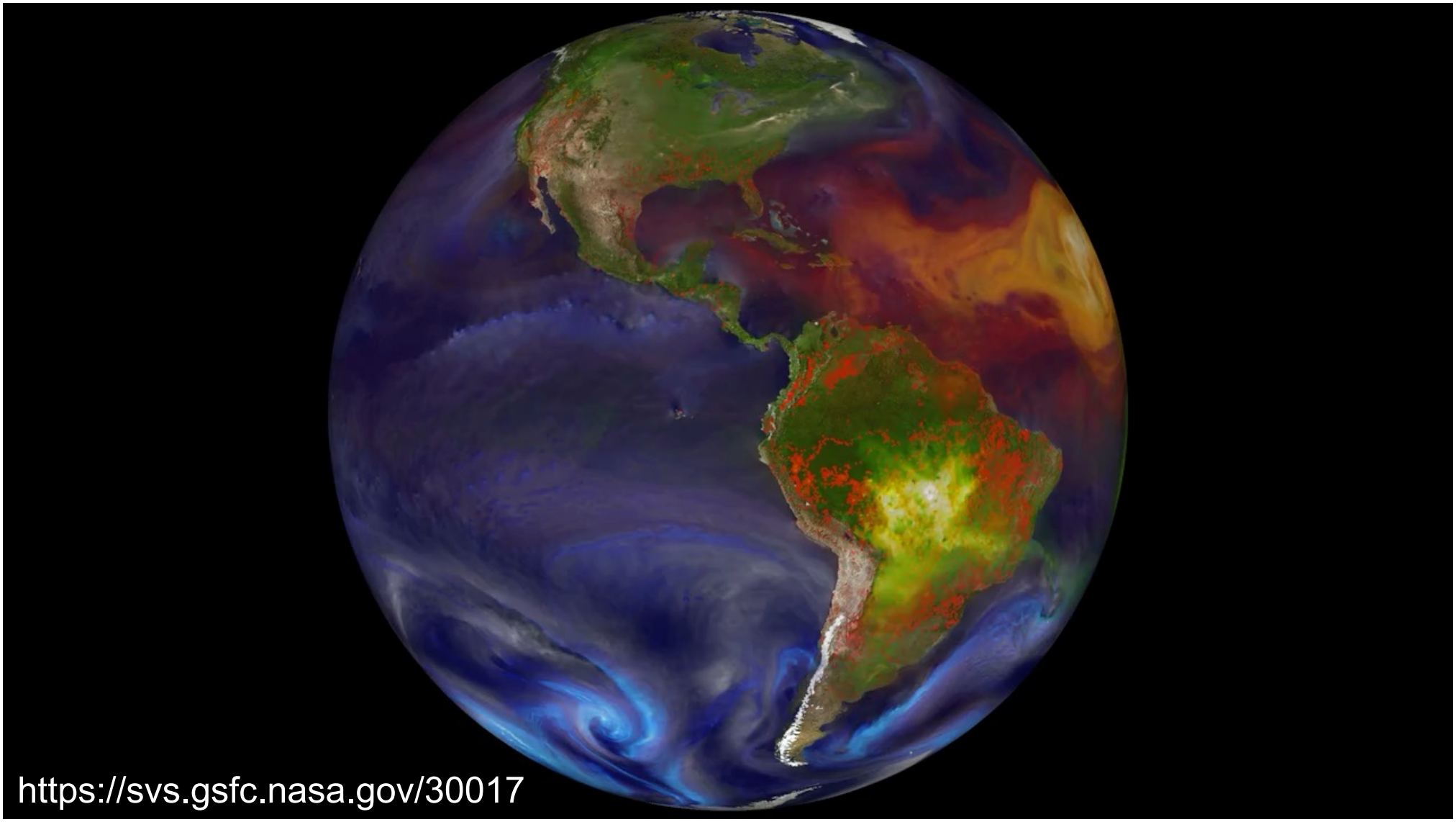
https://svs.gsfc.nasa.gov/30017

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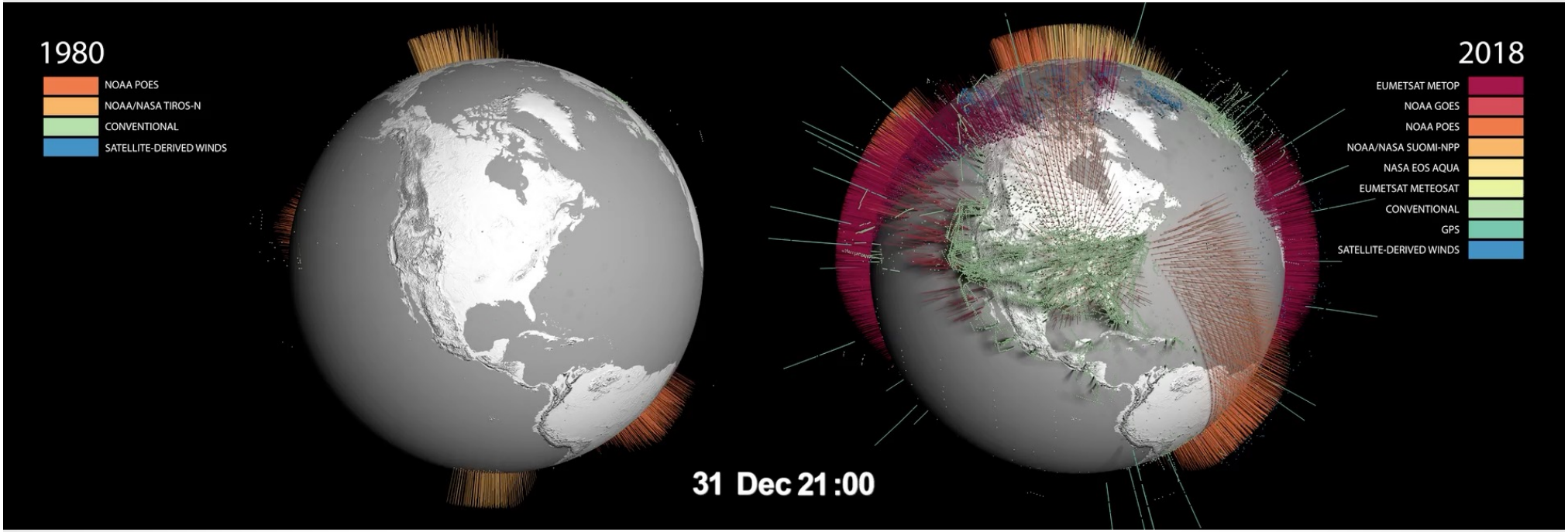
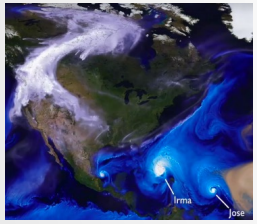
Changes to the observing system



https://svs.gsfc.nasa.gov/4654

NASA GMAO global meteorology and chemistry products



GEOS

Forecasting

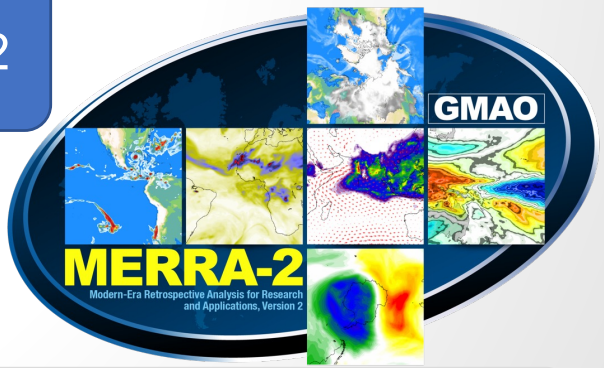
Reanalysis

GEOS FP

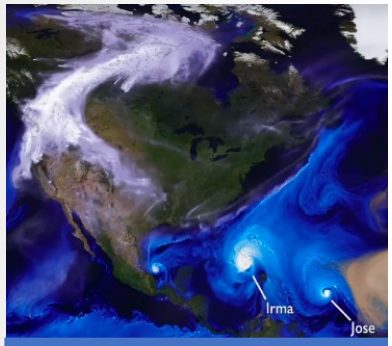
GEOS FP-IT

MERRA-2

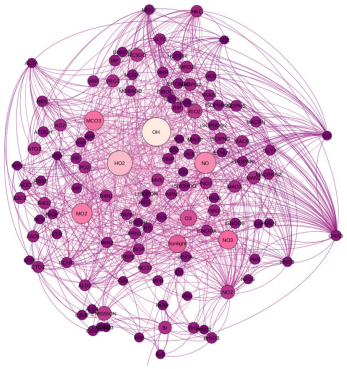
GEOS-CF



GEOS Composition Forecast



GEOS NWP



GEOS-Chem

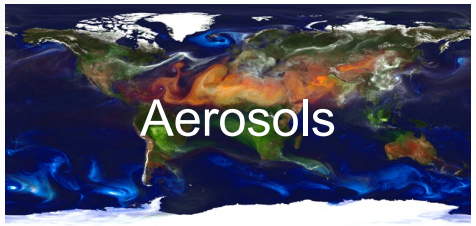
GEOS - CF

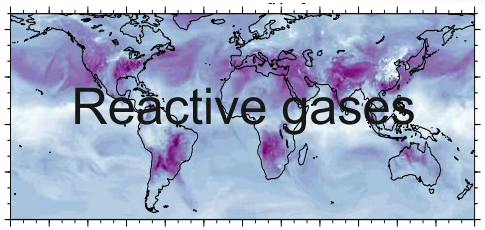
Version 12

Tropospheric and Stratospheric chemistry

- 250 Chemical Species
- 725 Chemical Reactions

Aerosol and Gas Phase Chemistry



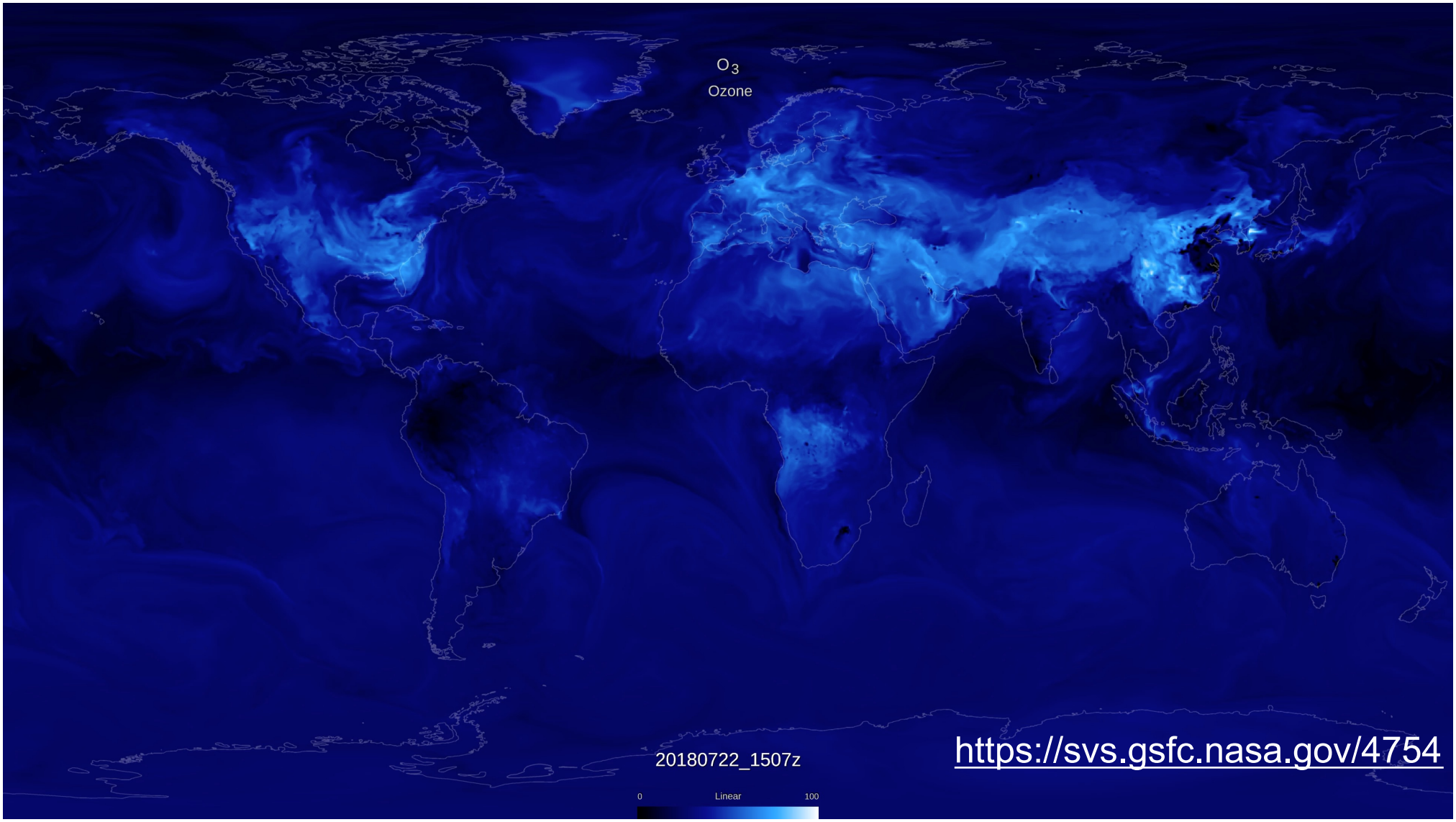


- Particulate matter:
  - Carbon
  - Sea salt
  - Dust
  - Sulfate
  - Nitrates
  - (Secondary Organics)

- Ozone (O_3)
- Nitrogen dioxide (NO_2)
- Carbon monoxide (CO)
- Volatile organic compounds (VOCs):
  - Formaldehyde
  - Benzene / Toluene
  - And many more!

GOCART

GEOS-Chem

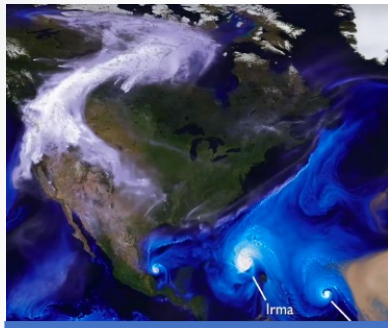

O_3
Ozone
20180722_1507z
0
Linear
100
https://svs.gsfc.nasa.gov/4754

Summary of major GMAO products

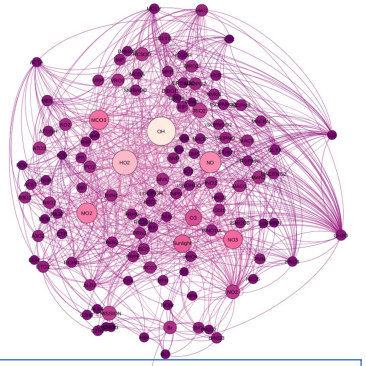
System	Focus	Customers/Applications
GEOS-FP "weather prediction"	Impacts of NASA observations on NWP: forefront resolution and complexity	NASA Field Missions (weather, aerosols) Multiple Agencies: NOAA/FAA; NOAA field stations; NRL
GEOS-CF "air quality"	Pioneering global system for atmospheric composition using multiple NASA assets	Health/Air Quality studies (via NASA Applied Sciences) Multiple agencies: NIH, US Army Public Health Center, NOAA
GEOS-S2S "seasonal prediction"	Ensembles of coupled Earth System predictions, emphasizing NASA observations	National ensembles (NMME, SubX), drought/sea-ice prediction Multiple Agencies and international linkages
MERRA-2 "reanalysis"	Stable product for climate studies, emphasizing NASA data	Only current national reanalysis: USGCRP/NCA applications Interagency use: DoE, DoT, NOAA, …
GEOS-FPIT "mission support"	Stable, well validated, low-latency product for use by NASA instrument teams	More than 20 NASA Instrument Teams
GEOS-Nature Run "mission planning"	Complex Earth System simulations at fine resolution with obs. simulators	Planning for new space-based missions NOAA and broad community; DoE/Smithsonian; NSF

GMAO's current products that are documented both technically and through robust file specifications, well validated, and released to the broad community for research and applications

Daily composition forecast



GEOS NWP

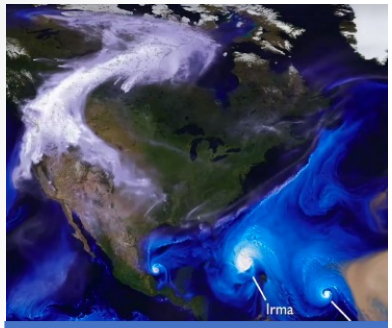


GEOS-Chem

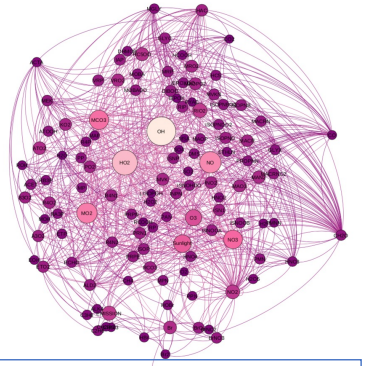
GEOS - CF

One **5-day forecast** per day

Daily composition forecast



GEOS NWP



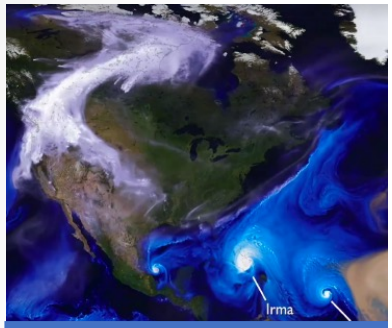
GEOS-Chem

GEOS - CF

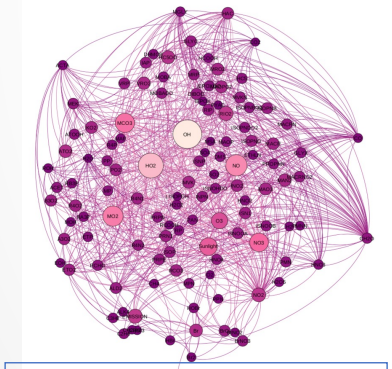
One **5-day forecast** per day

- 1-day meteorological replay "analysis"
- 5-day forecast

Daily composition forecast



GEOS NWP



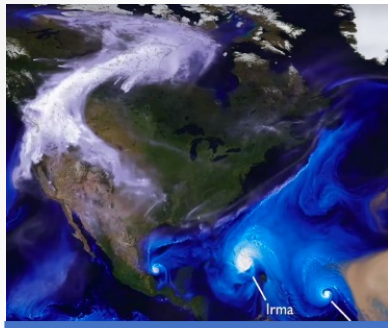
GEOS-Chem

GEOS - CF

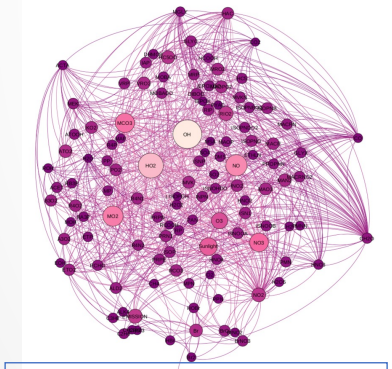
One **5-day forecast** per day

- 1-day replay
- 5-day forecast
- c360 (0.25°, **~25x25 km²**) resolution, 72 model layers

Daily composition forecast



GEOS NWP



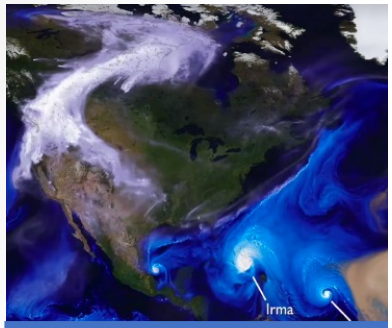
GEOS-Chem

GEOS - CF

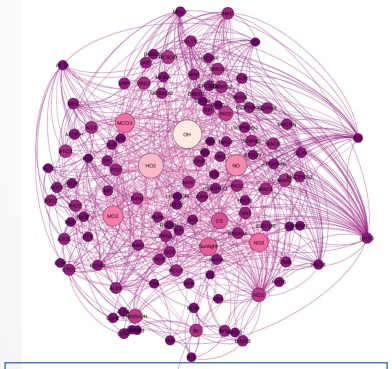
One **5-day forecast** per day

- 1-day replay
- 5-day forecast
- c360 (0.25°, **~25x25 km²**) resolution, 72 model layers
- O_3, NO_x, VOCs, PM ...
- T, U, V, RH ....

Daily composition forecast



GEOS NWP



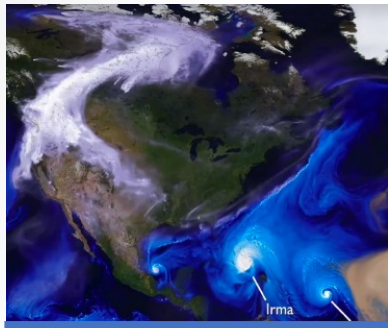
GEOS-Chem

GEOS - CF

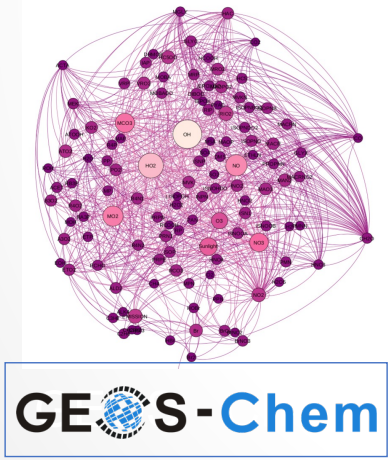
One **5-day forecast** per day

- 1-day replay
- 5-day forecast
- c360 (0.25°, ~25x25 km^2)
- **15 minute** "surface"
- **1-hour** average and instantaneous 2D & 3D

Daily composition forecast



GEOS NWP



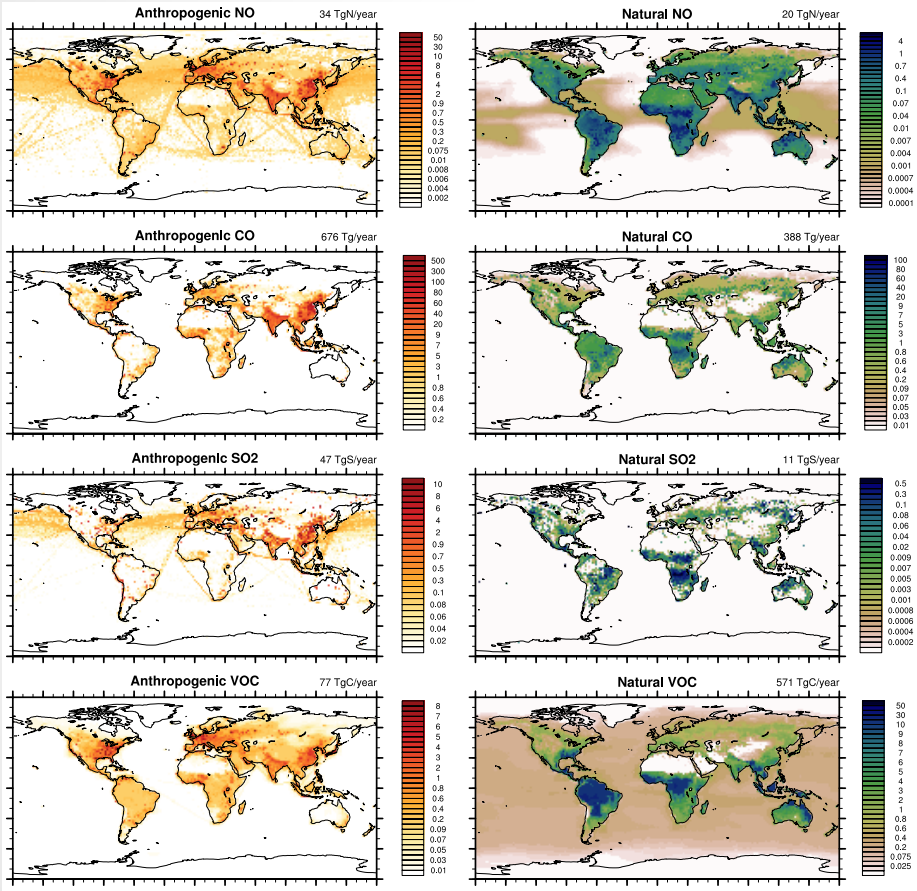
GEOS-Chem

GEOS - CF

One **5-day forecast** per day

- 1-day replay
- 5-day forecast
- c360 (0.25°, ~25x25 km^2)
- **Available since**
  - **1 January 2018** (replay)
  - **1 January 2019** (forecast)

GEOS-Chem emissions



Anthropogenic: HTAP, RETRO, DICE (Africa), AEIC (aircraft)

Biomass burning: QFED NRT

Biogenic: Megan 2.1

Lightning: online (Murray et al., 2012)

Soil NOx: online (Hudman et al. 2012)

Dust: online (Zender et al. 2003)

Sea salt: online (Jaegle et al., 2011)

Ocean: online: sea salt, DMS, acetone, acetaldehyde, HOI, I_2

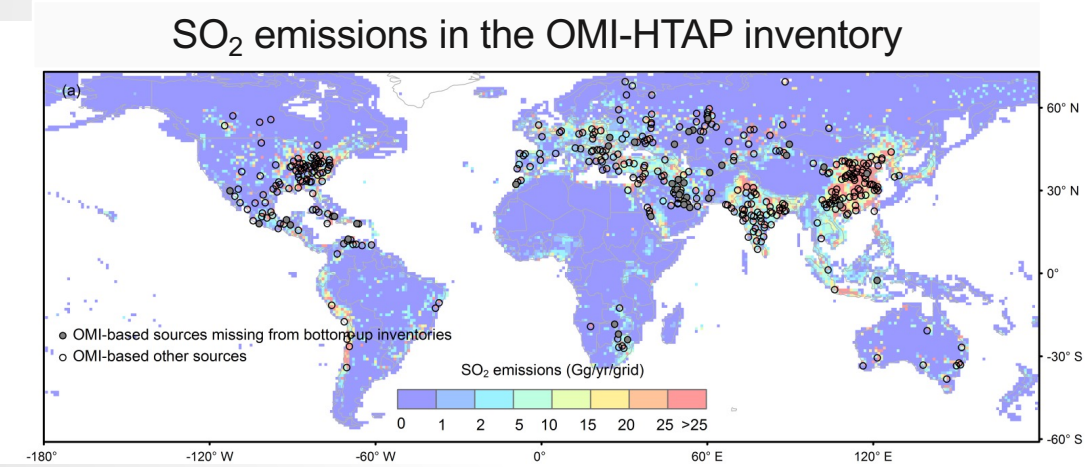
Prescribed: CFCs, VSLS, CH_4, CO_2

Year-to-year emissions changes

National Aeronautics and Space Administration

Emissions:

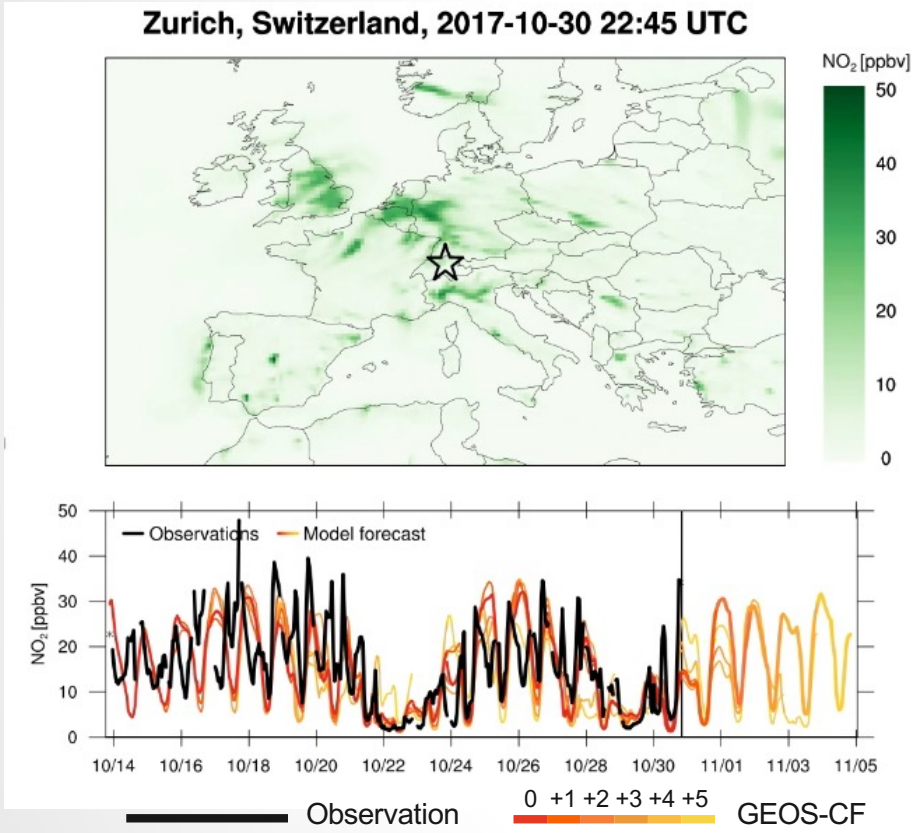
- Annual gridded scale factors based on satellite data are applied to the emissions of CO (Oda et al., 2017) and SO_2 (Liu et al., 2018).
- "Business-as-usual" assumed for 2020 and 2021



A new emission inventory, OMI-HTAP, combines OMI-based SO_2 emissions for large sources and the bottom-up inventory, HTAP, for smaller sources.

Liu, F., et al., *Atmos. Chem. Phys., 18*, 2018

Daily variations of emissions



- Scale factors applied to emissions for diurnal and weekly variations
- These are clearly beneficial for surface NO_2 analyses and forecasts
- Shown for Zurich - weather and diurnal/weekly signals are prominent
- Surface observations obtained through emerging connection to OpenAQ (openaq.org)

GEOS-CF output is available online in near real-time

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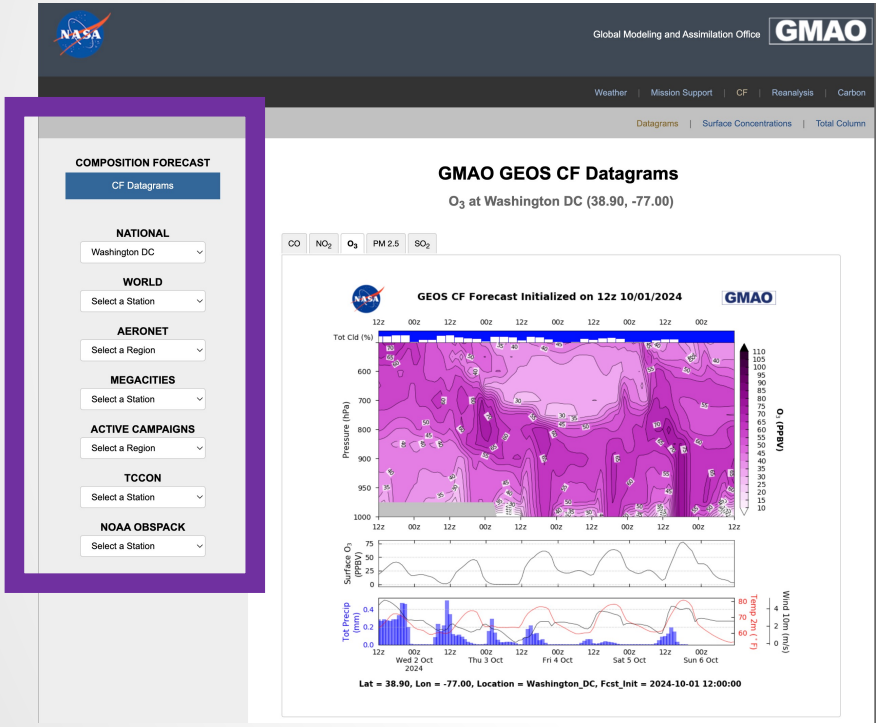
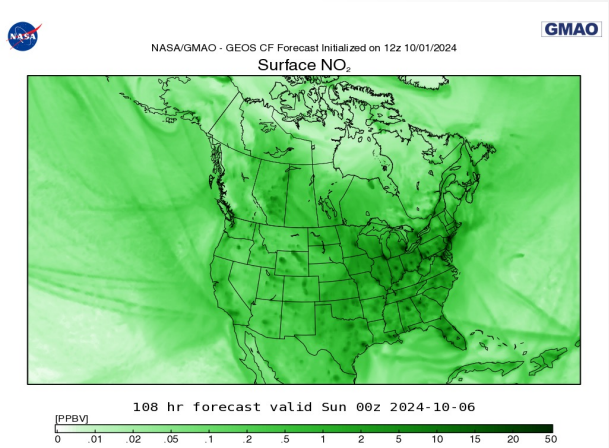
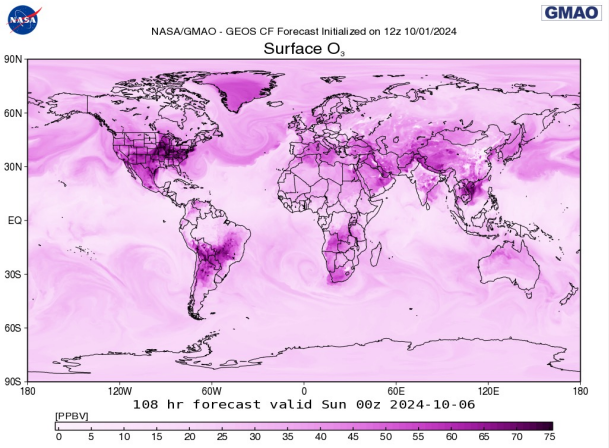
Fluid is a mobile-friendly website

https://fluid.nccs.nasa.gov/cf/







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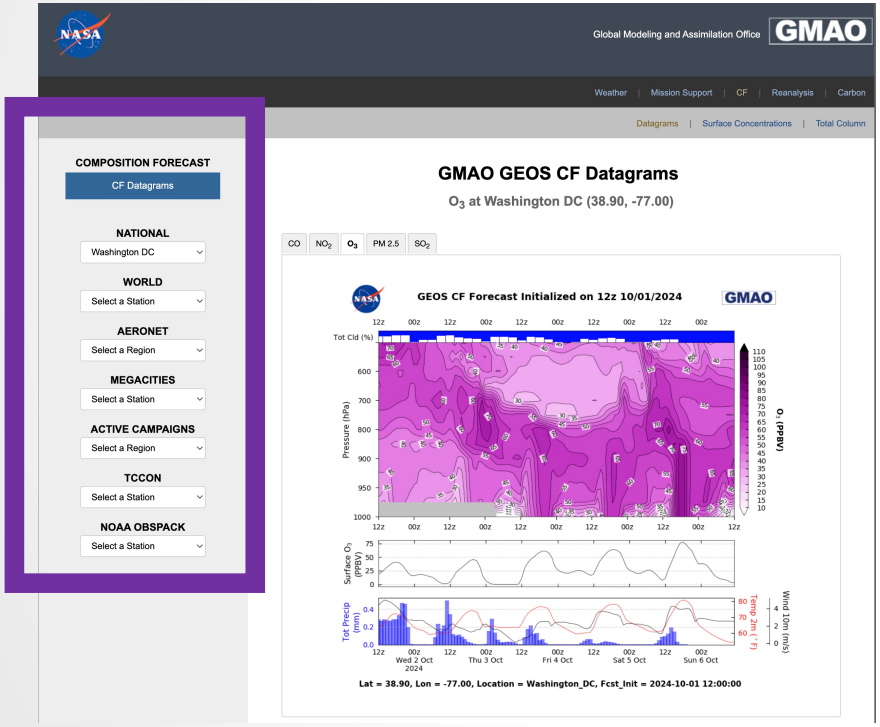
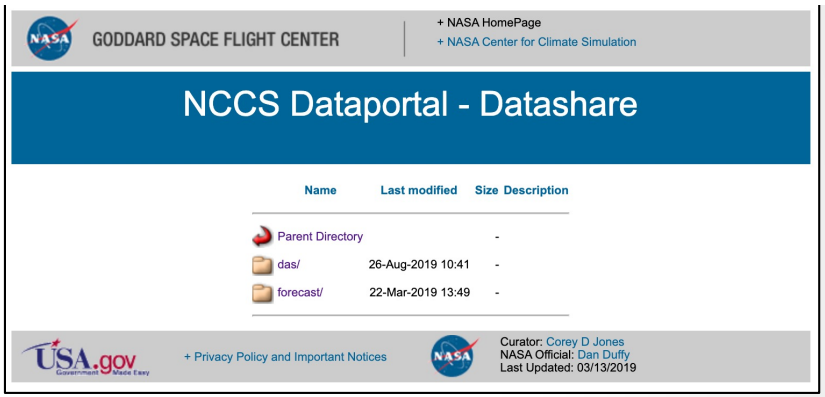


https://portal.nccs.nasa.gov/datashare/gmao/geos-cf/v1/



https://opendap.nccs.nasa.gov/dods/gmao/geos-cf/

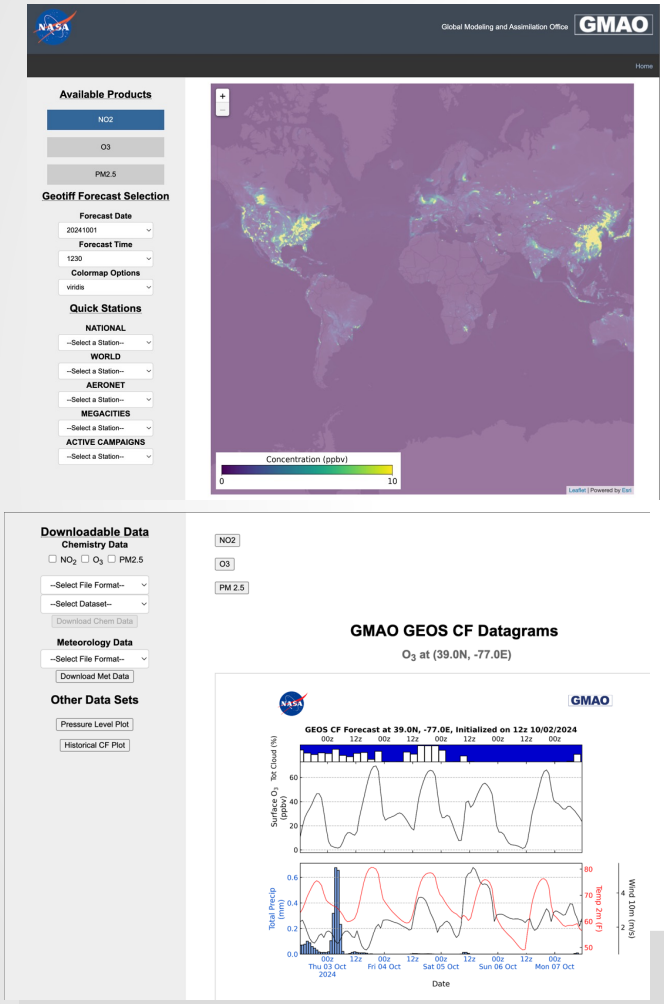
GrADS Data Server - info for /gmao/geos-cf/assim/chm_tavg_1hr_g1440x721_v1 : dds das

OPeNDAP/DODS Data URL: https://opendap.nccs.nasa.gov/dods/gmao/geos-cf/assim/chm_tavg_1hr_g1440x721_v1

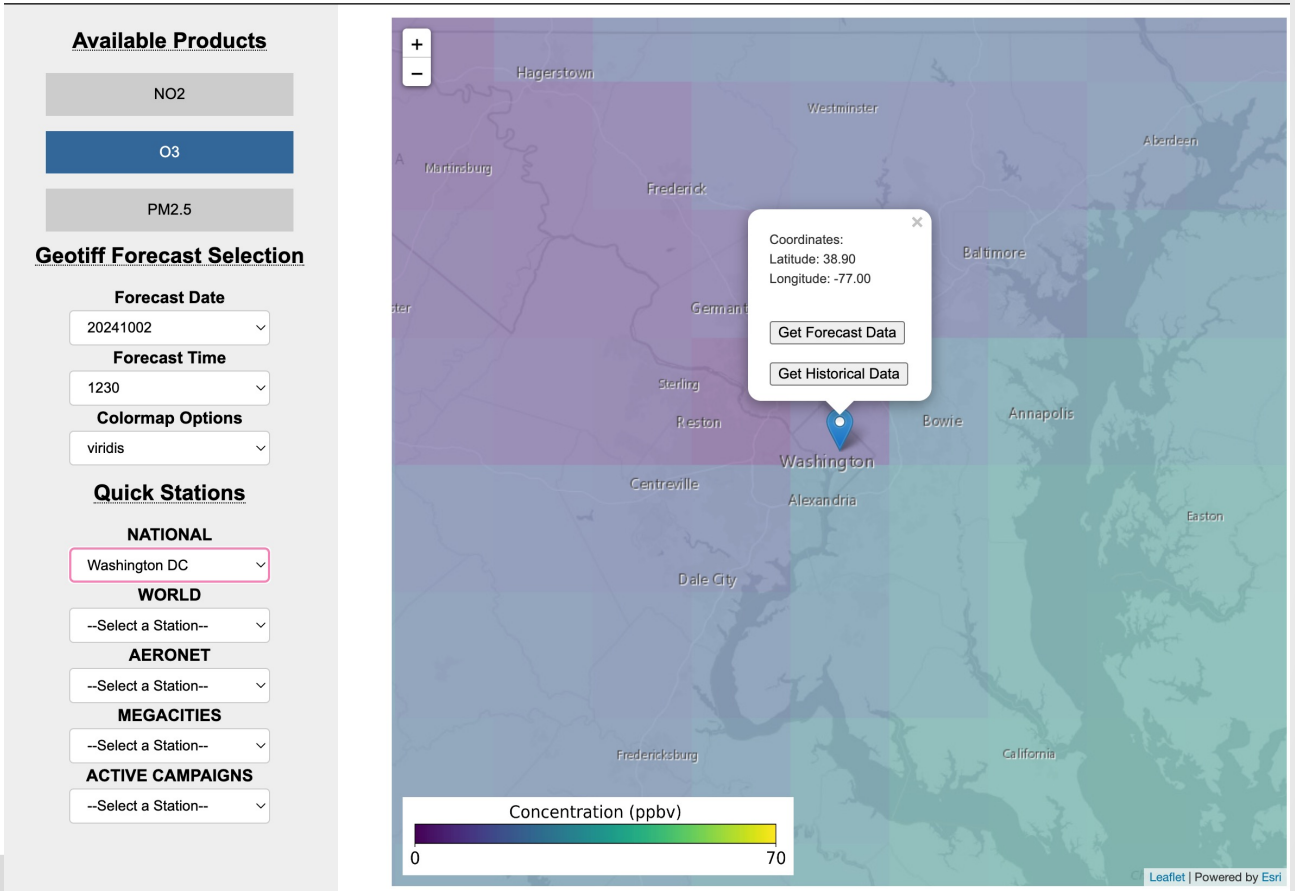
Description:	GEOS CF (Composition Forecast)	
Documentation:	(none provided)	
Longitude:	-180.00000000000°E to 179.75000000000°E	(1440 points, avg. res. 0.25°)
Latitude:	-90.00000000000°N to 90.00000000000°N	(721 points, avg. res. 0.25°)
Altitude:	72.00000000000 to 72.00000000000	(1 points)
Time:	00:30Z01JAN2018 to 11:30Z31OCT2019	(16044 points, avg. res. 0.042 days)
Variables:	**(total of 52)**	
xyle	xylene (c8h10, mw = 106.16 g mol-1) volume mixing ratio dry air	
dst2	dust aerosol, reff = 1.4 microns (mw = 29.00 g mol-1) volume mixing ratio dry air	
hno4	peroxynitric acid (hno4, mw = 79.00 g mol-1) volume mixing ratio dry air	
pm25su_rh35_gcc	sulfate_particulate_matter_with_diameter_below_2.5_um_rh_35	

GEOS-CF forecast imagery is available on-demand

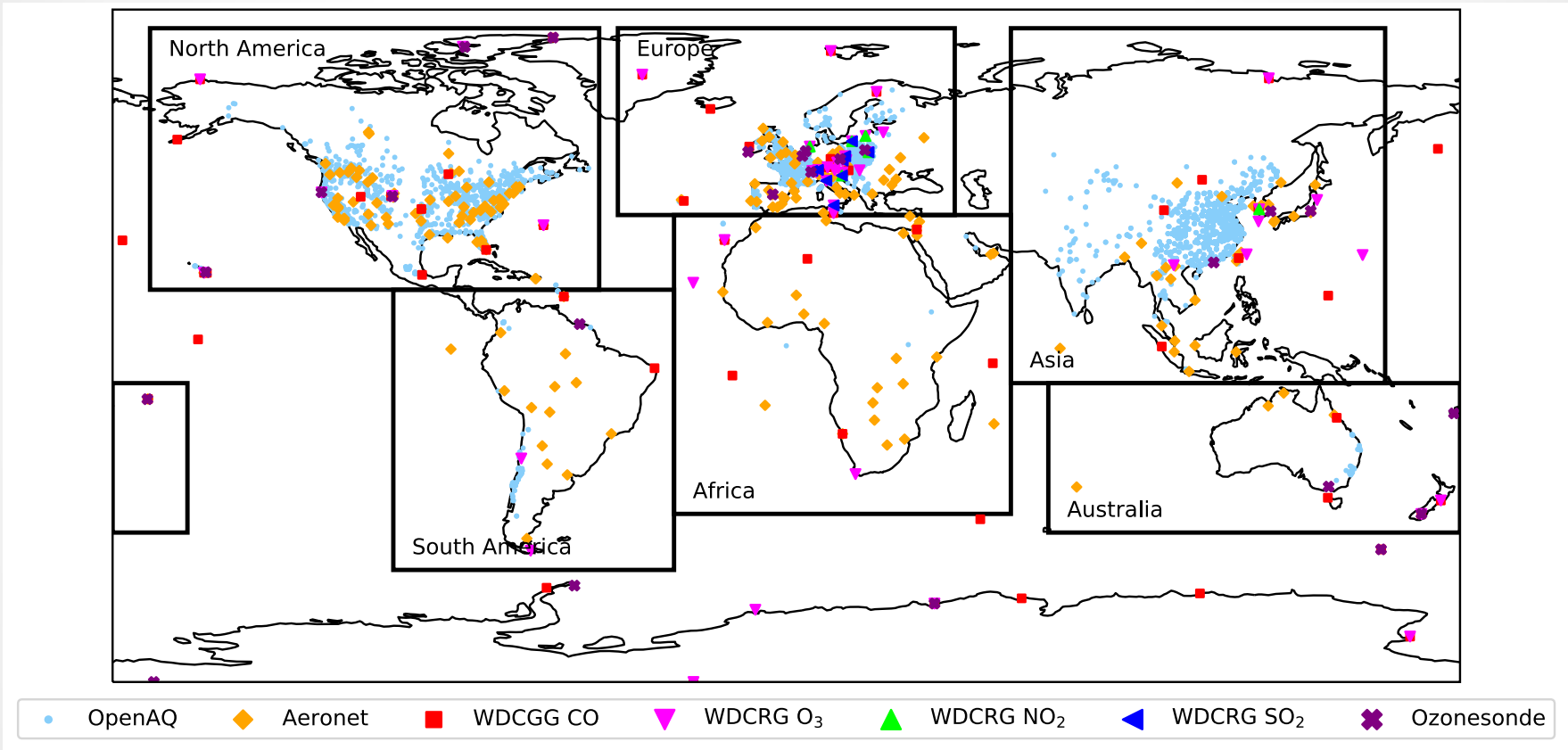
National Aeronautics and Space Administration



https://fluid.nccs.nasa.gov/cf_map/



Observations for evaluation



Keller et al., 2021 JAMES

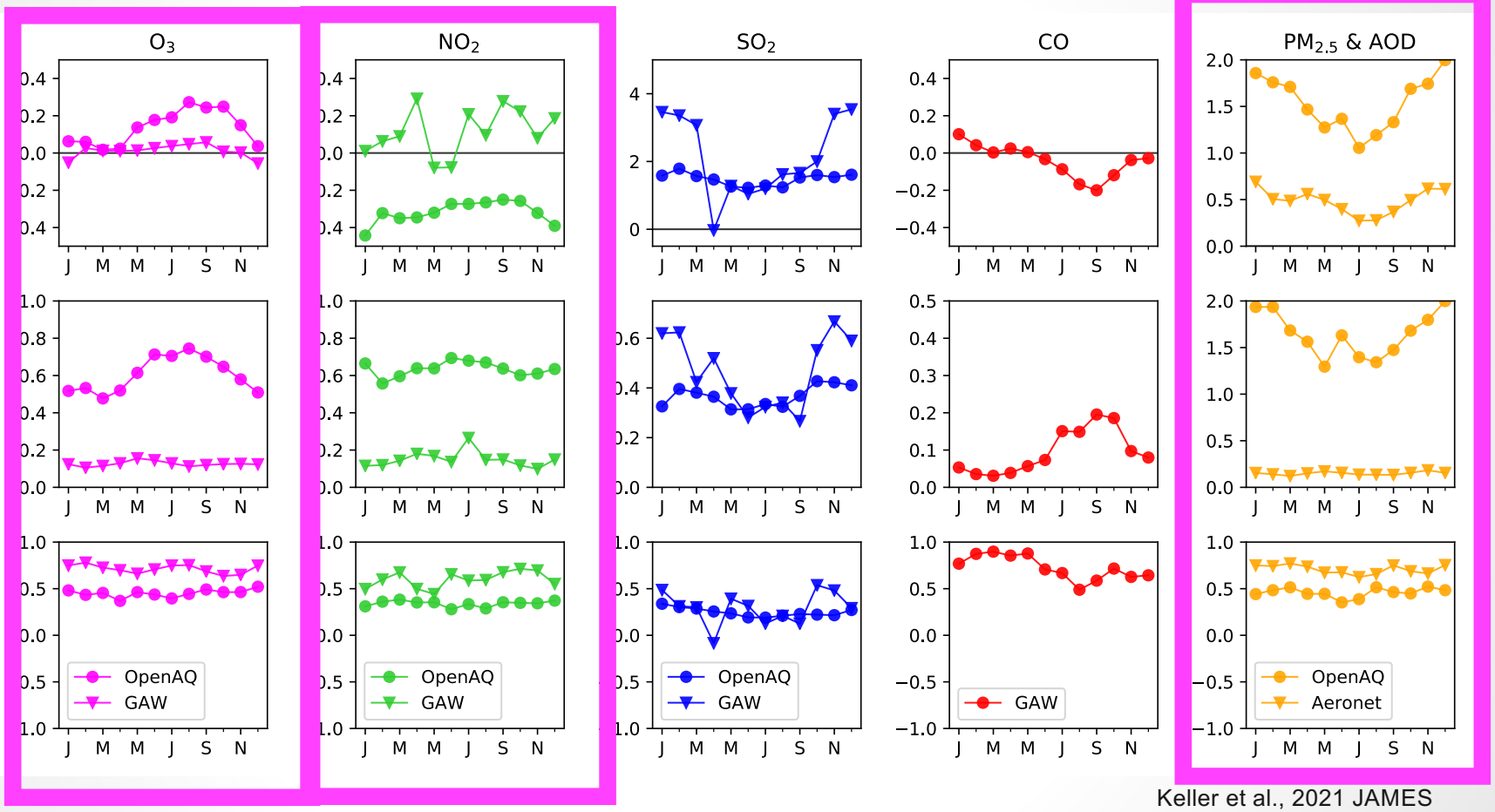
Global surface comparisons - monthly

National Aeronautics and Space Administration

Normalized Mean Bias (NMB)

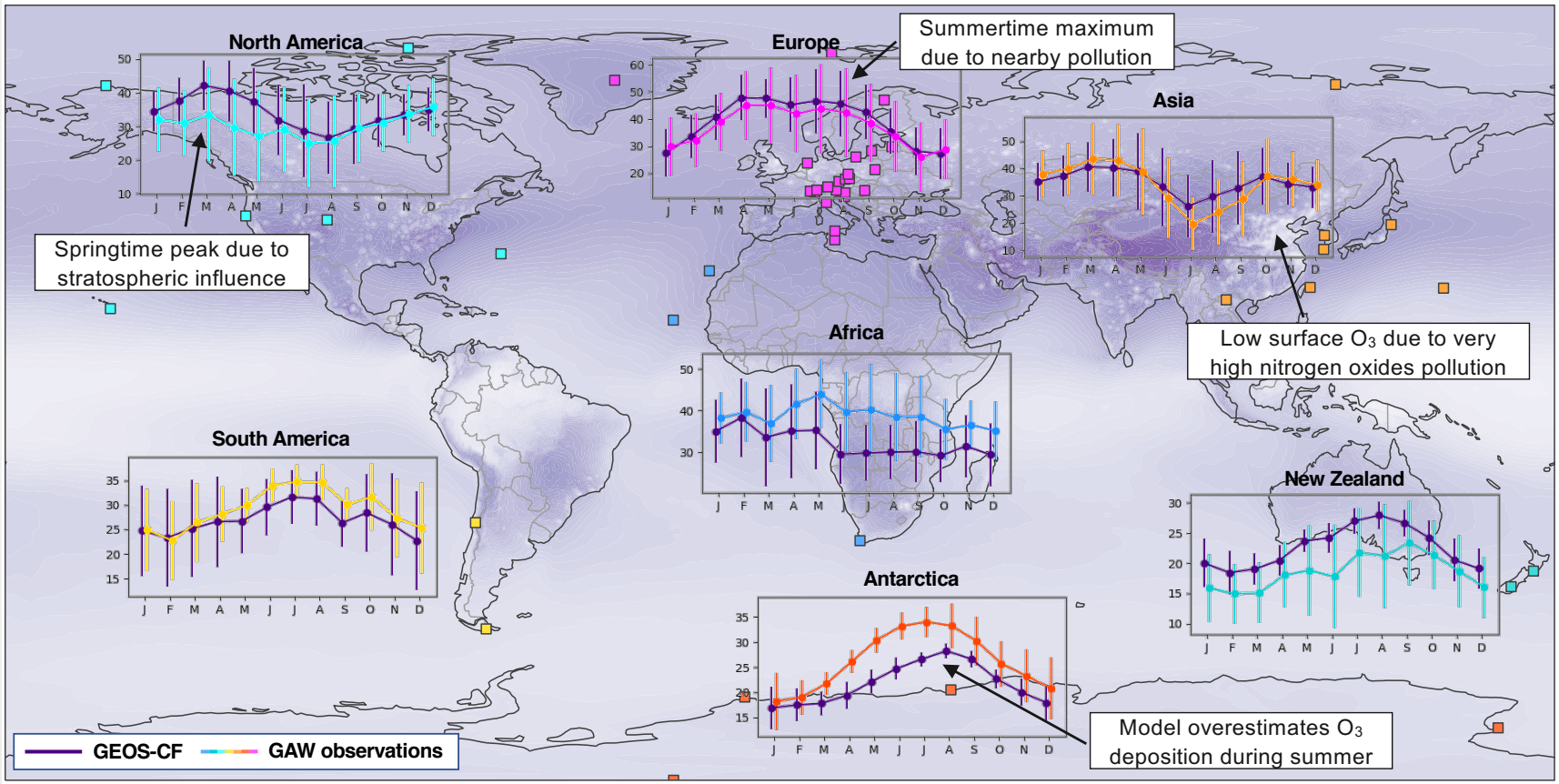
Normalized Root Mean Square Error (NRMSE)

Pearson Correlation Coefficient (R)

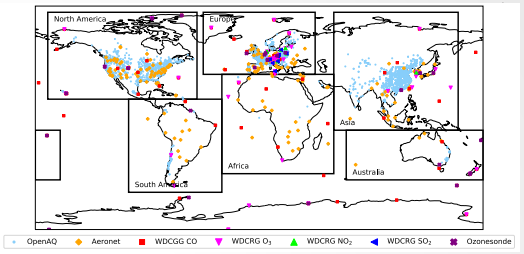


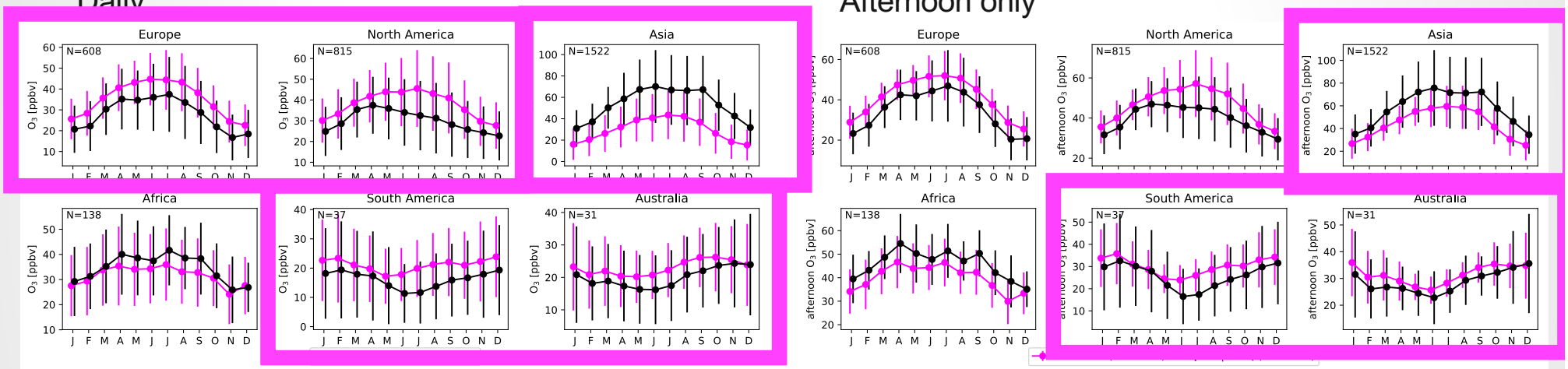
Keller et al., 2021 JAMES

GEOS-CF surface ozone compares well against background observations from the Global Atmospheric Watch (GAW) network



Surface O_3 (OpenAQ sites only)





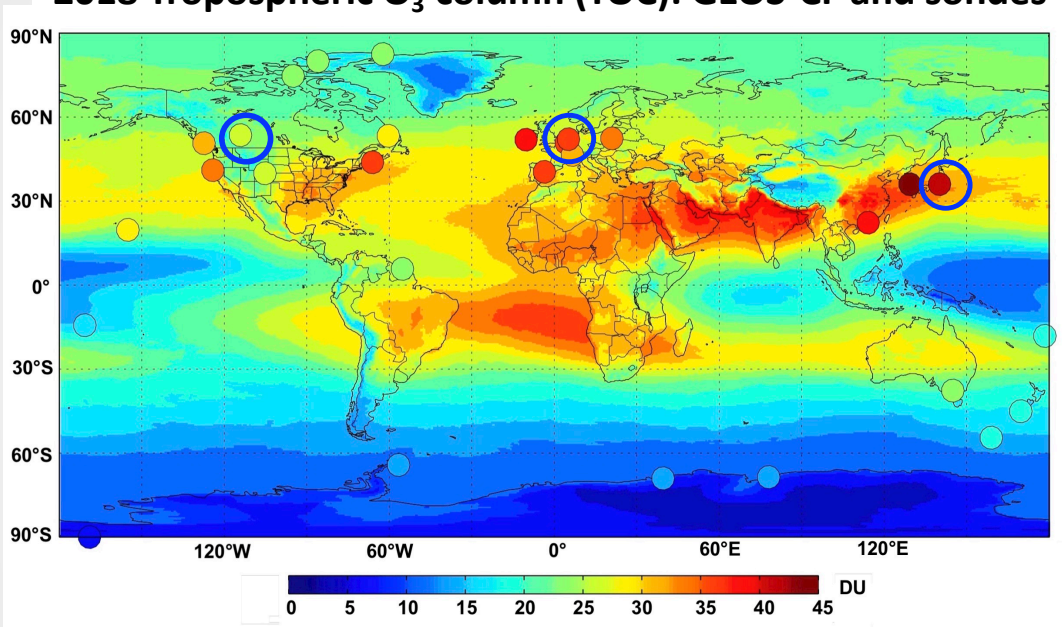
- GEOS-CF captures the overall seasonal cycle in the six regions, but generally overestimates in Europe, North & South America and Australia, while underestimating in Asia and Africa.
- In polluted regions, such as Asia, the bias is reduced when focusing on peak photochemical production period. GEOS-CF still has a bias over US during summer and fall, a known GEOS-Chem issue (Travis et al., 2016;2019; Hu et al., 2018).

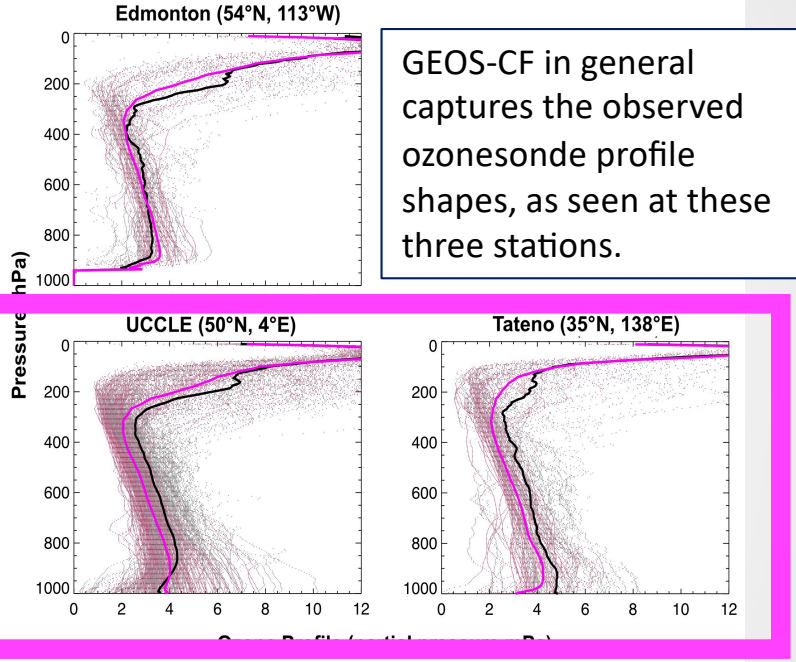
Observations GEOS-CF

Keller et al., 2021 JAMES

GEOS-CF captures the observed ozone spatial distribution and profile shapes shown by ozonesondes

2018 Tropospheric O_3 column (TOC): GEOS-CF and sondes





GEOS-CF in general captures the observed ozonesonde profile shapes, as seen at these three stations.

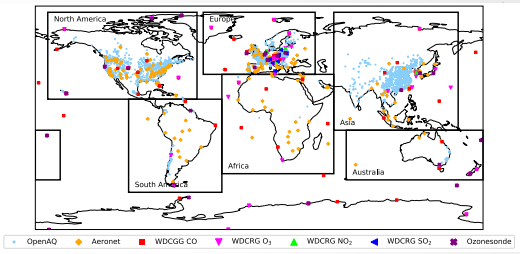
- GEOS-CF captures the overall spatial distribution of ozonesonde TOC, but with underestimates over polluted regions (e.g. sites over eastern US, Europe, east Asia).

Sondes GEOS-CF

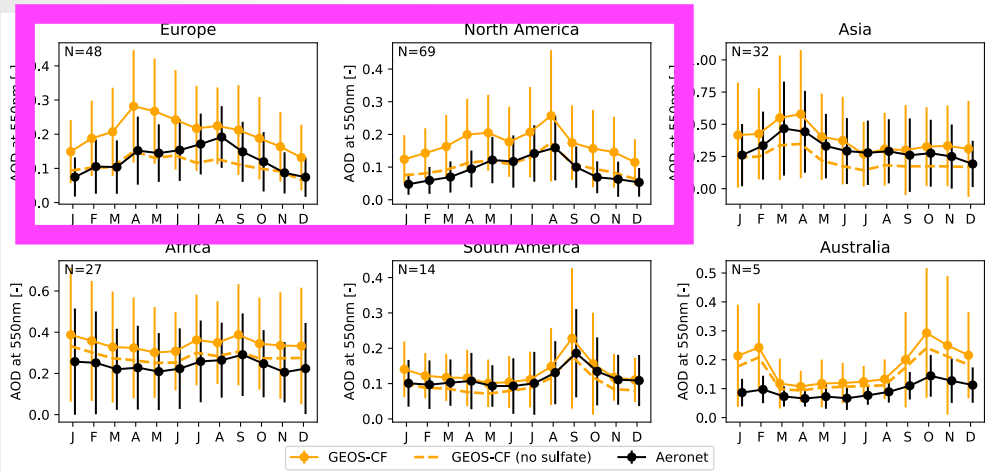
Figures courtesy of Junhua Liu

Thin lines: daily profiles in 2018
Thick lines: annual means

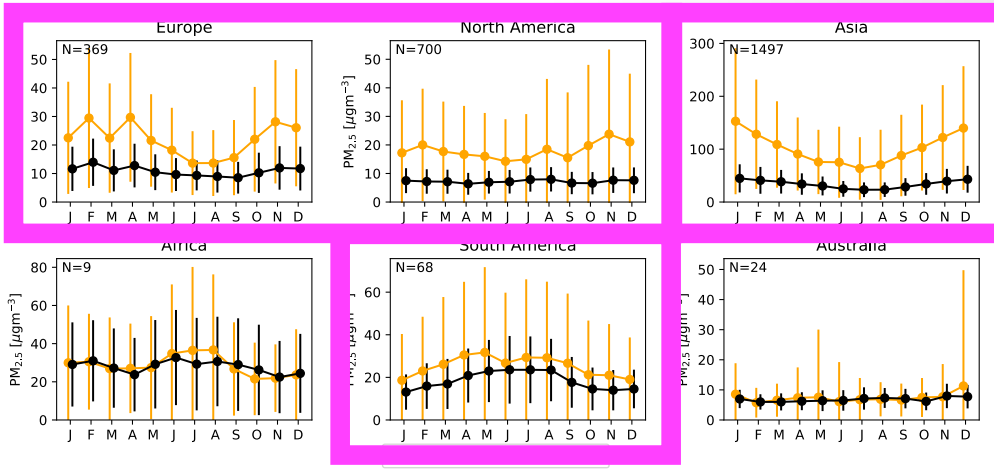
GEOS-CF generally overestimates aerosols (AOD and $PM_{2.5}$)



AOD from Aeronet network



PM2.5 from OpenAQ database



- GEOS-CF overestimates AOD 550 nm at most Aeronet sites. This is likely due to the overestimation of sulfates in the model.
- Similarly, GEOS-CF $PM_{2.5}$ is overestimated in Europe, North America, Asia and South America.

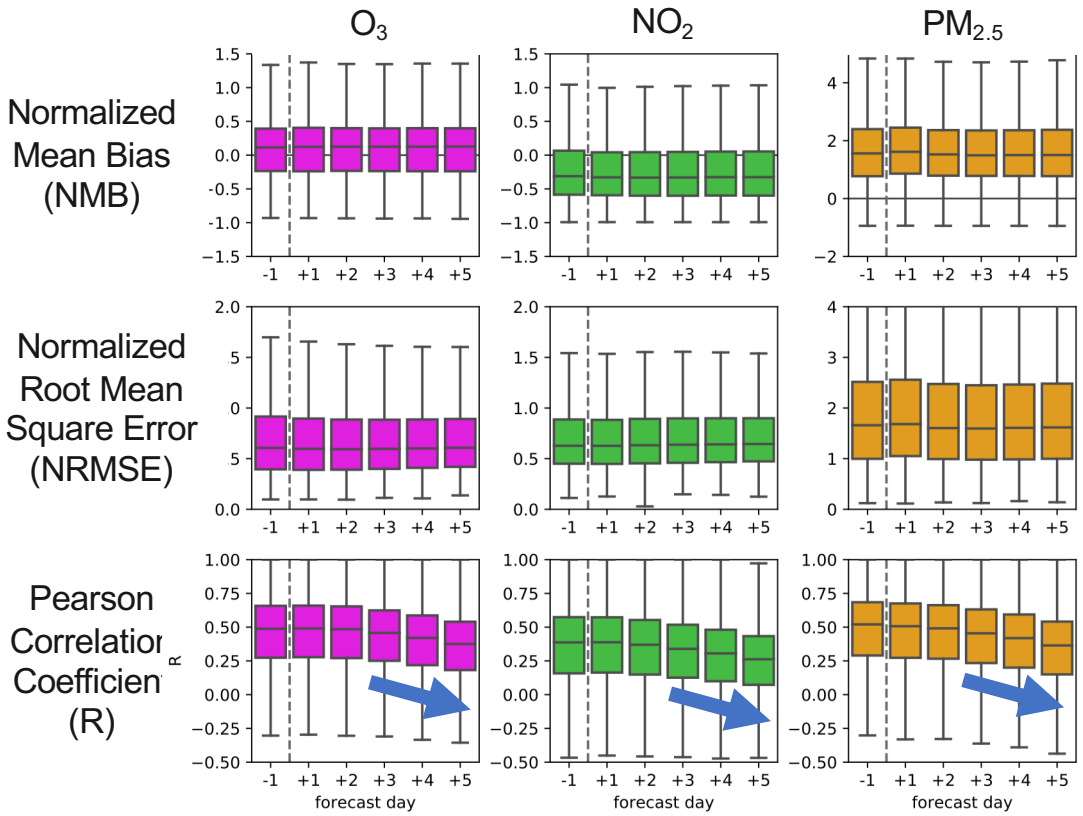
Observations GEOS-CF

Keller et al., 2021 JAMES

GMAO Global Modeling and Assimilation Office gmao.gsfc.nasa.gov
https://gmao.gsfc.nasa.gov/weather_prediction/GEOS-CF/
k.e.knowland@nasa.gov
GODDARD EARTH SCIENCES

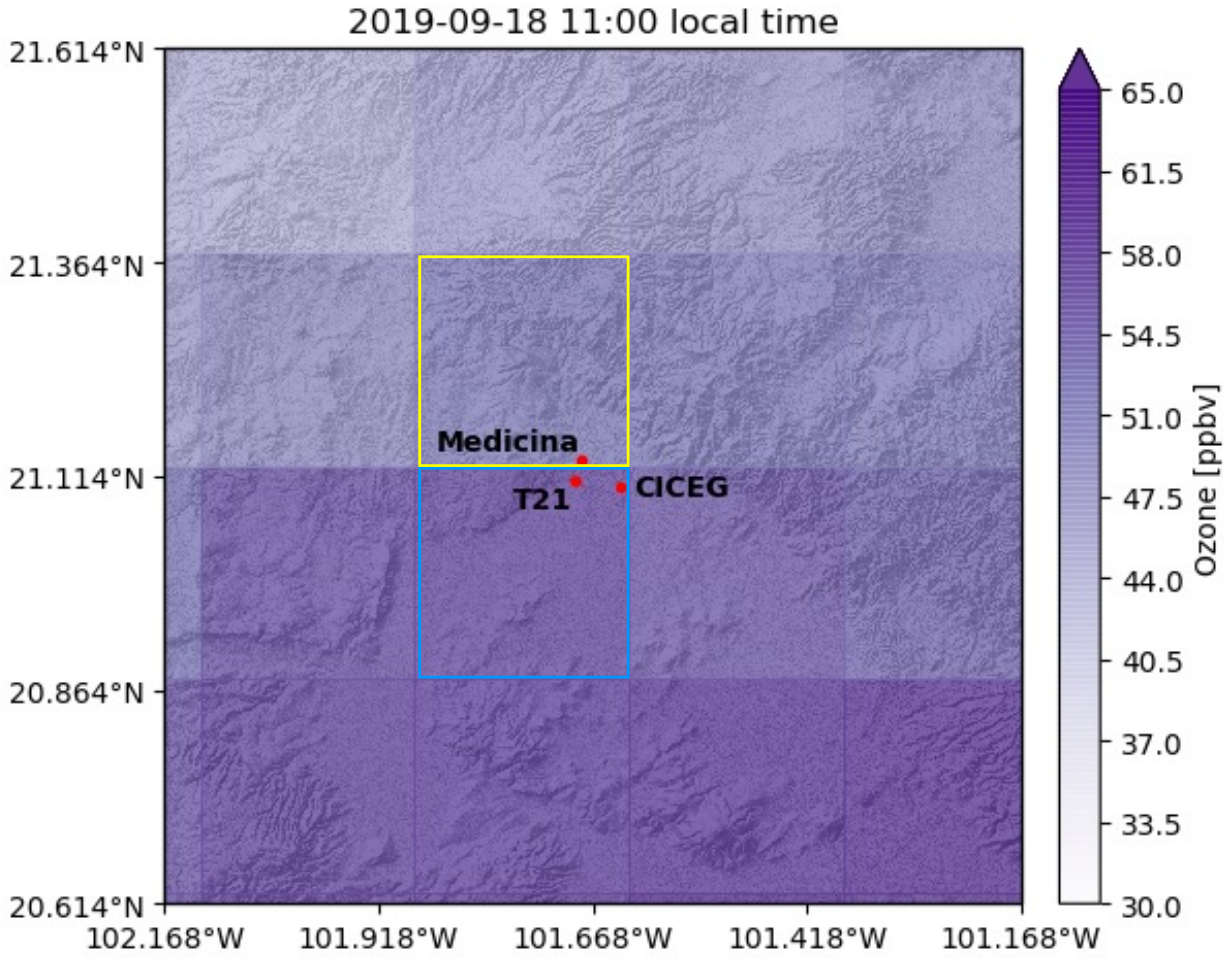
31

GEOS CF Forecast skill (GAW and OpenAQ)



- Little variation in the skill scores out to 5 days
- Correlation tends to decrease after day 2 and this is likely due to changes in the meteorological forecast and biomass burning emissions.

Keller et al., 2021 JAMES

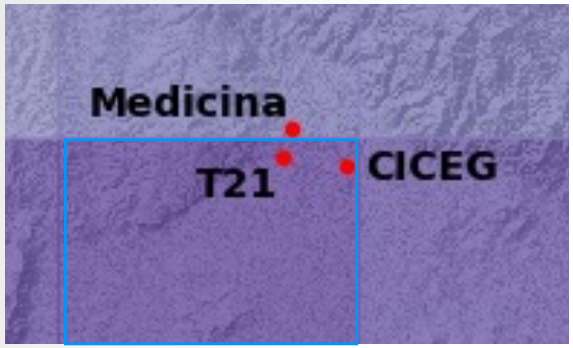


nprove local precasts using tatistical bias orrection

3 monitoring stations in Leon, Mexico

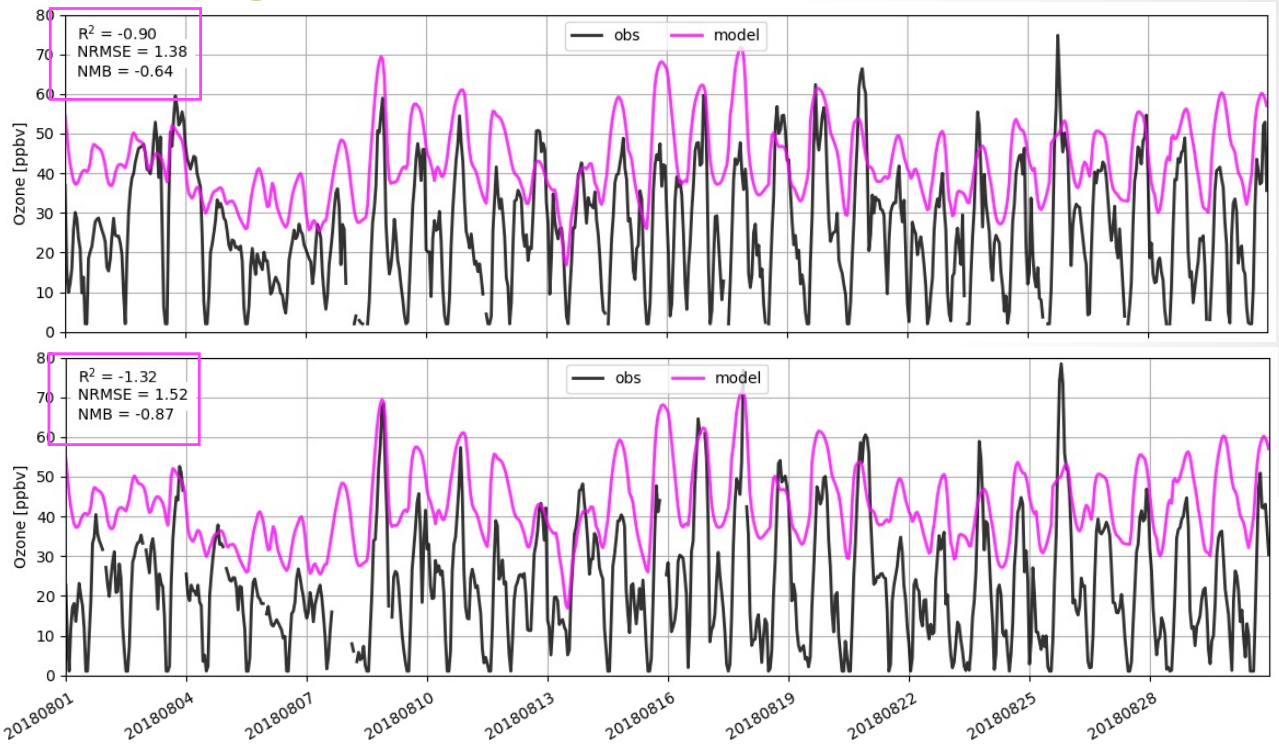
- 1 in one grid box
- 2 share a grid box
- Difficult terrain within each grid box

Improve local forecasts using statistical bias correction



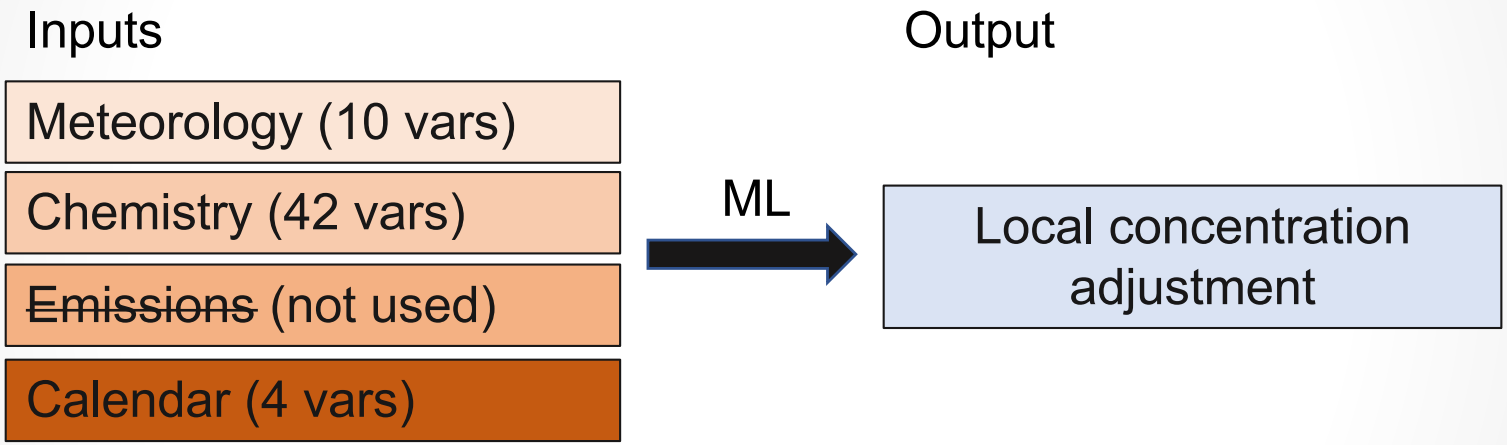
Two observation sites in the same grid box

- GEOS-CF generally over-estimates



Observations Model

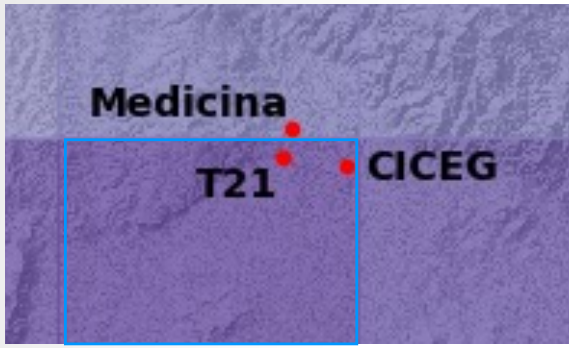
Use machine learning to correct for small scale variability and/or model biases



- Algorithm: gradient boosted decision trees (XGBoost)
- Train separate algorithm for each site

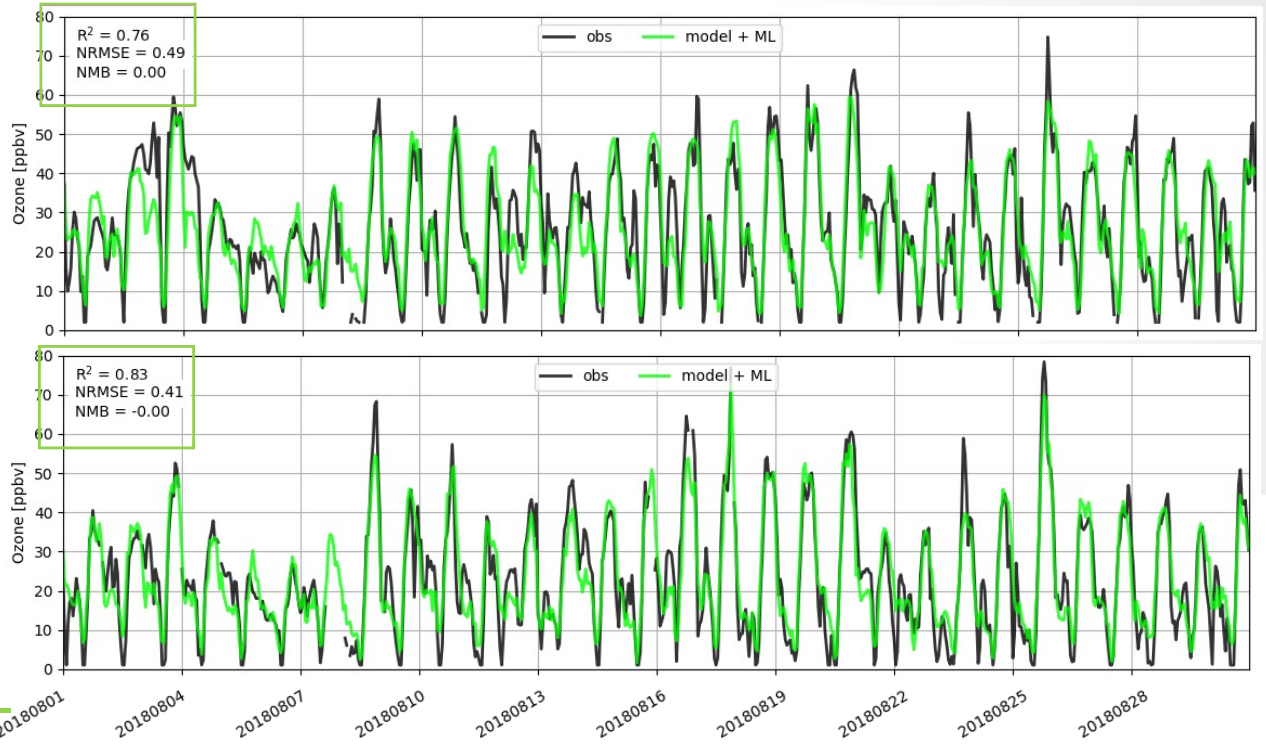
Keller et al., 2021 ACP

Improve local forecasts using statistical bias correction



Two observation sites in the same grid box

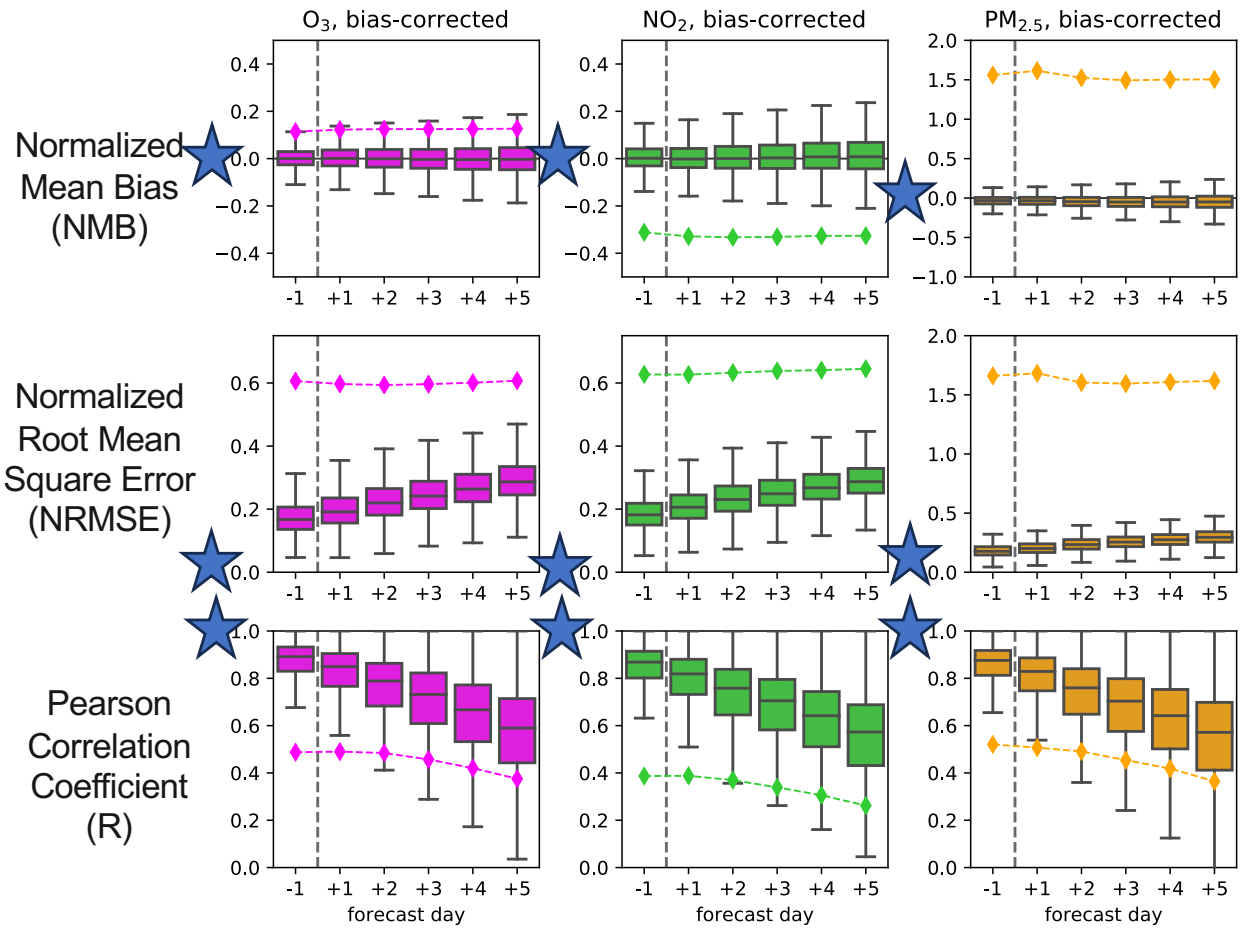
- GEOS-CF+ML captures diurnal variability at sub-grid scale



Observations Model + ML

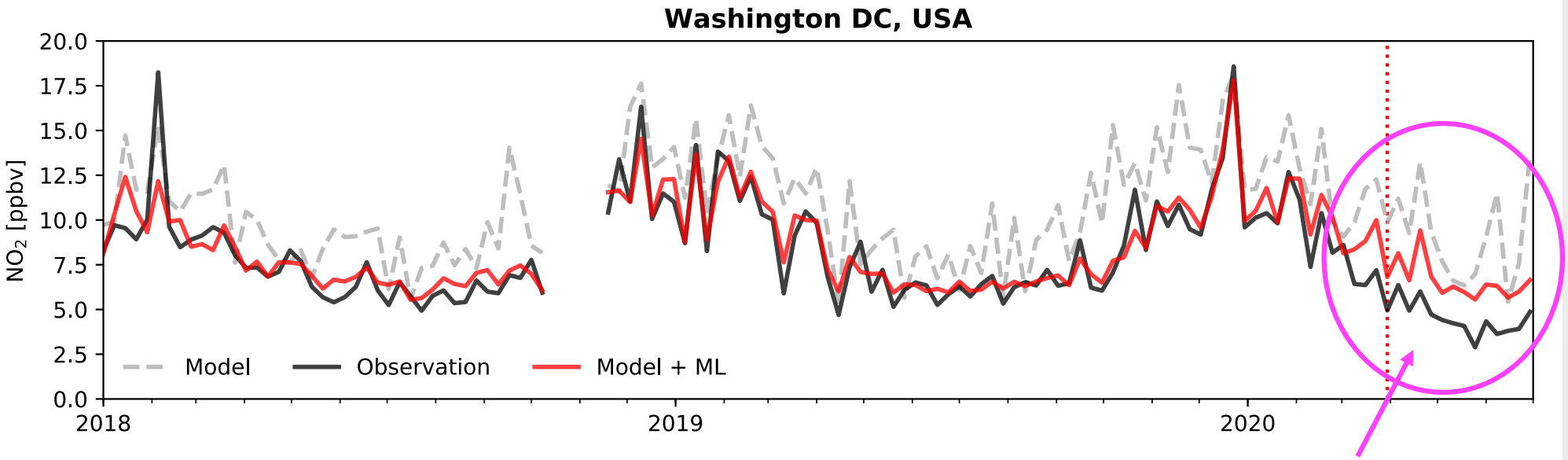
GEOS CF Forecast skill

- ✓ Using a Machine Learning (ML) algorithm to calculate bias-correction term for each monitoring site can drastically improve the forecast skill at the individual locations



Keller et al., 2021 JAMES

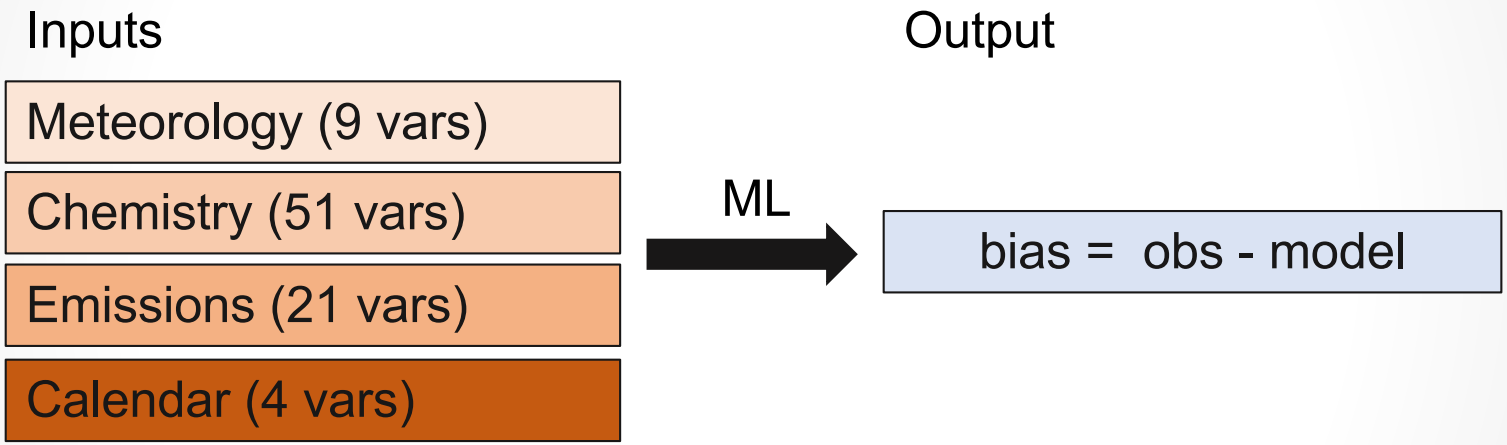
New application of the GEOS-CF ML algorithm



Impact of COVID-19 restrictions

Keller et al., 2021 ACP

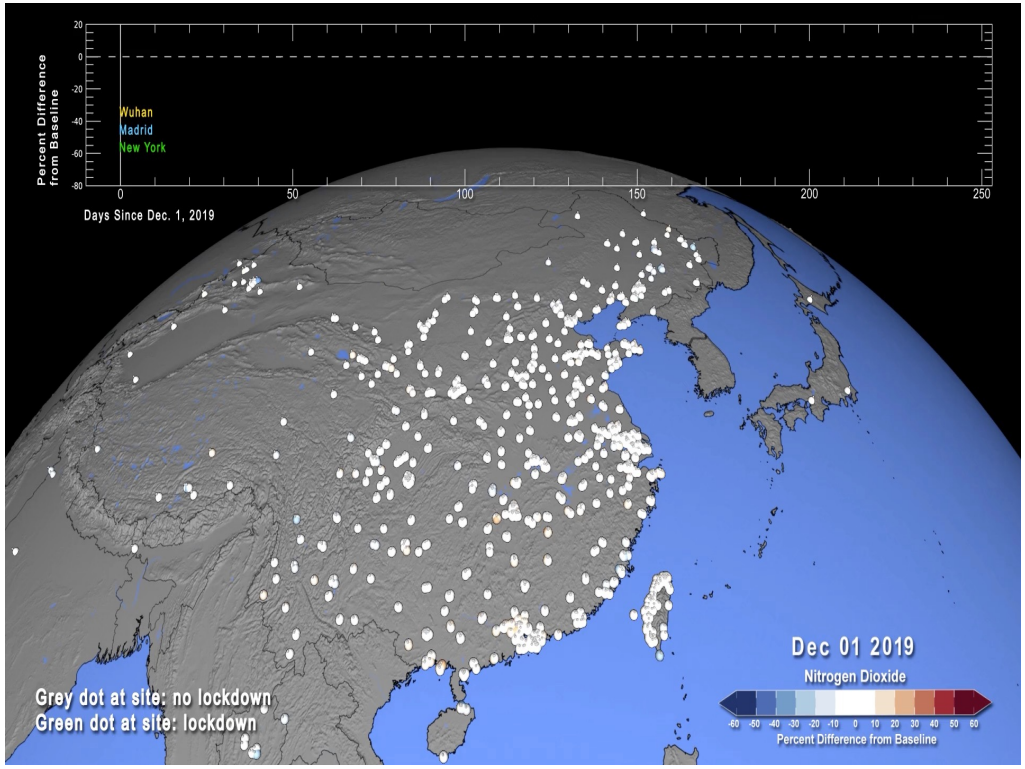
Apply bias-correction to model output using machine learning (using historical observation-model comparisons)



- Algorithm: gradient boosted decision trees (XGBoost)
- Training: 2018-2019 (8-fold cross validation)

Keller et al., 2021 ACP

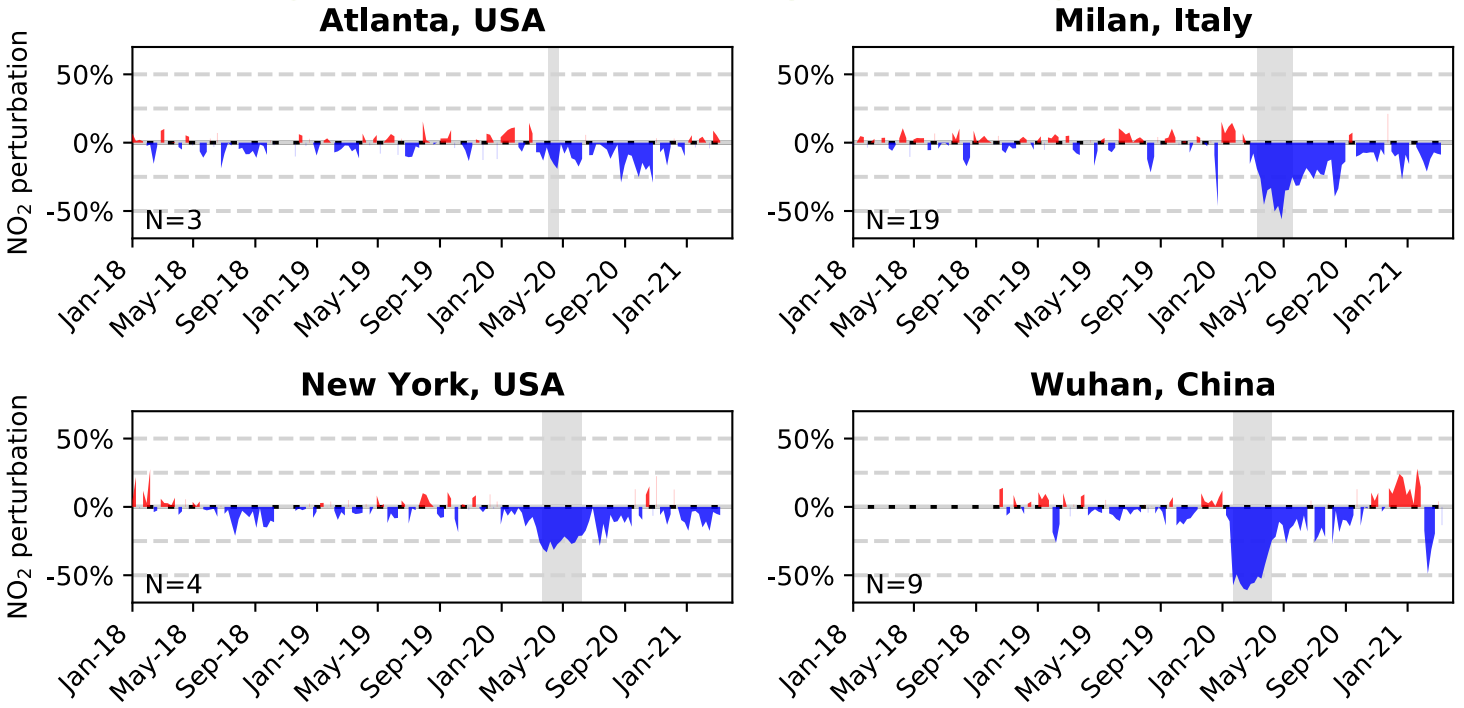
Apply analysis to 5756 sites worldwide



https://svs.gsfc.nasa.gov/13753 https://svs.gsfc.nasa.gov/4872

https://www.nasa.gov/feature/goddard/2020/nasa-model-reveals-how-much-covid-related-pollution-levels-deviated-from-the-norm

Observation-model differences indicate city-wide NO_2 declines of up to 50% early on and a halting recovery since then



Updated through March 16, 2021

Keller et al., 2021 ACP

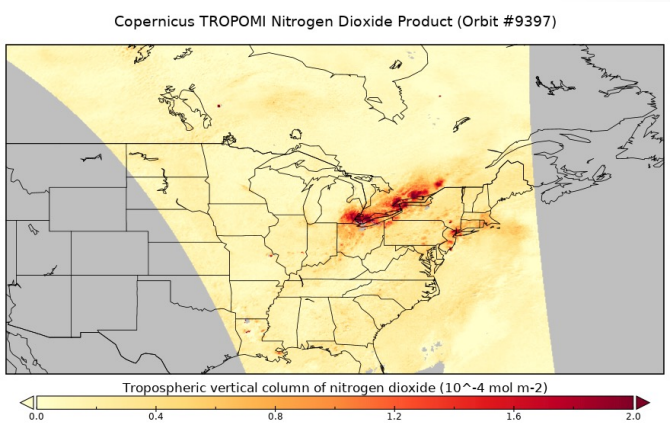
https://www.nasa.gov/feature/goddard/2020/nasa-model-reveals-how-much-covid-related-pollution-levels-deviated-from-the-norm

Multiple Sources of Air Quality Data

regulatory monitoring

+ accurate
- expensive
? representativity

form the "backbone" of the monitoring system, but insufficient alone



satellite retrievals

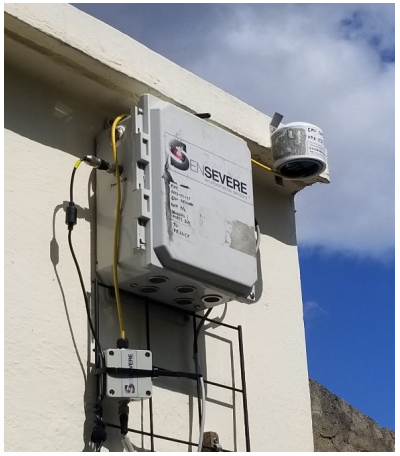
+ global coverage
- low time resolution
- column-integrated

good coverage and frequency, but need to be related to the ground-level situation

low-cost monitoring

+ relatively inexpensive
+ dense/remote deployment
- greater noise and bias

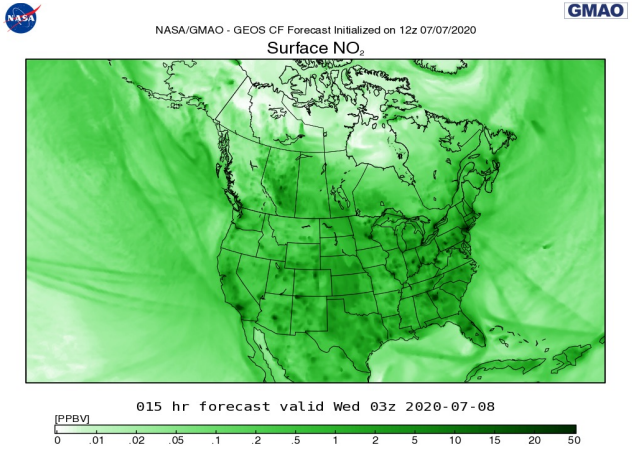
calibration is an open issue, but leveraging network density can offset some of these shortcomings



simulation models

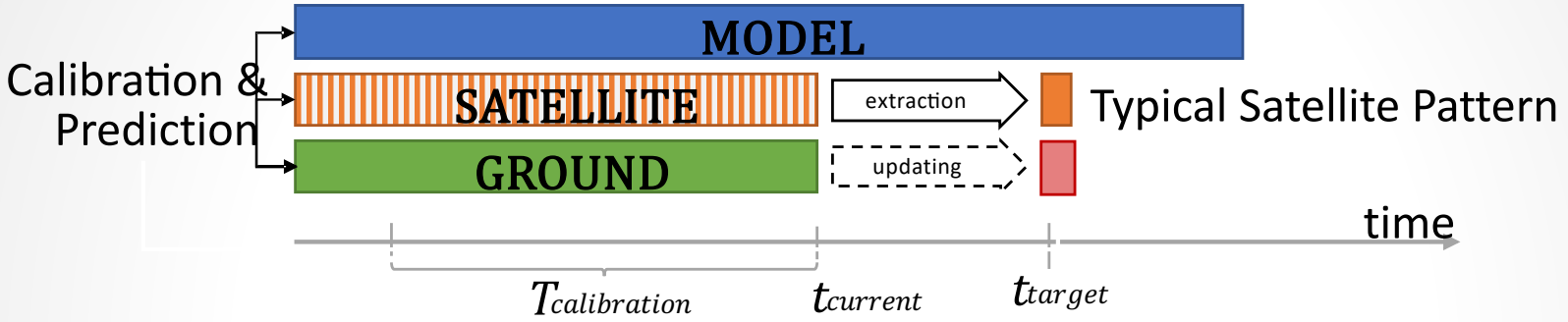
+ global coverage
+ forecasting
- limited resolution

The best tool for prediction, but need the support of other data sources for accuracy

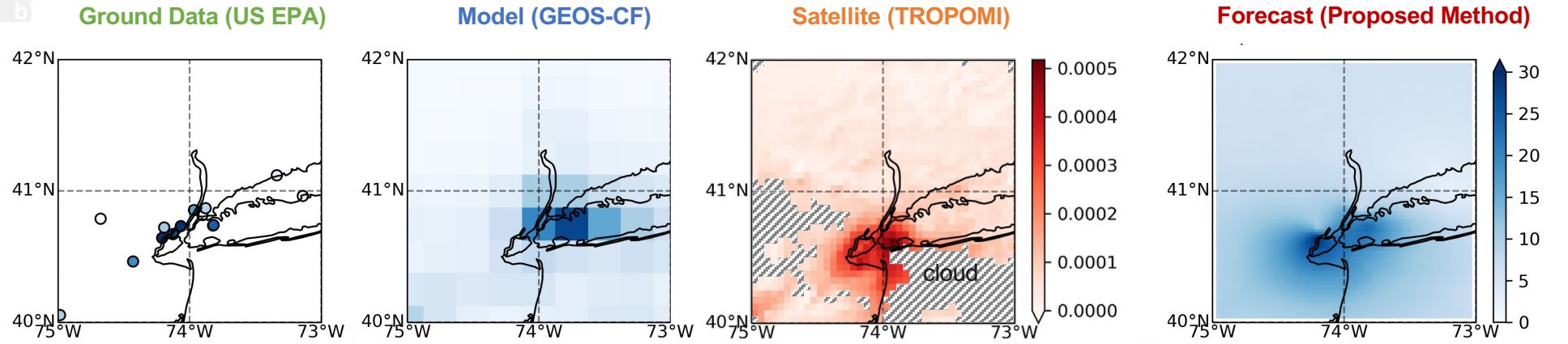


Data Fusion method for city-scale AQ forecasts

a)



b)



Malings et al., 2021 ESS

National Aeronautics and Space Administration

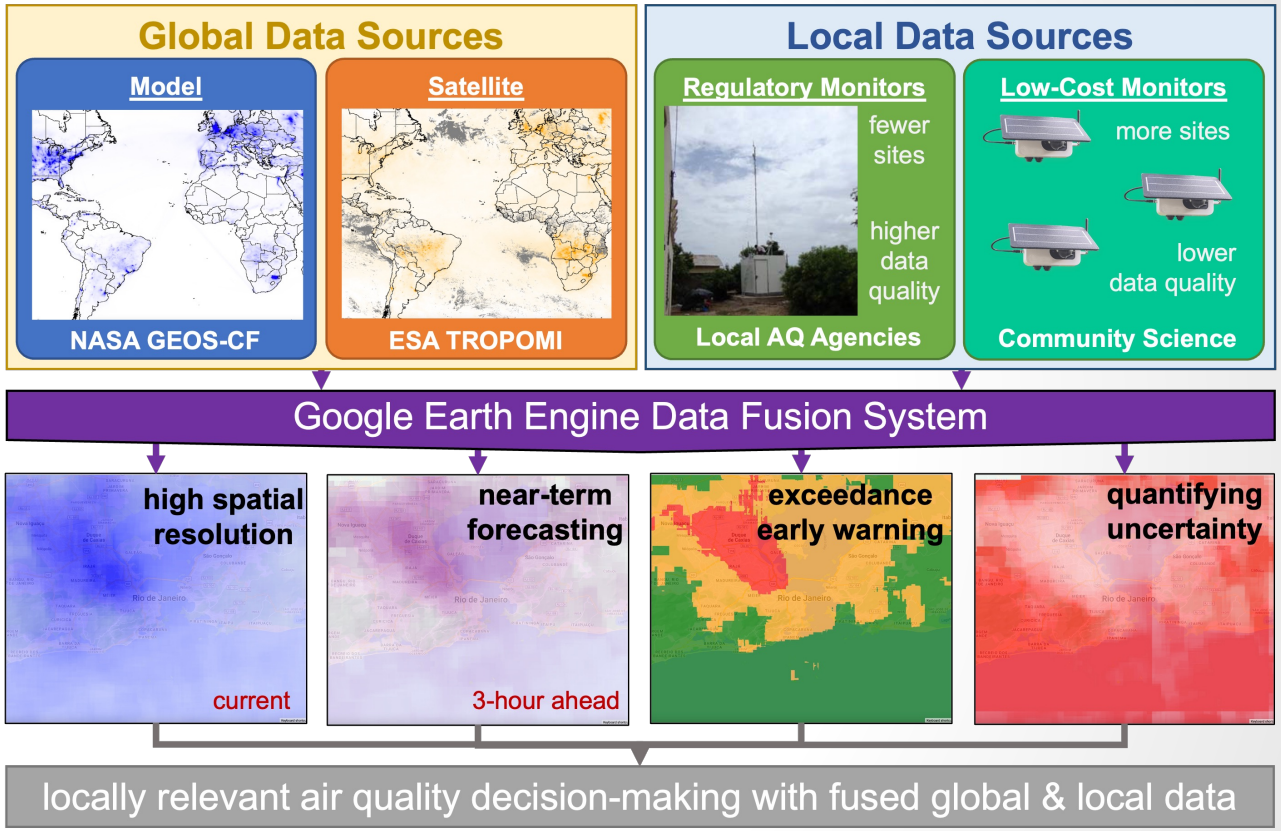
Project's objective to estimate air quality across a city

…integrate diverse **global** and **local** air quality data sources…

…using the cloud computing platform of **Google Earth Engine**…

…to provide synthesized **estimates** and **forecasts** of air quality at a **local scale** but with a **global scope**…

…which will be freely accessible by air quality managers worldwide, facilitating their **decision-making** processes.



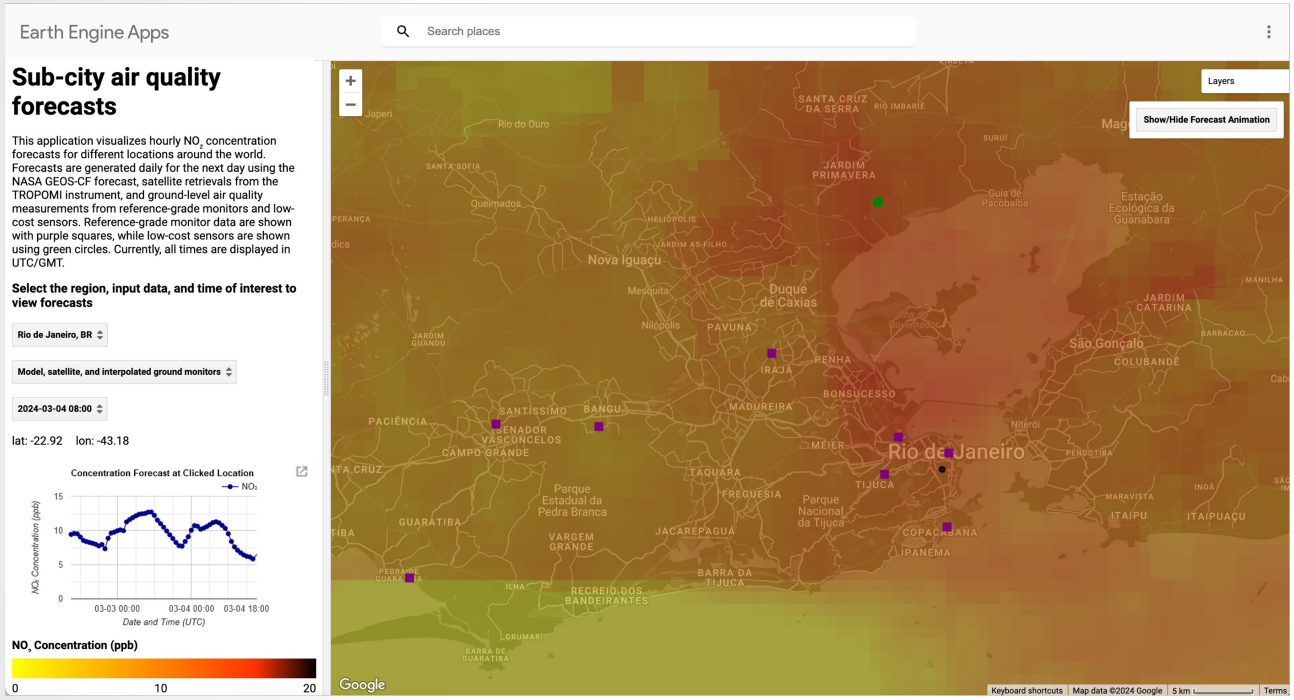
https://gmao.gsfc.nasa.gov/research/science_snapshots/2023/air_quality_data_fusion.php

PI K. Emma Knowland: k.e.knowland@nasa.gov
Co-I Nathan Pavlovic: npavlovic@sonomatech.com
Co-I Carl Malings carl.a.malings@nasa.gov

National Aeronautics and Space Administration

EARTH SCIENCE APPLIED SCIENCES

Pilot deployment of GEE tool in end-user domain of interest



https://gmao.gsfc.nasa.gov/research/science_snapshots/2023/air_quality_data_fusion.php

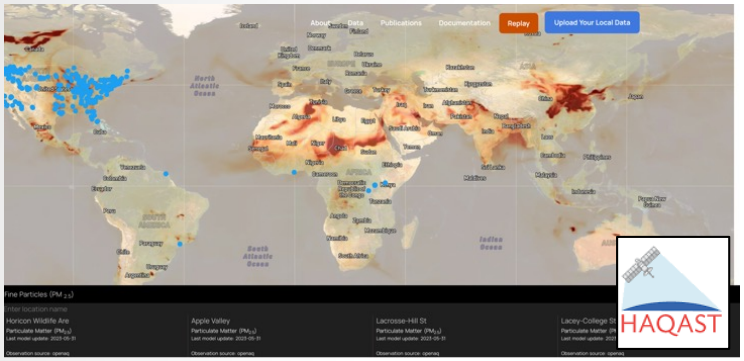
Developing an air quality forecasting model for Rio de Janeiro in collaboration with NASA has been identified as a key target for the Instituto Pereira Passos (IPP) for 2024 by the Rio de Janeiro Mayor's office.

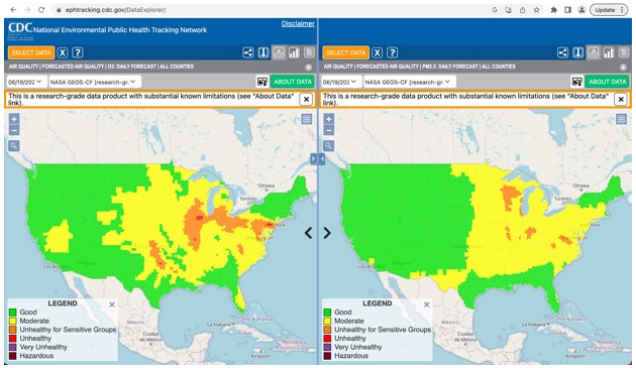
This indicates the value placed on the potential impact of such a tool by the local government and policy-makers.

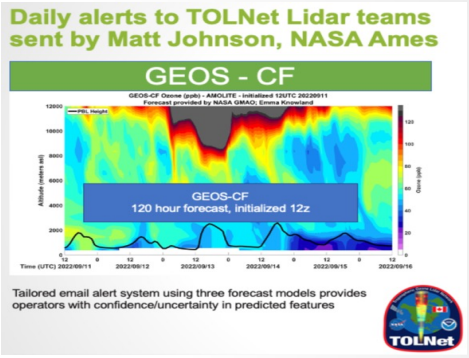
PI K. Emma Knowland: k.e.knowland@nasa.gov
Co-I Nathan Pavlovic: npavlovic@sonomatech.com
Co-I Carl Malings carl.a.malings@nasa.gov

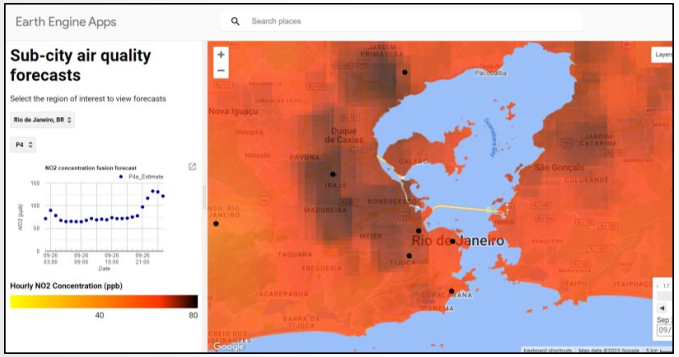
National Aeronautics and Space Administration

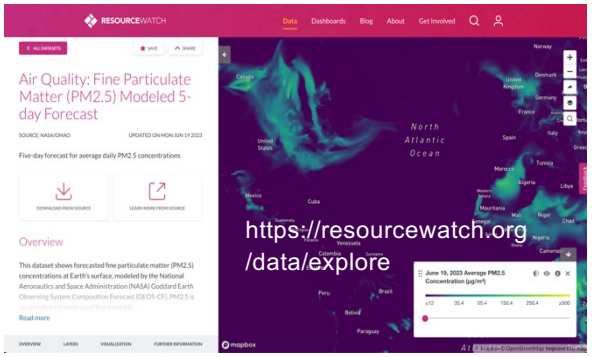
Actively Working With End Users to Meet Their Needs

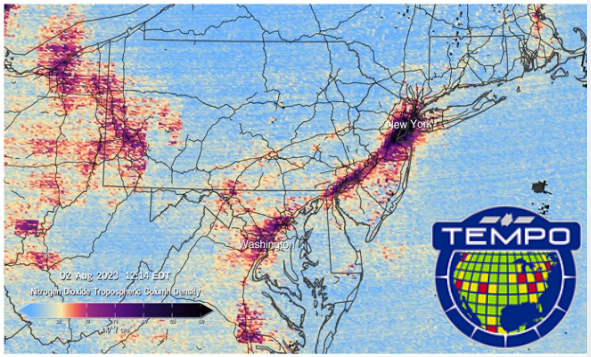






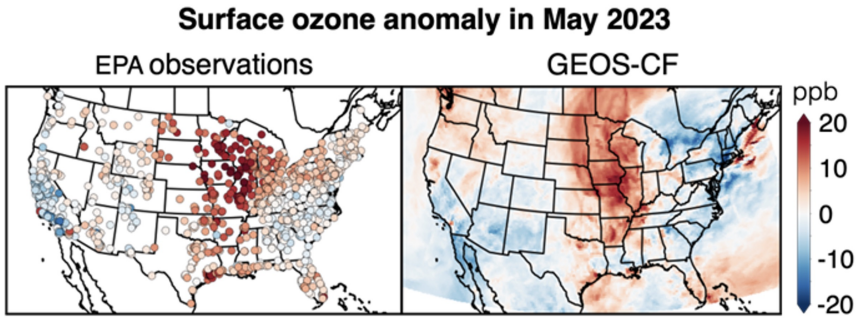


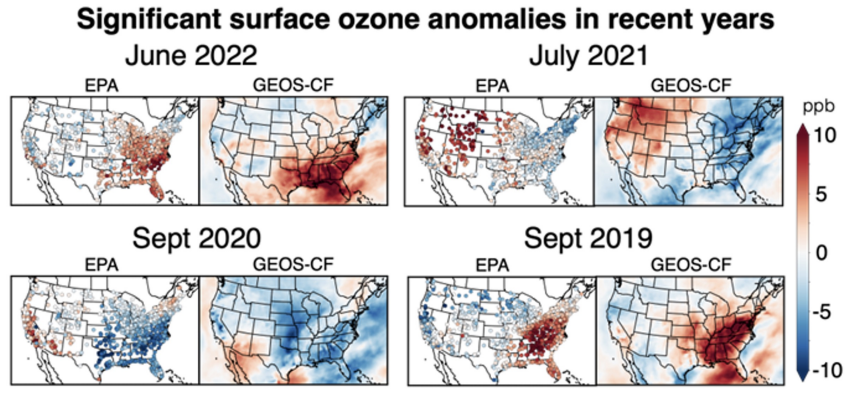


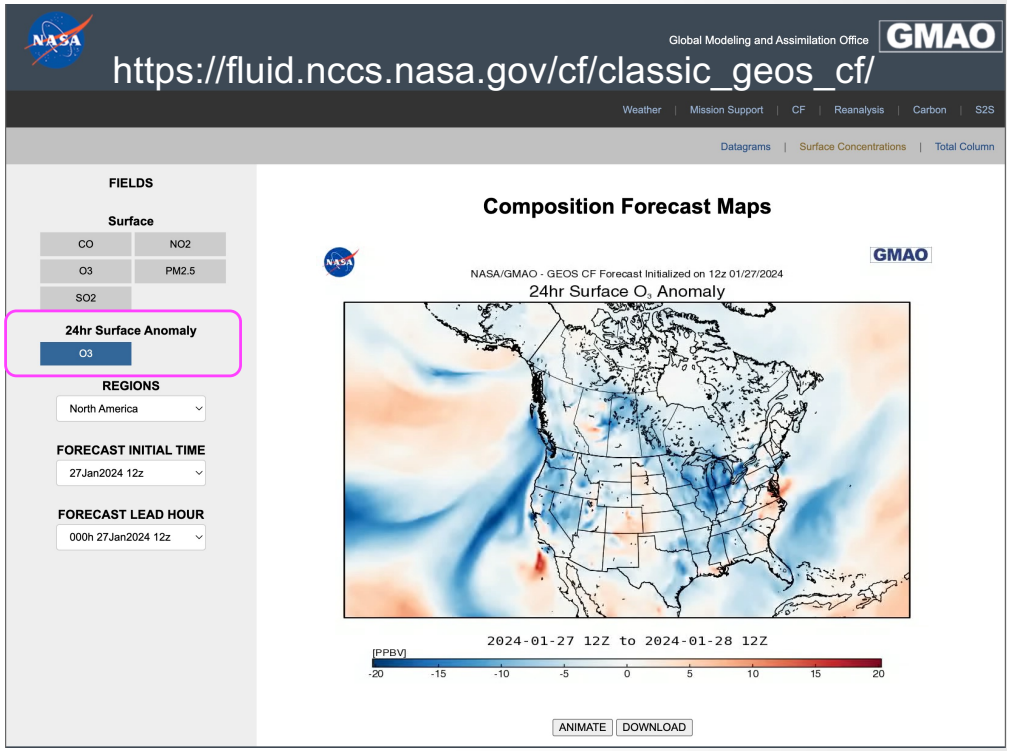


https://gmao.gsfc.nasa.gov/research/science_snapshots/2023/air_quality_data_fusion.php

Linking Surface Ozone Extremes to Weather Pattern Anomalies



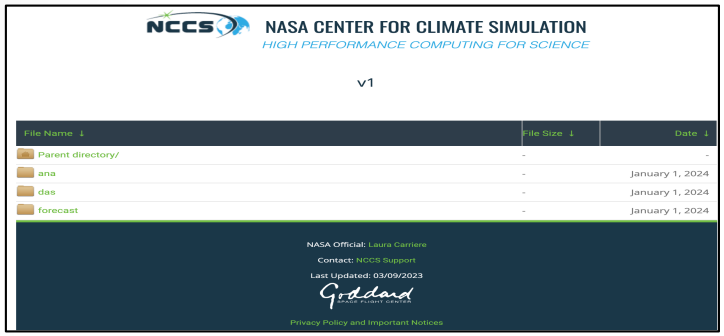


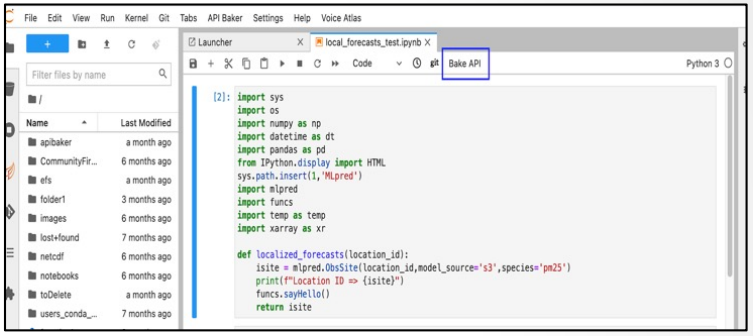


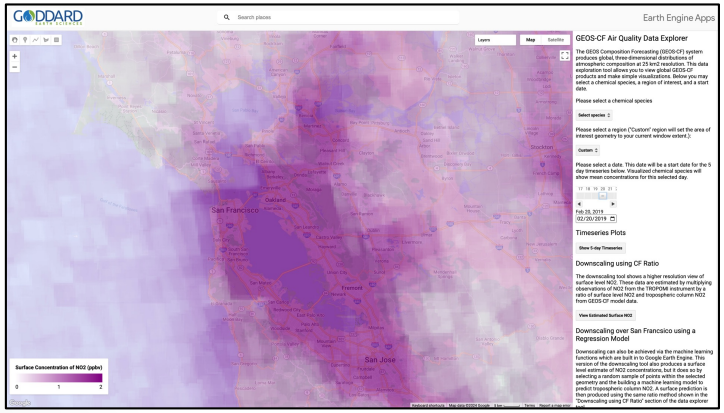
https://gmao.gsfc.nasa.gov/research/science_snapshots/2023/ozone-2023.php

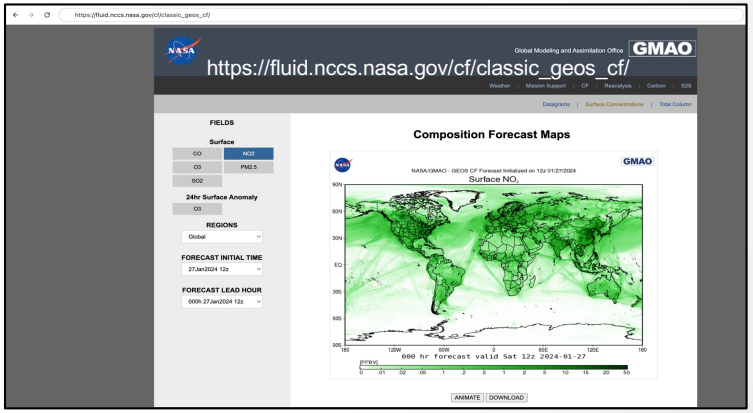
National Aeronautics and Space Administration

Ongoing Efforts to Expand Data Access – Demand & Opportunity









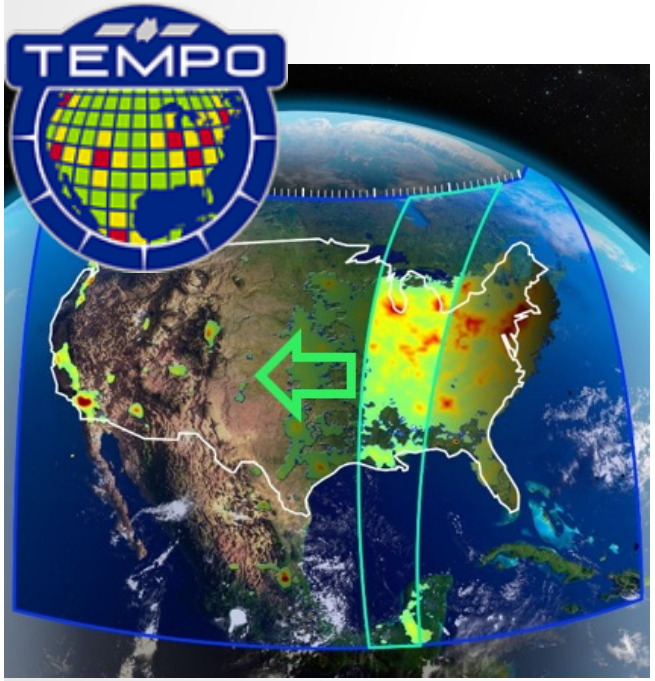
https://gmao.gsfc.nasa.gov/research/science_snapshots/2023/new-generation-gmao-apps.php

National Aeronautics and Space Administration

Daily *atmospheric composition* forecast

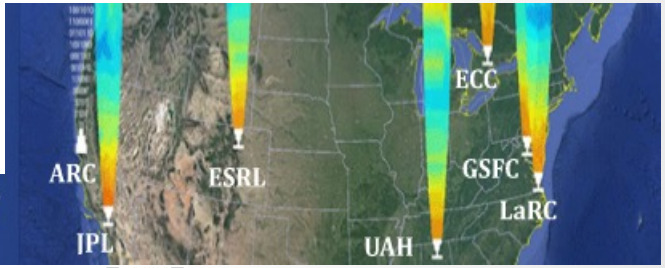
GEOS - CF

A realistic stratosphere in GEOS-CF is essential to support a broad range of NASA applications, including:



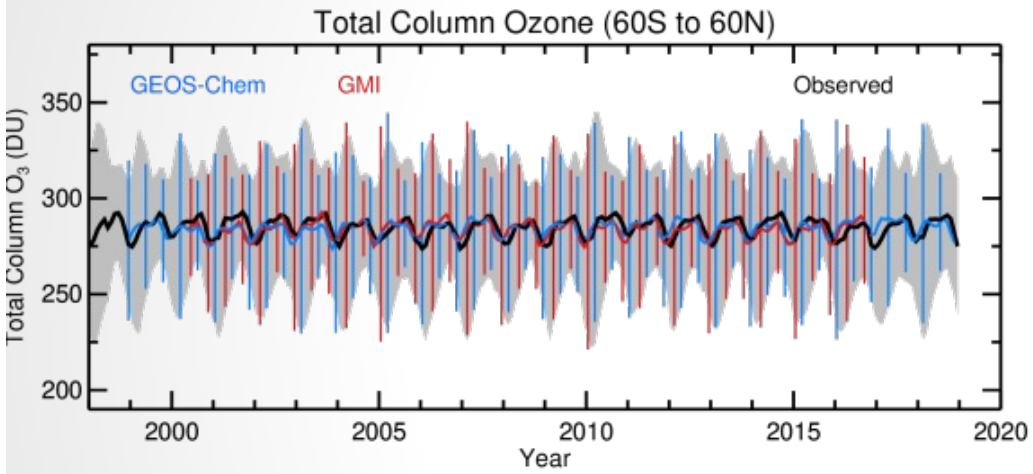
- Satellite retrievals of trace gases
- Airborne campaigns
- Stratosphere-troposphere exchange

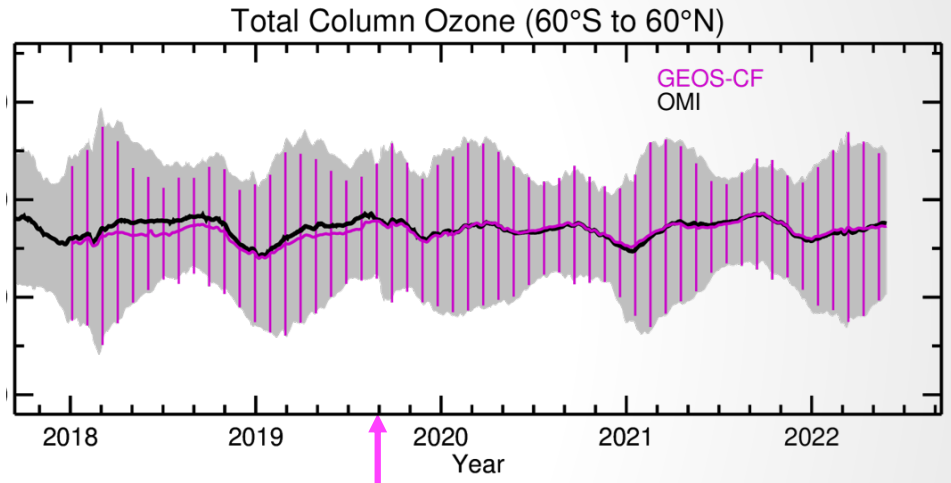
TOLNET
Tropospheric Ozone LIDAR Network



Stratospheric Composition Evaluation

- GEOS-CF Stratospheric O_3 is weakly nudged to the GEOS FP assimilated O_3



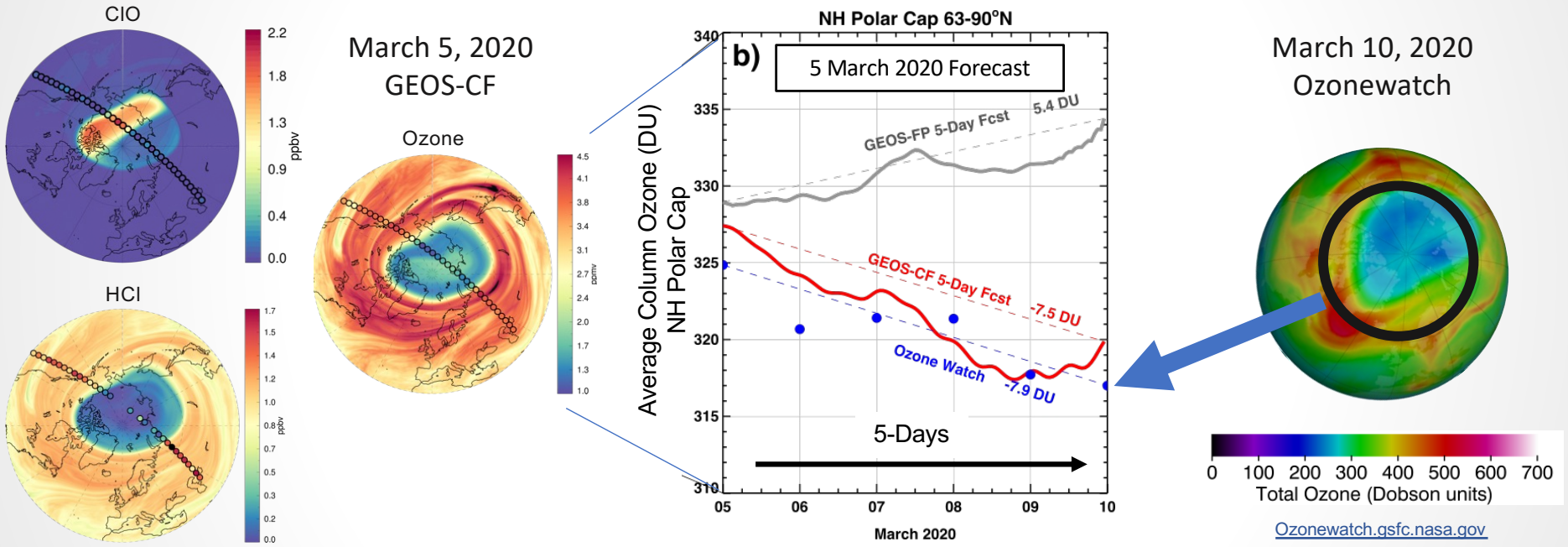


GEOS-Chem non-polar TCO agrees well with GMI simulated TCO and the observable TCO range

Updates were applied to GEOS-CF stratospheric mechanism on July 31, 2019, which improved the treatment of halogen and nitrogen families

Knowland et al., 2022, JAMES

Inclusion of Stratospheric Chemistry in GEOS-CF Provides GMAO Provides GMAO the capability of Realistic Ozone Forecasting

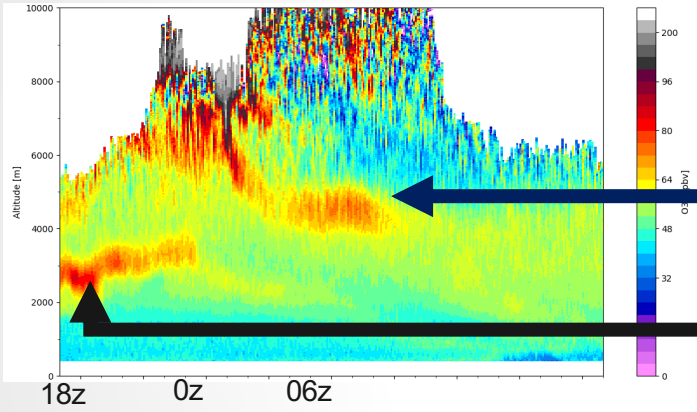


Knowland et al., JAMES, 2022

https://gmao.gsfc.nasa.gov/research/science_snapshots/2023/stratospheric-ozone.php

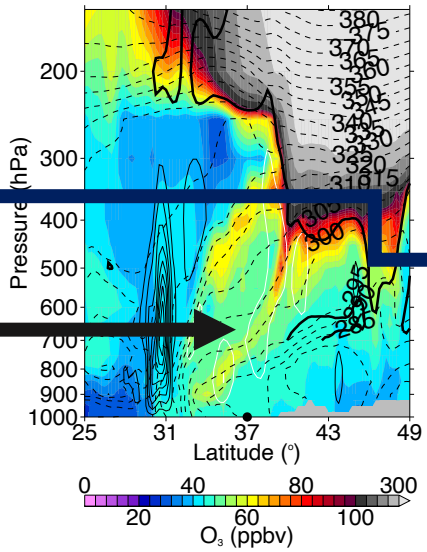
Stratosphere Troposphere Exchange

NASA LaRC Feb 13-14, 2019

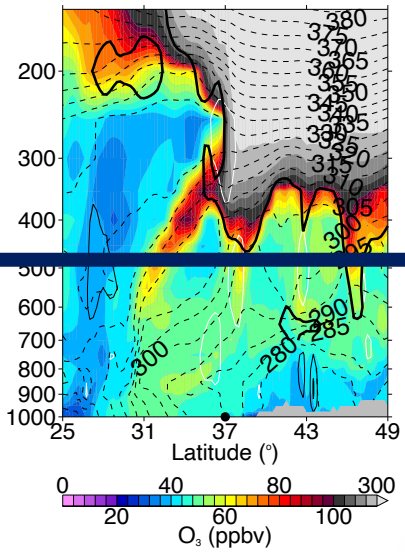


LMOL lidar plot courtesy of G. Gronoff

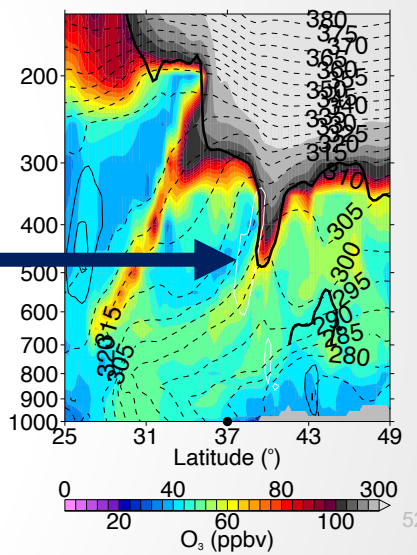
GEOS-CF
Feb 13, 2019 18z



Feb 14, 2019 00z



Feb 14, 2019 06z

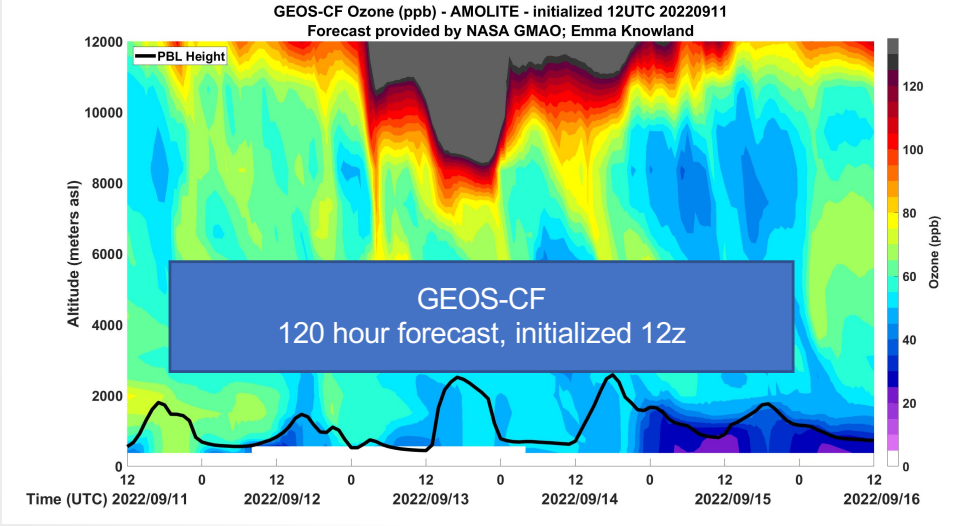


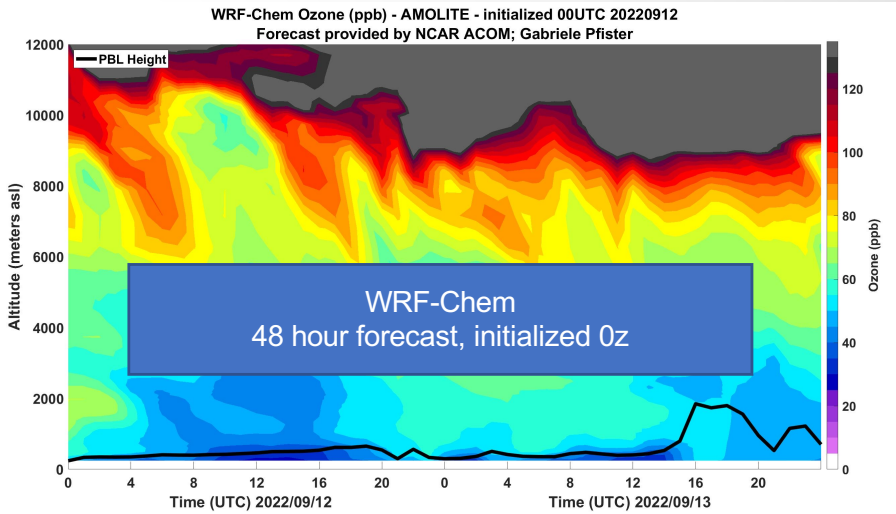
High ozone observed in the troposphere on February 13th and 14th of 2019 at LaRC have stratospheric origin, as indicated by the GEOS-CF curtain plots

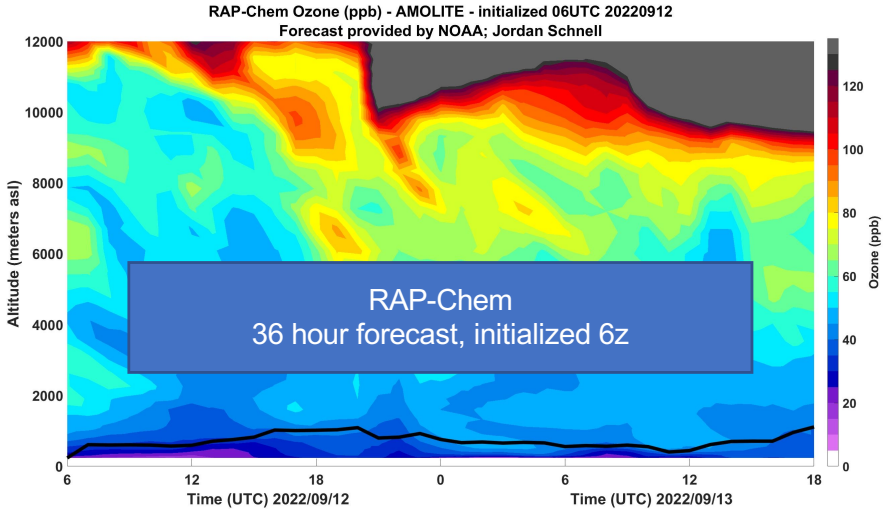
Gronoff, G., Berkoff, T., Knowland, K. E., et al. "Case study of stratospheric Intrusion above Hampton, Virginia: lidar-observation and modeling analysis." Atmos. Environ., 2021, DOI: 10.1016/j.atmosenv.2021.118498

Daily alerts to TOLNet Lidar teams sent by Matt Johnson, NASA AMES

GEOS - CF







Tailored email alert system using three forecast models provides operators with confidence/uncertainty in predicted features

Figures courtesy of Matt Johnson

Upgrade to GEOS-CF Version 2

Model components

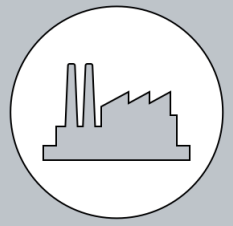
GEOSgcm v10.23 with new model physics

Replay to GEOS-IT

GEOS Chem 14.0

GEOS convective tranport

Emissions



HTAP → CEDS

Updated fire emission factors

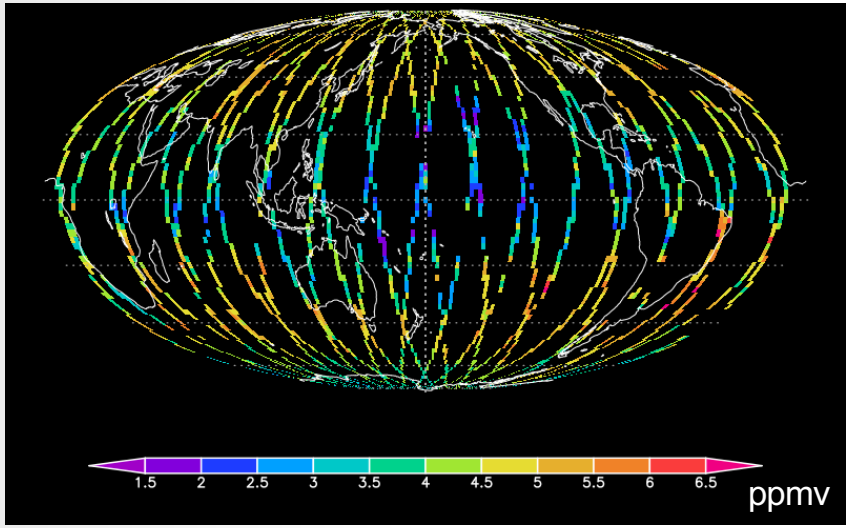
Redistributed lightning

Data assimilation

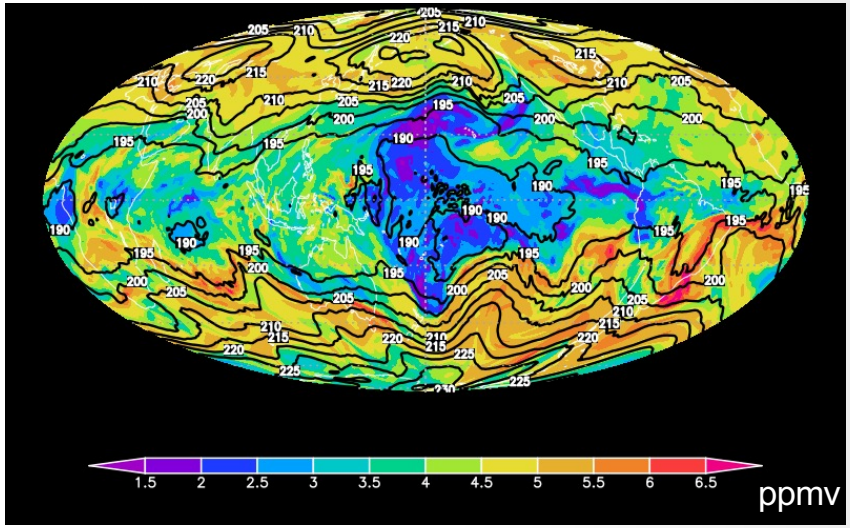
3D-Var assimilation of ozone, NO_2 and SO_2 satellite data

Constituent data assimilation

MLS water vapor at 100 hPa, 2 Jan 2016



Assimilated MLS water vapor and MERRA-2 temperature at 100 hPa, 2 Jan 2016



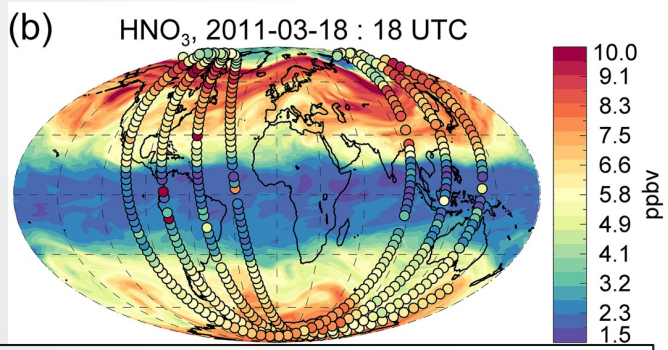
Data assimilation is a Bayesian method of combining and propagating information from observations in space and time using the governing equations and error estimates.

Figures courtesy of Kris Wargan

Constituent Data Assimilation System (CoDAS)

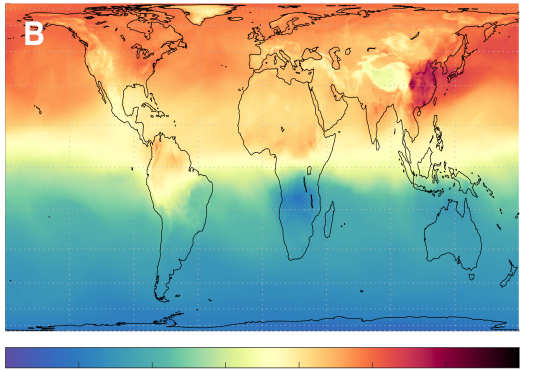
- Designed to be tracer agnostic: can assimilate any type of retrieved constituent observations with an averaging kernel or at a point
  - CoDAS builds on the Gridpoint Statistical Interpolation scheme developed at NCEP and GMAO
  - GMAO involved and invested in the constituent DA with JEDI

M2-SCREAM



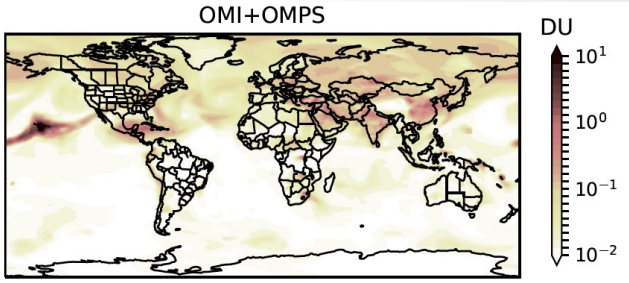
Wargan et al., ESS (2023). DOI: 10.1029/2022EA002632

GEOS-GHG



Weir et al., Sci. Adv. (2021) DOI:10.1126/sciadv.abf9415

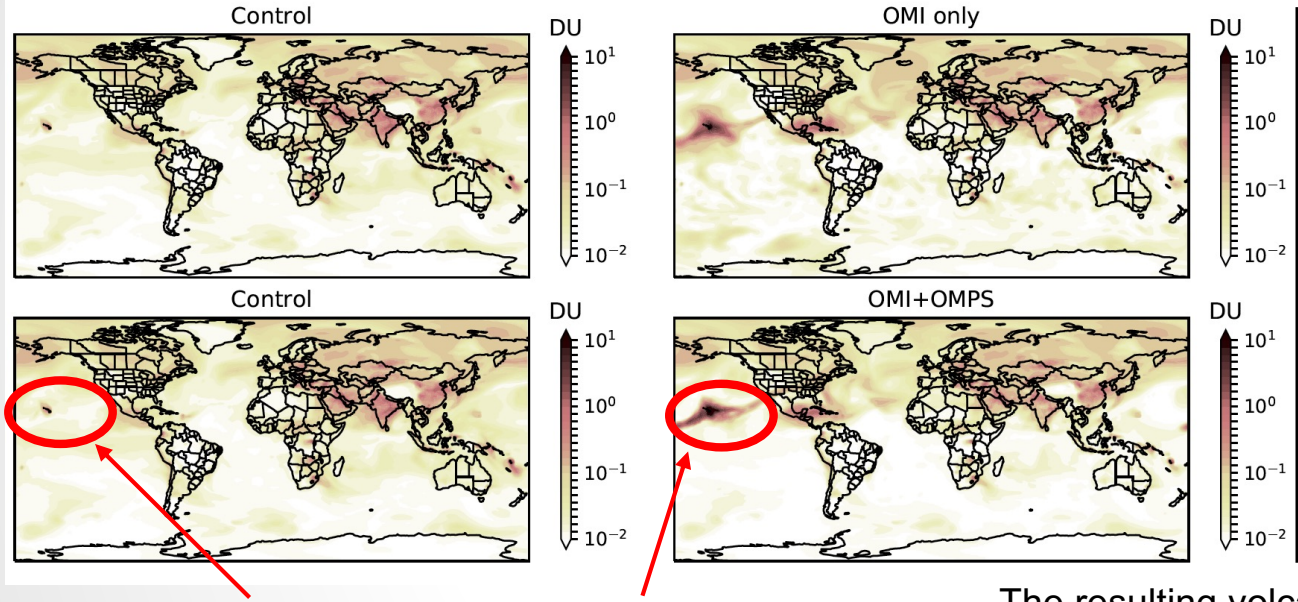
GEOS-CF v2



https://gmao.gsfc.nasa.gov/research/science_snapshots/2022/mauna-loa.php

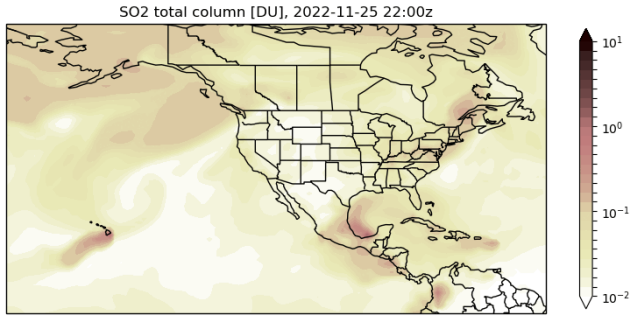
SO_2 assimilation: Mauna Loa's smoking gun

Simulated SO_2 total column [DU] for Dec 6, 2022



Mauna Loa eruption only captured in runs with assimilation

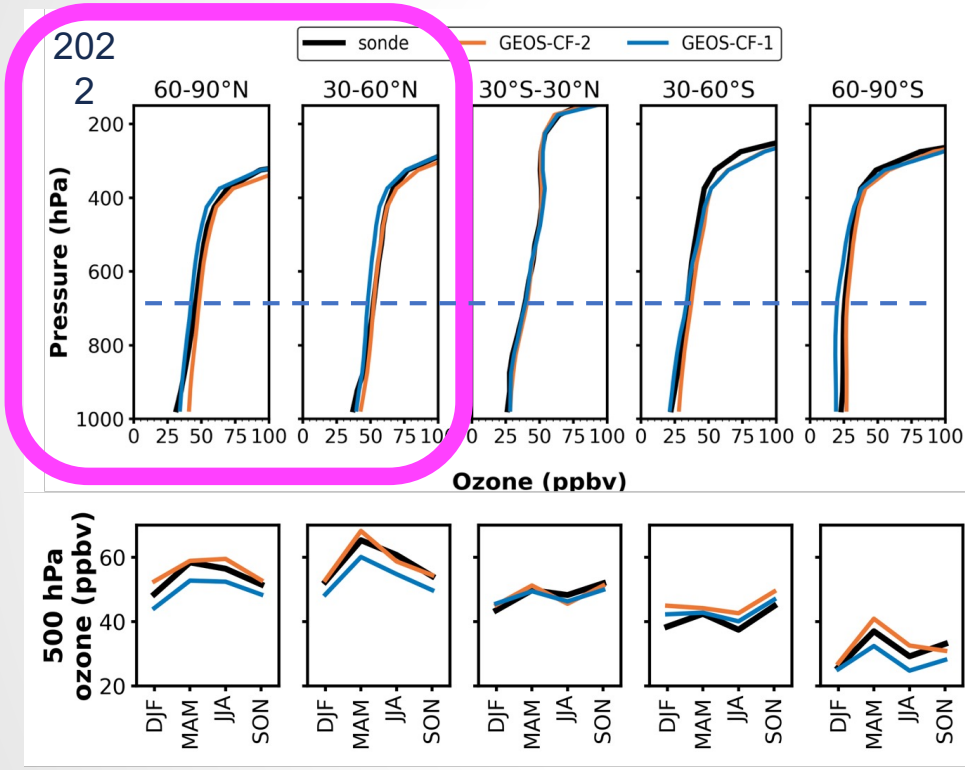
Evolution of assimilated SO_2 from the Mauna Loa eruption in November 2022



The resulting volcanic plume of sulfur dioxide (SO_2) can be seen from space with satellite instruments such as NASA's Ozone Monitoring Instrument (OMI).

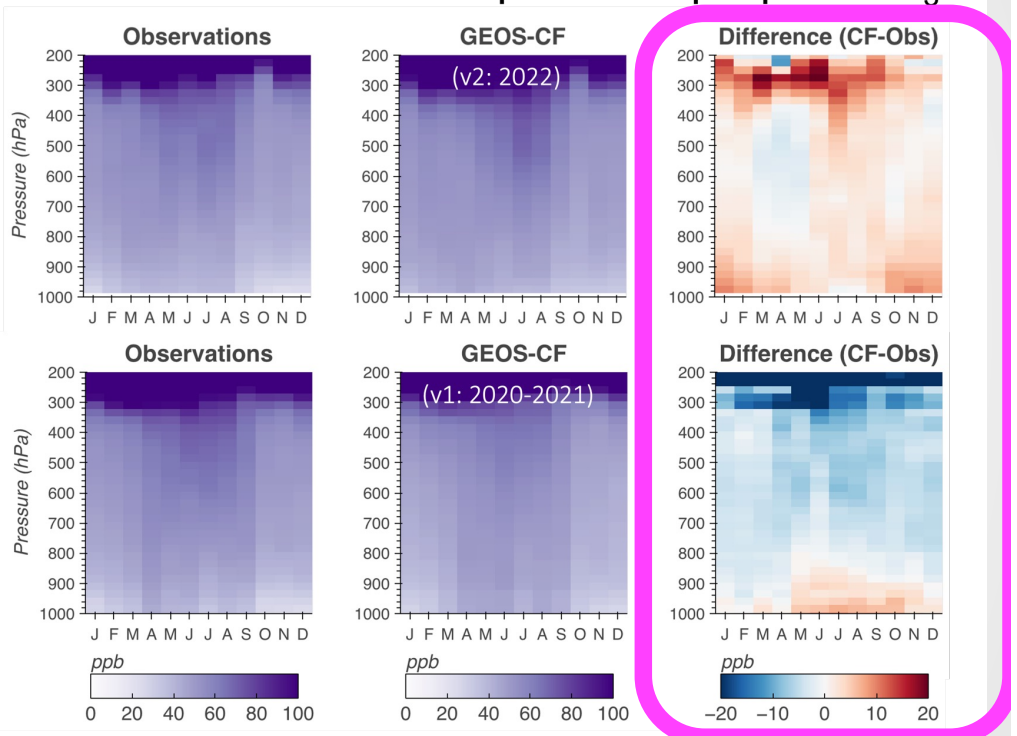
https://gmao.gsfc.nasa.gov/research/science_snapshots/2022/mauna-loa.php

Tropospheric Ozone in V2 is Improved Because of Direct Assimilation



Version 1 Version 2

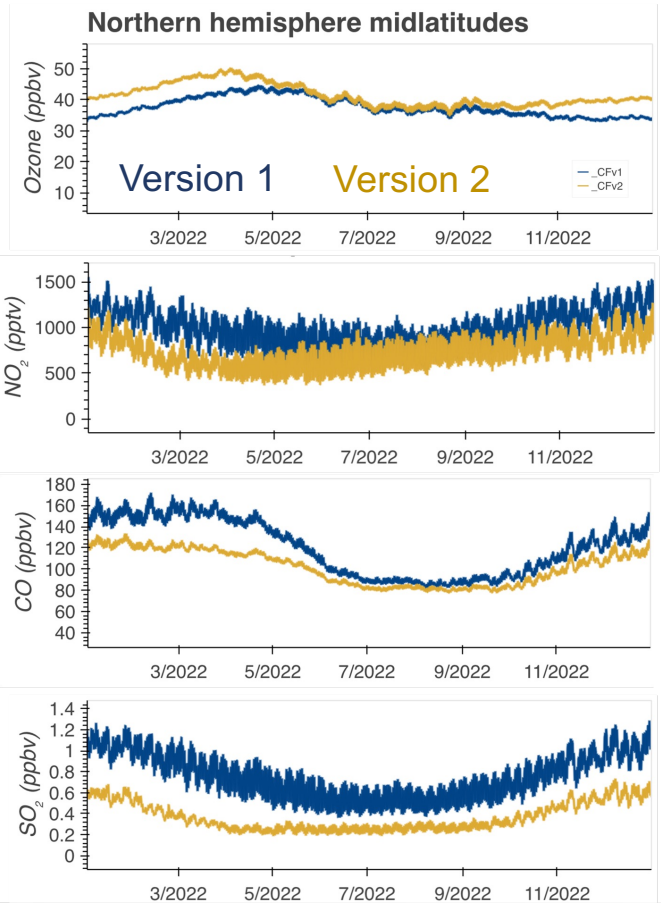
Ozone assimilation ➡ Improved tropospheric O_3



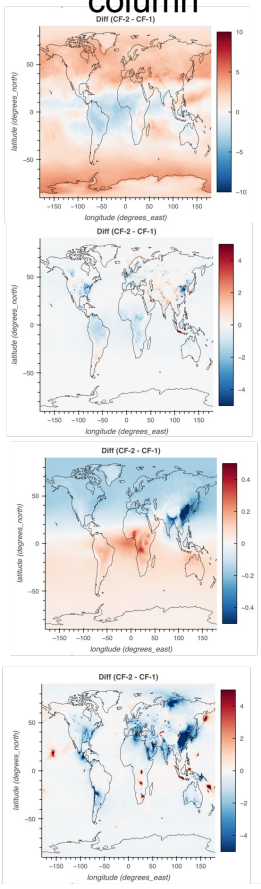
Composite of NA & European ozonesondes

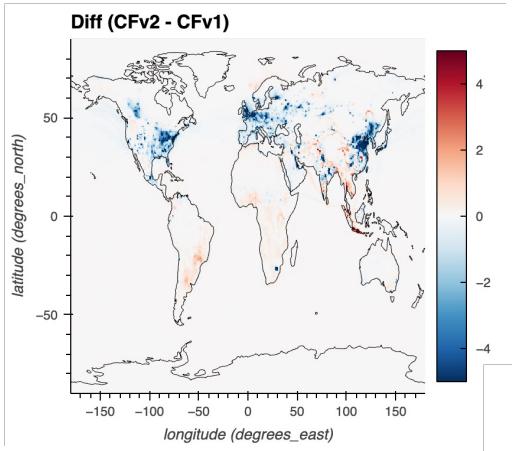
Lower NOx emissions is leading to higher Ozone in GEOS-CF version 2

2022 Annual surface concentration



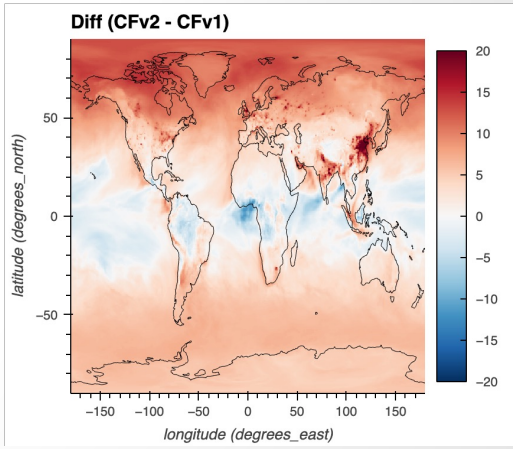
Annual tropospheric column





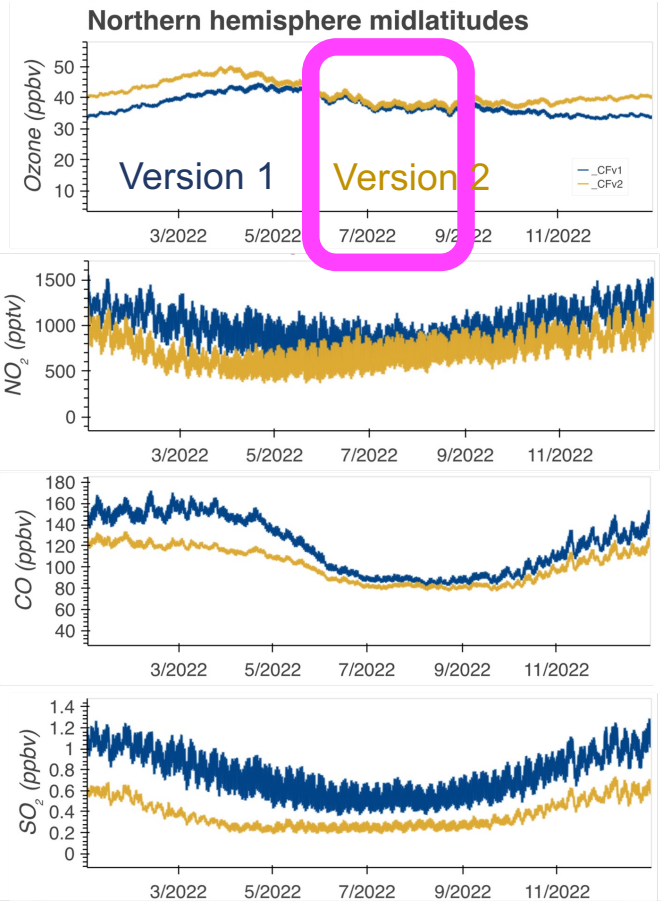
Surface NO_2 is lower in v2, especially in urban areas

this leads to higher surface O_3

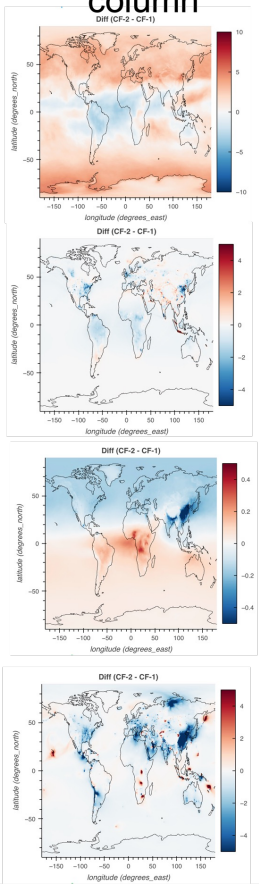


With updated GEOS met the summer O_3 bias in Southeast US is reduced

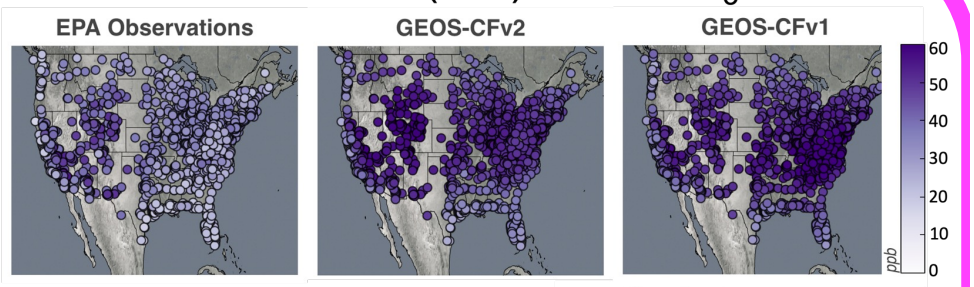
2022 Annual surface concentration



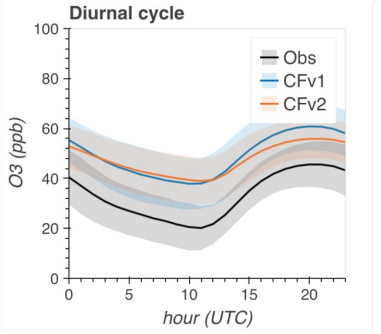
Annual tropospheric column



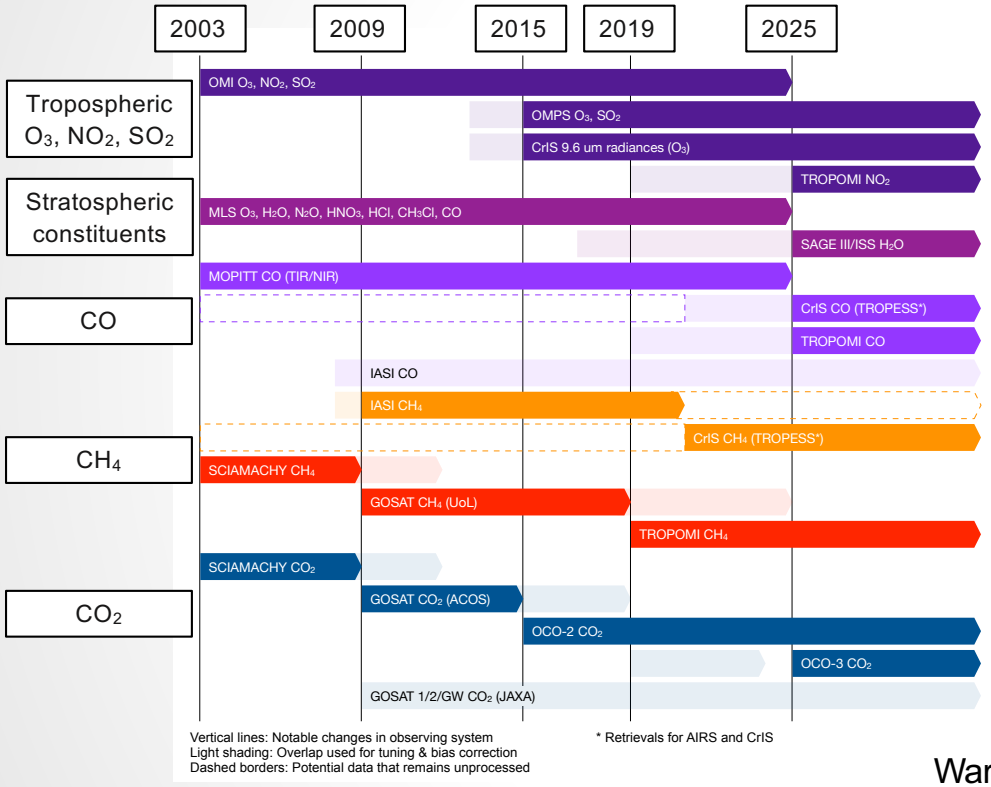
Summertime (JJA) surface O_3

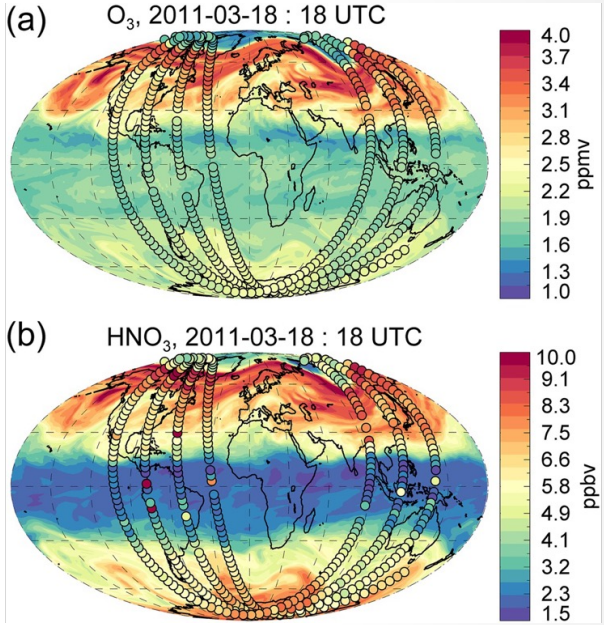


Surface O_3 in Western US ⬆ and Eastern US ⬇ in version 2 compared to version 1. Overall, the daytime bias ⬇, closer to observations



Next: A GEOS Composition Reanalysis for ~2000-2025, Based on GEOS-CF V2, M2-SCREAM, and GEOS-GHG

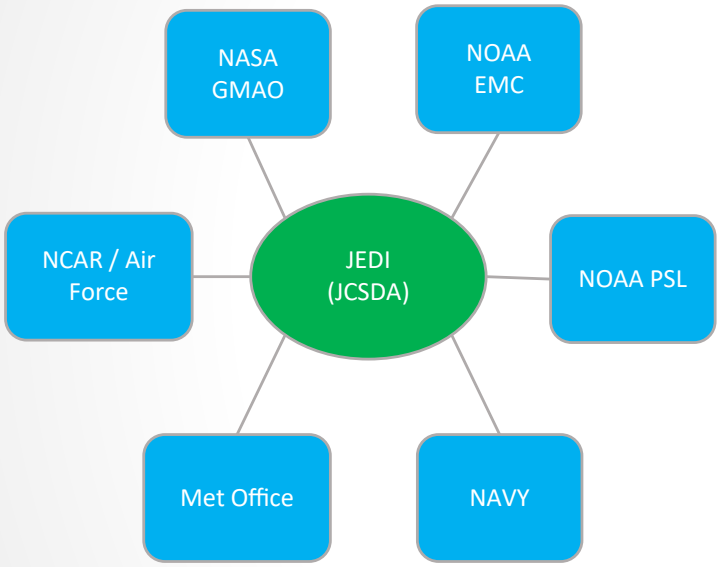




GSI-based Constituent Data Assimilation System (CoDAS) forms the backbone to constituent assimilation products

Wargan et al., JAMES, 2023, https://doi.org/10.1029/2022EA002632

Community benefit of JEDI data assimilation software



JEDI, managed by the Joint Center for Satellite Data Assimilation (JCSDA), is truly a community effort with no one agency dictating the development.

The only difference between the way GMAO uses JEDI and the way another center uses it is the configuration file.

It can be thought of as a repository exhibiting the state-of-the-art in data assimilation knowledge made available to everybody.

As new NASA data come online they can be made available to many users in very short order.

K. Emma Knowland
k.e.knowland@nasa.gov

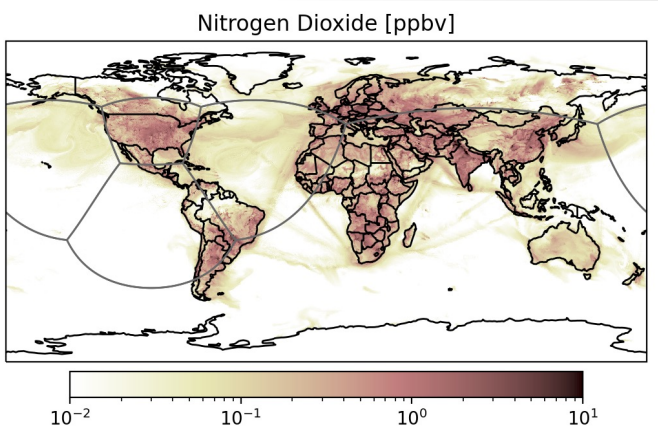
Summary and Long-Term Perspective

- Version 1 grew from ROSES funding and has expanded GMAO's role in global composition forecasting
  - New capabilities (stratospheric prediction, surface ozone anomalies, …)
  - Support of additional NASA science teams (providing a priori for TEMPO trace gas retrievals, field campaigns, …)
  - Rapid growth in users from the Applications (especially health) perspective
- Version 2 introduces assimilation and other improvements (model transport, emissions)
  - Basis for GMAO's constituent reanalysis
  - Explore web-based distribution and more open-source analysis tools (GEE, AWS,…)
- Also excited about …
  - Opening opportunities for data assimilation with JEDI (a community effort across agencies)
  - Regional grid refinements and higher vertical resolution in GEOS
  - Chemistry speed-ups

Questions about GEOS-CF may be submitted to our email List, geos-cf@lists.nasa.gov.

Sign up for notifications about GEOS-CF production issues and upgrades –

• To subscribe to "geos-cf-users@lists.nasa.gov":
Send an e-mail to geos-cf-users-join@lists.nasa.gov (no subject or text in the body is required).



Thank you!

National Aeronautics and Space Administration

Referred

Knowland, K. E., C. A. Keller, P. A. Wales, et al. (2022). NASA GEOS Composition Forecast Modeling System GEOS-CF v1.0: Stratospheric composition. *Journal of Advances in Modeling Earth Systems, 14, e2021MS002852.* https://doi.org/10.1029/2021MS002852

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Non-Refereed

Knowland, K. E., Keller, C. A. and Lucchesi, R. A. (2022), "File Specification for GEOS-CF Products." *GMAO Office Note No. 17 (Version 1.3), 54pp, available from http://gmao.gsfc.nasa.gov/pubs/office_notes*