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

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In collaboration with:

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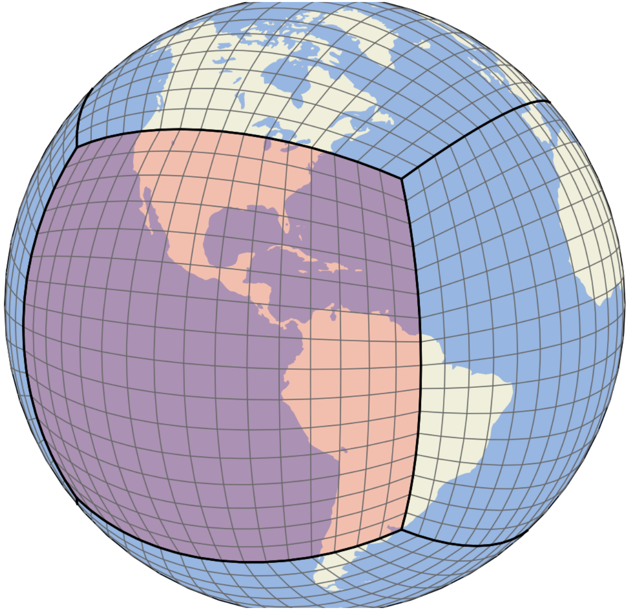
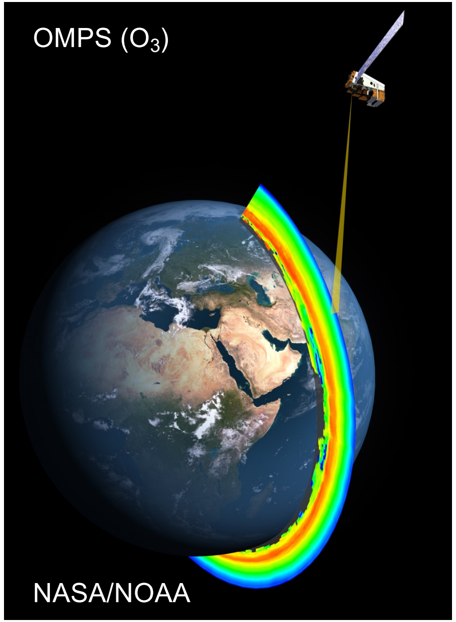
16 September 2022

NASA GMAO global meteorology and chemistry products

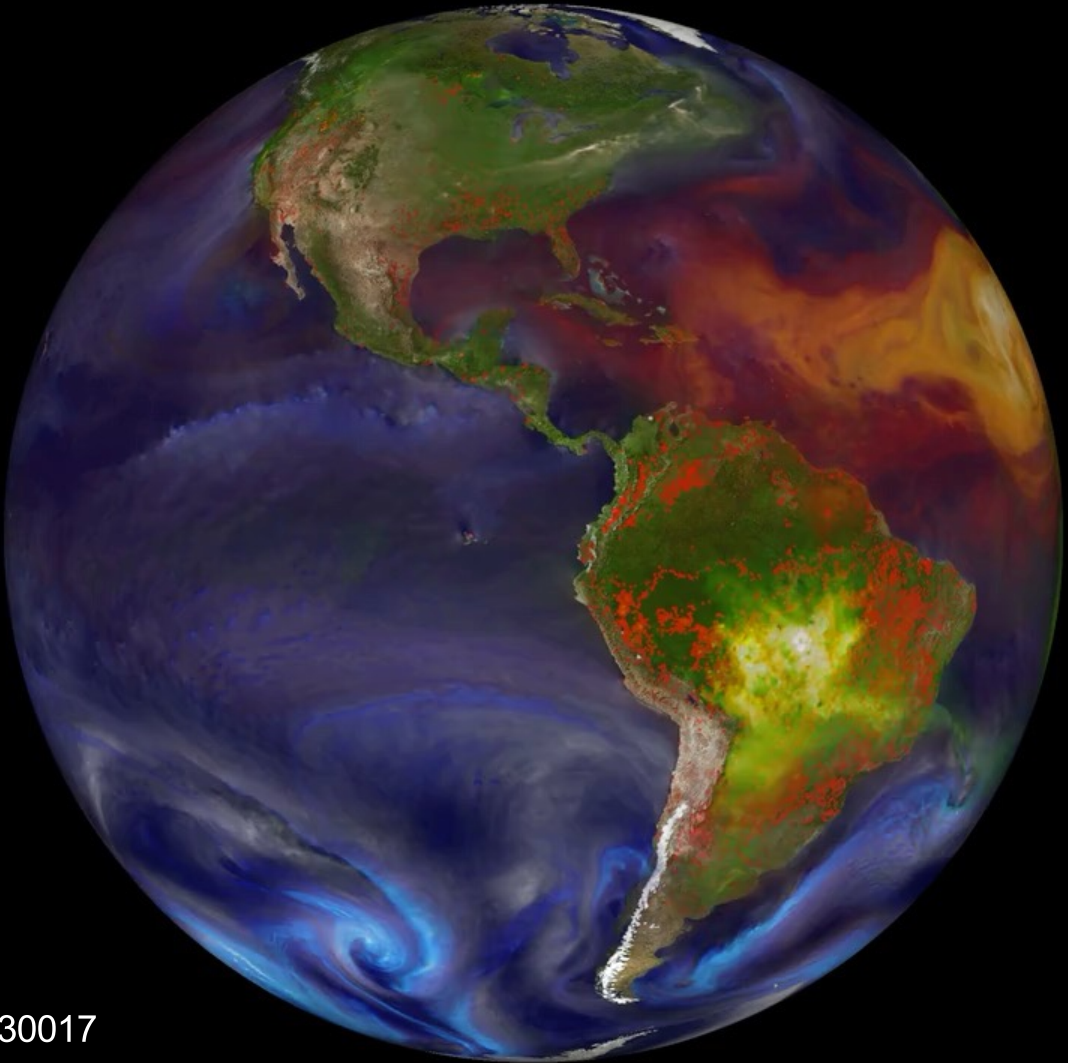
GEOS



Bindle et al., 2021 GMD



www.nasa.gov



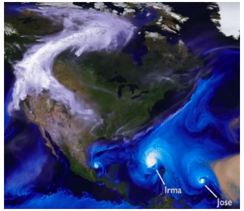
https://svs.gsfc.nasa.gov/30017

NASA GMAO global meteorology and chemistry products

GEOS

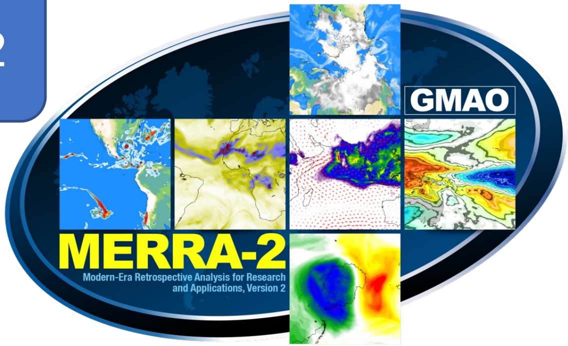
Forecasting

Reanalysis



GEOS FP

MERRA-2



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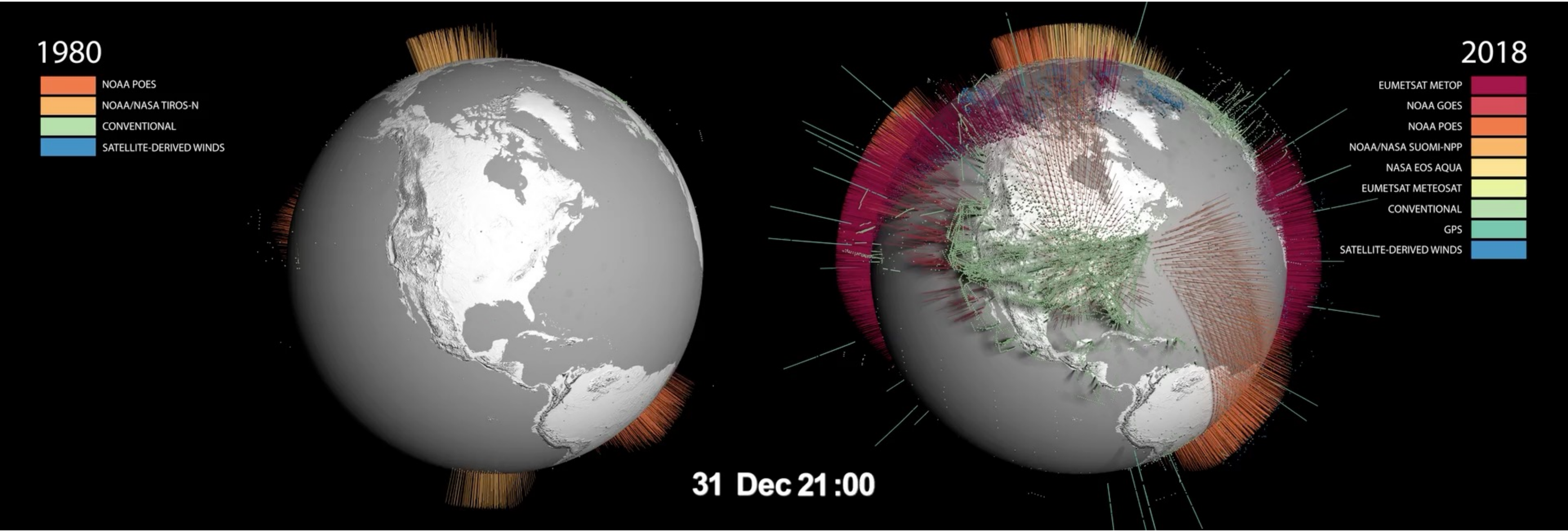
Changes to the observing system

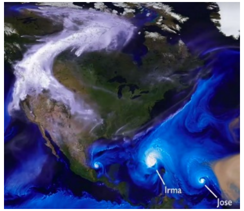


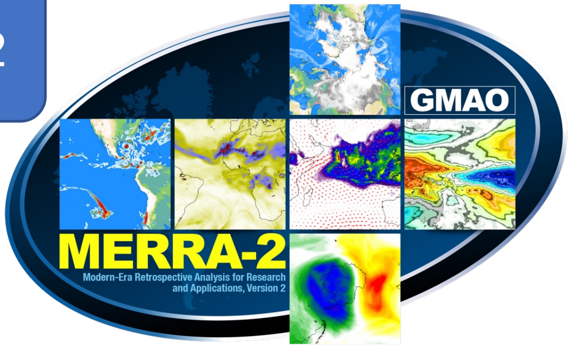
https://svs.gsfc.nasa.gov/4654

NASA GMAO global meteorology and chemistry products

GEOS

- Forecasting
  - GEOS FP
  - GEOS FP-IT
    - GEOS-CF
- Reanalysis
  - MERRA-2





https://gmao.gsfc.nasa.gov/GMAO_products/

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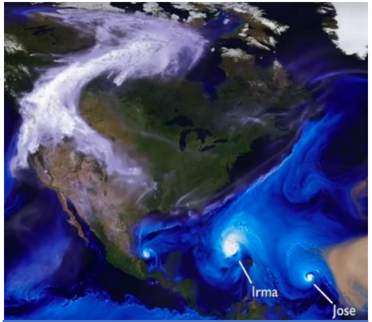
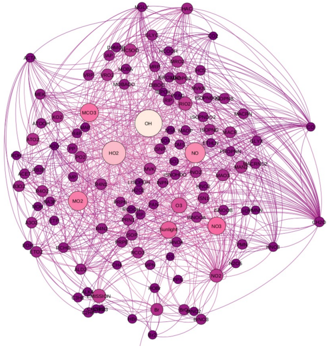
GEOS Composition Forecast



GEOS NWP

+



GEOS-Chem

→ GEOS - CF

Version 12

Tropospheric and Stratospheric chemistry

- 250 Chemical Species
- 725 Chemical Reactions

https://gmao.gsfc.nasa.gov/weather_prediction/GEOS-CF/

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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

https://gmao.gsfc.nasa.gov/GMAO_products/

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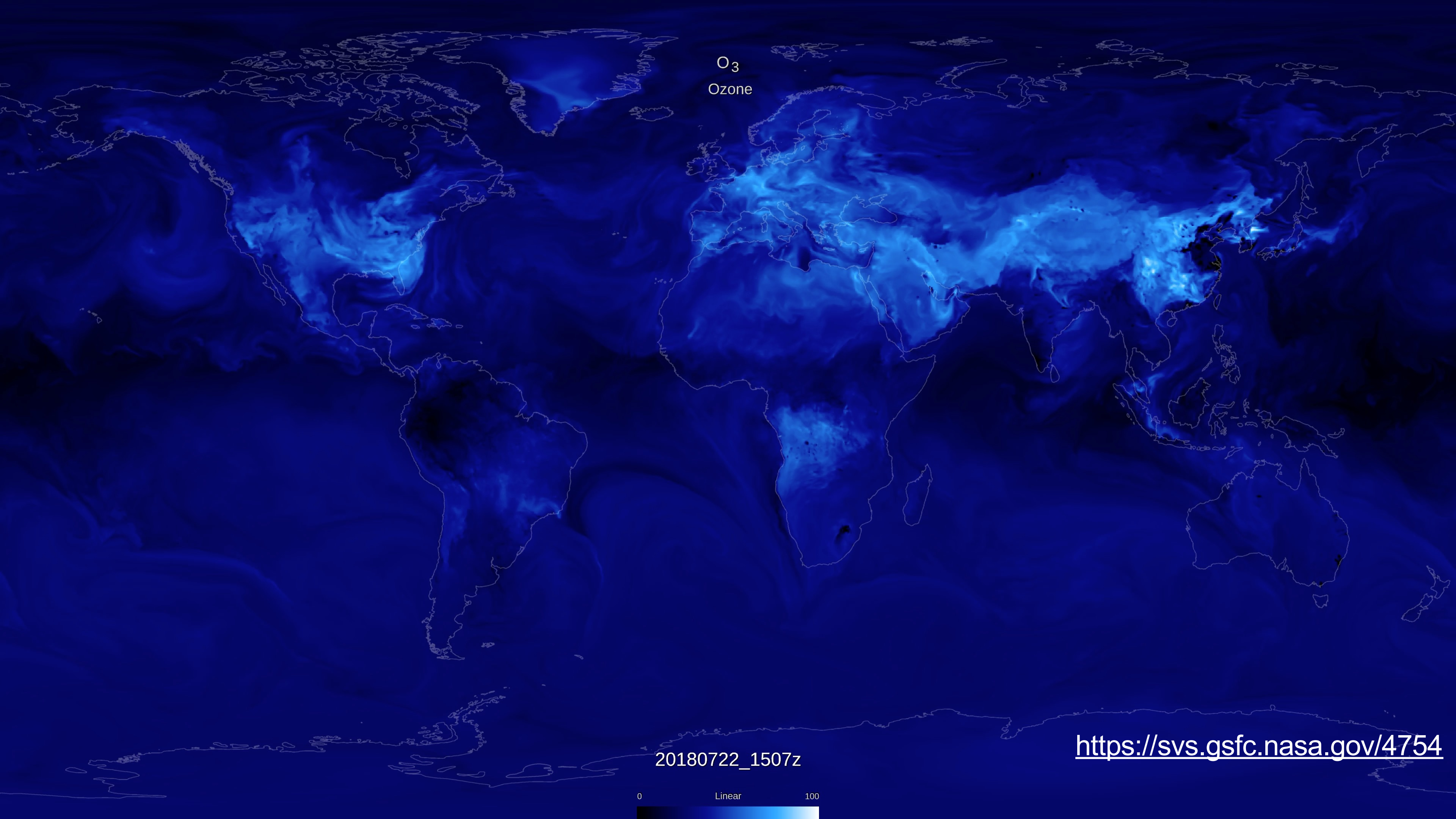
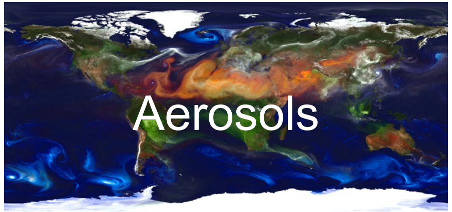
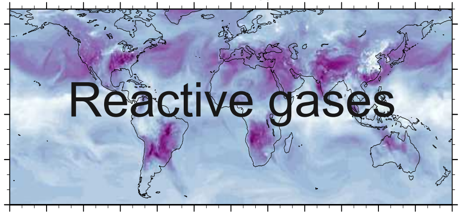


https://svs.gsfc.nasa.gov/4754

Aerosol and Gas Phase Chemistry





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

GOCART

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

GEOS-Chem

https://gmao.gsfc.nasa.gov/weather_prediction/GEOS-CF/

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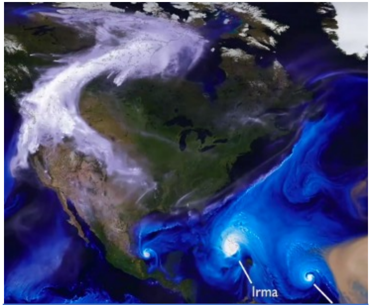
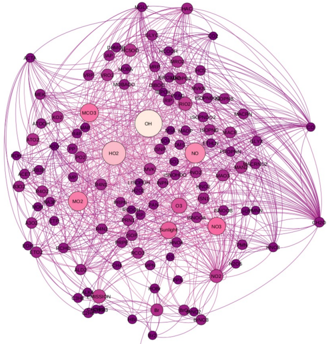
Daily composition forecast



GEOS NWP



GEOS - Chem

GEOS - CF

One **5-day forecast** per day

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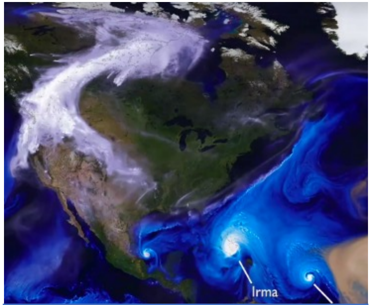
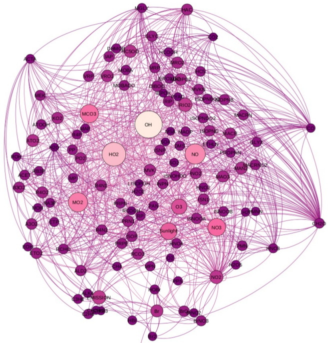
Daily composition forecast



GEOS NWP



GEOS - Chem

GEOS - CF

One **5-day forecast** per day

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

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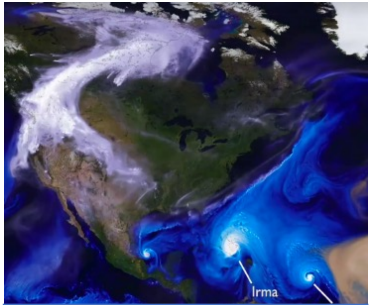
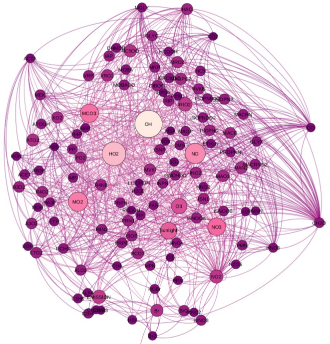
Daily composition forecast



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

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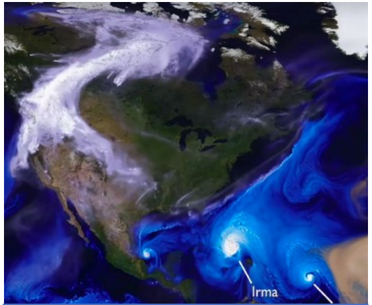
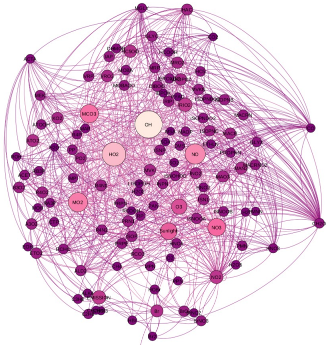
Daily composition forecast



GEOS NWP



GEOS - Chem

GEOS - CF

One **5-day forecast** per day

- 1-day replay
- 5-day forecast
- c360 (0.25°, **~25x25 km^2**) resolution, 72 model layers
- O_3, NO_x, VOCs, PM ...
- T, U, V, RH ....

https://gmao.gsfc.nasa.gov/weather_prediction/GEOS-CF/

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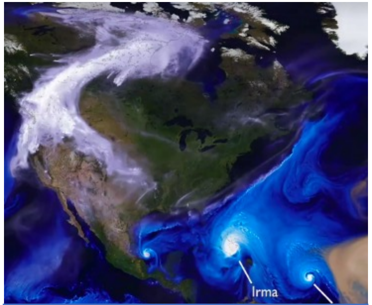
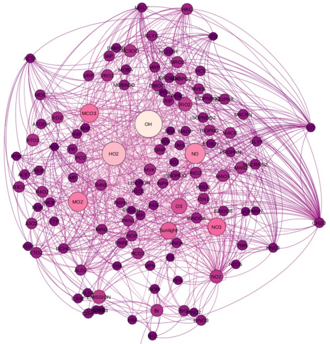
Daily composition forecast



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

https://gmao.gsfc.nasa.gov/weather_prediction/GEOS-CF/

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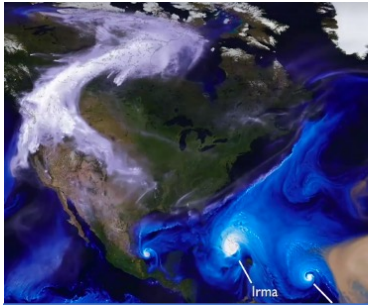
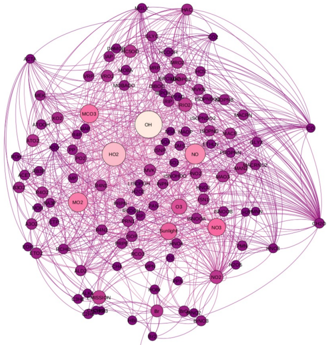
Daily composition forecast



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)

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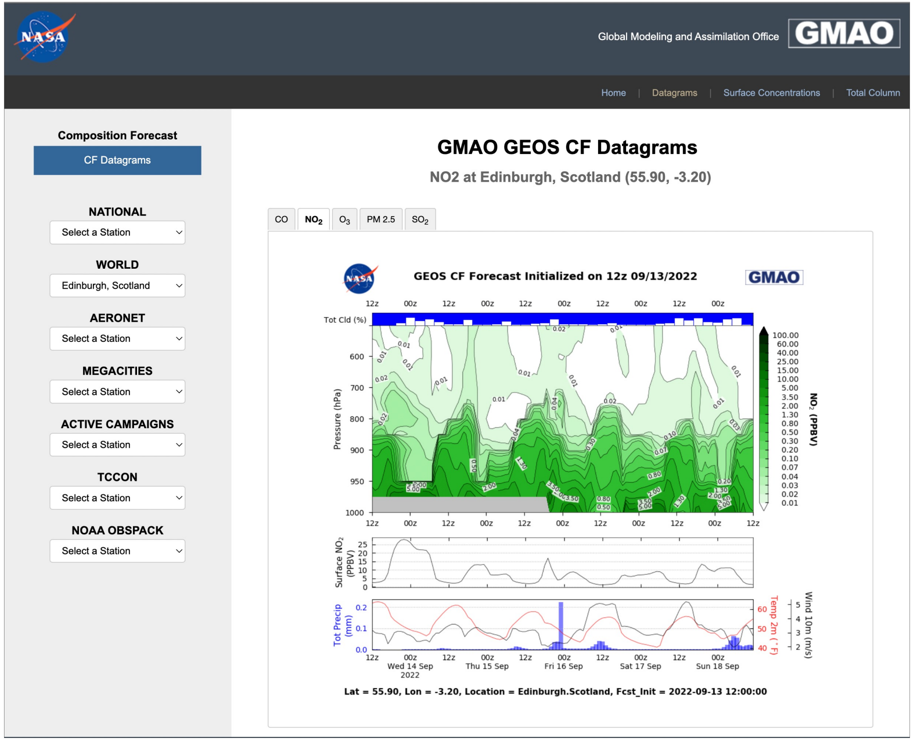
GEOS-CF are available online in near real-time

FLUID is a mobile-friendly website

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



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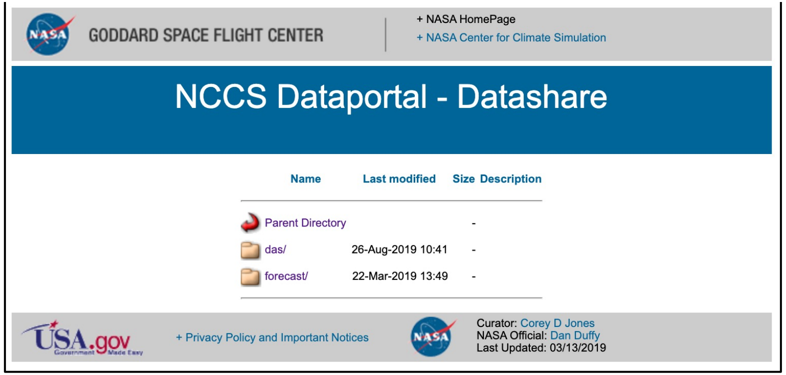

https://opendap.nccs.nasa.gov/dods/gmao/geos-cf/

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_with_diameter_below_2.5_um_rh_35	

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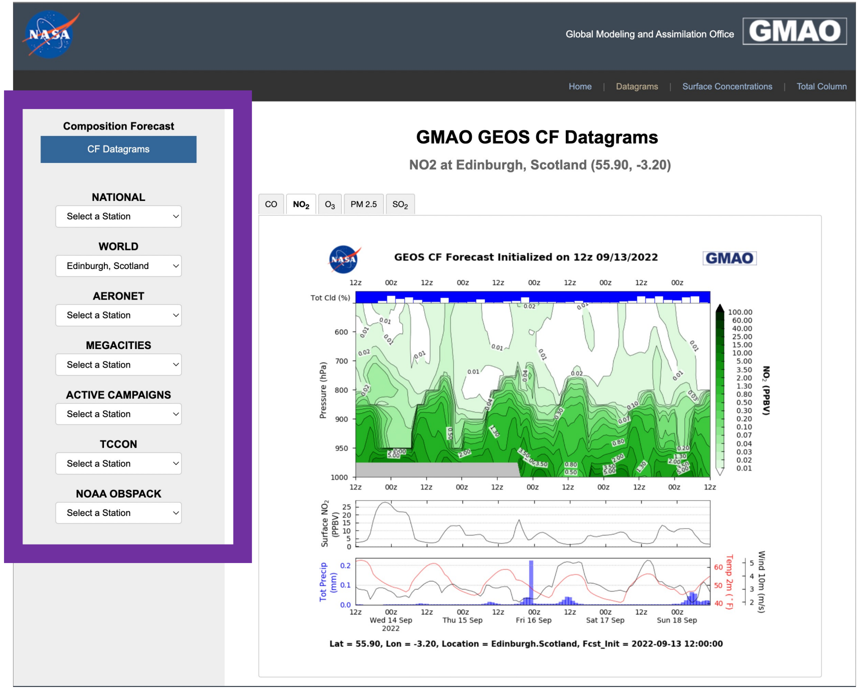
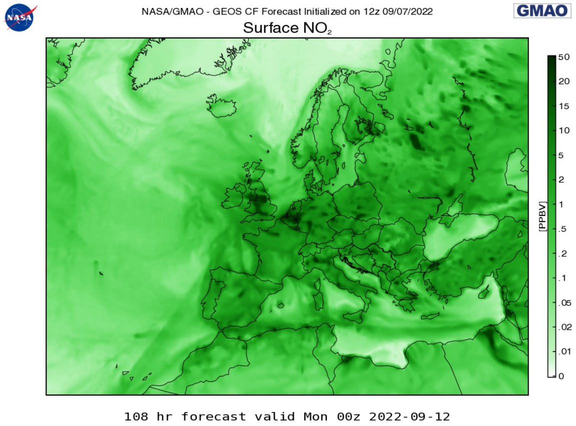
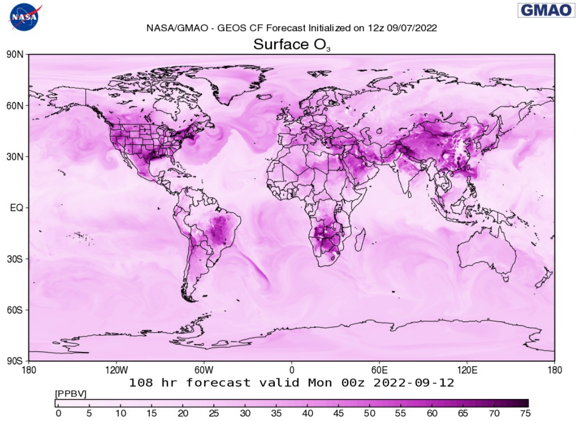
GEOS-CF output is available online in near real-time

Fluid is a mobile-friendly website

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







https://gmao.gsfc.nasa.gov/weather_prediction/GEOS-CF/

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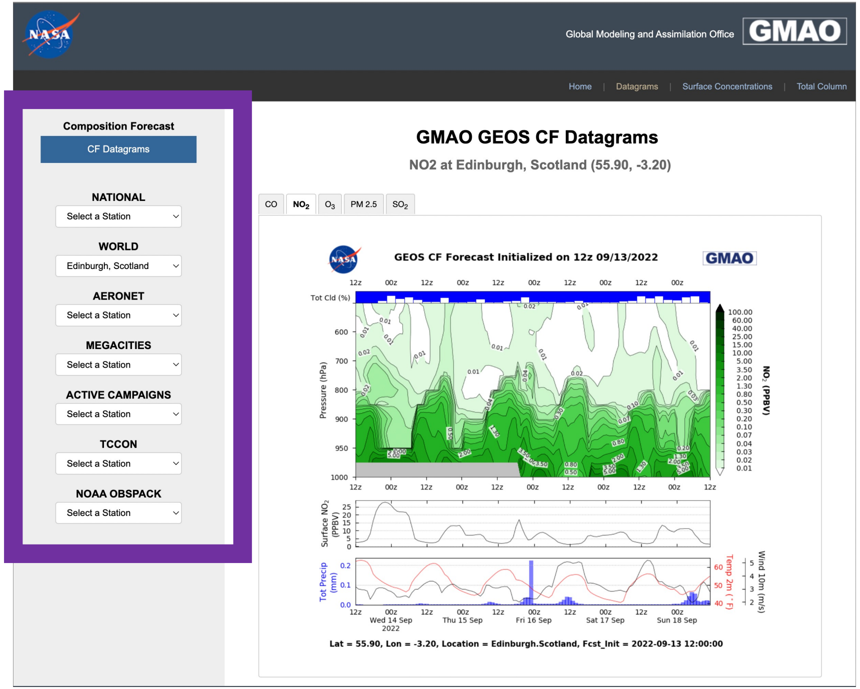

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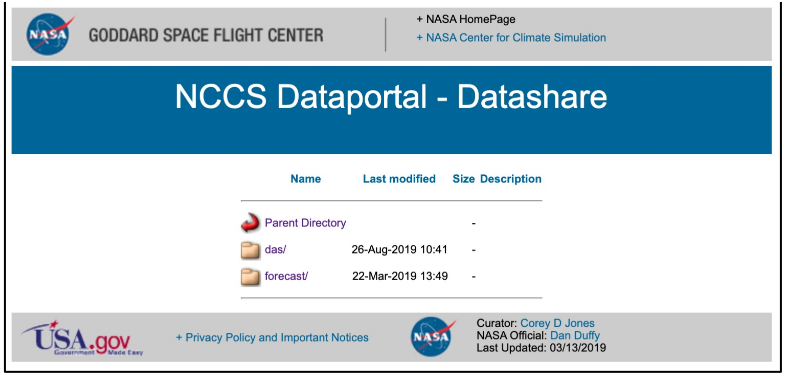

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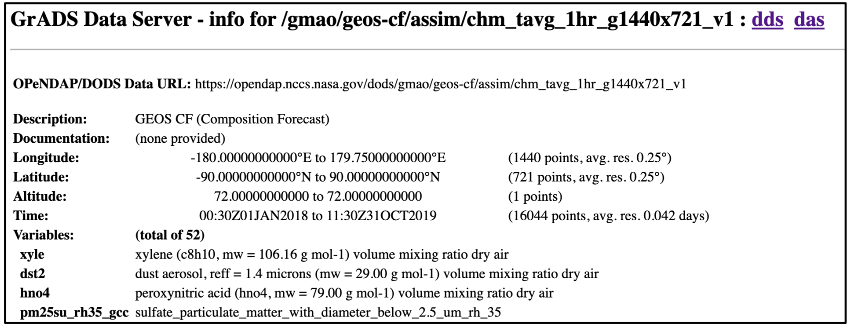

GrADS Data Server - info for /gmao/geos-cf/assim/chm_tavg_1hr_g1440x721_v1 : dds das

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

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pm25su_rh35_gcc	sulfate_particulate_matter_with_diameter_below_2.5_um_rh_35	

https://gmao.gsfc.nasa.gov/weather_prediction/GEOS-CF/
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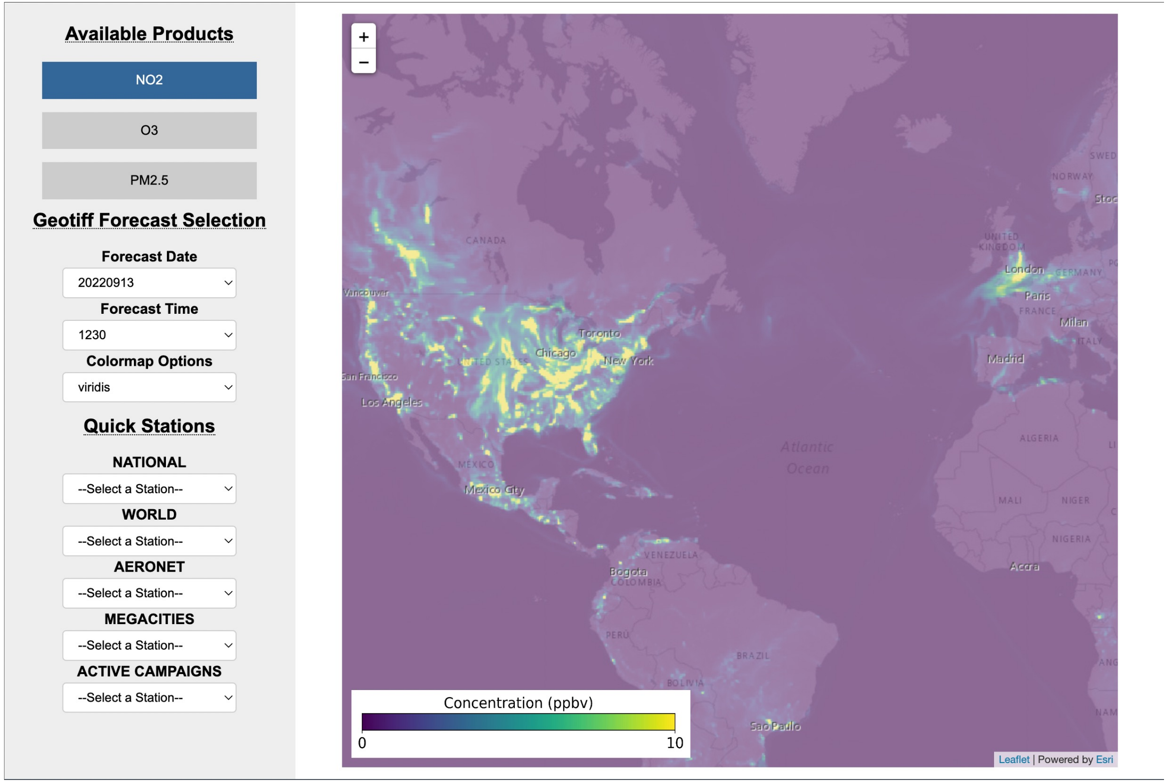
GEOS-CF output is available online in near real-time

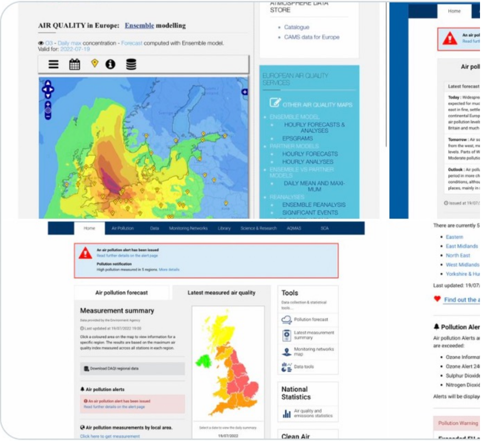
On-demand Forecast Imagery with cf_map tool

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



Clean Air in London
@CleanAirLondon

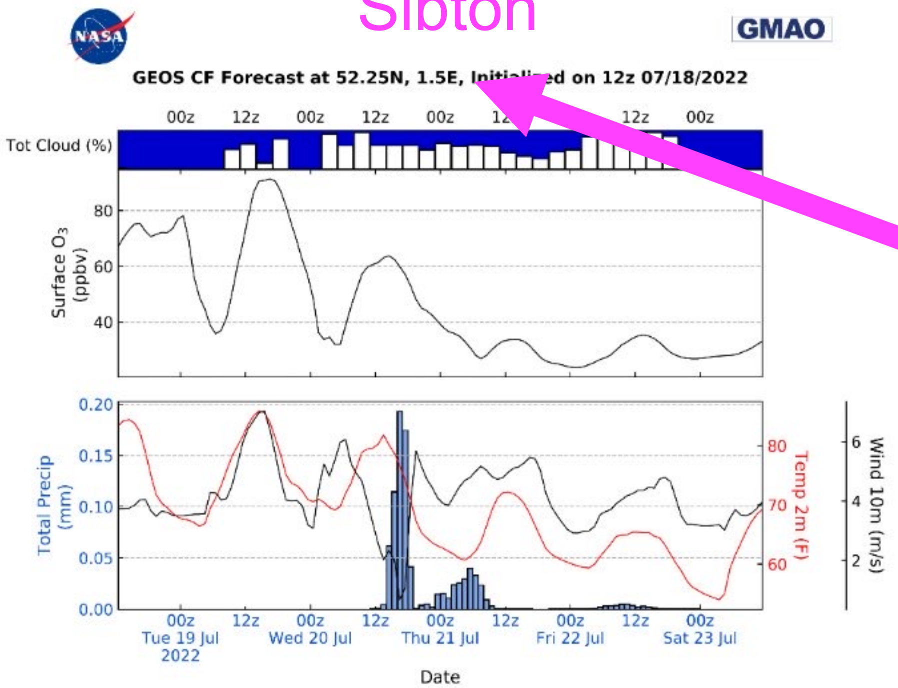
Towards the end of 7-long-days, w
to @LondonAir @MayorofLondon f
ozone #AirPollution alert and the i
@CopernicusECMWF @Copernicu
predicting the #PollutionBomb clip
England today. Thank you

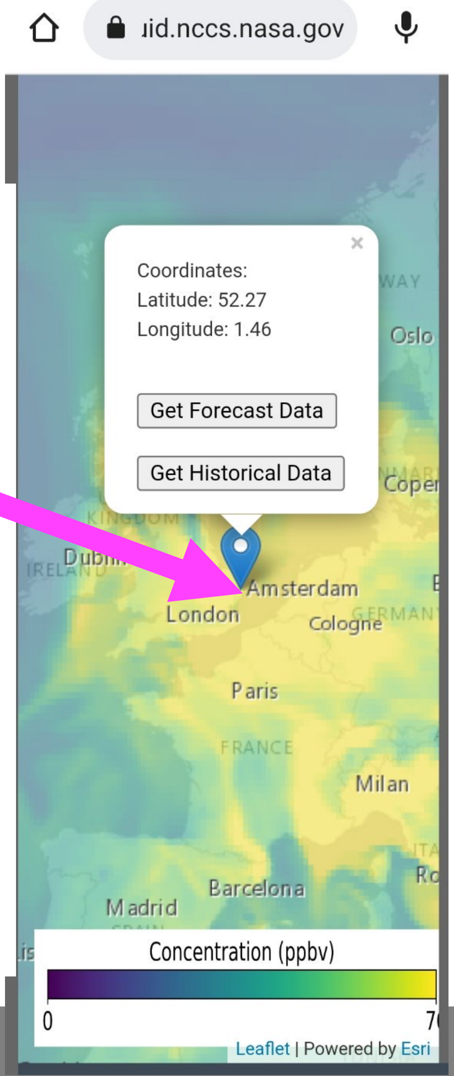


8:41 PM · Jul 19, 2022 · Twitter for iPad

4 Retweets **1** Quote Tweet **6** Likes

Sibton



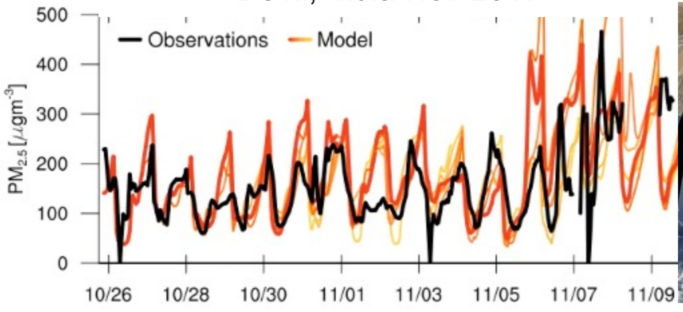


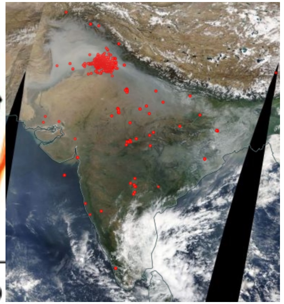
Near-real time updates from satellite data

- Biomass burning emissions from near-real time QFED v2.5
- GEOS-CF Stratospheric O_3 is weakly nudged to the GEOS FP assimilated O_3

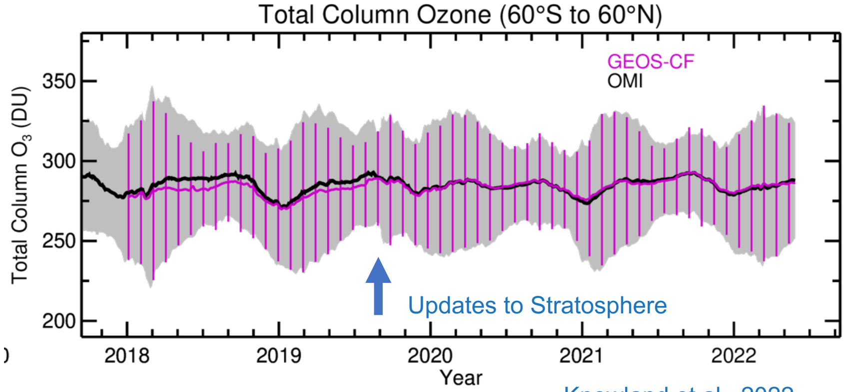
MODIS fires
Nov 01, 2017

Delhi, India Nov 2017





Observation
0 +1 +2 +3 +4 +5
GEOS-CF



Knowland et al., 2022, JAMES

Currently developing direct data assimilation of tropospheric constituents into GEOS

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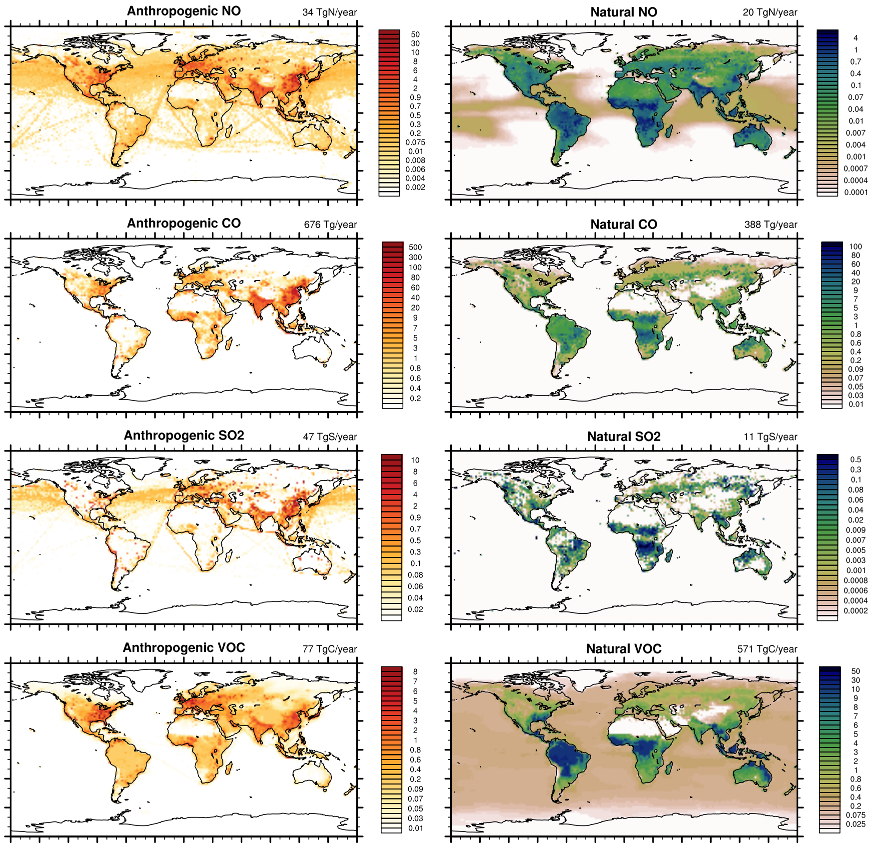
GEOS-Chem emissions



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

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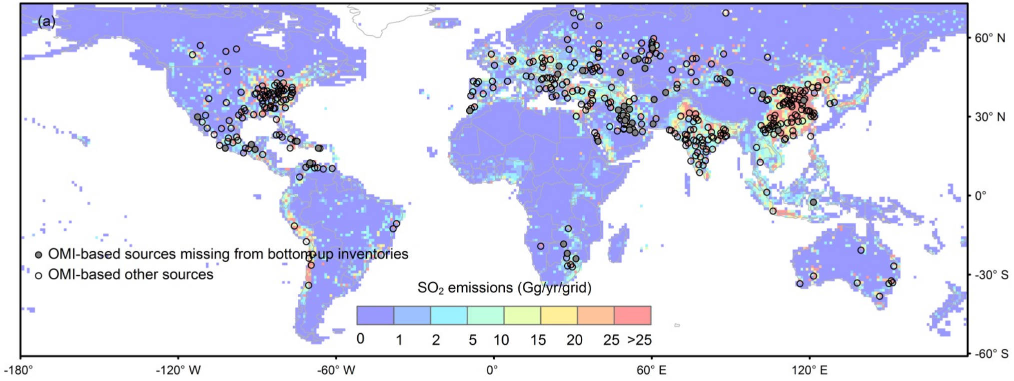
Year-to-year emissions changes

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

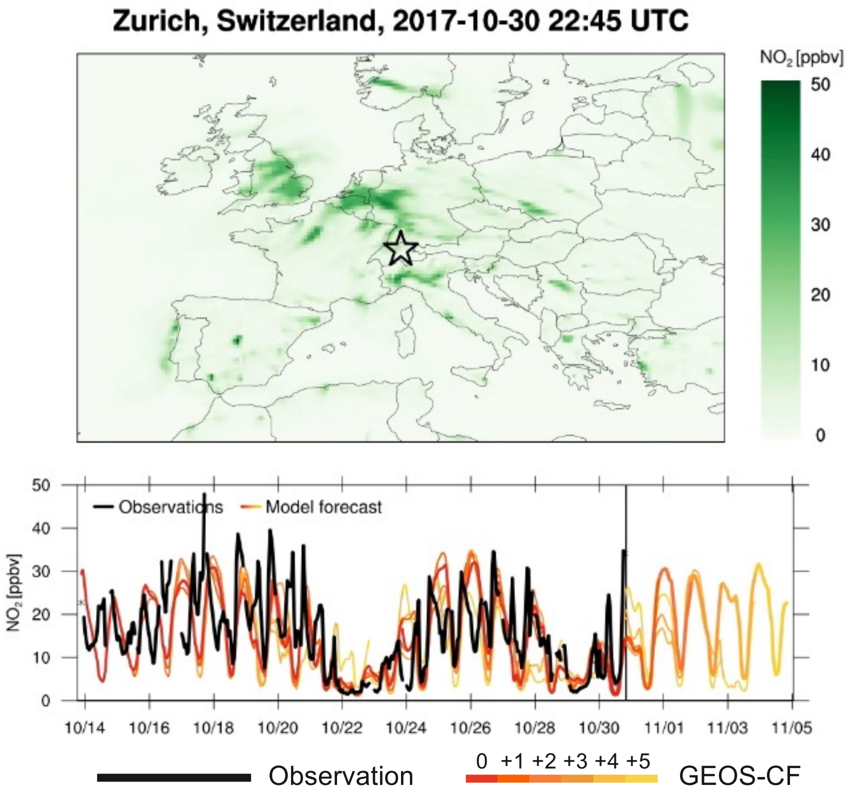
SO_2 emissions in the OMI-HTAP inventory



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

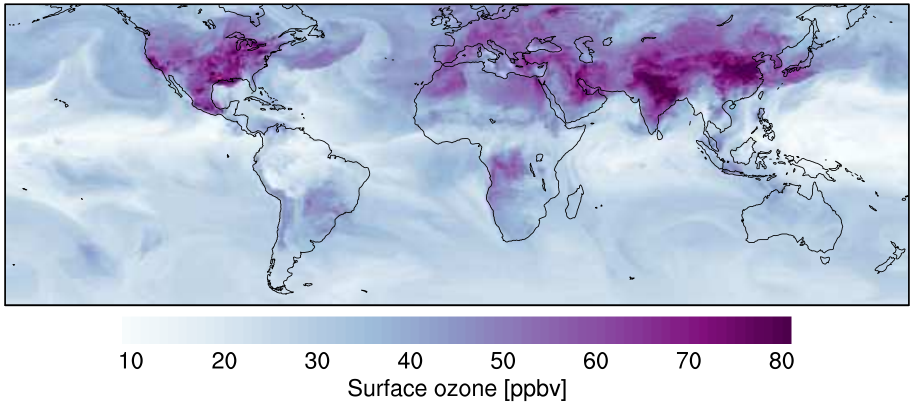


- ➢ Scale factors applied to emissions for diurnal and weekly variations
- ➢ These are clearly beneficial for surface NO_2 analyses and forecasts
- ➢ Shown for Zurich - weather and diurnal/weekly signals are prominent
- ➢ Surface observations obtained through emerging connection to OpenAQ (openaq.org)

Air quality and health applications

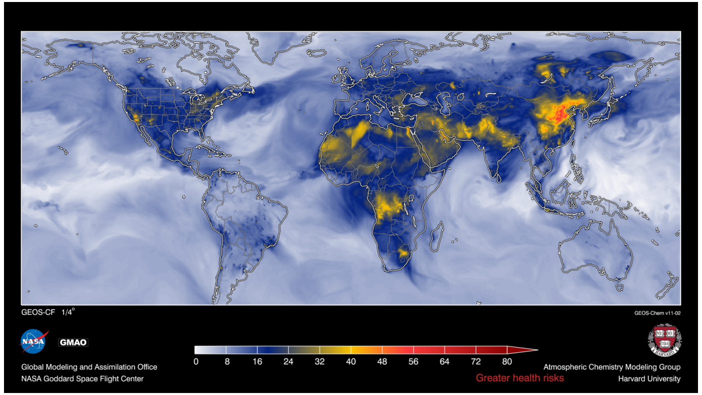
- **How good is the model?**

2019-06-09



Optimize model predictions

- **How bad is the air pollution?**



Global exposure assessment

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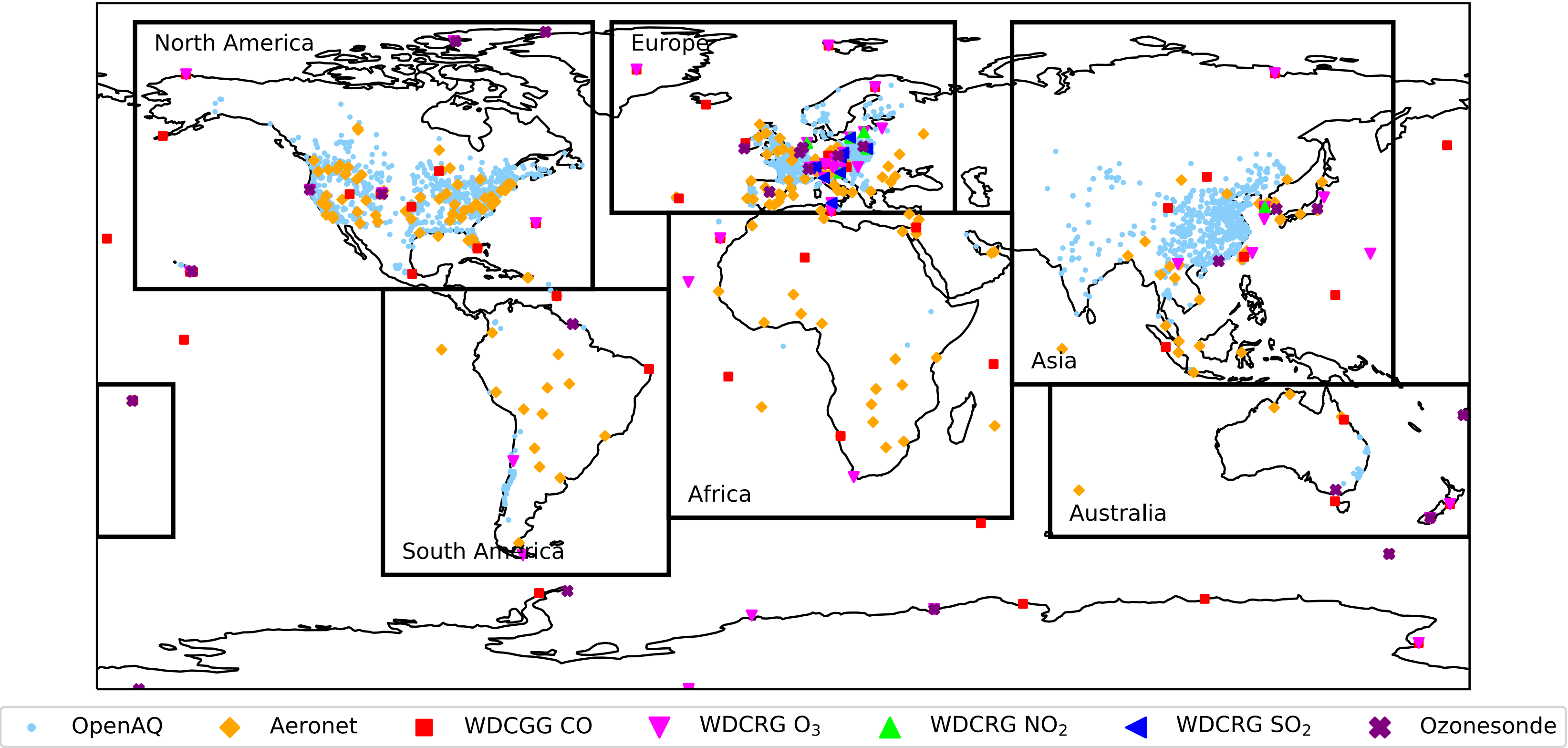
Observations for evaluation



Keller et al., 2021 JAMES

https://gmao.gsfc.nasa.gov/weather_prediction/GEOS-CF/

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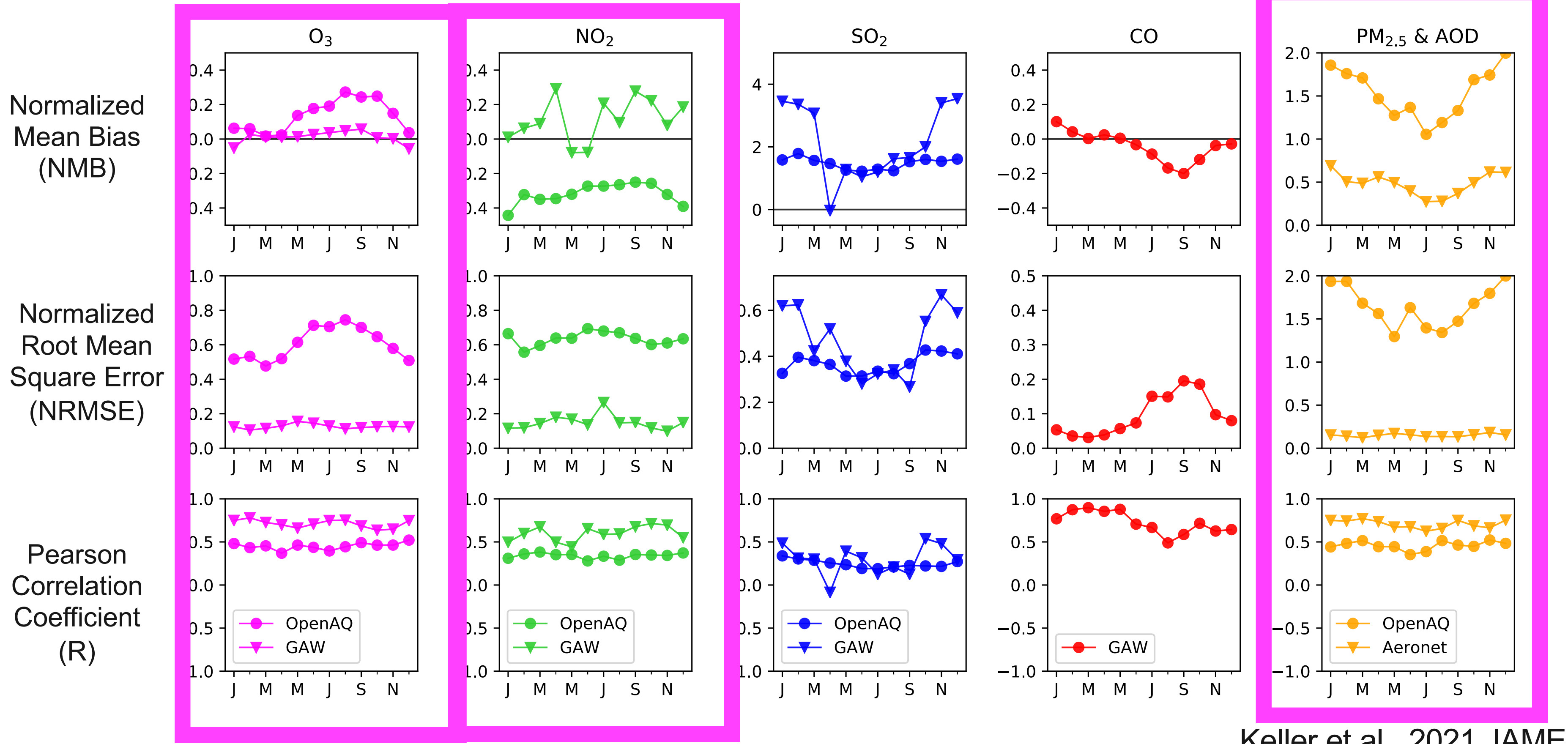
Global surface comparisons - monthly



Keller et al., 2021 JAMES

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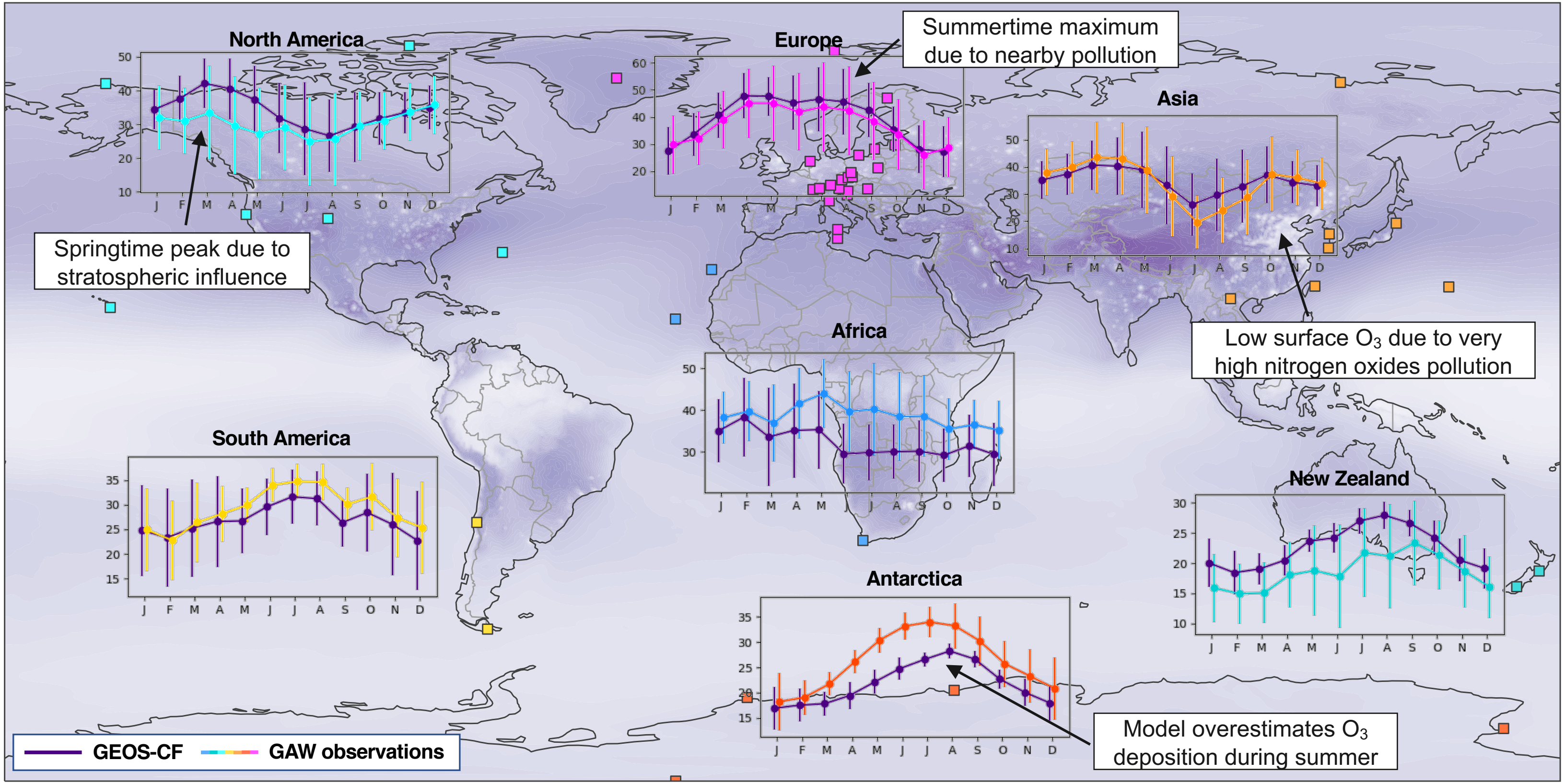
GEOS-CF surface ozone compares well against background observations from the Global Atmospheric Watch (GAW) network



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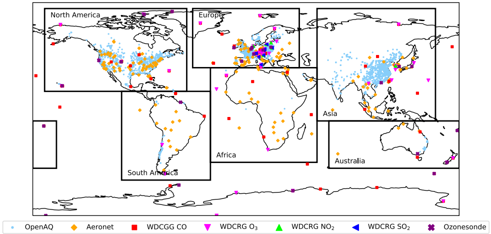
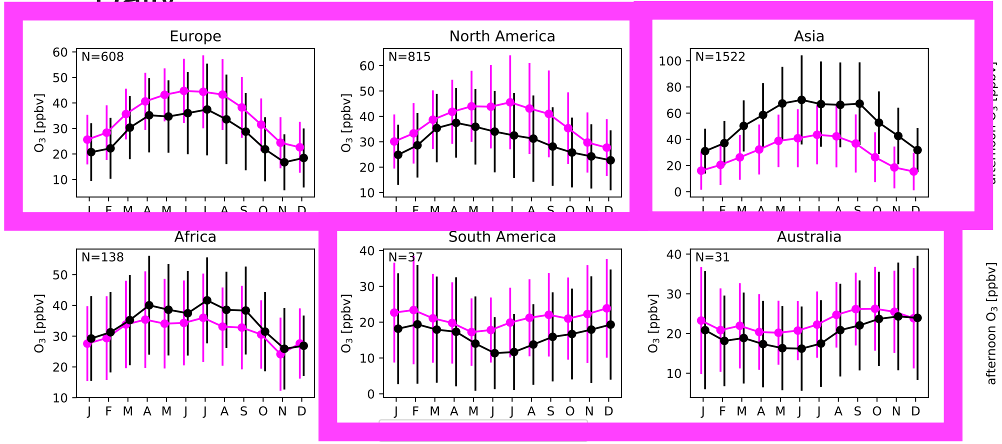
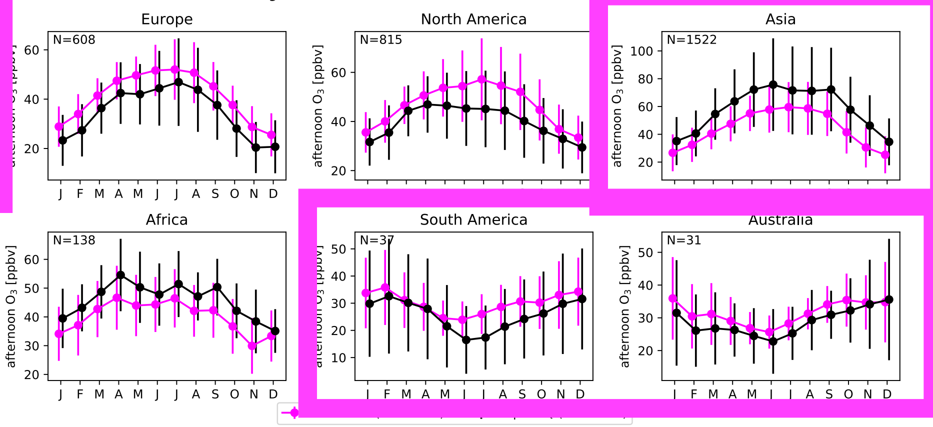
Surface O_3 (OpenAQ sites only)



Daily



Afternoon only



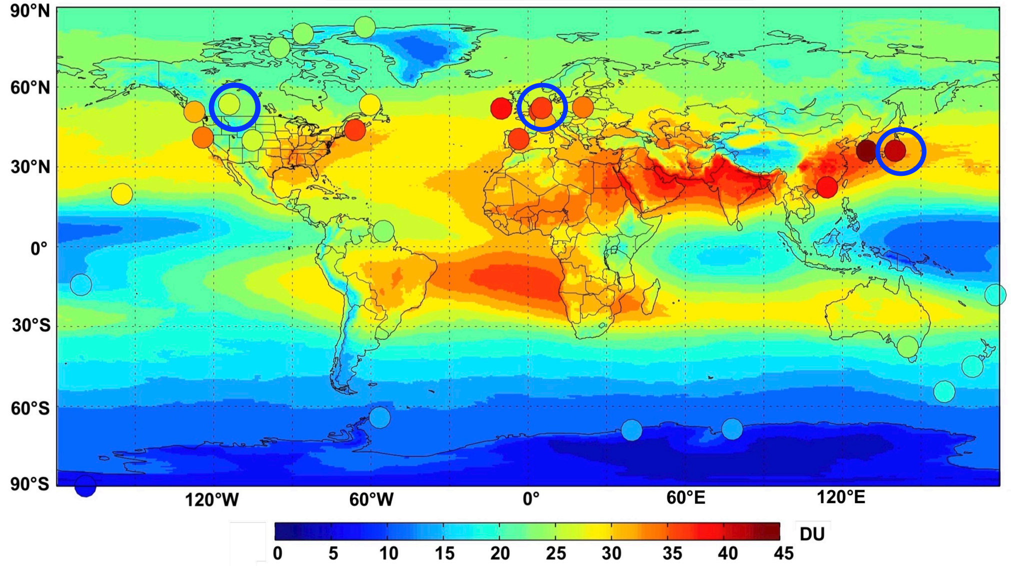
- GEOS-CF captures the overall seasonal cycle in the six regions, but generally overestimates in Europe, North & South America and Australia, while underestimating in Asia and Africa.
- In polluted regions, such as Asia, the bias is reduced when focusing on peak photochemical production period. GEOS-CF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

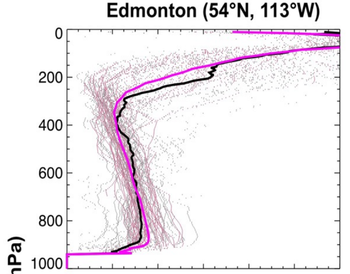
■ Observations ■ GEOS-CF

Keller et al., 2021 JAMES

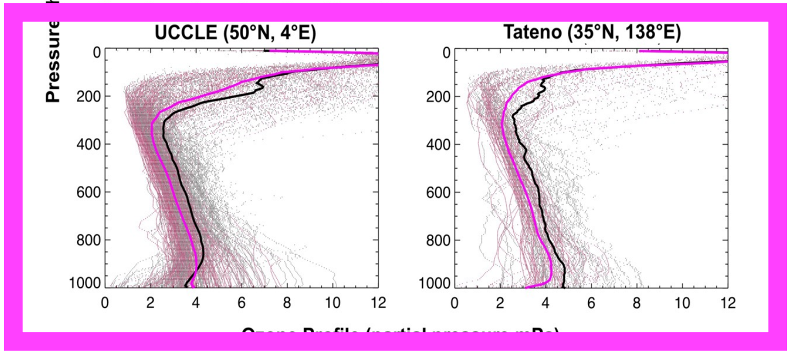
GEOS-CF captures the observed ozone spatial distribution and profile shapes shown by ozonesondes

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

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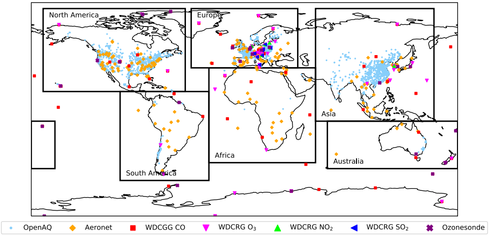
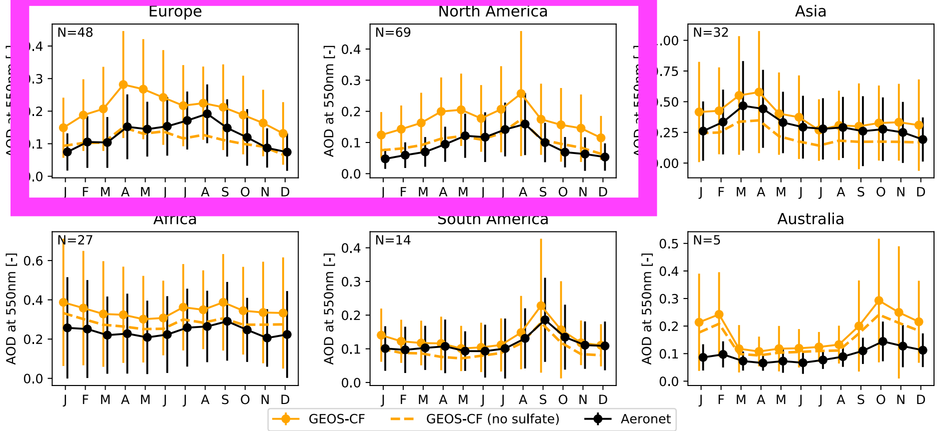
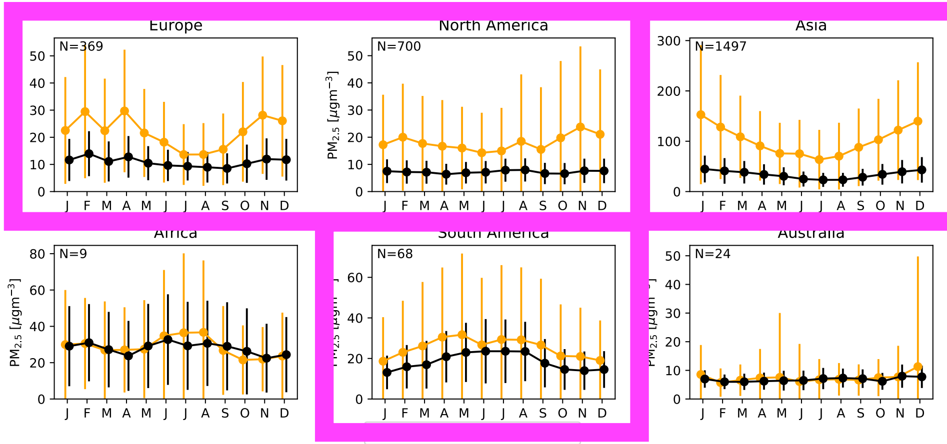
GEOS-CF generally overestimates aerosols (AOD and $PM_{2.5}$)



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

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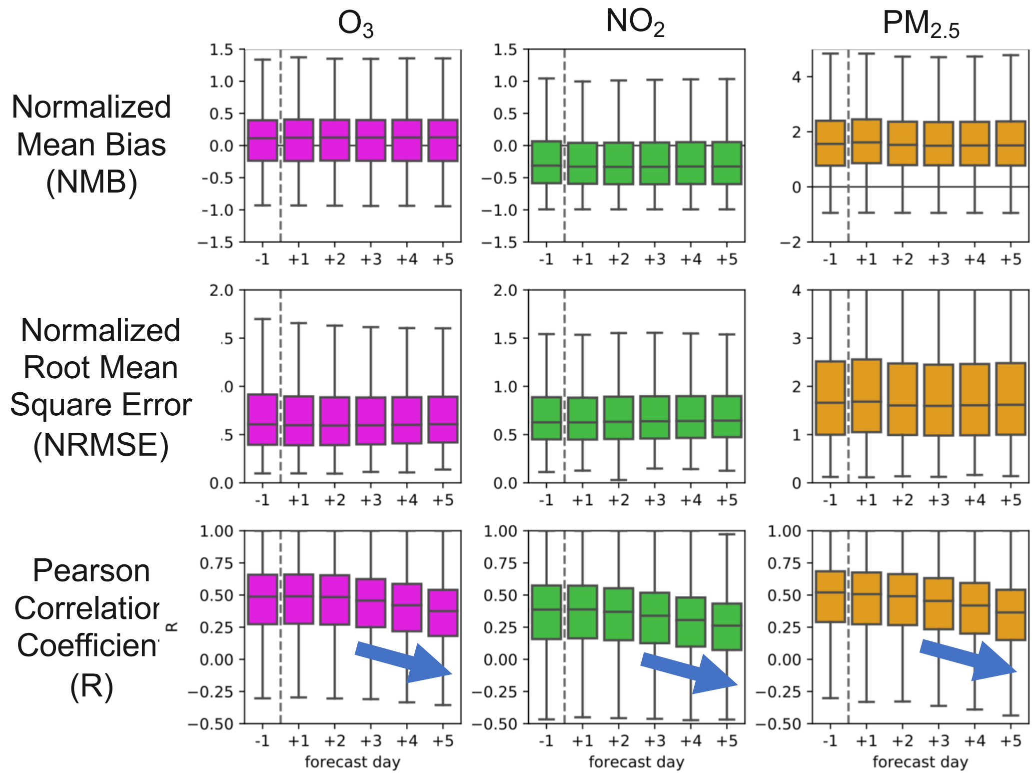
GEOS CF Forecast skill (GAW and OpenAQ)



- 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

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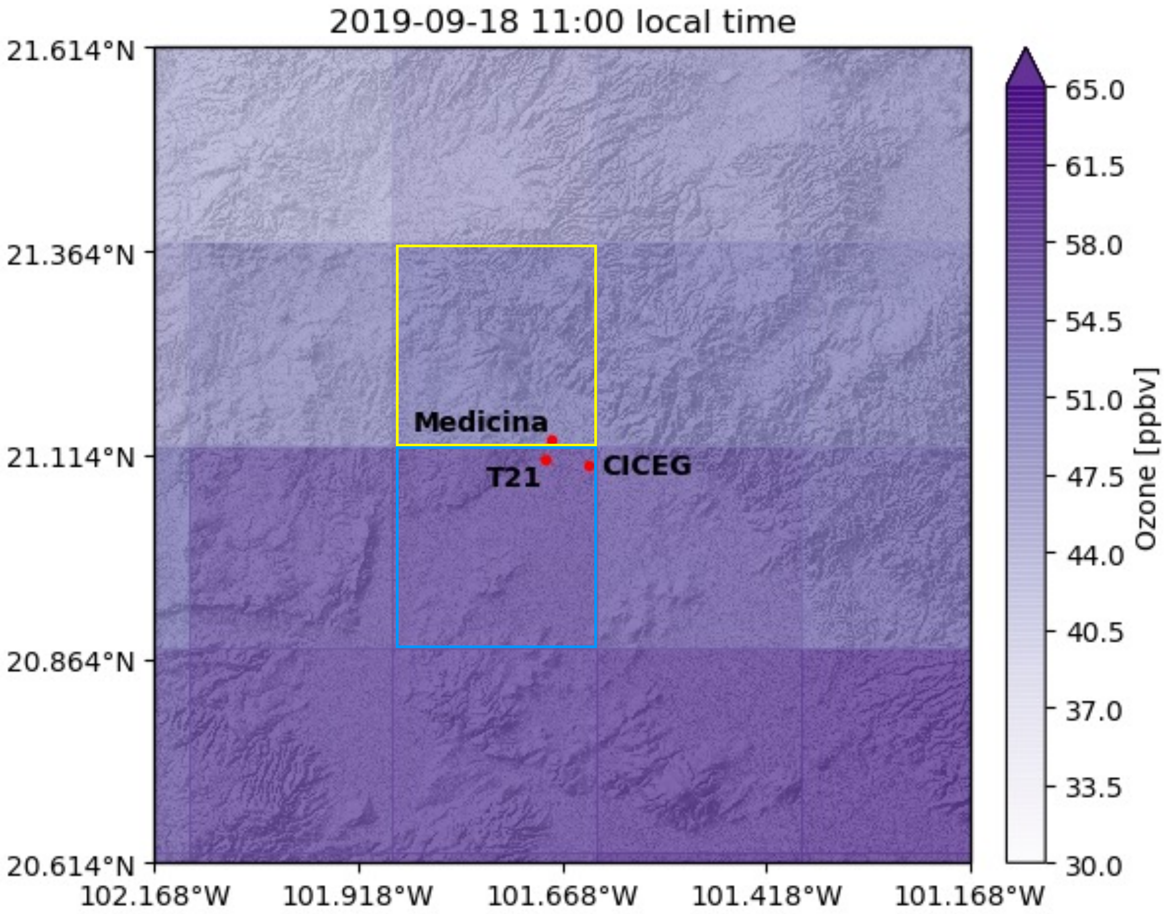

Improve local forecasts using statistical bias correction

3 monitoring stations in Leon, Mexico

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

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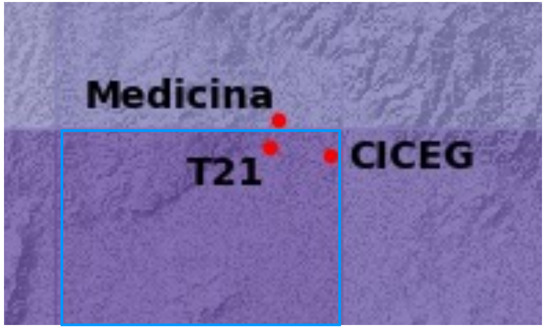
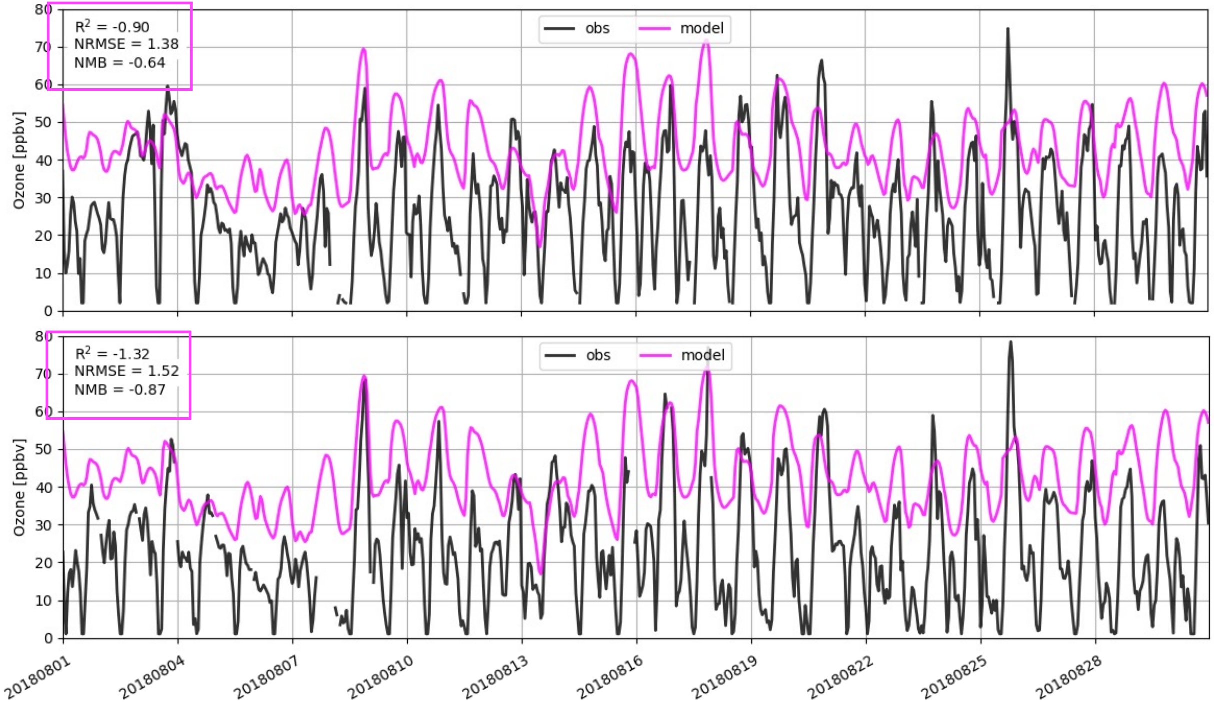
Improve local forecasts using statistical bias correction



Two observation sites in the same grid box

- ➢ GEOS-CF generally over-estimates



Observations Model

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

Inputs

- Meteorology (10 vars)
- Chemistry (42 vars)
- ~~Emissions~~ (not used)
- Calendar (4 vars)

→ ML →

Output

- Local concentration adjustment

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

Keller et al., 2021 ACP

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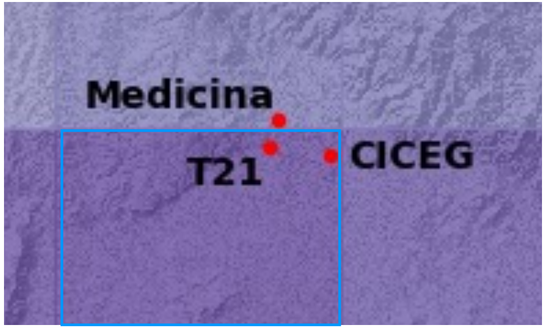
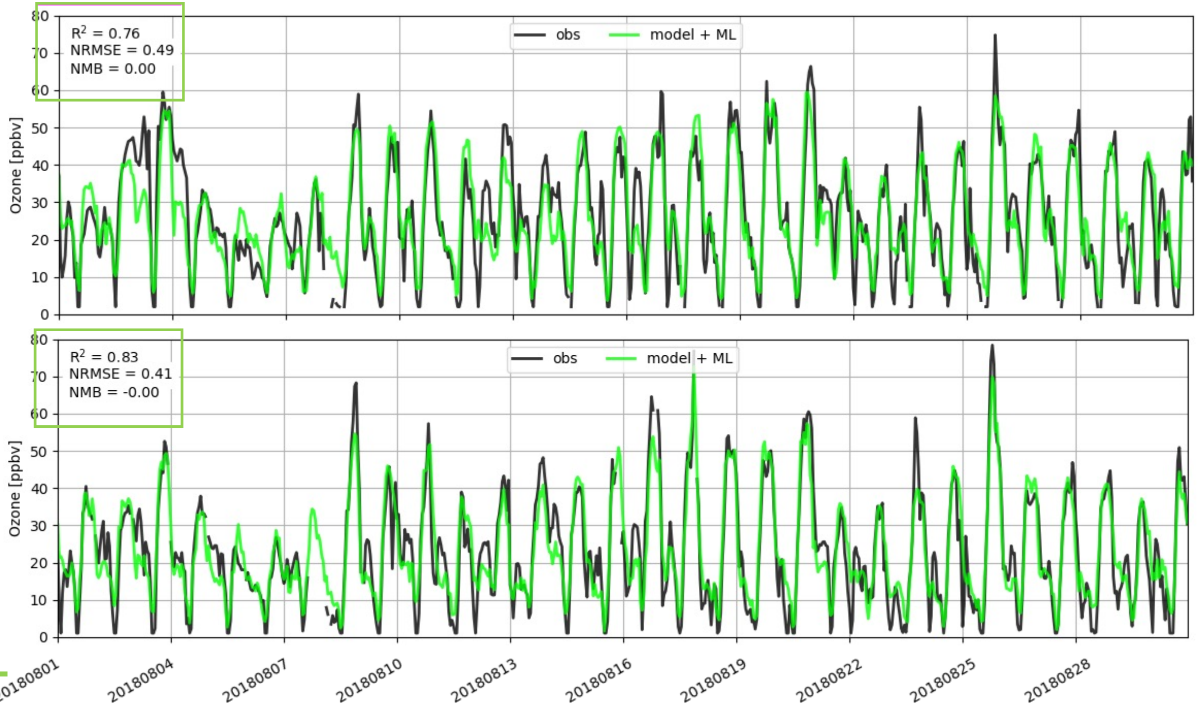
Improve local forecasts using statistical bias correction



Two observation sites in the same grid box

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



Observations Model + ML

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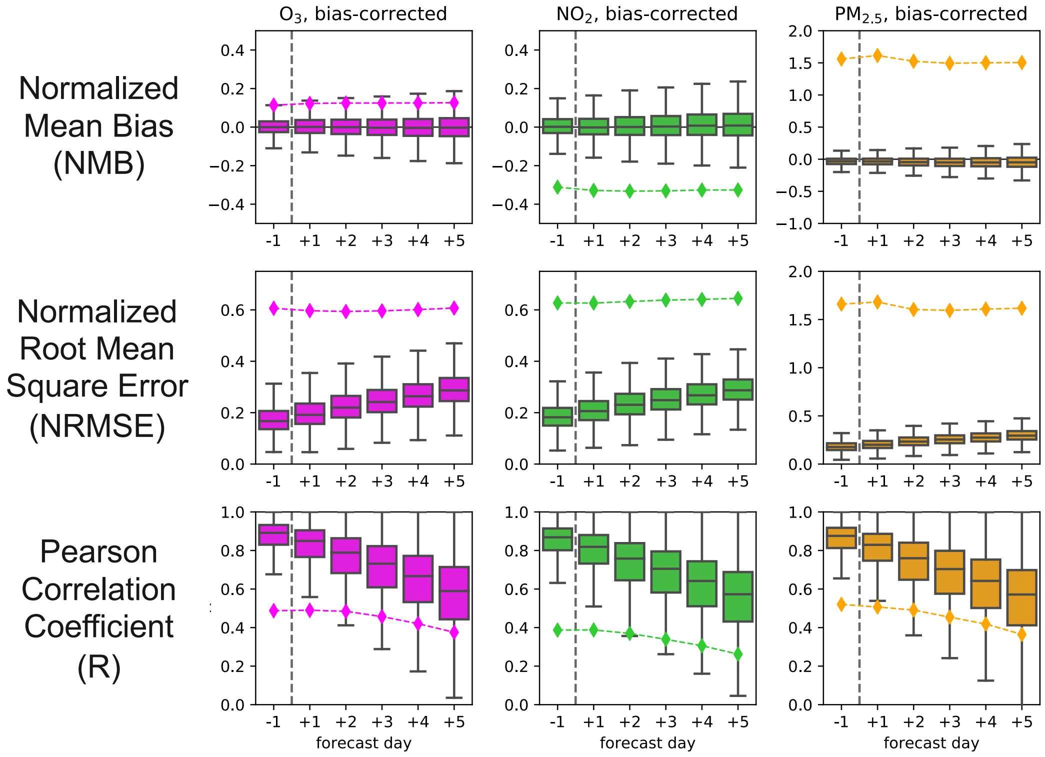
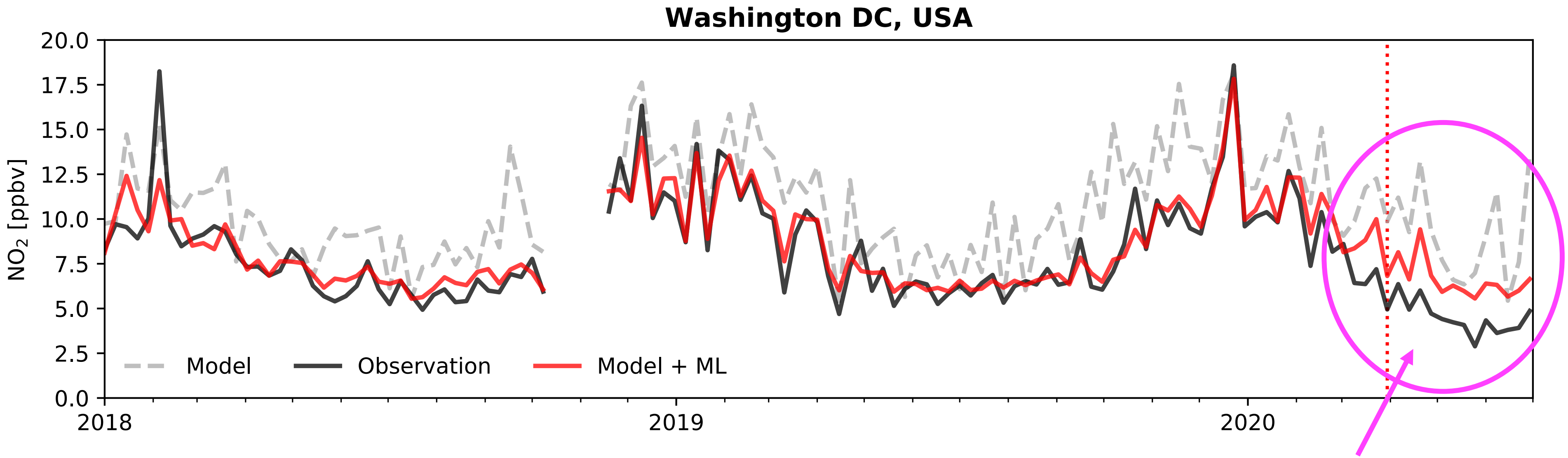
GEOS CF Forecast skill



- ✓ 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

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

Inputs

- Meteorology (9 vars)
- Chemistry (51 vars)
- Emissions (21 vars)
- Calendar (4 vars)

ML →

Output

bias = obs - model

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

Keller et al., 2021 ACP

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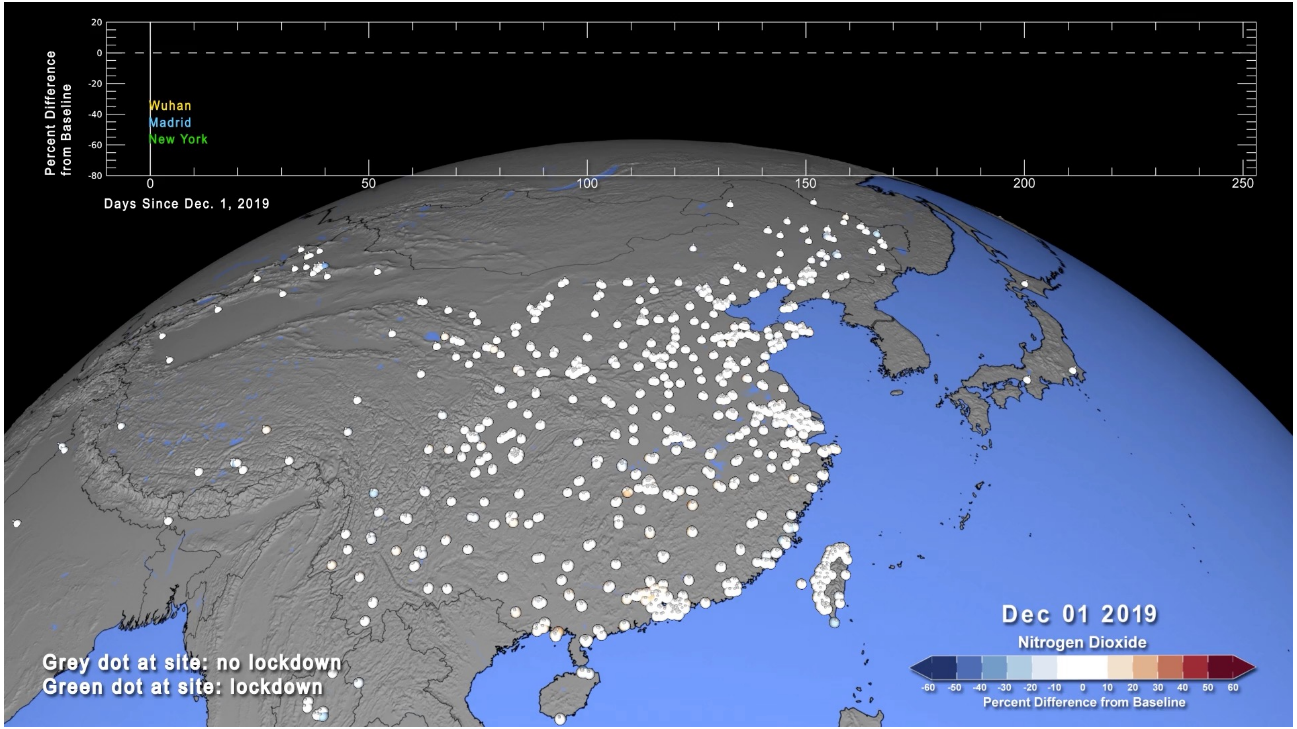
Apply analysis to 5756 sites worldwide



openaq

European Environment Agency

RIO PREFEITURA

QUITO ALCALDÍA

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

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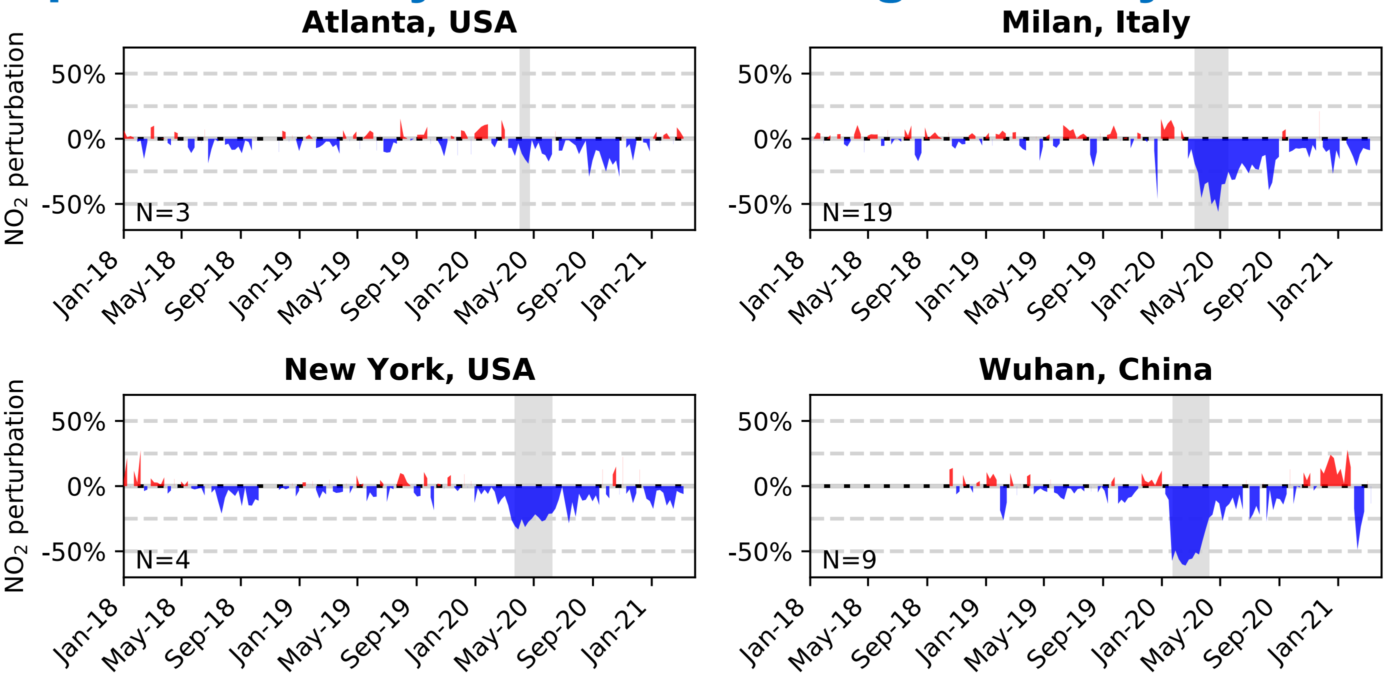
Observation-model differences indicate city-wide NO_2 declines of up to 50% early on and a halting recovery since then



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

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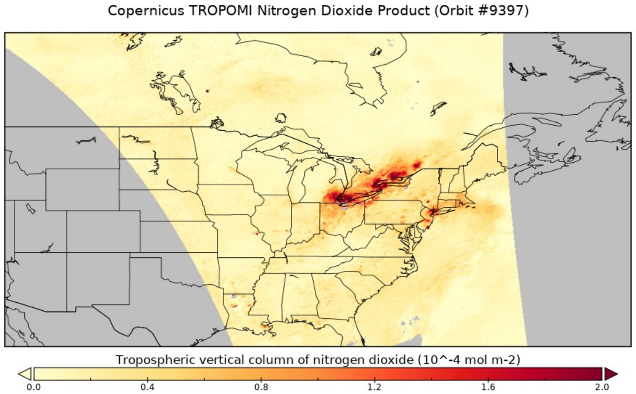
Multiple Sources of Air Quality Data

regulatory monitoring
+ accurate
- expensive
? representativity

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



satellite retrievals
+ global coverage
- low time resolution
- column-integrated

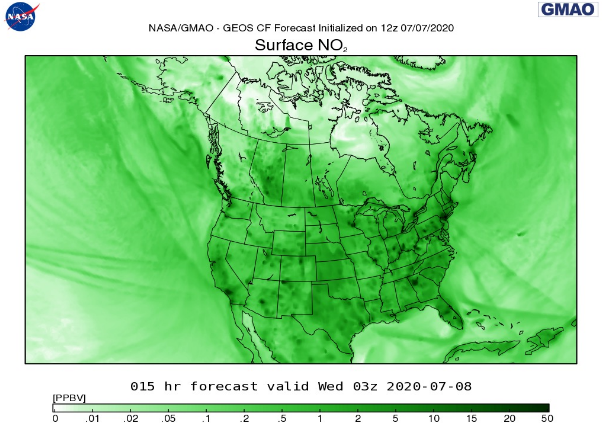
good coverage and frequency, but need to be related to the ground-level situation

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



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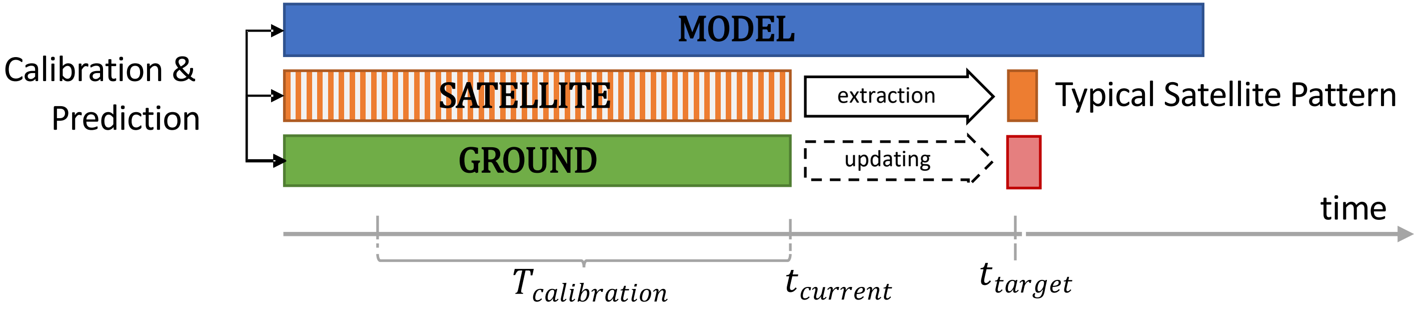
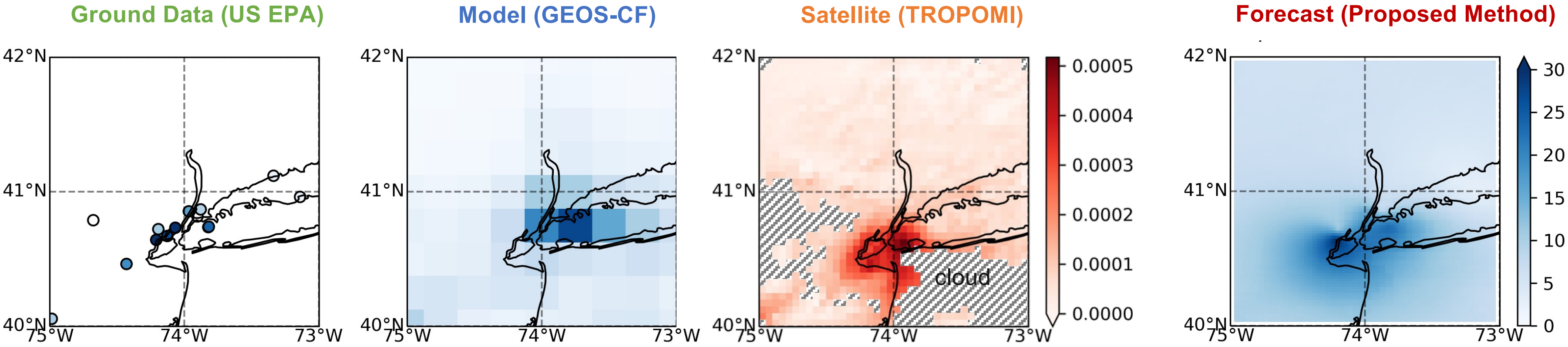
Data Fusion method for city-scale AQ forecasts





Malings et al., 2021 ESS

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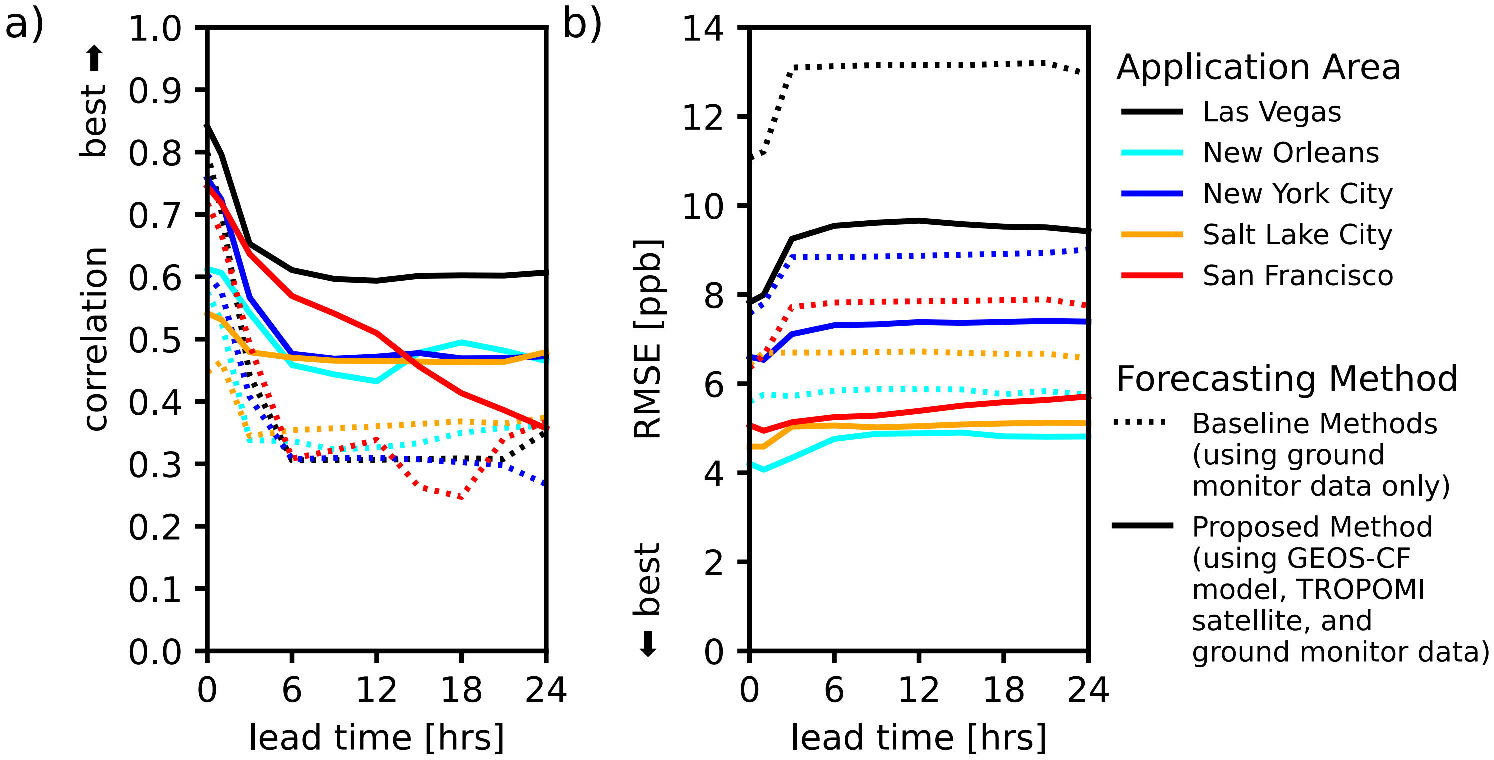
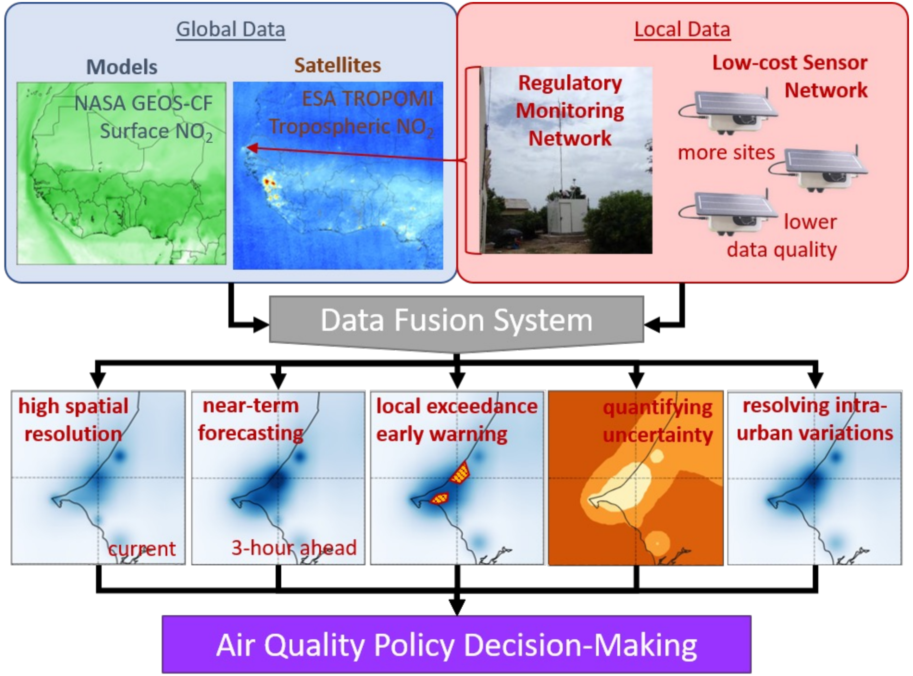
Data Fusion method for city-scale AQ forecasts



Malings et al., 2021 ESS

Ongoing & Future Work



NASA Earth Science Applications:
Health and Air Quality

Supporting local government public health and air quality decision-making with a sub-city scale air quality forecasting system from data fusion of models, satellite, in situ measurements, and low-cost sensors.

Cities: Dakar, **Senegal**
Rio de Janeiro, **Brazil**
Charleston, Denver, Boulder, Gulfport, Portland, **USA**

Co-Investigators: Sonoma Technology, Inc.

Collaborators: US EPA
UN Environment Programme
Clarity Movement, Co.
Columbia University, WUSTL

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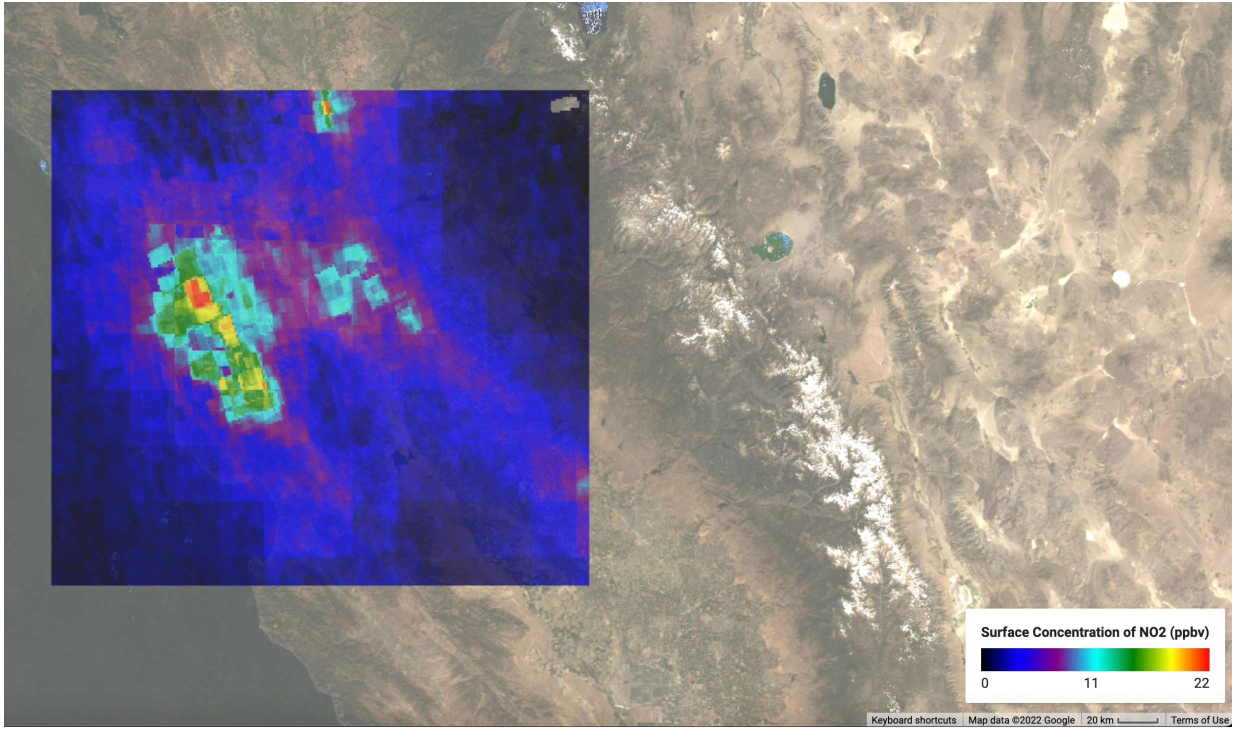
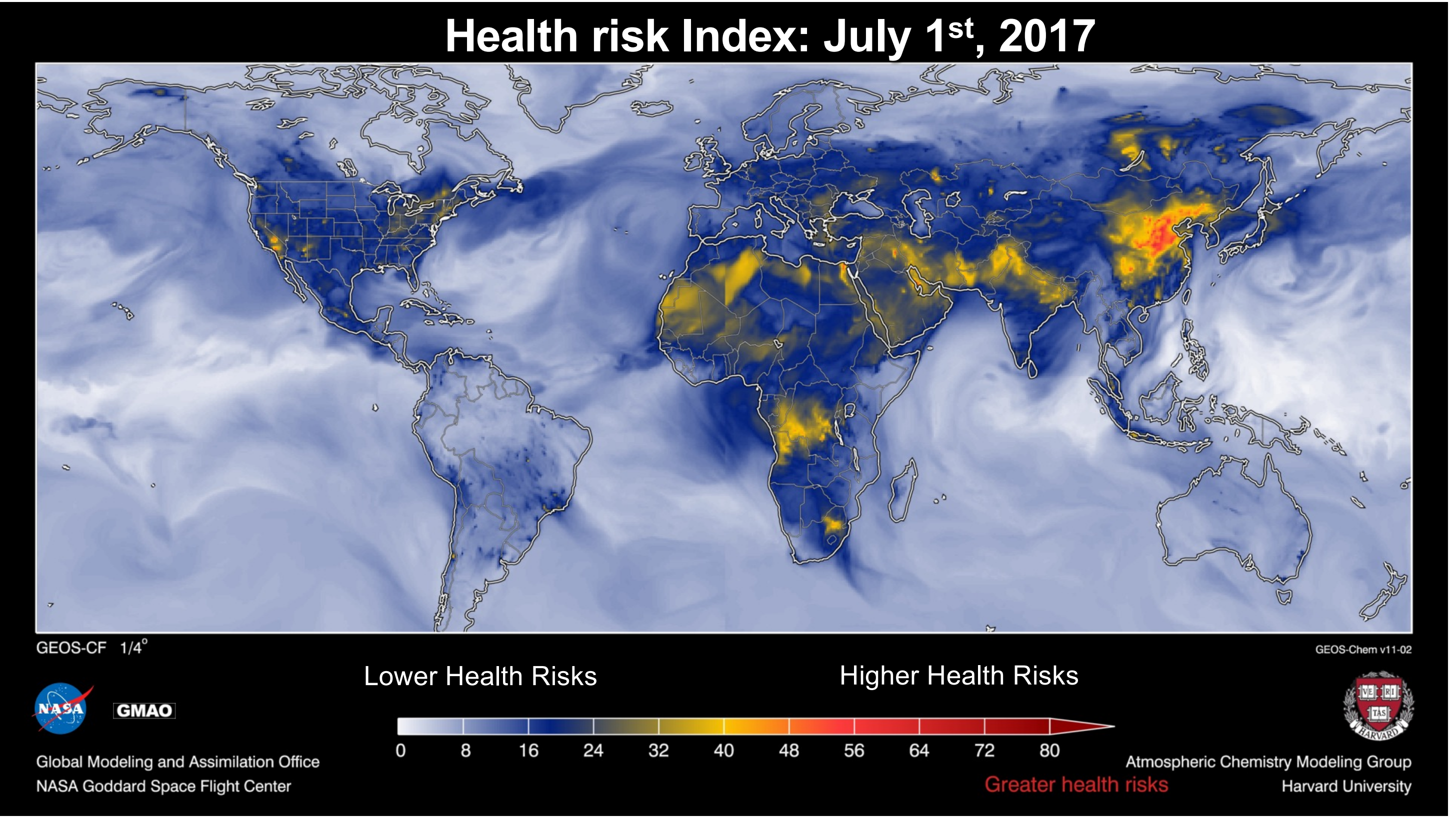
Work started on GEE with GEOS-CF to downscale NO_2



Figures courtesy of Callum Wayman

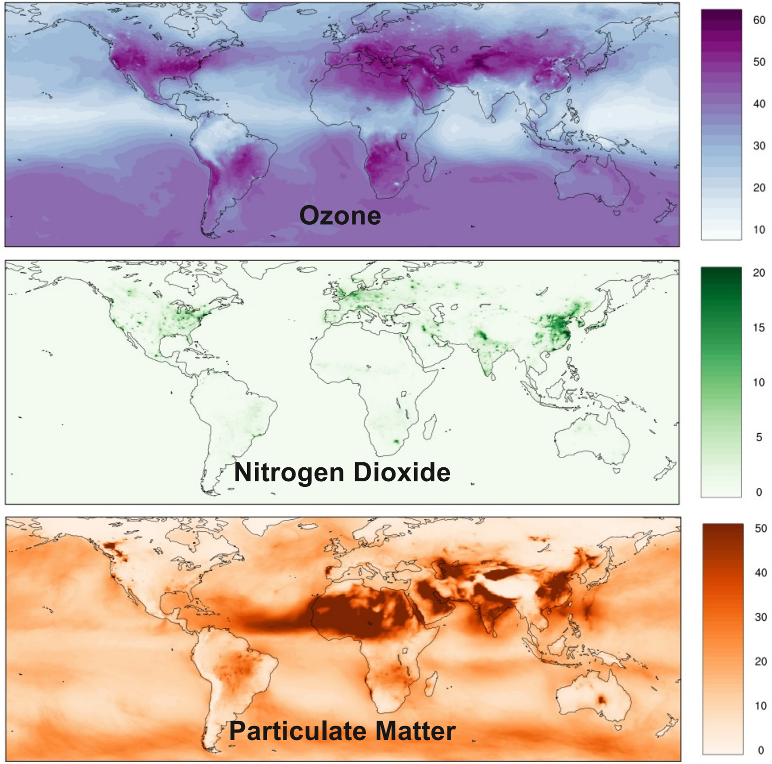
Forecast Application: Multi-pollutant Health Risk Index



Multi-pollutant index, developed by Kevin Cromar and NYU team (Gladson et al. *in prep*)

- Maximum daily 8-hour average (MDA8) O_3
- 24-hour-average NO_2
- 24-hour-average $PM_{2.5}$

Forecast Application: Multi-pollutant Health Risk Index



- O_3 influences Background levels
- NO_2 is Short-lived
- Extreme gradients
- $PM_{2.5}$ driver of spatial gradients

https://gmao.gsfc.nasa.gov/weather_prediction/GEOS-CF/

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WMO Air Quality and Climate Bulletin No. 2 - September 2022

Growing air pollution hazards from wildfires

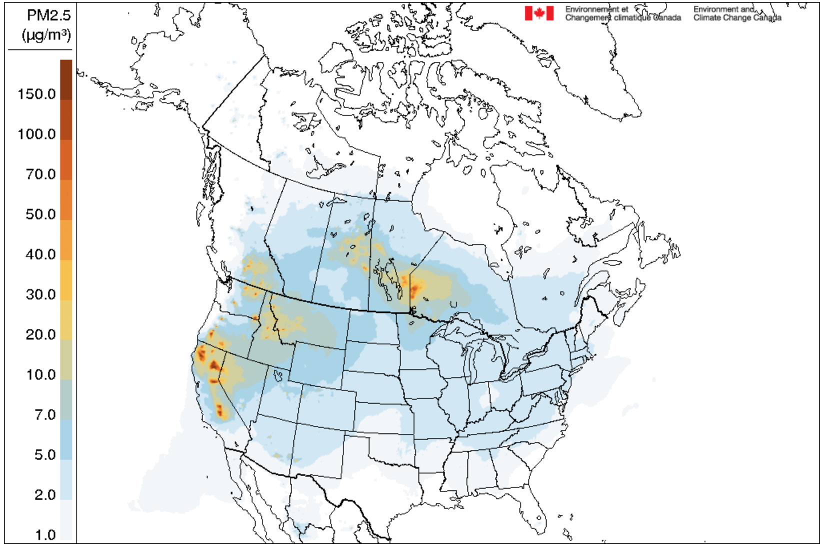
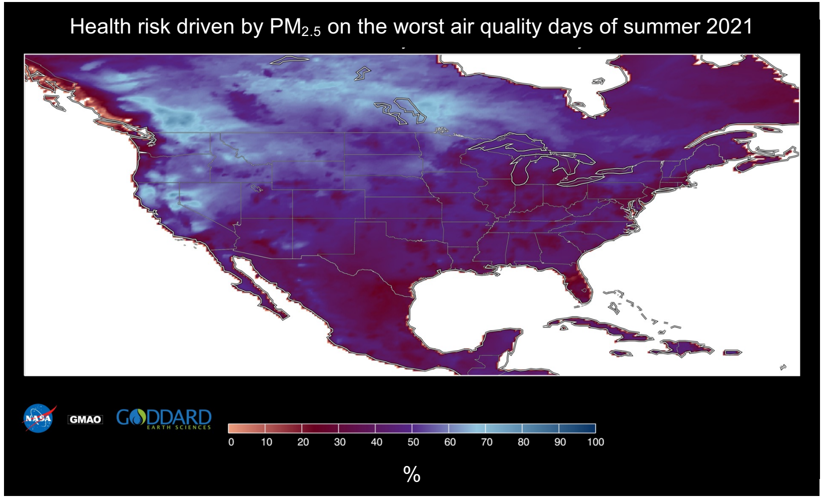


Figure 2: Seasonal (May-Sept mean) fire-$PM_{2.5}$ contribution to total forecasted surface $PM_{2.5}$ concentrations (µg/m³) for 2021 over North America.



The extreme $PM_{2.5}$ concentrations are largely driven by wildfire emissions and are primarily responsible for the highest adverse health risks in parts of Western and Northern North America.

https://public.wmo.int/en/our-mandate/focus-areas/environment/air_quality/wmo-air-quality-and-climate-bulletin-no.2

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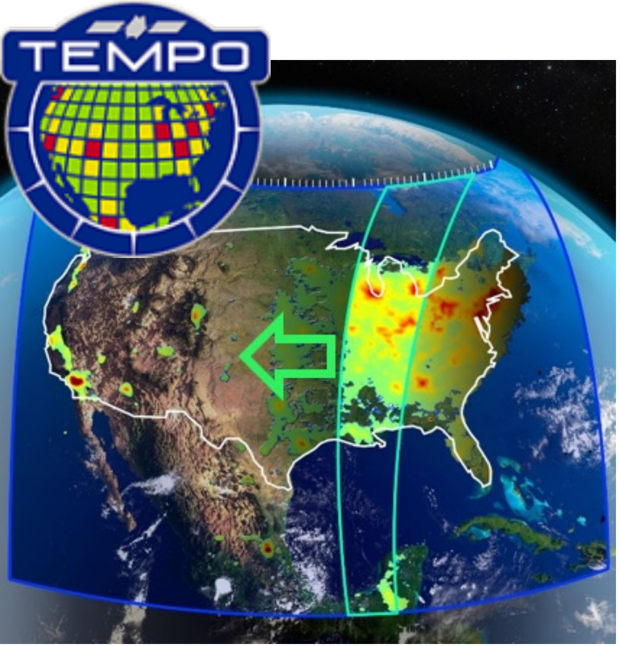
Daily *atmospheric composition* forecast

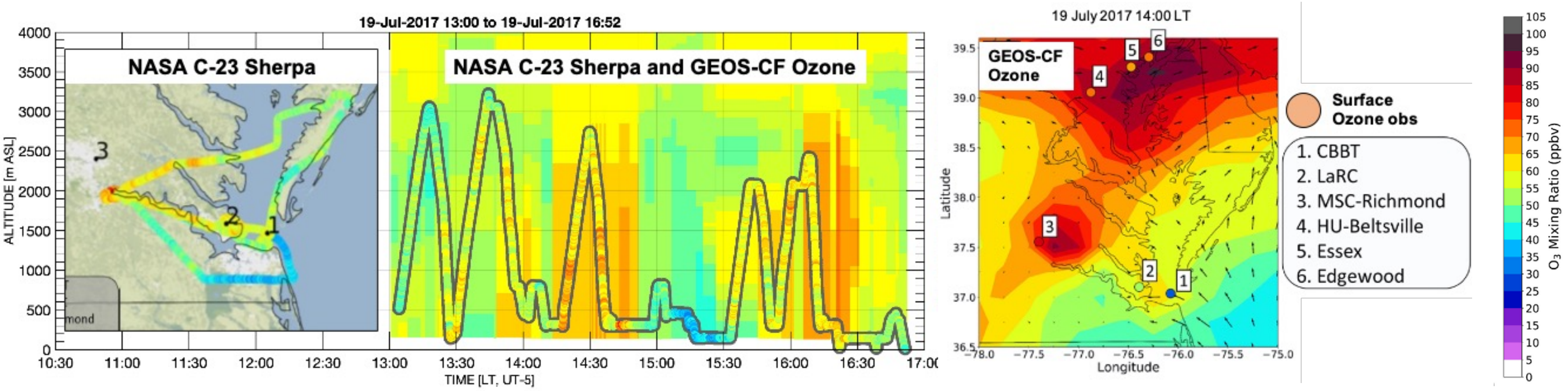
GEOS - CF

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



GEOS-CF evaluation with NASA’s OWLETS campaign observations



Dacic et al. (2020) used the GEOS-CF simulated ozone to put the OWLETS observations in ‘the big picture’, using the combined meteorology and chemistry to represent the synoptic conditions that lead to the observed ozone exceedances at surface observation sites.

From where the model and the observations diverged, we learned where there are missing local marine emission sources and errors in the boundary layer chemical and dynamical processes in the model over the Chesapeake Bay.

Dacic, N. et al., 2020, Atmos. Environ. “Evaluation of NASA’s high-resolution global composition simulations: Understanding a pollution event in the Chesapeake Bay during the summer 2017 OWLETS campaign”

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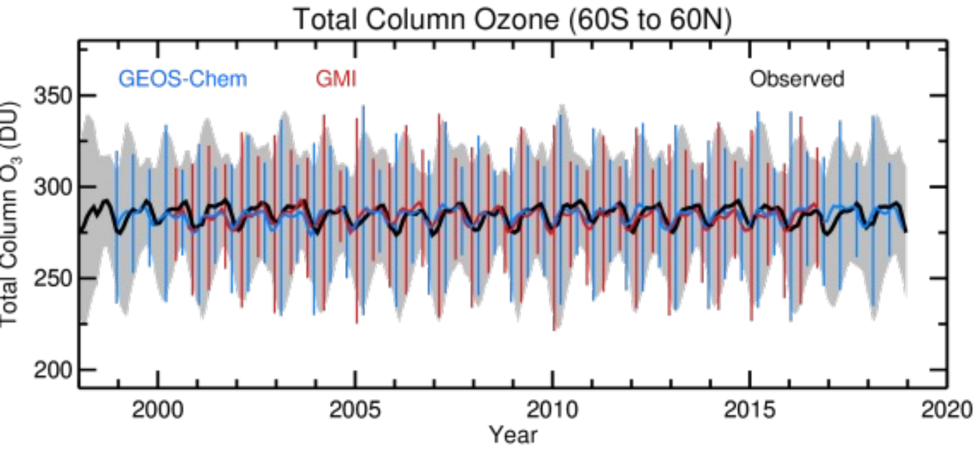
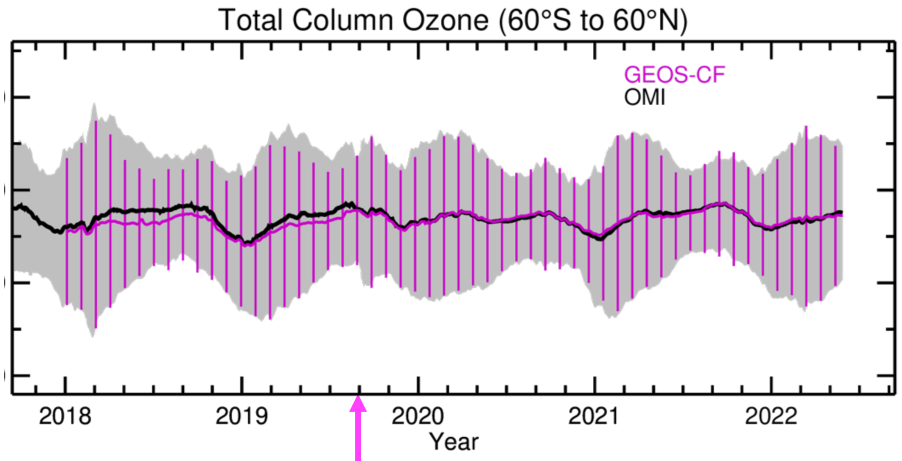
Stratospheric Composition Evaluation



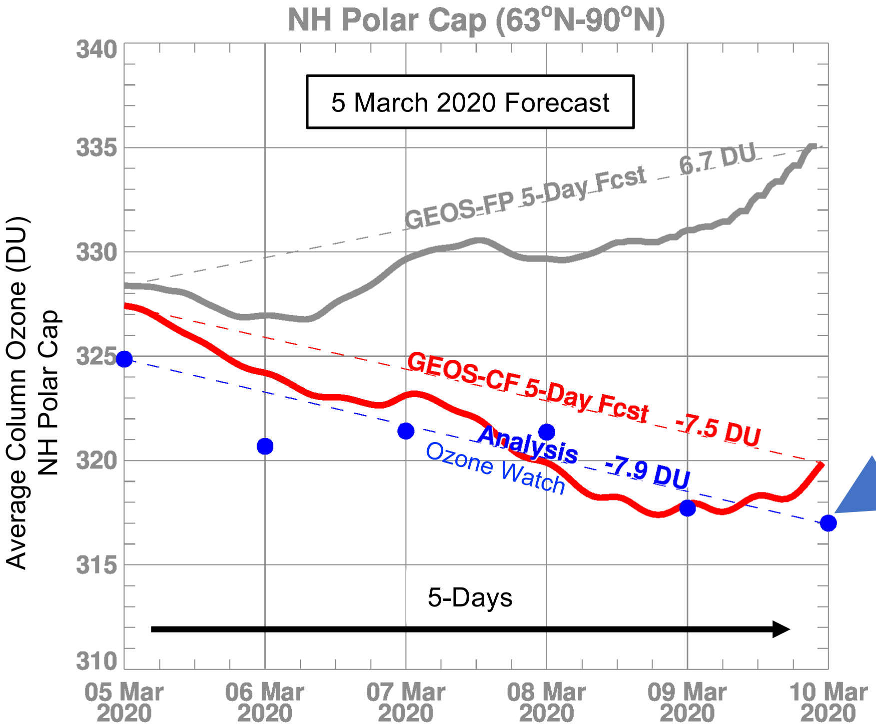


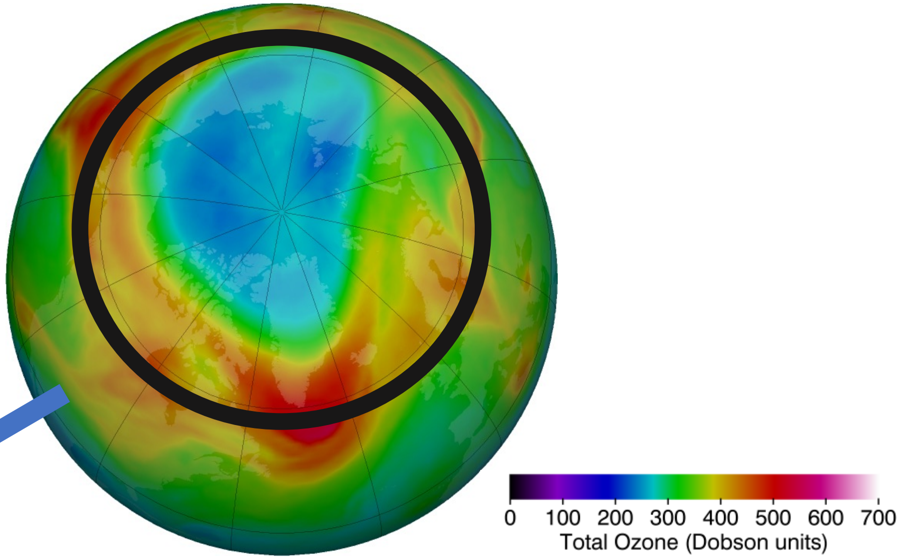
GEOS-Chem non-polar TCO agrees well with GMI simulated TCO and the observable TCO range

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

GEOS-CF has realistic stratospheric ozone forecasts





March 10, 2020: Ozonewatch.gsfc.nasa.gov

The GEOS-CF with stratospheric chemistry is responsible for the improved ozone forecasts adding realistic near-real-time stratospheric ozone forecasting capability to the NASA GMAO.

Knowland et al., 2022, JAMES

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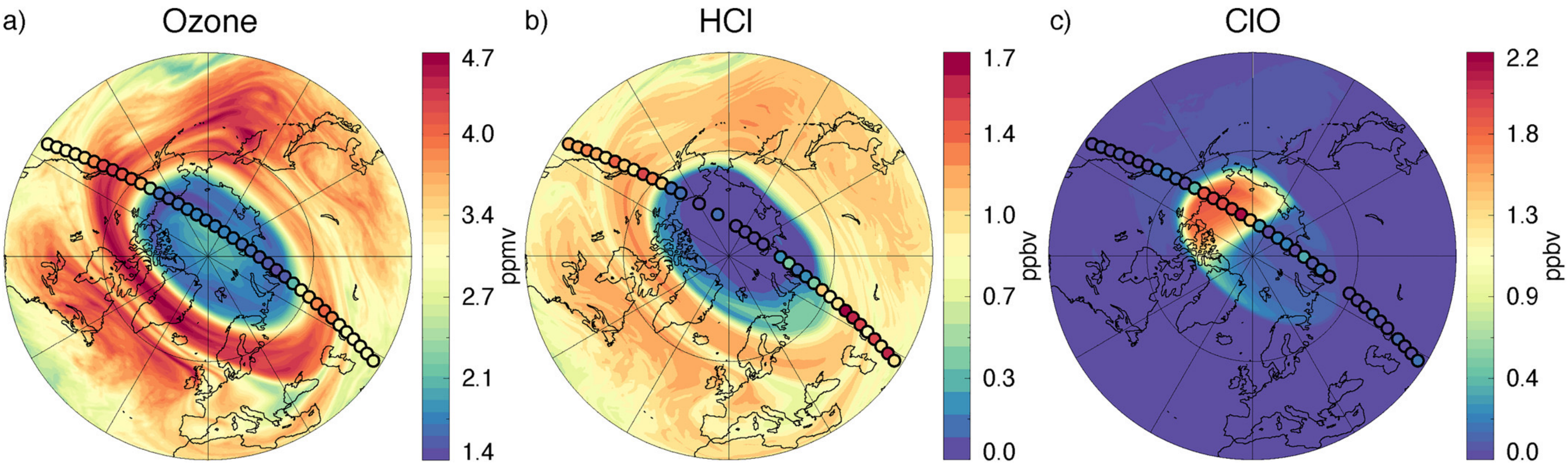
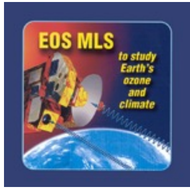
Evaluation GEOS-CF against MLS at 45 hPa

29 February 2020 at 22:00 UTC



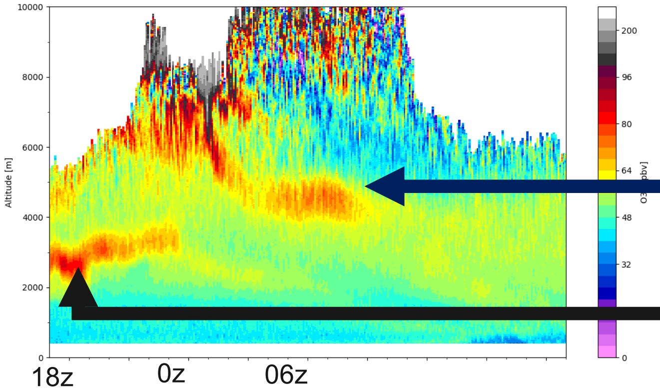
Within the vortex, HCl is expected to be converted into reactive chlorine (e.g., ClO), with high concentrations within the sunlight portion.



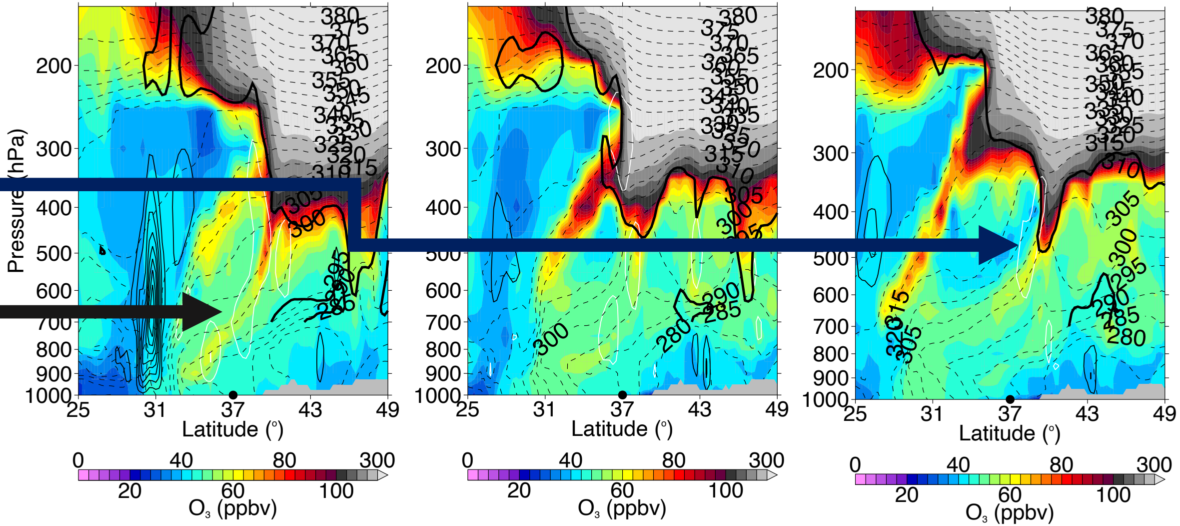
Knowland et al., 2022, JAMES

Stratosphere Troposphere Exchange

NASA LaRC Feb 13-14, 2019



LMOL lidar plot courtesy of G. Gronoff

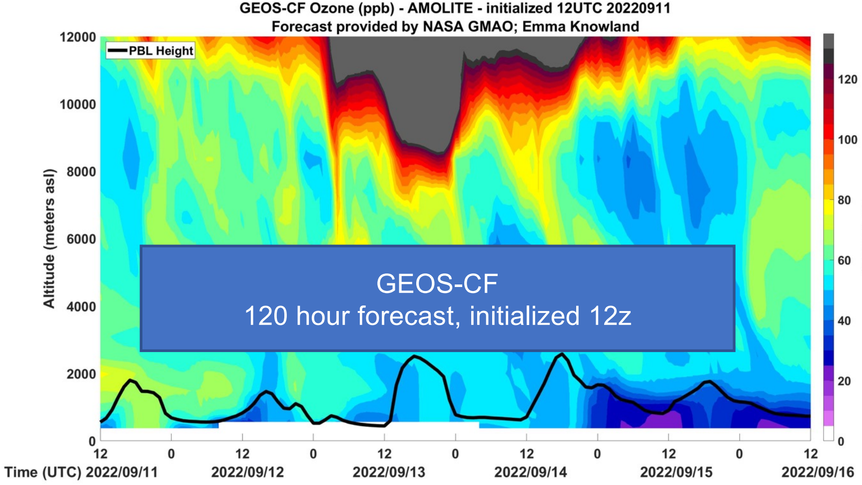


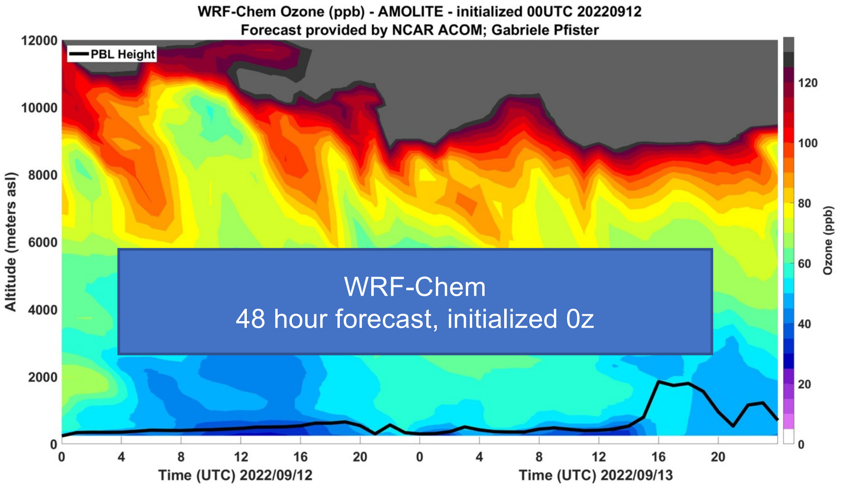
High ozone observed in the troposphere on February 13th and 14th of 2019 at LaRC have stratospheric origin, as indicated by the GEOS-CF curtain plots

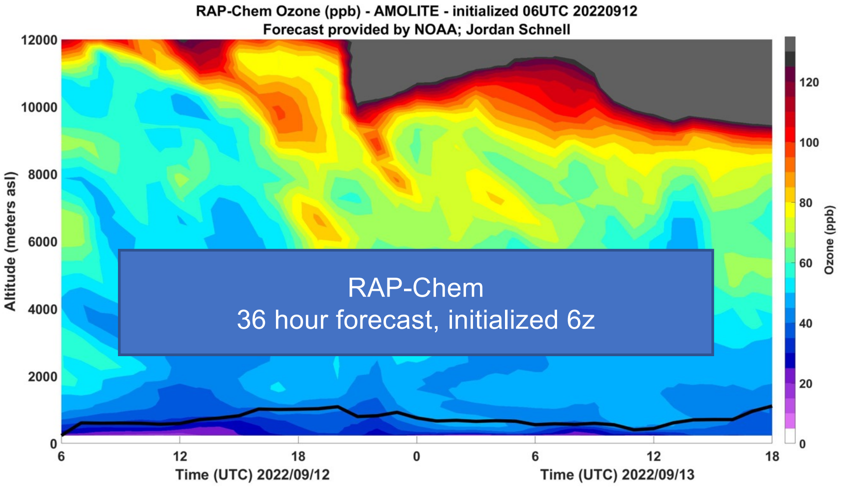
Gronoff, G., Berkoff, T., Knowland, K. E., et al. "Case study of stratospheric Intrusion above Hampton, Virginia: lidar-observation and modeling analysis." Atmos. Environ., 2021, DOI: 10.1016/j.atmosenv.2021.118498

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

GEOS - CF





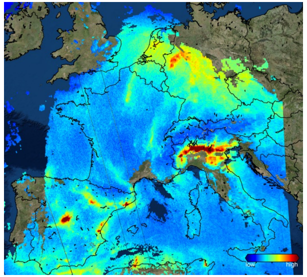


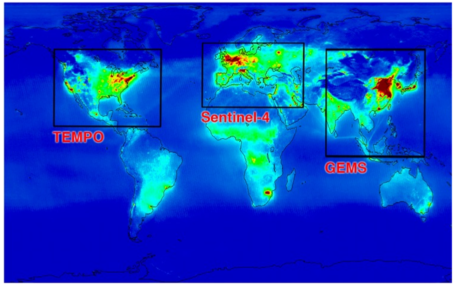
Tailored email alert system using three forecast models provides operators with confidence/uncertainty in predicted features

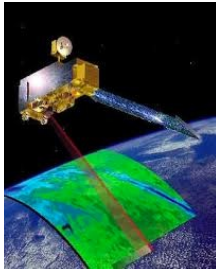
Figures courtesy of Matt Johnson

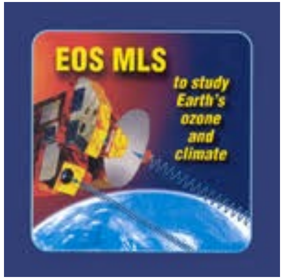
Planned upgrades for GEOS-CF

- Model update to GEOS-Chem v14
  - Improvements to ozone deposition
  - Updates to NO_3 washout ⇢ likely reduce PM2.5 bias
- GEOS AGCM update
- CEDS emission inventory (latest release through 2019)
- Constituent Data Assimilation System (CoDAS)
  - Multi-constituent assimilation with O_3, CO, NO_2 , SO_2









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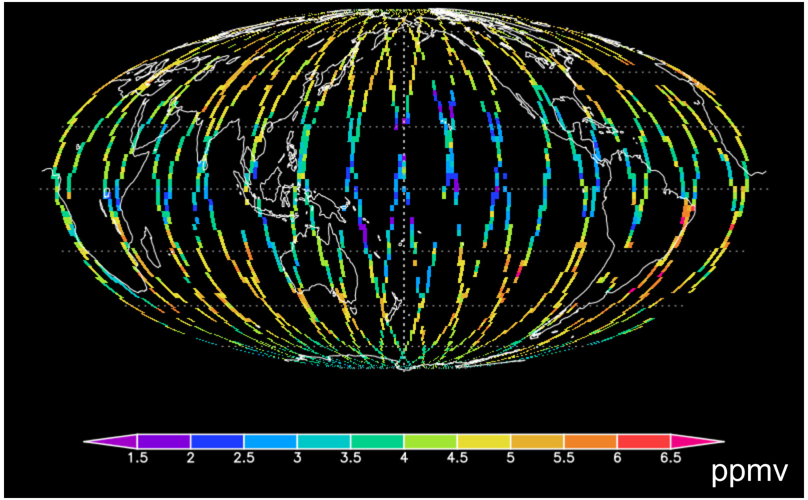
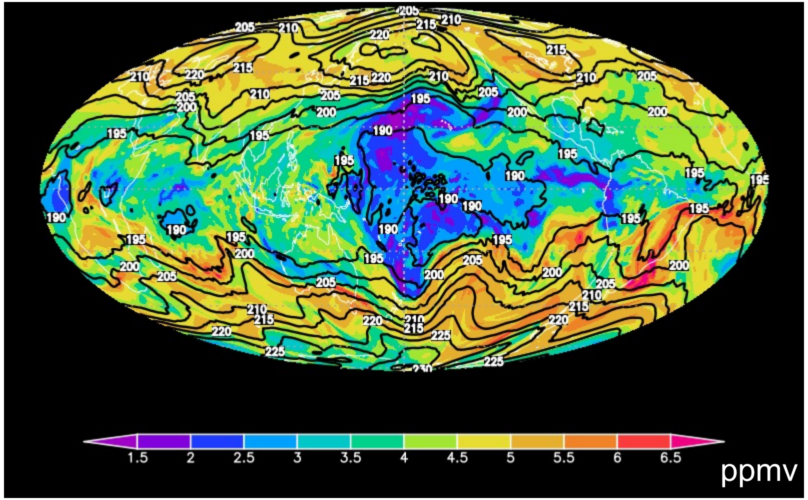
Constituent data assimilation

MLS water vapor at 100 hPa, 2 Jan 2016



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

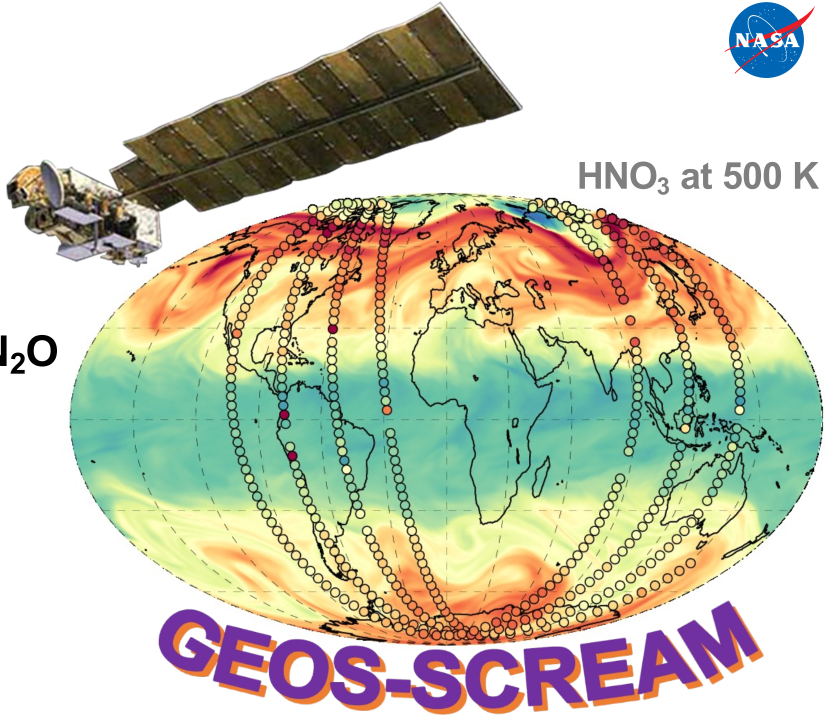


Data assimilation is a Bayesian method of combining and propagating information from observations in space and time using the governing equations and error estimates.

Figures courtesy of Kris Wargan

GEOS Stratospheric Composition Reanalysis with Aura MLS (GEOS-SCREAM)

Kris Wargan, Brad Weir, Gloria L. Manney, Stephen E. Cohn, Nathaniel J. Livesey and JPL colleagues

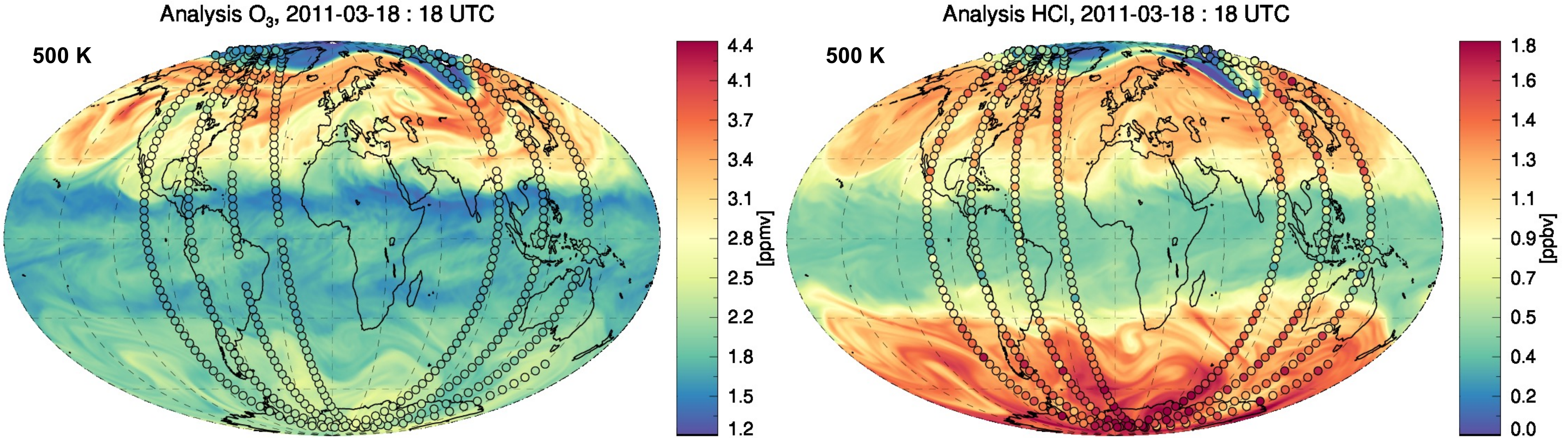


- Assimilating MLS v4.2 **ozone, H_2O, HCl, HNO_3,** & **N_2O** and **total ozone** from OMI
- Replay to MERRA-2
- GEOS “StratChem” stratospheric-only chemistry
- Period: September 2004 – December 2020+

✓ Close agreement with ACE-FTS and GLORIA data and the BRAM2 reanalysis

➢ GMAO Reanalysis of the 21st Century (R21C, ~2022) with chemistry

Wargan, K., Weir, B., Manney, G. L., Cohn, S. E., & Livesey, N. J. (2020). The anomalous 2019 Antarctic ozone hole in the GEOS Constituent Data Assimilation System with MLS observations. *Journal of Geophysical Research: Atmospheres*, 125, e2020JD033335. https://doi.org/10.1029/2020JD033335

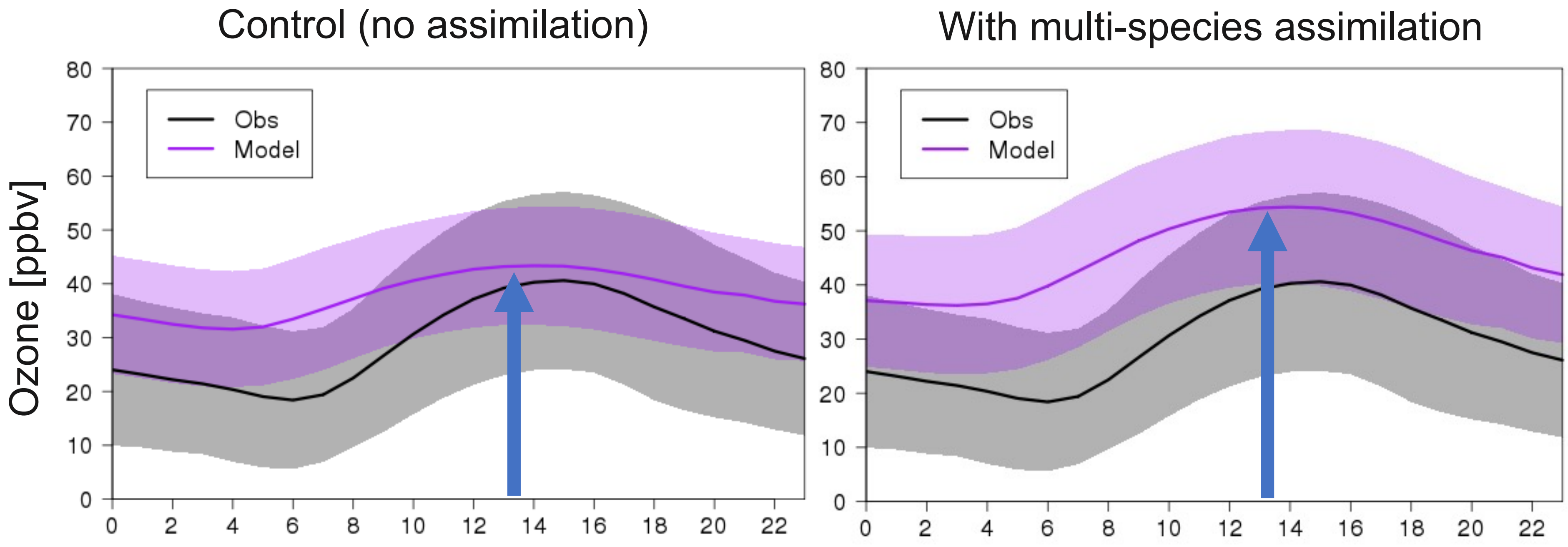


Maps of assimilated ozone and HCl and MLS observations (circles)

Close agreement between the constituent fields and assimilated MLS data.
Note dynamically driver features at mid- and high latitudes, and areas of depleted ozone and low HCl within the polar vortex.

Figures courtesy of Kris Wargan

Assimilation of NO_x and CO exacerbates tropospheric ozone bias



➢ Improved diurnal cycle, most likely due to improved afternoon NO_2

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Summary of GEOS-CF Status

- GEOS-CF daily global composition forecasts at 25km resolution are generated in near-real time:
  - High-resolution replay segments are available since January 2018
    - ✓ Model realisticly captures global distribution of the major pollutants, though aerosols and SO2 are biased high, when compared against surface observations, ozonesondes and satellite.
    - ✓ Due to grid-box size, model skill is typically worse for the urban sites (OpenAQ) than the background sites (GAW)
  - Forecasts accessible via data servers for two weeks, or since January
    - ✓ Forecast skill is improved using ML algorithm in post-processing step.
    - ✓ Now have realistic stratospheric ozone 5-day forecasts
- Emerging applications users, including:
  - NASA field missions (SCOAPE, FIREX-AQ, ACT-America, TRACER-AQ)
  - Daily alerts sent to NASA TOLNet lidar teams (Matt Johnson, NASA Ames)
  - TEMPO a priori for trace gas product

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Thank you!

Referred

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Keller, C. A., Evans, M. J., Knowland, K. E., Hasenkopf, C. A., Modekurty, S., Lucchesi, R. A., Oda, T., Franca, B. B., Mandarino, F. C., Díaz Suárez, M. V., Ryan, R. G., Fakes, L. H., and Pawson, S. (2021). Global impact of COVID-19 restrictions on the surface concentrations of nitrogen dioxide and ozone. *Atmos. Chem. Phys.,* 21, 3555–3592, https://doi.org/10.5194/acp-21-3555-2021

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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 1.2), 54pp, available from http://gmao.gsfc.nasa.gov/pubs/office_notes*

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Long-range transport of Siberian biomass burning emissions to North America during FIREX-AQ campaign

- GEOS-CF and satellite observations characterized the long-range transport pathway of Siberian smoke over the AMOLITE location during FIREX-AQ.
- The long-range transport agreed with the timing of aerosol and ozone lamina measured by AMOLITE.
- GEOS-CF, AMOLITE, and in situ data suggest that while surface air quality impacts in western Canada were small, there were significant free tropospheric ozone (>20 ppb) and aerosol (>30 μg m-3) enhancements.

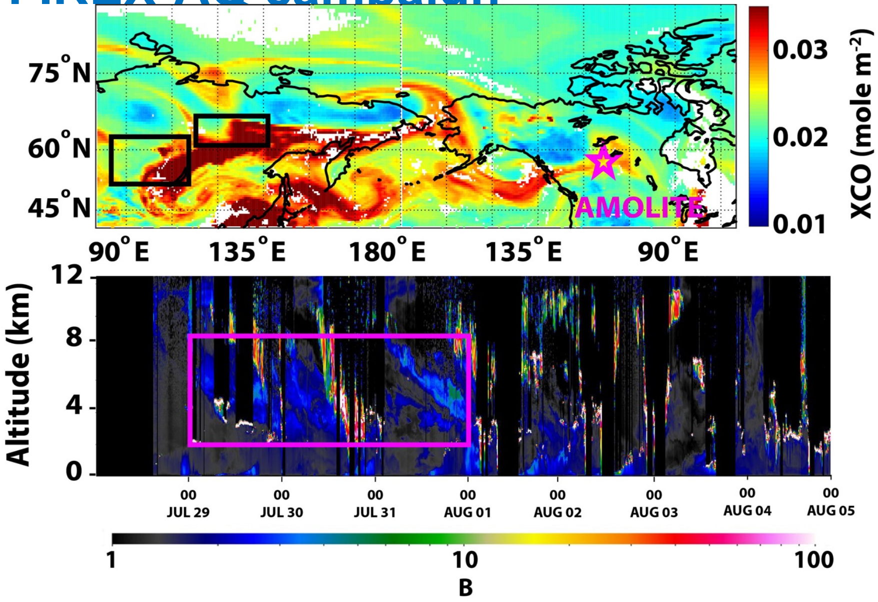


Figure 1. **GEOS-CF** XCO (mole m^{-2}) on July 29, 2019 (top) and AMOLITE aerosol backscatter ratio (B) between July 28 and August 5, 2019 (bottom). The magenta star and box highlight the location of AMOLITE and the large aerosol lamina observed by the system, respectively.

Johnson, M. S., Strawbridge, K., Knowland, K. E., et al., "Long-range transport of Siberian biomass burning emissions to North America during FIREX-AQ." Atmos. Environ., 2021. DOI: 10.1016/j.atmosenv.2021.118241

TEMPO specific collection: "sat_inst_1hr_r721x361_v72"

Regional Chemistry and Meteorology Diagnostics to support TEMPO satellite

Frequency: *hourly instantaneous from 00:00 UTC*

Spatial Grid: *3D, model-level, subset region of full horizontal resolution*

Dimensions: *longitude=721, latitude=361, every 0.25º*

longitude: 0º to -180º

latitude: 0º to 90º

vertical level: *72 layers*

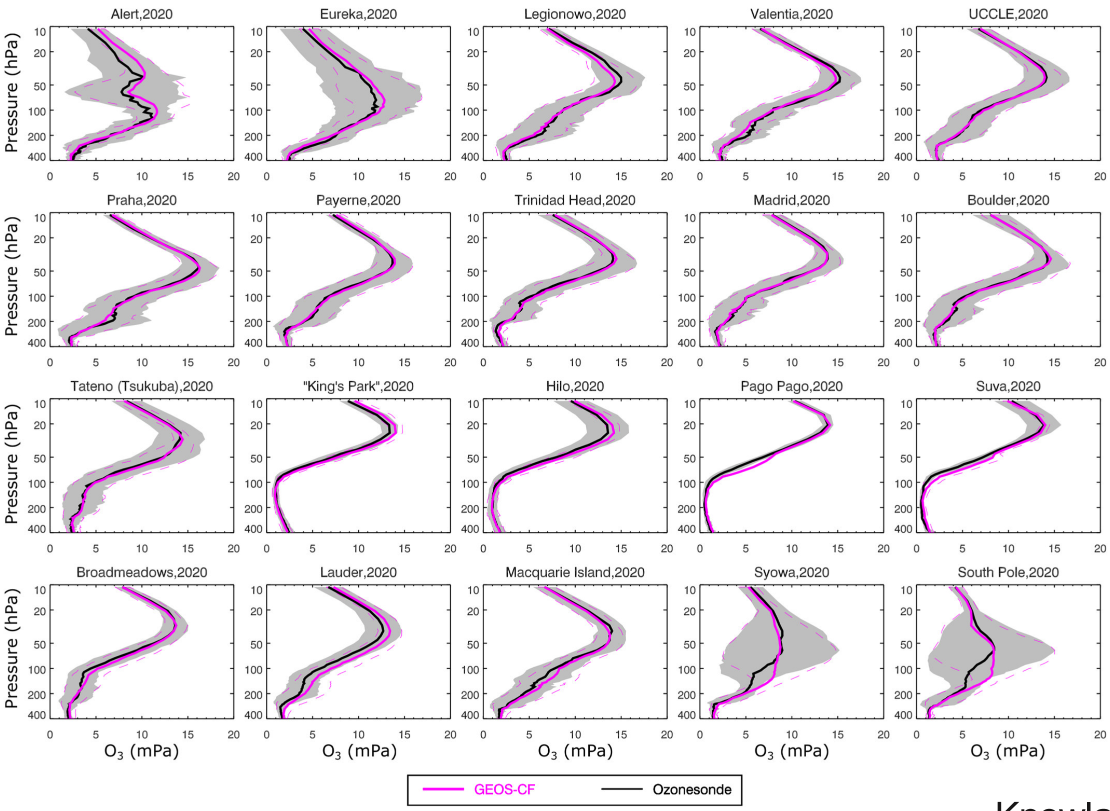
Granule Size: *~258 MB per file*

Start date: 00 UTC 1 January 2022

Mode: Replay only; Forecasts available based on mission requirements

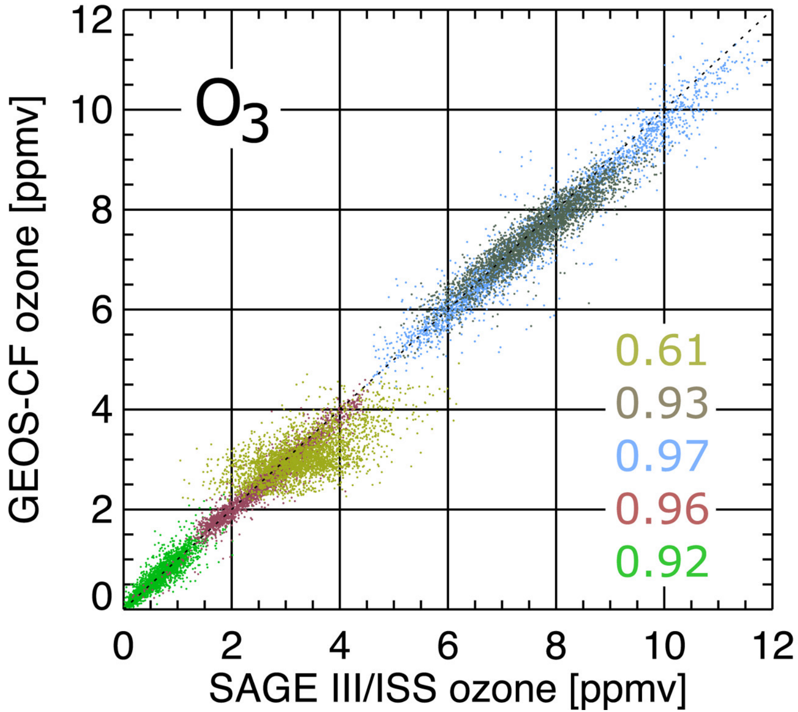
Knowland et al., 2022. "File Specification for GEOS-CF Products." *GMAO Office Note No. 17 (Version 1.2), available from http://gmao.gsfc.nasa.gov/pubs/office_notes*

Name	Dim	Description	Units
BrO	tzyx	Bromine monoxide (BrO, MW = 96.00 g mol-1) volume mixing ratio dry air	mol mol-1
FRSEAICE	tyx	ice covered fraction of tile	1
FRSNO	tyx	fractional area of land snowcover	1
GLYX	tzyx	Glyoxal (CHOCHO, MW = 58.00 g mol-1) volume mixing ratio dry air	mol mol-1
HCHO	tzyx	Formaldehyde (CH2O, MW = 30.00 g mol-1) volume mixing ratio dry air	mol mol-1
HNO2	tzyx	Nitrous acid (HNO2, MW = 47.00 g mol-1) volume mixing ratio dry air	mol mol-1
IO	tzyx	Iodine monoxide (IO, MW = 143.00 g mol-1) volume mixing ratio dry air	mol mol-1
NO2	tzyx	Nitrogen dioxide (NO2, MW = 46.00 g mol-1) volume mixing ratio dry air	mol mol-1
O3	tzyx	Ozone (O3, MW = 48.00 g mol-1) volume mixing ratio dry air	mol mol-1
OClO	tzyx	Chlorine dioxide (OClO, MW = 67.00 g mol-1) volume mixing ratio dry air	mol mol-1
PHIS	tyx	surface geopotential height	m+2 s-2
PS	tyx	surface pressure	Pa
Q	tzyx	specific humidity	kg kg-1
SNODP	tyx	snow depth	m
SNOMAS	tyx	Total snow storage land	kg m-2
SO2	tzyx	Sulfur dioxide (SO2, MW = 64.00 g mol-1) volume mixing ratio dry air	mol mol-1
T	tzyx	air temperature	K
TROPPB	tyx	tropopause pressure based on blended estimate	Pa
U2M	tyx	2-meter eastward wind	m s-1
V2M	tyx	2-meter northward wind	m s-1
ZPBL	tyx	planetary boundary layer height	m



Knowland et al., 2022, JAMES

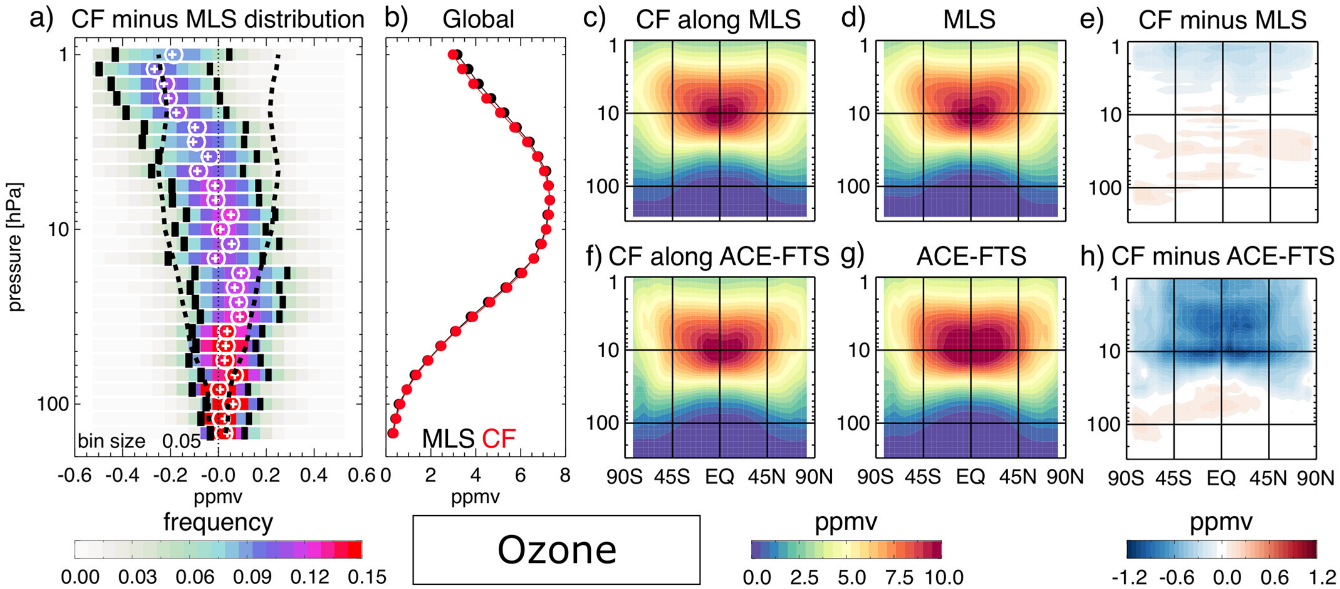
GEOS-CF vs SAGE III/ISS



1.0 hPa
4.6 hPa
10.0 hPa
46.0 hPa
100.0 hPa

Correlation coefficients per level in inset

Knowland et al., 2022, JAMES



Knowland et al., 2022, JAMES