NASA GEOS-CF: Overview, Applications, Future Direction

K. Emma Knowland

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In collaboration with many other scientists from NASA Goddard Space Flight Center and our partners

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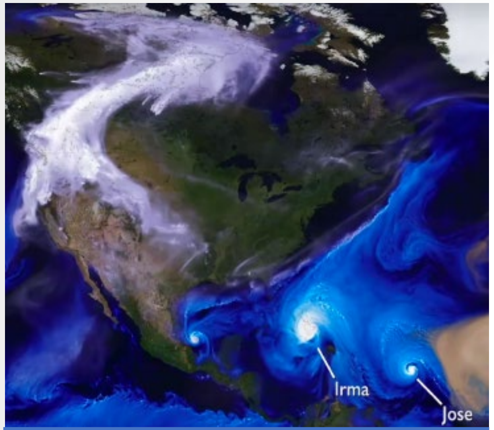
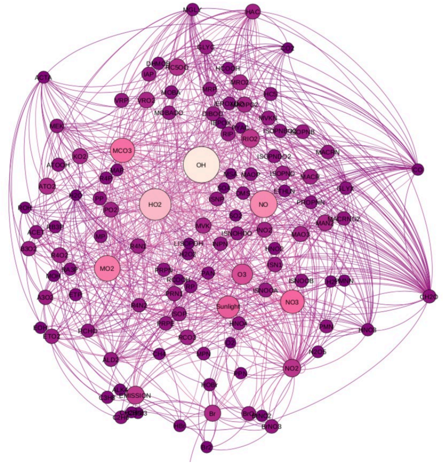
[3] Science Systems and Applications, Inc. (SSAI)

GEOS-CF produces daily global forecasts of atmospheric composition at 0.25° resolution

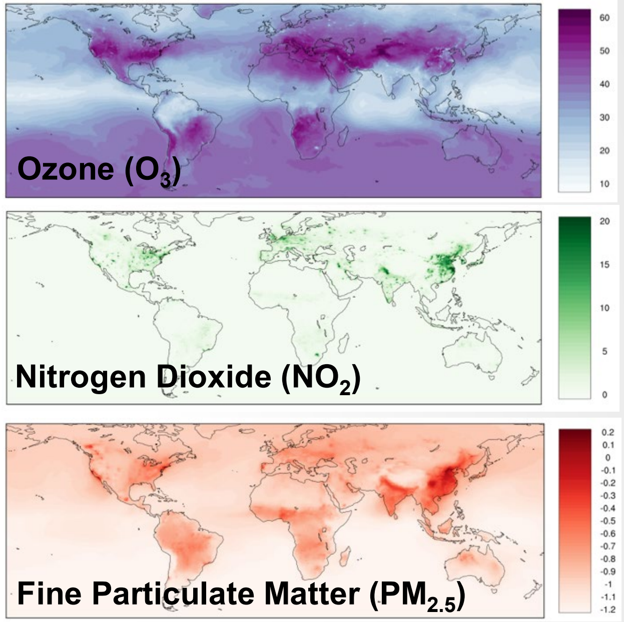
National Aeronautics and Space Administration



GEOS NWP



GEOS-Chem



Keller, C. A., Knowland, K. E., et al. (2021). **Description of the NASA GEOS composition forecast modeling system GEOS-CF v1.0**. *Journal of Advances in Modeling Earth Systems (JAMES)*, 13, e2020MS002413. https://doi.org/10.1029/2020MS002413

Knowland, K. E., Keller, C. A., et al. (2022). **NASA GEOS Composition Forecast Modeling System GEOS-CF v1.0: Stratospheric Composition.** *JAMES* https://doi.org/10.1029/2021MS002852

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

https://gmao.gsfc.nasa.gov/weather_prediction/GEOS-CF/
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GEOS-CF v1 Status

- Daily GEOS-CF global 5-day composition forecasts at 0.25° (25km) resolution are generated in near-real time:
  - High-resolution historical estimates for fields are available since January 2018
  - Forecast visualizations and links to data available at fluid.nccs.nasa.gov/cf and /cf_map

Keller, C. A., et al. (2021). **Description of the NASA GEOS composition forecast modeling system GEOS-CF v1.0**. *Journal of Advances in Modeling Earth Systems*, 13, e2020MS002413. https://doi.org/10.1029/2020MS002413

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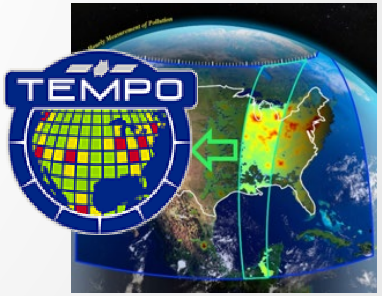
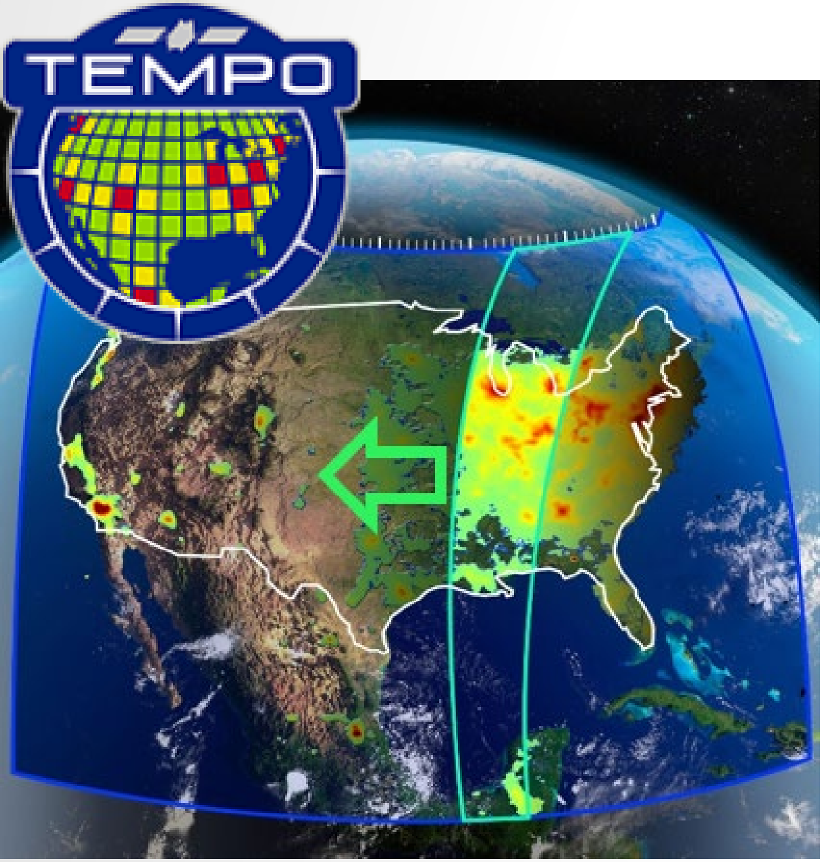
- Applications include:
  - NASA field missions (e.g., SCOAPE, FIREX-AQ, ACT-America, TRACER-AQ)
  - Daily alerts sent to NASA TOLNet lidar teams (Matt Johnson, NASA Ames)
  - TEMPO a priori for trace gas retrieval
  - Cloud platforms, e.g., Google Earth Engine, WRI Resource Watch, CDC Tracker

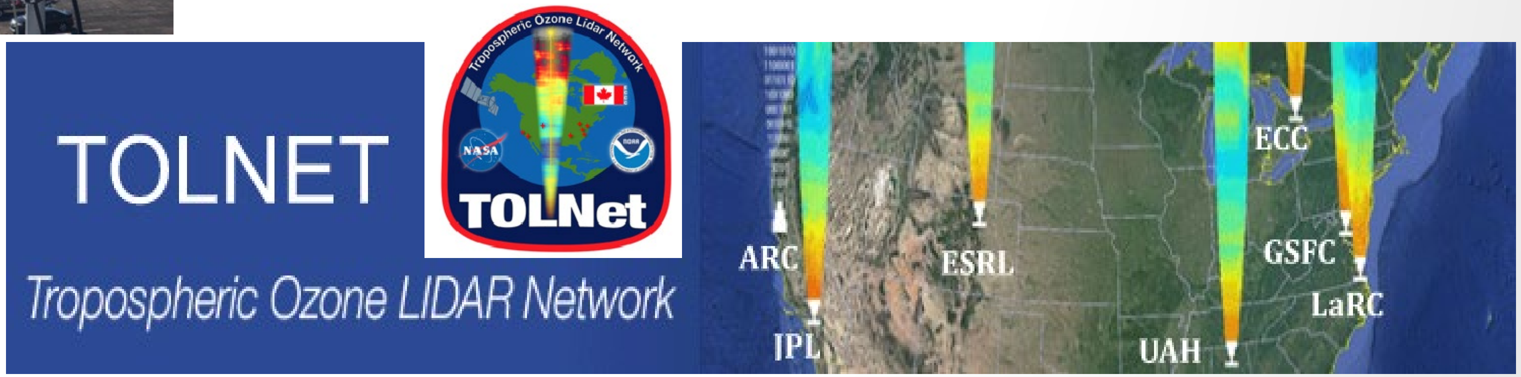


Realistic tropospheric and stratospheric composition is critical for many NASA applications



Realistic troposphere **and** stratosphere in GEOS-CF are essential to support a broad range of NASA applications, including:

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



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

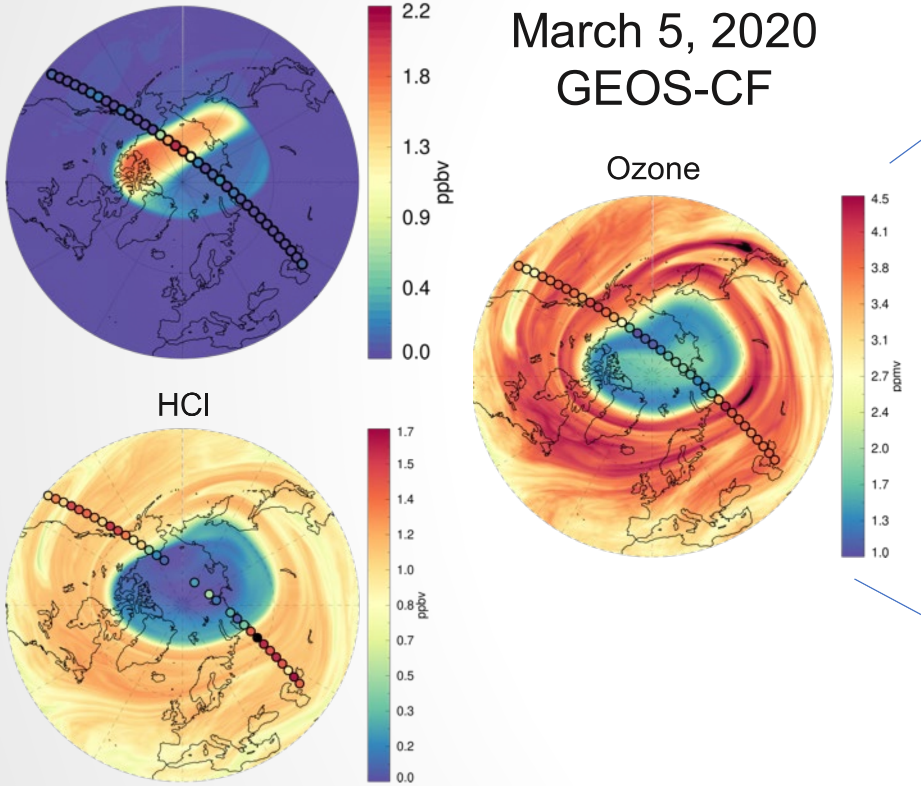
Mode: Replay only; Forecasts available based on mission requirements

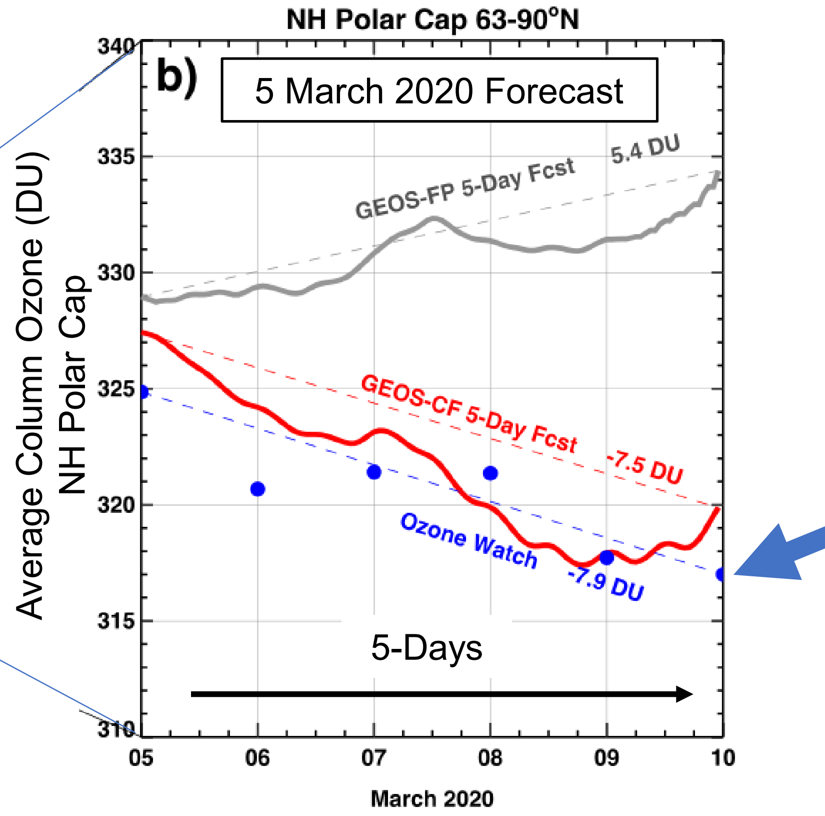
Name	Dim	Description	Units
BrO	tzyx	Bromine monoxide (BrO, MW = 96.00 g mol-1) volume mixing ratio dry air	mol mol-1
FRSEAICE	tyx	ice covered fraction of tile	1
FRSNO	tyx	fractional area of land snowcover	1
GLYX	tzyx	Glyoxal (CHOCHO, MW = 58.00 g mol-1) volume mixing ratio dry air	mol mol-1
HCHO	tzyx	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
OCIO	tzyx	Chlorine dioxide (OCIO, 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. "File Specification for GEOS-CF Products." *GMAO Office Note No. 17 (Version 1.3), available from http://gmao.gsfc.nasa.gov/pubs/office_notes*

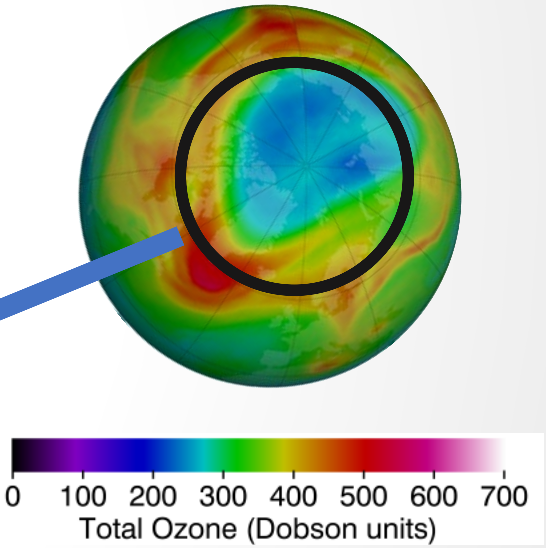
GEOS-CF with stratospheric chemistry adds near-real-time stratospheric ozone forecasting capability to the NASA GMAO

March 5, 2020
GEOS-CF





March 10, 2020
Ozonewatch

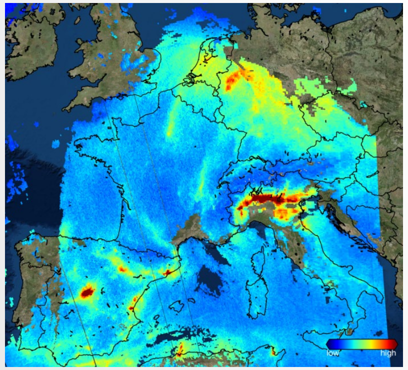


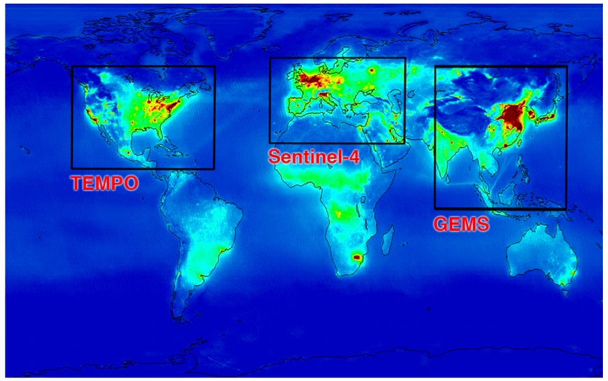
Ozonewatch.gsfc.nasa.gov

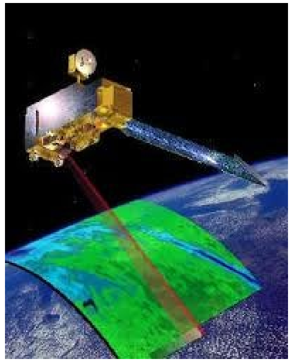
Knowland et al., JAMES, 2022, https://doi.org/10.1029/2021MS002852

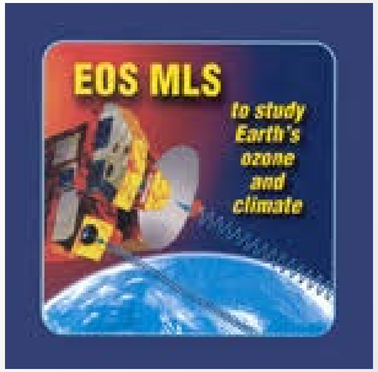
Spinning up GEOS-CF version 2

- ➢ Model update to GEOS-Chem v14.0
- ➢ GEOS AGCM update
- ➢ CEDS emission inventory (latest release through 2019)
- ➢ Constituent Data Assimilation System (CoDAS)
  - Multi-constituent assimilation with O_3, NO_2, SO_2
- Output will include simulated CO_2 and CH_4 (GOCART)









https://gmao.gsfc.nasa.gov/weather_prediction/GEOS-CF/
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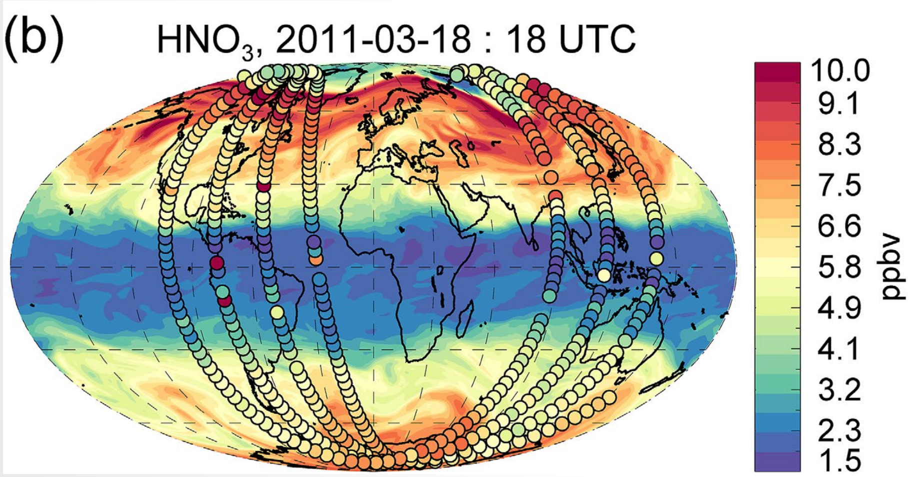
Constituent Data Assimilation System (CoDAS)

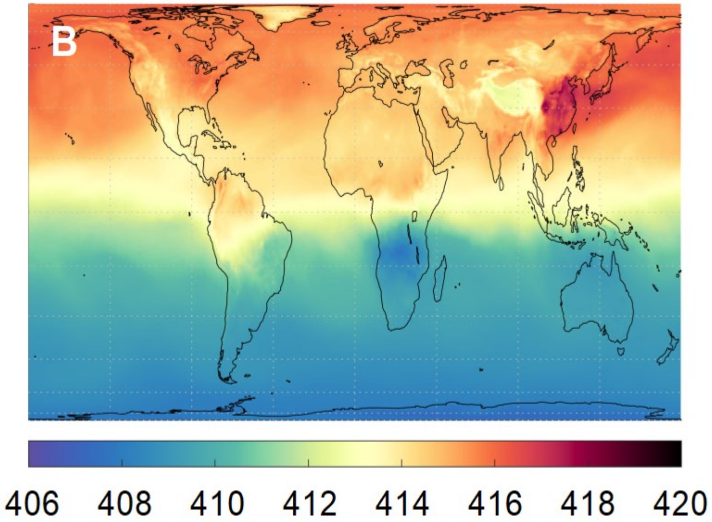
- Designed to be tracer agnostic: can assimilate any type of retrieved constituent observations with an averaging kernel or at a point
  - CoDAS builds on the Gridpoint Statistical Interpolation scheme developed at NCEP and GMAO

M2-SCREAM



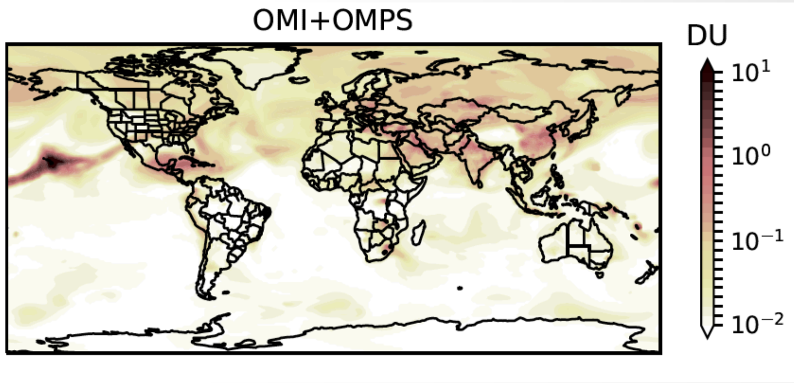
Wargan et al., ESS (2023).
DOI: 10.1029/2022EA002632

GEOS-GHG



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

GEOS-CF v2

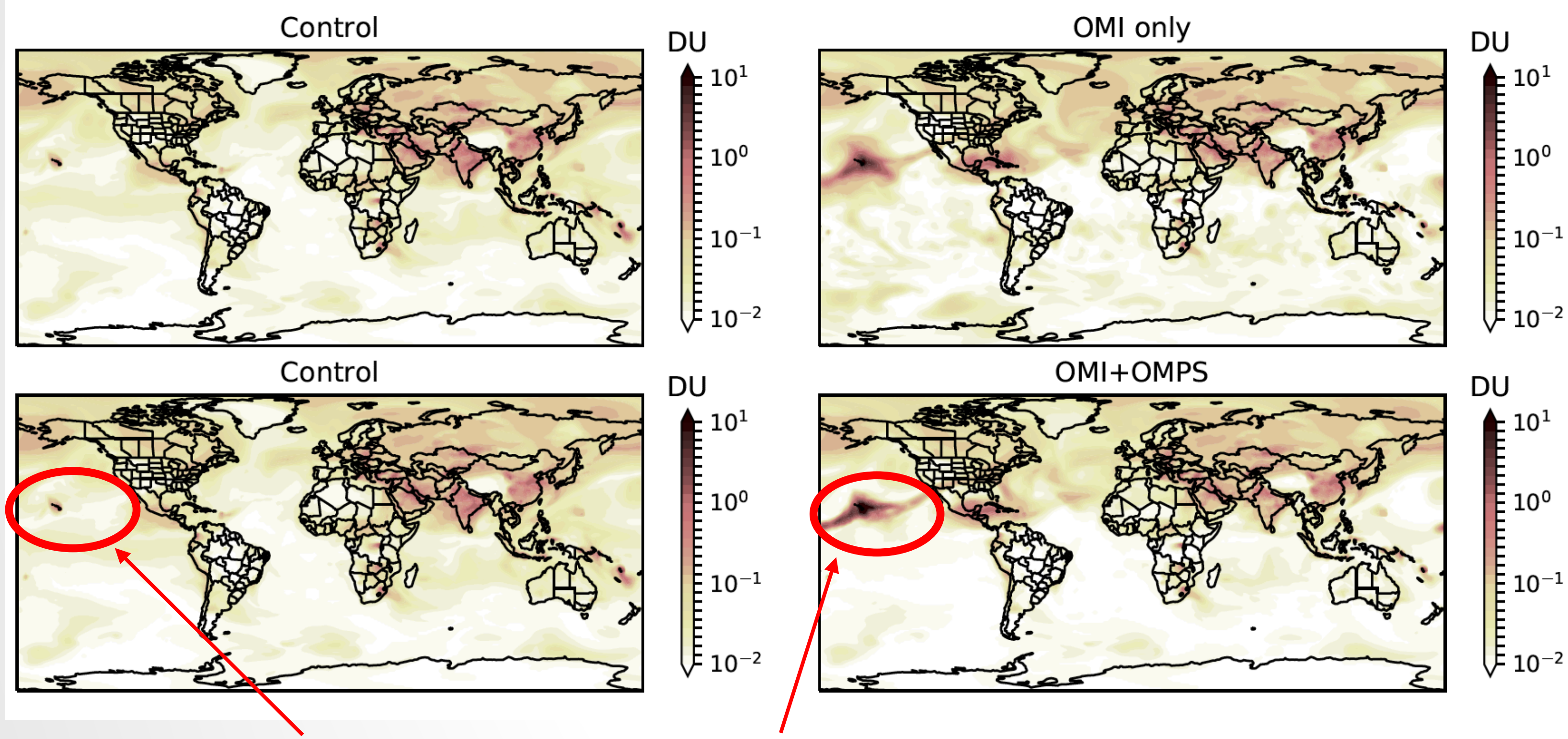


https://gmao.gsfc.nasa.gov/research/science_snapshots/2022/mauna-loa.php

➢ GMAO involved and invested in the constituent DA with JEDI

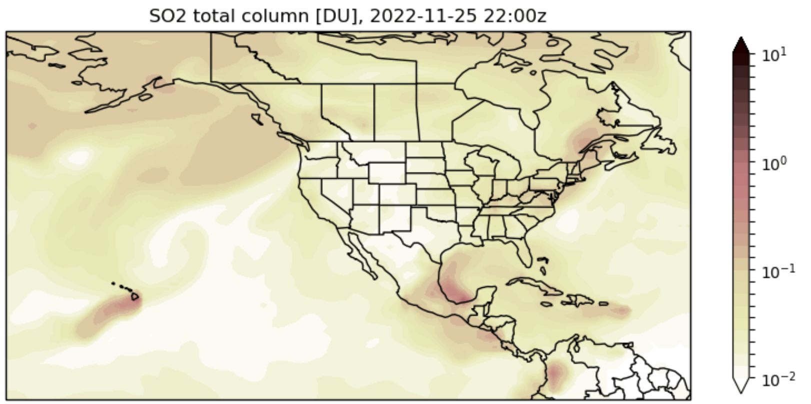
SO_2 assimilation: Mauna Loa's smoking gun

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

https://gmao.gsfc.nasa.gov/weather_prediction/GEOS-CF/
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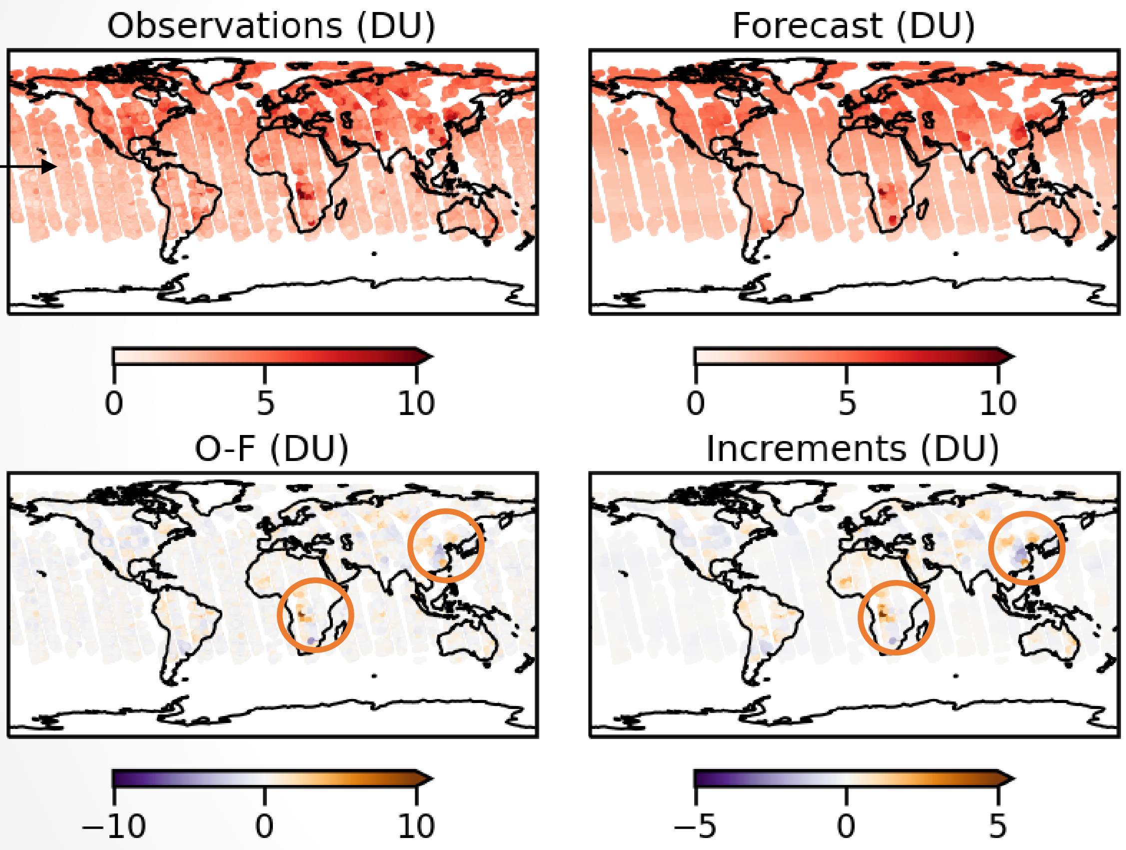
NO_2 assimilation ➡Improved NO_2 in polluted areas

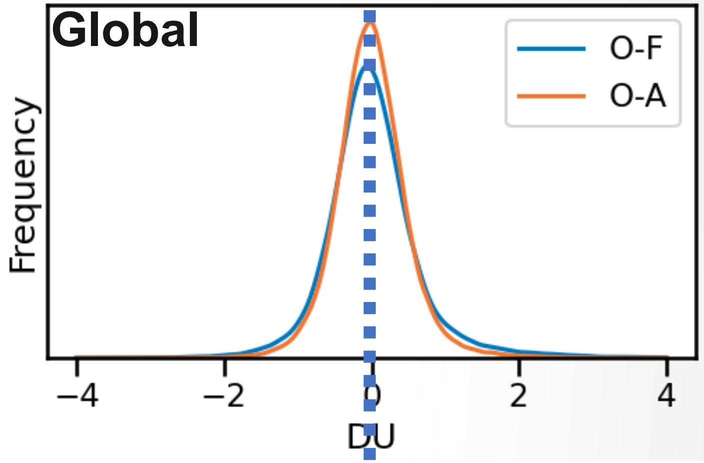
Assimilating OMI NO_2 total slant columns

Mostly Strat NO_2 in remote atmosphere

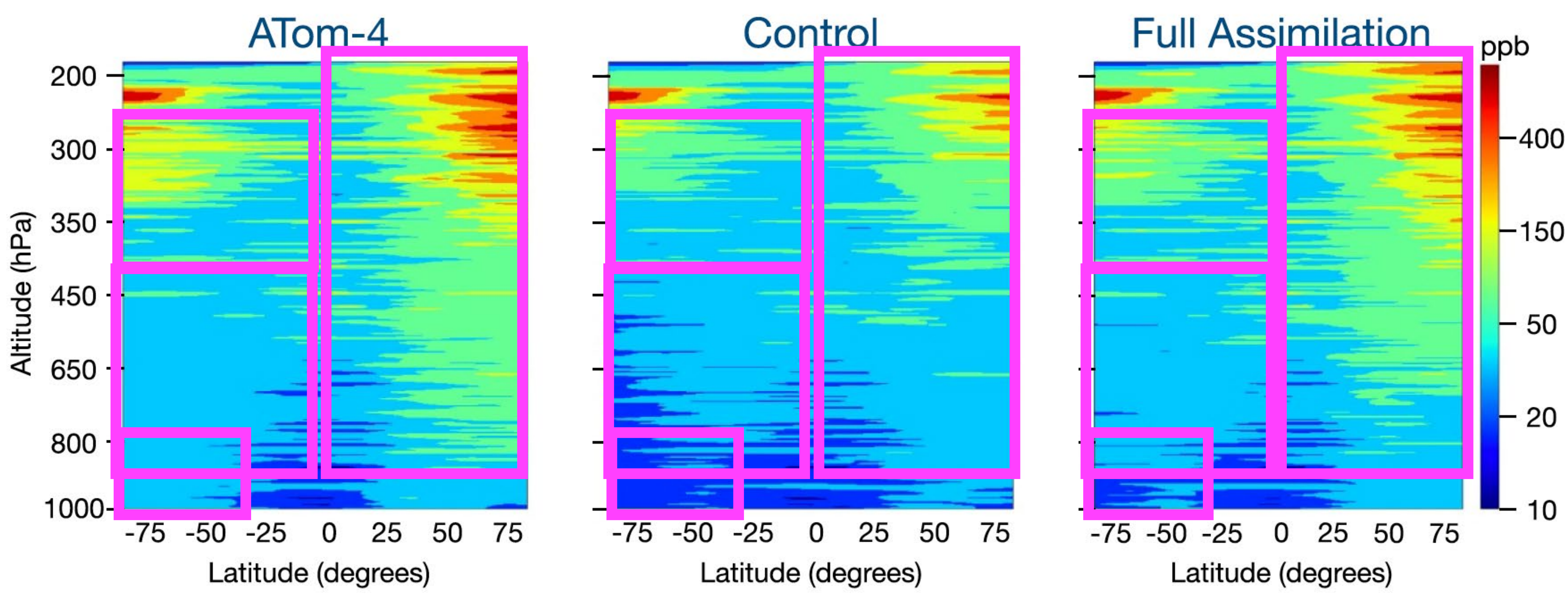


Increments smaller than O-F's – reflects the ratio of observation to background errors

Frequency distributions of O-F and O-A



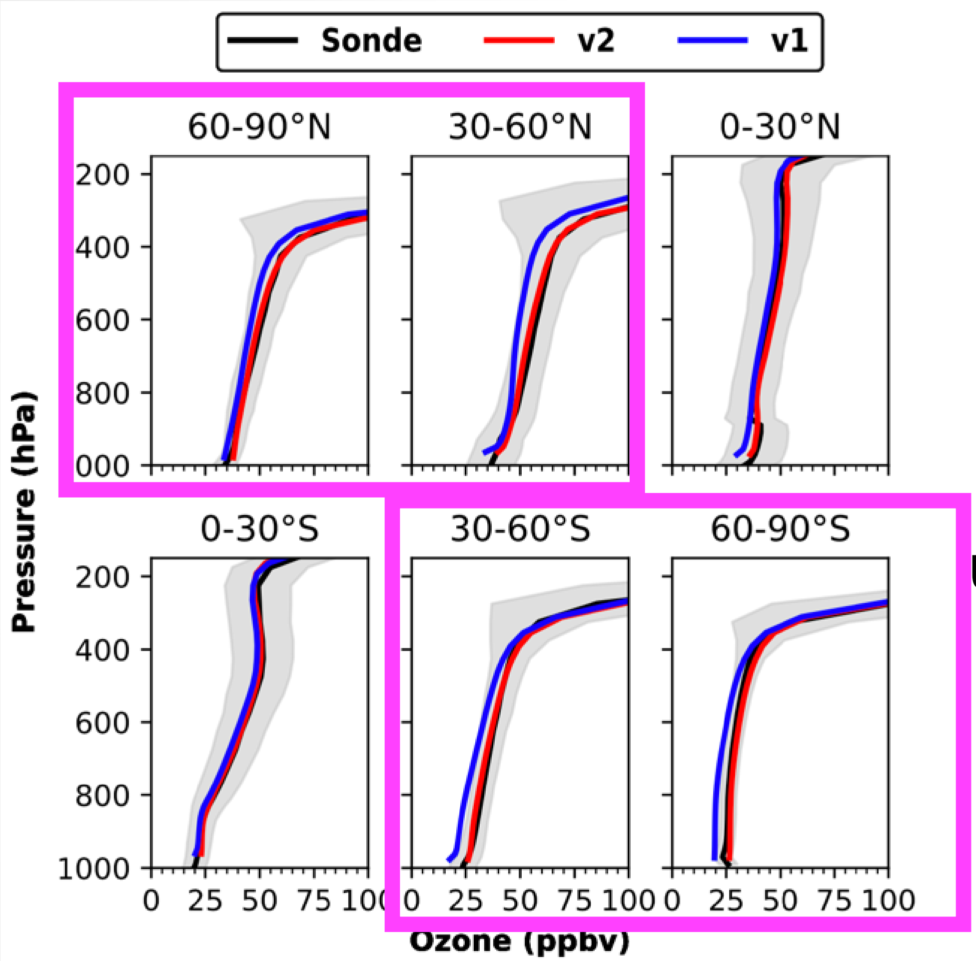
Ozone assimilation ➡Improved tropospheric ozone



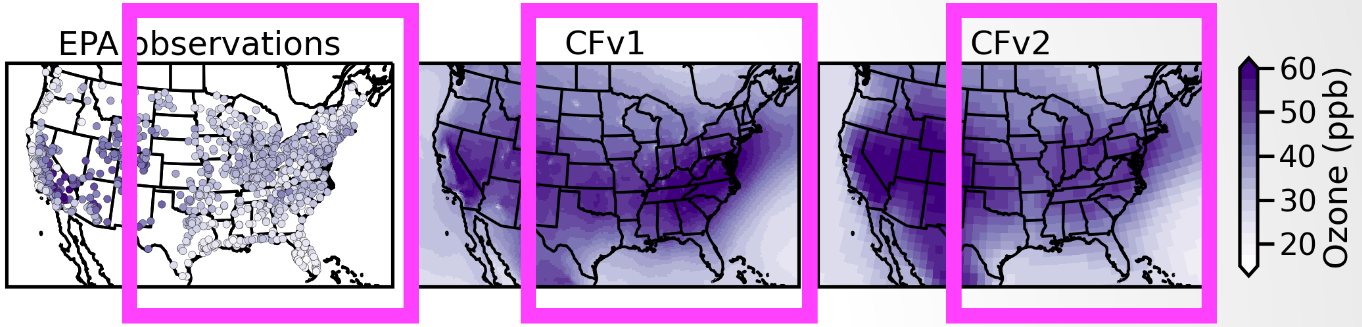
Ozone assimilation of MLS v4.2 profiles, Total Column Ozone from OMI, and 9.6-micron radiances drastically **improves the representation of ozone in the remote atmosphere** according to this comparison to ATom-4 measurements and a version of the GEOS-CF v2 system used in testing.

Figure reproduced from Makoto M Kelp *et al* 2023 *Environ. Res. Lett.* **18** 094036 **DOI** 10.1088/1748-9326/acf0b7

GEOS-CF v2 updates (including DA) positively impact O_3 and $PM_{2.5}$

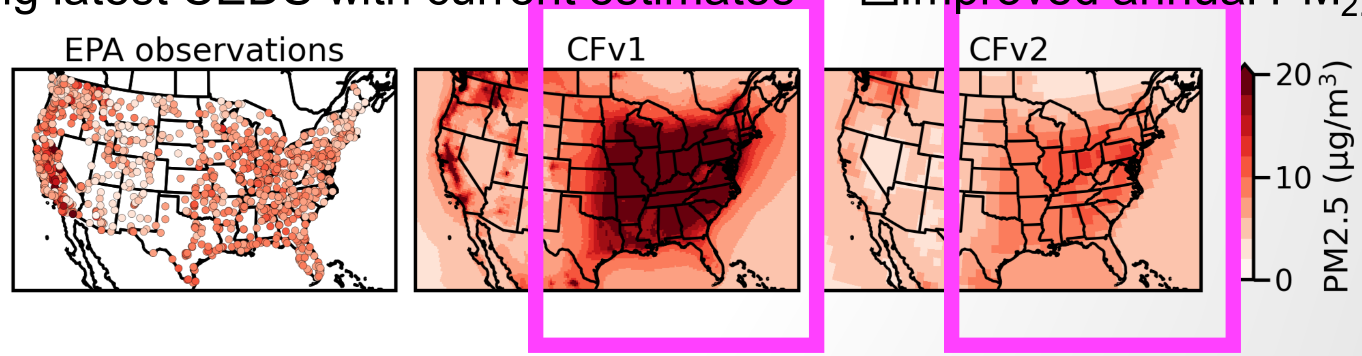


New Meteorology ➡☐Improved summertime (JJA) surface O_3



GEOS-CF v1 uses HTAP v2.2 which is now >10 years behind

Using latest CEDS with current estimates ➡☐Improved annual $PM_{2.5}$



Ozone assimilation ➡☐Improved tropospheric ozone

GEOS Composition Reanalysis for the 21st Century

Lines of development and legacy systems

GEOS CR development

MERRA-2 Stratospheric Composition Reanalysis with Aura MLS (M2-SCREAM)

M2-SCREAM pathfinder for composition reanalysis with coupled chemistry model and multi-constituent data assimilation

Greenhouse Gas data assimilation (GEOS-GHG)

Assimilation of chemically reactive carbon species: CO_2 and CH_4

Air quality / tropospheric chemistry modeling and assimilation

GEOS-CF v2 near-real time system with multi-constituent data assimilation of (mainly) tropospheric constituents

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

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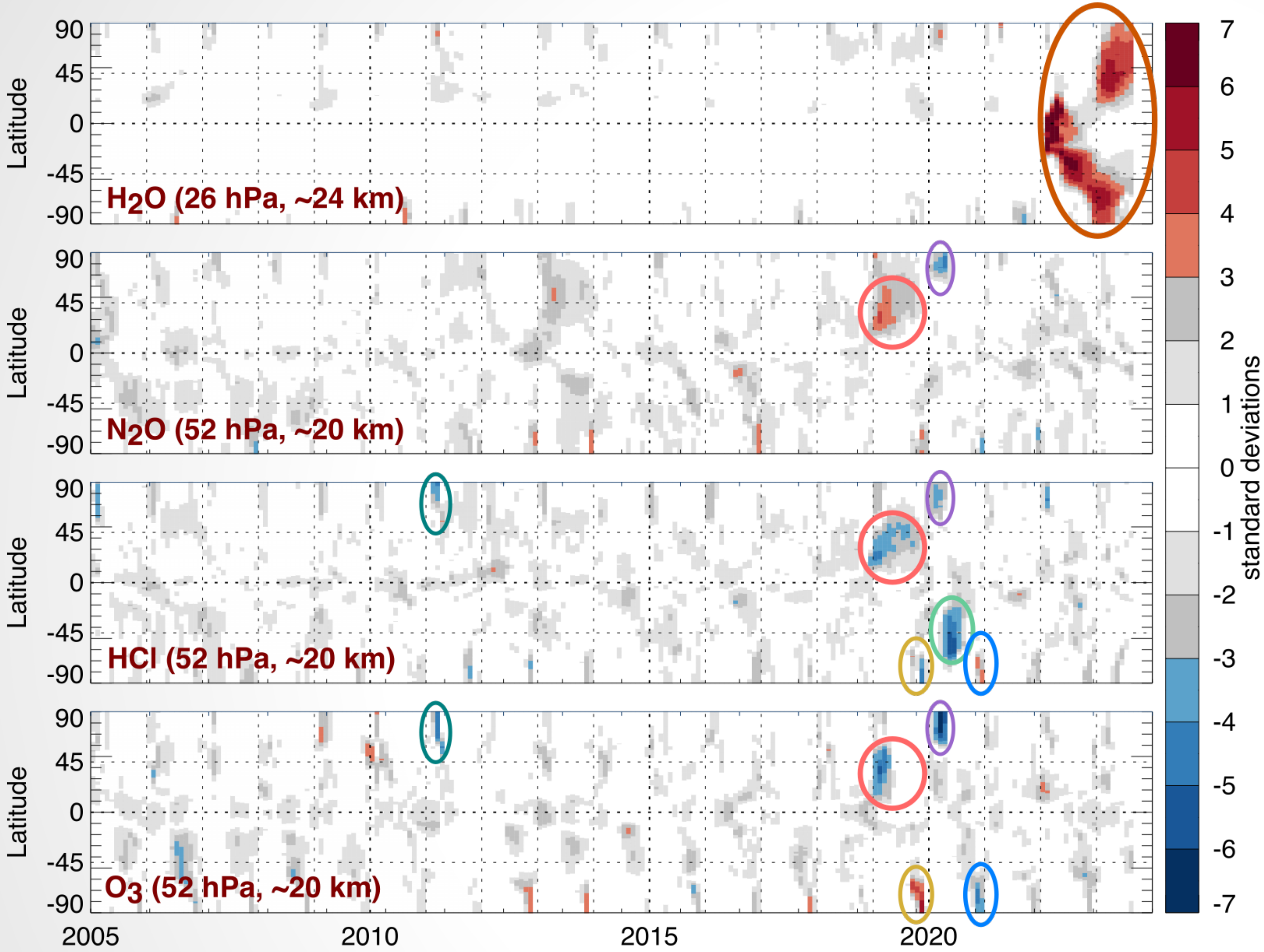
GEOS Composition Reanalysis of the 21st Century System Design

- Assimilation of selected gases important for stratospheric and tropospheric chemistry, with **CoDAS**
- Model: **GEOS AGCM** with the **GEOS-Chem** full chemistry model and a carbon module (developed from legacy **GOCART**)
  - Coupling GEOS-Chem to GOCART aerosols under development
- Constrained by temperature, winds, surface pressure, tropospheric water vapor from a GMAO reanalysis ("*meteorological replay*" technique)

Our surprising stratosphere



2022 Hunga Tonga - Hunga Ha'apai eruption

2020 Long-lasting ozone hole

2020 Australian New Year's wildfires

2020 Exceptionally strong Arctic ozone minimum

2019 Rare sudden stratospheric warming in the Southern Hemisphere

2019 Dynamically driven anomaly

2011 Strong Arctic ozone minimum

Detrended anomalies in constituent fields from M2-SCREAM

A series of large stratospheric perturbations occurred in the last five years.
Continuing measurements of the stratosphere will be essential for reanalyses.

Assimilated species and sensors

Retrievals

Sensor	Molecules	Observation type
OMI, TROPOMI, OMPS	NO_2, SO_2, O_3	Column
SCIAMACHY, GOSAT, TROPOMI	CH_4	Column
SCIAMACHY, GOSAT, OCO	CO_2	Column
MOPITT TIR & NIR	CO	Column
MLS	O_3, HCl, HNO_3, N_2O, H_2O, CH_3Cl, CO	Stratospheric limb profiles
OMPS-LP	O_3	Stratospheric limb profiles

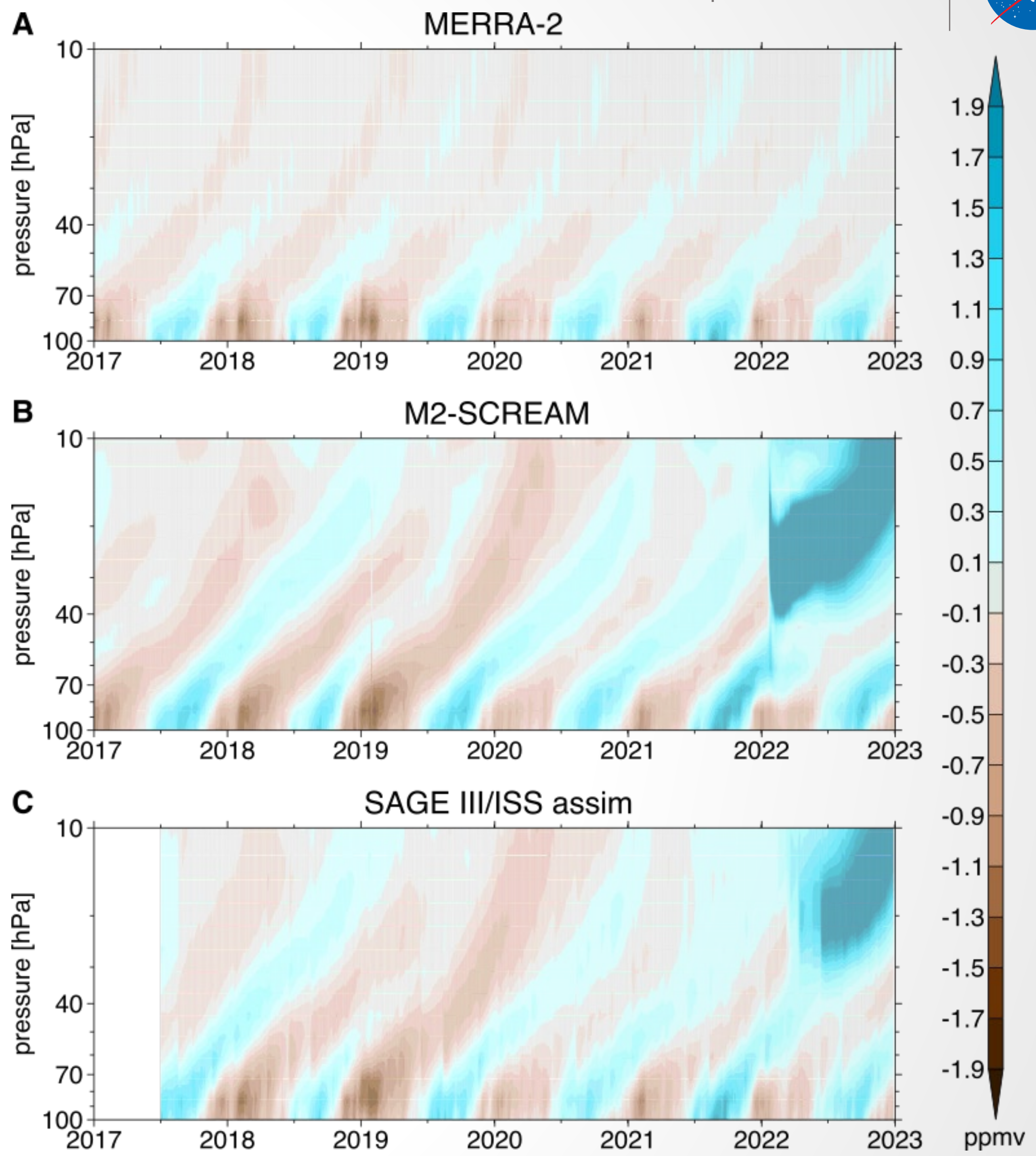
established new

Radiances

Sensor	Wavelength	Comment
AIRS, IASI (MetOp-A,B), CrIS FSR (potentially)	9.6 µm	Ozone-sensitive channels

Preparing for the end of EOS missions

- The assimilation of SAGE water vapor is now possible in the GEOS CoDAS framework to carry-on the trend and climate assessments after the Aura mission.
- There is a clear benefit to assimilating the less frequent SAGE III/ISS water vapor observations, especially after anomalous events like the period following the Hunga Tonga Eruption.



Tropical tape recorder signal assessed as anomalies in water vapor for 15°S to 15°N. Figure from Knowland et al. in prep

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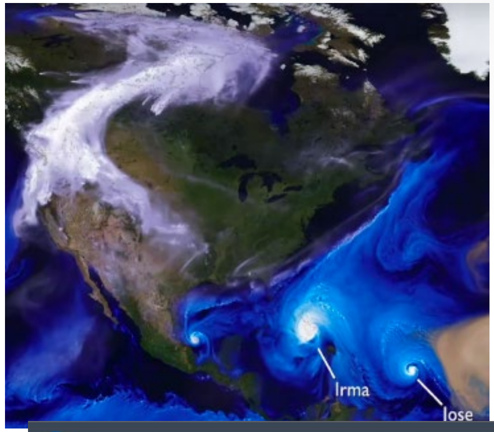
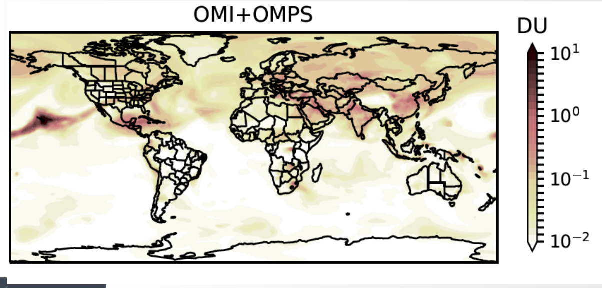
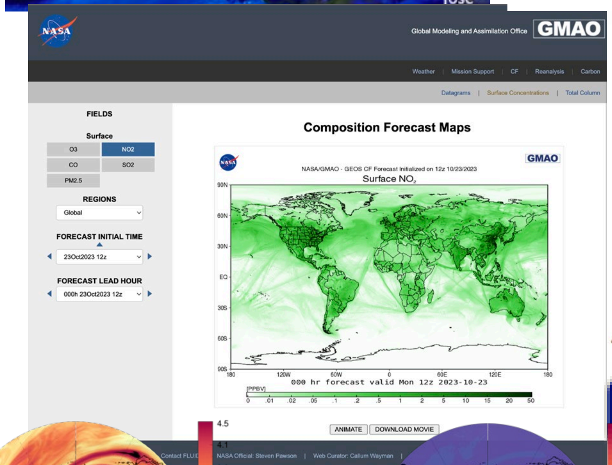
Summary

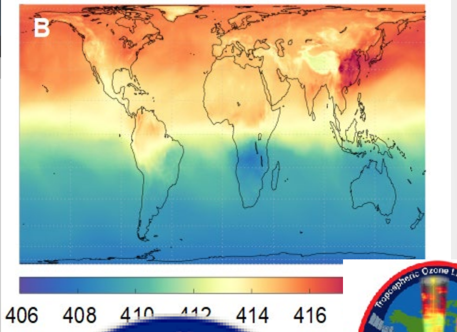
- GMAO has a state-of-the-science Earth System model and data assimilation system
- Daily GEOS-CF global 5-day composition forecasts at 0.25° (25km) resolution are generated in near-real time
- GEOS-CF v2 will include CoDAS with O_3, NO_2, and SO_2
- GEOS Composition Reanalysis builds on the development of tropospheric and stratospheric composition modeling and assimilation at GMAO
- Involved and invested in new data assimilation infrastructure for multi-constituent data assimilation system
- NASA products are research products

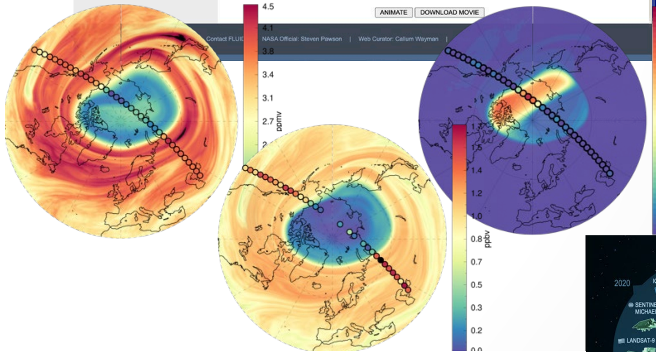
Thank you for listening!

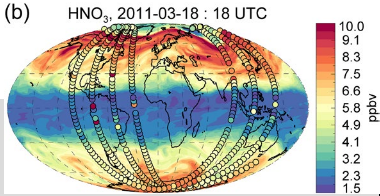


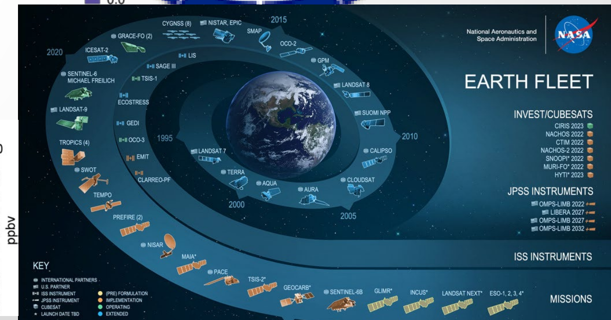












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