National Aeronautics and Space Administration

NASA GEOS-CF with Constituent Data Assimilation

K. Emma Knowland

Co-author: Christoph Keller[1,2,*], Viral Shah[2,3], Pam Wales[1,2], Kris Wargan[2,3], Brad Weir[1,2], Lesley Ott[2], Steven Pawson[2]

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

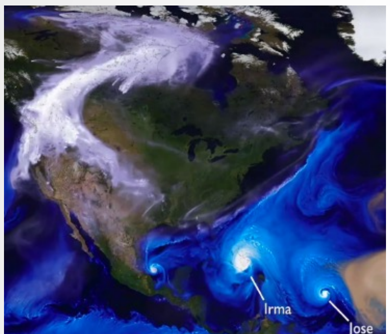
[1] Morgan State University/GESTAR-II

[2] NASA Global Modeling and Assimilation Office (GMAO)

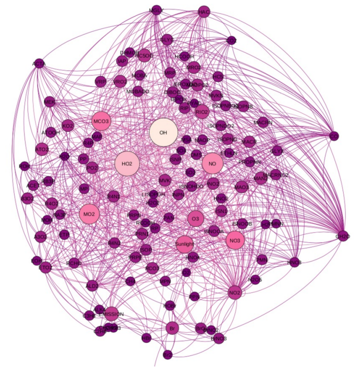
[3] Science Systems and Applications, Inc. (SSAI)

*Now at Swiss Re, Switzerland

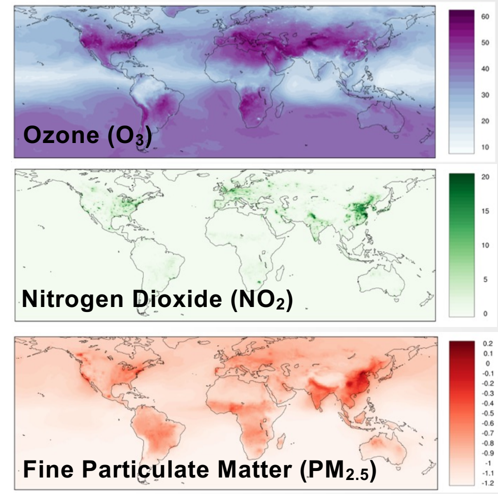
GEOS-CF produces daily global forecasts of atmospheric composition at 0.25° resolution



GEOS NWP



GEOS-Chem



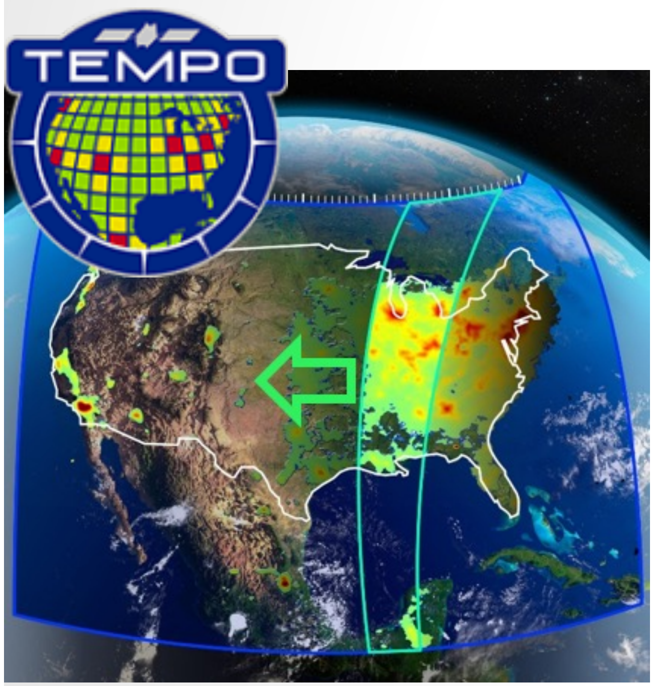
Daily GEOS-CF global 5-day composition forecasts at 0.25° (25km) resolution are generated in near-real time available since January 2018

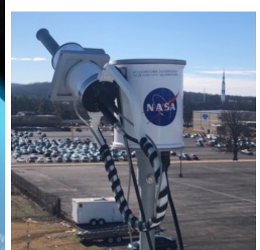
Keller, C. A., et al. (2021). **Description of the NASA GEOS composition forecast modeling system GEOS-CF v1.0**. *Journal of Advances in Modeling Earth Systems*, 13, e2020MS002413. https://doi.org/10.1029/2020MS002413

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

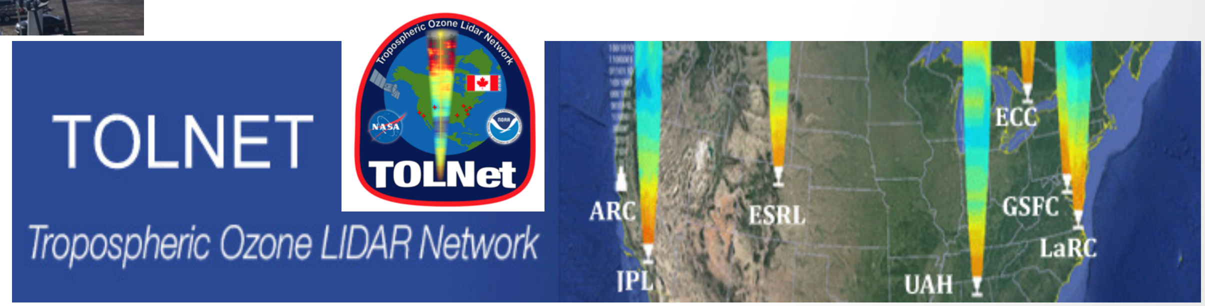
Realistic tropospheric and stratospheric composition is critical for many NASA applications

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





- TEMPO a priori for trace gas retrieval
- NASA field missions
  (e.g., SCOAPE, FIREX-AQ, TRACER-AQ, ASIA-AQ)
- Daily alerts sent to NASA TOLNet lidar teams
  (Matt Johnson, NASA Ames)



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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*

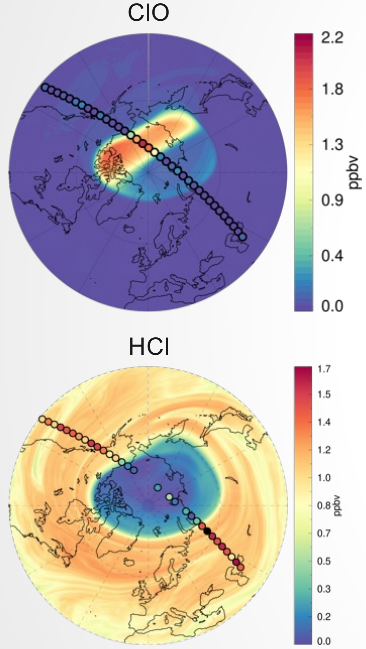
Start date: 00 UTC 1 January 2022

Mode: Replay only; Forecasts available based on mission requirements

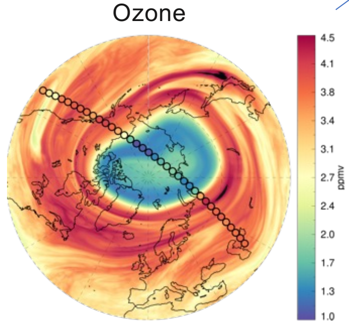
Knowland et al., 2022. "File Specification for GEOS-CF Products." *GMAO Office Note No. 17 (Version 1.2), available from http://gmao.gsfc.nasa.gov/pubs/office_notes*

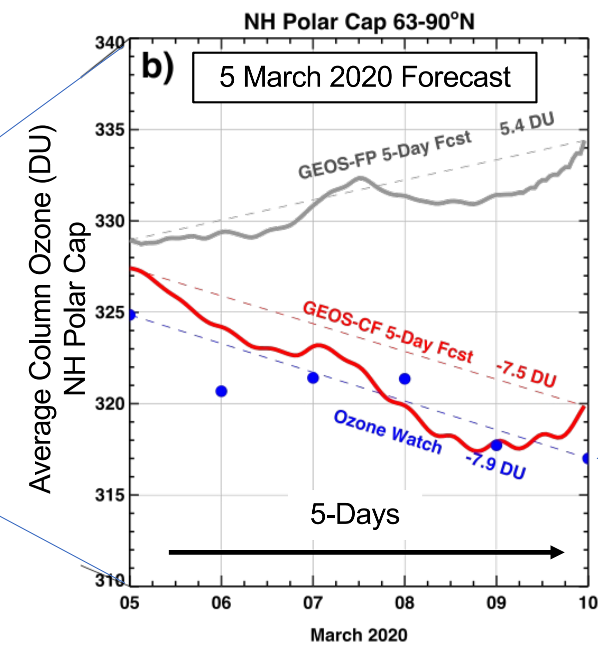
Name	Dim	Description	Units
BrO	tzyx	Bromine monoxide (BrO, MW = 96.00 g mol-1) volume mixing ratio dry air	mol mol-1
FRSEAICE	tyx	ice covered fraction of tile	1
FRSNO	tyx	fractional area of land snowcover	1
GLYX	tzyx	Glyoxal (CHOCHO, MW = 58.00 g mol-1) volume mixing ratio dry air	mol mol-1
HCHO	tzyx	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
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

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

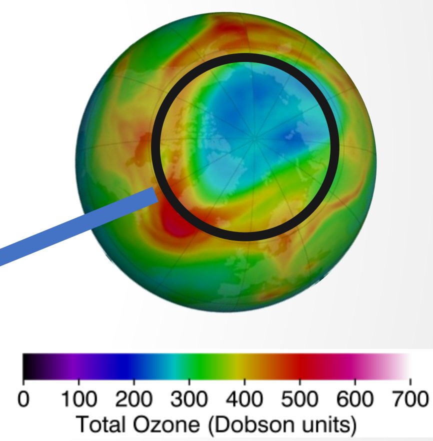


March 5, 2020
GEOS-CF





March 10, 2020
Ozonewatch



Ozonewatch.gsfc.nasa.gov

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

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

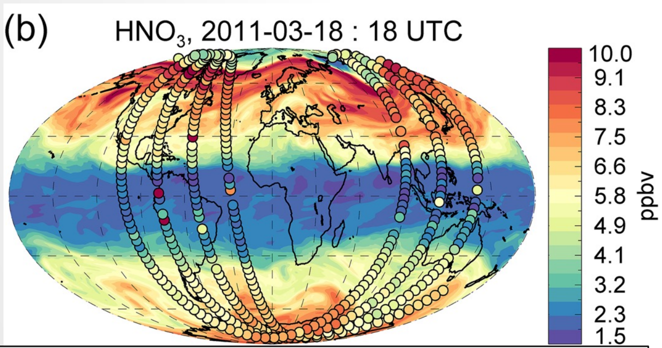
3D-Var assimilation of ozone, NO_2 and SO_2 satellite data

https://gmao.gsfc.nasa.gov/weather_prediction/GEOS-CF/
k.e.knowland@nasa.gov

Constituent Data Assimilation System (CoDAS)

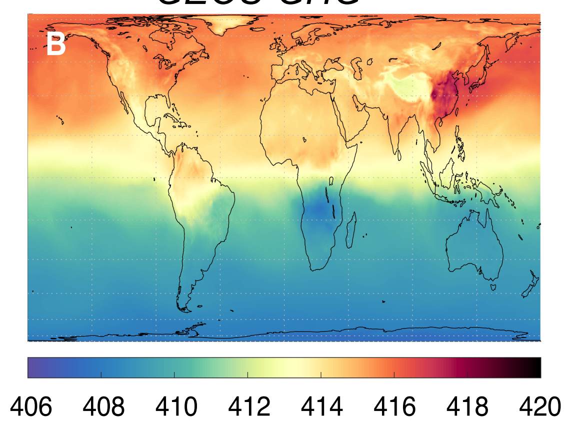
- Designed to be tracer agnostic: can assimilate any type of retrieved constituent observations with an averaging kernel or at a point
  - CoDAS builds on the Gridpoint Statistical Interpolation scheme developed at NCEP and GMAO
  - GMAO involved and invested in the constituent DA with JEDI

M2-SCREAM



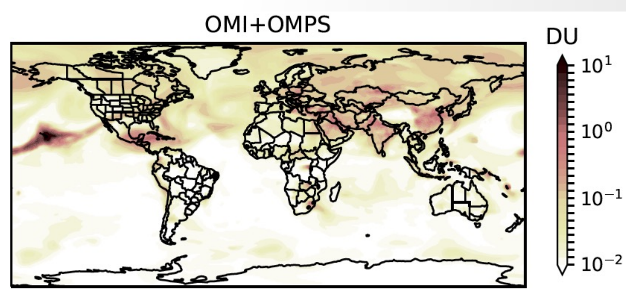
Wargan et al., ESS (2023). DOI: 10.1029/2022EA002632

GEOS-GHG



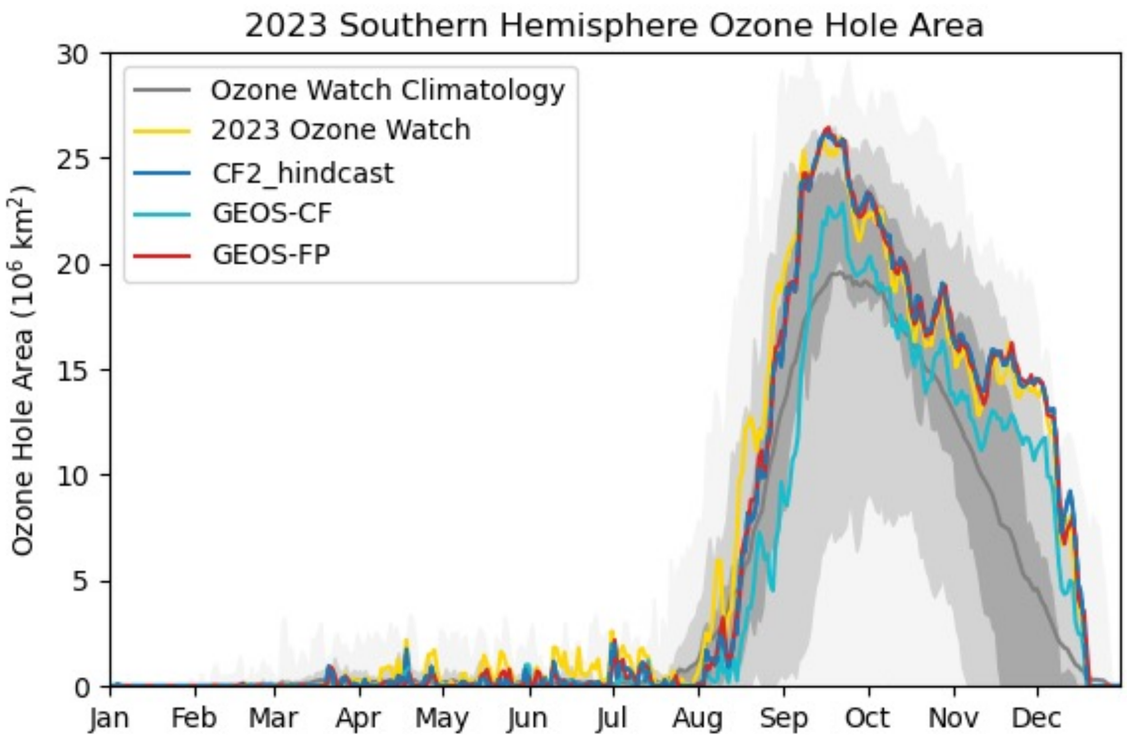
Weir et al., Sci. Adv. (2021) DOI:10.1126/sciadv.abf9415

GEOS-CF v2



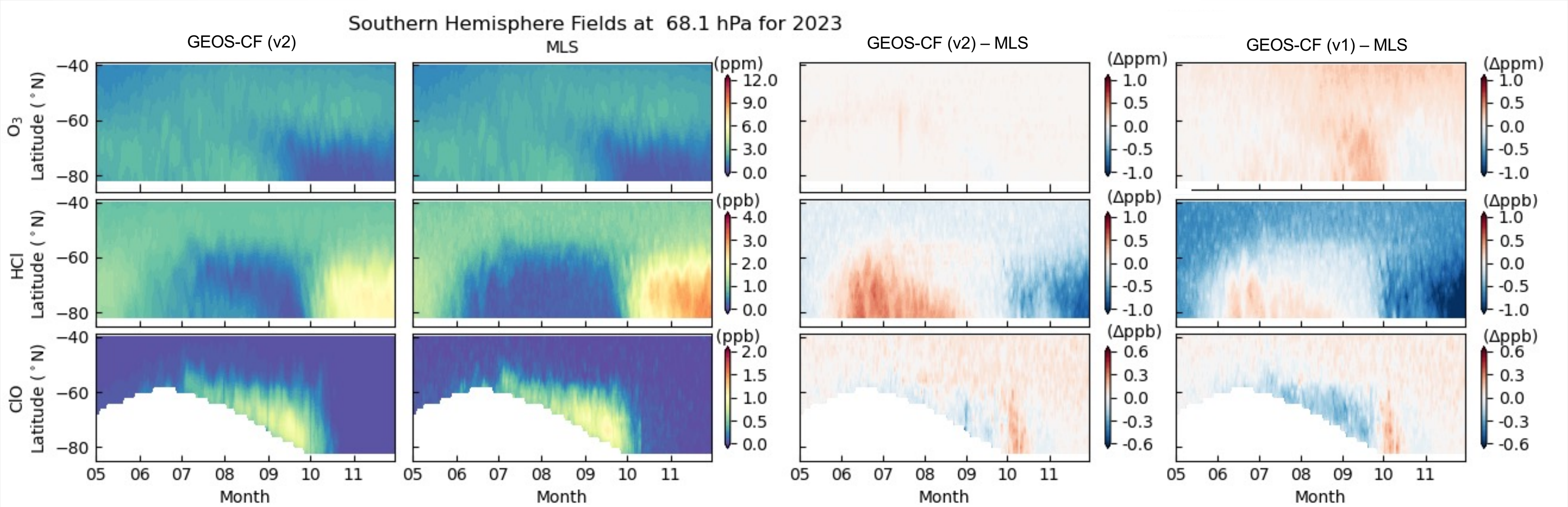
https://gmao.gsfc.nasa.gov/research/science_snapshots/2022/mauna-loa.php

Improved representation of Stratospheric Ozone Hole



Direct assimilation of Aura ozone measurements improves the representation of the Antarctic ozone hole in the updated GEOS-CF system (dark blue) vs the current GEOS-CF system (cyan) and Observations (yellow; ozonewatch based on OMPS for 2023 https://ozonewatch.gsfc.nasa.gov/)

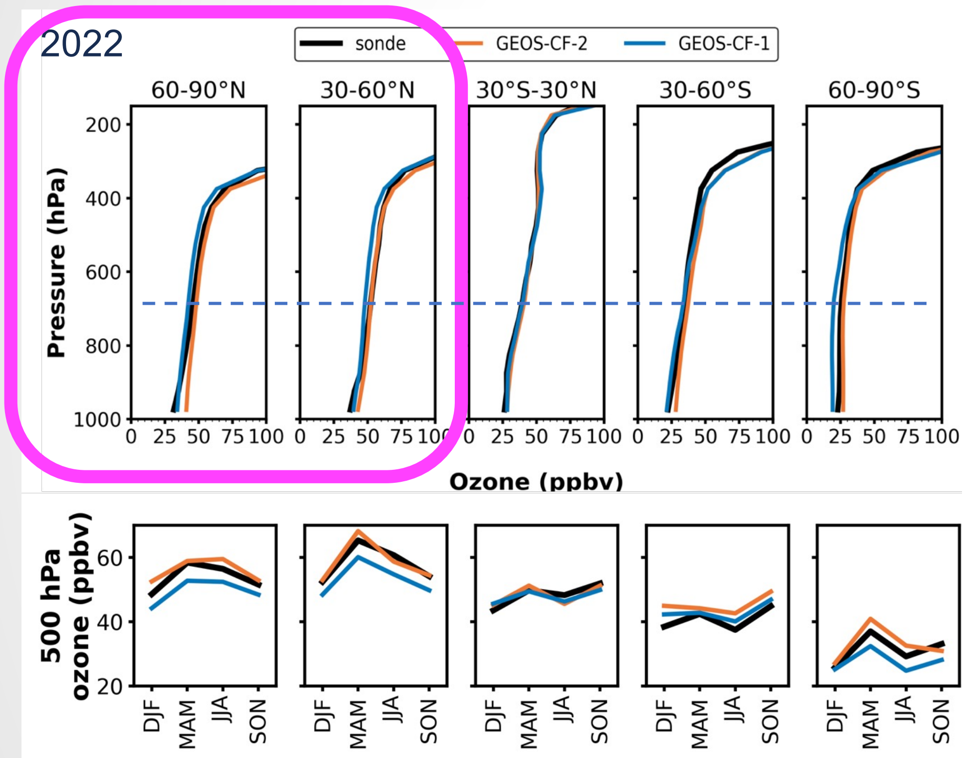
GEOS-Chem updates for improved stratospheric chemistry



The formation of the ozone hole involves chlorine-driven catalytic loss cycles

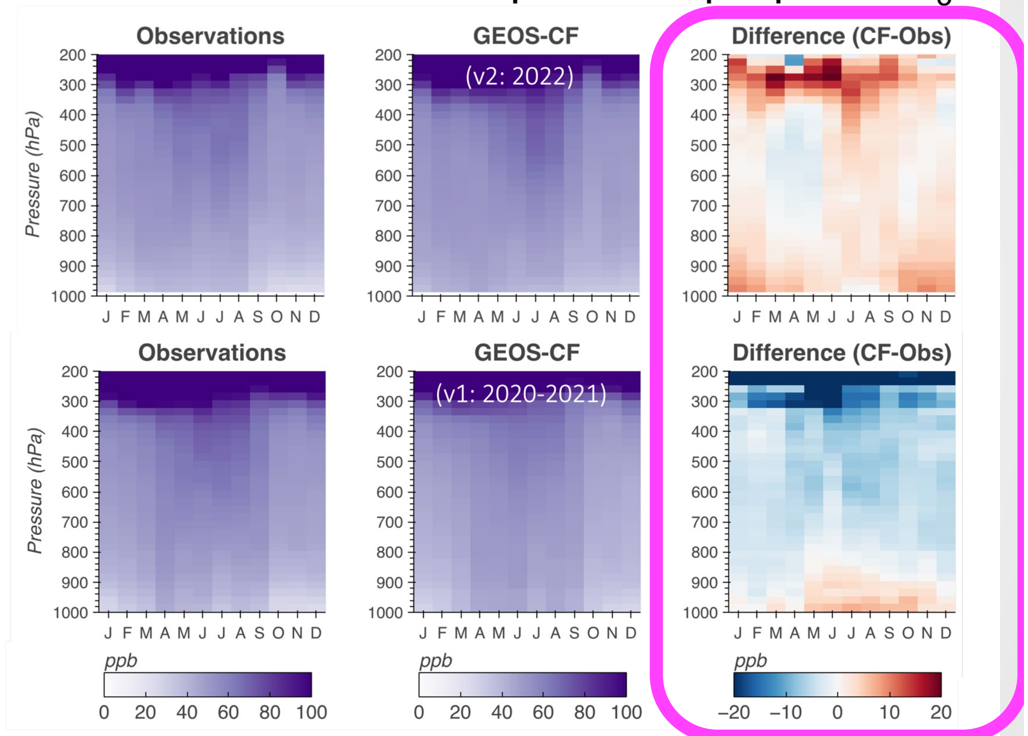
- Activation of chlorine chemistry is seen by MLS via the conversion of stable HCl to reactive ClO
- Updates in the GEOS-Chem tropospheric chlorine chemistry improve the representation of the ozone loss cycles in the lower stratosphere

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

Stratospheric Intrusion case study May 11, 2023

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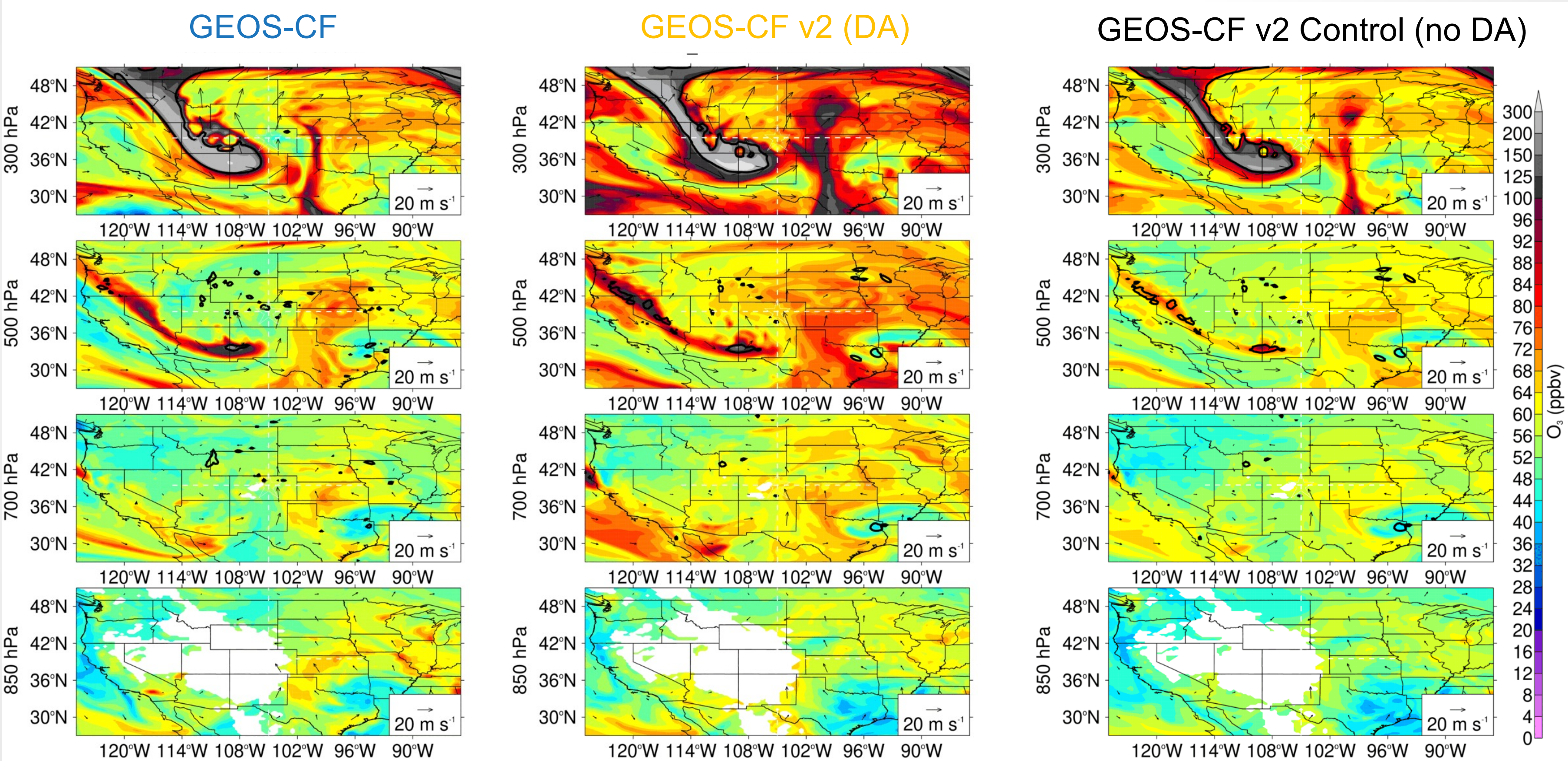
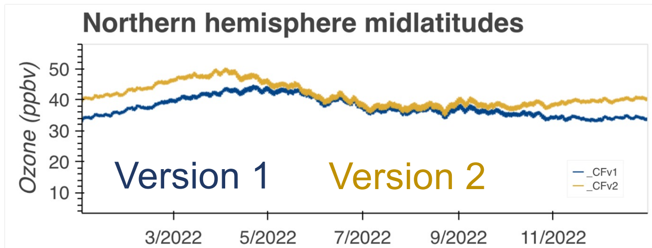
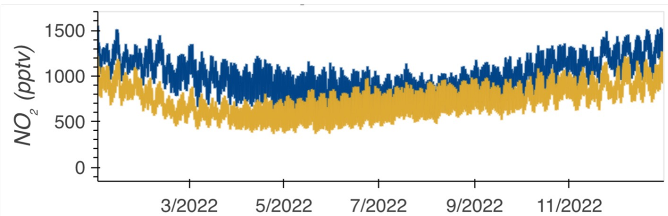
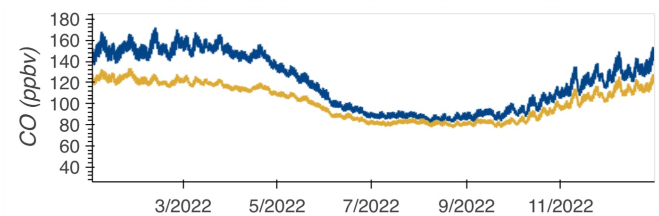


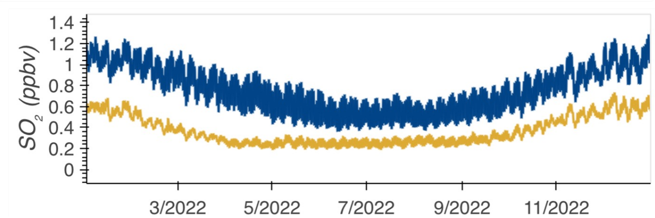
Lower NOx emissions is leading to higher Ozone in GEOS-CF version 2

2022 Annual surface concentration

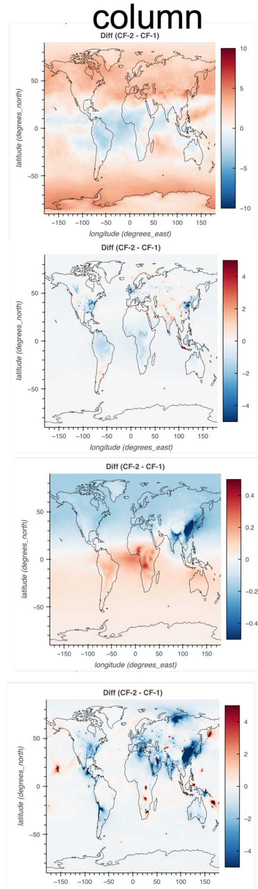


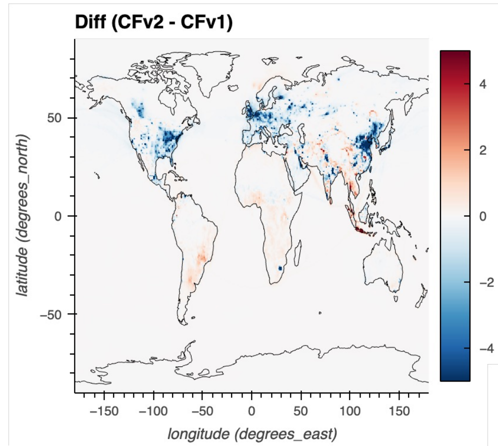






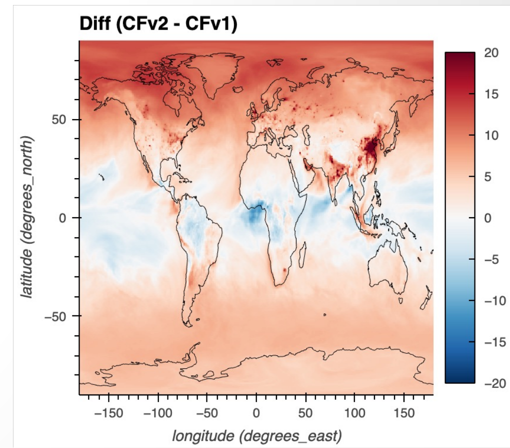
Annual tropospheric column





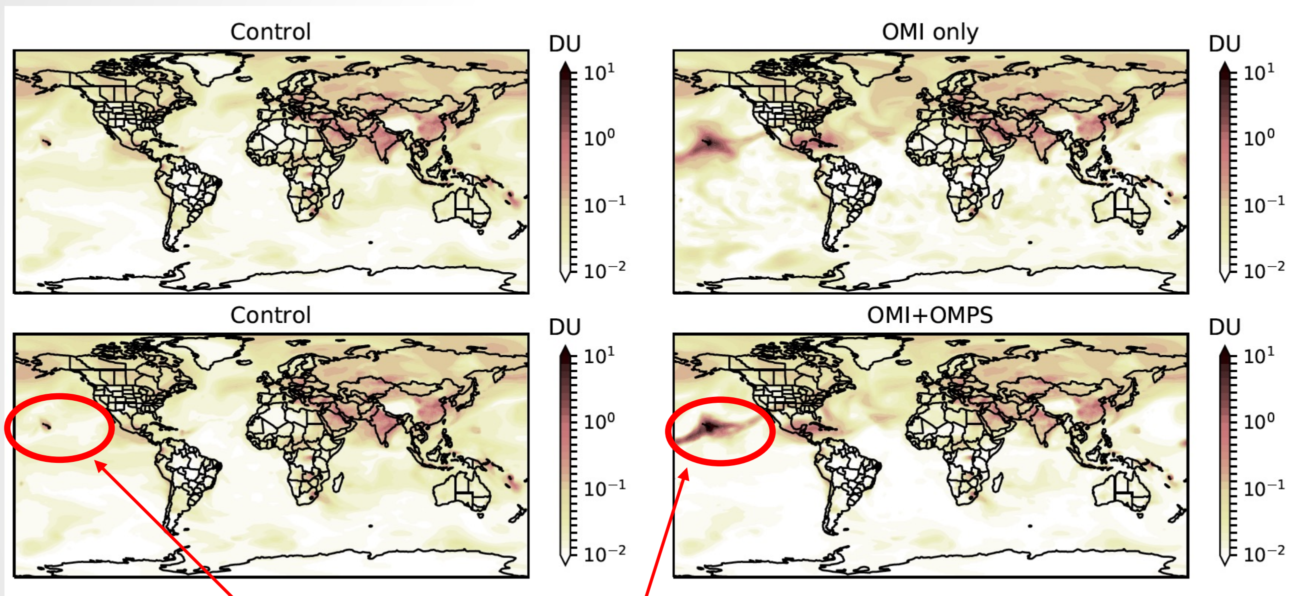
⬅ Surface NO_2 is lower in v2, especially in urban areas

➡ this leads to higher surface O_3



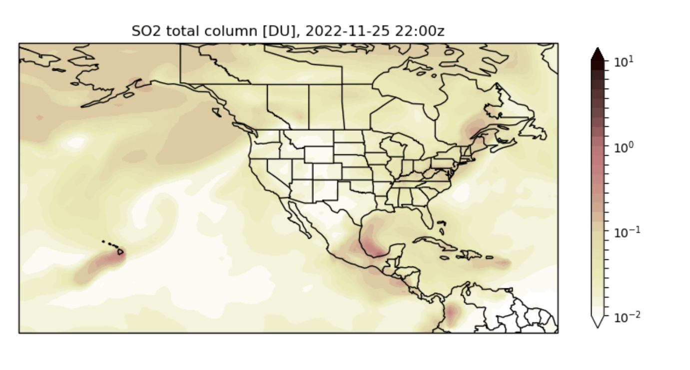
SO_2 assimilation: Mauna Loa's smoking gun

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).

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

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

GEOS Composition Reanalysis 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)

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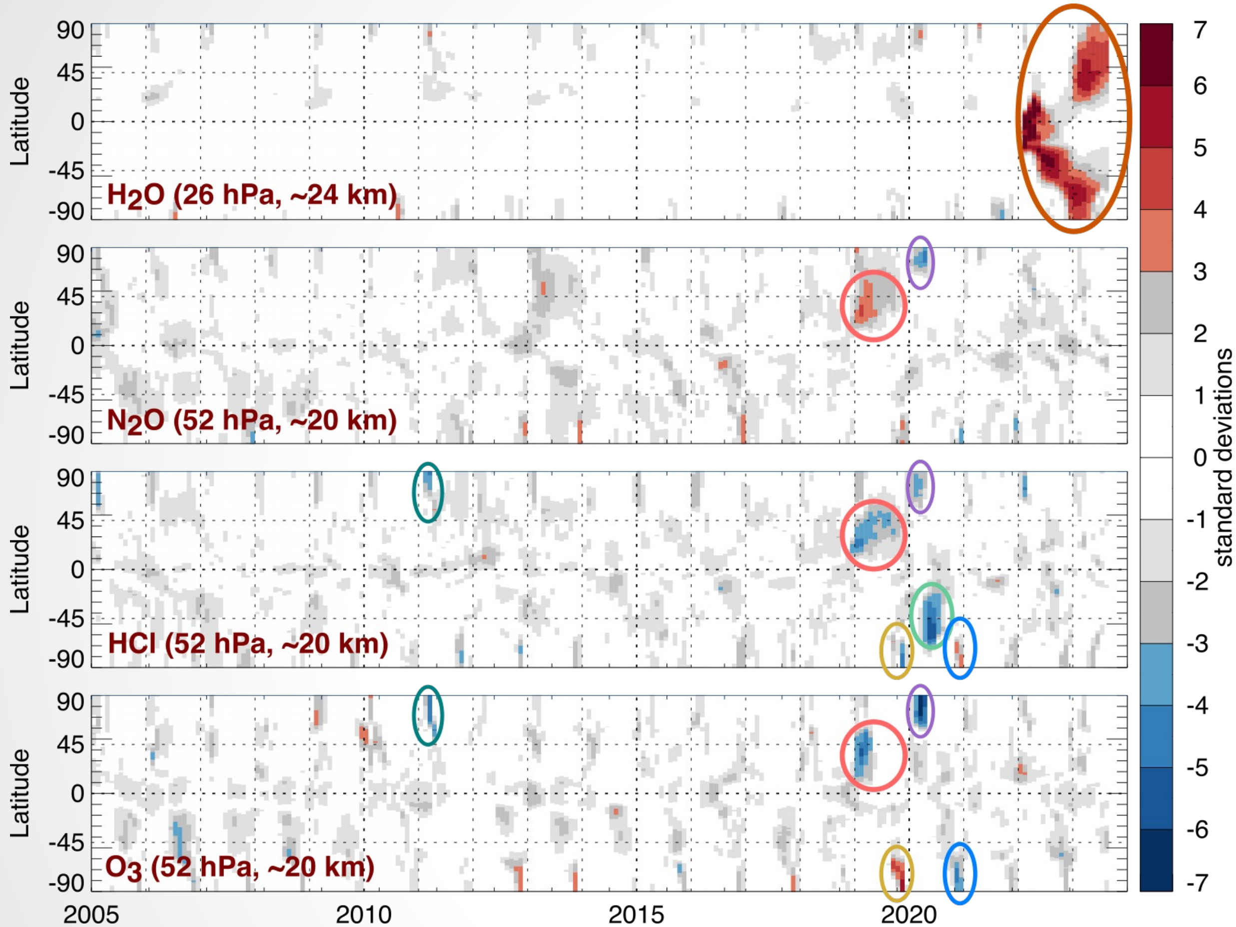

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Our surprising stratosphere

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.

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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

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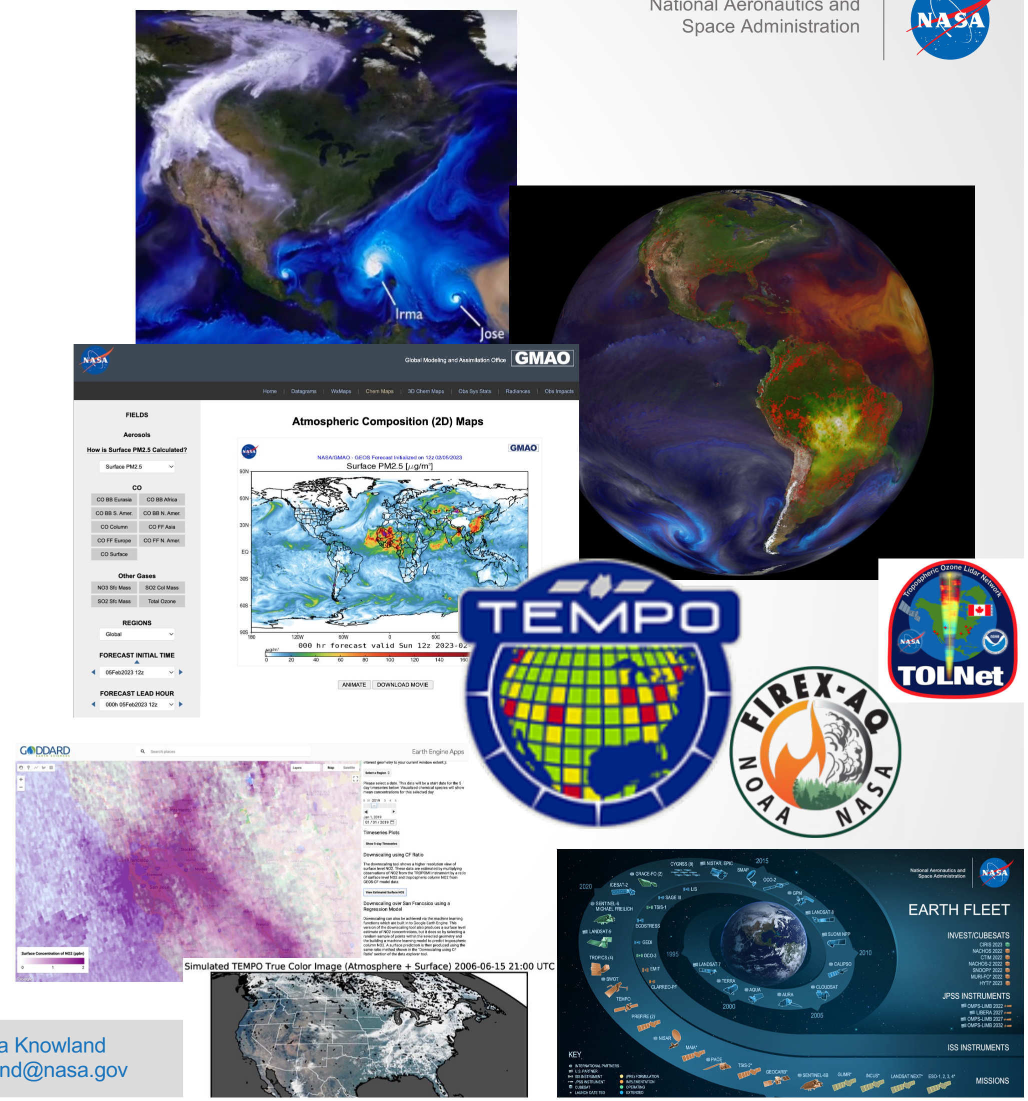
Summary

- GMAO has a state-of-the-science Earth System model and data assimilation system
- Involved and invested in new data assimilation infrastructure for multi-constituent data assimilation system
- GEOS-CF Version 1 grew from ROSES funding and has expanded GMAO's role in global composition forecasting
- Support of additional NASA science teams (providing a priori for TEMPO trace gas retrievals, field campaigns, …)
- GEOS-CF Version 2 introduces assimilation and other improvements (model transport, emissions) and is the basis for GMAO's constituent reanalysis

Thank you for listening!



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