NASA GEOS Composition Forecast System, GEOS-CF

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GMAO
Global Modeling & Assimilation Office

Introduction

GEOS is an Earth System Model designed to advance the use of satellite data products. Since it is a modular system, it can be run as a numerical weather prediction model and coupled to chemistry modules.

Fig 1: Example of cube sphere grid used in GEOS (Bindle et al., 2021 GMD)

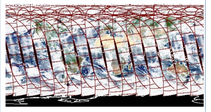

Fig 2: MODIS imagery stitched together to show global coverage (https://modis.gsfc.nasa.gov/)

GEOS-CF

For version 1 of GEOS-CF, the GEOS AGCM is coupled to the GEOS-Chem chemistry module (version 12) with full tropospheric and stratospheric chemistry

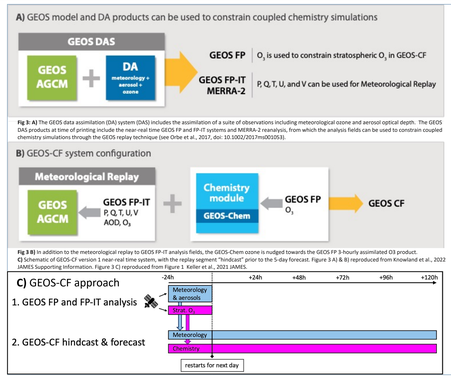

Fig 3: **A)** The GEOS data assimilation (DA) system (DAS) includes the assimilation of a suite of observations including meteorological ozone and aerosol optical depth. The GEOS DAS products at time of printing include the near-real time GEOS FP and FP-IT systems and MERRA-2 reanalysis, from which the analysis fields can be used to constrain coupled chemistry simulations through the GEOS replay technique (see Orbe et al., 2017, doi: 10.1002/2017ms001053).

Fig 3 **B)** In addition to the meteorological replay to GEOS FP-IT analysis fields, the GEOS-Chem ozone is nudged towards the GEOS FP 3-hourly assimilated O3 product. **C)** Schematic of GEOS-CF version 1 near-real time system, with the replay segment "hindcast" prior to the 5-day forecast. Figure 3 A) & B) reproduced from Knowland et al., 2022 JAMES Supporting Information. Figure 3 C) reproduced from Figure 1 Keller et al., 2021 JAMES.

One **5-day forecast** per day
- Initialized at 12z
- 1-day meteorological replay ("hindcast")
- 5-day forecast
- c360 (0.25°, ~**25x25 km²**)
- 72 layers (surface to 0.01hPa)
- GEOS-Chem v12.0.1

Data distributed via OpenDAP and HTTPS:
- 2D output at 15 minute and hourly frequency
- 3D output at hourly and three hourly frequency
- ❖ 1-hour 2D & 3D output, **including specific TEMPO file for trace-gas retrievals**
- Available since
  - **1 January 2018** (replay)
  - **1 January 2019** (forecast)

Emissions:
- HTAP v2.2 (global bottom-up) for anthropogenic
- Near real-time fires (QFED)
- Online dust, sea salt, plant emissions
  - Observation-constraints:
- Currently no direct data assimilation of constituents in GEOS-CF
- GOCART aerosols constrained by satellite measurements of AOD
- Biomass burning emissions from QFED

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*

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

Validation

GEOS-CF v1 has been evaluated for both tropospheric and stratospheric composition and forecast skill (Keller et al., 2021; Knowland et al., 2022). Examples given below.

Ozonesonde

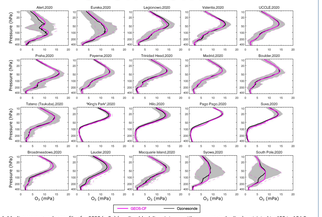

Fig 5: Median ozonesondes profiles for 2018-2019 (opaly) (median black line, interquartile range gray shading) restricted to 1000 to 200 hPa to focus on troposphere. Co-located GEOS-CF profiles (median, magenta). Reproduced from Keller et al. 2021 (JAMES)

Surface observations

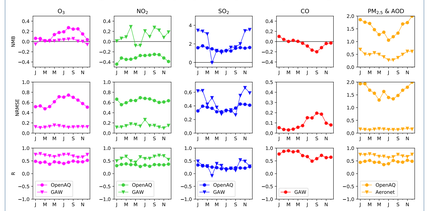

Fig 6: Monthly skill scores means, calculated from daily mean concentrations and aggregated by observation source (Global Atmosphere Watch, "GAW"; OpenAQ database; Aeronet). Top row Normalized Mean Bias (NMB). Middle row Normalized Root Mean Square Error (NRMSE); Bottom row Pearson's correlation (R). Reproduced from Keller et al. 2021 (JAMES)

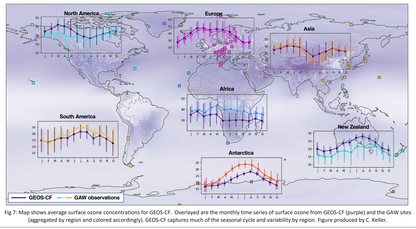

Fig 7: Map shows average surface ozone concentrations for GEOS-CF. Overlayed are the monthly time series of surface ozone from GEOS-CF (purple) and the GAW sites (aggregated by region and colored accordingly). GEOS-CF captures much of the seasonal cycle and variability by region. Figure produced by C. Keller.

Satellite observations

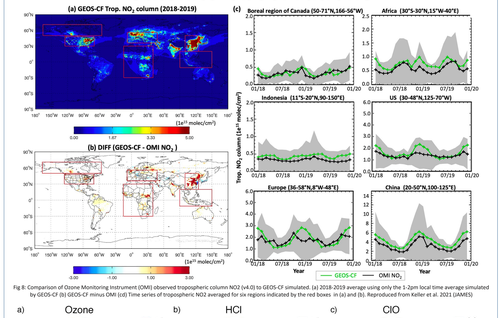

Fig 8: Comparison of Ozone Monitoring Instrument (OMI) observed tropospheric column NO2 (v4.0) to GEOS-CF simulated. (a) 2018-2019 average using only the 1-2pm local time average simulated by GEOS-CF (b) GEOS-CF minus OMI (col) Time series of tropospheric NO2 averaged for six regions indicated by the red boxes in (a) and (b). Reproduced from Keller et al. 2021 (JAMES)

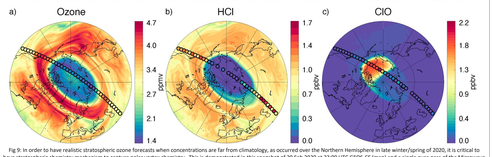

Fig 9: In order to have realistic stratospheric ozone forecasts when concentrations are far from climatology, as occurred over the Northern Hemisphere in late winter/spring of 2020, it is critical to have stratospheric chemistry mechanism to capture polar vortex chemistry. This is demonstrated in this snapshot of 29 Feb 2020 at 22:00 UTC GEOS-CF (map) and a single over-pass of the Microwave Limb Sounder (MLS) (colored circles, measurements from 21:43 UTC to 22:14 UTC) at 45 hPa for a) Ozone, b) Hydrogen Chloride, c) Chlorine Monoxide. Reproduced from Knowland et al. 2022 (JAMES)

TEMPO support

A special collection was created for TEMPO "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; Forecasts during mission

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 (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

- Files are accessed by the TEMPO team from the NCCS Dataportal e.g., https://portal.nccs.nasa.gov/datashare/gmao/geos-cf/v1/forecast/Y2022/M01/D23/H12/GEOS-CF.v01.rpl.sat_inst_1hr_r720x361_v72*.nc4
- The replay files are available since January 1, 2022 e.g., https://portal.nccs.nasa.gov/datashare/gmao/geos-cf/v1/das/Y2022/M01/D01/GEOS-CF.v01.rpl.sat_inst_1hr_r720x361_v72*.nc4
- In addition, hourly climatologies are provided to the TEMPO team for the Northern Hemisphere in case of any long delays in GEOS-CF production during mission operation.

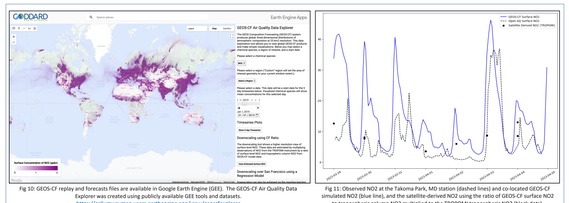

Fig 10: GEOS-CF replay and forecasts files are available in Google Earth Engine (GEE). The GEOS-CF Air Quality Data Explorer was created using publicly available GEE tools and datasets. https://ullahnewman.users.earthengine.app/view/geos5explorer

Fig 11: Observed NO2 at the Takoma Park, MD station (dashed lines) and co-located GEOS-CF simulated NO2 (blue line), and the satellite-derived NO2 using the ratio of GEOS-CF surface NO2 to tropospheric column NO2 multiplied to the TROPOMI tropospheric NO2 (black dots). Figure produced by C. Wayman

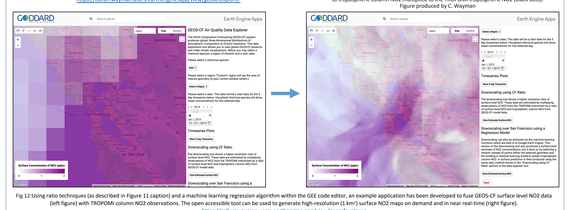

Fig 12:Using ratio techniques (as described in Figure 11 caption) and a machine learning regression algorithm within the GEE code editor, an example application has been developed to fuse GEOS-CF surface level NO2 data (left figure) with TROPOMI column NO2 observations. The open accessible tool can be used to generate high-resolution (1 km) surface NO2 maps on demand and in near real-time (right figure). https://ullahnewman.users.earthengine.app/view/geos5explorer

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Applications

The GEOS-CF forecasts for the individual TOLNet locations are provided to Matt Johnson (NASA Ames) for tailored email alerts

GEOS-CF is now in Google Earth Engine thanks to the NASA-Google Partnership. This enables new avenues for data fusion capabilities for downscaling the forecasts

Tropospheric Ozone Lidar Network (TOLNet)

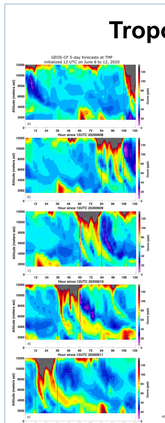

Fig 11: GEOS-CF 5-day forecasts for the grid box (34.25 °N, 117.25 °W) closest to NASA Jet Propulsion Laboratory Table Mountain Facility located at 2290 m elevation and about 1.5 hours northeast from Los Angeles, initialized at 12:00 UTC on a) 8 June, b) 9 June, c) 10 June, d) 11 June, and e) 12 June 2020. Vertical dashed pink lines indicate the 24-hour period of 13 June 2020 in each forecast which aligns with the measured ozone profiles from the TOLNet lidar at TMF "TMTOL" (Fig 12). Reproduced from Knowland et al. 2022 (JAMES)

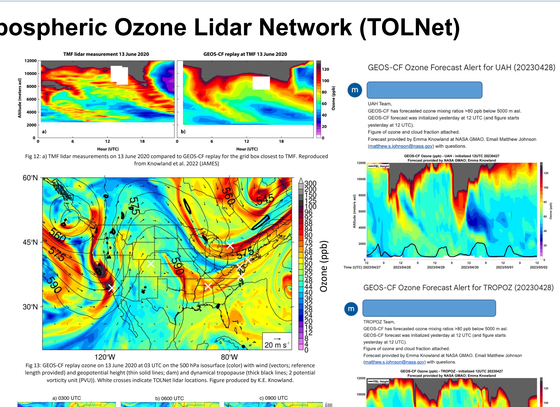

Fig 12: a) TMF lidar measurements on 13 June 2020 compared to GEOS-CF replay for the grid box closest to TMF. Reproduced from Knowland et al. 2022 (JAMES)

Fig 13: GEOS-CF replay ozone on 13 June 2020 at 03 UTC on the 500 hPa isosurface (color) with wind (vectors; reference length provided) and geopotential height (thin solid lines; dam) and dynamical tropopause (thick black lines; 2 potential vorticity units (PVU)). White crosses indicate TOLNet lidar locations. Figure produced by K.E. Knowland.

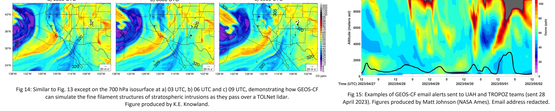

Fig 14: Similar to Fig. 13 except on the 700 hPa isosurface at a) 03 UTC, b) 06 UTC and c) 09 UTC, demonstrating how GEOS-CF can simulate the fine filament structures of stratospheric intrusions as they pass over a TOLNet lidar. Figure produced by K.E. Knowland.

Fig 15: Examples of GEOS-CF email alerts sent to UAH and TROPOZ teams (sent 28 April 2023). Figures produced by Matt Johnson (NASA Ames). Email address redacted.

GEOS-CF NO_2 profiles

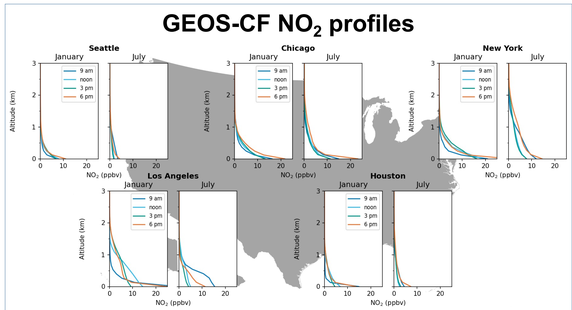

Fig 16: Seasonal and hourly comparisons of GEOS-CF simulated NO2 profiles in the bottom 3 km at 5 major US cities demonstrates the magnitude of variation of NO2 concentrations as a result of changes in emissions, oxidation and boundary layer height during the daytime. Figure produced by V. Shah.

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