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


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

- 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

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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 0.25° longitude: 0° to -180° latitude: 0° to 90° 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


<table>
<thead>
<tr>
<th>Name</th>
<th>Dim</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>BrO</td>
<td>tzyx</td>
<td>Bromine monoxide (BrO, MW = 96.00 g mol⁻¹) volume mixing ratio dry air</td>
<td>mol mol⁻¹</td>
</tr>
<tr>
<td>FRSEAICE</td>
<td>txy</td>
<td>ice covered fraction of tile</td>
<td>1</td>
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<tr>
<td>FRSN0</td>
<td>txy</td>
<td>fractional area of land snowcover</td>
<td>1</td>
</tr>
<tr>
<td>GLYX</td>
<td>tzyx</td>
<td>Glyoxal (CHOCHO, MW = 58.00 g mol⁻¹) volume mixing ratio dry air</td>
<td>mol mol⁻¹</td>
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<tr>
<td>HCHO</td>
<td>tzyx</td>
<td>Formaldehyde (CH₂O, MW = 30.00 g mol⁻¹) volume mixing ratio dry air</td>
<td>mol mol⁻¹</td>
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<tr>
<td>HNO₂</td>
<td>tzyx</td>
<td>Nitrous acid (HNO₂, MW = 47.00 g mol⁻¹) volume mixing ratio dry air</td>
<td>mol mol⁻¹</td>
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<tr>
<td>IO</td>
<td>tzyx</td>
<td>Iodine monoxide (IO, MW = 143.00 g mol⁻¹) volume mixing ratio dry air</td>
<td>mol mol⁻¹</td>
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<tr>
<td>NO₂</td>
<td>tzyx</td>
<td>Nitrogen dioxide (NO₂, MW = 46.00 g mol⁻¹) volume mixing ratio dry air</td>
<td>mol mol⁻¹</td>
</tr>
<tr>
<td>O₃</td>
<td>tzyx</td>
<td>Ozone (O₃, MW = 48.00 g mol⁻¹) volume mixing ratio dry air</td>
<td>mol mol⁻¹</td>
</tr>
<tr>
<td>OClO</td>
<td>tzyx</td>
<td>Chlorine dioxide (OClO, MW = 67.00 g mol⁻¹) volume mixing ratio dry air</td>
<td>mol mol⁻¹</td>
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<tr>
<td>PHIS</td>
<td>txy</td>
<td>surface geopotential height</td>
<td>m²⁺ s⁻²</td>
</tr>
<tr>
<td>PS</td>
<td>txy</td>
<td>surface pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>Q</td>
<td>txy</td>
<td>specific humidity</td>
<td>kg kg⁻¹</td>
</tr>
<tr>
<td>SNODP</td>
<td>txy</td>
<td>snow depth</td>
<td>m</td>
</tr>
<tr>
<td>SNOMAS</td>
<td>txy</td>
<td>Total snow storage land</td>
<td>kg m⁻²</td>
</tr>
<tr>
<td>SO₂</td>
<td>tzyx</td>
<td>Sulfur dioxide (SO₂, MW = 64.00 g mol⁻¹) volume mixing ratio dry air</td>
<td>mol mol⁻¹</td>
</tr>
<tr>
<td>T</td>
<td>tzyx</td>
<td>air temperature</td>
<td>K</td>
</tr>
<tr>
<td>TROPPB</td>
<td>txy</td>
<td>tropopause pressure based on blended estimate</td>
<td>Pa</td>
</tr>
<tr>
<td>U2M</td>
<td>txy</td>
<td>2-meter eastward wind</td>
<td>m s⁻¹</td>
</tr>
<tr>
<td>V2M</td>
<td>txy</td>
<td>2-meter northward wind</td>
<td>m s⁻¹</td>
</tr>
<tr>
<td>ZPBL</td>
<td>txy</td>
<td>planetary boundary layer height</td>
<td>m</td>
</tr>
</tbody>
</table>

https://gmao.gsfc.nasa.gov/weather_prediction/GEOS-CF/
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GEOS-CF with stratospheric chemistry adds near-real-time stratospheric ozone forecasting capability to the NASA GMAO

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)

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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

GEOS-GHG

GEOS-CF v2

GMAO involved and invested in the constituent DA with JEDI

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

DOI: 10.1126/sciadv.abf9415

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SO$_2$ assimilation: Mauna Loa’s smoking gun

Simulated SO$_2$ total column [DU] for Dec 6, 2022

Evolution of assimilated SO$_2$ from the Mauna Loa eruption in November 2022

Mauna Loa eruption only captured in runs with assimilation

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).

NO$_2$ assimilation ➡️ Improved NO$_2$ in polluted areas

Assimilating OMI NO$_2$ total slant columns

Mostly Strat NO$_2$ in remote atmosphere

Observations (DU)  Forecast (DU)

O-F (DU)  Increments (DU)

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

Frequency distributions of O-F and O-A

Global

https://gmao.gsfc.nasa.gov/weather_prediction/GEOS-CF/  
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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 O₃ and PM₂.₅

New Meteorology ➡️ Improved summertime (JJA) surface O₃

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

Using latest CEDS with current estimates ➡️ Improved annual PM₂.₅

Ozone assimilation ➡️ Improved tropospheric ozone

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GEOS Composition Reanalysis for the 21\textsuperscript{st} Century

Lines of development and legacy systems

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

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

GEOS CR development

Greenhouse Gas data assimilation (GEOS-GHG)

Assimilation of chemically reactive carbon species: CO\textsubscript{2} and CH\textsubscript{4}

Air quality / tropospheric chemistry modeling and assimilation

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

**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
## Assimilated species and sensors

### Retrievals

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Molecules</th>
<th>Observation type</th>
</tr>
</thead>
<tbody>
<tr>
<td>OMI, TROPOMI, OMPS</td>
<td>NO$_2$, SO$_2$, O$_3$</td>
<td>Column</td>
</tr>
<tr>
<td>SCIAMACHY, GOSAT, TROPOMI</td>
<td>CH$_4$</td>
<td>Column</td>
</tr>
<tr>
<td>SCIAMACHY, GOSAT, OCO</td>
<td>CO$_2$</td>
<td>Column</td>
</tr>
<tr>
<td>MOPITT TIR &amp; NIR</td>
<td>CO</td>
<td>Column</td>
</tr>
<tr>
<td>MLS</td>
<td>O$_3$, HCl, HNO$_3$, N$_2$O, H$_2$O, CH$_3$Cl, CO</td>
<td>Stratospheric limb profiles</td>
</tr>
<tr>
<td>OMPS-LP</td>
<td>O$_3$</td>
<td>Stratospheric limb profiles</td>
</tr>
</tbody>
</table>

established  new

### Radiances

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Wavelength</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIRS, IASI (MetOp-A,B), CrIS FSR (potentially)</td>
<td>9.6 μm</td>
<td>Ozone-sensitive channels</td>
</tr>
</tbody>
</table>

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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.
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!