Air Quality Forecasting with NASA GEOS-CF

Presenter

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DISCLAIMER

Most of the material I will present today is taken (with permission and occasional modification) from materials created by the **NASA Applied Remote Sensing Training (ARSET) Program**. They provide detailed multi-hour training sessions going through how to use NASA data for many applications, including air quality. Trainings are recorded, and the recordings, slides, and example codes are available on their website. This is the resource I go to when I want to know more about how to use any NASA data product.



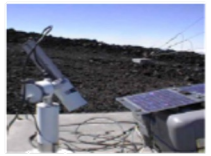
For the best information, go to the source!

https://appliedsciences.nasa.gov/what-we-do/capacity-building/arset/arset-health-air-quality-trainings

There are many sources of air quality information

traditional monitors





low-cost sensors

Ground Measurements





atmospheric observations (lidar)

Air & Space Observations

satellites





aircraft
balloons

Models

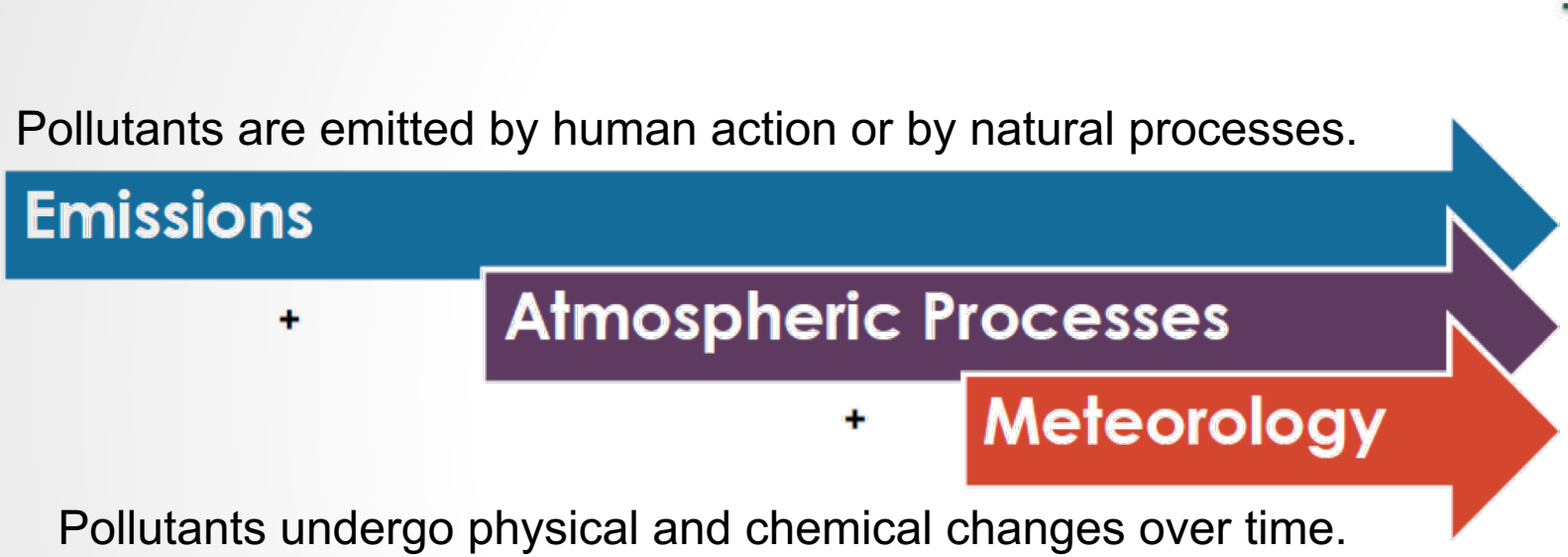


global models
regional models

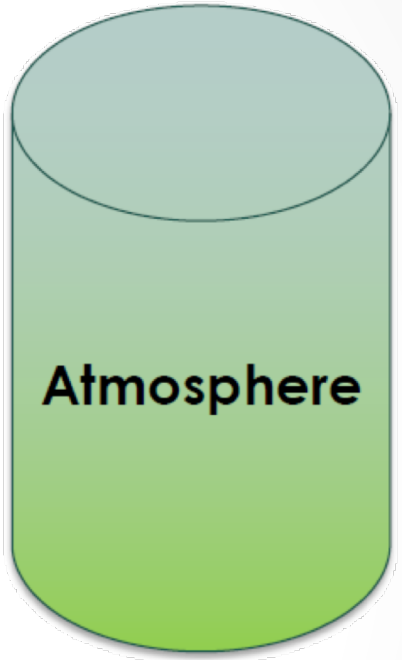
Source: Gupta, P.; Follette-Cook, M. (2018). Satellite Remote Sensing of Air Quality. NASA Applied Remote Sensing Training Program (ARSET). https://appliedsciences.nasa.gov/join-mission/training/english/arset-satellite-remote-sensing-air-quality

What determines air quality?

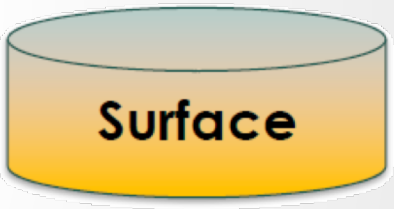
Pollutants are emitted by human action or by natural processes.



Pollutants undergo physical and chemical changes over time.
Pollutants are also moved and removed by meteorological processes.



Pollutants are distributed in the atmosphere; only pollutants near the surface have direct immediate impacts to human health and activities.



air quality models seek to capture these processes in a simplified way to explain air quality changes in space and time.

Source: Gupta, P.; Follette-Cook, M.; Parrington, M.; Stewart, C. (2021). *Introduction and Access to Global Air Quality Forecasting Data and Tools*. NASA ARSET.
https://appliedsciences.nasa.gov/join-mission/training/english/arset-introduction-and-access-global-air-quality-forecasting-data-and

Air quality forecasts vary in scope, purpose, complexity

- **"Zero Order" methods**

  persistence: current AQ situation continues

  climatology: use typical monthly/daily AQ

- **Criteria or decision tree methods**

  "If X then Y" forecasts based on simple rules

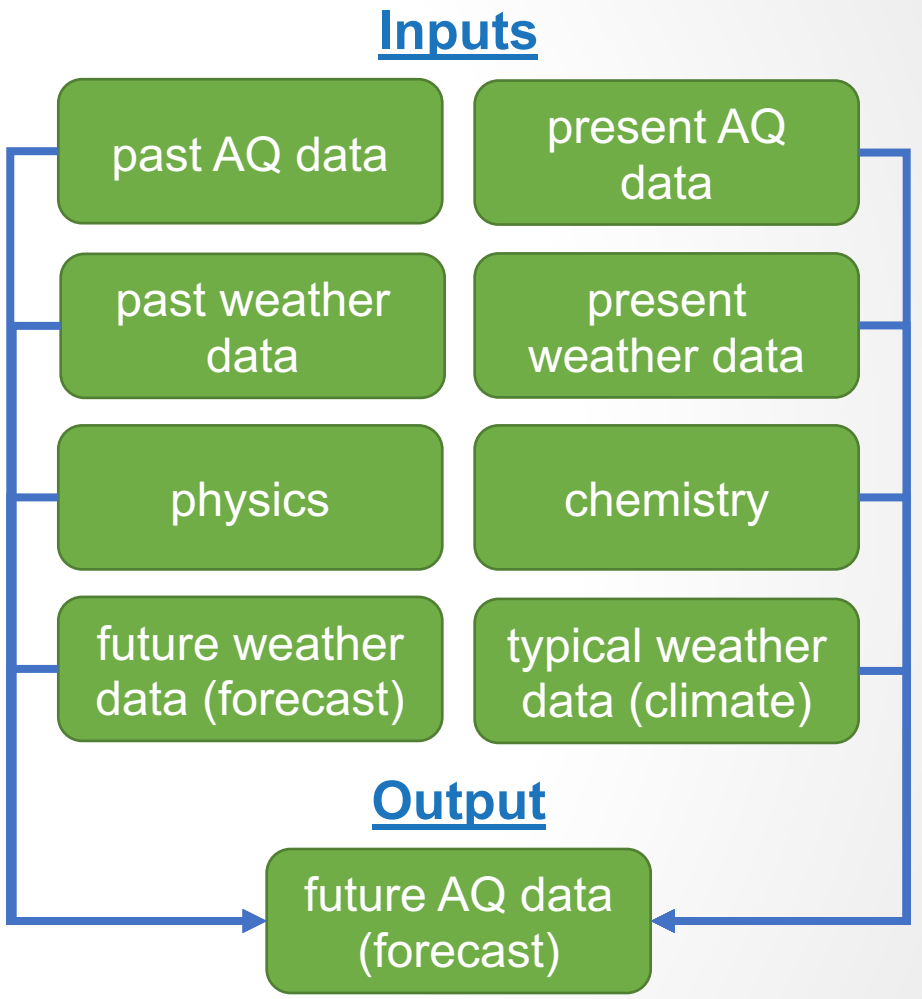
- **Statistical methods (incl. machine learning)**

  use typical relationships between AQ and explanatory factors to give forecasts

- **Chemical transport models**

  Lagrangian: tracking of "plumes"

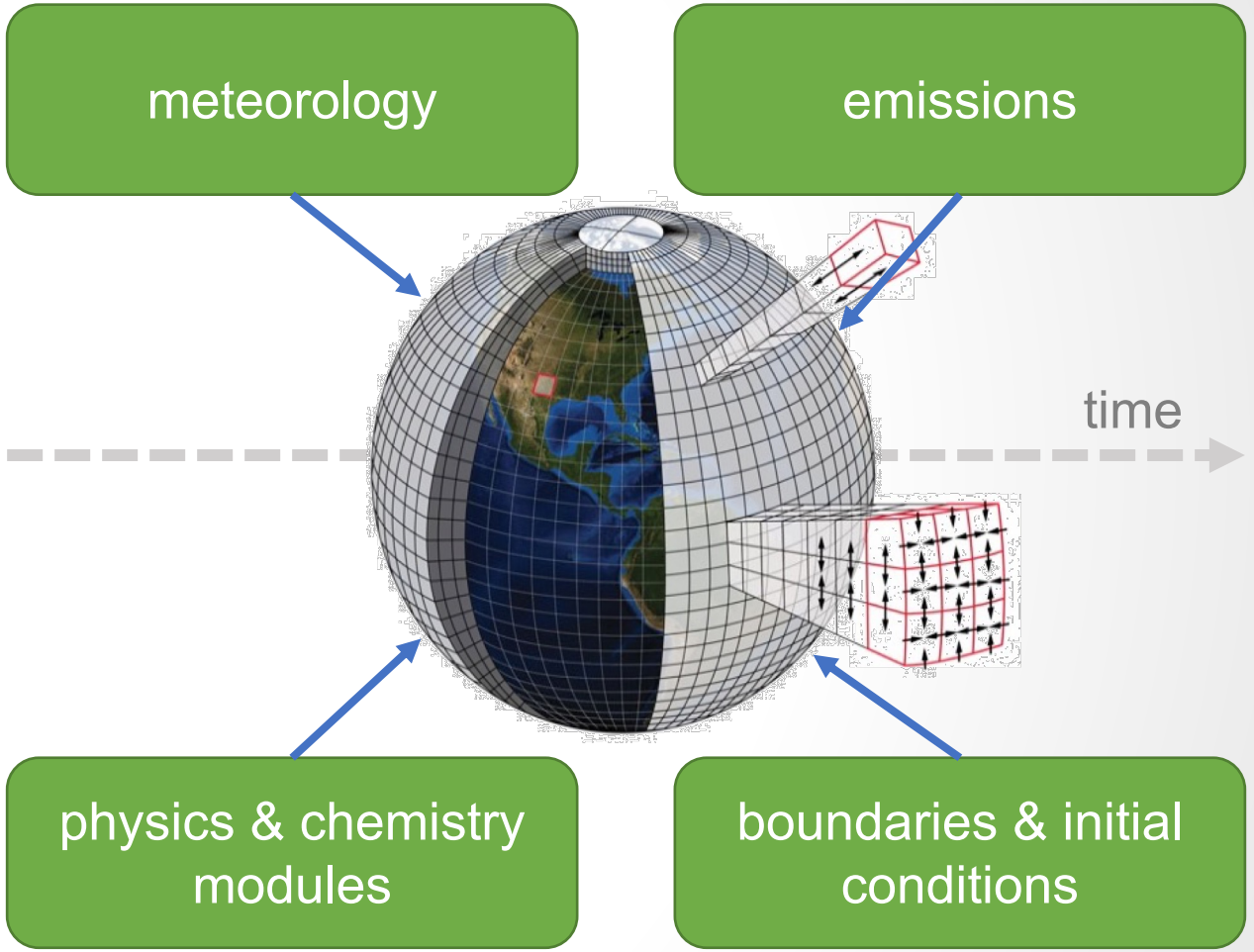
  Eulerian: interconnected "boxes"



Source: Gupta, P.; Follette-Cook, M.; Parrington, M.; Stewart, C. (2021). *Introduction and Access to Global Air Quality Forecasting Data and Tools*. NASA ARSET. https://appliedsciences.nasa.gov/join-mission/training/english/arset-introduction-and-access-global-air-quality-forecasting-data-and

Atmospheric transport & chemistry models

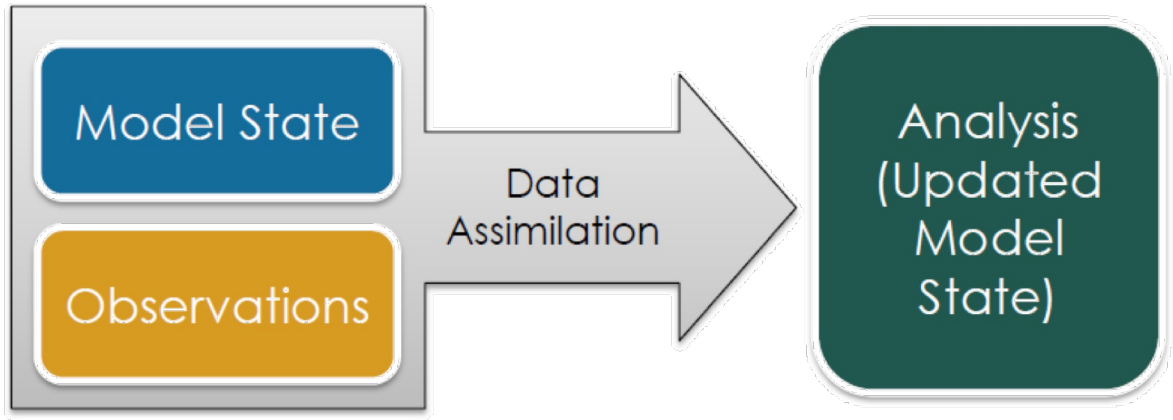
- **Mathematically represent the processes which influence air quality** (emission, transport, diffusion, transformation, removal)
- Operate on a **4D grid** with a specified resolution (horizontal, vertical, temporal)
- Can be part of an **Earth Systems Model** simulating the atmosphere, hydrosphere, geosphere, biosphere, etc.
- Models require decades of research and development; **updates integrate the latest science**, but make it harder to compare between different versions of the model
- **Different models use different approaches**, and so give different results.



Source: Gupta, P.; Follette-Cook, M.; Parrington, M.; Stewart, C. (2021). *Introduction and Access to Global Air Quality Forecasting Data and Tools*. NASA ARSET. https://appliedsciences.nasa.gov/join-mission/training/english/arset-introduction-and-access-global-air-quality-forecasting-data-and

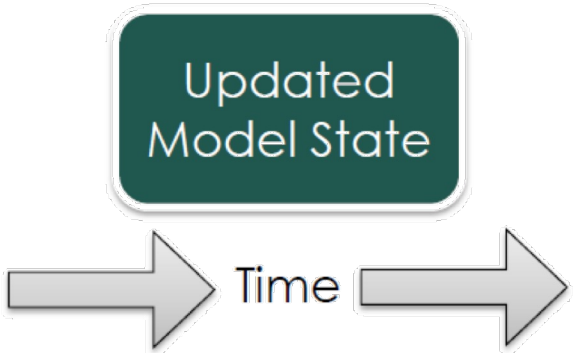
Assimilation, analysis, reanalysis & forecasting

Data assimilation describes the process of assimilating, or incorporating, observations into a model state to produce the best estimate of the atmosphere, land, and ocean conditions.



An **analysis** is the blend of the model and observations.

A **reanalysis** blends observations with model simulations of the past using a single model version.

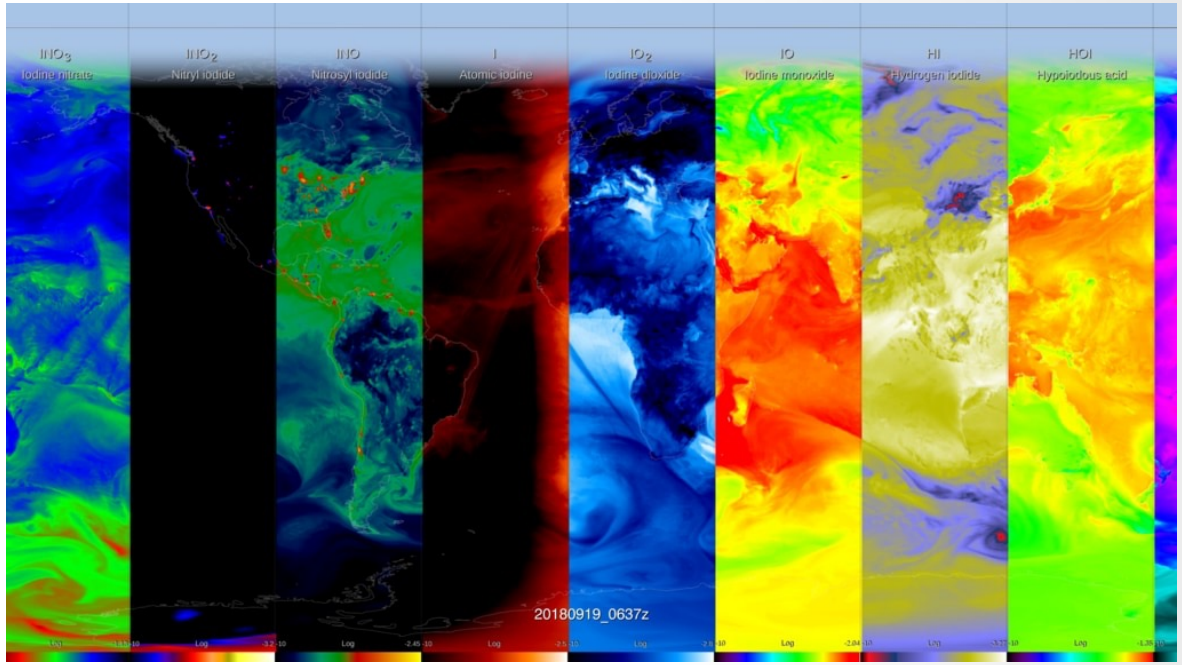


A **forecast** is a model simulation run forward in time to predict a future state.

Source: Gupta, P.; Follette-Cook, M.; Parrington, M.; Stewart, C. (2021). *Introduction and Access to Global Air Quality Forecasting Data and Tools*. NASA ARSET. https://appliedsciences.nasa.gov/join-mission/training/english/arset-introduction-and-access-global-air-quality-forecasting-data-and

Advantages of air quality models

- Simulate physical and chemical processes which affect air quality; **data are self-consistent**.
- Applicable to **many space & time scales**.
- **No "missing data"**. The model grid is complete.
- Can forecast **future conditions**.
- Can utilize measurements (through data assimilation), but do not require measurements; this makes models **useful in data-sparse regions**.
- **Freely available** global models are run by various groups (including NASA), whose outputs can be used by anyone around the world for free.
- Simulations can **identify sources** of pollution and their relative importance to local air quality.

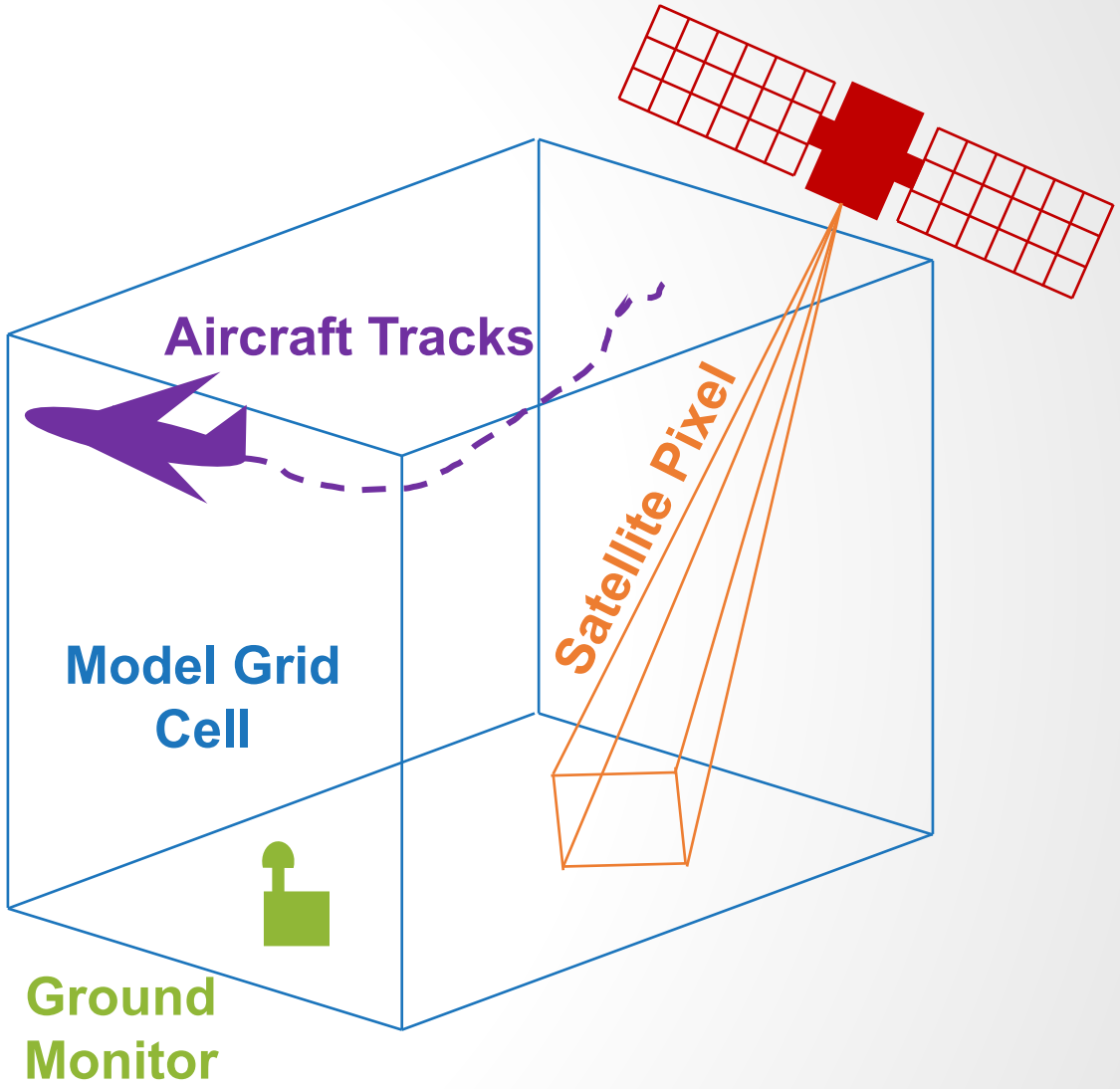


Visualization of several outputs from the NASA GEOS atmospheric chemistry model system.
Source: https://svs.gsfc.nasa.gov/4754

Source: Gupta, P.; Follette-Cook, M.; Parrington, M.; Stewart, C. (2021). *Introduction and Access to Global Air Quality Forecasting Data and Tools*. NASA ARSET. https://appliedsciences.nasa.gov/join-mission/training/english/arset-introduction-and-access-global-air-quality-forecasting-data-and

Weaknesses of air quality models

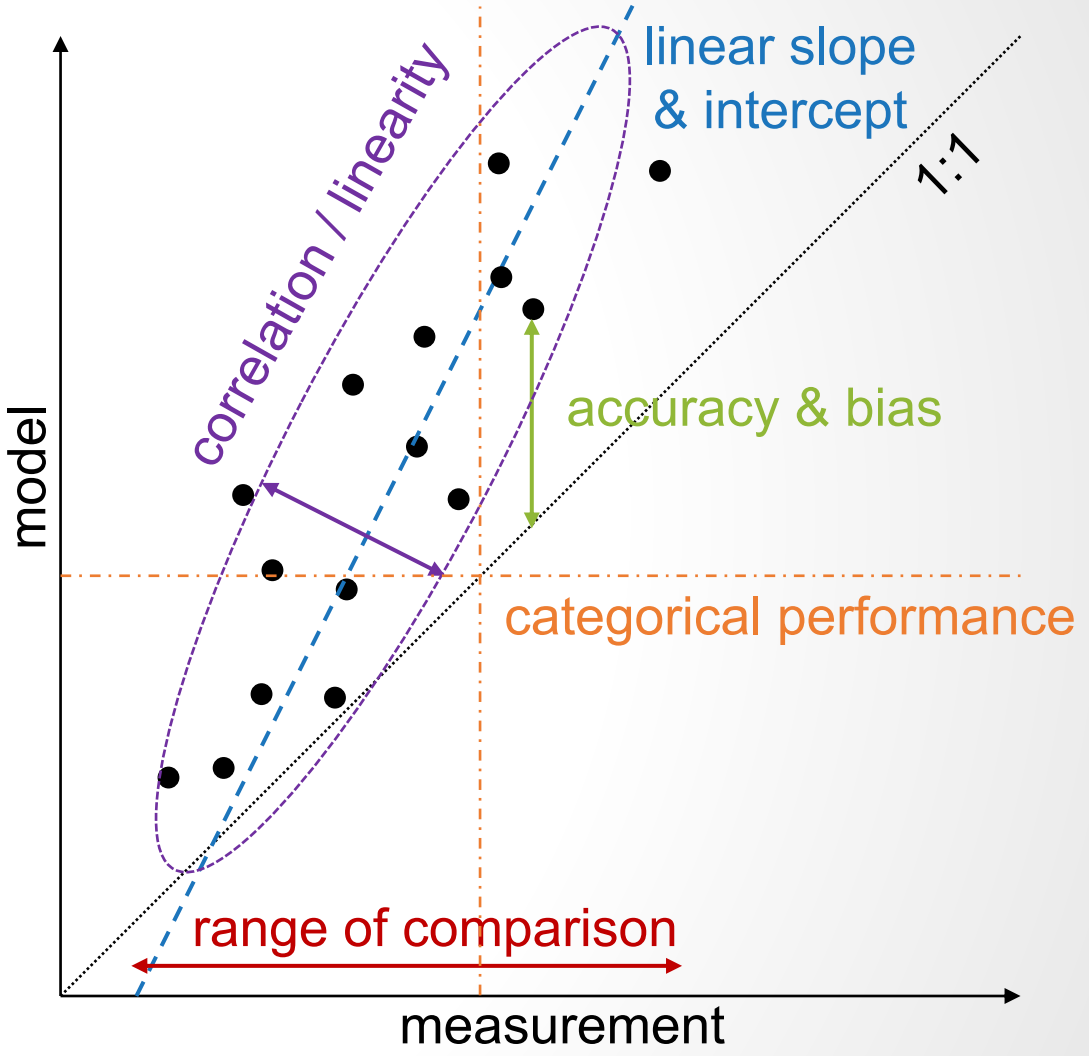
- **"garbage in, garbage out"**; model outputs are only as good as the emissions data, model assumptions, and initial conditions that are used.
- **Out of date** and/or **coarse resolution emissions inventories** cause uncertainty.
- **Model outputs are not directly comparable to ground or other data sources** due to the scale mis-match; the model estimates average concentrations across its grid, which are not the same as measurements at specific locations.
- Models are difficult and **computationally intensive** to run.
- **Large amount of data** requires expertise & software to interpret and visualize.



Source: Gupta, P.; Follette-Cook, M.; Parrington, M.; Stewart, C. (2021). *Introduction and Access to Global Air Quality Forecasting Data and Tools*. NASA ARSET. https://appliedsciences.nasa.gov/join-mission/training/english/arset-introduction-and-access-global-air-quality-forecasting-data-and

Assessing the accuracy of air quality models

- **Comparisons** to independent data sources: ground data, airborne data, satellite data
- **Metrics for Comparison**:
  - correlation (anomaly correlation)
  - bias (may be different for different ranges)
  - accuracy (e.g., root mean square error)
  - spatial/temporal/concentration ranges
- **Sensitivity & Specificity**: ability to categorically forecast poor air quality events
- **Is the model "fit for purpose"?** Are the forecast timescale, frequency, accuracy, and data interpretability appropriate for the intended use?



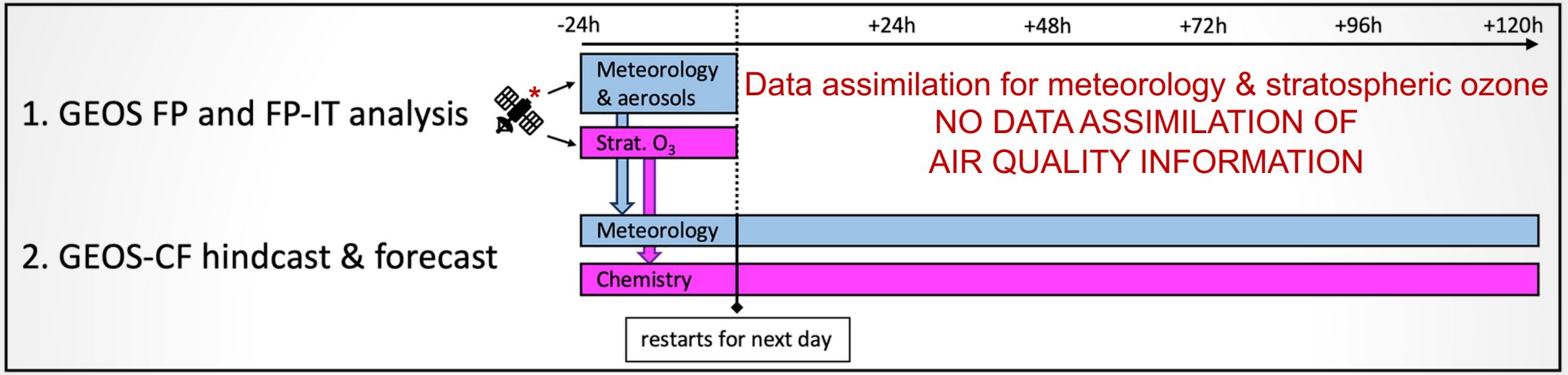
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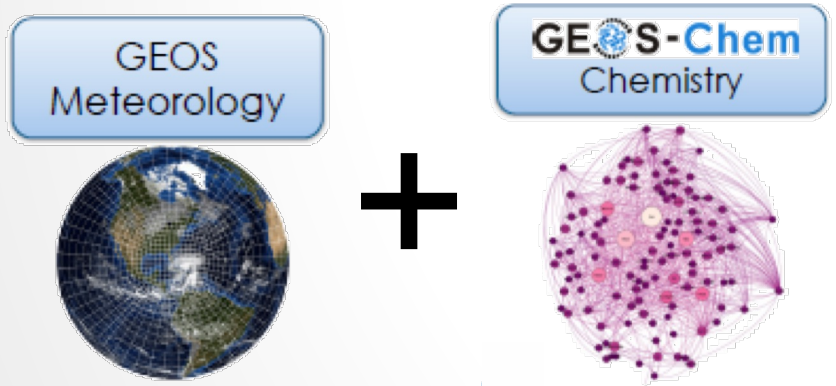
NASA Goddard Earth Observing System (GEOS)

	GEOS FP	GEOS-CF	MERRA-2
Type	Analysis + Forecast	Replay + Forecast	Reanalysis
Domain	Global	Global	Global
Spatial Resolution	Simulation: ~12 km Output: ~25 km (0.25°x0.312°)	~25 km (0.25°x0.312°)	~50km (0.5°x0.625°)
Temporal Resolution	2-D data: Hourly 3-D data: Every 3 h	15 min, Hourly	Hourly, Daily, Monthly
Vertical Levels	72 (near surface-0.1 hPa)	72 (near surface-0.1 hPa)	72 (near surface-0.1 hPa)
Output available	Analysis: 2014 – Present Forecast: ~20 days	Replay: 2018 – Present Forecast: 2019 – Present (aqc collection) ~14 days (all collections)	1980-Present
Initialization	Daily 10-day forecast at 00Z Daily 5-day forecast at 12Z	Daily 5-day forecast at 12Z	~1-2 months behind real time
Data Assimilation	Yes	No	Yes
File Specification Doc	https://gmao.gsfc.nasa.gov/pubs/docs/Lucchesi1203.pdf *	https://gmao.gsfc.nasa.gov/pubs/docs/Knowland1204.pdf *	https://gmao.gsfc.nasa.gov/pubs/docs/Bosilovich785.pdf *

Source: Gupta, P.; Follette-Cook, M.; Parrington, M.; Stewart, C. (2021). *Introduction and Access to Global Air Quality Forecasting Data and Tools*. NASA ARSET. https://appliedsciences.nasa.gov/join-mission/training/english/arset-introduction-and-access-global-air-quality-forecasting-data-and

GEOS Composition Forecast (GEOS-CF)





- Combine GEOS meteorology with GEOS-Chem chemistry
- 250 chemical species
- Hourly temporal resolution
- 0.25 degree (25 km) spatial resolution
- Global coverage
- Daily 1-day hindcast and 5-day forecast

Source: Keller, C., et al. (2021) "Description of the NASA GEOS Composition Forecast Modeling System GEOS-CF v1.0". *Journal of Advances in Modeling Earth Systems*, 13:4. https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020MS002413

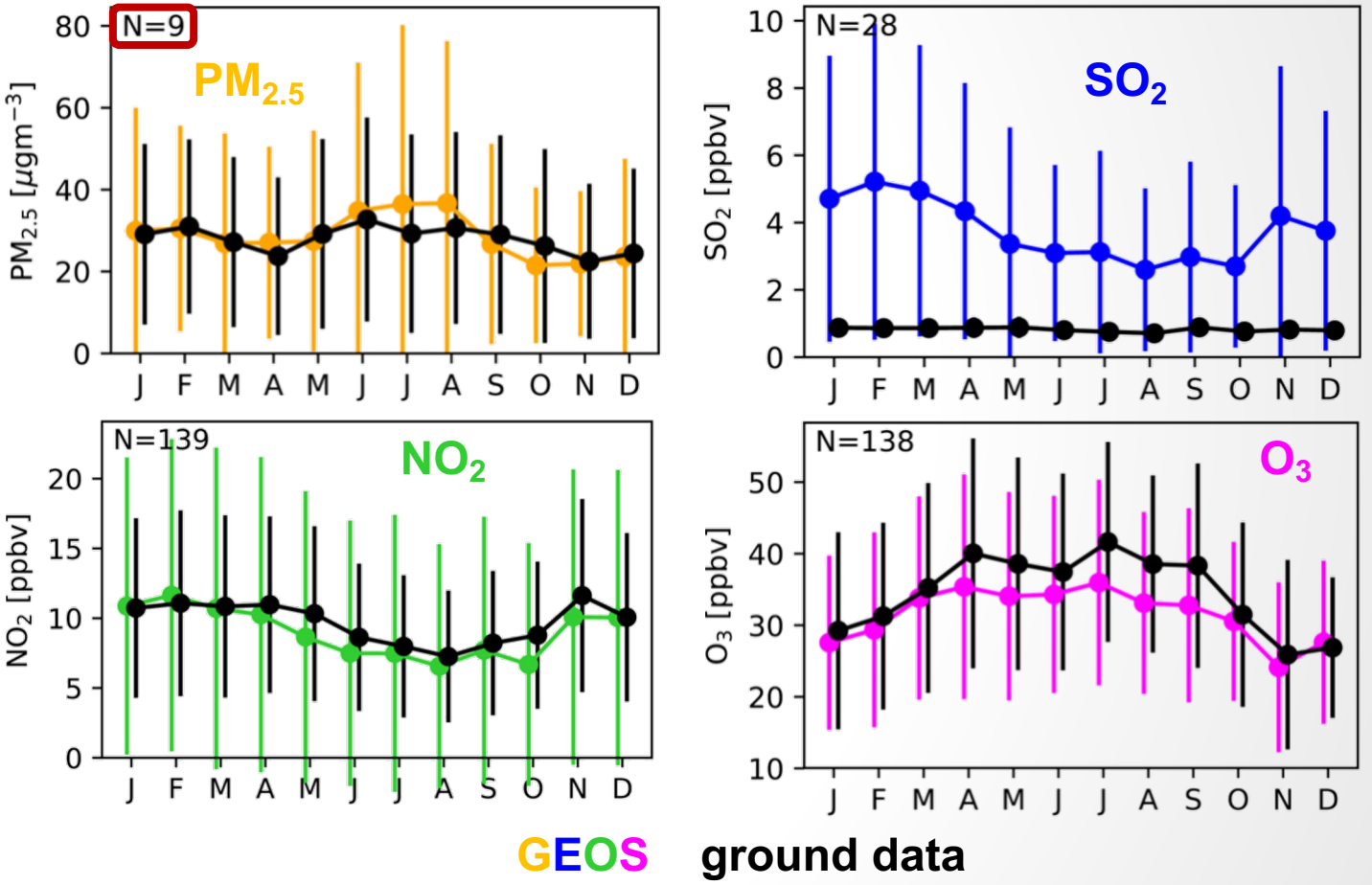
GEOS-CF performance evaluation

In general, GEOS-CF estimates and forecasts agree well with ground-based data for air quality relevant quantities.

HOWEVER:

- Agreement can vary annually, seasonally and by region.
- There can be high bias at individual locations due to local impacts.
- Many regions have limited ground data for verification.
- Some pollutants are not well represented yet (SO_2 is biased high globally).

Monthly average concentrations at sites in Africa



Source: Keller, C., et al. (2021) "Description of the NASA GEOS Composition Forecast Modeling System GEOS-CF v1.0". *Journal of Advances in Modeling Earth Systems*, 13:4. https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020MS002413

GEOS-CF file specification & data access

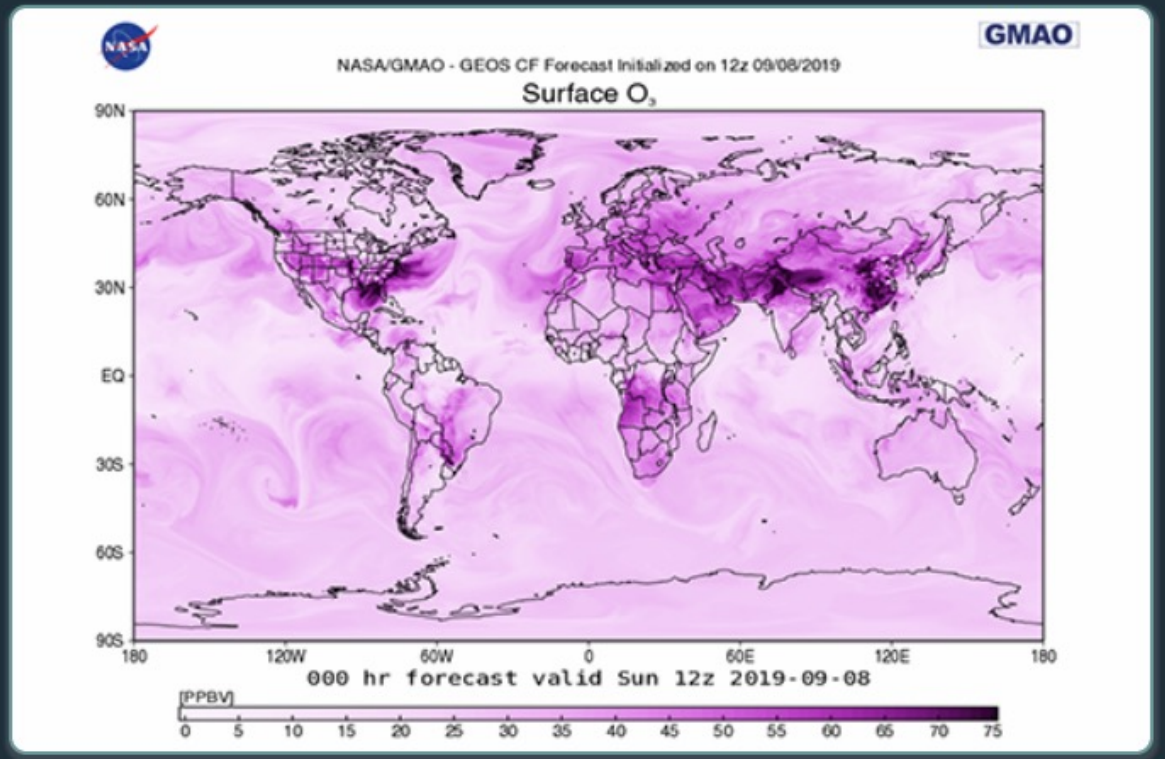
Access to raw data outputs (NetCDF4 format) and FLUID online visualizations

File specifications and technical description of the GEOS-CF system

- GEOS-CF Project
- Data Access
- Documentation
- Highlights
- Videos
- Publications
- GMAO Weather Analysis and Prediction
- GEOS-CF Email List

GEOS Composition Forecasts (GEOS-CF)

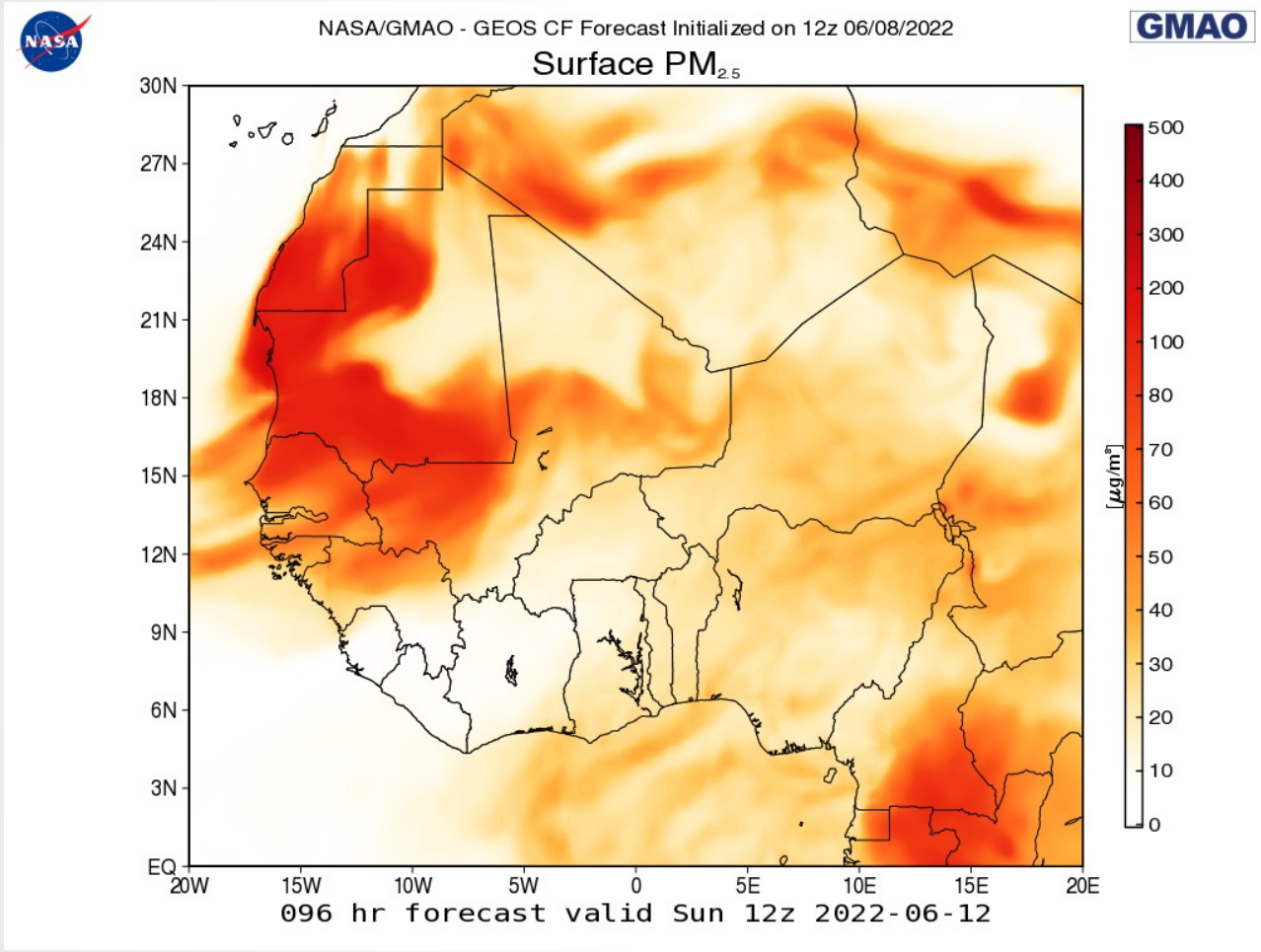
The GEOS Composition Forecasting (GEOS-CF) system produces global, three-dimensional distributions of atmospheric composition. The spatial resolution is 25km. Using meteorological analyses from other GEOS systems, the GEOS-CF products include a running atmospheric replay to provide near-time estimates of surface pollutant distributions and the composition of the troposphere and stratosphere. A single five-day forecast is generated daily, beginning at 12Z.



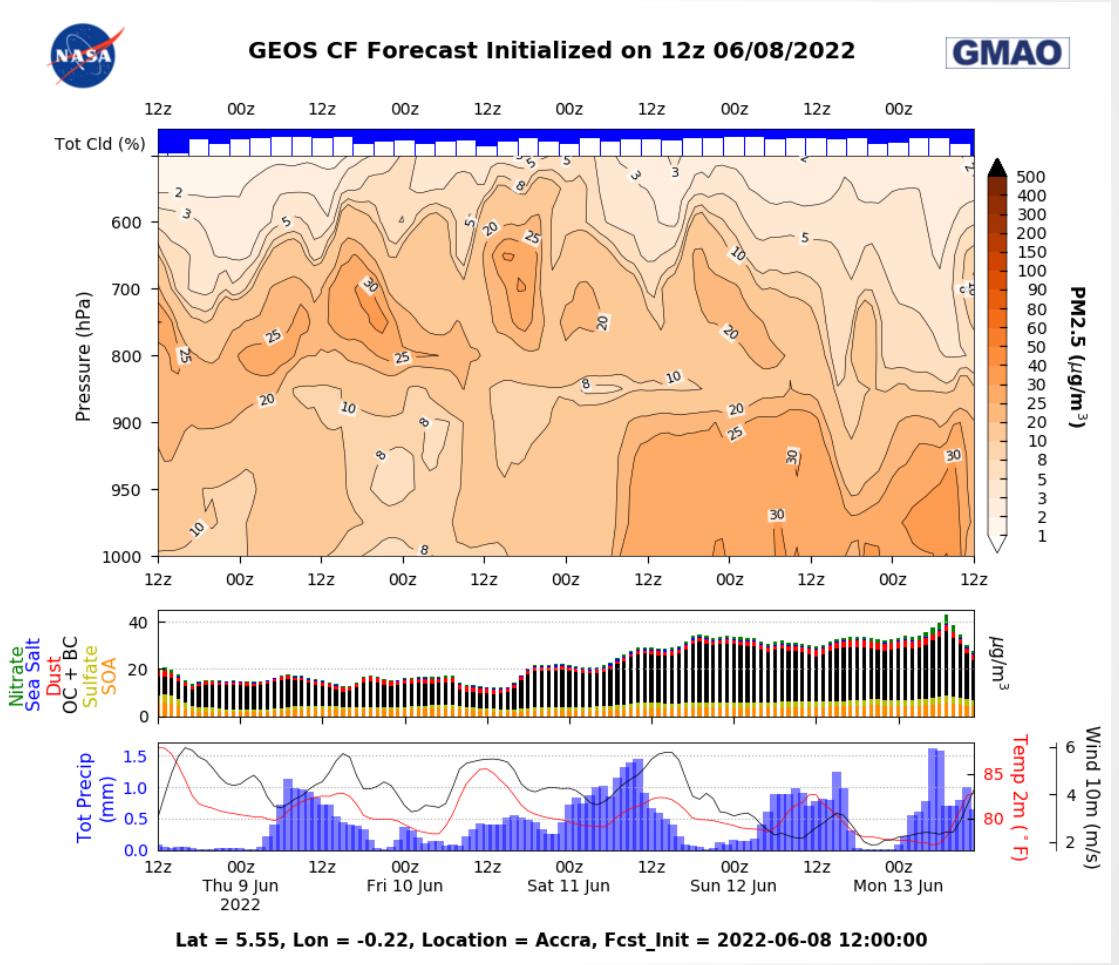
https://gmao.gsfc.nasa.gov/weather_prediction/GEOS-CF/

Examples of FLUID online visualizations

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



Surface Concentration Map



Datagrams

Other air quality forecasting models

- **Community Multiscale Air Quality model (CMAQ)**

  Developed by US EPA, many users around the world contribute to ongoing development

  https://www.epa.gov/cmaq

- **Weather Research and Forecasting models with coupled Chemistry (WRF-Chem)**

  Developed by US NOAA, many users around the world operate their own forecasts

  https://ruc.noaa.gov/wrf/wrf-chem/

- **Copernicus Atmosphere Monitoring Service (CAMS) global atmospheric composition forecasts**

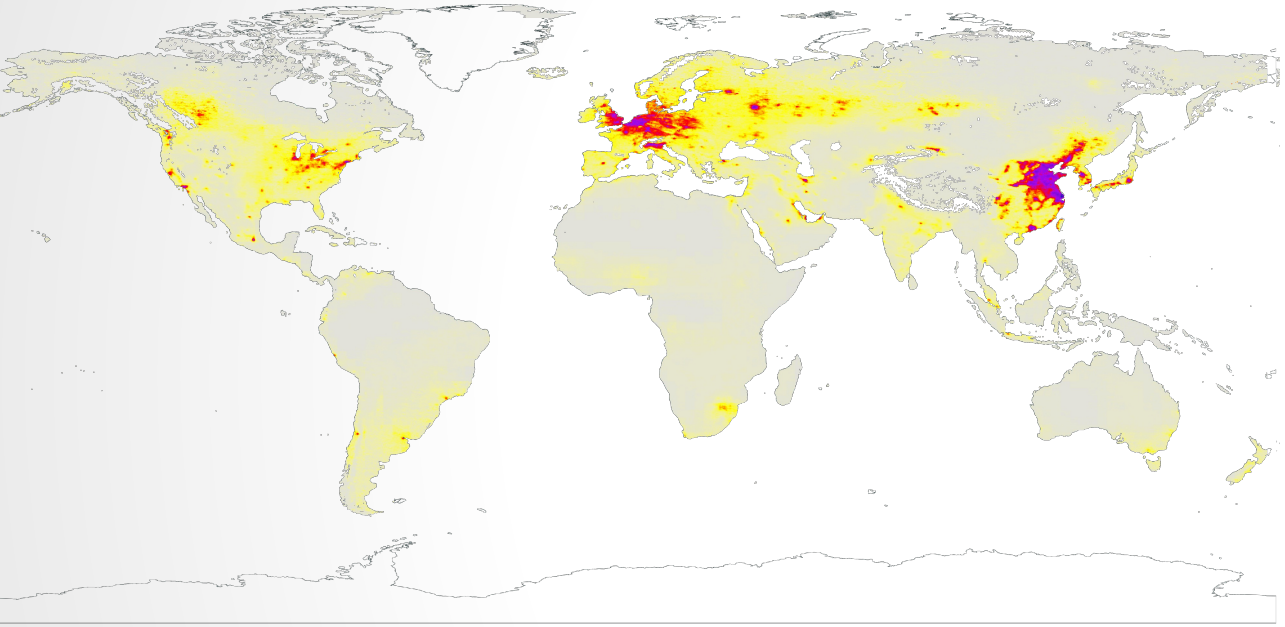
  Operated by the European Center for Medium-range Weather Forecasts (ECMWF)

  https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-global-atmospheric-composition-forecasts

Source: Gupta, P.; Follette-Cook, M.; Parrington, M.; Stewart, C. (2021). *Introduction and Access to Global Air Quality Forecasting Data and Tools*. NASA ARSET. https://appliedsciences.nasa.gov/join-mission/training/english/arset-introduction-and-access-global-air-quality-forecasting-data-and

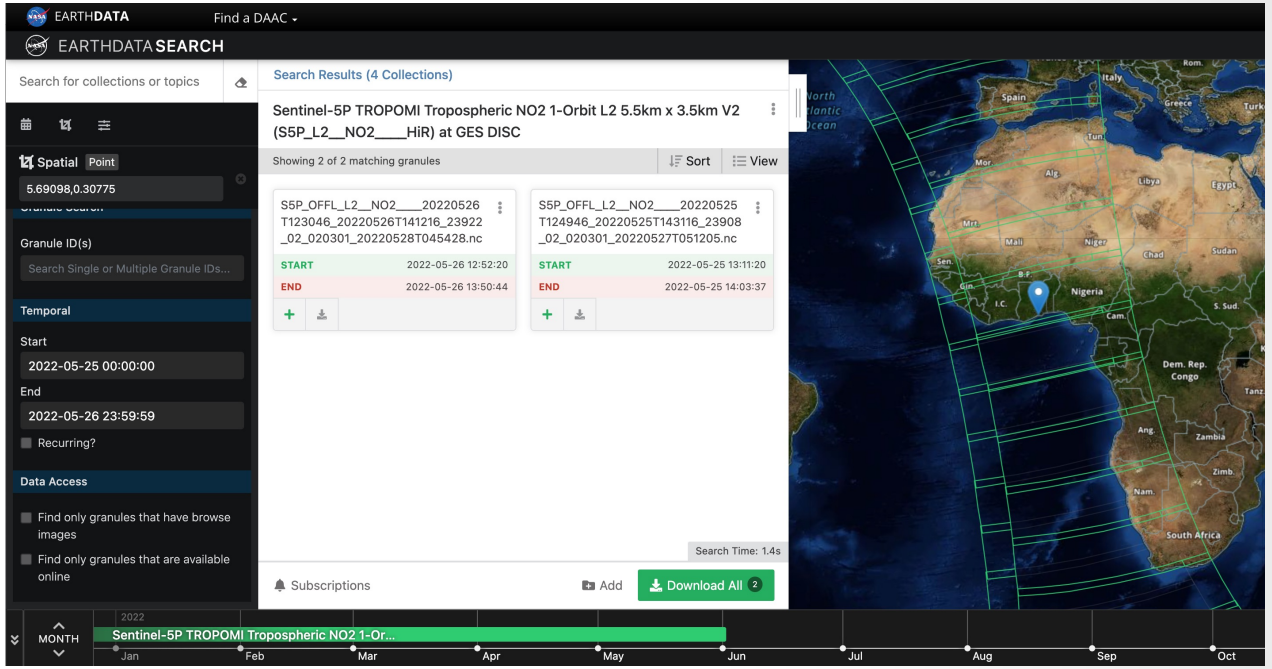
Examples in Worldview and Earthdata

https://worldview.earthdata.nasa.gov/



Online tool for visualizing some NASA (and other) model & satellite datasets (e.g., annual average NO_2 estimates)

https://www.earthdata.nasa.gov/

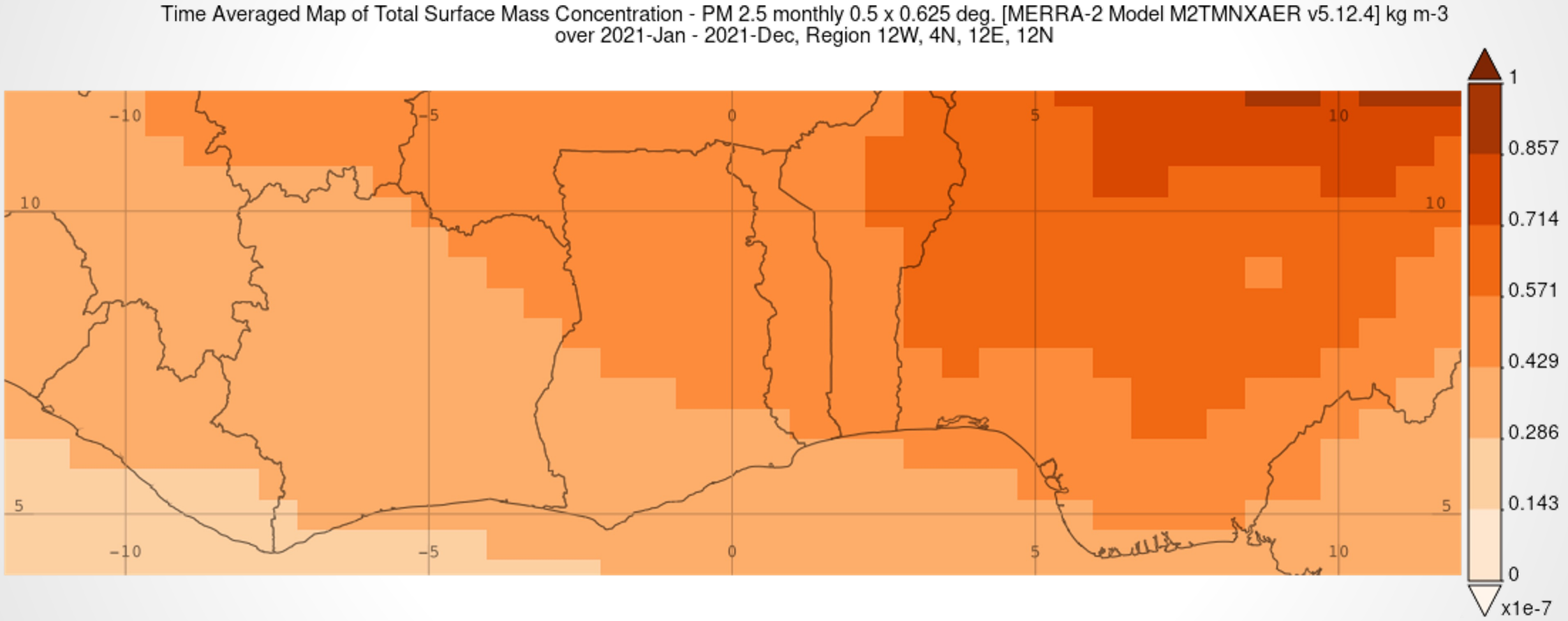


Online tool for sub-setting and downloading NASA (and other) model & satellite datasets for offline analysis

Health and Air Quality Data Pathfinder:
https://www.earthdata.nasa.gov/learn/pathfinders/health-and-air-quality-data-pathfinder

Examples in Giovanni

https://giovanni.gsfc.nasa.gov/giovanni/



MERRA-2 (reanalysis) average surface-level $PM_{2.5}$ for 2021

NASA Applied Remote Sensing Training (ARSET)

https://appliedsciences.nasa.gov/arset

- ***ARSET provides accessible, relevant, and cost-free training on remote sensing satellites, sensors, methods, and tools.***
- Our trainings are:
  - Online and in-person
  - Open to everyone
  - Live, instructor-led, or self-guided
  - Provided at no cost, with materials and recordings available from our website
  - Often multi-lingual
  - Tailored to those with a range of experience in remote sensing, from **introductory** to **advanced**



ARSET offers trainings for:

- Disasters
- Health & Air Quality
- Land Management
- Water Resources
- Climate





Thank You

Questions?