A Survey of Applications of the NASA GEOS-CF Global Atmospheric Composition Forecasts: case studies for NASA open data and Earth science to action

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ABSTRACT

The Goddard Earth Observing System Composition Forecast (GEOS-CF) is a global atmospheric constituent forecasting system created and operated by the Global Modeling and Assimilation Office at National Aeronautics and Space Administration (NASA) Goddard Space Flight Center. In alignment with the NASA Earth Science to Action Strategy, GEOS-CF forecasts support a variety of research and practical applications, including NASA satellite missions, aircraft campaigns and instrument teams, local and regional air quality forecasters, and public and occupational health experts investigating air pollutant exposure. In alignment with the NASA Open-Source Science Initiative, GEOS-CF supports several data access methods, thereby serving a range of users with varying technical capabilities. This paper surveys several case studies of applications making use of GEOS-CF, investigating how the data were accessed and examining the perceived benefits and limitations of GEOS-CF in each case. The global coverage and data availability of multi-constituent information at a relatively low data latency was broadly perceived as the strength of GEOS-CF, while cited weaknesses included the relatively coarse spatial resolution for local-scale applications, lack of outputs of interest to specific applications, and uncertain data quality for regions and outputs with limited validation observations. Our goal is to present these examples and lessons learned to the broader community both as illustrations of NASA's Earth Science to Action Strategy and Open-Source Science Initiative and to inform future developments of GEOS-CF and similar systems, with the aim of improving the free and open provision of actionable Earth science information for societal benefit.

SIGNIFICANCE STATEMENT

The NASA Goddard Earth Observing System Composition Forecast (GEOS-CF) is a global atmospheric constituent forecasting system, each day producing five-day forecasts of airborne trace gases and particulate matter. These forecasts support a variety of users, including NASA missions and science teams, regional and local air quality forecasters, and public health and occupational exposure experts. This paper surveys several use-cases, identifying how GEOS-CF is accessed and used, the benefits and limitations of GEOS-CF for each case, and what future improvements could improve its application. We share these insights with the community to provide examples of successes, lessons learned, and important points to consider for others

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developing similar products in alignment with open science principles for providing actionable Earth science data.

CAPSULE

Aligned with NASA Earth Science to Action and Open-Source Science priorities, GEOS-CF data are accessible through various methods to support NASA missions, air quality forecasting, and health applications.

1. Introduction

Atmospheric composition impacts and is impacted by a range of natural and human activities, and modeling atmospheric composition at a global scale has many scientific and practical applications (Flemming et al., 2009; Marécal et al., 2015; Bhattacharjee et al., 2018; Emmons et al., 2020). Model outputs can be used to study chemical trends and processes in the upper atmosphere and remote regions where in-situ observations are sparse (K. E. Knowland et al., 2022; Wales et al., 2023). Atmospheric composition impacts air quality, a global public health issue resulting in millions of premature deaths annually (Murray et al., 2020; HEI, 2024). Poor air quality has additional economic consequences, such as reduced agricultural yield due to ozone exposure, reduced tourism revenue and travel safety due to low visibility, and loss of labor productivity (Ainsworth et al., 2012; OECD, 2016; Li et al., 2022). Forecasting air quality using atmospheric composition models can support advanced warnings to mitigate the public health and economic impacts of pollution (Wen et al., 2009; Neidell and Kinney, 2010; Saberian et al., 2017).

To address societally relevant challenges such as understanding and forecasting atmospheric composition, the National Aeronautics and Space Administration (NASA) has promulgated an Earth Science to Action Strategy (https://science.nasa.gov/earth-science/earth-science-to-action/). This strategy aims to "accelerate and advance the impact of NASA's Earth science…for the benefit of all humankind", and includes the delivery of trusted information that can support decisions to address or mitigate the impacts of societal challenges such as poor air quality (NASA, 2024). Furthermore, the Open-Source Science Initiative (https://science.nasa.gov/open-science/) articulates NASA's commitment to building a "collaborative culture enabled by technology that empowers the open sharing of data, information, and knowledge within the

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scientific community and the wider public" (NASA, 2025). This initiative includes expanding the availability and accessibility of NASA datasets by providing data in formats and via platforms which are accessible to a variety of user communities. Together, these strategies emphasize that providing Earth science information such as atmospheric composition forecasts derived from NASA data and models in accessible and actionable formats is a priority for NASA.

The Goddard Earth Observing System Composition Forecast (GEOS-CF) is a global atmospheric constituent forecasting system operated by the NASA Global Modeling and Assimilation Office (GMAO) of the Goddard Space Flight Center (GSFC). The system builds on the GEOS meteorological and aerosol data assimilation and forecasting system developed collaboratively by multiple GSFC Earth Science labs (Molod et al., 2015; Nielsen et al., 2017). GEOS-CF integrates the open-source GEOS-Chem chemistry module (Bey et al., 2001), allowing simulation of hundreds of chemical species and several aerosol composition and size fraction categories. Notably, in alignment with the NASA Open-Source Science Initiative, GEOS-Chem is supported by an active international user community, with GEOS-CF benefitting from ongoing community contributions. The system runs daily, producing a simulation of the previous day and a five-day forecast. A full description of GEOS-CF, including versions of its components and emissions inventories, is available elsewhere (Keller et al., 2021; Knowland et al., 2020; K. E. Knowland et al., 2022).

In alignment with NASA's Earth Science to Action Strategy, GEOS-CF supports several research and practical applications. In fulfillment of the GMAO's core mission, GEOS-CF supports NASA missions (field campaigns, ground-based networks, and satellite retrievals) with necessary prior information on the state of the atmosphere. While GEOS-CF is a research-grade product, not suitable for assessing compliance with ambient air quality regulations, it can provide insight into the potential causes of poor air quality and advance notice of air quality events, enabling preparatory actions and public health advisories. The use of NASA resources including GEOS-CF to augment air quality management and forecasting has been described by Duncan et al. (2021).

This paper presents case studies of how GEOS-CF has been used by communities in Earth science, air quality forecasting, and public health. In each case study, we focus on (1) the use

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case being addressed, (2) how GEOS-CF outputs were accessed, (3) which attributes of the system (e.g., parameters, resolution, latency) were most relevant to the use case, and (4) lessons learned which inform GEOS-CF development. Our goal is to draw conclusions about common factors which have made these applications successful, as well as lessons learned which can improve the success of other applications in the future. This is especially relevant considering the second version of the GEOS-CF system, which was publicly released in September 2025, provides opportunities to change how results are presented or made available, which could facilitate future applications and overcome identified barriers. These case studies also provide illustrative examples of how NASA data have been provided to and used by the air quality management and public health communities, in alignment with both the Earth Science to Action Strategy and the Open-Source Science Initiative. Finally, we expect these insights and experiences will be of broader value to the community developing and delivering data products which are accessible and actionable, delivering societal benefit from fundamental Earth science understanding.

2. Description of GEOS-CF and its Data Access

GEOS-CF is run daily to produce a "replay" of the previous day as well as a forecast for the next five days (Keller et al., 2021). The model is run with a c360 cubed-sphere horizontal grid with 72 layers, extending from the surface to 0.01 hPa, with the lowest model level representing near-surface concentration having a depth nominally about 130 m. Output is provided with a 0.25° $\times$ 0.25° resolution (~25 km), and a temporal resolution of either 15 minutes or 1 hour. Model outputs are grouped into thematic collections; for example, lowest model level carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3), and fine particulate matter mass ($PM_{2.5}$) concentrations, commonly used for quantifying air quality, are grouped together in an air quality collection (AQC). There are also collections of variables supporting satellite mission retrievals (SAT), as well as collections of additional GEOS-Chem diagnostics (XGC) with variables relevant for comparison with satellite data, e.g., aerosol optical depth. The time between the forecast initialization and the availability of outputs (latency) is typically about 14 hours, meaning the practical forecasting lead time of GEOS-CF is slightly over four days. Specifications for GEOS-CF collections are provided in the File Specification Document (K.E. Knowland et al., 2022).

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Like all NASA Earth science datasets, GEOS-CF outputs are available cost-free to the global public. However, simple provision of these data is not sufficient to meet the needs of the NASA Open-Source Science Initiative. To qualify as “open”, data must be findable, accessible, interoperable, and reusable (the FAIR principles for open data; https://www.go-fair.org/fair-principles/). Delivering accessible and usable NASA Earth Science data to support public policy and decision-making is also an objective of the NASA Earth Science to Action Strategy. Making GEOS-CF data available in a variety of formats and access methods improves findability, accessibility, and interoperability of the data among diverse user communities. These methods are described below and summarized in Table 1. They are also linked from the GEOS-CF Data Access webpage (https://gmao.gsfc.nasa.gov/gmao-products/geos-cf/data-access_geos-cf/).

Data Science Skills Required	Method	Example Use Case	Sec.
Fewer	FLUID interactive map	Explore a “nowcast” of current global conditions	2b
	FLUID predefined maps	Look at an animation and time series of forecasts for the next several days	2b
	CFAPI	Create a widget for a website which displays forecasts for a user’s location	2c
	GEOS-CF in GEE	Plot a global map comparing GEOS-CF outputs with satellite datasets	2d
	OpeNDAP	Access a subset of GEOS-CF outputs for a specific region across multiple days	2a
More	NCCS Data Portal	Download full global information from GEOS-CF	2a

Table 1. Various methods to access and analyze GEOS-CF data, ranked according to the relative data science skill required. Sample use cases are listed to illustrate each method. Note that this ranking only considers data access, and not the atmospheric science domain knowledge necessary to interpret GEOS-CF outputs.

a. Direct and Remote File Access

GEOS-CF outputs are publicly available for direct download via the NASA Center for Climate Simulation (NCCS) data portal (https://portal.nccs.nasa.gov/datashare/gmao/geos-cf/). While straightforward, this access method can be cumbersome if large amounts of data from different times are needed, or if only data for specific locations are required. For this reason,

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remote access via the Open-source Project for a Network Data Access Protocol (OPeNDAP; https://opendap.nccs.nasa.gov/dods/gmao/geos-cf) is also provided. This allows subsets of the GEOS-CF output to be accessible remotely using common programming languages, as described in the NASA OPeNDAP User Guide (https://www.earthdata.nasa.gov/engage/open-data-services-software/earthdata-developer-portal/opendap/user-guide#client). This access method eliminates the need to search for and download complete data files.

b. Interactive Visualization

The GMAO Framework for Live User-Invoked Data (FLUID) website (https://fluid.nccs.nasa.gov/cf/) allows online visualization of GMAO products. Available displays include static and animated maps of outputs for specific regions and "datagrams" showing the forecasts for specific locations such as US and global cities; examples of how this information can be used are provided by Duncan et al. (2021), Section 3.3. Additionally, a GEOS-CF interactive map tool (https://fluid.nccs.nasa.gov/cf_map/) allows users to freely pan and zoom to explore the latest GEOS-CF forecasts of three AQC variables ($PM_{2.5}$, O_3, NO_2). Clicking a point on the map brings up an option to display a time series of forecasts or historical data, and to download these in simple, accessible formats (e.g., spreadsheets or text files). This access method allows users with limited coding expertise to visualize and access GEOS-CF data using a graphical interface.

c. Application Programming Interface

An application programming interface (API) has been developed for GEOS-CF, the CFAPI (https://fluid.nccs.nasa.gov/cfapi/docs/). This allows querying GEOS-CF historical or forecast data at a specific latitude and longitude coordinate. The CFAPI is useful for website or application developers seeking to integrate GEOS-CF outputs. A Python package CFTools (https://github.com/GEOS-ESM/CFTools/tree/main) has been developed, implementing the API alongside basic plotting functionality. The GEOS-CF-Tutorials GitHub (https://github.com/GEOS-ESM/GEOS-CF-Tutorials/tree/main) includes demonstrations of the CFAPI (https://github.com/GEOS-ESM/GEOS-CF-Tutorials/blob/main/GEOS-CF-API/CFAPI_Tutorial.ipynb) and the package (https://github.com/GEOS-ESM/CFTools/blob/main/notebooks/CFTools_Usage.ipynb).

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d. Google Earth Engine

Facilitated by a NASA-Google partnership agreement (https://www.nasa.gov/missions/terra/nasa-and-google-team-up-to-better-track-local-air-pollution/), GEOS-CF outputs are included in the Google Earth Engine (GEE) data catalog (https://developers.google.com/earth-engine/datasets/tags/geos). Those already familiar with GEE or similar Geographic Information Systems can readily visualize GEOS-CF outputs, compare these with other available datasets, and create derived data products incorporating GEOS-CF within the GEE cloud computing environment. An example application, the GEOS-CF Air Quality Data Explorer (https://callumwayman.users.earthengine.app/view/geoscfexplorer), illustrates this access method, and tutorials are also available in the GEOS-CF-Tutorials Github (https://callumwayman.users.earthengine.app/view/geoscfexplorer).

3. Case Studies in Applying GEOS-CF

This section explores case studies where GEOS-CF has been applied to end-user problems in domains such as supporting NASA missions, regional to local air quality forecasting, and assessment of pollutant exposure for public health.

a. Support to NASA Missions

In support of GMAO's role within NASA, GEOS-CF provides atmospheric composition data needed by NASA missions. This includes providing a priori profiles throughout the troposphere and stratosphere that are necessary to retrieve atmospheric composition observations from satellite instruments, such as the Tropospheric Emissions Monitoring of Pollution (TEMPO) mission (Abad et al., 2025; Nowlan et al., 2025; Wang et al., 2025). GEOS-CF also supports planning and execution of NASA suborbital campaigns, for example the Asian Summer Monsoon Chemical and Climate Impact Project (ACCLIP Science Team, 2022; Pan et al., 2022, 2024), the Airborne and Satellite Investigation of Asian Air Quality (Crawford et al., 2022; ASIA-AQ Science Team, 2024), and multiple years of the Student Airborne Research Program (Schaller et al., 2022; SARP Science Team, 2025). Customized FLUID mission support pages (https://fluid.nccs.nasa.gov/missions/) include visualizations of GEOS-CF and other GMAO products specific to the mission needs, e.g., curtain plots along planned flight tracks. NASA

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campaigns can request this support from the GMAO suborbital campaign webpage (https://gmao.gsfc.nasa.gov/field-campaigns/support-requests/). NASA ground-based remote sensing networks also use GEOS-CF outputs, as discussed in the case study below.

1) CASE STUDY: PRIORITIZING OPERATIONS FOR TOLNET

Use Case: The Tropospheric Ozone Lidar NETwork (TOLNet; https://tolnet.larc.nasa.gov/) provides high temporal and vertical resolution ground-based profiling of ozone in the troposphere. To prioritize TOLNet operations, a daily automated forecast alert is disseminated to each TOLNet site from NASA Ames Research Center. This uses a suite of models including GEOS-CF, NCAR WRF-Chem (Kumar et al., 2021), RAP-Chem (Graham, 2021), and HRRR-Smoke (Benjamin et al., 2016) to notify measurement groups of expected atmospheric conditions. Certain interesting forecasted events (e.g., stratospheric ozone intrusions, air quality exceedance events, fires, etc.) might warrant additional or extended TOLNet observations. Furthermore, to analyze TOLNet data, a python package has been developed to plot GEOS-CF ozone profiles alongside TOLNet profiles for the locations and times of measurements; an example comparison is provided in Fig. 1.

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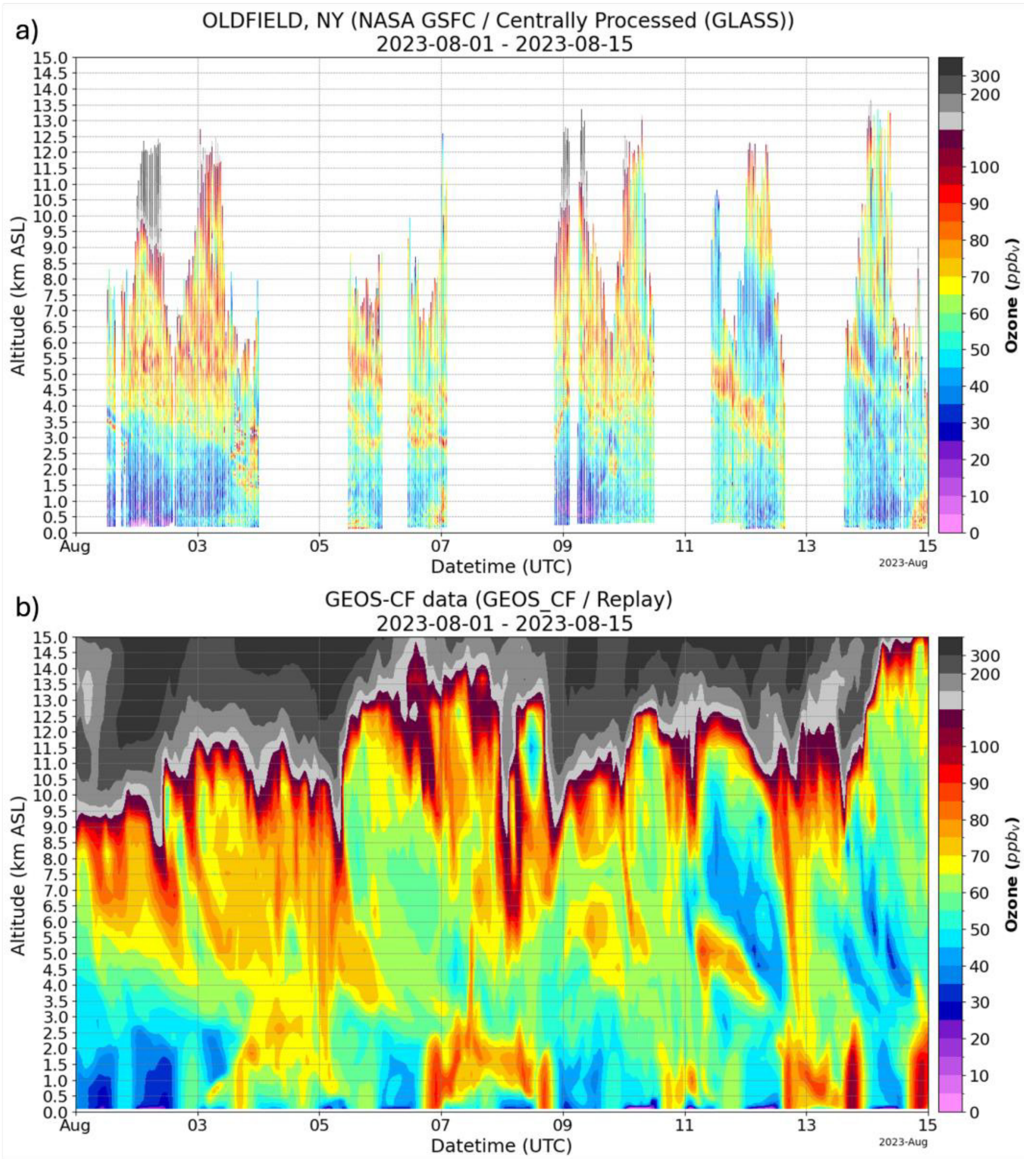

Fig. 1. A comparison of TOLNet ozone profiles (a) over Oldfield, New York in August 2023 with GEOS-CF historical outputs for the same location and times (b). These examples are reproduced from the NASA Atmospheric Science Data Center's Data and User Services tutorial for the TOLNet python package (https://nasa.github.io/ASDC_Data_and_User_Services/TOLNet/tutorial_for_TOLNet_API_with_examples_of_plotting_and_GEOS-CF.html).

Access Method: The CFAPI supports both forecasting and analysis use cases. The ability to query the full 72 layer meteorology and chemistry profiles at a specific location was built into the CFAPI specifically to support this use case.

Relevant Attributes: The ability of GEOS-CF to forecast ozone vertical profiles is ideal for the use case of informing TOLNet operators of relevant events. Furthermore, GEOS-CF

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historical information allows "filling in" times when TOLNet sites are not operational, facilitating long-term analysis.

Lessons Learned: While "replay" data from all collections as well as past forecasts from the AQC collection are available since January 2019, forecasts of other collections (including those with vertical profiles) are only available to the public for the last 2 weeks due to the file sizes. Thus, the CFAPI is limited to querying recent forecasts for TOLNet, making it more difficult to study how well past GEOS-CF forecasts predicted ozone profiles. Furthermore, the CFAPI does not allow simultaneous queries of multiple nearby locations, which would be useful for assessing pollutant dispersion and transport. An alternative data access method, e.g., OpeNDAP, might facilitate such a case. Ultimately, TOLNet observations contribute to the evaluation and improvement of GEOS-CF (Dacic et al., 2020; Gronoff et al., 2021; Bernier et al., 2022; Langford et al., 2022); integration of GEOS-CF with TOLNet facilitates such positive feedback.

b. Regional and Local Air Quality Forecasting

GEOS-CF outputs have been combined with other information to improve location-specific air quality forecasts. In areas which already run local or regional air quality forecast models, GEOS-CF has provided lateral boundary conditions. GEOS-CF also supports analysis of air quality events; for example, 24-hour ozone anomaly maps (https://fluid.nccs.nasa.gov/cf/classic_geos_cf/?stream=GEOSCFFC&field=o3sfc_anom) were added to the GEOS-CF FLUID interface based on interest from US air quality managers seeking to explain high ozone pollution events (Shah et al., 2023). GEOS-CF has also contributed to ensemble forecasts aiming to better predict extreme conditions, e.g., wildfire smoke impacts, which any single model may struggle with. Conversely, in areas where air quality forecasting capabilities are absent or limited, GEOS-CF can provide this capability as a cost-effective alternative and/or as a motivation to spur development of local forecasting systems (e.g., Cromar et al., 2019).

1) CASE STUDY: FIREAQ ENSEMBLE FORECAST FOR ALASKAN AIR QUALITY

Use Case: The University of Alaska Fairbanks (UAF) has developed an Air Quality Forecasts for Alaska FIREAQ website (http://fireaq.alaska.edu/; Fig. 2). The site presents three-day regional forecasts of $PM_{2.5}$ and visibility, as well as satellite aerosol optical depth and in-situ

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$PM_{2.5}$ measurements. The forecasts utilize an ensemble of three models: GEOS-CF, GEOS-FP (Rienecker et al., 2008), and the Navy Aerosol Analysis and Prediction System (Lynch et al., 2016). The website is used to communicate air quality and visibility risks to stakeholders such as the Bureau of Land Management. This is a regional complement to the University of Iowa FireAQ project (https://fireaq.uiowa.edu/briefings.php).

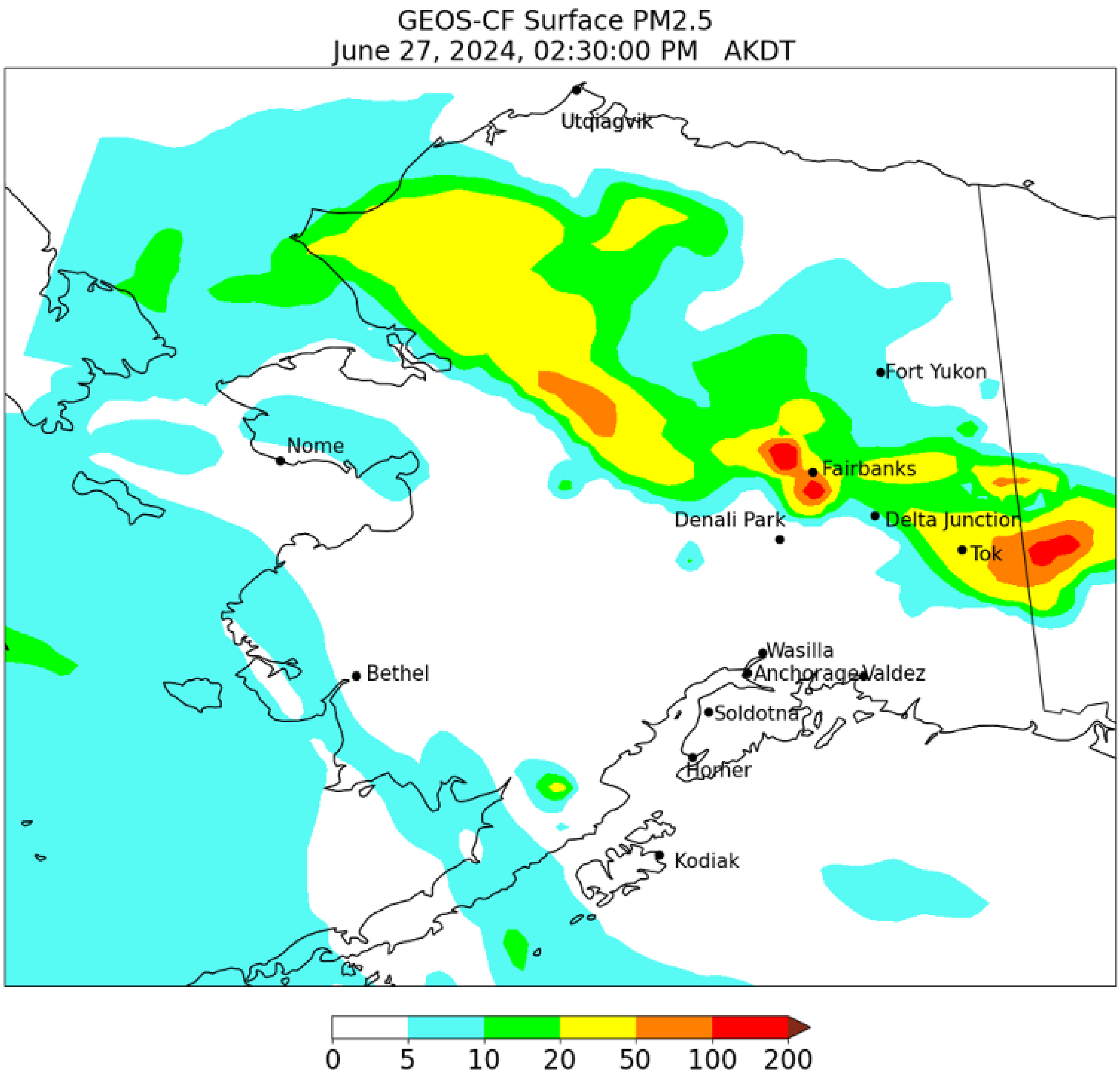

Fig. 2. Screenshot of the Alaska FIREAQ website for GEOS-CF $PM_{2.5}$ forecasts from June 27th, 2024. Note the high spatial variability near Fairbanks; resolving localized impacts is key for this use case.

Access Method: Full GEOS-CF forecast files are accessed via the NCCS data portal. $PM_{2.5}$ forecasts for the region of interest are extracted and plotted. This is automated with a custom python script which is run daily.

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Relevant Attributes: The daily availability of GEOS-CF forecasts and their coverage of Alaska (which is not included in some regional forecasts focused on the contiguous US, CONUS) are important aspects for this use case.

Lessons Learned: GEOS-CF outputs are of insufficient granularity to resolve highly localized air quality impacts for Alaskan villages, and wildfire $PM_{2.5}$ is often overestimated. Furthermore, at this high latitude, the difference between the horizontal and vertical spacing of the regular latitude-longitude output grid is readily apparent. A visibility output from GEOS-CF would facilitate its use by certain stakeholders, e.g., pilots. Additional outputs which might support improved assessment of smoke impacts include brown carbon and vertically integrated smoke. Finally, occasional latency issues prevented GEOS-CF forecasts from being available at the time when the scripts are run to produce the forecast maps displayed on the FIREAQ website; earlier forecast initialization could address this.

2) CASE STUDY: LOCATION-SPECIFIC AIR QUALITY FORECASTS FOR CITIES VIA CANAIRY ALERY WEBSITE AND THE WORLD RESOURCES INSTITUTE WEB-BASED INTERFACE

Use Case: Due to its spatial resolution and reliance on mainly predetermined emissions inventories, GEOS-CF can fail to fully capture the location-specific variability of air quality, such as would be recorded by an air quality monitoring station. Using past information from GEOS-CF and air quality monitoring stations, statistical models can calibrate GEOS-CF to site-specific conditions. The model can then be applied to GEOS-CF forecasts, creating a forecast specifically tailored to that station's conditions. Developing such a machine learning model (extreme gradient boosted decision trees) has been described by Keller et al. (2020) and Lazrak et al. (2022, 2024). Here, we focus on the approach used by the World Resources Institute (WRI) to provide location-specific forecasts at select global air quality monitoring sites (121 sites in 21 cities) via the CanAIRy Alert website (https://canairy.squarespace.com/demo) and the Resource Watch web-based interface (https://resourcewatch.org/data/explore/cit004brw0nrt-Air-Quality-Nitrogen-Dioxide-NO-Station-Forecasts).

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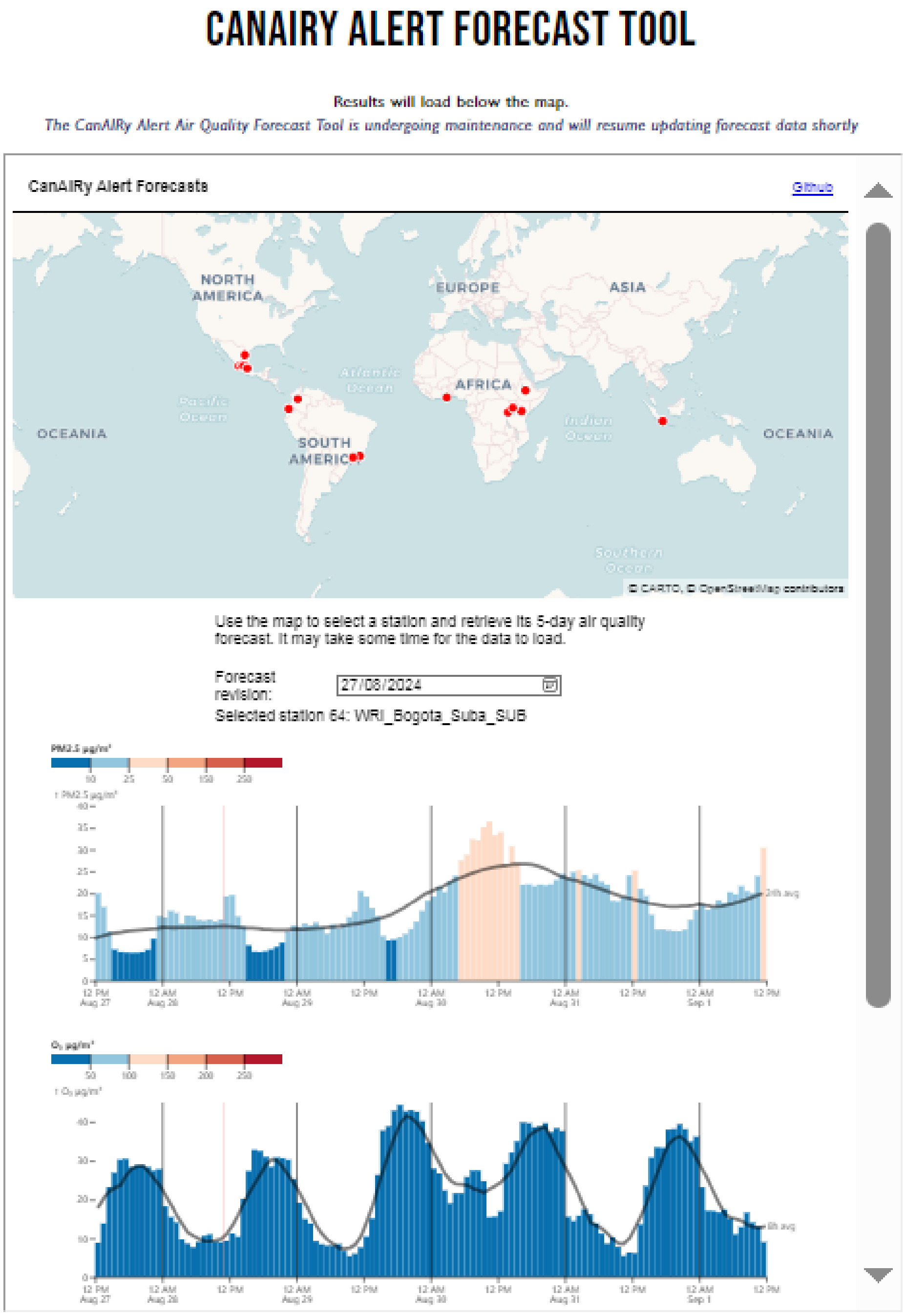

Fig. 3. A screenshot of the CanAIRy Alert website. The map at the top shows cities for which air quality forecasts are available. The graphs at the bottom show air quality forecasts of $PM_{2.5}$ and Ozone from August 27th to September 1st, 2024. Bars indicate the hourly forecast values,

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colored according to the concentration range. Black lines denote 24-hour (for $PM_{2.5}$) or 8-hour (for Ozone) rolling averages.

Access Method: For training machine learning models, air quality monitor data were provided by local and national authorities with support from WRI. GEOS-CF data were accessed via OpeNDAP for the collocated model grid and time period of each training dataset. For forecasting, the need to support a live, interactive website necessitated a different data storage and access approach. Each day, GEOS-CF forecast outputs are appended into a Zarr archive hosted by Amazon Web Services (AWS). From there, site-specific calibrated machine learning models are applied to produce the localized forecasts. Daily-average maps of GEOS-CF outputs are also visible in Resource Watch and the CanAIRy Alert website (see Fig. 3).

Relevant Attributes: The global coverage of GEOS-CF enables location-specific forecasts to be developed for any location with sufficient in-situ data to calibrate the machine learning model. GEOS-CF provides both the atmospheric constituent and meteorological inputs required by the machine learning model. Relatively low latency of GEOS-CF is also important to this forecasting application.

Lessons Learned: While OpeNDAP or the CFAPI can provide the location-specific information required in this approach, the need to rapidly access data for multiple locations necessitated a new database that is "closer" (in cyberspace) to the data processing and web interface. This highlights the importance of having data "on the cloud" for certain applications. Users also identified the need for forecasts of PM_{10} (particulate matter with an aerodynamic diameter of 10 micrometers or less), a key air quality indicator internationally.

3) CASE STUDY: AIR QUALITY FORECASTING FOR RIO DE JANEIRO

Use Case: While the previous case study focused on location-specific forecasts, improving city-scale forecasts requires a different approach incorporating satellite remote sensing and in-situ data to inform the spatial variability of air pollutants (Malings et al., 2021, 2024). This technique is implemented for several cities, including Rio de Janeiro, Brazil, where relatively few air quality monitors, especially for $PM_{2.5}$, limit the utility of location-specific forecasts.

Access Method: Using GEE allows GEOS-CF to be combined with satellite remote sensing of aerosols and trace gases already available in GEE, as well as local monitor data brought into GEE for this project. Generating forecasts using GEE cloud computing resources also limits the

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burden on local systems in Rio. Finally, ready-made user interface options built into GEE are used to display the information (Fig. 4), reducing the burden of developing a custom user interface.

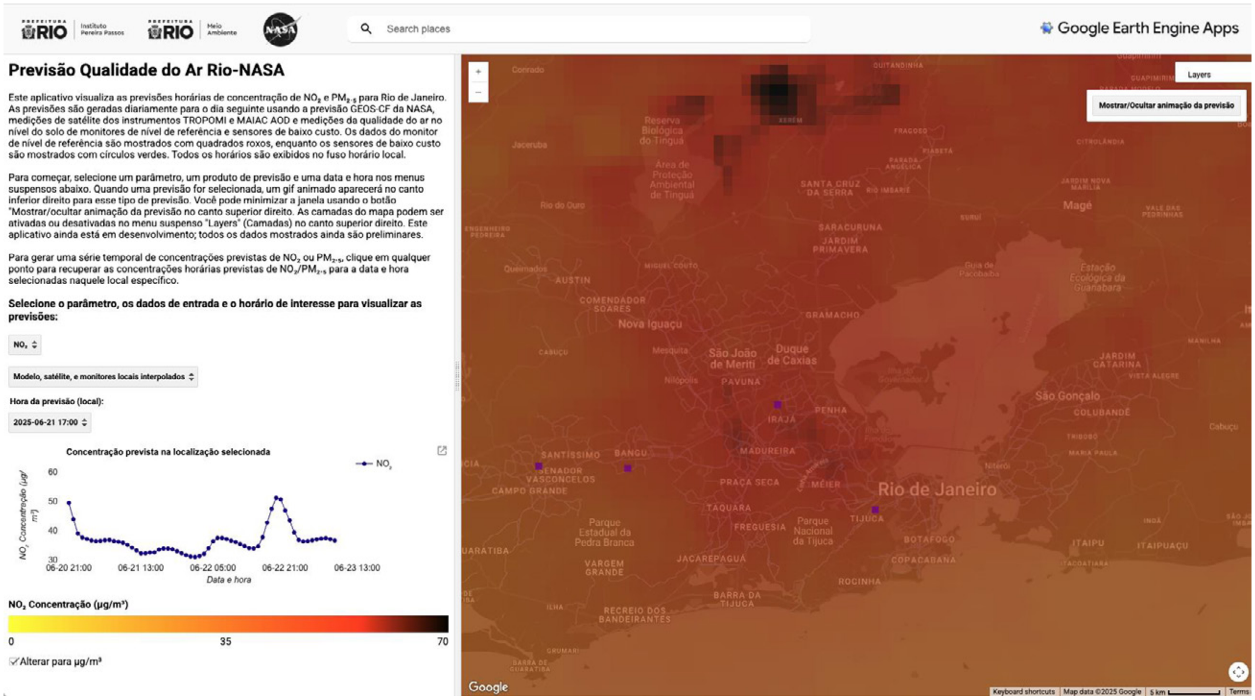

Fig. 4. A screenshot of a Rio city NO_2 forecast map for June 21st, 2025. A forecast time series for a selected point is displayed to the left, and a map is displayed to the right. Integration of GEOS-CF with other datasets, user interface development and site hosting are facilitated though GEE.

Relevant Attributes: Availability of both near-surface and column pollutant concentrations in GEOS-CF enables integration of satellite remote sensing and in-situ data in this application. Relatively fine spatial resolution compared to other global atmospheric constituent forecasts also supports using GEOS-CF at city scale (Huneeus et al., 2022).

Lessons Learned: The availability of GEOS-CF via GEE facilitated its interoperability with other Earth observation data and streamlined computation and visualization of forecasts. However, the additional latency associated with making GEOS-CF available in GEE, performing the computation to combine it with other information sources, and generating results limits the overall effective forecasting lead time of the system to about three days. Some of these challenges might be addressed through purchasing additional cloud computation resources in

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GEE. Finally, PM_{10}, a key pollutant relevant to Rio, could not be forecast due to its absence in GEOS-CF outputs.

c. Exposure and Health

While the GEOS-CF provides information on air pollutants via its AQC, further translation into health-relevant messaging is an important step for public health. Although forecasting is the primary focus of GEOS-CF, the availability of historical data as well (since 2018) facilitates retrospective studies of exposures to air pollutants and their health impacts.

1) CASE STUDY: CDC ENVIRONMENTAL PUBLIC HEALTH TRACKING

Use Case: The US Centers for Disease Control and Prevention's (CDC) National Environmental Public Health Tracking Network (Tracking Network; https://ephtracking.cdc.gov/) provides timely integrated environmental and public health data, supporting actions which improve public health. Data are provided via the Tracking Network's online Data Explorer tool (https://ephtracking.cdc.gov/DataExplorer/). More details on the inclusion of low-latency NASA datasets, such as GEOS-CF, in the Tracking Network are provided by Amos et al. (2023); we briefly summarize their relevant conclusions below.

Access Method: The Tracking Network provides GEOS-CF information at the spatial scale of US counties. Each day, a python script accesses the latest GEOS-CF air quality forecasts from the NCCS data portal. Hourly averages are calculated for each US county using area-weighted averages from the original GEOS-CF resolution. Timesteps are adjusted from UTC to local time. Finally, the US Air Quality Index (AQI) value is calculated for GEOS-CF pollutants, following procedures established by the US Environmental Protection Agency (https://www.airnow.gov/publications/air-quality-index/technical-assistance-document-for-reporting-the-daily-aqi/); for example, this required computing the maximum daily 8-hour-average ozone concentration. Data are then included in the database used for the Data Explorer; Fig. 5 provides an example of data visualized in the Data Explorer.

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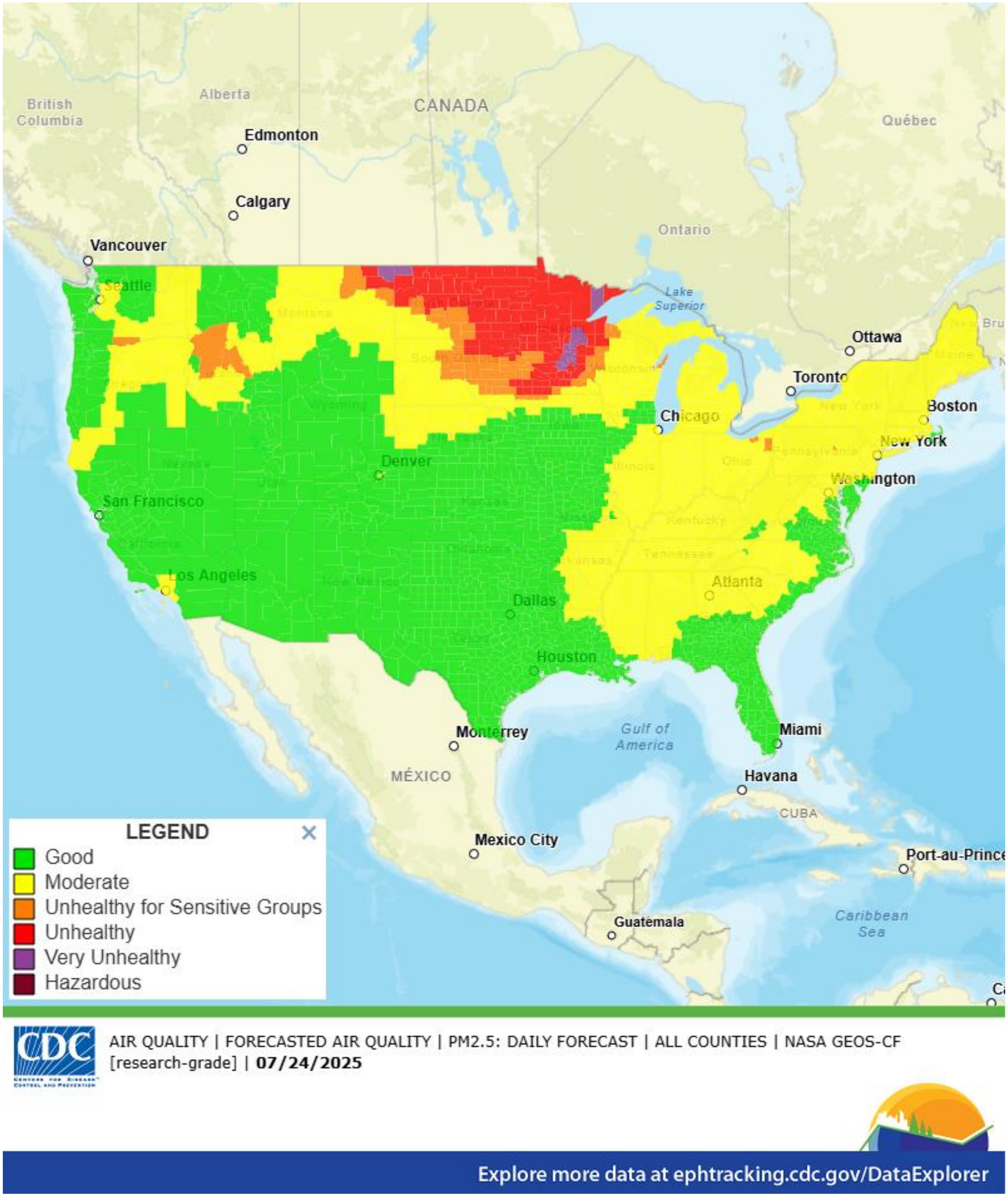

Fig. 5. An example displaying GEOS-CF $PM_{2.5}$ for July 24th, 2025 in the CDC Tracking Network's online Data Explorer tool. Values are colored according to the US AQI scale.

Relevant Attributes: Although GEOS-CF is not suitable for assessing compliance with US air quality regulations, its ability to forecast five of the seven US criteria air quality pollutants

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(https://www.epa.gov/criteria-air-pollutants/naaqs-table) up to four days ahead provides situational awareness and early warning to promote actions which can mitigate the health impacts of poor air quality. The availability of GEOS-CF via the CDC Tracking Network allows public health professionals to easily incorporate air quality forecasts into their processes, and to demonstrate this to others in their community (e.g., students and teachers, community health organizations, etc.), empowering them to become more aware and active in the environmental health of their community.

Lessons Learned: The spatial resolution of GEOS-CF is currently too coarse to provide meaningful forecasts at the scale of US census tracts, which was the desired resolution for the CDC Tracking Network. Furthermore, while GEOS-CF forecasts cover Alaska, Hawaii, Puerto Rico, and other US territories, technical limitations in the data post-processing limited the data available in the CDC Tracking Network to the CONUS region.

2) CASE STUDY: EXPOSURE ASSESSMENTS FOR THE DEFENSE CENTERS FOR PUBLIC HEALTH

Use Case: The US Defense Centers for Public Health at Aberdeen conduct Periodic Occupational and Environmental Monitoring Summaries (POEMS) to assess occupational and environmental health risks to troops during their deployment at various base camps throughout the world. POEMS provide a qualitative summary of health risks identified at the base camp, including air pollution, and any potential medical implications. While in-situ samples are collected whenever feasible to support these assessments, limitations in sampling frequency and spatial availability lead to data gaps. GEOS-CF is an additional tool incorporated into POEMS to address these data gaps.

Access Method: Originally, GEOS-CF data were accessed via the GEOS-CF interactive map tool. However, this method was limited to downloading 90 days of data for each pollutant at a time, which made creating multi-year, multi-pollutant data records cumbersome. Later, a python notebook implementing the CFAPI was developed, allowing a year or more of data from multiple pollutants to be downloaded with a single run of the script. Post-processing applied to these data includes calculation of high, low, and average concentration values and comparison with exposure guidelines.

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Relevant Attributes: The hourly concentration data provided by GEOS-CF is useful for providing a better picture in trends and filling the gaps of in-situ sampling, which often only provides information for a single point on a single day. GEOS-CF is also useful in austere environments where sample equipment may be limited due to access or electricity. The spatial resolution of GEOS-CF is currently sufficient for providing representative concentration information for US military bases, which are often of a similar scale. Currently, GEOS-CF data on $PM_{2.5}$, ozone and nitrogen dioxide are used in POEMS, based on the accuracy established for these constituents in past publications (Keller et al., 2021); inclusion of additional pollutants, e.g., carbon monoxide, is contingent upon both demonstrating sufficient quality of the data as well as its relevance to medical assessments. Finally, provision of GEOS-CF data in a spreadsheet-compatible format allows interoperability with other data considered for POEMS.

Lessons Learned: Switching to the CFAPI facilitated point-specific bulk data access, although occasional issues with server time-outs persist due to the volumes of data being queried. Accuracy in the provided data is the number one priority; reports on model performance and skill scores are included in each POEMS report to support for the accuracy and uncertainties of the included data. To date, relatively limited in-situ data for verifying the global performance of GEOS-CF for other pollutants, e.g., many VOCs, means that the accuracy of GEOS-CF for these constituents cannot be established to the degree required for the POEMS. Finally, providing concentration estimates closer to the surface (rather than up to 130m, as in the current system) would improve exposure characterization.

4. Summary and outlook

Table 2 summarizes the strengths and weaknesses of GEOS-CF identified across use cases considered here. First, in alignment with the NASA Open-Source Science Initiative, provision of GEOS-CF data through several open platforms in multiple formats improves accessibility and facilitates use by varied communities. This flexibility allows users to operate in environments with which they are already familiar, and to integrate GEOS-CF data into existing tools and workflows. In some use cases, suitable data access pathways were already available (e.g., direct file access by University of Alaska Fairbanks), while in others, existing access methods were adapted or new ones created in partnership with the users (e.g., tailoring the CFAPI to meet the needs of TOLNet). While flexible data access options are important for open science,

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maintaining multiple pathways requires a sustained commitment of resources. It is an important and ongoing consideration to strike an appropriate balance, supporting data access methods which best serve the widest portion of the user community.

Use Case	**GEOS-CF Attributes**				
	Resolution	Coverage	Latency	Access	Other key factor
TOLNet forecasts		✓	✓	✓	✓ vertical profiles
UAF ensemble forecast	✗	✓	~		✗ missing products
WRI forecasts		✓	✓	~	✓ multi-pollutant
Rio forecasts	✓		~	✓	✓ full columns
CDC Tracking Network	✗	~	✓	~	✓ multi-pollutant
Defense Health POEMS	~	✓		~	~ accuracy

Table 2. Matrix of GEOS-CF attributes identified in the case studies presented here as strengths (✓), weaknesses (✗), or mixed strengths and weaknesses (~). Common attributes considered are Resolution, referring to the horizontal and vertical spatial resolution, Coverage, referring to the spatial extent of outputs, Latency, referring to the time of availability for forecasts after they are generated, and Access, referring to the ease of accessibility of the data.

Typical reasons cited for using GEOS-CF are its global availability and coverage, ability to provide information on multiple pollutants (especially trace gases), and relatively low latency, allowing timely information about current and near-future conditions. Some users, however, noted that the latency was sometimes inconsistent. The migration of NASA Earth science data to commercial cloud environments (https://www.earthdata.nasa.gov/about/earthdata-cloud-evolution), a further aspect of the Open-Source Science Initiative, may allow users to mitigate these issues by implementing analysis software and hosting web services in the same cloud environment, and streamline re-gridding and integration with satellite and in-situ observations. For example, this might enable virtual "fly-throughs" of GEOS-CF and other data products for suborbital campaign planning.

The native resolution of GEOS-CF, while an important positive factor for some users, was noted by others as being insufficient to capture air quality at local scales relevant to their use-cases. The use of GEOS-CF as an input to localized forecasts, as in the cases of WRI and Rio de

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Janeiro, seeks to address this limitation but requires additional in-situ and satellite data and post-processing beyond what is available directly from GEOS-CF. GMAO is planning to produce analogous products to GEOS-CF with a regionally improved resolution, e.g., implementing a stretched model grid for higher spatial resolution over CONUS. Such a product may address the resolution concerns of certain users, e.g., the CDC Tracking Network.

The development of a new version of GEOS-CF, which was publicly released in September 2025, provides opportunities to address certain limitations identified here. For example, the need for PM_{10} forecasts identified by several users prompted the inclusion of PM_{10} diagnostics from GEOS-Chem (Zhai et al., 2021) in the air quality data collection of the new GEOS-CF version. Furthermore, a new atmospheric composition reanalysis data product is being developed using a system similar to the new GEOS-CF version to provide a long-term record of atmospheric constituents globally, as other GMAO products have enabled for $PM_{2.5}$ (e.g., Keller, 2021). Certain use cases, such as the Defense Centers for Public Health POEMS, may transition to using this long-term dataset, while those requiring forecasts will continue with GEOS-CF. These changes are an illustration of the Earth Science to Action Strategy, where user requirements guide decisions about the development and delivery of NASA Earth science data products, ensuring the resulting data are more directly usable and actionable.

The development of GEOS-CF has involved extensive community and user feedback, including GEOS-Chem community (https://geoschem.github.io/index.html), contributions and consultations with system users as documented above. This involvement, along with efforts to provide GEOS-CF data through a range of access options as noted in Table 1, is illustrative of the NASA Open-Source Science Initiative. In alignment with this initiative, we have sought to increase transparency and collaborator involvement both for the GEOS-CF data themselves as well as for the scientific process through which the GEOS-CF system is developed. The ability to respond to needs articulated by product users is also an important aspect of the NASA Earth Science to Action strategy with priorities for GEOS-CF development and implementation being guided both by NASA mission needs and those of communities seeking to apply these data to decisions regarding key societal challenges, such as air quality and public health. In the spirit of these initiatives, we are sharing our approaches and lessons learned with the broader community, in the hope that these can facilitate similar efforts to provide Earth science data to those who will use it to take actions which benefit society.

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Data Availability Statement.

GEOS-CF data are available via the data access methods outlined in Section 2 of this manuscript, as summarized in Table 1.

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