FireAQ: Monitoring Fire and Air Quality Forecasts

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A primer on a new decision support system for fire monitoring and air quality forecasts under smoke conditions

Smoke emitted from wildland fires contains fine particulate matter ($PM_{2.5}$), ozone (O_3), and other air pollutants.[1] These emissions compromise air quality and can pose health risks to individuals in affected areas. Smoke and $PM_{2.5}$ are particularly interconnected when assessing air quality and its impact on environmental health. $PM_{2.5}$ refers to fine particles with a diameter of 2.5 micrometers or smaller, which are the main component of smoke.[2] Accurate near-real-time (NRT) predictions of these air pollutants are crucial for local communities to efficiently mitigate public exposure during high pollution events, particularly in the presence of smoke. Additionally, these predictions aid health authorities issue advisories and implement public health safety measures.

Existing forecast models have notable uncertainties stemming from discrepancies in fire emissions and accurate modeling of smoke plume heights. Local and state air quality and public health (AQPH) agencies use satellite data products to enhance these models. However, certain satellite-derived products, such as aerosol optical depth (AOD), lack information about the vertical distribution of aerosols, which is necessary for more accurate surface $PM_{2.5}$ estimation. Air quality management becomes more complex when considering exceptional events, defined as unusual or naturally occurring events that can affect air quality but are not reasonably controllable using techniques that tribal, state, or local air agencies may implement to attain and maintain the National Ambient Air Quality Standards.[3] These events can significantly impact air quality predictions and management strategies.

Real-time forecasts of $PM_{2.5}$ and O_3 concentrations are essential for communities to reduce public exposure, particularly among vulnerable populations, during periods of high pollution. To address these challenges, we developed FireAQ, a decision-support platform designed to visualize forecasts of $PM_{2.5}$ and O_3 and support exceptional events analyses. This article introduces FireAQ, beginning with an overview of the platform and its main features and services, followed by a case study of an exceptional event that demonstrates how FireAQ supports the analysis of such events.

FireAQ Overview, Features and Services

FireAQ aims to enhance the analysis and prediction of air quality during smoky conditions. Due to significant variations in fire emissions and modeled plume heights, air quality forecast models exhibit considerable variability and pose significant challenges for AQPH managers. FireAQ is developed in collaboration with four AQPH agencies, including the South Coast Air Quality Management District, Maine Department of Environmental Protection, Colorado Department of Public Health & Environment, and Oklahoma Department of Environmental Quality, along with the Lake Michigan Air Directors Consortium, a regional air quality consortium. Representatives from these agencies have been stakeholders in the platform's development process since the conceptual design phase. Initial interviews were conducted to gather their input on data needs and interface preferences, ensuring alignment with FireAQ's main goals. This feedback has guided the creation of key features and data displays to support decision-making and facilitate user data exploration. Continuous input has contributed to the platform's iterative improvements. The FireAQ platform has been operational since January 2023, with services extended to the present, and development is set to continue through 2025.

The primary goal of FireAQ is to improve decision-making processes in AQPH management for smoky conditions, encompassing both day-to-day forecasts and the analysis of exceptional events. To achieve this, FireAQ mainly leverages:

1. Goddard Earth Observing System Forward Processing (GEOS-FP)[4] and GEOS Composition Forecasts (GEOS-CF)[5] systems, developed by NASA;
2. Navy Aerosol Analysis and Prediction System (NAAPS) from Naval Research Laboratory (NRL)[6];
3. Aerosol Optical Centroid Height (AOCH) and Aerosol Optical Depth (AOD) products from AOCH-O2AB[7] derived from the Tropospheric Monitoring Instrument (TROPOMI);
4. Fire Light Detection Algorithm Version 2 (FILDA-2),[8] derived from the Visible Infrared Imaging Radiometer Suite (VIIRS); and
5. Observations from the U.S. Environmental Protection Agency (EPA) AirNow program.[9]

Table 1 summarizes FireAQ's services, including the respective data sources, resolution, and forecast duration for the data presented on the system. Following this, the platform's main services are described.

Figure 1 shows an example of the web page displaying the predicted $PM_{2.5}$ daily average. The webpage offers several features, including:

A. Visualization of the daily-averaged 72-hr forecast of the individual models (GEOS-FP, GEOS-CF, and NAAPS) and the mean of these models (ENSEMBLE).
B. The ability to zoom in and out while retaining location details in the basemap layer.
C. Exploration of locations by searching for a specific address or clicking on the map.

Table 1. FireAQ Services Summary

Service	Description	Data Source	Resolution/Fcst Duration
Time Series Forecasts	Hourly $PM_{2.5}$ forecasts	GEOS-FP GEOS-CF NAAPS	0.25°/72 hr 0.25°/72 hr 0.33°/72 hr.
$PM_{2.5}$ Daily Average	Daily averaged $PM_{2.5}$ predictions from a single model	GEOS-FP, GEOS-CF, NAAPS	0.25°/72 hr
ENSEMBLE	Daily average of $PM_{2.5}$ from 3 model prediction	GEOS-FP, GEOS-CF, NAAPS	0.25°/72 hr
AOCH-O_2AB	AOCH and AOD products	TROPOMI-derived AOCH-O_2AB algorithm developed in-house	0.05°/3 hr (NRT)
FILDA-2	Fire Combustion Efficiency, Fire Radiative Power, Active Fire Location products	VIIRS-derived FILDA-2 algorithm developed in-house	0.006° hourly (NRT)
AQI for you	Air Quality Index (AQI) and EPA's corresponding recommendations	ENSEMBLE product from FireAQ	0.25°/72 hr
Daily Images Subscription	Email service providing daily $PM_{2.5}$ forecast images	ENSEMBLE product from FireAQ	0.25°/72 hr
AirNow Observations	Near real-time $PM_{2.5}$ observations for air quality monitors	EPA AirNow	Hourly (NRT)

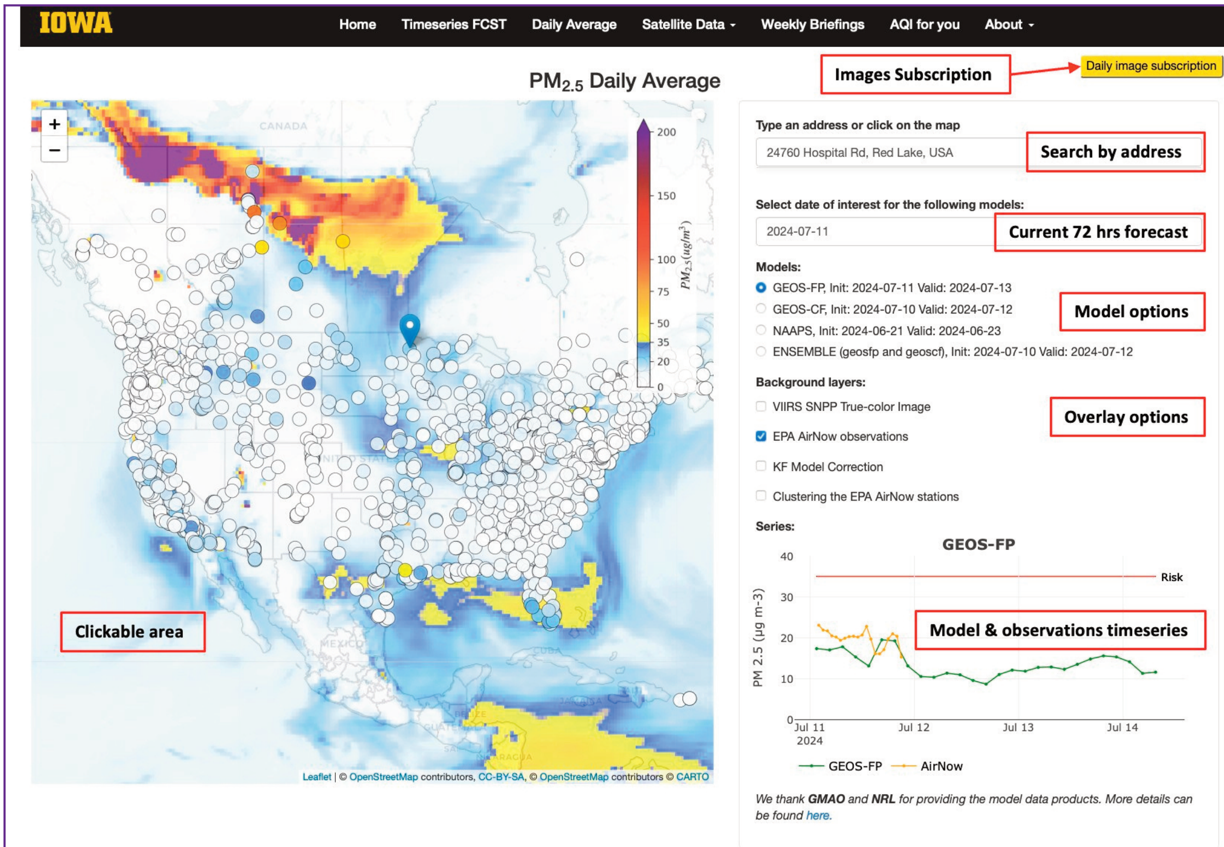

Figure 1. Screenshot of FireAQ entry dashboard, allowing users to select date and model to view and query $PM_{2.5}$ daily average.
Source: http://esmc.uiowa.edu:3838/pm25_fcst_index/.

D. Overlay of true color imagery from VIIRS SNPP.
E. Display of the hourly forecasted $PM_{2.5}$ for a specified location.
F. Display of time series of EPA AirNow observations.

Figure 2 illustrates an example of the "Time Series Forecasts" web interface, which displays hourly $PM_{2.5}$ predictions through maps and time series line plots. The map plots are presented in a carousel format and retain several features from the daily average web interface (Features B, C, and E). Additionally, surface O_3 concentrations from the GEOS-CF model are displayed.

North American Summer Exceptional Event

During the spring and summer of 2023, North America experienced one of the largest fire seasons in decades. Canada faced its most severe wildland fire season on record, with wildfires spreading across all provinces and territories. This widespread burning resulted in significantly degraded air quality throughout North America, with smoke even reaching Europe.[10] The severe wildfires in the Canada's boreal forests raised widespread concern, not only for the cumulative burned area, exceeding 156,000 km^2 (1.7% of Canada's total land) as of August 31, 2023, but also because of the unprecedented levels of air pollutants, including $PM_{2.5}$ and NOx, released into the atmosphere.[1] Recent studies have identified climate change as a major factor driving these extraordinary fire events, contributing to the increasing frequency and intensity of wildfires.[11-13]

Forecasting smoke transport can be challenging for AQPH managers, particularly as the altitude of the smoke layer is unknown in certain satellite products. For example, AOD is widely used to represent the spatial extent of atmospheric aerosol loading; however, AOD alone cannot distinguish the vertical location of aerosols within the atmospheric column. In other words, AOD provides limited insight into surface $PM_{2.5}$ concentrations. A different satellite-based parameter, AOCH, represents the altitude at which aerosol extinction peaks and can be used to help constrain estimates of surface $PM_{2.5}$ derived from AOD observations.[7] For example, given a value of AOD, higher AOCH indicates lower surface $PM_{2.5}$ and vice versa.[14] Additionally, it is important to consider the combustion state of the fire, often referred to as Modified Combustion Efficiency (MCE). This quantity indicates how completely the fuel source has burned and plays a vital role in predicting the composition and behavior of $PM_{2.5}$ emissions from wildfires, where lower MCE values typically indicate larger smoke emissions.[8]

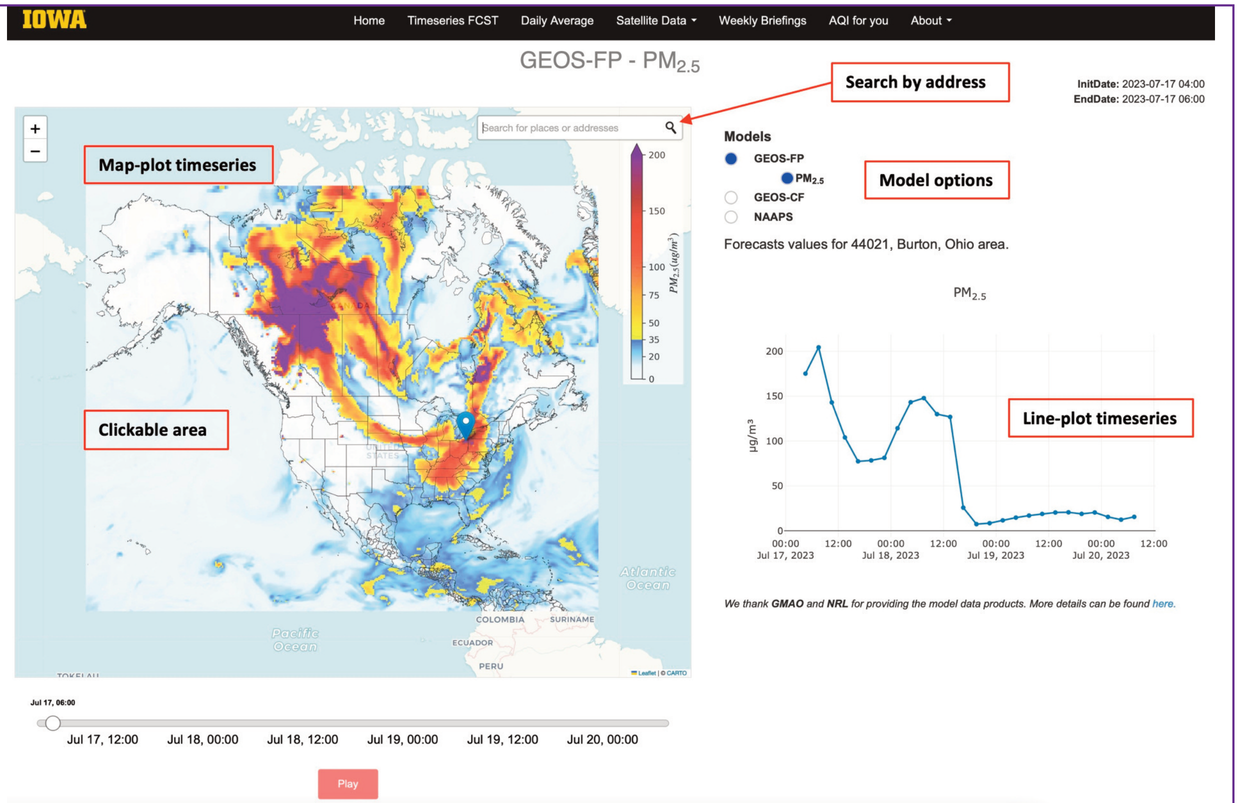

Figure 2. Screenshot of the FireAQ Time Series Predictions, allowing users to view the hourly forecast of $PM_{2.5}$ concentration at a user-specified location from a single forecast model.
Source: https://fireaq.uiowa.edu/forecasts/models_timeseries.php.

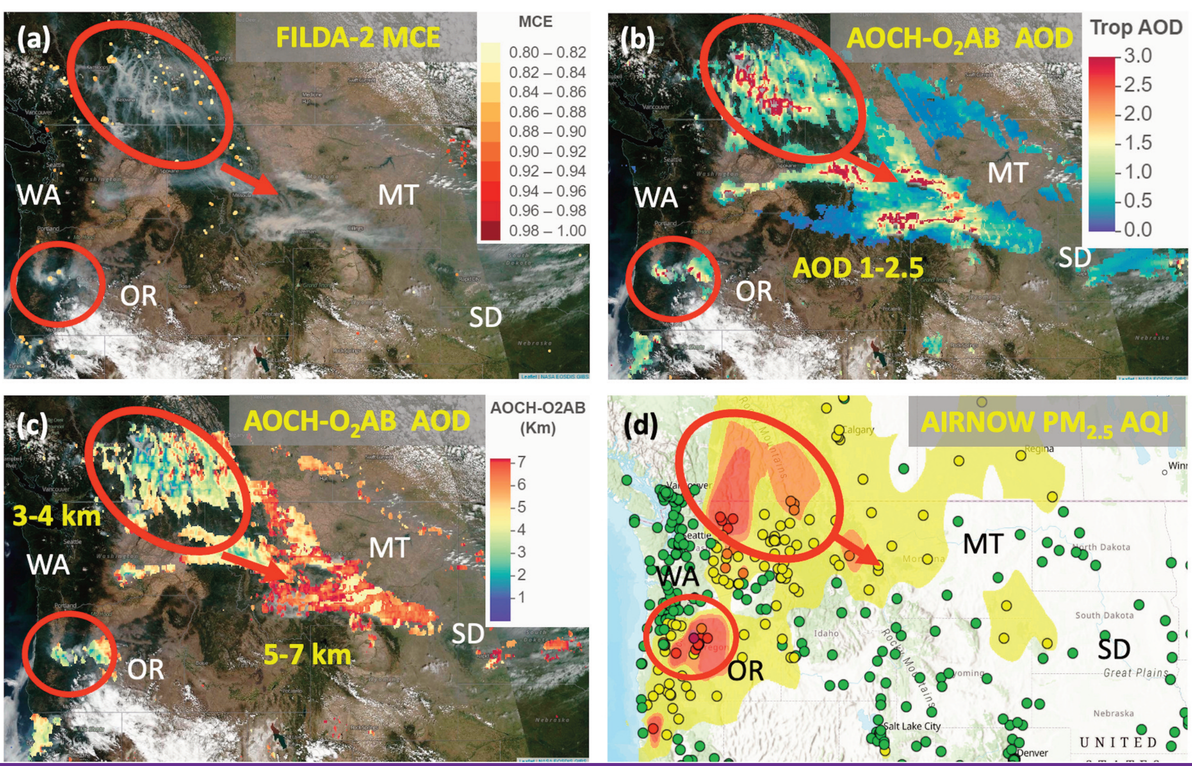

Figure 3. Satellite-derived products and in-situ observations depicting the exceptional wildfire event on August 16, 2023.

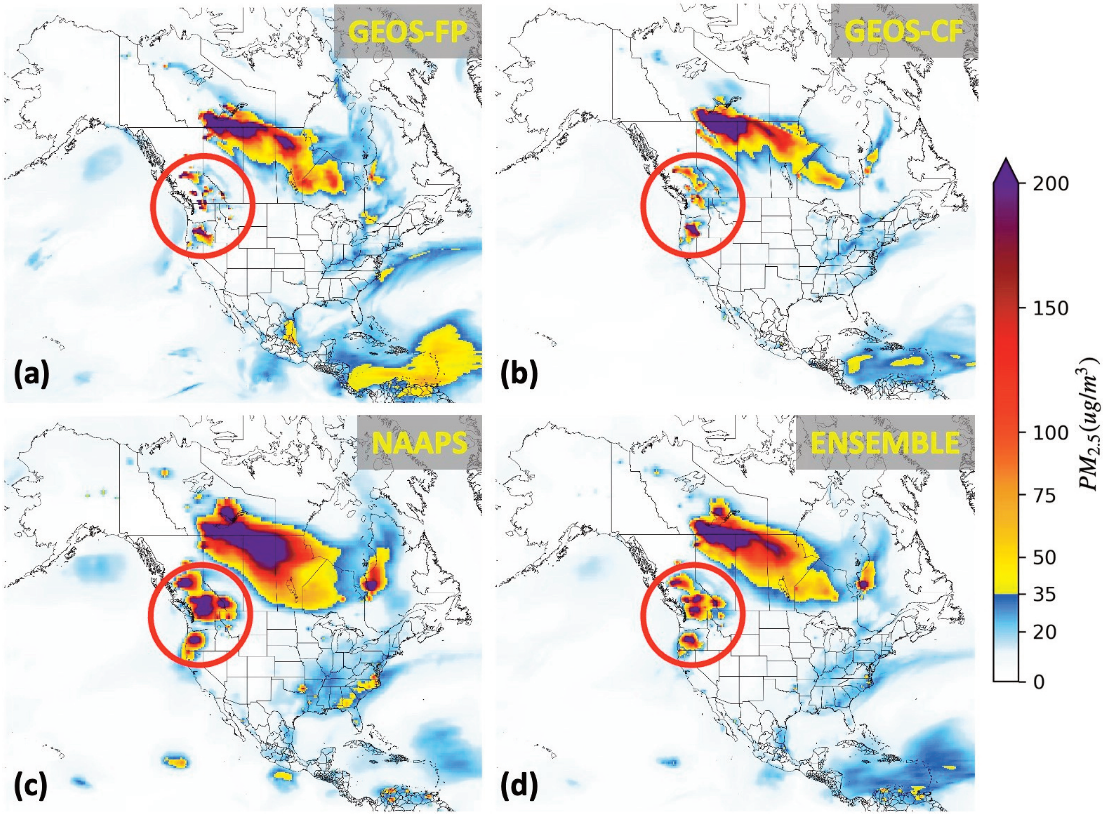

Figure 4. $PM_{2.5}$ forecasts and their mean (ENSEMBLE) depicting air pollutant levels in the atmosphere during the exceptional wildfire event on August 16, 2023.

Figure 3 illustrates how FireAQ data services were used to analyze an exceptional smoke event that began a few days prior to August 16, 2023, in Canada, affecting several northwestern U.S. states. The analysis incorporated satellite-derived products such as MCE from FILDA-2 and AOCH and AOD from AOCH-O_2AB. Additionally, $PM_{2.5}$ AQI values from EPA's AirNow were included to compare with the data products available on FireAQ.

Lower MCE values on August 16, 2023 (Figure 3a) suggest incomplete combustion (smoldering) of the fire and higher production of smoke, which is visible in the VIIRS True-Color Image. Additionally, aged smoke particles were transported into the northwestern United States from fires in British Columbia. AOCH-O_2AB AOD ranged from 1–3 km for both near-source and transported smoke (Figure 3b). However, the surface $PM_{2.5}$ AQI does not follow the same spatial pattern as the AOD (Figure 3d) and is unhealthy (red) near the source and drops to moderate (yellow) as the aged smoke enters Montana. This difference can be explained from the shift in AOCH (Figure 3c). The smoke layer is closer to the surface near the fires (2–3 km), correlating with unhealthy AQI, and rises aloft (5–7 km) as it is transported toward Montana, consistent with the lower impacts reflected in the AQI.

Regarding the forecast models, all three predicted different spatial variations and overestimated the maximum surface $PM_{2.5}$ concentrations in areas affected by the transported smoke during the exceptional fire event (see Figure 4). This suggests the models underestimate the smoke plume heights.

FireAQ Weekly Briefings

In July 2023, FireAQ began hosting weekly briefings to provide retrospective analyses of air quality, discuss current forecasts, and engage with community members. The first season concluded in October 2023 with 47 members from 22 participating entities, including five universities, ten state agencies, and seven federal organizations. Presentations and forecast summaries are archived and available on the FireAQ website (https://fireaq.uiowa.edu/briefings.php). The 2024 briefing series resumed on July 15 and is set to conclude in mid-October. Membership has remained consistent, with an average of 25 participants per session (although the number of subscribers to our weekly briefing has increased). The briefings will resume each fire season, and new participants are welcome to join and engage with FireAQ service (fireaq@googlegroup.com). It is worth noting that participants have expressed appreciation for the overviews provided in the briefings, particularly for highlighting key trends to watch for later in the week. Additionally, they have found the archived briefing resources valuable as a compilation of useful images that they can revisit when needed.

Conclusions

FireAQ integrates data derived from satellite imagery and air quality forecast models, while providing dynamic web interfaces for data exploration. This system provides AQPH managers with an integrated view of fires, smoke, and air contaminants, such as $PM_{2.5}$, originating from wildland fires. By assessing the MCE of a fire, users can evaluate the effectiveness of the burning process and qualitatively estimate the emissions generated by the fire. The web interfaces displaying hourly and daily forecasts for $PM_{2.5}$ facilitate the monitoring and prediction of pollutant transport patterns. Additionally, examining the AOCH product provides information on the altitude of the smoke layer across regions impacted by smoke from fires, which is necessary to constrain other widely used satellite-based observations, such as AOD, to indicate poor air quality. The services offered by the FireAQ platform comprise a set of tools designed to facilitate the analysis of exceptional wildfire events, and the insights provided by each service support decision-making processes for managing air quality during smoky conditions. **em**

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