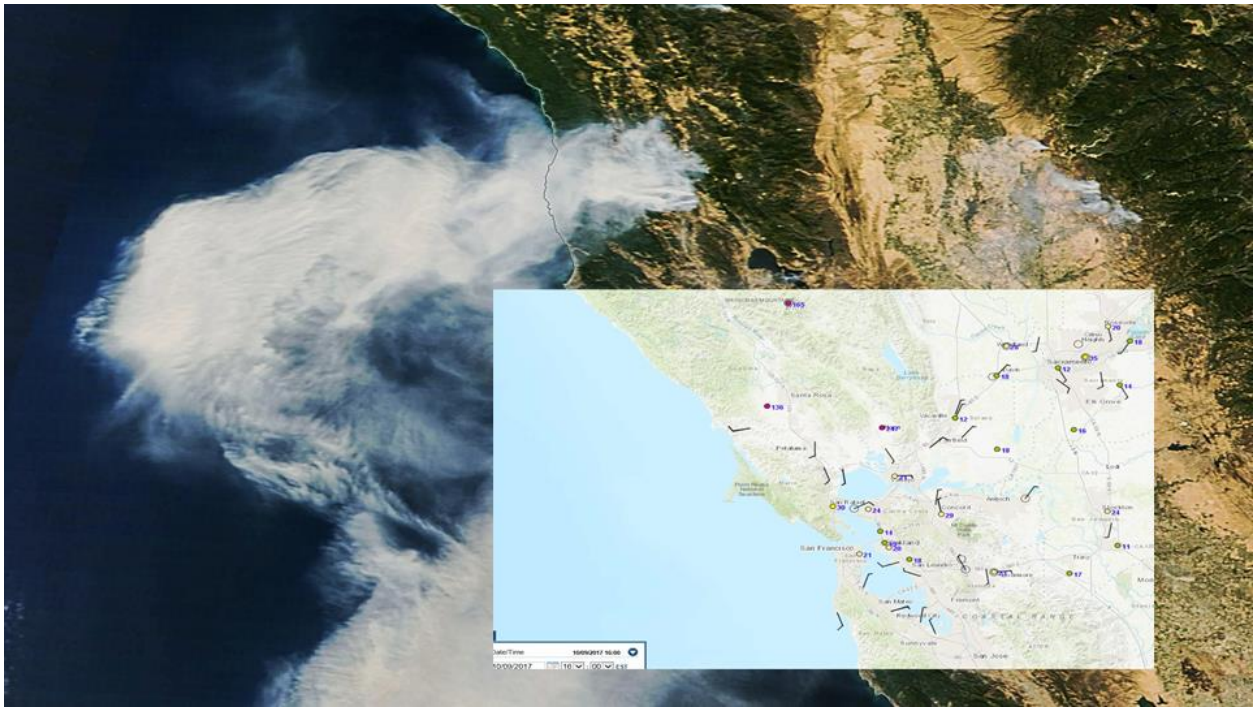
Version 6-18

Connecticut Department of
ENERGY &
ENVIRONMENTAL
PROTECTION

Guide to Using Satellite Images in Support of Exceptional Event Demonstrations



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CTDEEP

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Using Satellite Data for Exceptional Event Analysis

1. Introduction

The Exceptional Events Rule, contained in Title 40 of the Code of Federal Regulations Part 50.14 (40CFR50.14), was revised by EPA in October of 2016[1]. The revised rule describes the procedures for treating data which has been influenced by an exceptional event. Accordingly, an exceptional events demonstration must include the following elements:

1) A narrative conceptual model that describes the event(s) causing the exceedance or violation and a discussion of how emissions from the event(s) led to the exceedance or violation at the affected monitor(s);

2) A demonstration that the event affected air quality in such a way that there exists a clear causal relationship between the specific event and the monitored exceedance or violation;

3) Analyses comparing the claimed event-influenced concentration(s) to concentrations at the same monitoring site at other times. The Administrator shall not require a State to prove a specific percentile point in the distribution of data;

4) A demonstration that the event was both not reasonably controllable and not reasonably preventable;

5) A demonstration that the event was caused by human activity that is unlikely to recur at a particular location or was a natural event; and

6) Documentation that the submitting air agency followed the public comment process.

For $PM_{2.5}$ and ozone, wildfires are the most common cause for an exceptional event data request to be pursued. Wildfires are defined at 40 CFR 50.1(n) as "…any fire started by an unplanned ignition caused by lightning; volcanoes; other acts of nature; unauthorized activity; or accidental, human-caused actions, or a prescribed fire that has developed into a wildfire. A wildfire that predominantly occurs on wildland is a natural event." EPA has prepared guidance specific to analyzing the influence of wildfires on ozone events[2].

Furthermore, 40CFR50.14(b)(4) states that the EPA " … Administrator shall exclude data from use in determinations of exceedances and violations where a State demonstrates to the Administrator's satisfaction that emissions from wildfires caused a specific air pollution concentration in excess of one or more national ambient air quality standard at a particular air quality monitoring location and otherwise satisfies the requirements of this section. Provided the Administrator determines that there is no compelling evidence to the contrary in the record, the

[1] Federal Register / Vol. 81, No. 191 / Monday, October 3, 2016: Treatment of Data Influenced by Exceptional Events

[2] Guidance on the Preparation of Exceptional Events Demonstrations for Wildfire Events that May Influence Ozone Concentrations, Final, US EPA OAQPS, Research Triangle Park, North Carolina, September 2016.

Administrator will determine every wildfire occurring predominantly on wildland to have met the requirements identified in paragraph (c)(3)(iv)(D) [item (4) above] of this section regarding the not reasonably controllable or preventable criterion."

Although many elements go into the technical support document for an exceptional event, this guidance will cover the resources available from satellite images and data to support the weight of evidence. The following guidance played a critical role for the State of Connecticut in its successful demonstration to exclude ozone data from May 25-26, 2016 at several of its monitors because of the transport of pollutants from the wildfires at Fort McMurray, Alberta, Canada.

On May 1, 2016, a wildfire began southwest of Fort McMurray and within days, it swept through the community, destroying approximately 2,400 homes and buildings and forcing the largest wildfire evacuation in Albertan history. The fire, most likely the result of human activity[3], spread across approximately 590,000 hectares (1,500,000 acres) and became the costliest natural disaster in Canadian history[4] before it was declared to be under control on July 5, 2016.

Figure 1. Wildfire as it approaches Fort McMurray. This photo taken, Wednesday, May 4, 2016 shows the plume rising into the atmosphere forming pyro-cumulus clouds. (photo by Jeff McIntosh/CP).

[3] Canadian Broadcasting Corporation, *Someone likely sparked the Fort McMurray wildfire, but was it a crime? RCMP ask*. June 14, 2016

[4] Insurance Bureau of Canada, *Northern Alberta Wildfire Costliest Insured Natural Disaster in Canadian History – Estimate of insured losses:$3.58 billion*. July 7, 2016.

2. Visible Satellite Images with Aerosol Optical Depth (AOD)

Aerosol optical depth is a measure of the amount of sunlight scattered or absorbed by particles in the atmosphere. The NOAA ESRL Global Monitoring Division provides an introduction to AOD here.

One of the most useful tools for tracking smoke plumes and aerosols are the AOD products retrieved from several satellite instruments. The NASA ARSET web page is a great place to get started with tutorials on these products, for those unfamiliar with them. The following table is adapted from one of their presentations that gives a quick overview of several aerosol products available from current satellite instruments (columns). These are instruments on various polar orbiting satellites (listed in the last row of the table) that make one daylight pass over any area daily. I have used the MODIS and VIIRS products most extensively for my analysis of wildfires because of their finer spatial resolution and swath coverage.

Table 1. Polar Orbiting Satellite Aerosol Products

	MODIS	MISR	OMI	VIIRS
Strengths	• Coverage • Resolution • Calibration • Accuracy	• Calibration • Accuracy • Particle Shape • Aerosol height for thick layer or plume	• Indication of absorbing or scattering particles	• Coverage • Resolution • Calibration • Smaller bow-tie effect
Weaknesses	• Bright surfaces • Ocean glint • Non-spherical particles	• Coverage	• Resolution • Cloud contamination	• Bright surfaces • Ocean glint
Main Products	• AOD • Ocean-5 wavelengths • Land-3 wavelengths • Fine Fraction (Ocean only)	• AOD • 4 wavelengths • Spherical/Non-Spherical Ratio • Particle Size (3 bins)	• AOD • AAOD • Aerosol Index	• AOD • Aerosol Type

Product Resolution	• 250 m (bands 1 and 2) • 500 m (bands 3-7) • 1 km (bands 8-36)	• 17.6 km	• 13 x 24 km	• 750m Bands M1-M5, M7-M8, M10-M116 km • 375m Bands I1- I3
Satellite	• TERRA • AQUA	• TERRA	• AURA	• Suomi NPP

MODIS (or Moderate Resolution Imaging Spectroradiometer) is a key instrument aboard the Terra (originally known as EOS AM-1) and Aqua (originally known as EOS PM-1) satellites. Terra's orbit around the Earth is timed so that it passes from north to south across the equator in the morning, while Aqua passes south to north over the equator in the afternoon. These satellites provide near real-time images and have been very useful for observing wildfire locations and plumes.

VIIRS, a scanning radiometer, collects visible and infrared imagery and radiometric measurements of the land, atmosphere, cryosphere, and oceans. VIIRS data is used to measure cloud and aerosol properties, ocean color, sea and land surface temperature, ice motion and temperature, fires, and Earth's albedo. Suomi National Polar-orbiting Partnership (NPP), which hosts the VIIRS instrument is in a polar orbit-circling the Earth from the North Pole to the South Pole and back about 14 times a day.

Another instrument that is useful (but not on the chart above) is Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO). CALIPSO combines an active LIDAR instrument with passive infrared and visible imagers to probe the vertical structure and properties of thin clouds and aerosols over the globe. CALIPSO was launched on April 28, 2006 with the cloud profiling radar system on the CloudSat satellite. CALIPSO has a very narrow swath (64km), but it can provide information regarding the vertical profile of aerosols in the troposphere.

3. The Earth Observing System Data and Information System (EOSDIS) Worldview

The Worldview website offers a great selection of satellite images with the ability to add multiple layers. For the aerosol optical depth, they have included products from Aura/OMI, Suomi-NPP/OMPS, Aqua/MODIS, Terra/MODIS, Aqua and Terra/MODIS, Terra/MISR and SeaWiFS Deep Blue. According to the website, "*This app from NASA's EOSDIS provides the capability to interactively browse over 600 global, full-resolution satellite imagery layers and then download the underlying data. Many of the available imagery layers are updated within three hours of observation, essentially showing the entire Earth as it looks "right now"*."

The following figures were downloaded from Worldview for May 18, 2016, during the Fort McMurray wildfire and used in the Exceptional Event demonstration. They show a variety of products available to track wildfire plumes. Besides the aerosol products, I found that the AIRS

(aboard the Aqua satellite) carbon monoxide column tracked very well with smoke plumes. The example below first zoomed in over the region of interest (Western Canada and Northwestern U.S.), selected the day of interest in the bottom left (scroll or direct typing are possible). Worldview is nicely organized by application, so if you click, "add layers", and then select the tab that says, "Hazards and Natural Disasters", you can click on "Fires". From there you have options to select satellite products relevant to fires.

The example below then selected the following layers (all available under the "Fires" category):

Figure 2 shows:

- Fires & Thermal Anomalies
    - → Suomi NPP/VIIRS →Fires and Thermal Anomalies (both day and night options);
    - Aqua and Terra / MODIS → Fires and Thermal Anomalies (day and night)
- Fires & Thermal Anomalies
    - → Suomi NPP/VIIRS →Fires and Thermal Anomalies (both day and night options);
    - Aqua and Terra / MODIS → Fires and Thermal Anomalies (day and night)

Figure 3 adds on top of Figure 2 the AOD the Aerosol Optical Depth from Aqua/MODIS.

Figure 4 adds a layer with the Aerosol Index derived from Suomi NPP/OMPS.

Figure 5 adds the daily CO Column product retrieved from the AIRS instrument aboard the Aqua satellite.

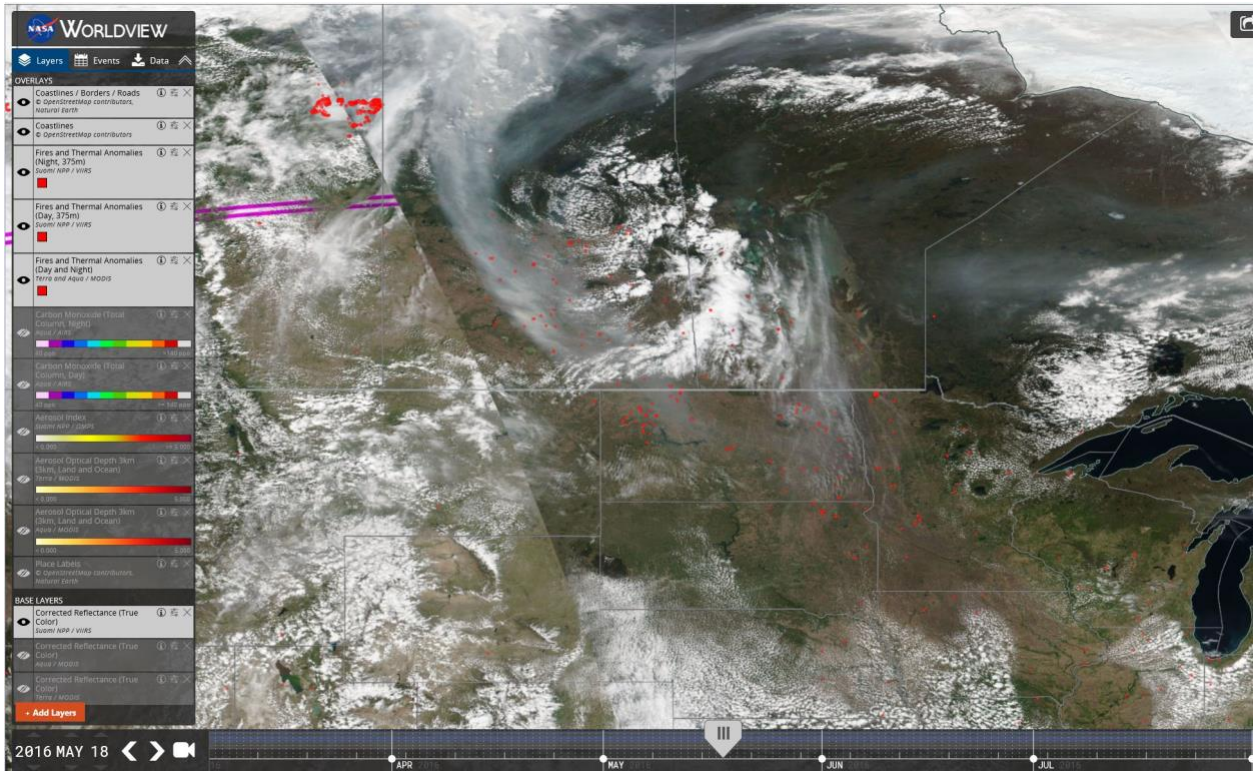

Figure 2. VIIRS Visible Image with fires indicated as Thermal Anomalies (red dots) on May 18, 2016

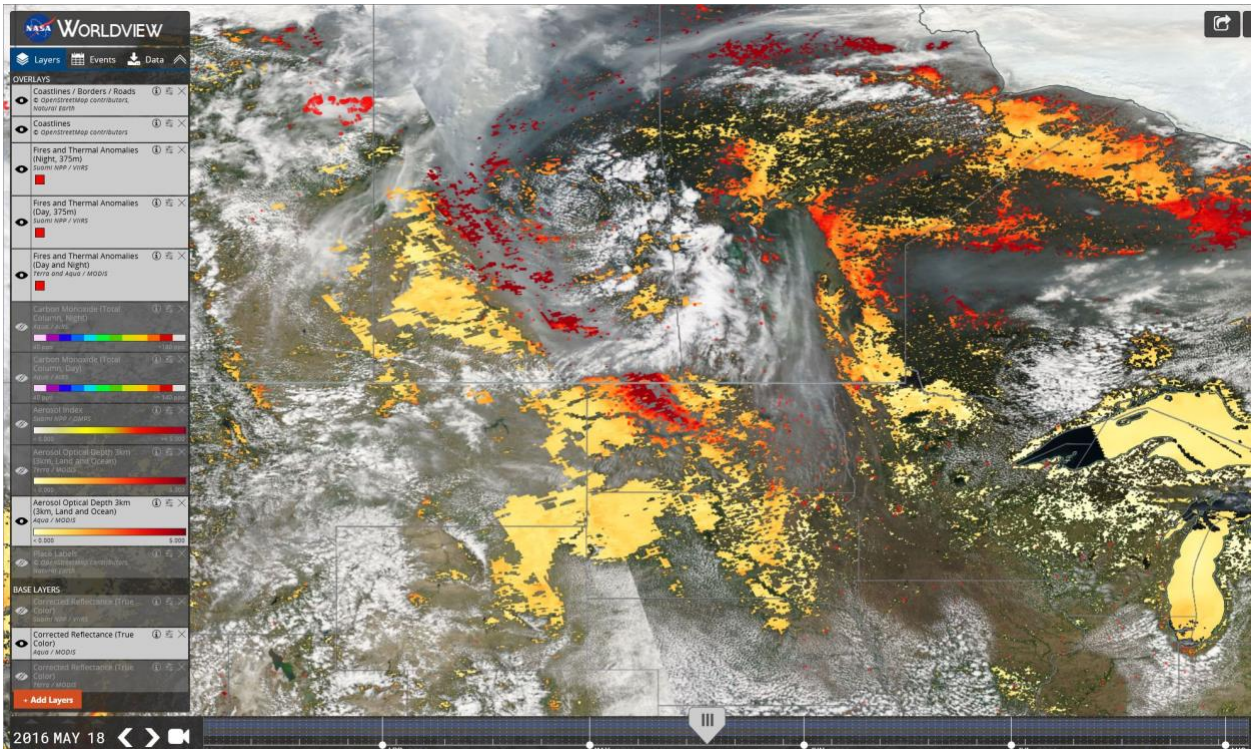

Figure 3. AQUA/MODIS Visible Image with Aerosol Optical Index (AOD) shown in color (higher AOD is shown in red) on May 18, 2016

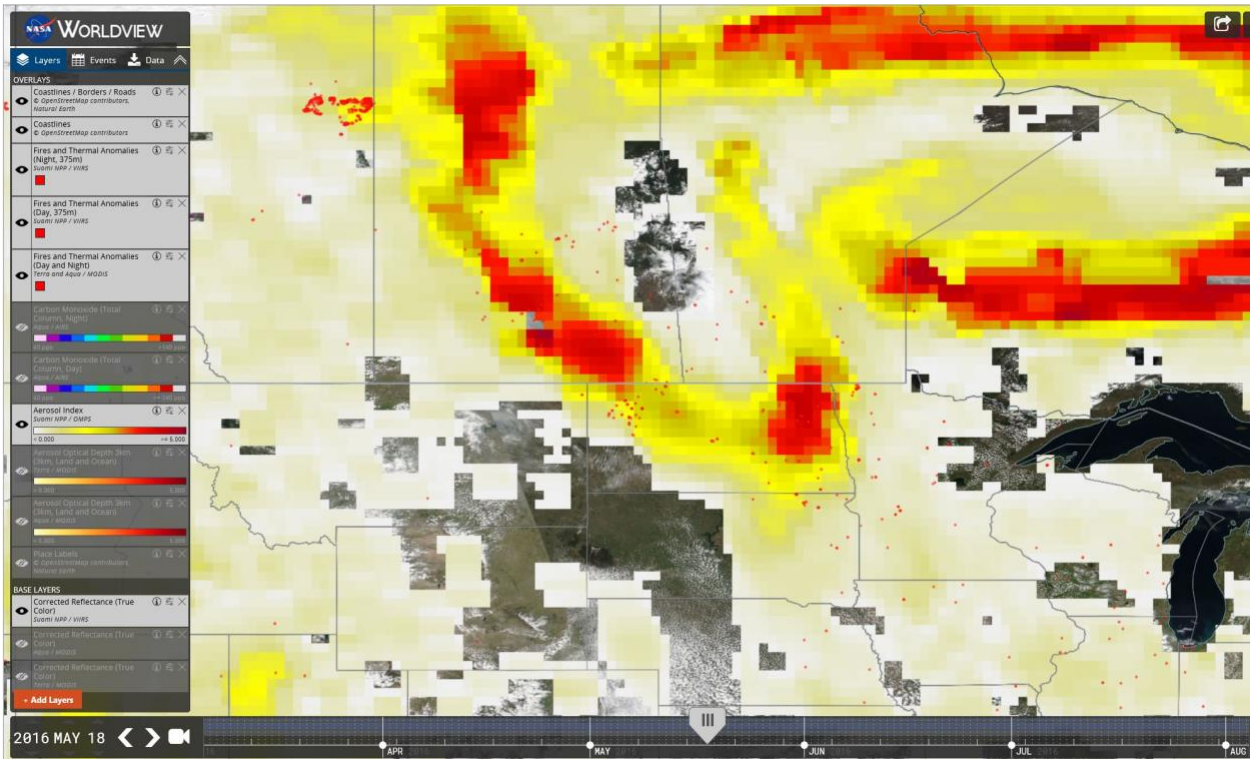

Figure 4. VIIRS Visible with the Suomi NPP/OMPS Aerosol Index on May 18, 2016

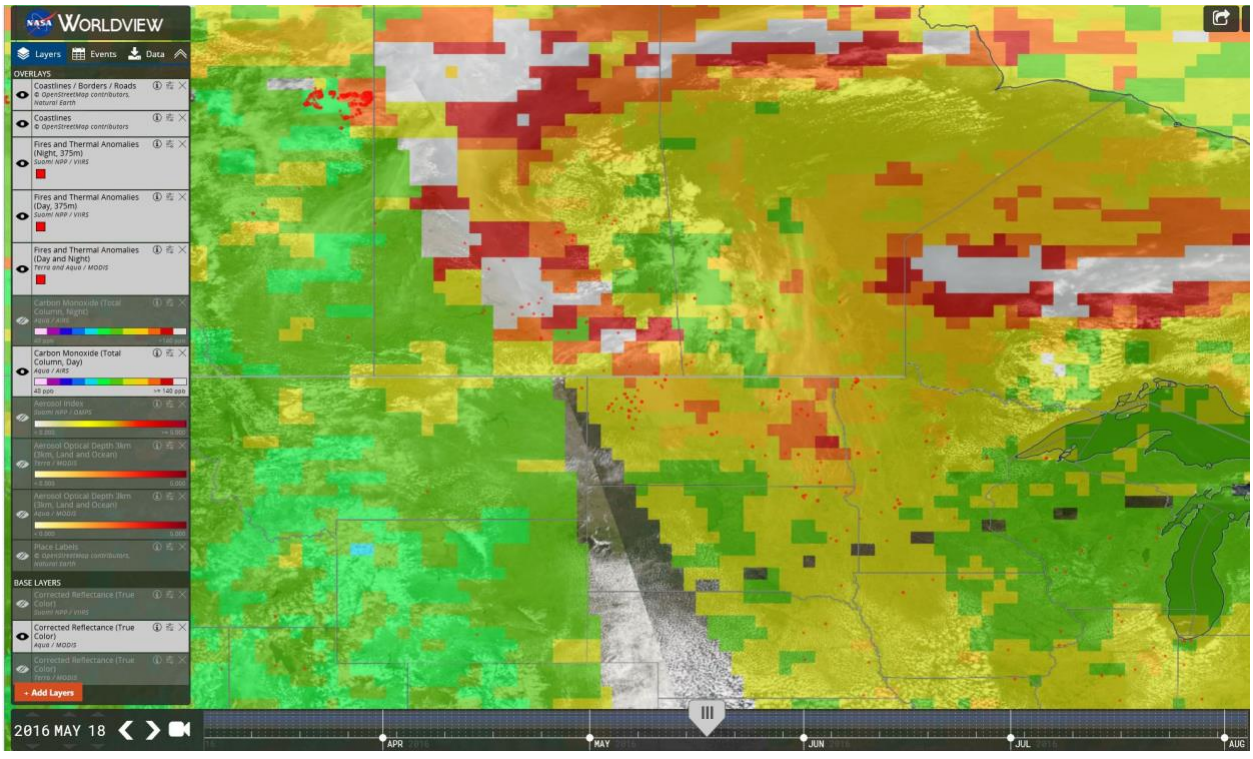

Figure 5. AQUA AIRS Carbon Monoxide Column on May 18, 2016

4. The eIDEA Website

IDEA (Infusing satellite Data into Environmental air quality Applications) is a NASA-EPA-NOAA partnership to improve air quality assessment, management, and prediction by infusing (NASA) satellite measurements into (EPA, NOAA) analyses for public benefit. The eIDEA website is the latest version of this collaboration, offering aerosol and smoke/fire products associated with the VIIRS instrument. They have incorporated trajectories and smoke masks into the product, as well as a product that estimates surface $PM_{2.5}$. The image in Figure 6 is available simply by selecting the date near the top of the website. Options shown in Figure 6 along the right hand column can be toggled on and off to allow superimposing e.g., the AIRNOW $PM_{2.5}$ measurements or the AOT (aerosol optical thickness shown in Figure 7) or the forecast model trajectories (Figure 8).

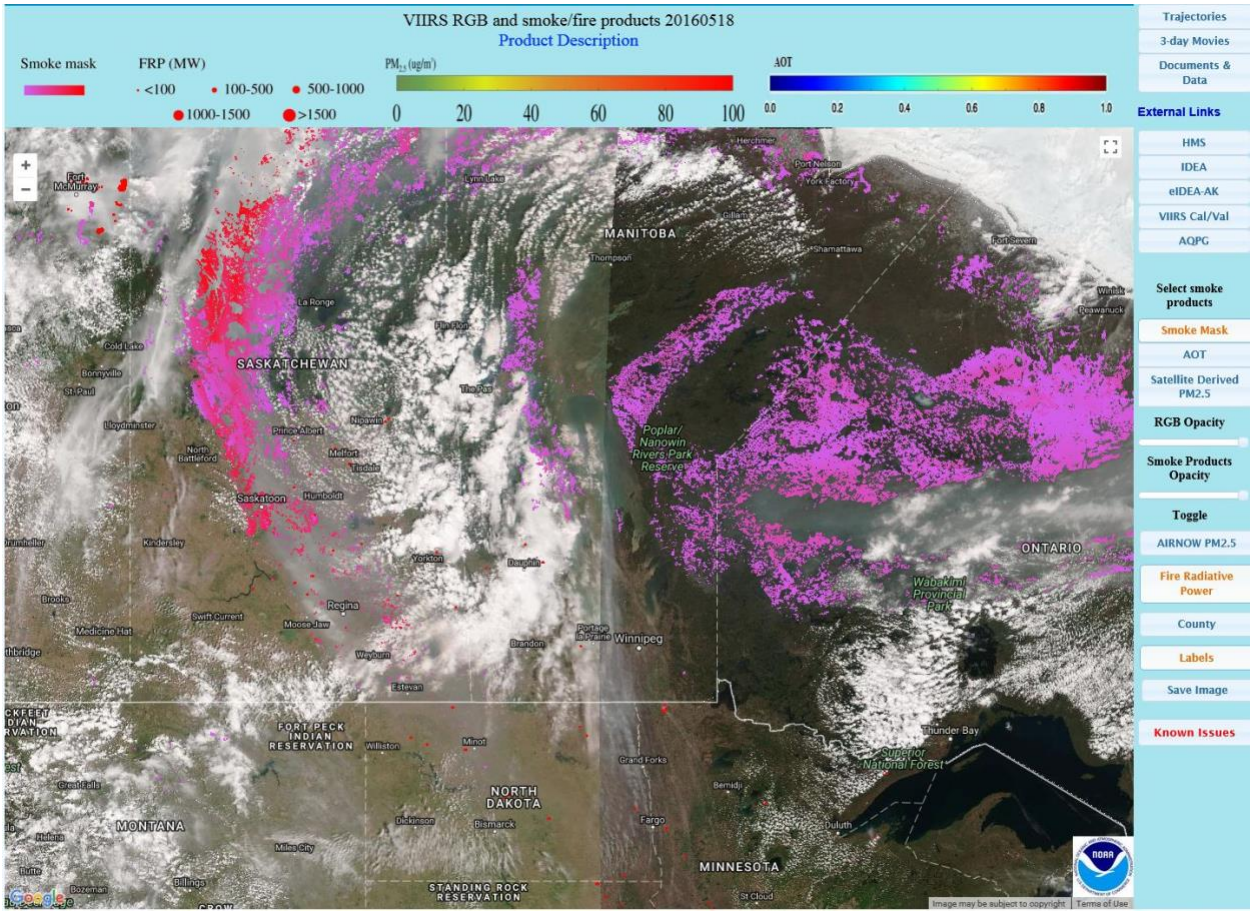

Figure 6. eIDEA VIIRS Smoke Mask on May 18, 2016

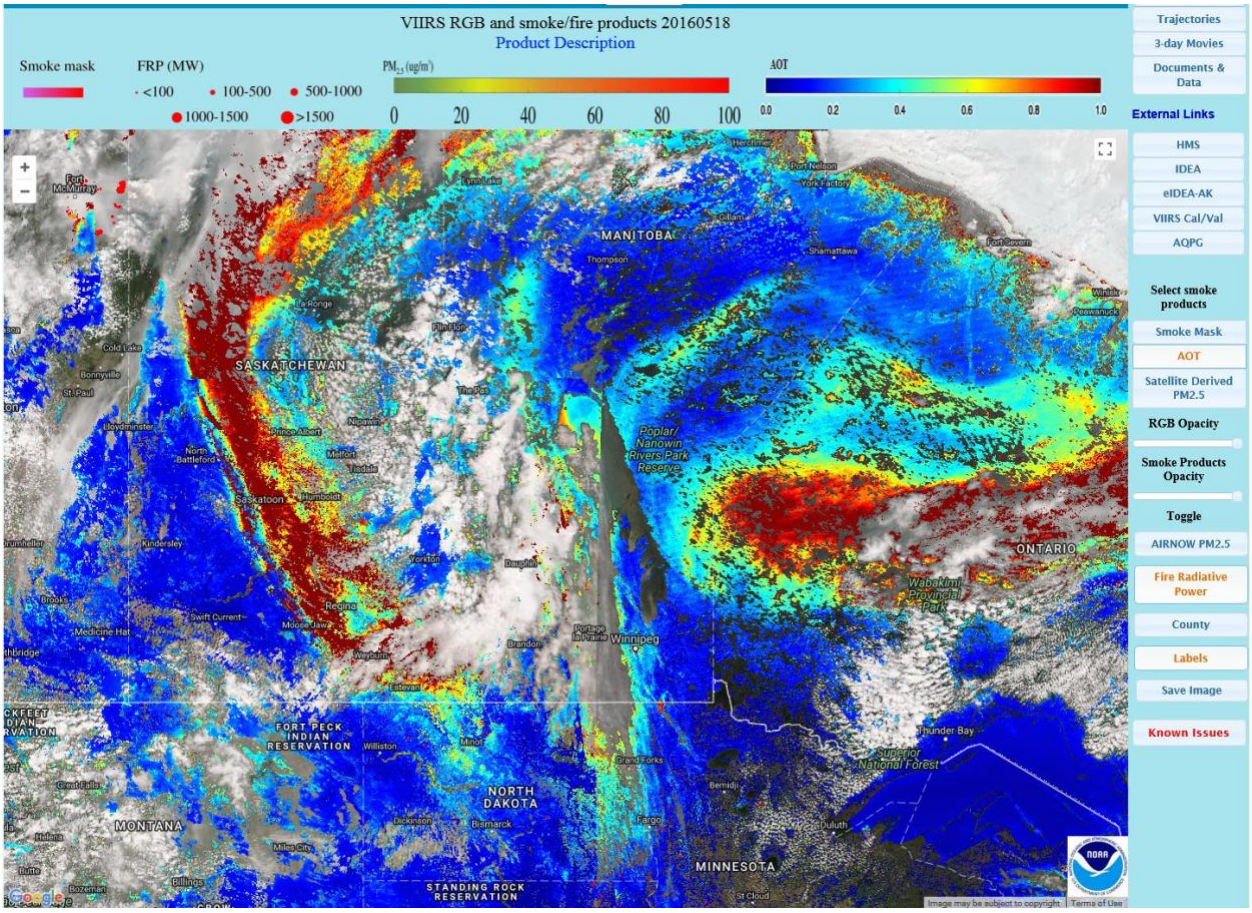

Figure 7. eIDEA VIIRS Aerosol Optical Thickness on May 18, 2016

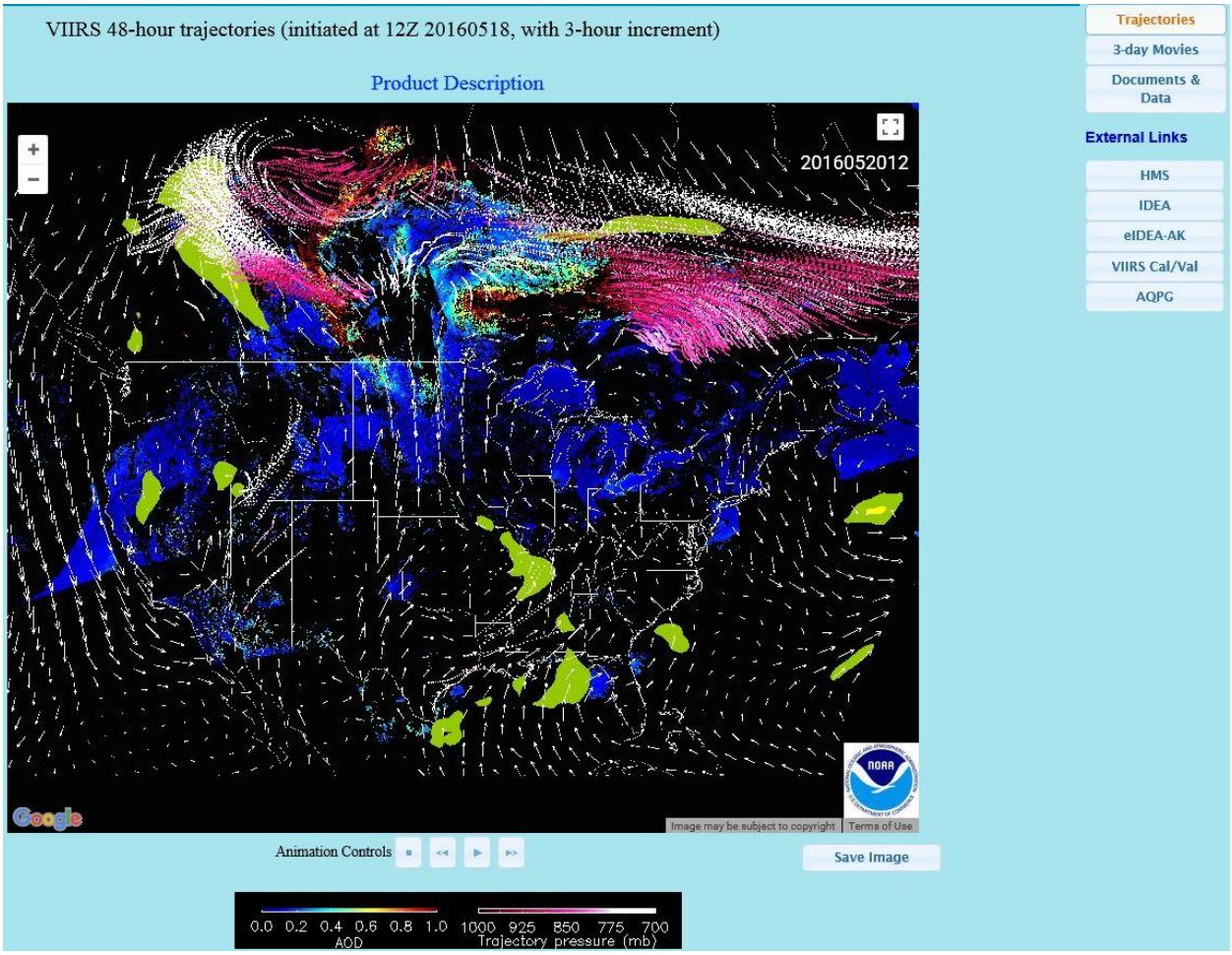

Figure 8. eIDEA VIIRS Modeled Trajectories from 12z on May 18, 2016

5. CALIPSO Images

Vertical atmospheric profiles can be generated from the CALIPSO website. According to the website: *"Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) was launched on April 28, 2006 to study the impact of clouds and aerosols on the Earth's radiation budget and climate. It flies in formation with five other satellites in the international "A-Train" constellation for coincident Earth observations. The CALIPSO satellite comprises three instruments, the Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP), the Imaging Infrared Radiometer (IIR), and the Wide Field Camera (WFC). CALIPSO is a joint satellite mission between NASA and the French Agency, CNES."* Although it has a horizontal swath of only 64 km, it can provide valuable source of information if it passes over the target area. The following figure shows the position of Calipso within the A-train satellite series.

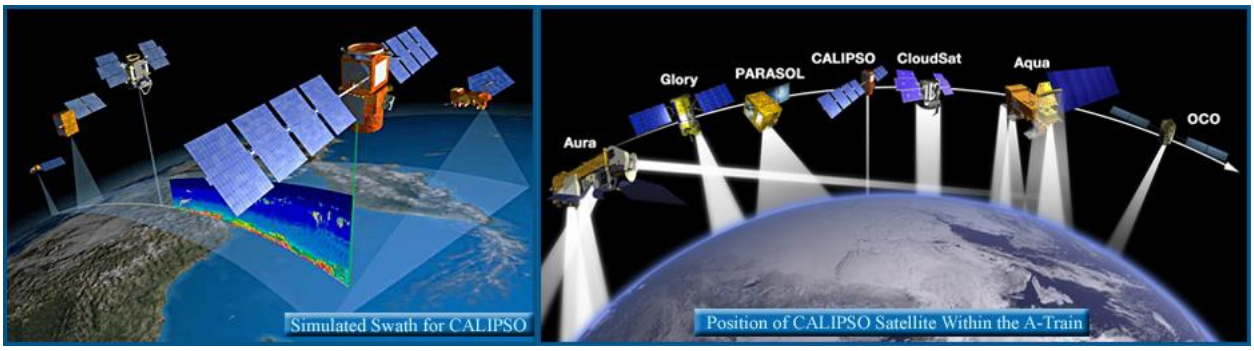

Figure 9. Simulated Images of CALIPSO within the A-Train.

The following image (figure 10) shows the ascending (south to north) path that the satellite imaged during the day on May 24, 2016. The path through the eastern Great Lakes coincides to the area that was experiencing high ozone levels, the day before the aerosol plume reached Connecticut.

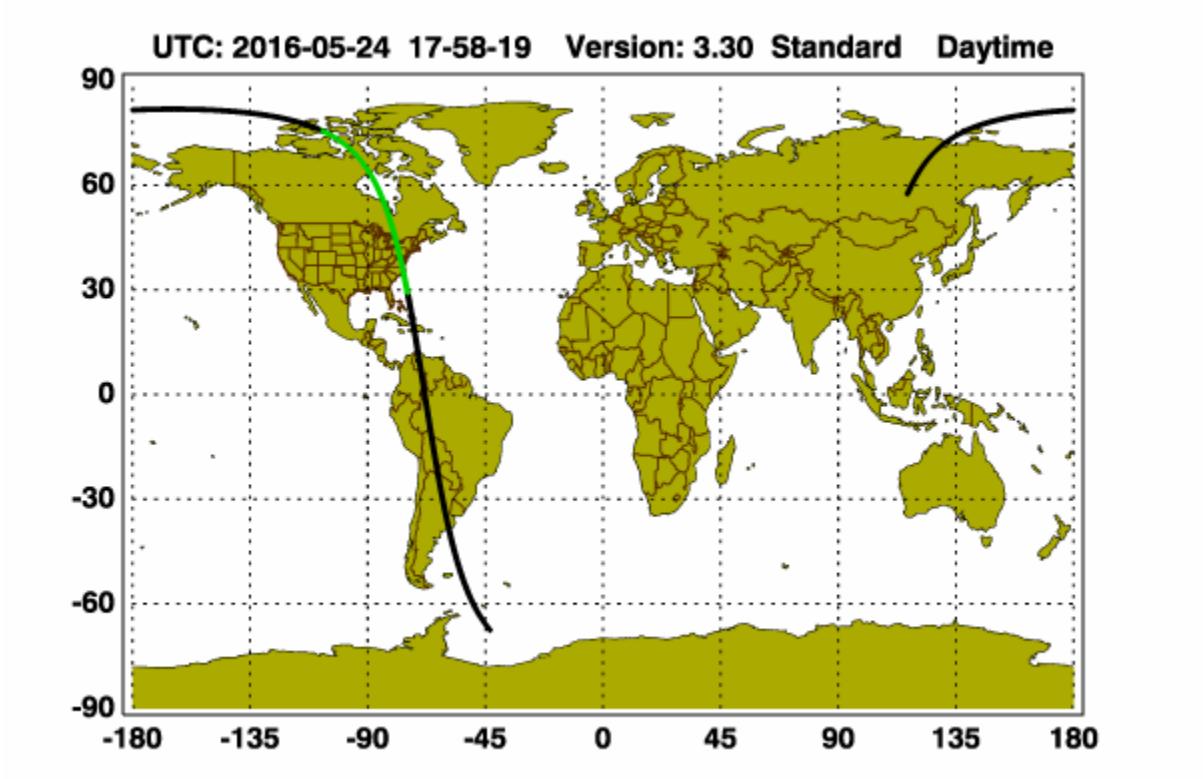

Figure 10. Daytime Path of CALIPSO over North America (green line) on May 24, 2016

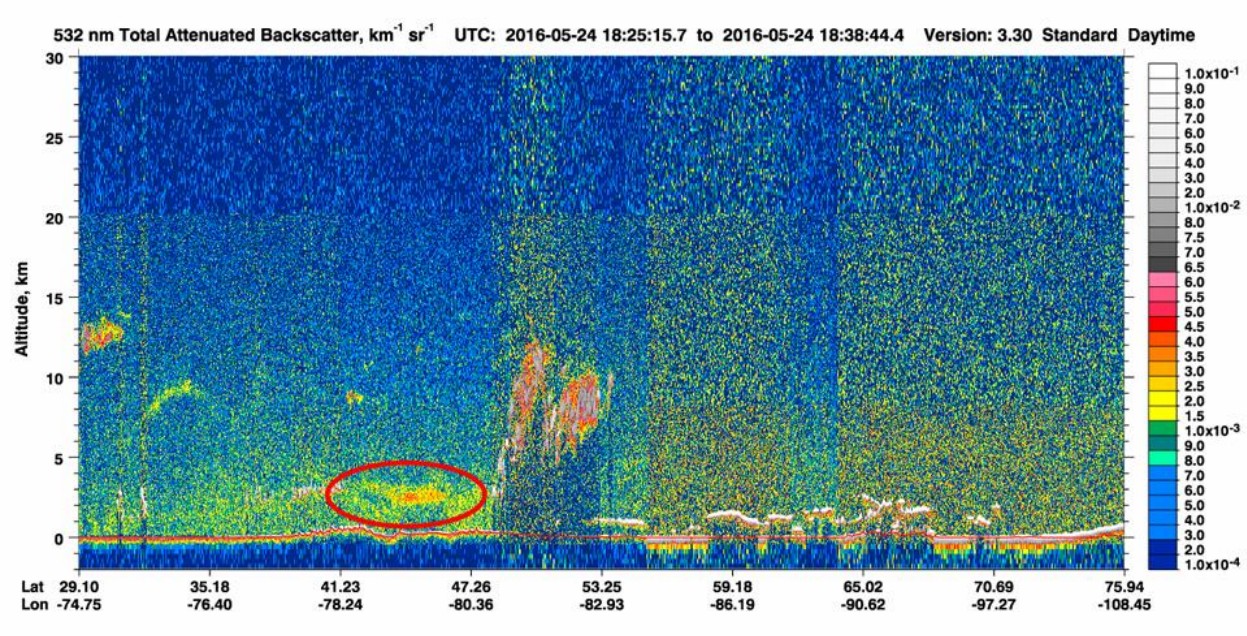

Figure 11. CALIPSO Image from May 24, 2016

Figure 11 shows the actual image retrieved from the Calipso browse-images web site. The area of interest from satellite images during the day was centered on latitude 45° north and longitude 80° west. The aerosol plume is easy to pick out (red circle). Figure 12 was also one of the images produced and is a vertical feature mask that uses an algorithm to categorize the backscatter. In this case, it shows a large area of aerosols below 3000 meters (as orange).

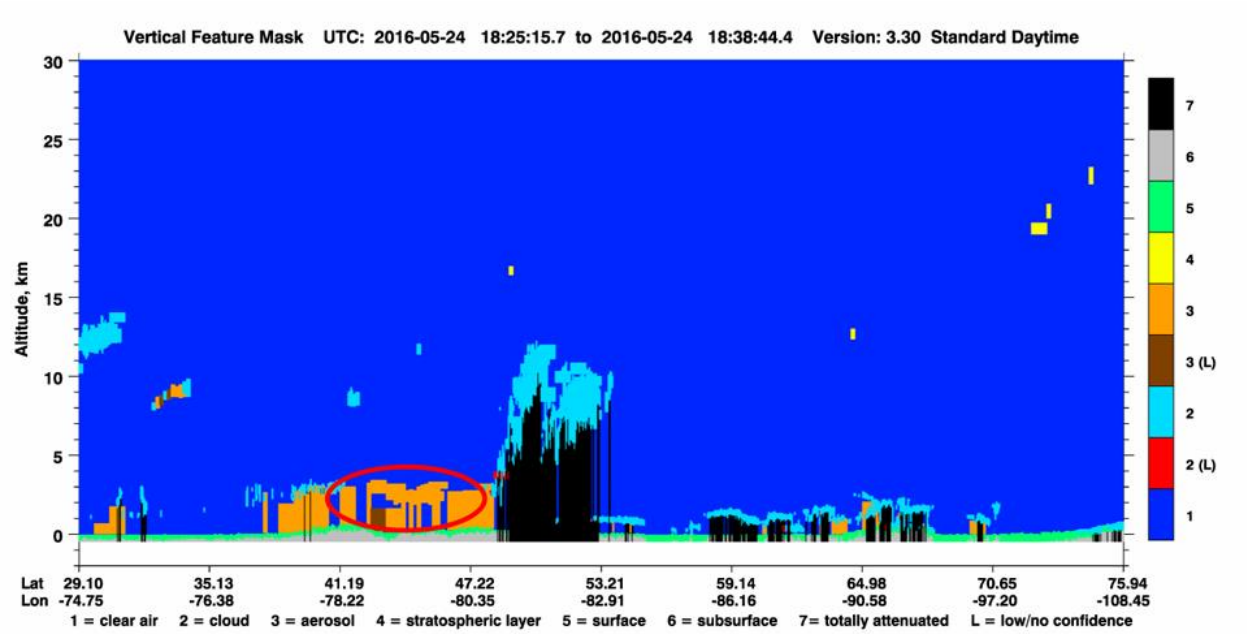

Figure 12. Calipso Vertical Mask from May 24, 2016

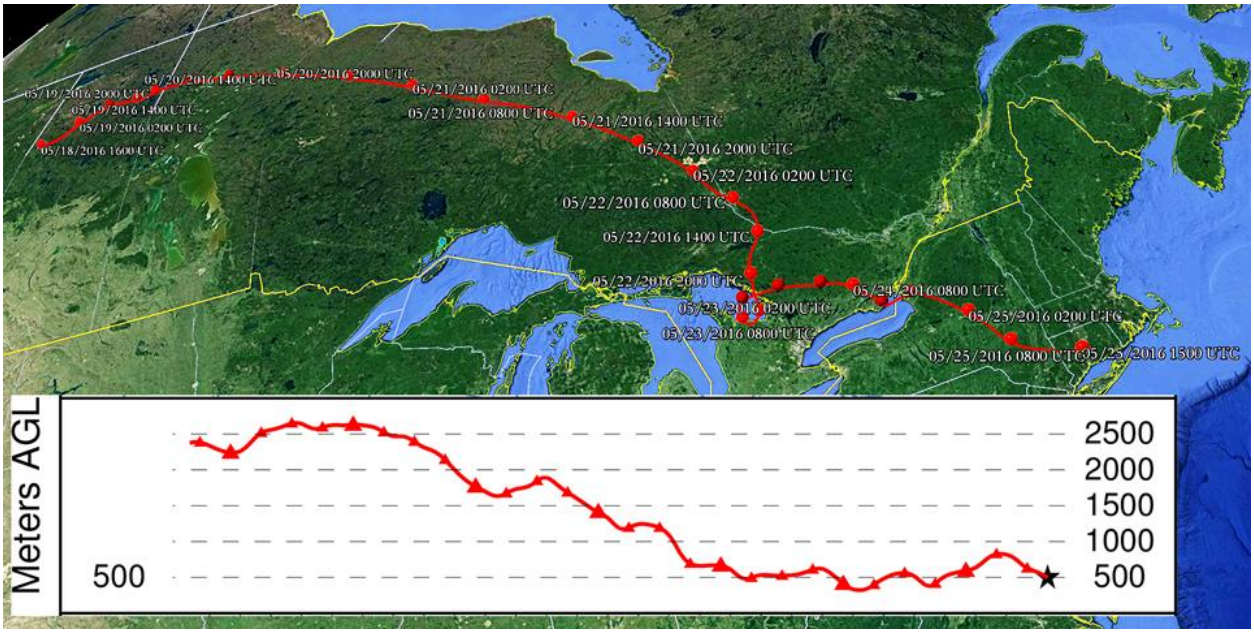

Figure 133. May 25, 2016, 7-day Back trajectory from Connecticut ending at 500 meters.

These images are useful for tracking the plume, but one must still do a back trajectory analysis using HYSPLIT to determine the path and altitude of the plume. The following back trajectory analysis from Connecticut on May 25, 2016, from 500 meters height (figure 13), shows a reasonable agreement with the location of the aerosol backscatter on the Calipso cross section on May 24, over the eastern Great lakes. This part of the plume traveled to Connecticut, after reaching near ground level after Lake Huron. This HYSPLIT analysis did show the plume starting above 2000 meters altitude before descending to near ground level (500 meters). One must then use visibility web cams and monitoring data to verify that the plume has reached the ground.

6. Hazard Mapping System (HMS) Fire and Smoke Product

According the HMS Website: "The initial HMS product for the current day is created and updated by a satellite analyst roughly between 8am and 10am Eastern Time. After 10am, the analysis is fine-tuned as time permits as additional satellite data becomes available. Areas of smoke are analyzed and added to the analysis during daylight hours as visible satellite imagery becomes available. The product is finalized and "completed" for the archive the following morning - generally by around 800am." Analyzed smoke plume images are archived for six months and provide further proof for smoke transport impacting a possible exceptional event..

Figure 14 shows the progression of the smoke plumes over North America, as analyzed by the Hazard Mapping System (HMS) staff at NOAA, using the satellite images. This series of maps shows the movement of the Fort McMurray smoke plume as it tracks over the Connecticut region on May 21-26, 2016.

As a reminder that not all wildfires end up influencing air quality far downwind of the fire, I include Figure 15. This figure is an image from a more recent fire from September 4, 2017

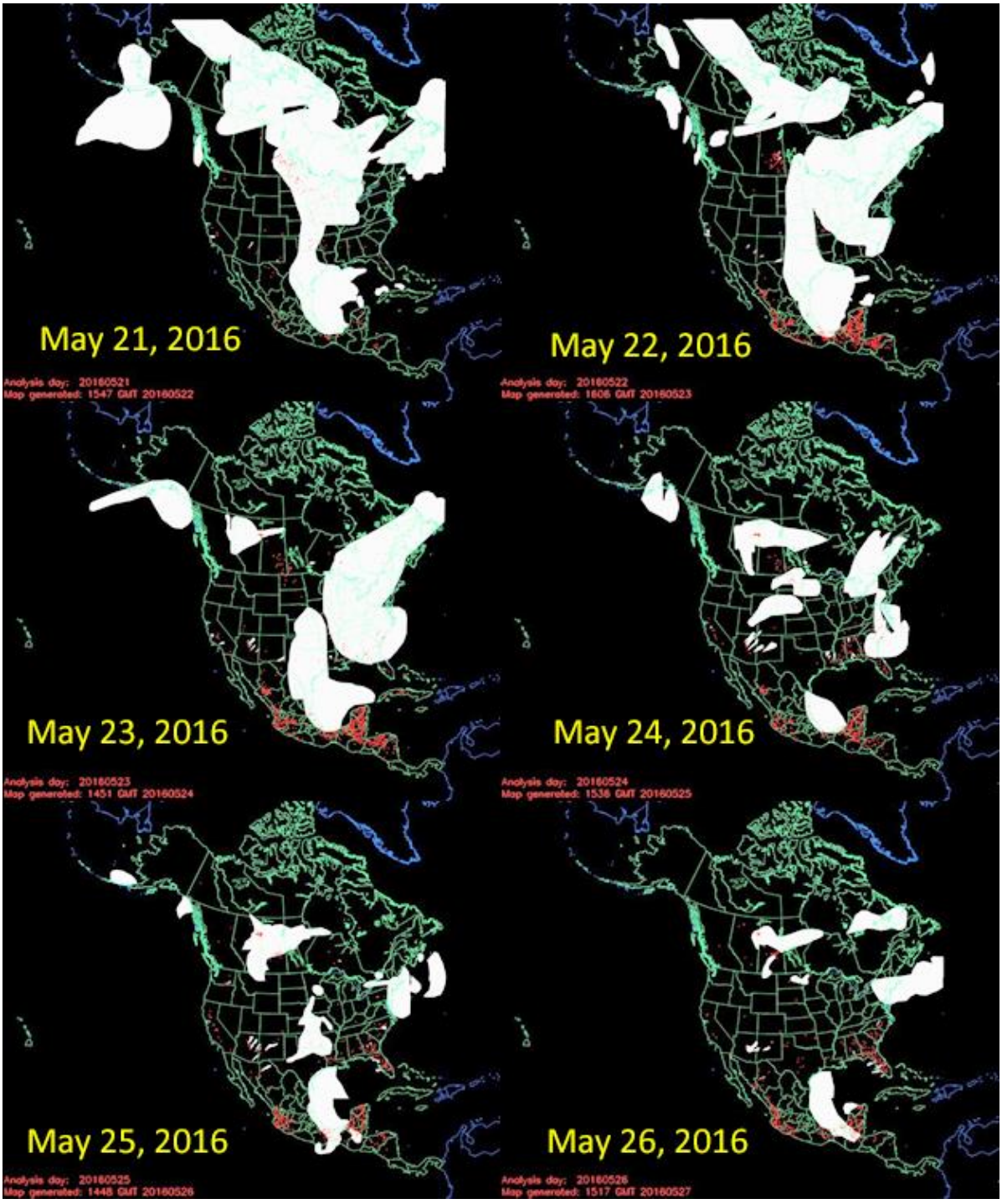

Figure 144. HMS Smoke Plume Analysis with Active Fires from May 21-26, 2016

where air quality was severely impacted in the Pacific Northwest, but the plume stayed mostly

aloft over the eastern States. Figure 16 shows the corresponding Air Quality Index colors for PM2.5 at monitors on that day. One is reminded that the presence of a smoke plume on a satellite image does not necessarily mean that it is significantly impacting air quality at the ground level.

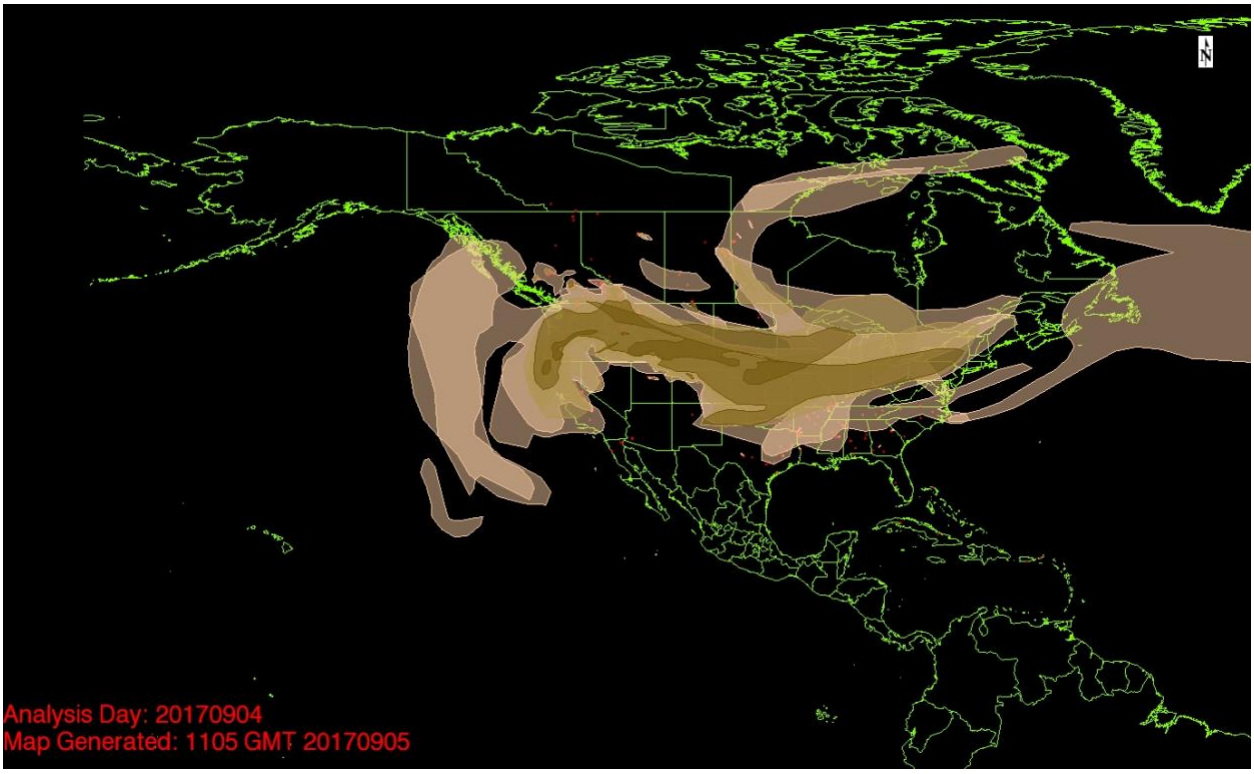

Figure 1516. HMS Analyzed Smoke Plumes on September 4, 2017

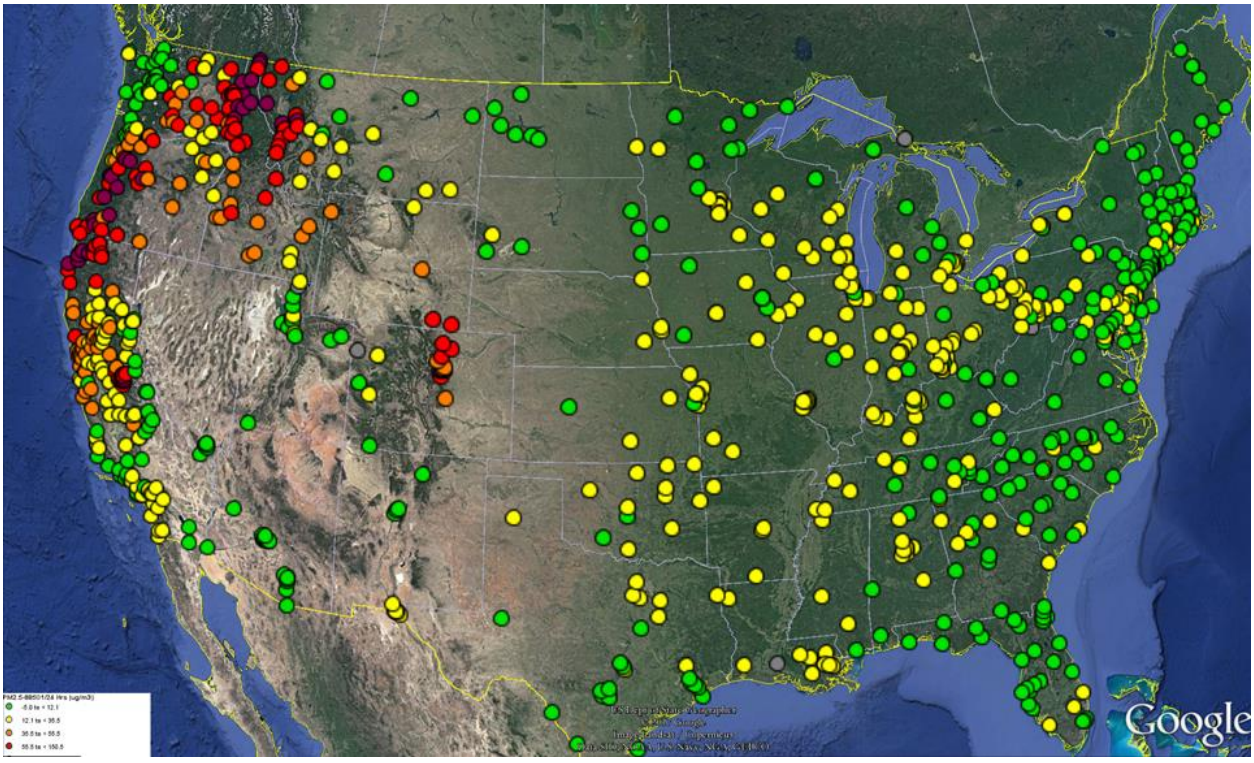

Figure 1615. PM2.5 AQI levels on September 4, 2017

7. Geostationary Satellite Images (GOES)

Until the fall of 2017, the GOES visible satellite images could not compete with the spatial resolution of MODIS on the polar orbiting satellites. That changed with the launch of the GOES-16, which replaced the GOES-E during December of 2017. The new generation GOES use the Advanced Baseline Imaginer (ABI), which has the following capabilities:

- **Full Disk:** Hemispheric Coverage of 83° local zenith angle, temporal resolution of 5-15 minutes, and spatial resolution of 0.5 to 2km
- **Mesoscale:** Provides coverage over a 1000x1000km box with a temporal resolution of 30 seconds, and spatial resolution of 0.5 to 2km.
- **Continental US:** The CONUS scan is performed every 5 minutes, providing coverage of the 5000km (E/W) and 3000km (N/S) rectangle over the United States. The spatial resolution is 0.5 to 2km.
- **Flex Mode:** The flex mode provides a full disk scan every 15 minutes, a CONUS every 5 minutes, and two mesoscale every 60 seconds (or one sub-region every 30 seconds).
- Aerosol Detection (Including Smoke and Dust)
- Aerosol Optical Depth (AOD)
- Fire/Hot Spot Characterization

High resolution images are now available from the new beta website provided by NOAA, named Aerosol Watch. Figure 17 shows the western U.S. smoke plume on September 4, 2017, spanning the entire width of the country and figure 18 adds the (beta) smoke/dust mask to the image.

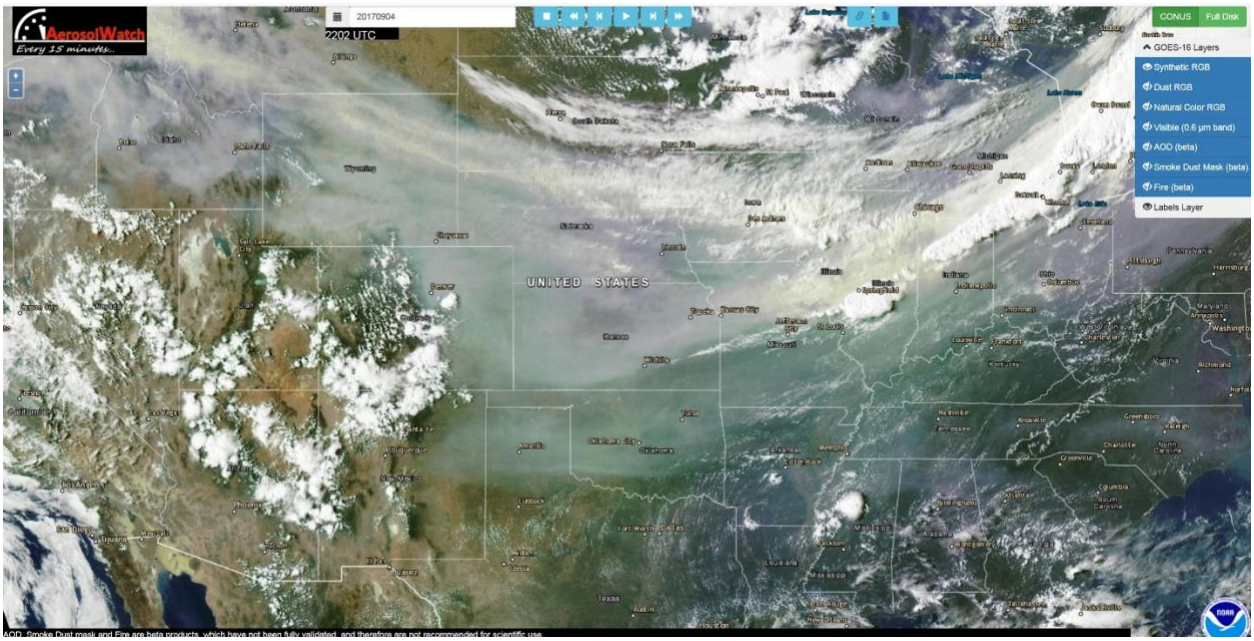

Figure 17. GOES-16 Image Showing the Smoke Plume Spanning the U.S on September 4, 2017

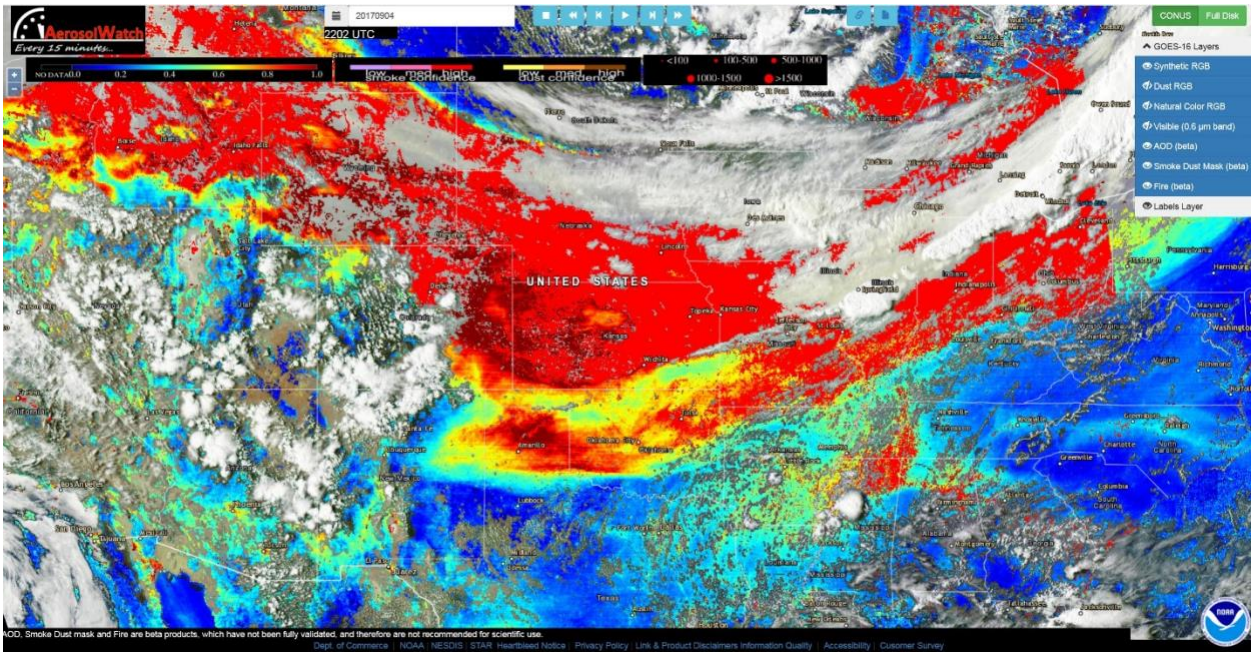

Figure 18. GOES-16 Image with the (beta) Smoke/dust Mask on September 4, 2017

These images are updated every 15 minutes, so they can be easily animated.

On March 1, 2018, the GOES-S satellite was launched and, when operational, will become the GOES-17, replacing the current GOES-W. This will complete the high resolution geostationary satellite coverage for the entire CONUS.

8. Next Generation Satellites

On November 18, 2017, NASA successfully launched the JPSS-1 (now NOAA-20), the first in a series of four highly advanced polar-orbiting satellites, equipped with next-generation technology and designed to improve the accuracy of U.S. weather forecasts out to seven days. Capitalizing on the success of Suomi NPP, NOAA-20 features five similar instruments: (1) VIIRS, (2) CrIS, (3) ATMS, (4) OMPS-N, and (5) CERES-FM6. NOAA-20 has a design life of seven years and it will circle the Earth in the same orbit as Suomi NPP, although the two satellites will be separated in time and space by 50 minutes. It will provide meteorologists with observations of atmospheric temperature and moisture, clouds, sea-surface temperature, ocean color, sea ice cover, volcanic ash, and fire detection.

The TEMPO (Tropospheric Emissions: Monitoring Pollution) mission will launch in 2019 (or later) and provide a revolutionary new dataset of atmospheric chemistry measurements from space as a geostationary satellite. TEMPO will be the first space-based instrument to monitor major air pollutants across the North American continent every daylight hour at high spatial resolution. This mission will provide high resolution data to the air quality community:

- Spatial resolution: 2 km/pixel in the north-south direction, 4.5 km /pixel in the east-west direction at the center of the FOR (Field of Regard) which is desired to be 36.5° N, 100° W. Co-add/cloud clear as needed for specific data products.
- Standard data products will include:
    - NO_2, O_3, aerosol, and cloud products sampled hourly;
    - H_2CO, $C_2H_2O_2$, SO_2 sampled 3 times/day;
    - Ozone profile products include 0–2 km O_3, free tropospheric O_3, and the stratospheric O_3 column.

In October of 2017, the European Space Agency (ESA) launched the Sentinel-5P satellite. It contains the Tropospheric Monitoring Instrument (Tropomi) with a swath width of 2600 km and a spatial resolution as high as 7 km x 3.5 km. This allows the whole planet to be mapped every 24 hours. The satellite flies in a Sun-synchronous orbit 824 km above Earth and is in 'loose formation' with the US NASA–NOAA Suomi-NPP weather satellite (loose formation here means that Sentinel-5P flies 3.5 minutes behind Suomi-NPP). Level-2 products are to be supplied within three hours after sensing. This 'near real-time' service will deliver products for ozone, sulphur dioxide, nitrogen dioxide, formaldehyde and carbon monoxide, vertical profiles of ozone as well as cloud/aerosol distributions.

For information on more products, NASA provides a more complete list of available satellite data on their Air Quality Resources and Outreach Webpage.

In particular, note the tab at https://airquality.gsfc.nasa.gov/ for Air Managers, where this and other technical guidance documents will be posted.