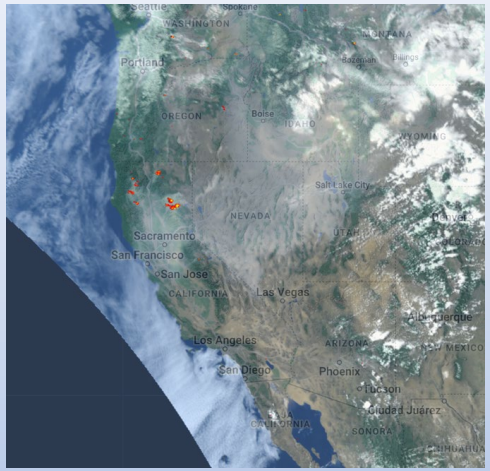
Using Satellite Images and Data and Multidisciplinary Tools to Create a Storyboard for the Transport of Smoke from Sources to Receptors

National Exceptional Events Workshop * Hosted by the Western States Air Resources Council

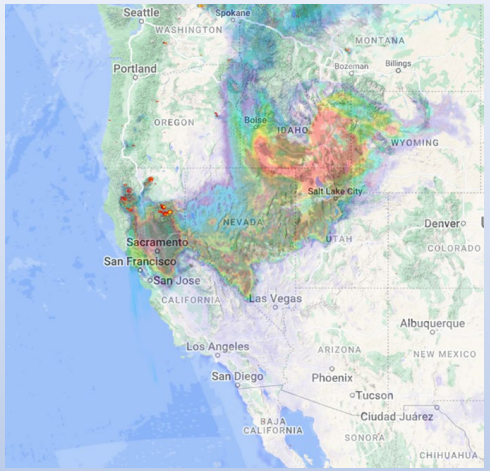


February 27-29, 2024

St. Louis, MO

Patrick Reddy

preddyresearch@gmail.com



PATRICK J. REDDY
ATMOSPHERIC SCIENTIST

Satellite, Air Quality, & Climate Data Analyst
Providing services in air quality, atmospheric, and environmental sciences

P.O. Box 451, Crestone, CO, 81131
preddyresearch@gmail.com

My Background:

- Forecasting, Meteorological Analyses, and Exceptional Event Analyses for the Colorado Department of Public Health & Environment, Air Pollution Control Division: 1990 - 2022.
- Independent/Freelance Research Scientist
- NASA Health and Air Quality Applied Sciences Team Ambassador, 2023 - present.
- www.linkedin.com/in/patrick-reddy-0981a8284

This Presentation:

- I will highlight tools and data sources for developing a storyboard, narrative, and data for wildfire smoke events affecting surface ozone and PM2.5 concentrations.

- I will showcase products from *Smoke and Air Quality Assessment with Satellites (SAQAS)*, a prototype toolkit I developed using Google Earth Engine. Google Earth Engine is a powerful tool for spatial analysis of large datasets.

- I will demonstrate the versatility and utility of the NOAA NESDIS AerosolWatch website (https://www.star.nesdis.noaa.gov/smcd/spb/aq/AerosolWatch/). This site has many features including smoke masks, accurate satellite estimates of surface PM2.5, and one-hour and daily surface PM2.5.

- I will include products from the AirNow Tech website (https://www.airnowtech.org/index.cfm).

The tools and data sources discussed here can be used to address the following questions and to flag or document potential exceptional events:

- What fires produced the smoke affecting ozone and PM2.5 concentrations at a specific site?
- Which fires were responsible for most of the smoke at the sites of interest?
- How long did it take smoke to travel from fires to a monitor? How far away were the fires?
- Is there compelling evidence that smoke caused exceedances of the standards?
- Are there sites that were affected by smoke even though there was little visible smoke on satellite imagery?
- Did dense smoke increase PM2.5 and ozone or only PM2.5?
- Are the exceedances in smoke exceptionally different from normal high-concentration episodes?

Key Variables in SAQAS for Tracking the Impacts of Smoke on Surface Ozone and PM2.5

- Total column Carbon Monoxide (CO) is an excellent tracer for wildfire smoke, and I use data from the TROPospheric Ozone Monitoring Instrument (TROPOMI) onboard the Sentinel 5P satellite.
- The TROPOMI Ultraviolet Absorbing Aerosol Index (AAI) is an excellent high-resolution index for tracking smoke plumes, their sources, and transport history. It is most sensitive to smoke above 2 kilometers and can be useful for determinations of whether smoke reached the surface. It resolves terrain effects on smoke.
- The MODIS Tera and Aqua satellite MAIAC aerosol optical depths at 550 nanometers (AOD) is a high-resolution variable for tracking smoke plumes. It resolves terrain effects on smoke.
- NASA FIRMS and MODIS satellite fire detections.
- TROPOMI NO_2. NO_2 is visible in fresh smoke and abundant in urban areas and can be useful for identifying areas where smoke and urban emissions interact.
- TROPOMI formaldehyde (HCHO) is a tracer for VOC photochemistry. It can be abundant in plumes of aged smoke where smoke VOCs persist.
- GOES 16 bands 1, 4, and 3 true color satellite imagery for visual tracking of smoke.
- Surface black carbon (BC) concentrations from the NASA Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2) are an excellent tracer for wildfire smoke and can provide evidence that smoke has reached the ground.

Why use MERRA-2 Black Carbon?

- MERRA-2 is a reanalysis model with assimilated aerosol diagnostics producing hourly data for every day - with a coarse resolution of 69 x 55 km.

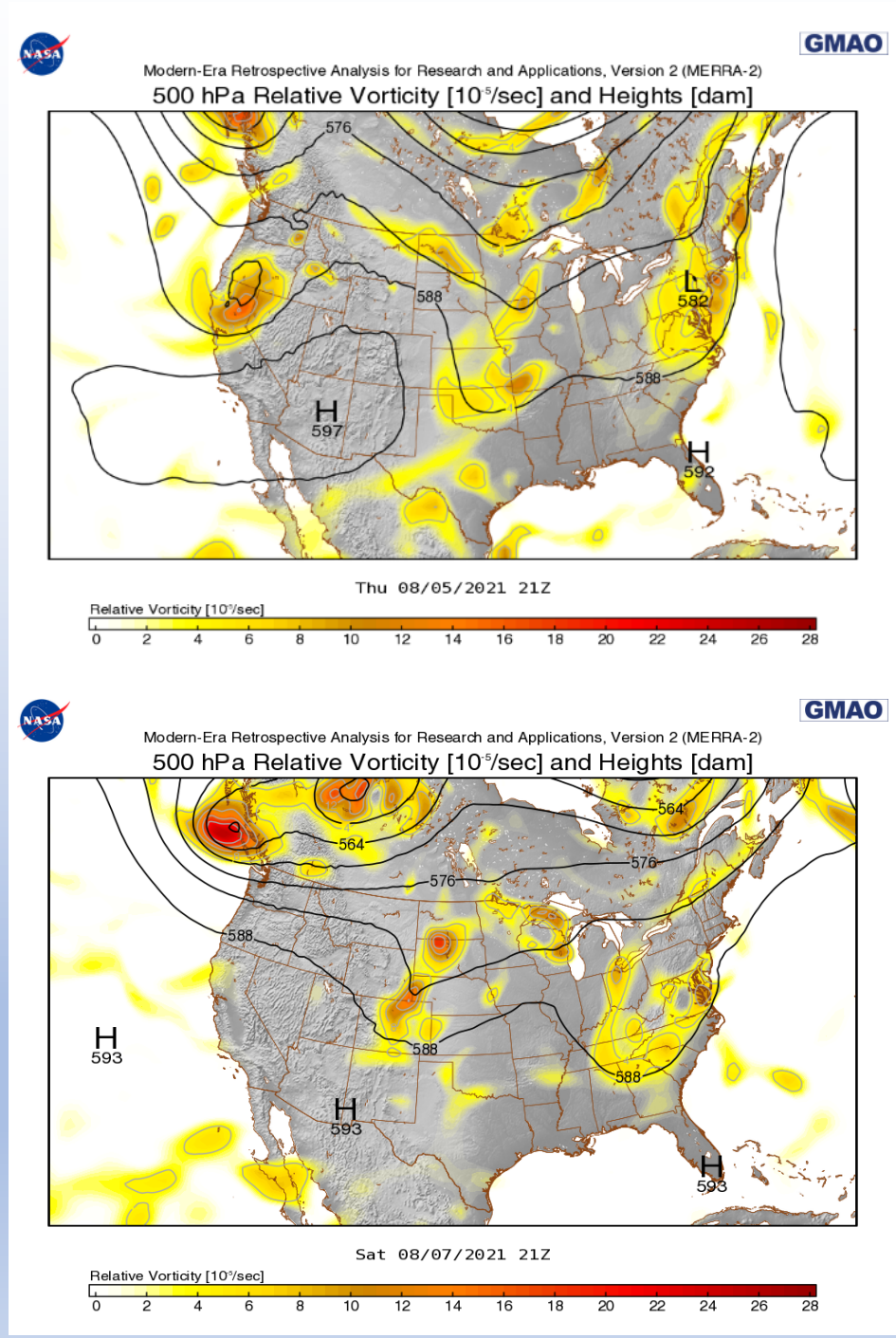
- Reanalysis "is the process whereby an unchanging data assimilation system is used to provide a consistent reprocessing of meteorological observations… The process relies on an underlying forecast model to combine disparate observations in a physically consistent manner, enabling production of gridded datasets for a broad range of variables, including ones that are sparsely or not directly observed." (Gelaro et al., 2017, https://doi.org/10.1175/JCLI-D-16-0758.1).

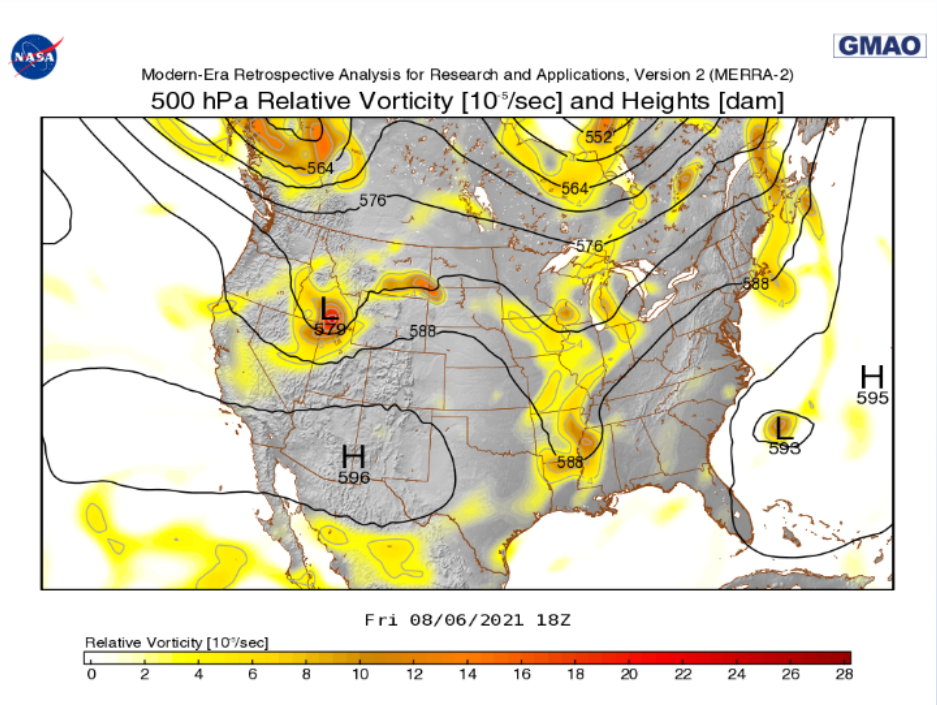
- It matches the satellite indicators spatially and temporally.

- MERRA-2 BC allows us to track broad areas of smoke for every hour, day or night, and within areas of extensive cloud cover to quantify smoke movement and impacts.

- Site-specific time series of BC can be used along with other satellite, meteorological, and air quality variables for screening, statistical analyses, verification, and impact quantification.

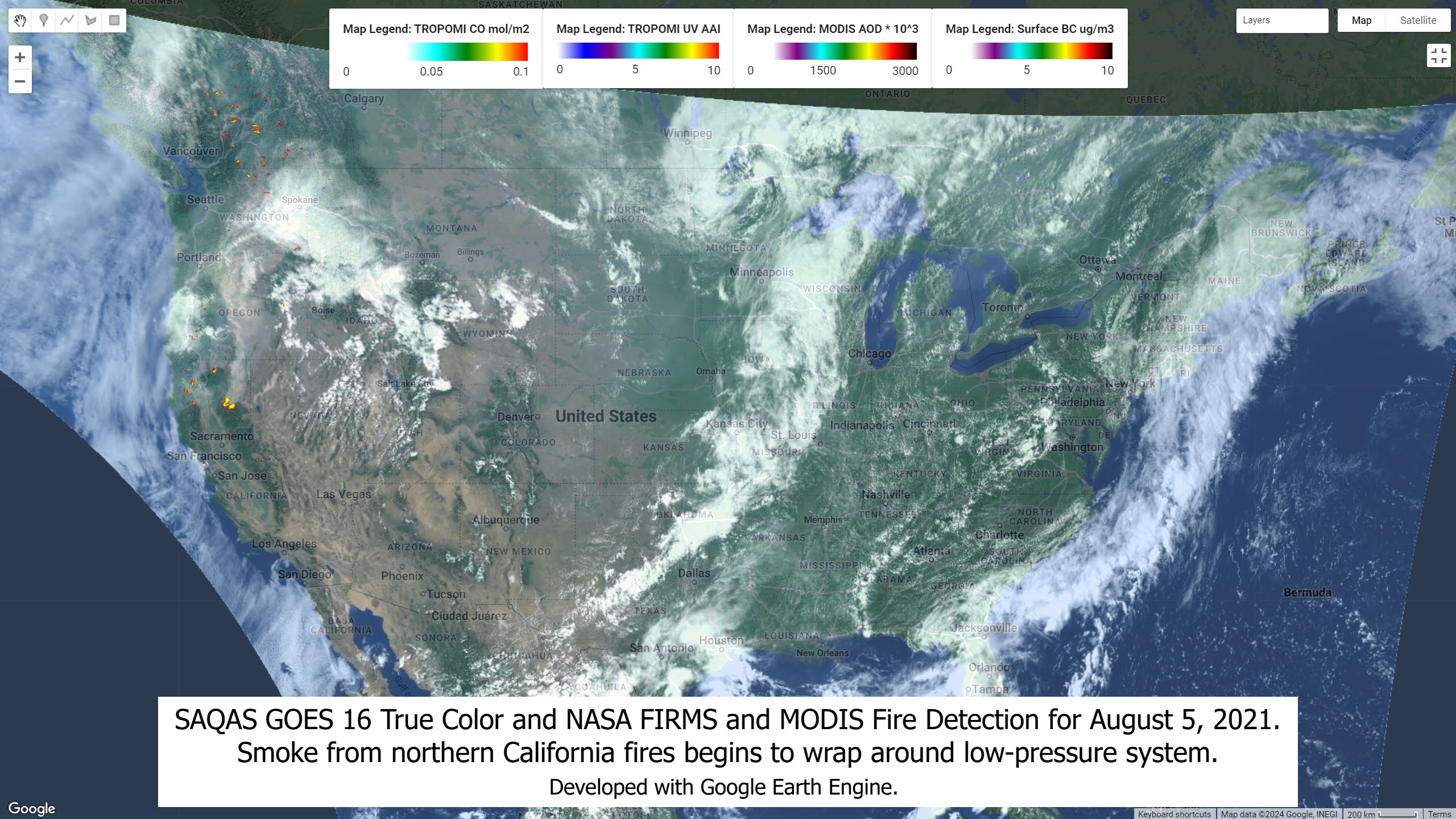
The August 5-7, 2021, Wildfire Smoke Event in the Western US.





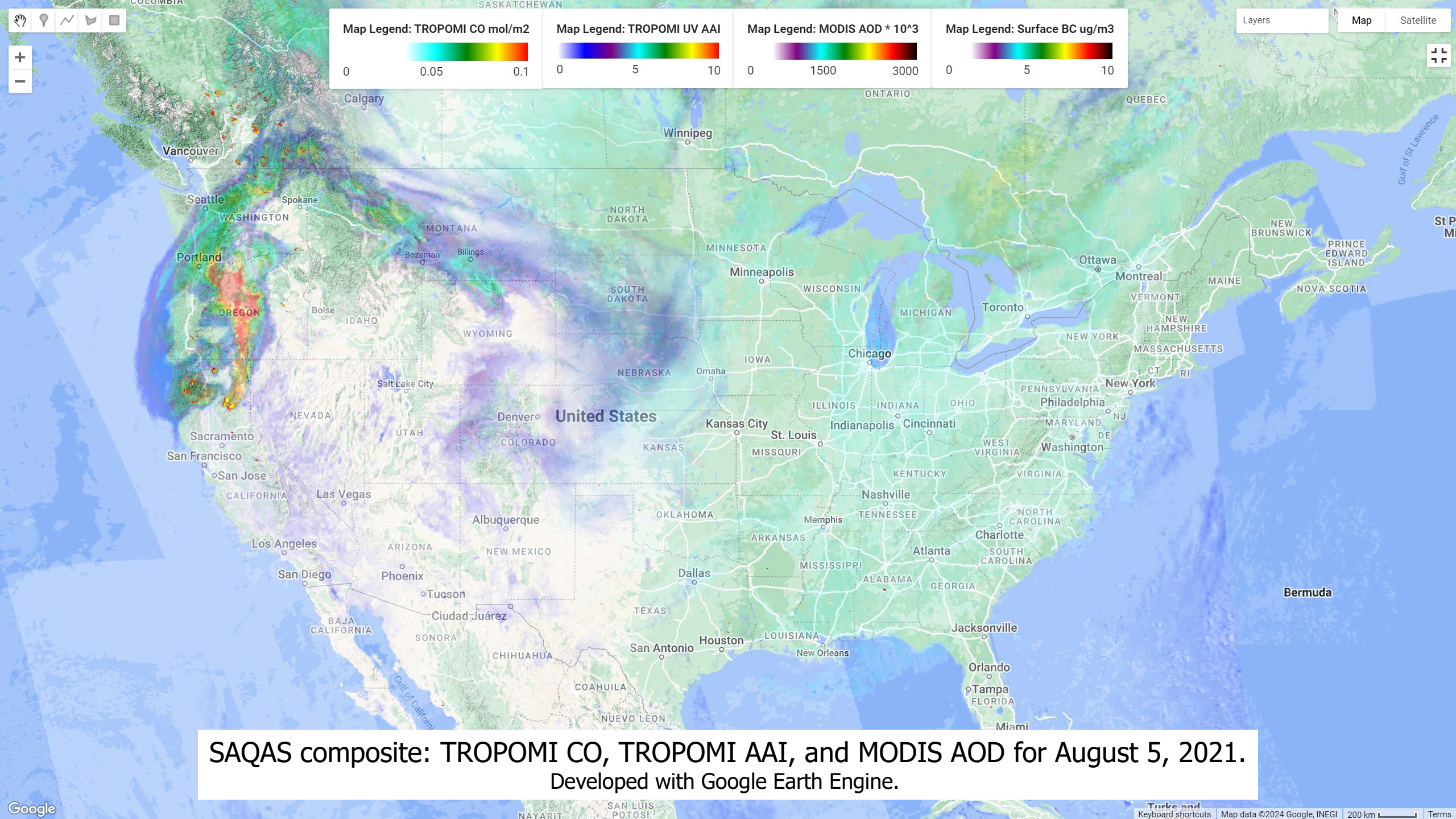
NASA MERRA-2 reanalysis timeline for 500 mb low associated with smoke transport from fires in Northern California and eventual high concentrations of smoke PM2.5 on August 5-7, 2021.

The low split into two systems on August 7, one near Denver and the other over the Dakotas.



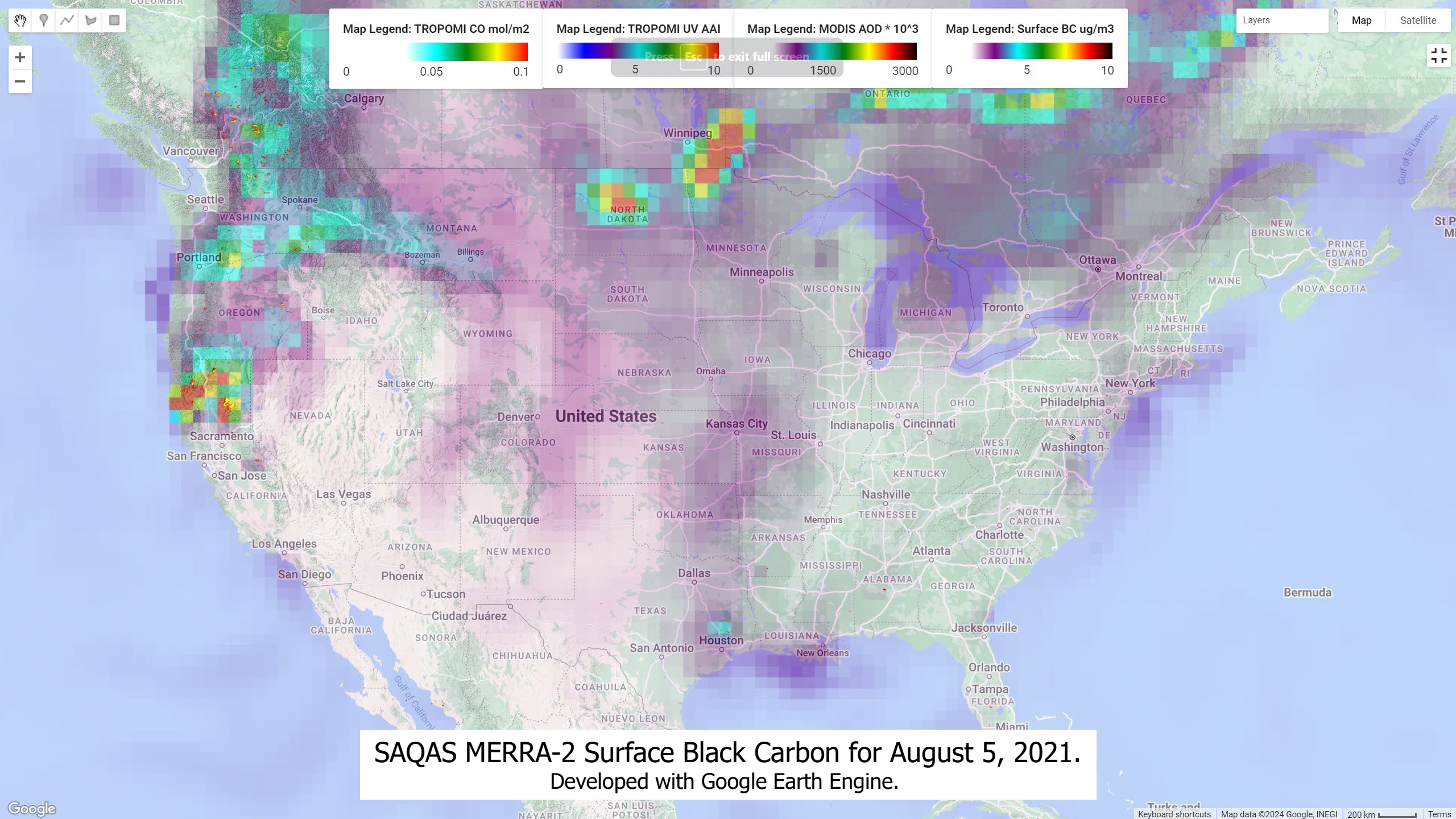
SAQAS GOES 16 True Color and NASA FIRMS and MODIS Fire Detection for August 5, 2021.
Smoke from northern California fires begins to wrap around low-pressure system.

Developed with Google Earth Engine.



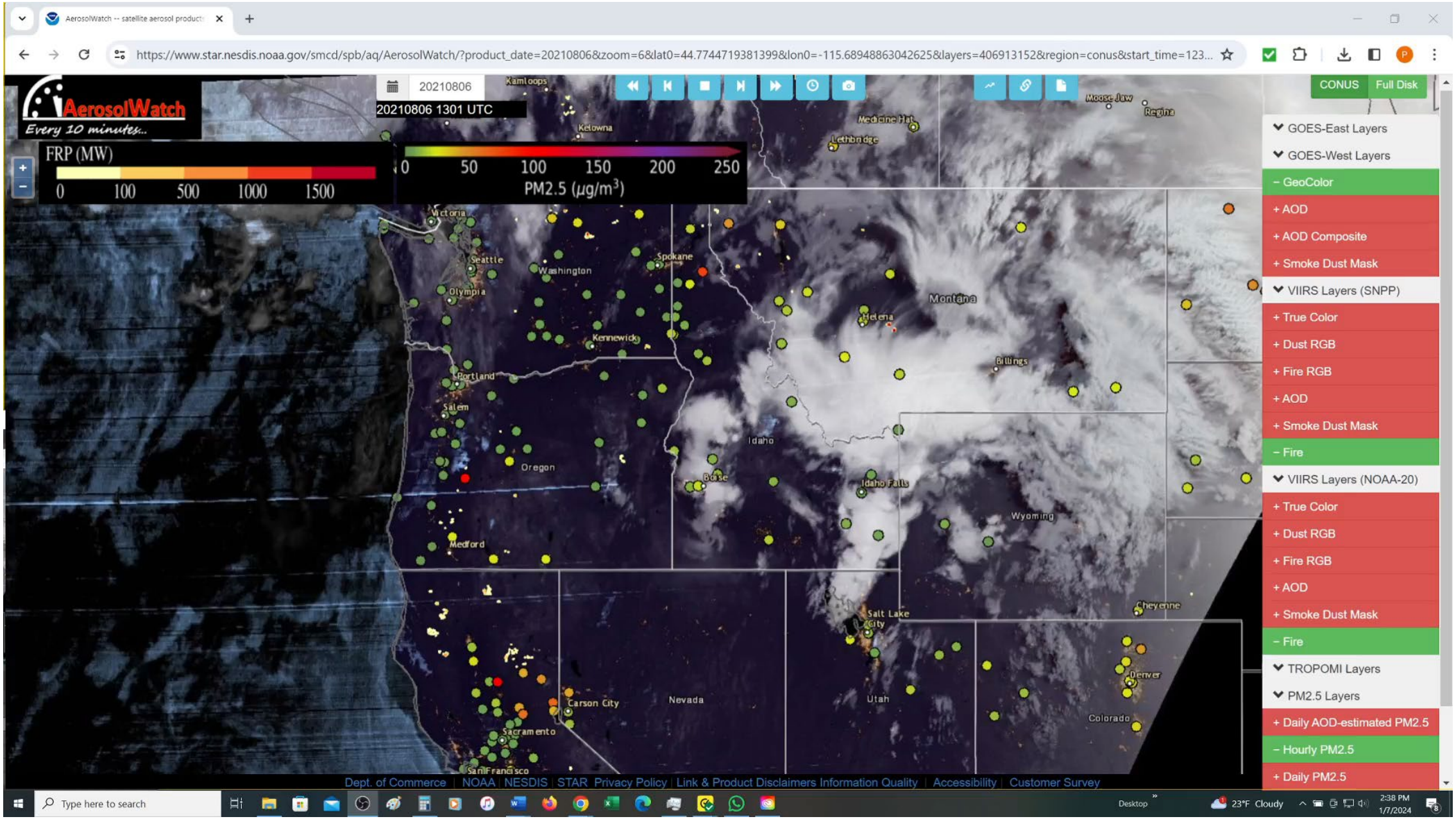
SAQAS composite: TROPOMI CO, TROPOMI AAI, and MODIS AOD for August 5, 2021.

Developed with Google Earth Engine.

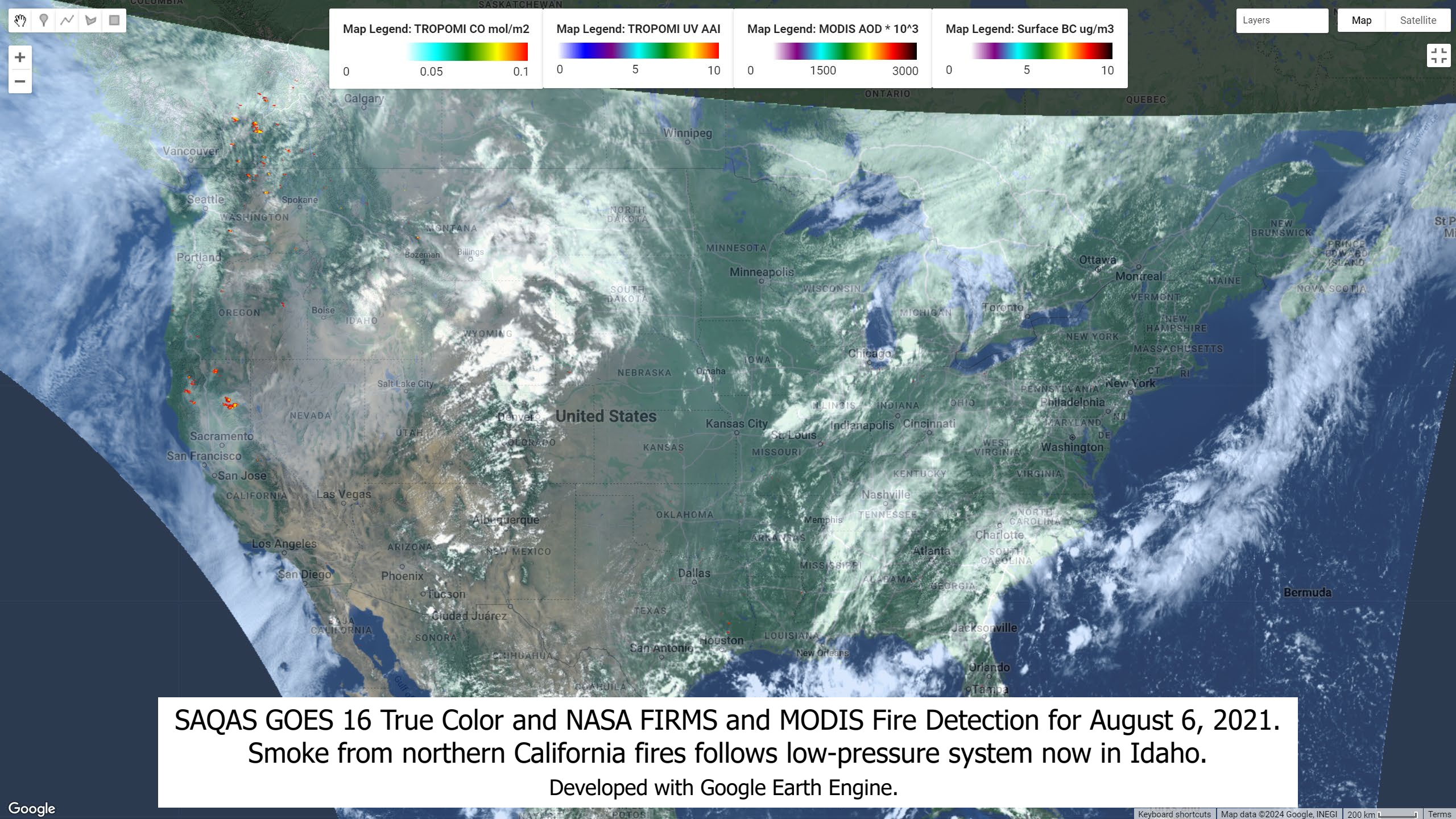


SAQAS MERRA-2 Surface Black Carbon for August 5, 2021.

Developed with Google Earth Engine.

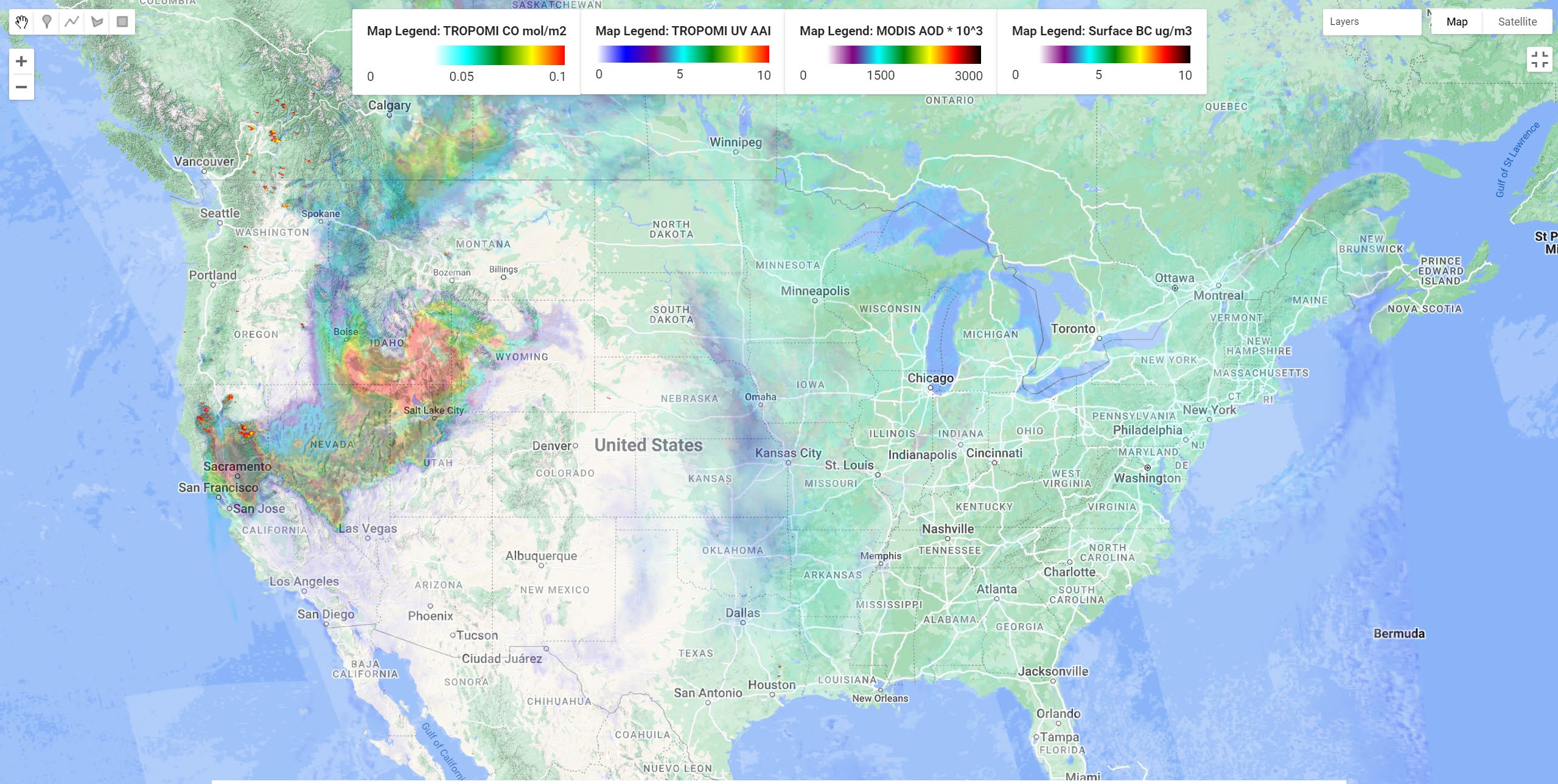


Video: AerosolWatch: Visible smoke and hourly surface PM2.5 showing the impacts of transiting low pressure on 08/06/21.



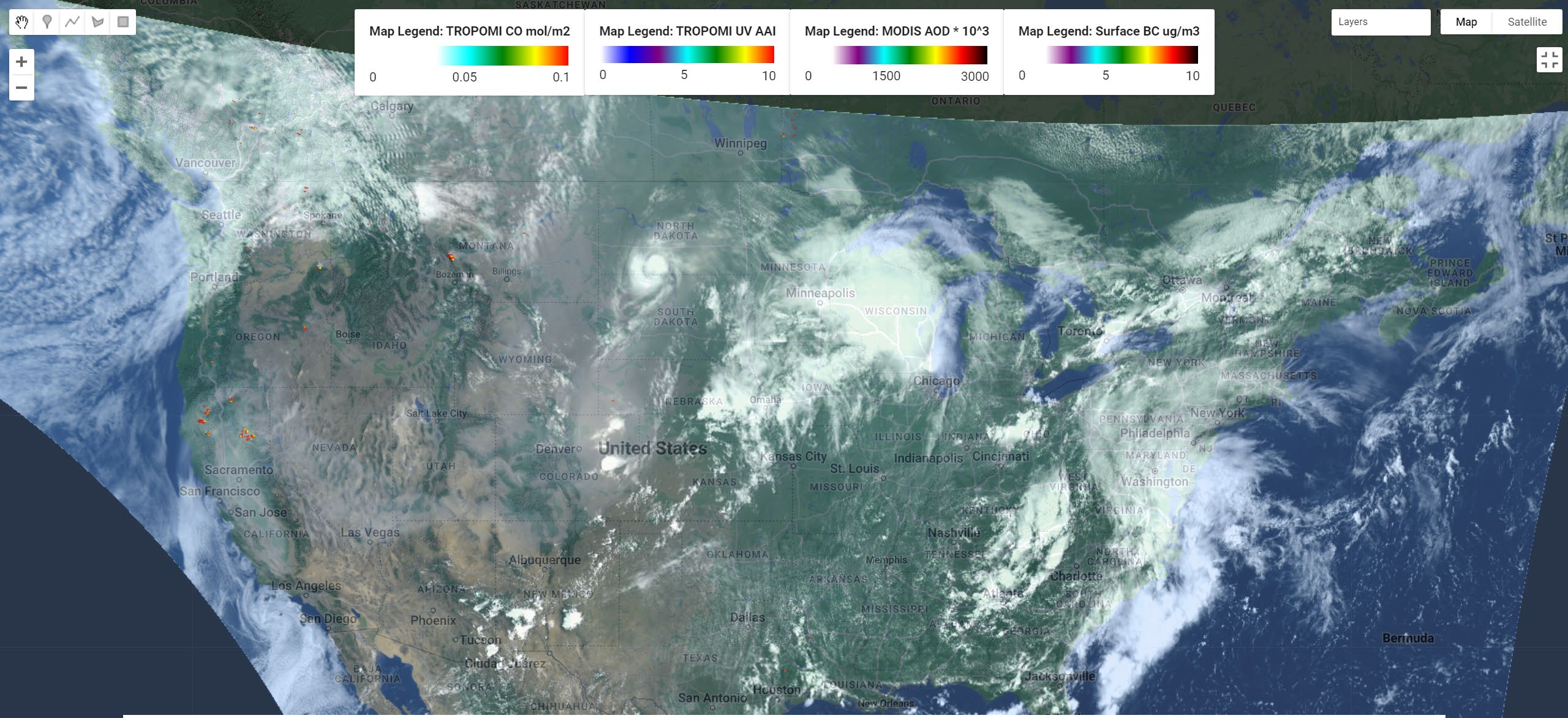
SAQAS GOES 16 True Color and NASA FIRMS and MODIS Fire Detection for August 6, 2021.
Smoke from northern California fires follows low-pressure system now in Idaho.

Developed with Google Earth Engine.



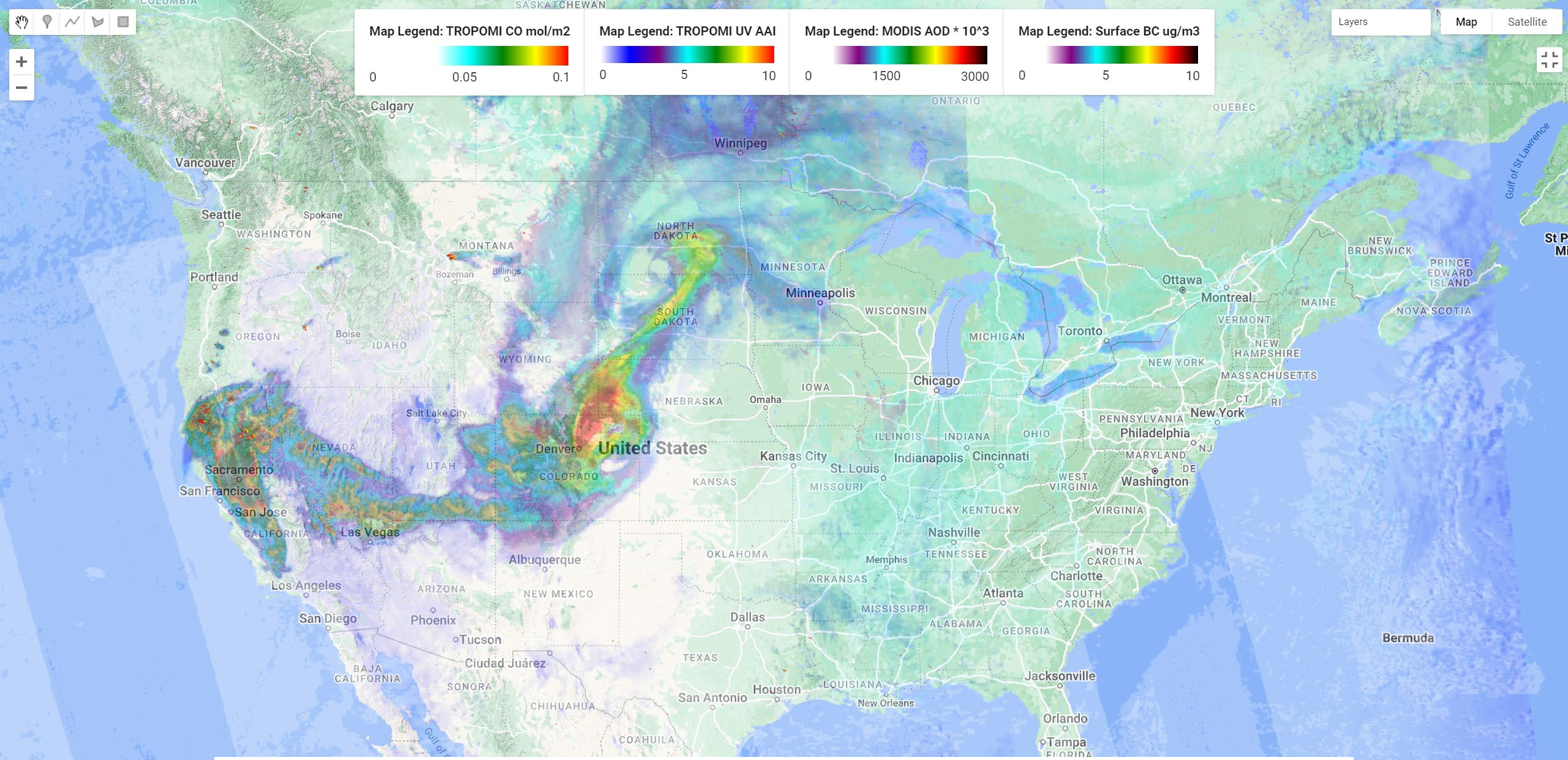
SAQAS composite: TROPOMI CO, TROPOMI AAI, and MODIS AOD for August 6, 2021.

Developed with Google Earth Engine.



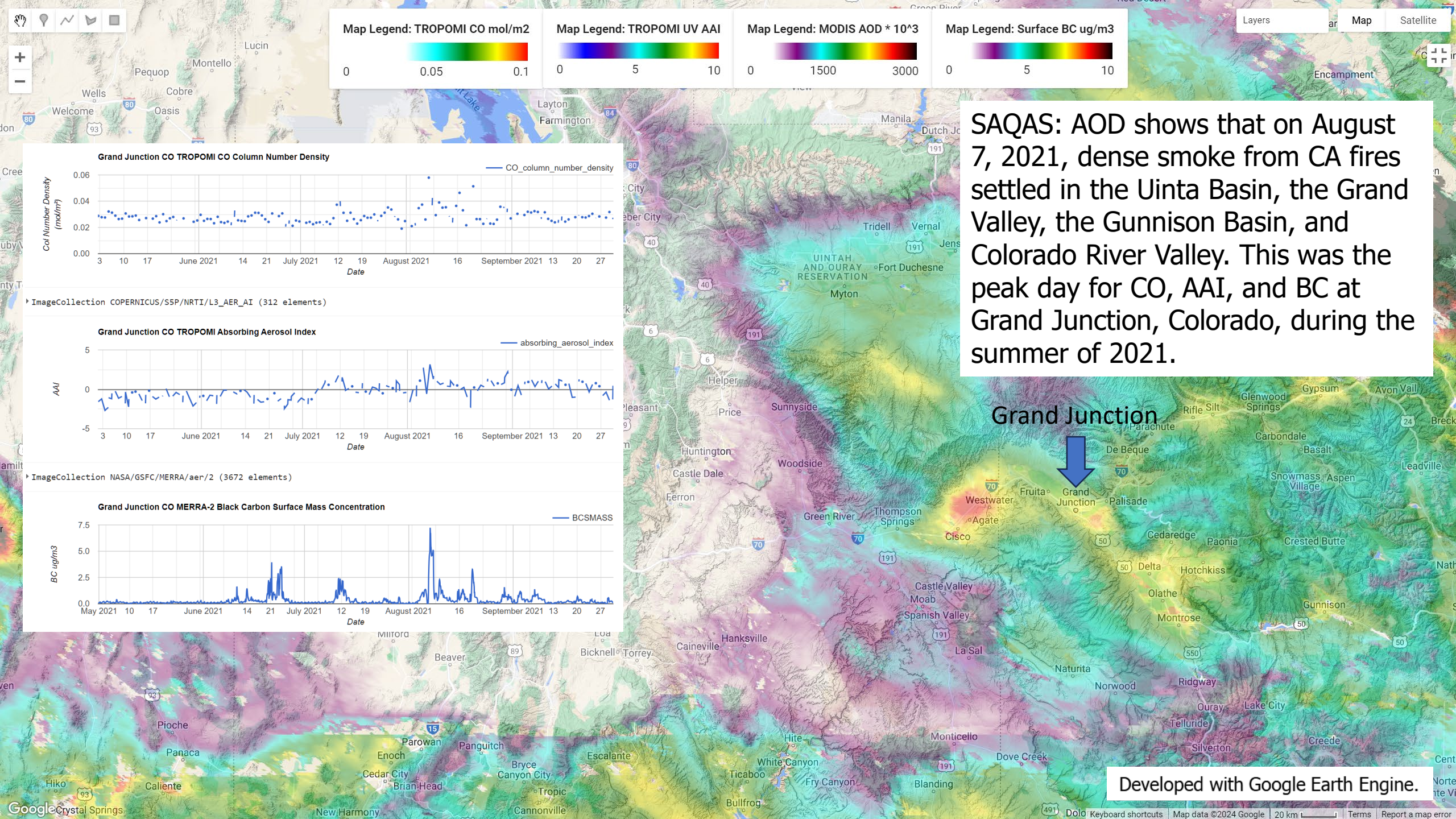
SAQAS GOES 16 True Color and NASA FIRMS and MODIS Fire Detection for August 7, 2021. Smoke from northern California fires carried by two low-pressure systems, one near Denver the other over the Dakotas. Smoke from Canada and Montana fires in MT and northern WY.

Developed with Google Earth Engine.



SAQAS composite: TROPOMI CO, TROPOMI AAI, and MODIS AOD for August 7, 2021.
Thick, dense smoke from California fires within low near Denver.
Developed with Google Earth Engine.

When smoke settles in valleys and is below local ridgetops, mountains, and higher terrain then there is a strong probability that it has reached the ground. The next slide shows smoke concentrated over lower terrain on August 7, 2021.


Map Legend: TROPOMI CO mol/m2
0
0.05
0.1
Map Legend: TROPOMI UV AAI
0
5
10
Map Legend: MODIS AOD * 10^3
0
1500
3000
Map Legend: Surface BC ug/m3
0
5
10
Layers
Map
Satellite
Grand Junction CO TROPOMI CO Column Number Density
CO_column_number_density
Col Number Density (mol/m²)
0.06
0.04
0.02
0.00
3 10 17 June 2021 14 21 July 2021 12 19 August 2021 16 September 2021 13 20 27
Date
ImageCollection COPERNICUS/S5P/NRTI/L3_AER_AI (312 elements)
Grand Junction CO TROPOMI Absorbing Aerosol Index
absorbing_aerosol_index
AAI
5
0
-5
3 10 17 June 2021 14 21 July 2021 12 19 August 2021 16 September 2021 13 20 27
Date
ImageCollection NASA/GSFC/MERRA/aer/2 (3672 elements)
Grand Junction CO MERRA-2 Black Carbon Surface Mass Concentration
BCSMASS
BC ug/m3
7.5
5.0
2.5
0.0
May 2021 10 17 June 2021 14 21 July 2021 12 19 August 2021 16 September 2021 13 20 27
Date
SAQAS: AOD shows that on August 7, 2021, dense smoke from CA fires settled in the Uinta Basin, the Grand Valley, the Gunnison Basin, and Colorado River Valley. This was the peak day for CO, AAI, and BC at Grand Junction, Colorado, during the summer of 2021.
Grand Junction
Developed with Google Earth Engine.
Google
Keyboard shortcuts
Map data ©2024 Google
20 km
Terms
Report a map error

The following slides show correlations and relationships between daily max ozone and PM2.5 concentrations and visible smoke, TROPOMI CO, and MODIS AOD.

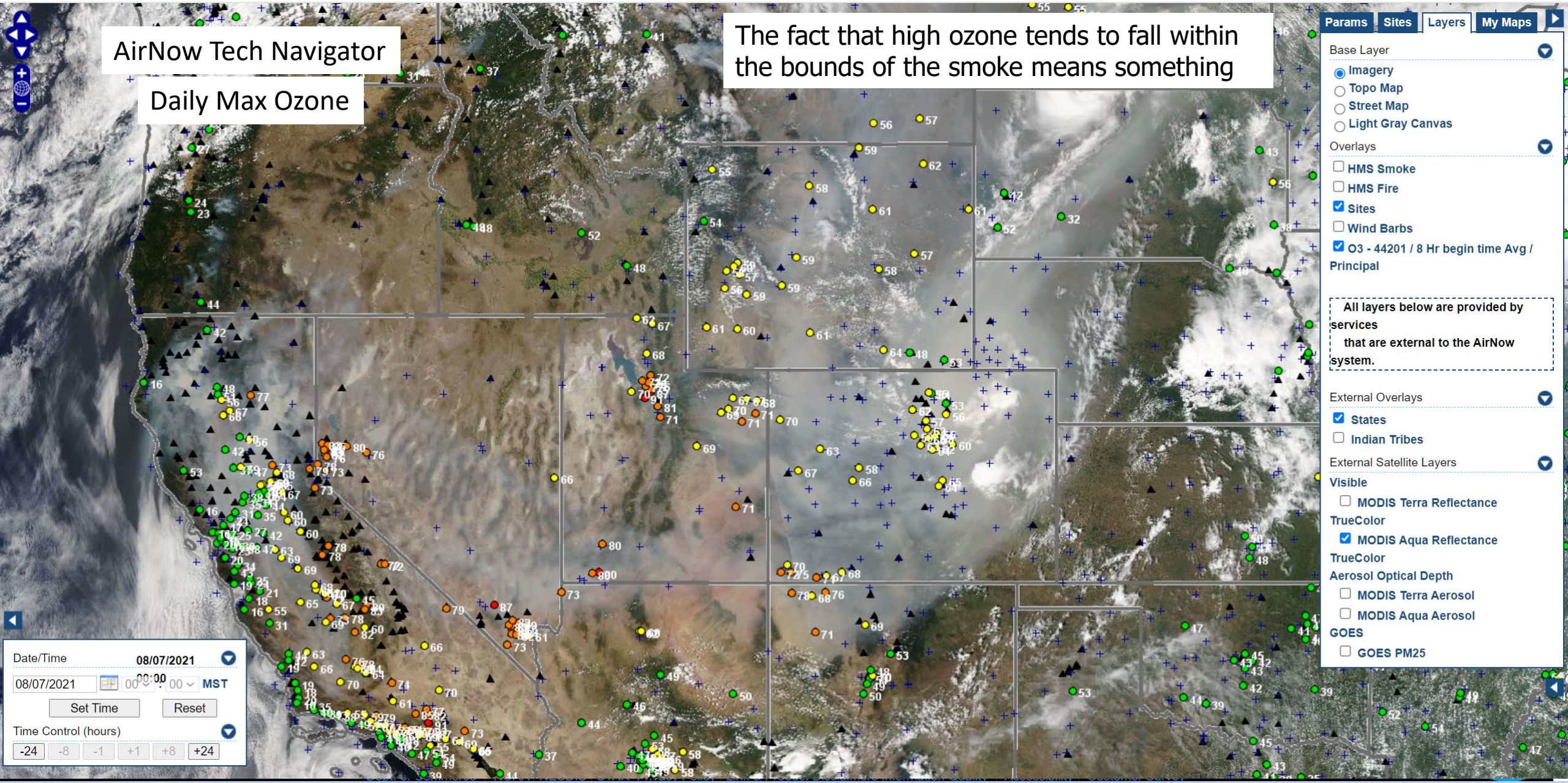

AirNow Tech Navigator
Daily Max Ozone
The fact that high ozone tends to fall within the bounds of the smoke means something
Params
Sites
Layers
My Maps
Base Layer
Imagery
Topo Map
Street Map
Light Gray Canvas
Overlays
HMS Smoke
HMS Fire
Sites
Wind Barbs
O3 - 44201 / 8 Hr begin time Avg / Principal
All layers below are provided by services that are external to the AirNow system.
External Overlays
States
Indian Tribes
External Satellite Layers
Visible
MODIS Terra Reflectance TrueColor
MODIS Aqua Reflectance TrueColor
Aerosol Optical Depth
MODIS Terra Aerosol
MODIS Aqua Aerosol
GOES
GOES PM25
Date/Time
08/07/2021 00:00
08/07/2021
00 : 00 MST
Set Time
Reset
Time Control (hours)
-24
-8
-1
+1
+8
+24

Table 1. Bayesian Pearson Correlations Between PM2.5 and Satellite Variables for Nine Sites from August 5-7, 2021.

		n	Pearson's r	BF_{+0}
PM25	- TROPOMI CO	23	0.931 ***	$1.310\times10^{+8}$
PM25	- ln(TROPOMI CO)	23	0.938 ***	$3.394\times10^{+8}$
PM25	- TROPOMI AAI	27	0.625 ***	152.709
PM25	- MAIAC AOD 550 nm	26	0.730 ***	2332.111
TROPOMI CO	- TROPOMI AAI	23	0.913 ***	$1.526\times10^{+7}$
TROPOMI CO	- MAIAC AOD 550 nm	22	0.946 ***	$4.430\times10^{+8}$
ln(TROPOMI CO)	- TROPOMI AAI	23	0.881 ***	941074.752
ln(TROPOMI CO)	- MAIAC AOD 550 nm	22	0.905 ***	$2.988\times10^{+6}$
TROPOMI AAI	- MAIAC AOD 550 nm	26	0.914 ***	$2.368\times10^{+8}$

* $BF_{+0} > 10$, ** $BF_{+0} > 30$, *** $BF_{+0} > 100$

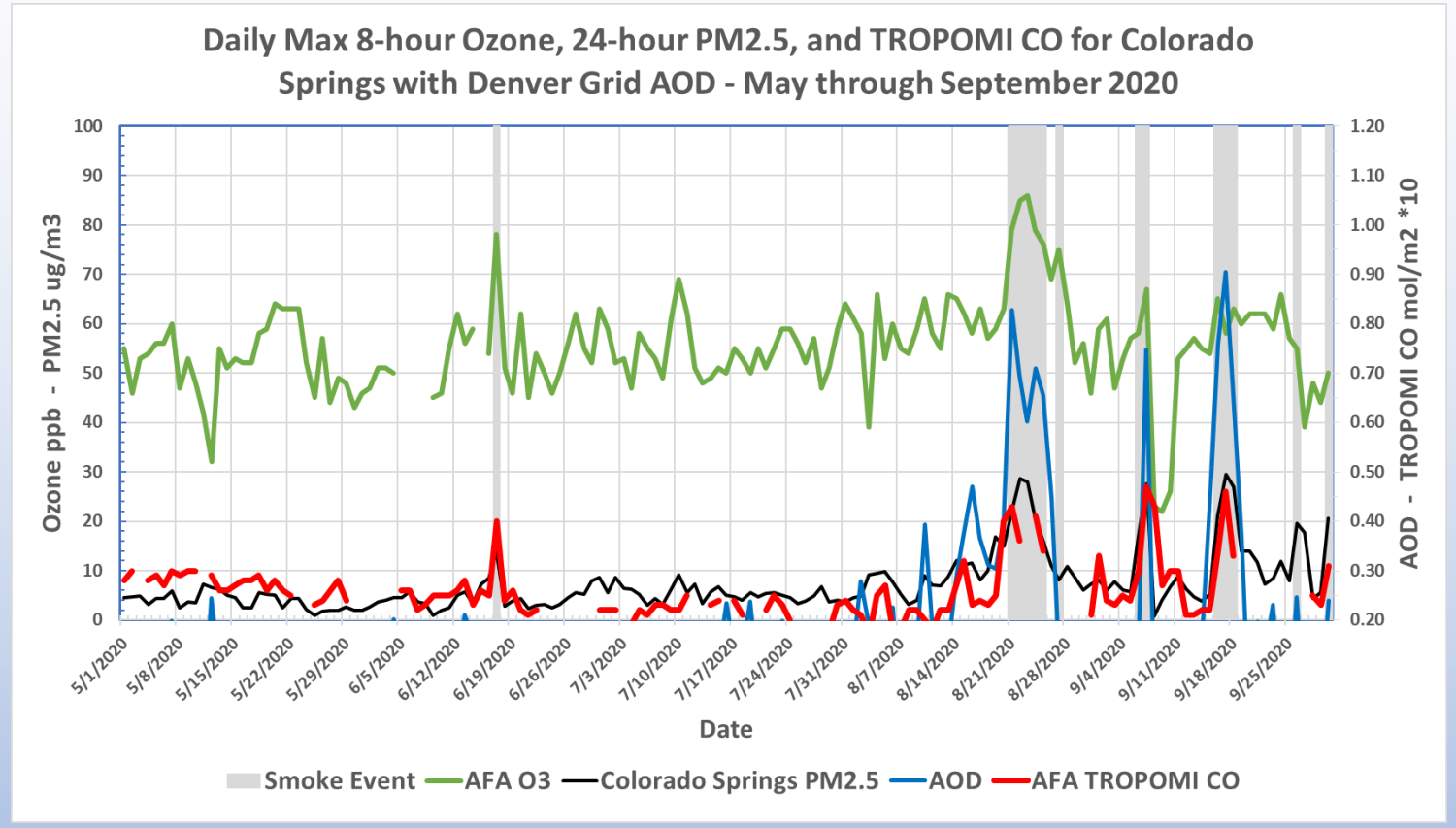
Note. For all tests, the alternative hypothesis specifies that the correlation is positive.

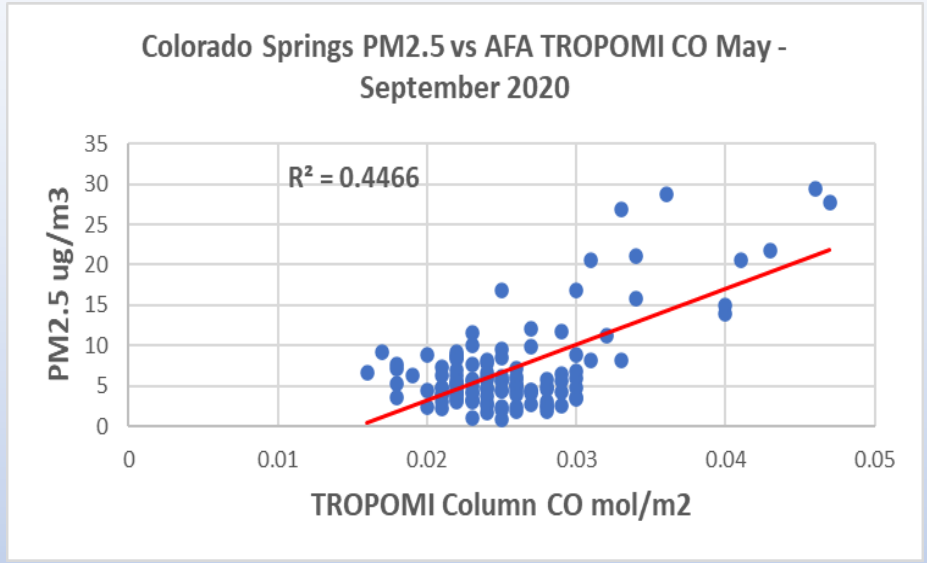
Table 2. Bayesian Pearson Correlations Between O_3 and Satellite Variables for Nine Sites from August 5-7, 2021.

			n	Pearson's r	BF_{+0}
Max O_3	-	TROPOMI CO	23	0.778***	3953.463
Max O_3	-	ln(TROPOMI CO)	23	0.817***	20771.225
Max O_3	-	TROPOMI AAI	27	0.271	1.053
Max O_3	-	MAIAC AOD 550 nm	26	0.302	1.312
TROPOMI CO	-	TROPOMI AAI	23	0.913***	$1.526\times10^{+7}$
TROPOMI CO	-	MAIAC AOD 550 nm	22	0.946***	$4.430\times10^{+8}$
ln(TROPOMI CO)	-	TROPOMI AAI	23	0.881***	941074.752
ln(TROPOMI CO)	-	MAIAC AOD 550 nm	22	0.905***	$2.988\times10^{+6}$
TROPOMI AAI	-	MAIAC AOD 550 nm	26	0.914***	$2.368\times10^{+8}$

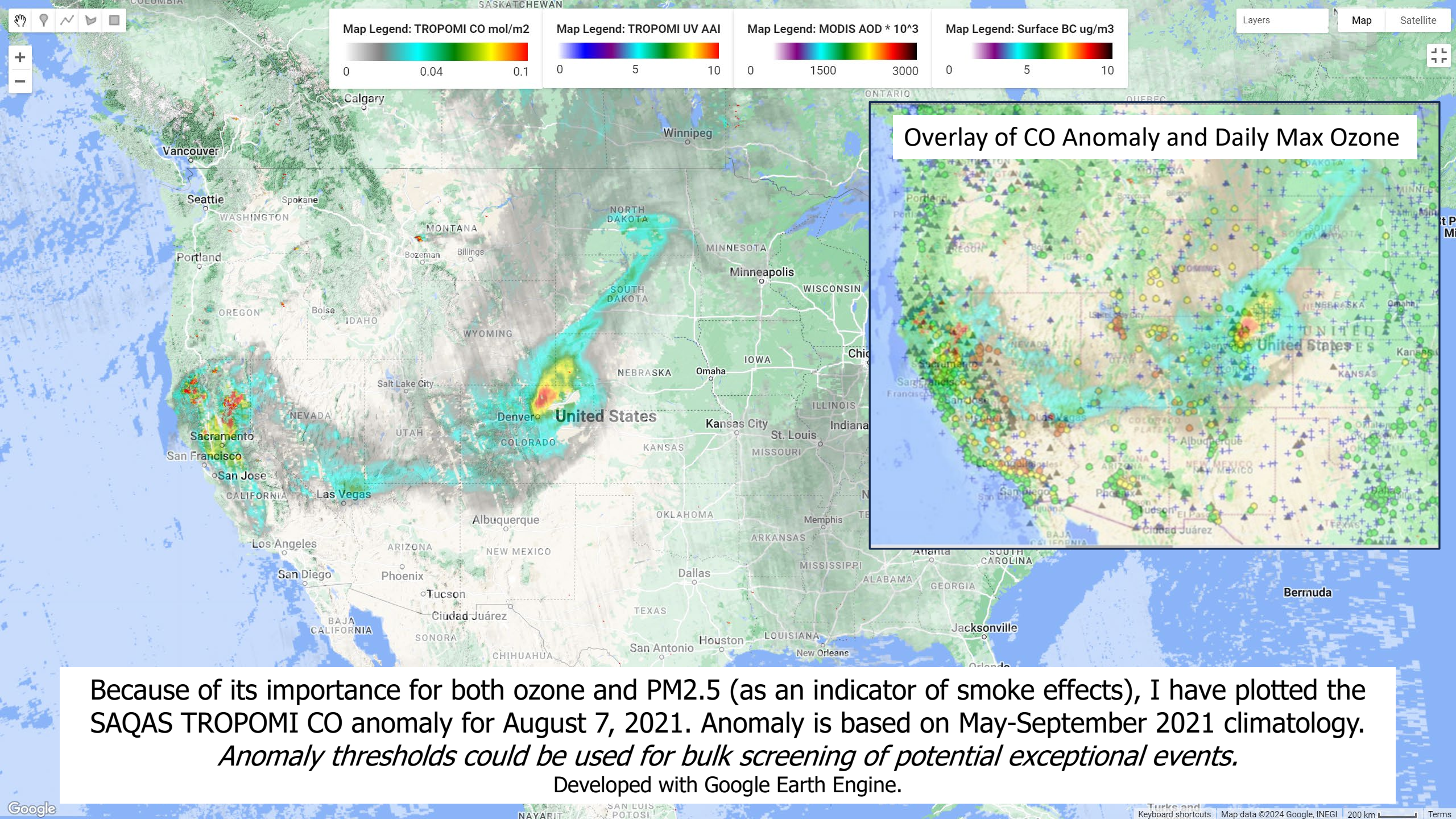
* $BF_{+0} > 10$, ** $BF_{+0} > 30$, *** $BF_{+0} > 100$

Note. For all tests, the alternative hypothesis specifies that the correlation is positive.





May-September 2020: Colorado Springs PM2.5 is strongly correlated with local TROPOMI CO (r=0.67). Smoke events in the left figure are shaded in grey. Both TROPOMI CO and MODIS AOD could be useful for flagging and analyzing both ozone and PM2.5 events.



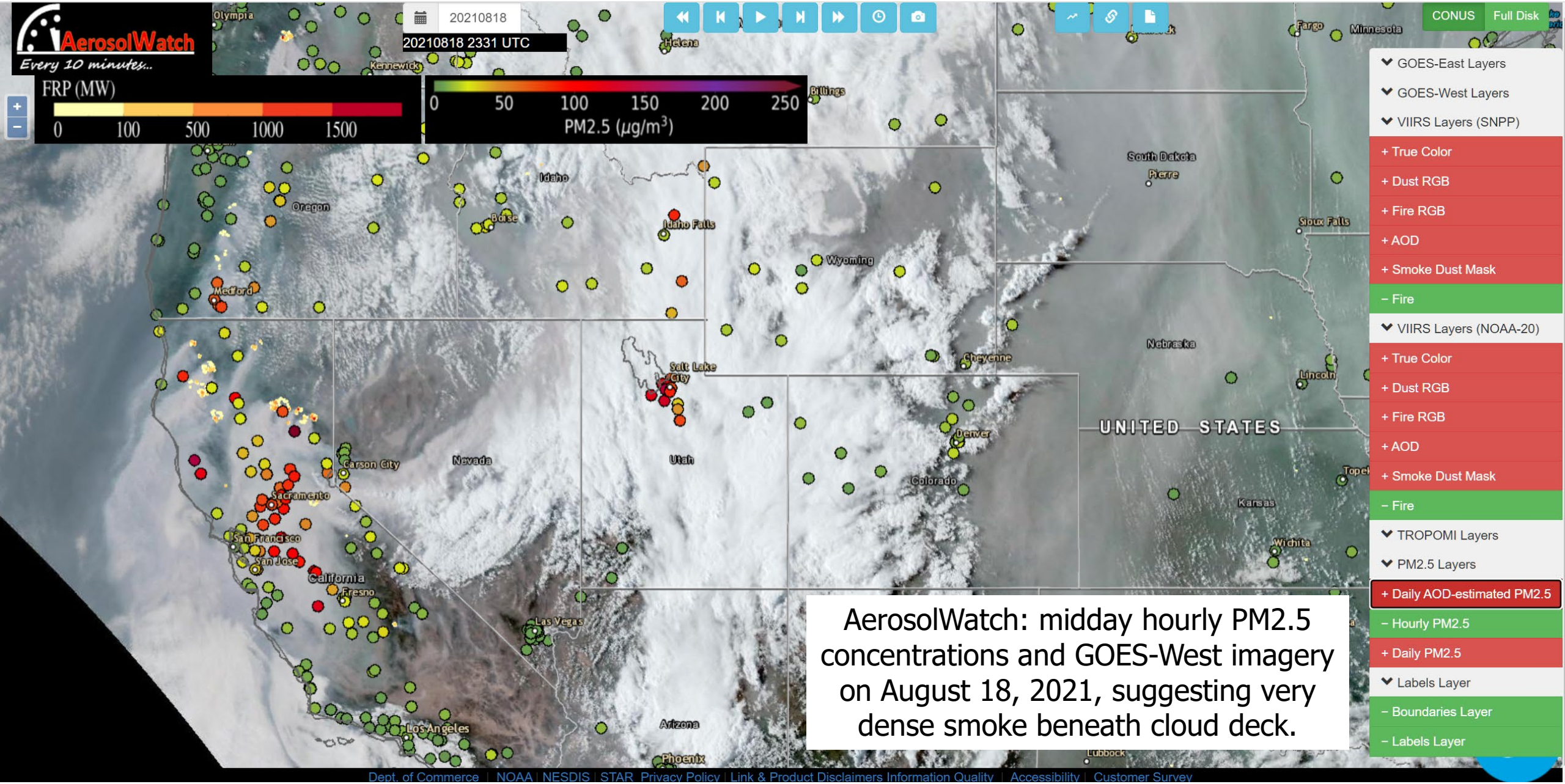
Because of its importance for both ozone and PM2.5 (as an indicator of smoke effects), I have plotted the SAQAS TROPOMI CO anomaly for August 7, 2021. Anomaly is based on May-September 2021 climatology.

Anomaly thresholds could be used for bulk screening of potential exceptional events.

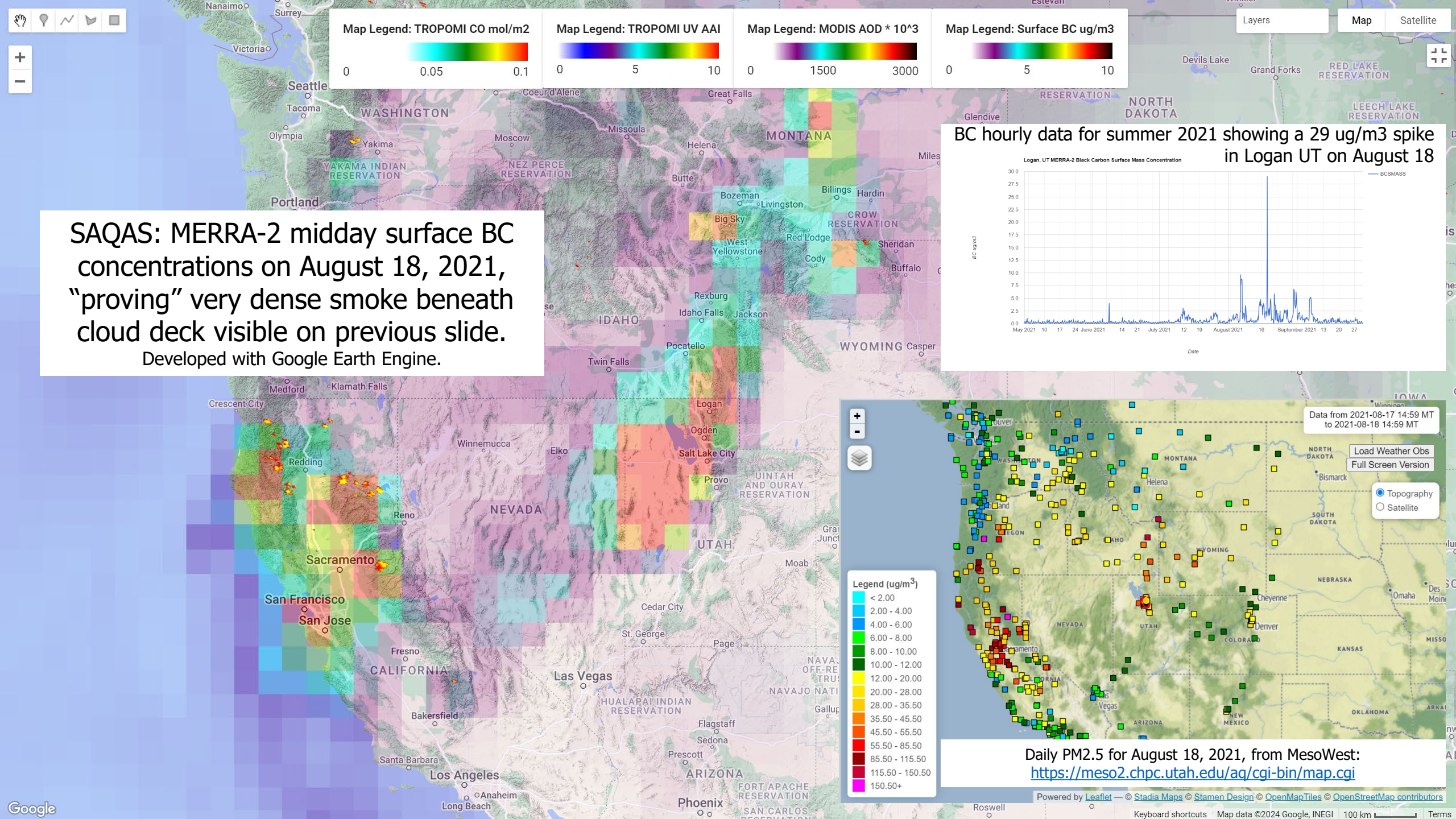
Developed with Google Earth Engine.

- This analysis confirms that fires in Northern California were likely the primary source of smoke causing the August 5-7, 2021, ozone and PM2.5 exceedances in much of the West.
- Much of the evidence arises from animations of the event. In an exceptional event demonstration, snapshots for key moments in the evolution of the event can be included in a demonstration report.
- Smoke from the western coastal states and Canada can take days to reach Wyoming or Colorado in weaker summer flows, and heavy residual smoke can sometimes linger well after transport patterns have shifted.
- While HYSPLIT trajectories of 48 to 72 hours will often be sufficient, trajectories for up to 96 to 120 hours will sometimes be necessary (this was the case for the Colorado exceedances in late August of 2020).

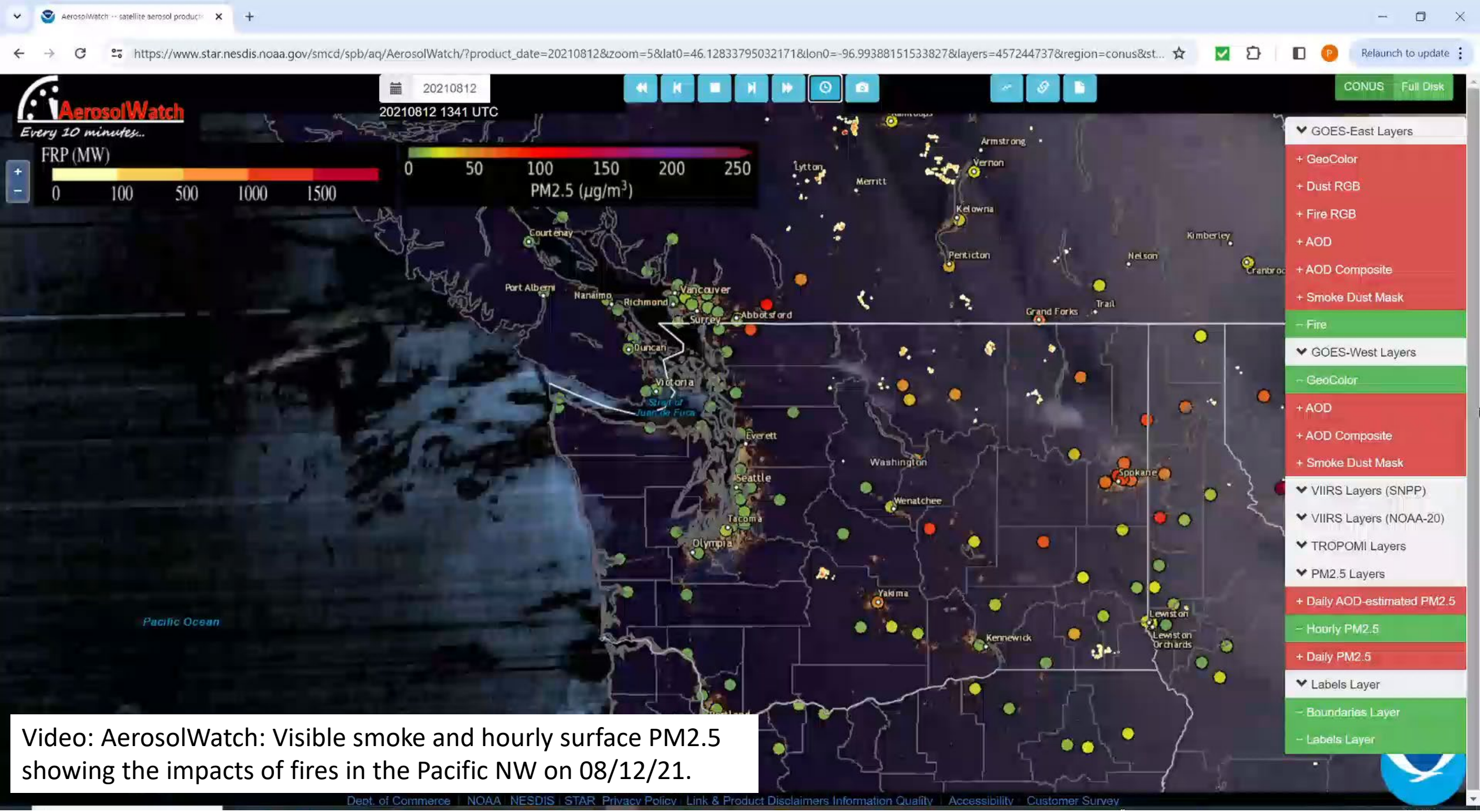
August 18, 2021, Clouds and Smoke Over Utah.



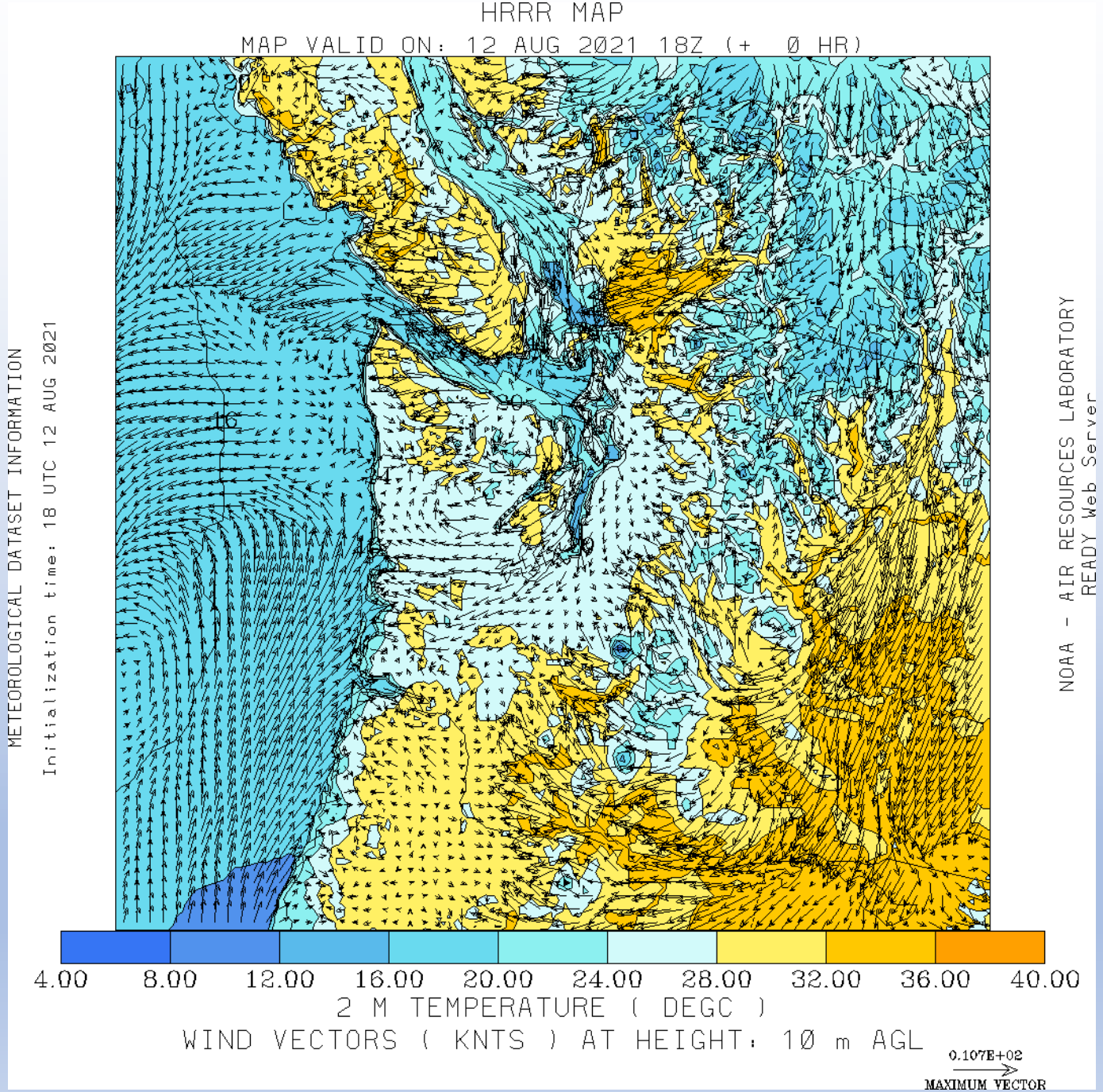
AerosolWatch: midday hourly PM2.5 concentrations and GOES-West imagery on August 18, 2021, suggesting very dense smoke beneath cloud deck.


Map Legend: TROPOMI CO mol/m2
0
0.05
0.1
Map Legend: TROPOMI UV AAI
0
5
10
Map Legend: MODIS AOD * 10^3
0
1500
3000
Map Legend: Surface BC ug/m3
0
5
10
Layers
Map
Satellite
SAQAS: MERRA-2 midday surface BC concentrations on August 18, 2021, "proving" very dense smoke beneath cloud deck visible on previous slide.
Developed with Google Earth Engine.
BC hourly data for summer 2021 showing a 29 ug/m3 spike in Logan UT on August 18
Logan, UT MERRA-2 Black Carbon Surface Mass Concentration
BCSMASS
BC ug/m3
Date
Data from 2021-08-17 14:59 MT to 2021-08-18 14:59 MT
Load Weather Obs
Full Screen Version
Topography
Satellite
Legend (ug/m3)
< 2.00
2.00 - 4.00
4.00 - 6.00
6.00 - 8.00
8.00 - 10.00
10.00 - 12.00
12.00 - 20.00
20.00 - 28.00
28.00 - 35.50
35.50 - 45.50
45.50 - 55.50
55.50 - 85.50
85.50 - 115.50
115.50 - 150.50
150.50+
Daily PM2.5 for August 18, 2021, from MesoWest:
https://meso2.chpc.utah.edu/aq/cgi-bin/map.cgi
Powered by Leaflet — © Stadia Maps © Stamen Design © OpenMapTiles © OpenStreetMap contributors
Google
Keyboard shortcuts
Map data ©2024 Google, INEGI
100 km
Terms

August 12, 2021, Complex Pacific Northwest Smoke Event.

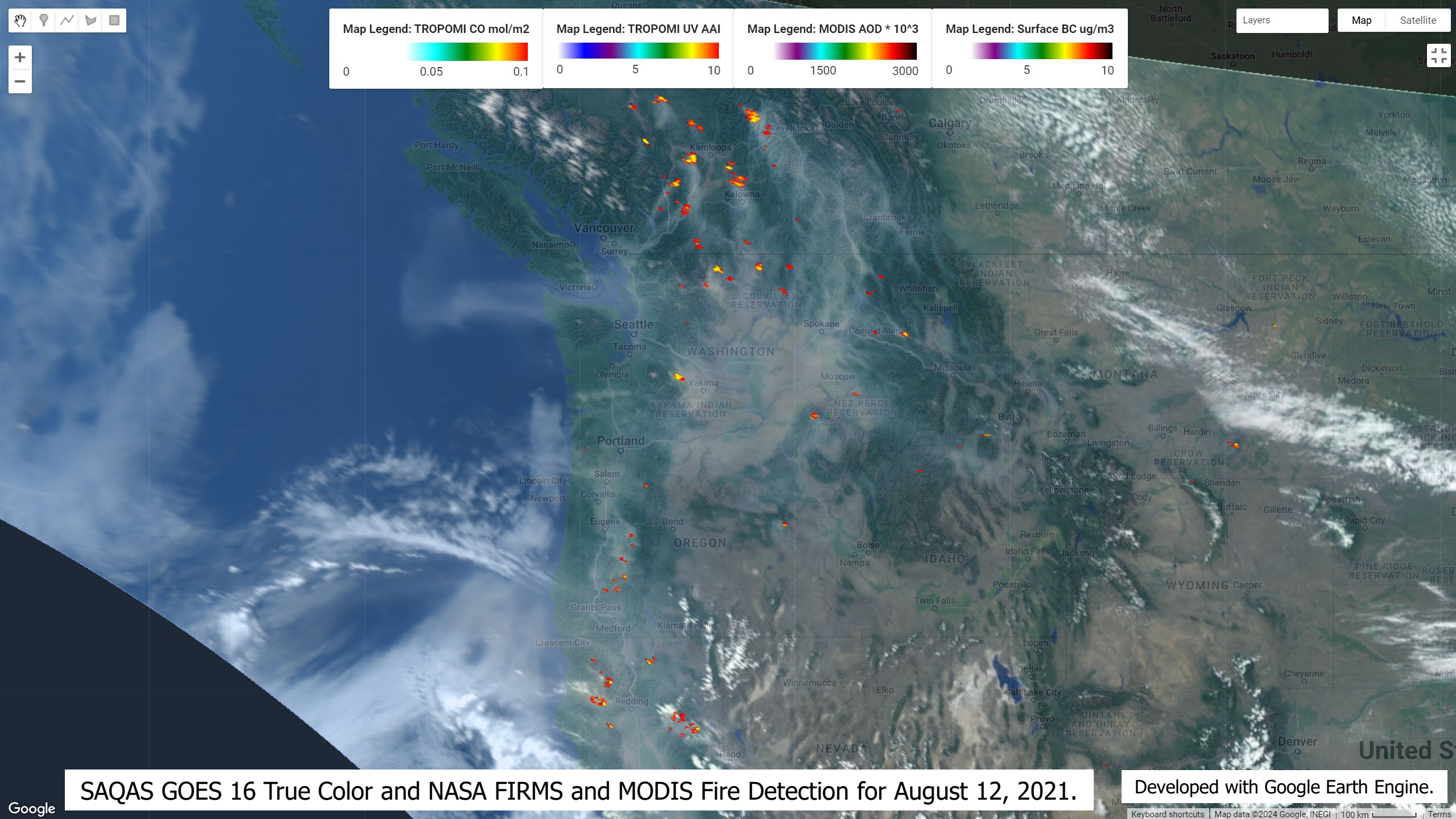


Video: AerosolWatch: Visible smoke and hourly surface PM2.5 showing the impacts of fires in the Pacific NW on 08/12/21.



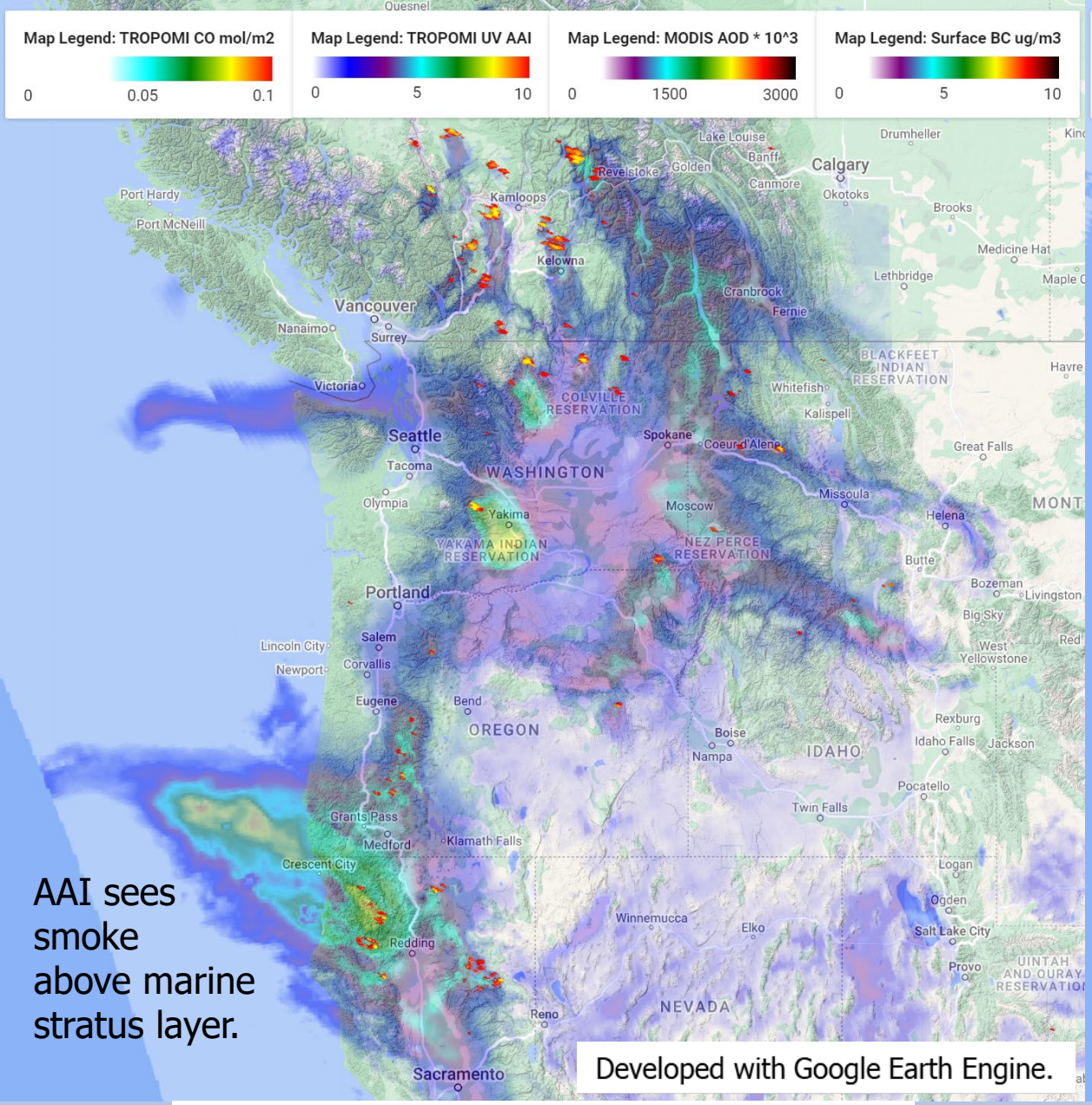
High Resolution Rapid Refresh (HRRR) meteorological model surface winds for August 12, 2021, 18 UTC.
https://www.ready.noaa.gov/READYamet.php

Model resolves the low-level jets over the Strait of San Juan de Fuca and the Strait of Georgia, synoptic-scale northeasterlies over British Columbia, and easterlies over the Chehalis Gap.



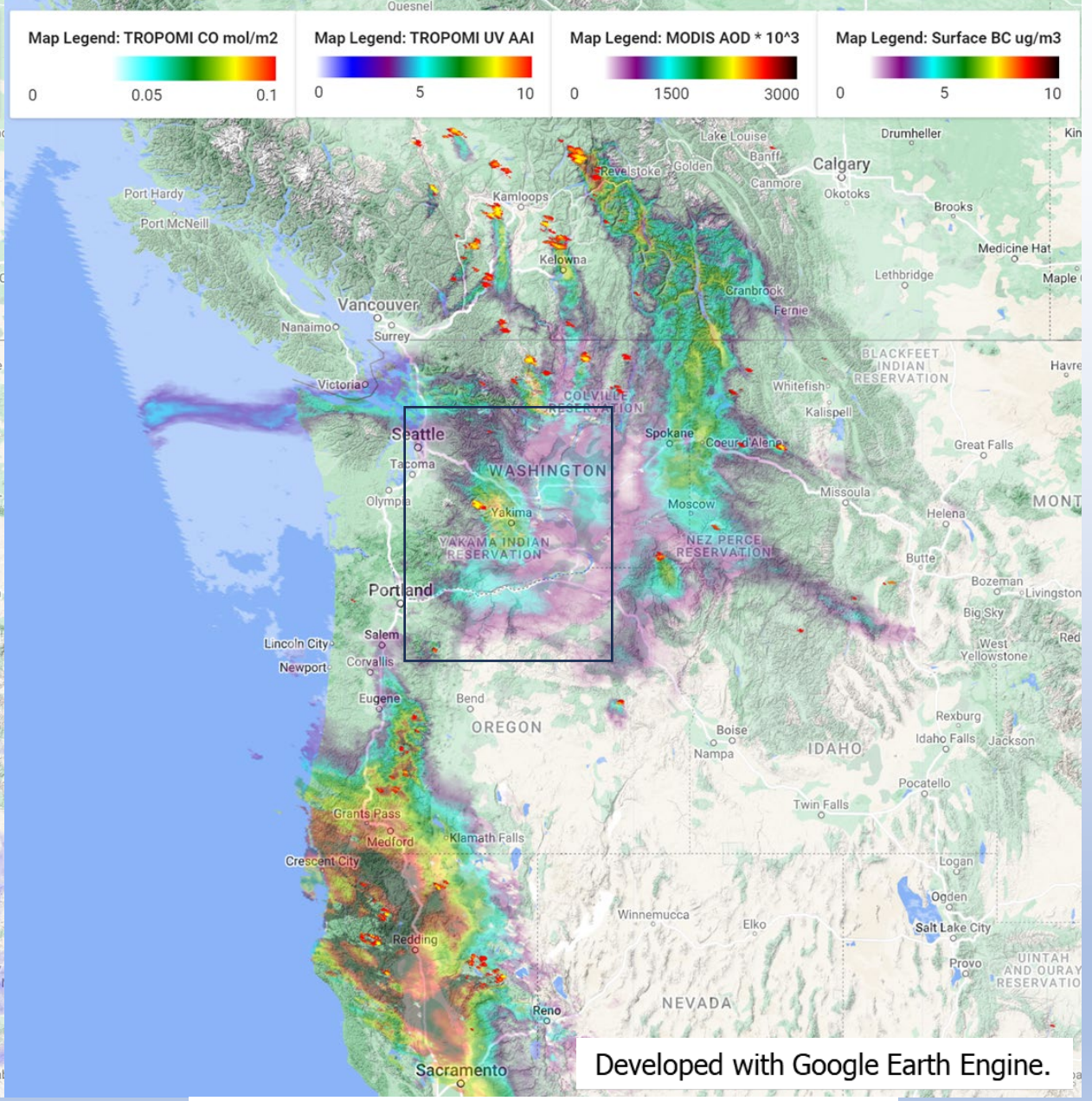
SAQAS GOES 16 True Color and NASA FIRMS and MODIS Fire Detection for August 12, 2021.

Developed with Google Earth Engine.



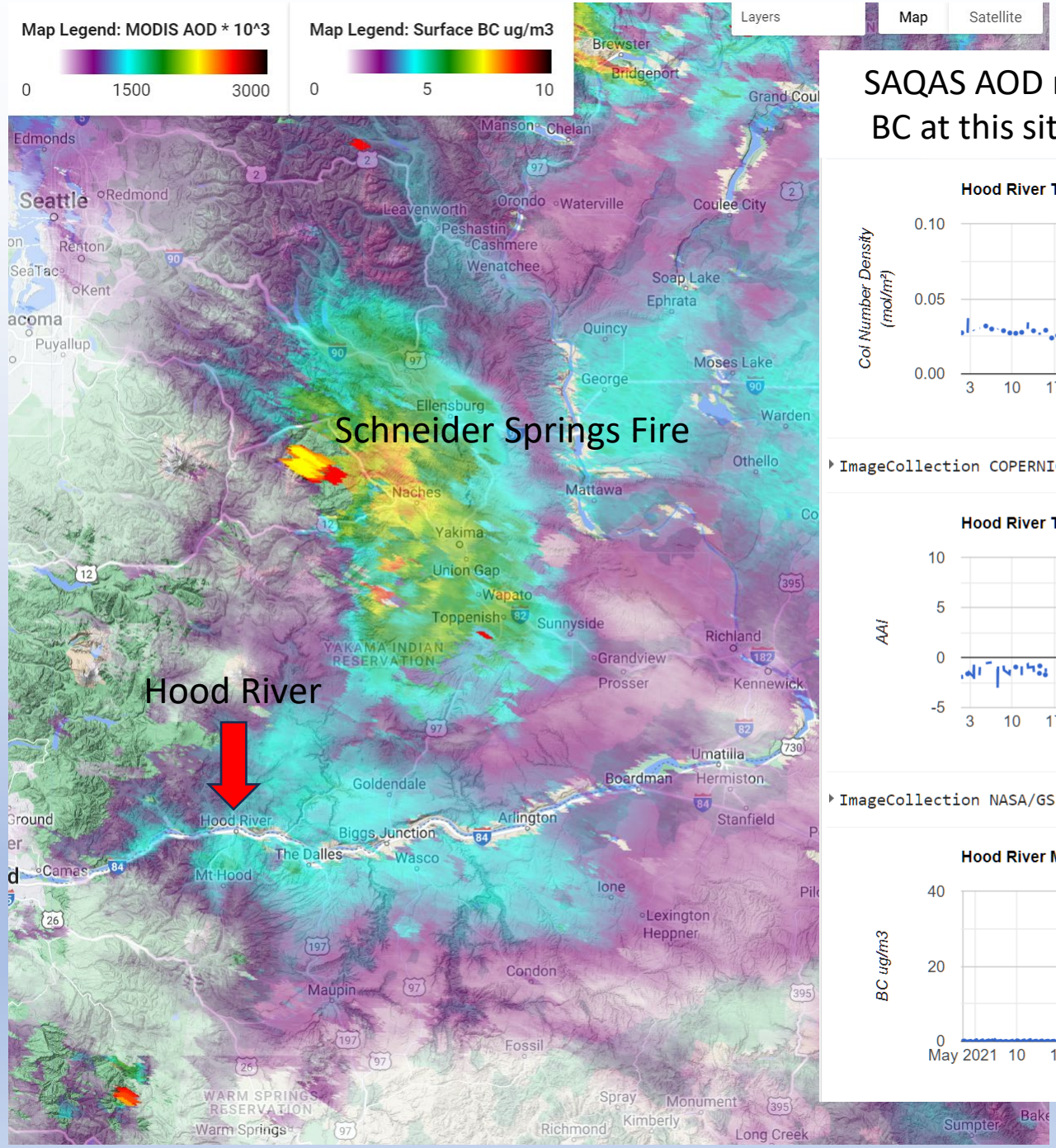
AAI sees smoke above marine stratus layer.

SAQAS TROPOMI AAI for August 12, 2021.

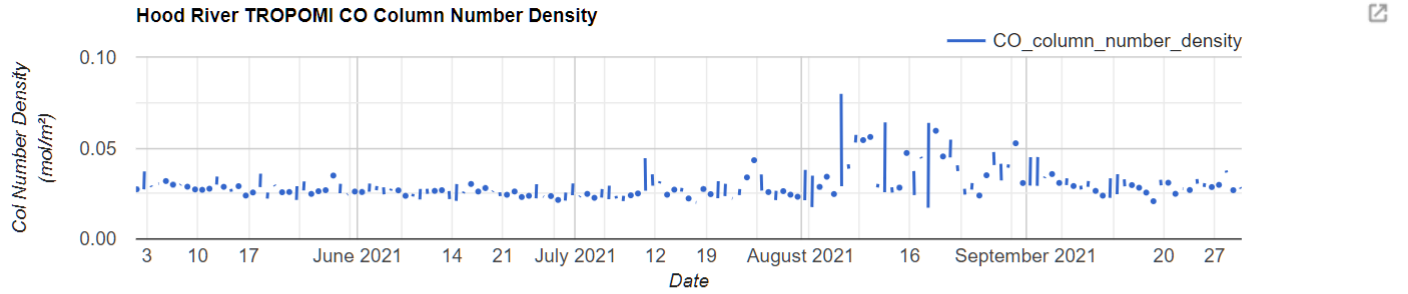


SAQAS MODIS AOD for August 12, 2021.

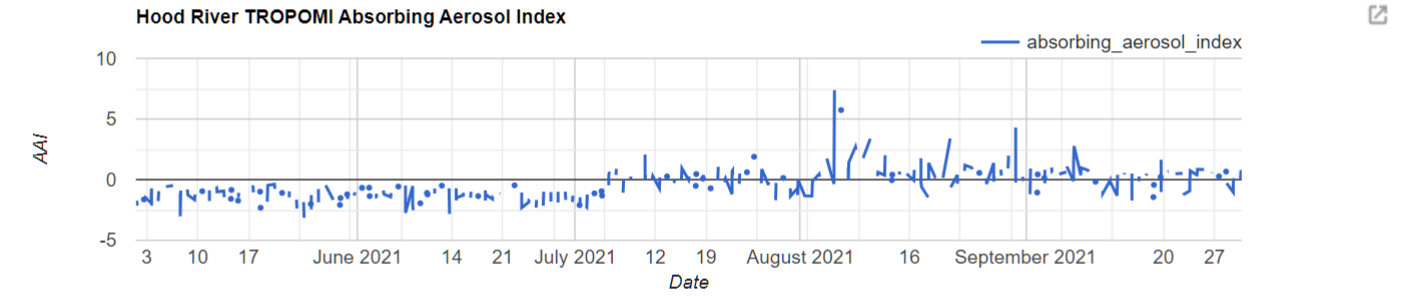
AOD in the black rectangle captures settling of smoke in valleys. AAI does not show this.



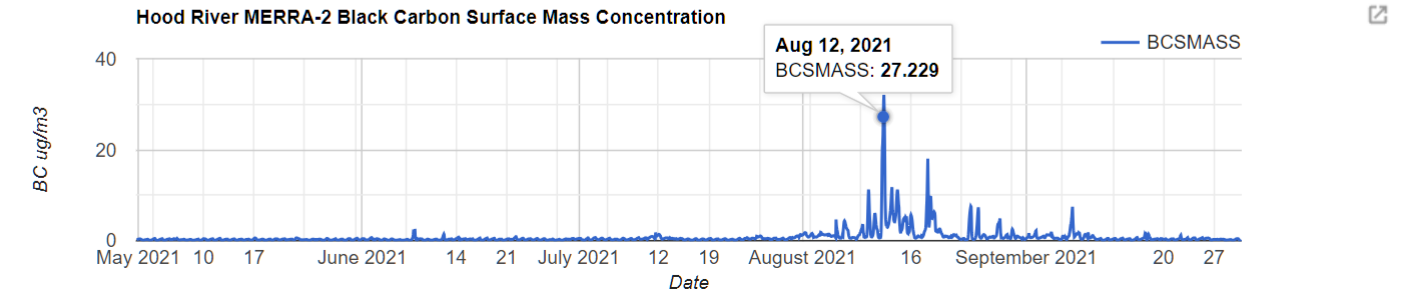
SAQAS AOD near Hood River, OR., 08/12/2021, & time series for CO, AAI, & BC at this site for May-September 2021. This was the peak day for BC here.



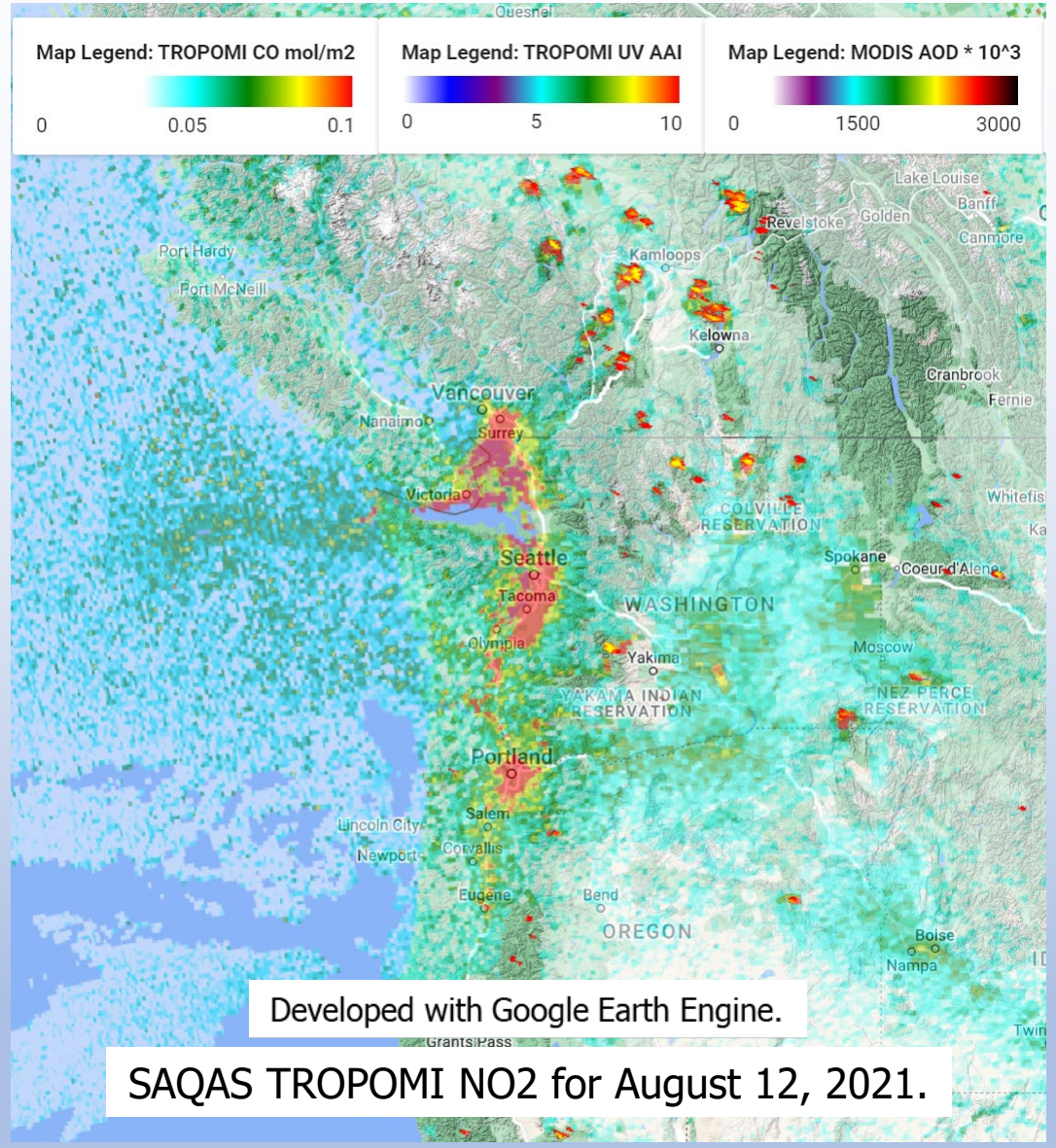
ImageCollection COPERNICUS/S5P/NRTI/L3_AER_AI (509 elements) JSON



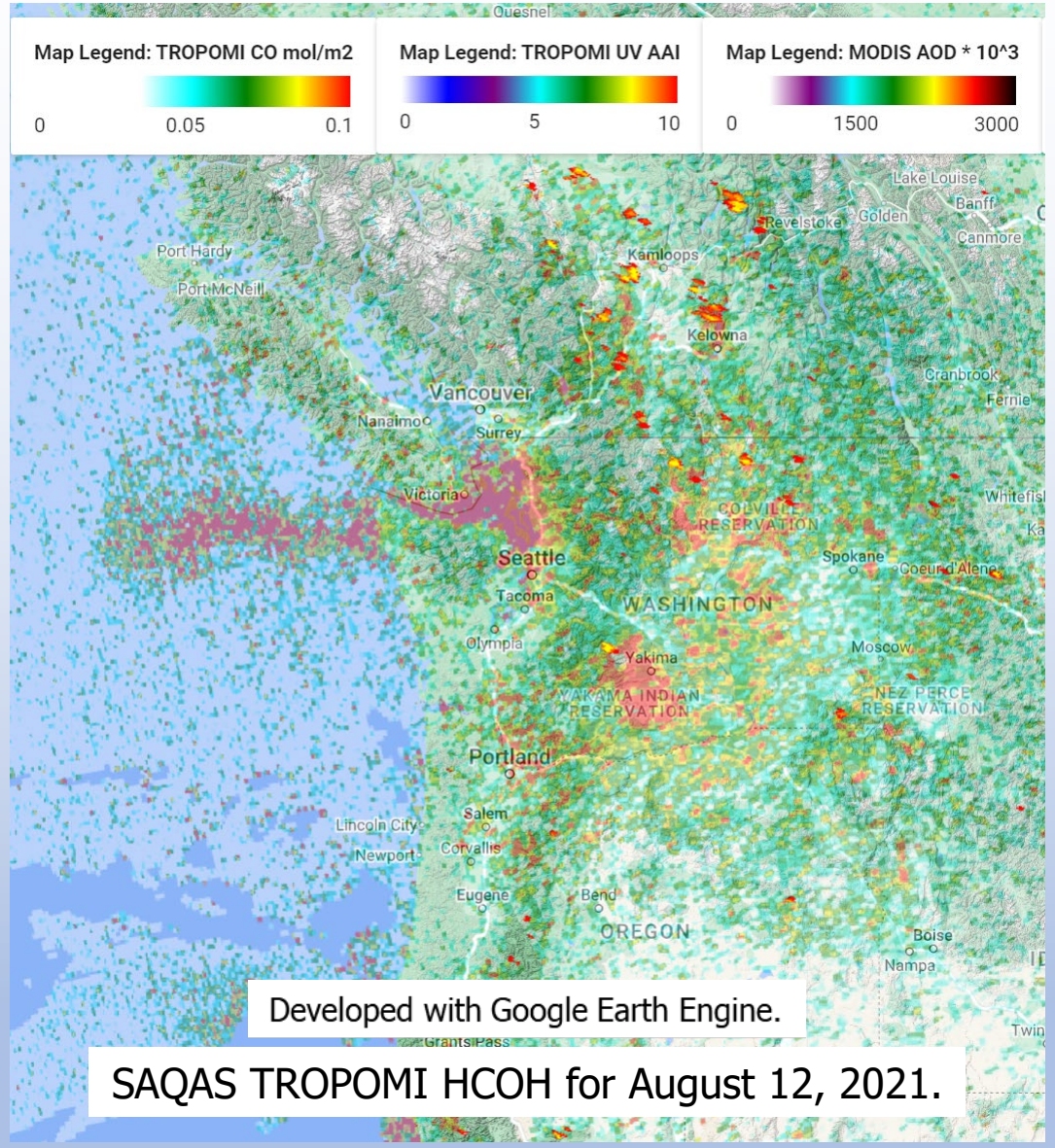
ImageCollection NASA/GSFC/MERRA/aer/2 (3672 elements) JSON



Maps and charts produced with Google Earth Engine.



SAQAS TROPOMI NO2 for August 12, 2021.



SAQAS TROPOMI HCOH for August 12, 2021.

TROPOMI NO2 (left) shows large urban sources from Vancouver BC to Takoma and urban emissions characteristics for the plume over the ocean. HCOH (right) suggests smoke influences in this plume. Anomalously high CO also confirms a smoke influence over the urban area and within the plume.

Map Legend: TROPOMI CO mol/m2

0 0.05 0.1

Map Legend: TROPOMI UV AAI

0 5 10

Map Legend: MODIS AOD * 10^3

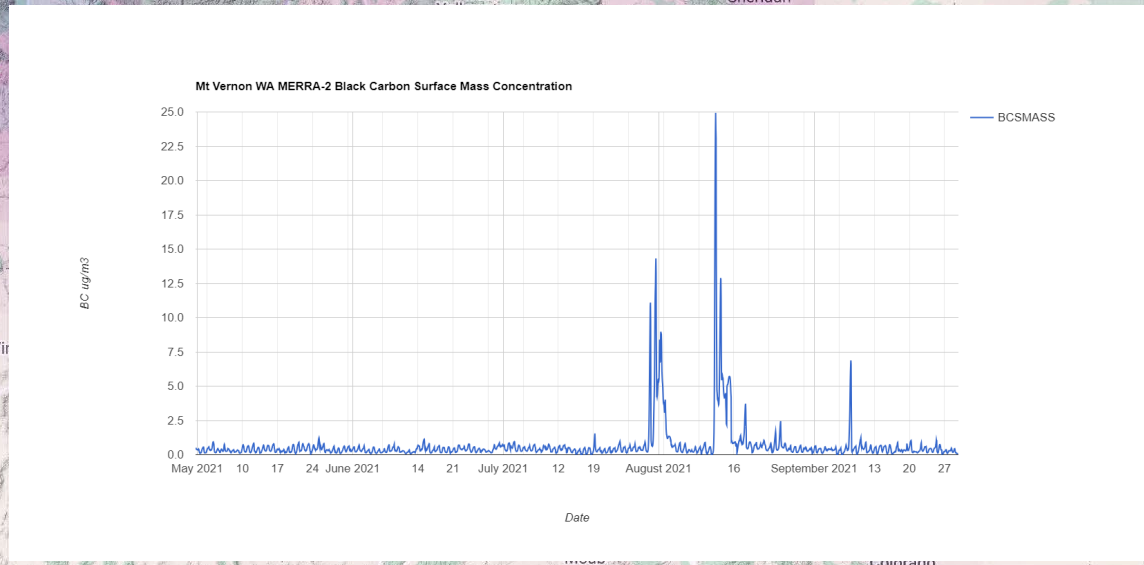
0 1500 3000

Map Legend: Surface BC ug/m3

0 5 10

Layers Map Satellite

BC spikes at 25 ug/m3 in Mt Vernon WA
on August 12, 2021,
the high for the summer



SAQAS MERRA-2 BC for midday August 12, 2021.

Developed with Google Earth Engine.

Google

Keyboard shortcuts Map data ©2024 Google, INEGI 100 km Terms

Google Earth Engine Licensing for Use Cases for SAQAS or Similar Scripts

- As a training tool: noncommercial, free license for trainer and students.
- As a government, academic, nonprofit, or individual research tool: noncommercial, free license.
- For agency's annual internal screening of potential exceptional events: ???
- For the general development of routine monthly or annual products (this might include annual exceptional event reports/analyses): a commercial subscription is required.
- As a platform for commercial use: a commercial subscription is required.

Noncommercial Google Earth Engine account restrictions for government agencies (https://earthengine.google.com/noncommercial/):

- For all other government agencies, Earth Engine is free of charge if it is used for Government Research Activities. For your use to qualify as Government Research Activities all of the following requirements must be met:
- The project work is question-driven.
- The project work has a stated start & (estimated) end date.
- The project work has a limit on the amount of compute and data, such that it isn't "operational," or repeated periodically over time. If Government Research Activities are repeated periodically over time, that would then be considered an operational use case. As an example, a government agency's use of Earth Engine to run the same algorithm on a monthly or annual basis would not qualify as Government Research Activities.
- The project work is meant to result in scholarly output, e.g. manuscripts in a peer reviewed scholarly journal, white papers, or other documentation about the scientific methods. Findings should be made public: e.g. code libraries or datasets (results and training/validation) shared with the scientific community.

Useful Tools and Data Sources

- AerosolWatch site: GOES and VIIRS visible imagery, satellite aerosol optical depth (AOD), fire detections, smoke masks, surface PM2.5, PM2.5 estimated using satellite (AOD), and TROPOMI satellite CO : https://www.star.nesdis.noaa.gov/smcd/spb/aq/AerosolWatch/ . AerosolWatch can be used as a workspace to identify fire influences and transport patterns and timing.

- NCAR ACOM Worldview: Visible satellite imagery; fires; a wealth of satellite measurements; TROPOMI satellite CO; AOD; modeled O3, PM2.5, and CO; and more: https://worldview.acom.ucar.edu/

- AirNow Tech Navigator: Air quality data, HMS smoke coverage, trajectories, O3 wind roses, GOES and MODIS imagery, and meteorology: https://www.airnowtech.org/navigator/index.cfm#

- HYSPLIT forward and back trajectories: https://www.ready.noaa.gov/HYSPLIT_traj.php . An ensemble approach is recommended. Assess backward and forward trajectories for multiple locations near monitors of interest or source region fires at multiple altitudes and for multiple times. A single set of backward trajectories (for 3 altitudes) for one time and/or one location is not likely to provide enough information to identify the most influential source regions.

- Weather maps and meteorological reanalysis data sets from the NASA MERRA-2 and North American Regional Reanalysis (NARR): https://fluid.nccs.nasa.gov/reanalysis/classic_merra2/ https://psl.noaa.gov/cgi-bin/data/narr/plotday.pl

- NASA MERRA-2 atmospheric composition analyses for surface and column black carbon and PM2.5: https://fluid.nccs.nasa.gov/reanalysis/chem2d_merra2/?region=nam

- MODIS Aerosol Optical Depth (550_Dark_Target_Deep_Blue_Combined_Mean from: https://giovanni.gsfc.nasa.gov/giovanni/

- EPA's air quality data site: https://www.epa.gov/outdoor-air-quality-data