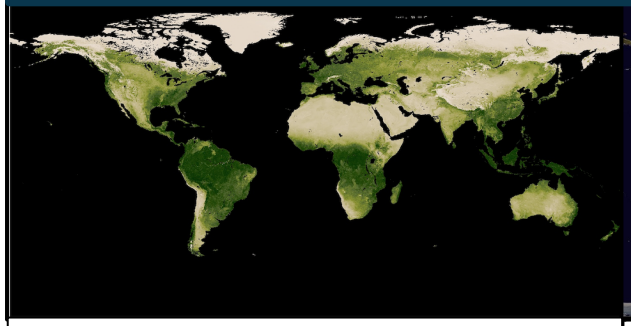
Part 4: During-Fire
Fire Emissions and Smoke Forecasting

Melanie Follette-Cook, Pawan Gupta, and Ana Prados

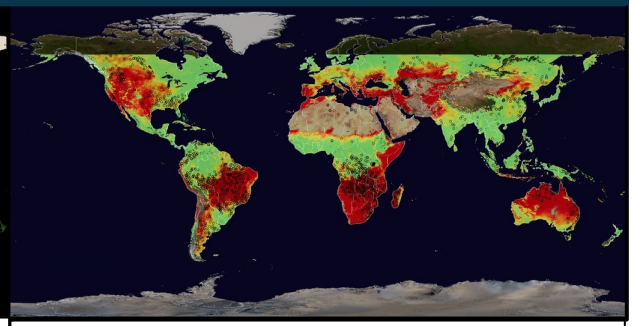
May 20, 2021

Webinar Agenda

Pre-Fire

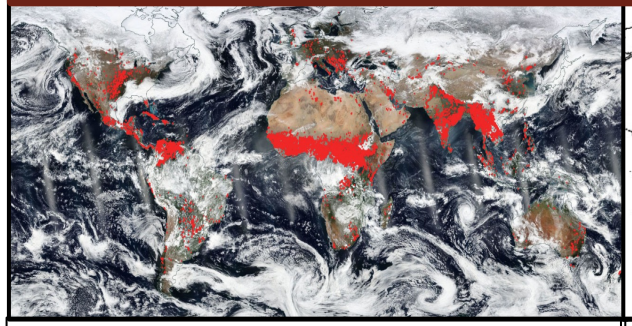


Session 1:
Climate and Hydrology

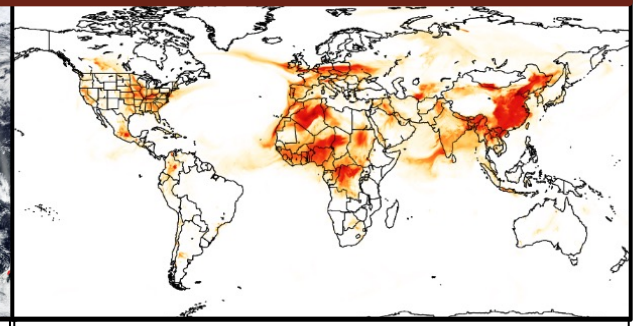


Session 2:
Vegetation

During Fire

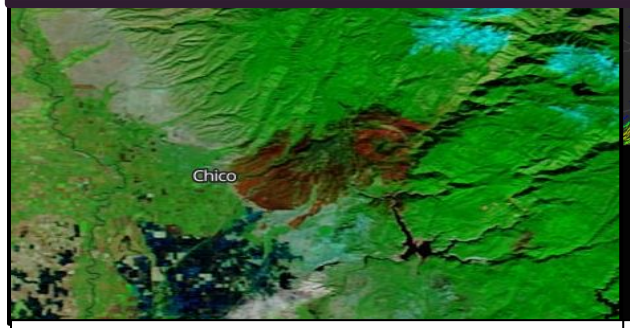


Session 3:
Active Fires and Smoke

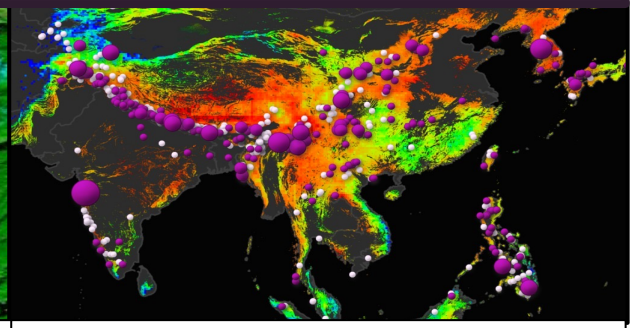


Session 4:
Smoke Forecasting

Post-Fire



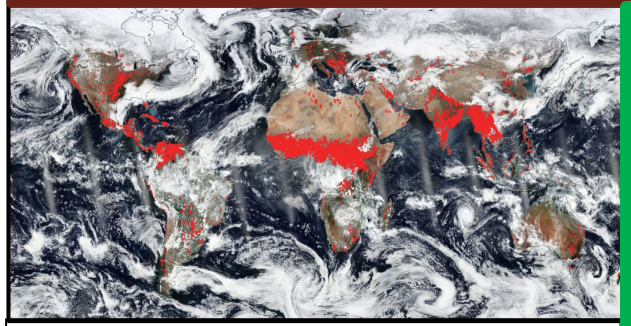
Session 5:
Climate & Hydrology



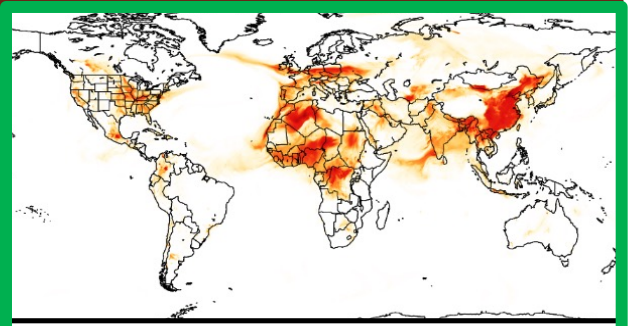
Session 6:
Vegetation

Webinar Agenda

During Fire



Session 3:
Active Fires and Smoke



Session 4:
Smoke Forecasting

Melanie Follette-Cook

Pawan Gupta

Ana Prados

Learning Objectives

- Understand the different ways fire emissions can be estimated using satellite observations
- Identify several different fire emissions datasets available
- Locate several global and US air quality forecasts

Questions

- Please enter your questions in the Q&A box. We will answer them in the order they were received at the end of today's presentation.

- We will post the Q&A to the training website following the conclusion of the webinar.

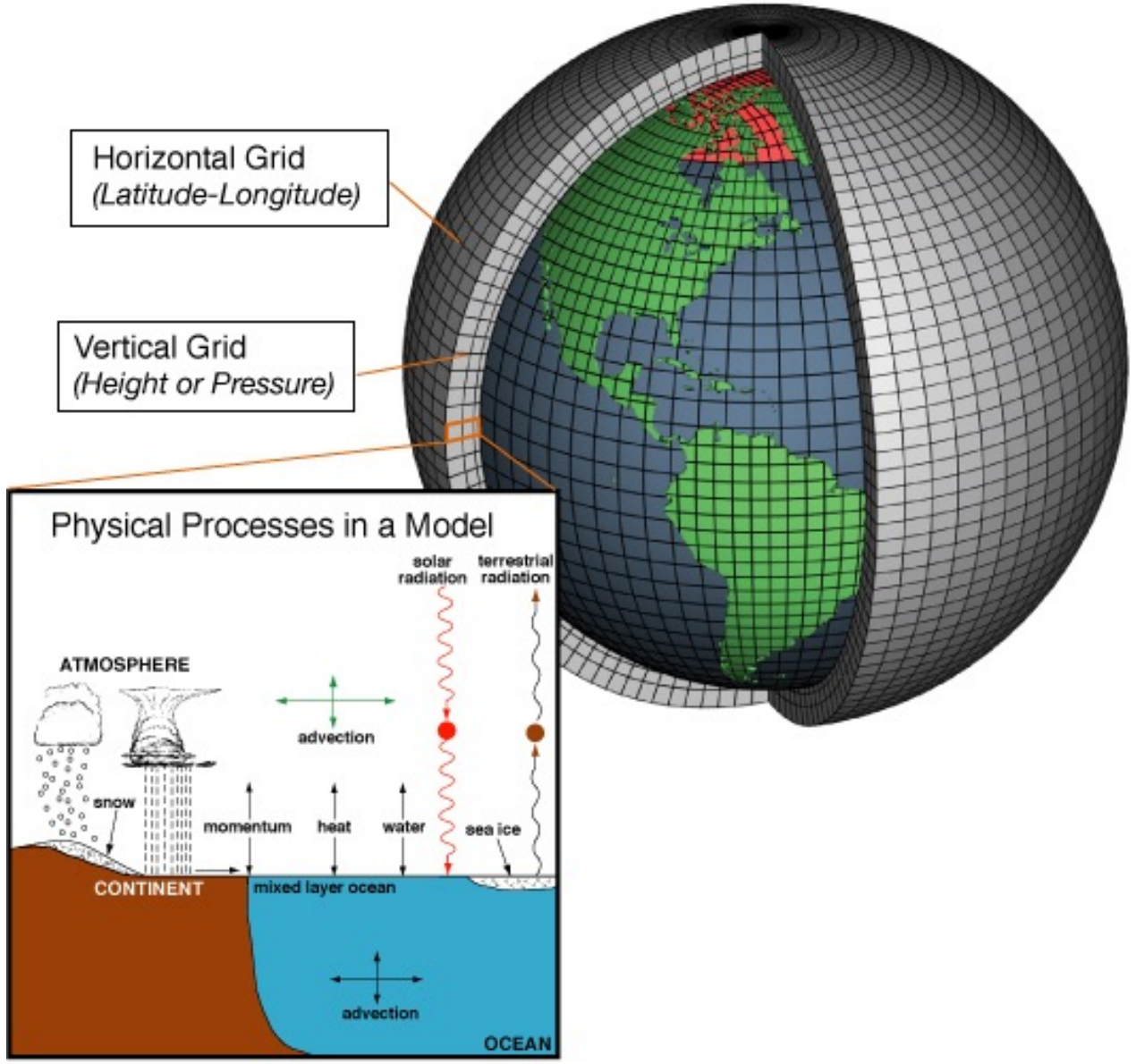
Why do we want to model smoke from fires?

- Cloud Physics and Chemistry
- Radiative Budget
- Greenhouses Gases
- Air Quality and Health

- Smoke from fires is an important source of trace gases and aerosols, or particulate matter (PM)
  - 50% of global CO emissions
  - 20% NOx emissions
  - ~40% Black Carbon emissions
  - ~74% Organic Carbon emissions
- Smoke also…
  - Reduces visibility
  - Contributes to O3 formation
  - Causes negative health impacts from increased PM

Modeling Smoke in the Atmosphere

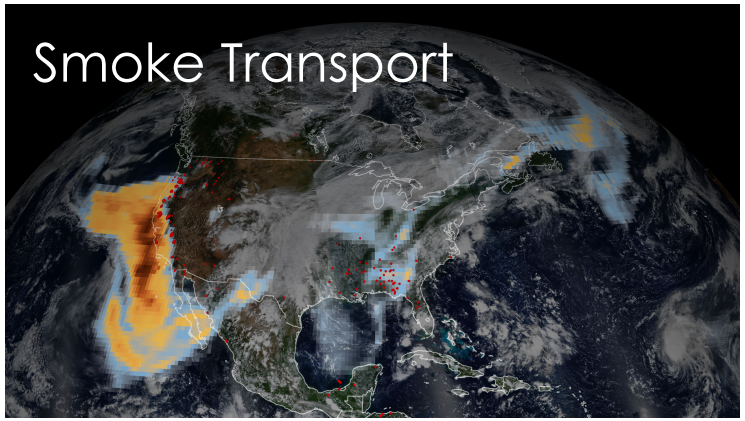
- Meteorology
- Chemistry
- Emissions



How do models simulate fires and smoke?

Fire

Emissions from a Fire



- Observations
  - Satellite
  - Aircraft
  - Ground
- Predictive
  - Use an ignition and fire spread model to predict fires

- Trace gases
- Aerosols

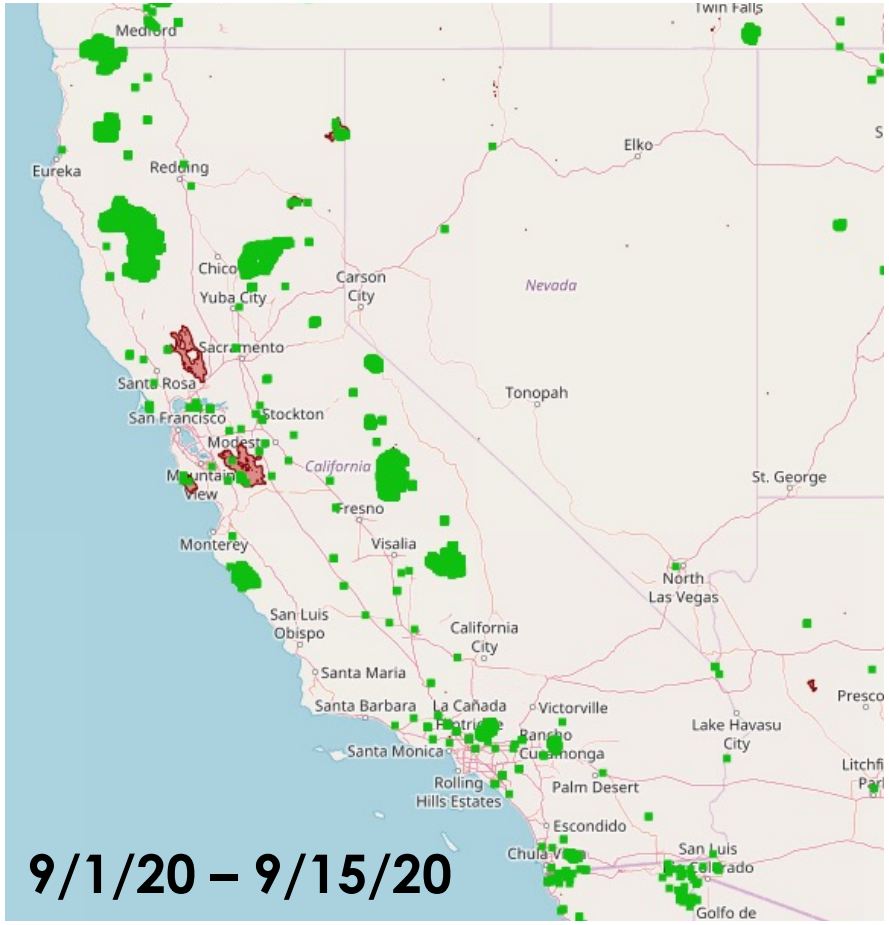
- Injection Height
  How high is the smoke?
- Persistence
  How long does the fire last?
- Timing
  Are the emissions always the same, or do they change by the hour?

Satellite Observations used to Calculate Fire Emissions

- Burned Area
  - Spatial extent of recent fires
  - Not available in near real time (NRT)
  - More details in Part 6

- Thermal Anomalies
  - Detects thermal anomalies from active fires
  - Used to report fire locations and Fire Radiative Power (FRP)
  - Available in near real time (NRT)
  - More details in Part 3

MODIS Burned Area +
VIIRS Active Fire Detections



Created using the GWIS tool

Fire Emissions – What is in smoke?

- Smoke contains both trace gases and aerosols…
- Greenhouse Gases (CO_2, CH_4)
- Trace Gases (NO_2, CO, O_3)
- Aerosols ($PM_{2.5}$, BC, OC)
- NMOC (non-methane organic compounds)
  - e.g., aldehydes, alcohols, alkenes, alkanes, etc.
  - HCHO, and other ozone and aerosol precursors

- Actual composition of emissions will be a function of:

Fuel Source
(What is burning?)

Environmental Conditions
(e.g., is the fuel very dry?)

Calculating Fire Emissions

The amount, or mass, of a species emitted is related to the amount of dry fuel burned, through an *emission factor*. These emission factors usually vary by species and by biome and vegetation type.

$$M_s = EF_s * M_{dry}$$

Mass of Species, s

Emission Factor of Species, s

Mass of Dry Fuel

Emission factors carry a lot of uncertainty. Most are the result of controlled experiments in a laboratory or have been calculated through in-situ measurements.

Satellite Observations to Estimate the Amount of Fuel Burned

There are two common ways to estimate the amount of fuel burned:

Burned Area Approach

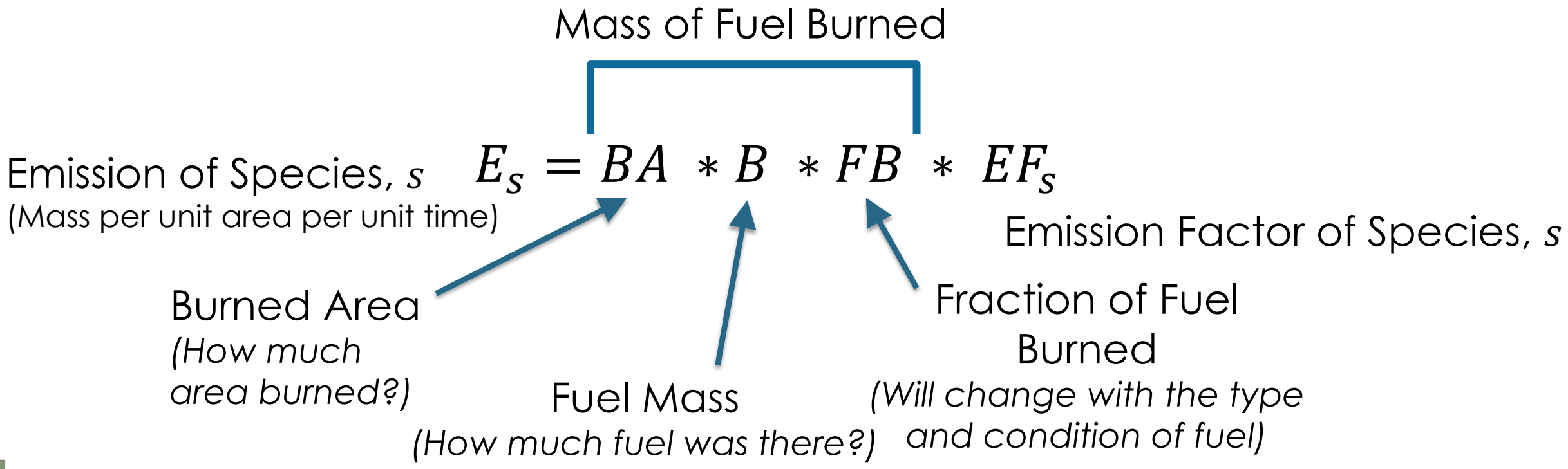
- Burned area sources:
  - MODIS burned area product
  - Calculated using fire pixel counts
- Emissions Datasets:
  - GFED (uses burned area, fire counts)
  - FINN (uses fire counts)

Fire Radiative Power Approach

- Use Fire Radiative Power (FRP)
- Emissions Datasets:
  - QFED
  - GFAS
  - FEER

Burned Area Approach - Theory

The mass of fuel burned can be calculated with additional information about the mass of available fuel, as well as combustion completeness.



Wiedinmyer et al., 2011

FRP Approach: Theory

The energy emitted by a fire is directly related to the brightness temperature at ~4 μm.

$$FRP = 4.34\ x\ 10^{19}\ (T_4\ -\ T_{4b})$$

FRP (Units = MW) is the rate of radiative energy emitted by a fire.

T_4: Fire pixel brightness temperature in the ~4 μm channel

T_{4b}: 4 μm brightness temperature of the background around the fire pixel

FRP Approach: Theory

Studies have shown that burning dry vegetation yields a similar amount of energy, regardless of vegetation type. So:

Emission of Species, s

$$E_s = \alpha * EF_s * FRP$$

← Fire Radiative Power

Emission Factor of Species, s

A Constant Relating FRP to the Amount of Dry Fuel Burned

Examples:
GFAS
QFED

FRP Approach: Theory

Studies have shown that burning dry vegetation yields a similar amount of energy, regardless of vegetation type. So:

Emission of Species, s $E_s = \alpha * FRP$ ← Fire Radiative Power

Emission coefficient relating FRP to emission of a given species

Example: FEER

Global Fire Emissions Datasets

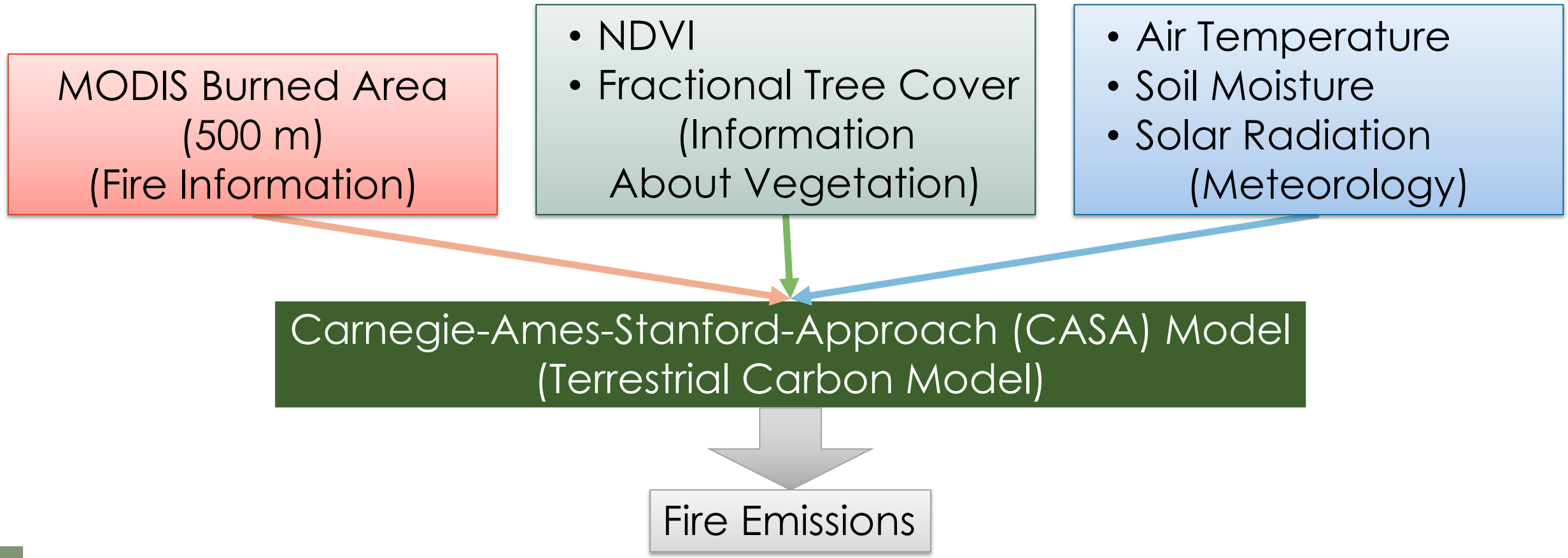
Fire Emissions: Quick Guide

	GFED4s	FINN	QFED	GFAS	FEER
Product	Burned Area, Active Fire Counts	Active Fire Counts	FRP	FRP	FRP
Time Period	1997 - Present	2002 - Present	2000 - Present	2003 - Present	2003 - Present
Resolution	0.25°	1 km	0.1°	0.1°	0.1°
Reference	Giglio et al. (2013); Randerson et al. (2012); Van der werf et al. (2017)	Wiedinmyer et al. (2011)	Darmenov and Da Silva (2015)	Kaiser et al. (2012)	Ichoku and Ellison (2014)
Website	https://www.globalfiredata.org/	https://www2.acom.ucar.edu/modeling/finn-fire-inventory-ncar	https://portal.nccs.nasa.gov/datashare/iesa/aerosol/emissions/QFED/v2.5r1/	https://atmosphere.copernicus.eu/global-fire-emissions	https://feer.gsfc.nasa.gov/

GFED

Global Fire Emissions Database (GFED)

GFED is probably the most well-known and widely used fire emissions dataset.



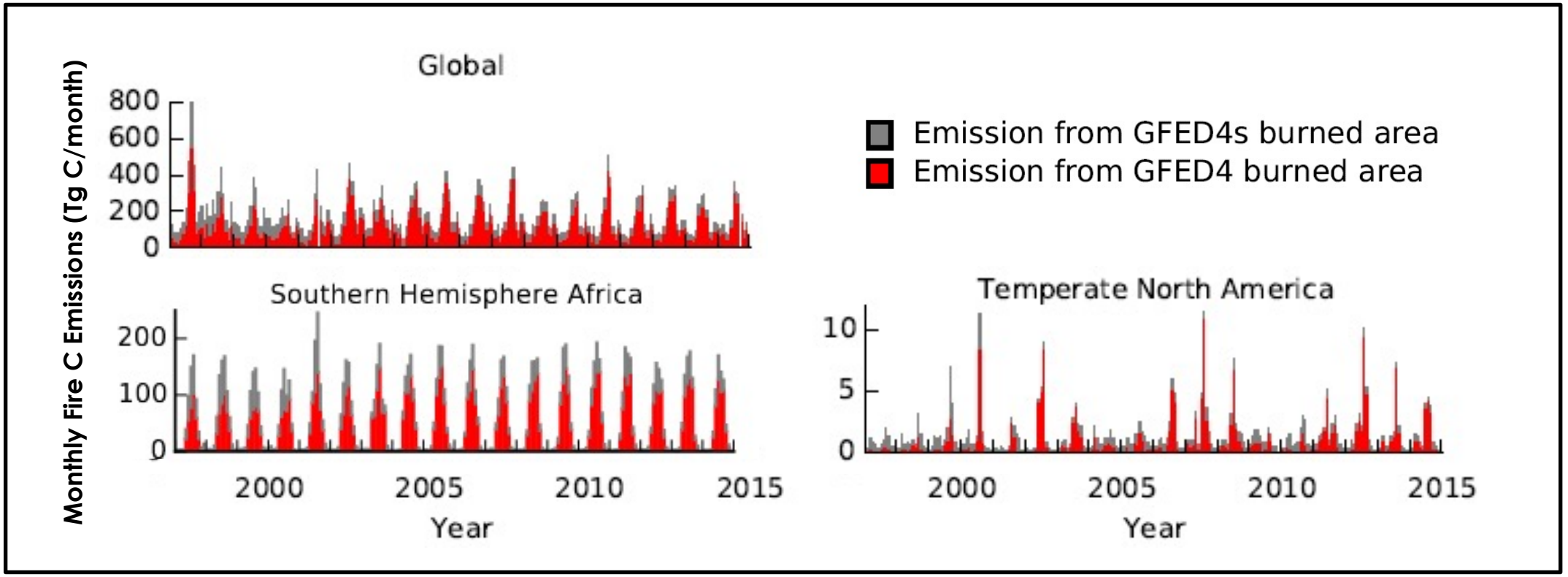
GFED Fire Emissions Data

	GFED4	GFED 4s (GFED 4 + small fires)	GFED NRT
Satellite Observations	MODIS burned area	MODIS burned area, surface reflectance	VIIRS thermal anomalies
	Active fire data from VIRS and ATSR (Pre-MODIS era)	MODIS thermal anomalies	
Spatial Resolution	0.25° x 0.25°	0.25° x 0.25°	~550 m x 550 m
Time Period	1997 – 2016	1997 – 2016 (2017-2020 beta files available)	2019 – Present
Temporal Resolution	Monthly, Daily, 3-Hourly (2000 - Present)	Monthly, Daily, 3-Hourly	Daily
File Format	HDF	HDF5	

Python and Matlab readers available for hdf5 on the GFED website.

How much do small fires matter?

GFED4 vs. GFED4s

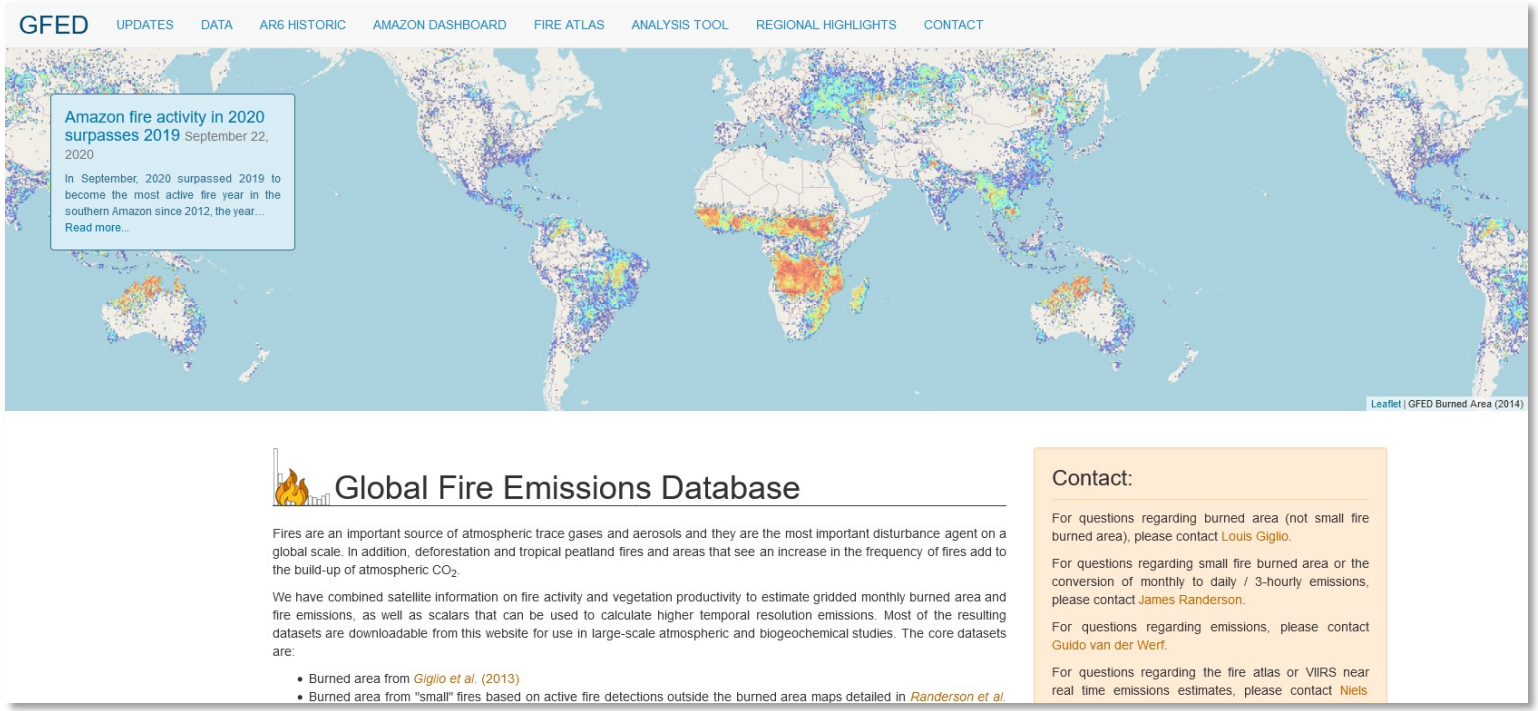


Not including small fires results in an underestimation of emissions.

GFED Website

https://www.globalfiredata.org/

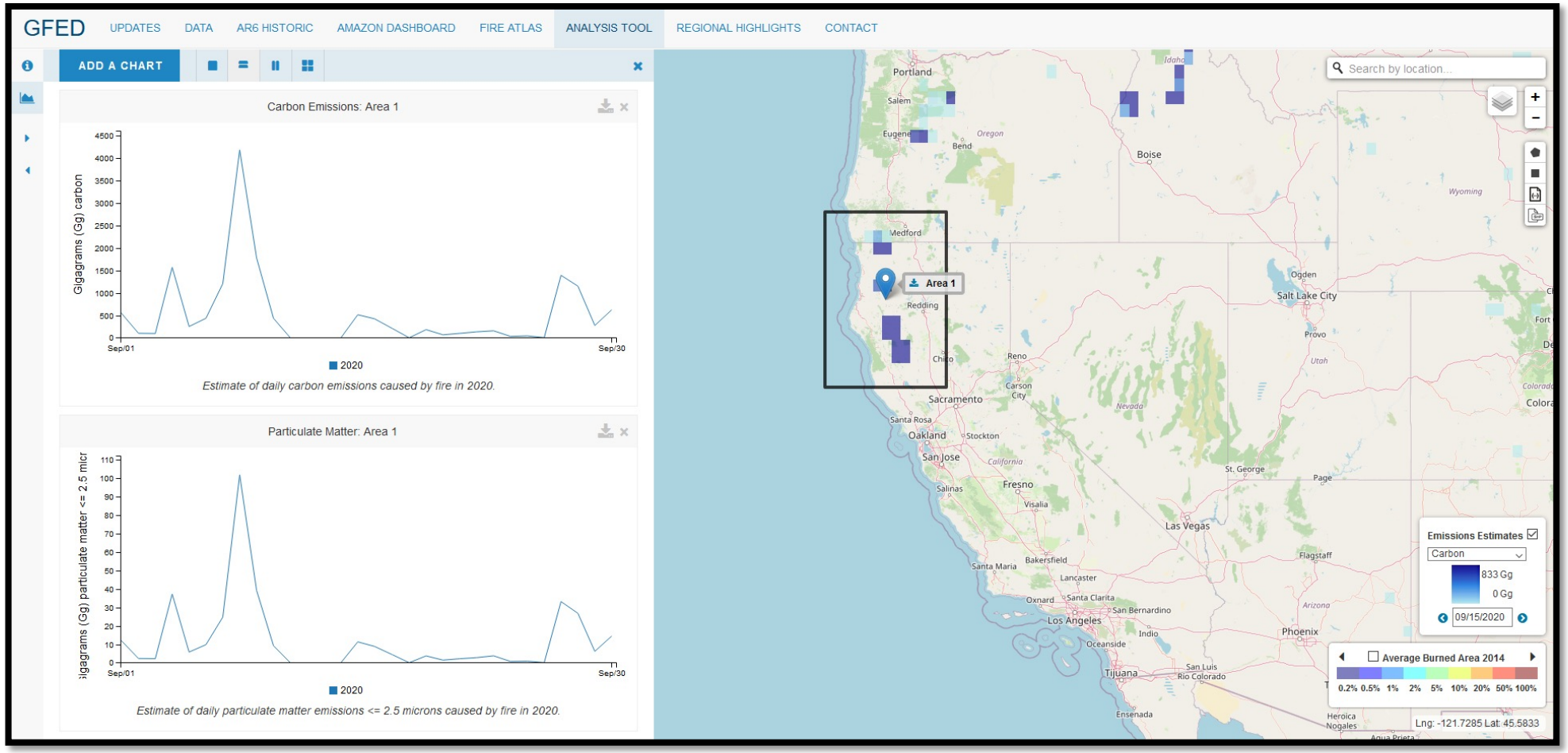
- Download GFED Emissions
- Amazon Dashboard
- Fire Atlas Data
- Analysis Tool
  - Subset and download emissions



GFED Website Demo

https://www.globalfiredata.org/

- We will recreate this figure.



FINN

Fire INventory from NCAR (FINN)

FINN is a global, high-resolution (1 km^2) fire emissions dataset.

MODIS Thermal Anomalies
(Fire Pixel Locations)
(Fire Information)

MODIS Land Cover Type
MODIS Vegetation Continuous Fields (VCF)
(Information About Vegetation)

$$E_s = BA * B * FB * EF_s$$

Emission of Species, s

Emission Factor of Species, s

Burned Area

Fuel Mass

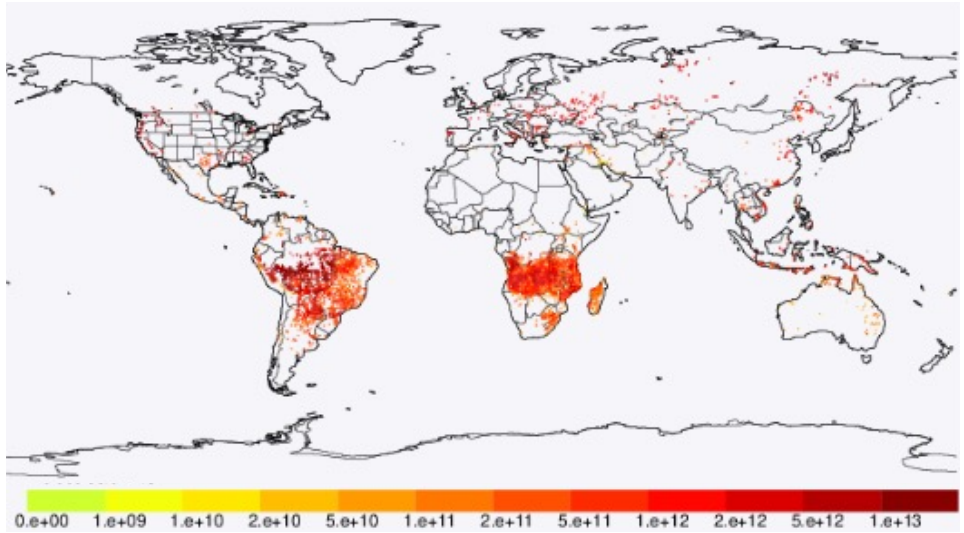
Fraction of Fuel Burned

FINN v2.2

https://www2.acom.ucar.edu/modeling/finn-fire-inventory-ncar

- Global
- 2002 – Present
  - (MODIS + VIIRS available 2012-2019)
- ~1 km^2 Spatial Resolution
- Daily
- ASCII (text) files
- Trace gas and aerosol speciation for three chemical mechanisms (.csv files):
  - MOZART4
  - SAPRC99
  - GEOS-Chem
- Utilities to grid FINN emissions to NetCDF for use in WRFChem or global models

FINN CO Emissions: Sep 12, 2020



Fire Emissions of CO [molecules/cm^2/s]

*binned to 0.5 deg

https://www.acom.ucar.edu/acresp/forecast/fire-emissions.shtml

QFED

Quick Fire Emissions Database (QFED)

QFED emissions are used in the NASA GEOS forecast model.

MODIS Thermal Anomalies
(FRP)
(Fire Information)

IGBP-INPE Dataset
International Geosphere-Biosphere Programme – Brazilian Institute of Space Research
(Information About Vegetation)

$$E_s = \frac{FRP * EF * \alpha}{Area}$$

Emission of Species, s

Emission Coefficient

Pixel Area

The emission coefficients for QFED have been tuned based on MODIS AOD data.

Quick Fire Emissions Database (QFED)

https://portal.nccs.nasa.gov/datashare/iesa/aerosol/emissions/QFED/v2.5r1/

- Global
- 2000 - Present
- 0.1° x 0.1°, 0.25° x 0.25° Spatial Resolution
- Daily Emissions, NRT
- NetCDF4
- Two Gridded Products:
  - FRP
  - Trace gas and aerosol emissions
- Caution should be used in using these emissions in other models besides GEOS.

GFAS

Global Fire Assimilation System (GFAS)

GFAS emissions are used in ECMWF Copernicus Atmosphere Monitoring Service (CAMS) forecasts.

MODIS Thermal Anomalies
(FRP)
(Fire Information)

Land Classification from GFED v 3.1
(Information About Vegetation)

$$E_s = \frac{FRP * EF * \alpha}{Area}$$

Conversion Factor

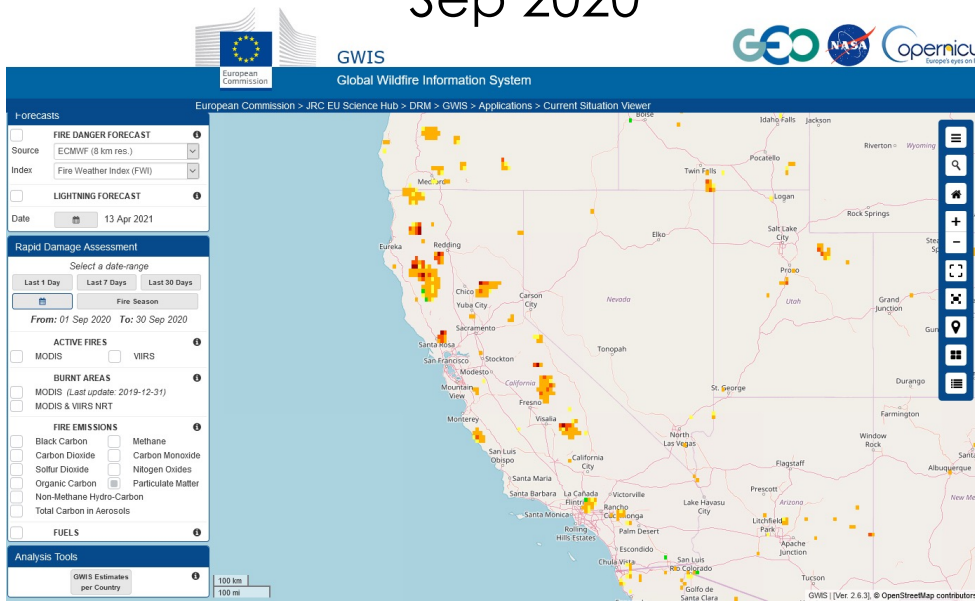
Derived using GFED v3.1

GFAS

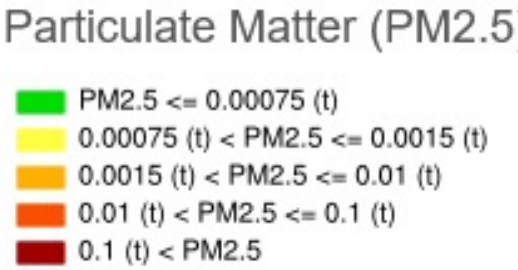
https://atmosphere.copernicus.eu/global-fire-emissions

- Global
- 2003 – Present
- 0.1° x 0.1° Spatial Resolution
- Daily, NRT
- GRIB file format
- Includes information on:
  - Injection height (from a plume rise model)
  - FRP
  - Emissions of trace gases and aerosols

GFAS PM Emissions
Sep 2020



Created using the GWIS tool.



Global Wildfire Information System (GWIS)

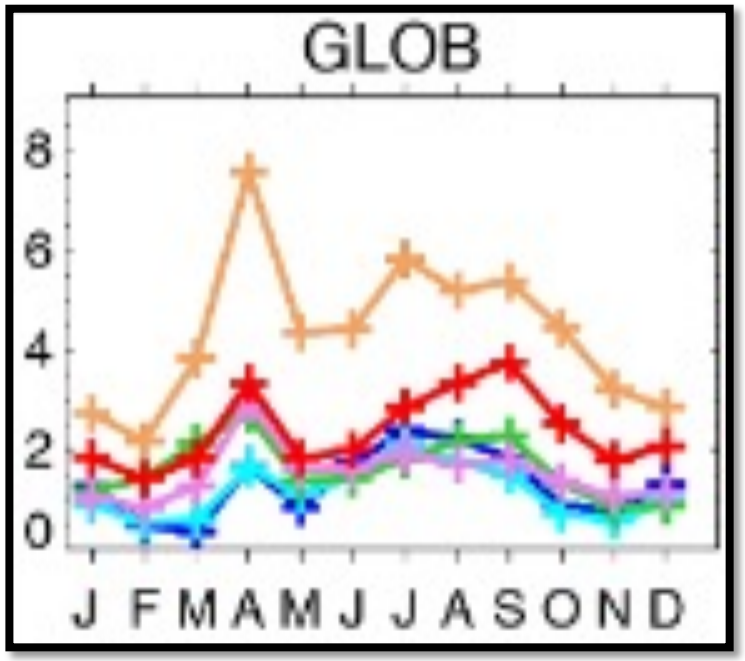
https://gwis.jrc.ec.europa.eu/

- Visualize Current Observations
  - Fire Danger and Lightning Forecast
  - MODIS and VIIRS Active Fire Detections
  - MODIS and VIIRS Burned Area
  - GFAS Emissions
  - Fuel Classes
- Historical Overviews
  - Continent/Country/Sub-Country
  - Number of fires, burned area, fire size, seasonality
  - Single or multi-year images and data
- Download Data

Burned Area vs. Thermal Energy: Sources of Uncertainty

Burned Area	Thermal Energy (FRP)
Omission of small fires (MODIS limit is fires > 100 m^2)	Omission of small fires (MODIS limit is fires > 100 m^2) VIIRS detects 3-4x more fires than MODIS
Omission of fires obscured by clouds	Omission of fires obscured by clouds
Misidentification of land cover type	Omission of fire with weak thermal signatures (e.g., smoldering fires)
Inaccurate fuel estimates, combustion completeness	Conversion factor estimation
Emission factors	Emission factors

How do these datasets compare?



Adapted from Figure 4
Pan et al., 2020

Emissions Dataset	Total Organic Carbon Emissions from Fire – 2008 (Tg)
GFED v3.1	15.65
GFED v4s	13.76
FINN v1.5	19.48
GFAS v 1.2	18.22
FEER v1.0	28.48
QFED v 2.4	51.93

QFED and FEER tend to show the highest emissions as a result of tuning the emissions to match MODIS AOD.

Air Quality and Smoke Forecasting

Air Quality (AQ) Forecasting

- Provide the public with health alerts
- Provide visibility/haze advisories
- Inform emergency response
- Help environmental regulators decide if temporary emissions reductions are needed

Air Quality Forecasts vs. Smoke Forecasts

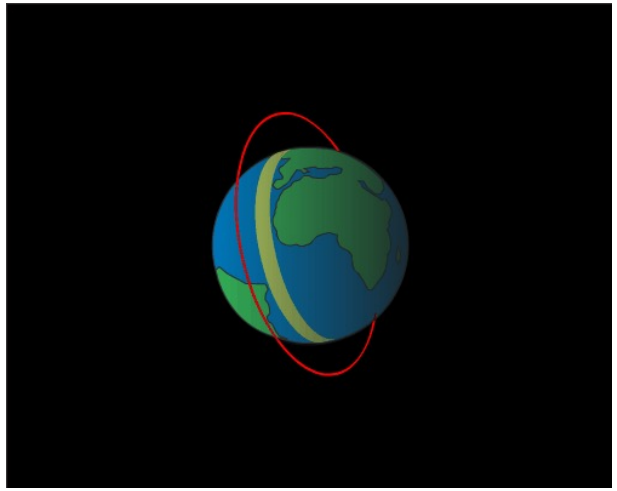
AQ Forecast

- Forecasts pollutants that are important for AQ
- Includes emissions/pollutant sources other than fire
- Aerosol forecasts (e.g., GEOS-FP) forecast aerosols only
- Composition forecasts (e.g., GEOS-CF, CAMS) forecast trace gases and aerosols

Smoke Forecast

- Forecasts the transport of smoke from fires (e.g., the estimated $PM_{2.5}$ emitted from a fire)
- Component of AQ forecast or standalone forecast

Forecasting Smoke – Limitations and Considerations



Frequency of Fire Observations

Forecast models can only transport emissions from fires that are viewed by satellite.

Image source

Fire Persistence

A satellite might see a fire one day, and not the next. Models make assumptions about how long fires last.

Smoke Injection Height

The altitude of smoke injection is critical to transporting the smoke accurately.

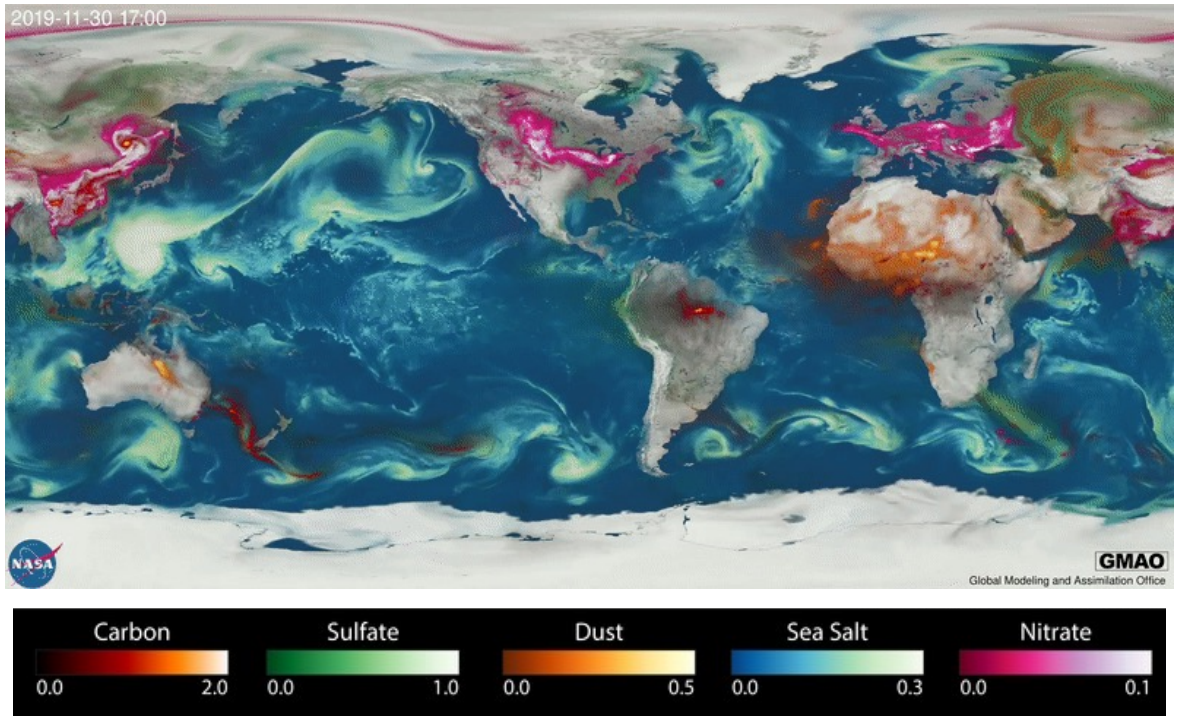
Image source

Global Air Quality Forecasts

NASA Goddard Earth Observing System (GEOS) Model

https://gmao.gsfc.nasa.gov/weather_prediction/

- Developed and maintained by the Global Modeling and Assimilation Office (GMAO)
- GEOS provides NRT weather and composition forecasts
- ~25 km Spatial Resolution
  - Weather forecast (Forward Processing (FP)) includes aerosols and CO
  - Composition forecast (CF) includes trace gases like ozone and NO_2, as well as $PM_{2.5}$



AOD (550 nm)

https://svs.gsfc.nasa.gov/31100

Available GEOS Forecasts

https://portal.nccs.nasa.gov/datashare/gmao/

Forward Processing (FP)	Composition Forecast (CF)
10-day forecast of meteorology and aerosols	1 day Analysis + 5-day forecast of meteorology, aerosols, and trace gases
Data assimilation (including AOD)	No data assimilation
Initialized daily at 00Z and 12Z	Initialized daily at 12Z
~25 km spatial resolution	~25 km spatial resolution
QFED fire emissions	QFED fire emissions

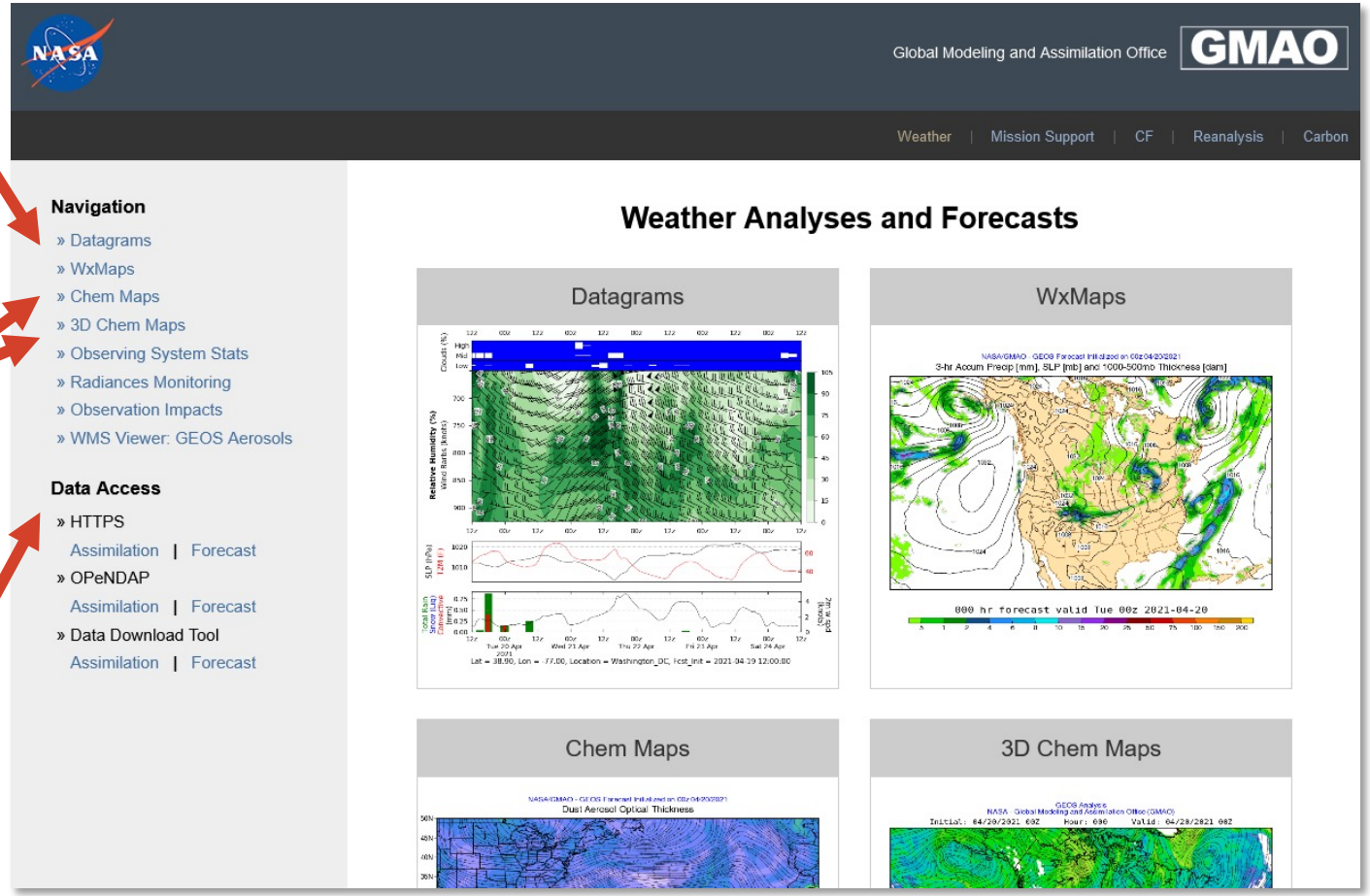
GEOS-FP: Data Access and Aerosol Forecast Maps

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

Datagrams

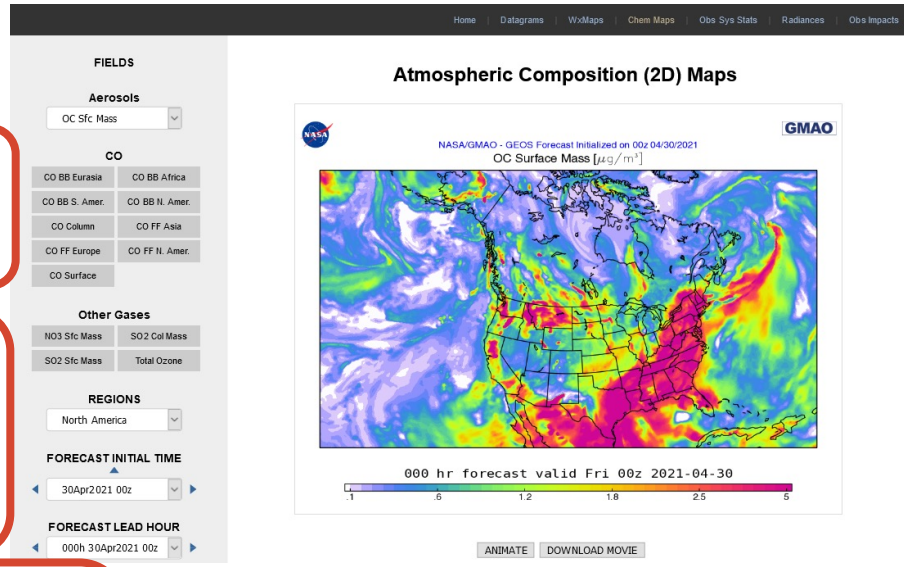
Aerosol Maps (2D and 3D)

Download the forecast output



GEOS-FP: Maps

Chem Maps



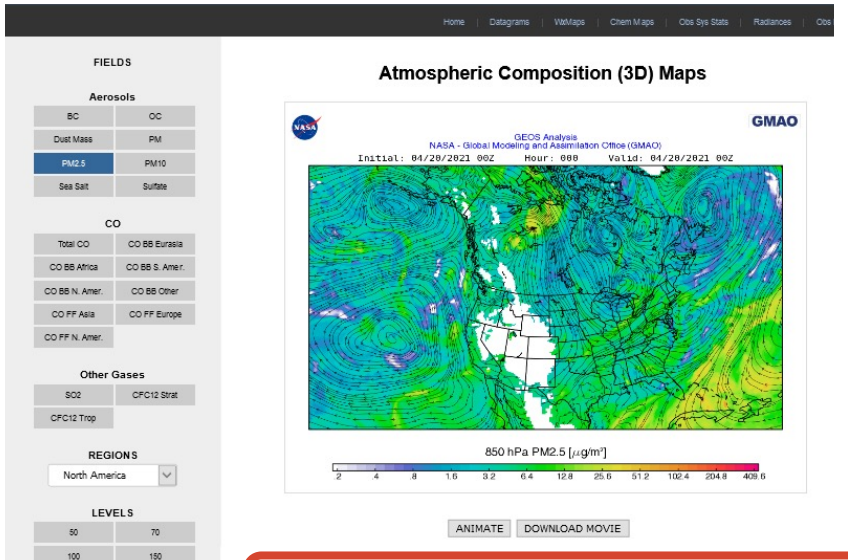
Select a variable

Select a map region

Select a forecast

Animate the map

3D Chem Maps



Select a variable

Select a region

Select a pressure level

Animate the map

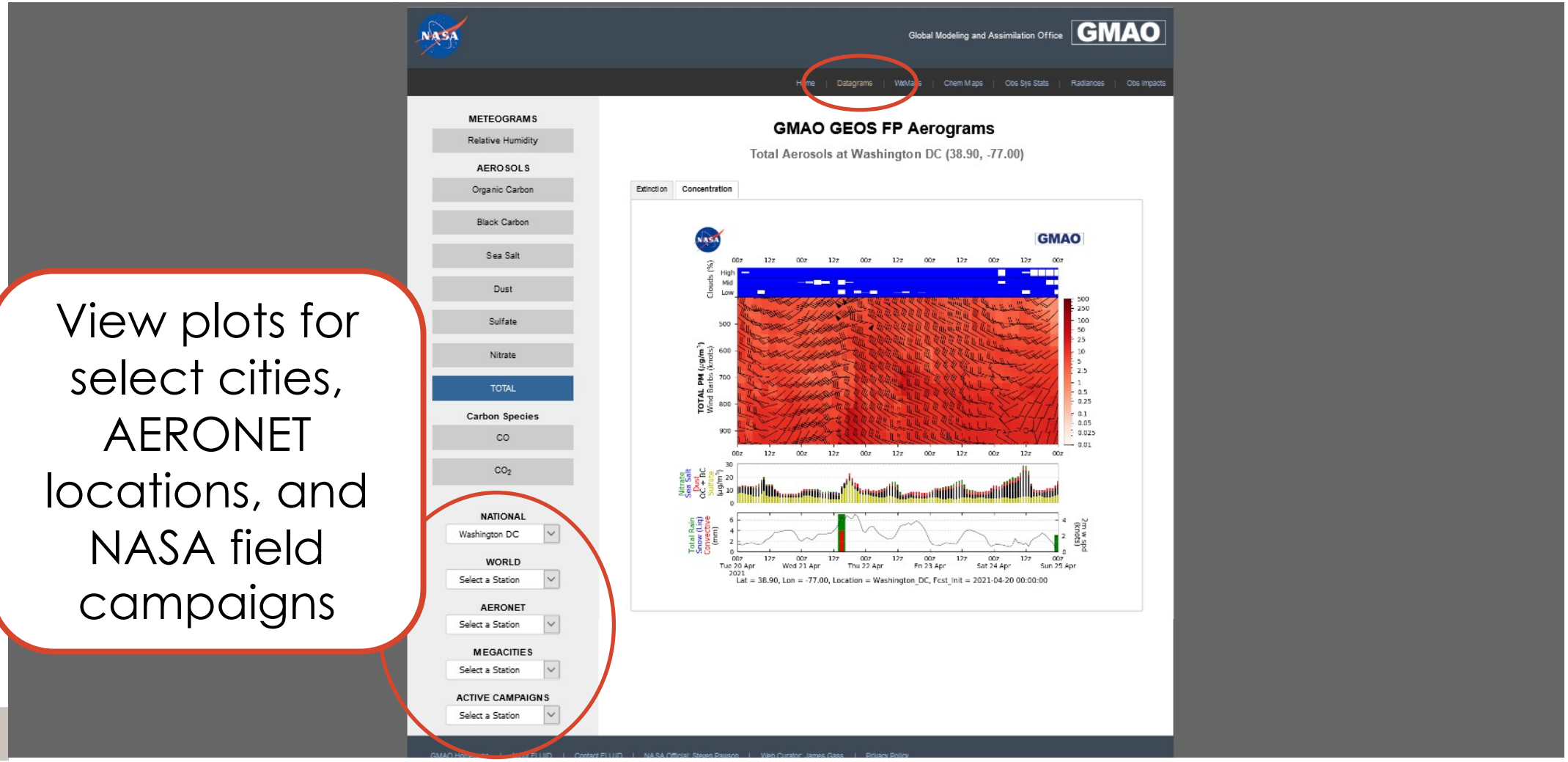
Select a forecast

https://fluid.nccs.nasa.gov/wxmaps/chem2d/

https://fluid.nccs.nasa.gov/wxmaps/chem3d/

GEOS-FP: Datagrams

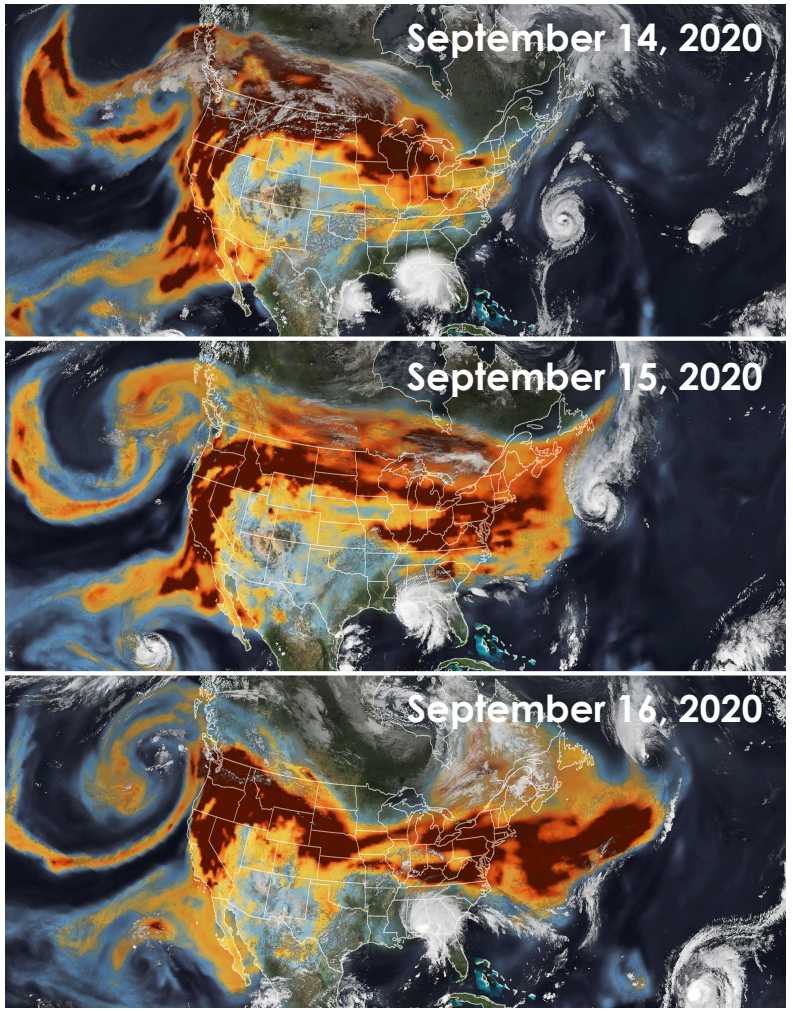
Datagrams show the vertical profile of the aerosol forecast at a given location, along with information about aerosol types.



View plots for select cities, AERONET locations, and NASA field campaigns

GEOS-FP + QFED Emissions: CA Fires, Sep 2020

- QFED emissions in the NASA GEOS-FP forecast show the transport of smoke from fires along the west coast of the United States across the country and beyond.

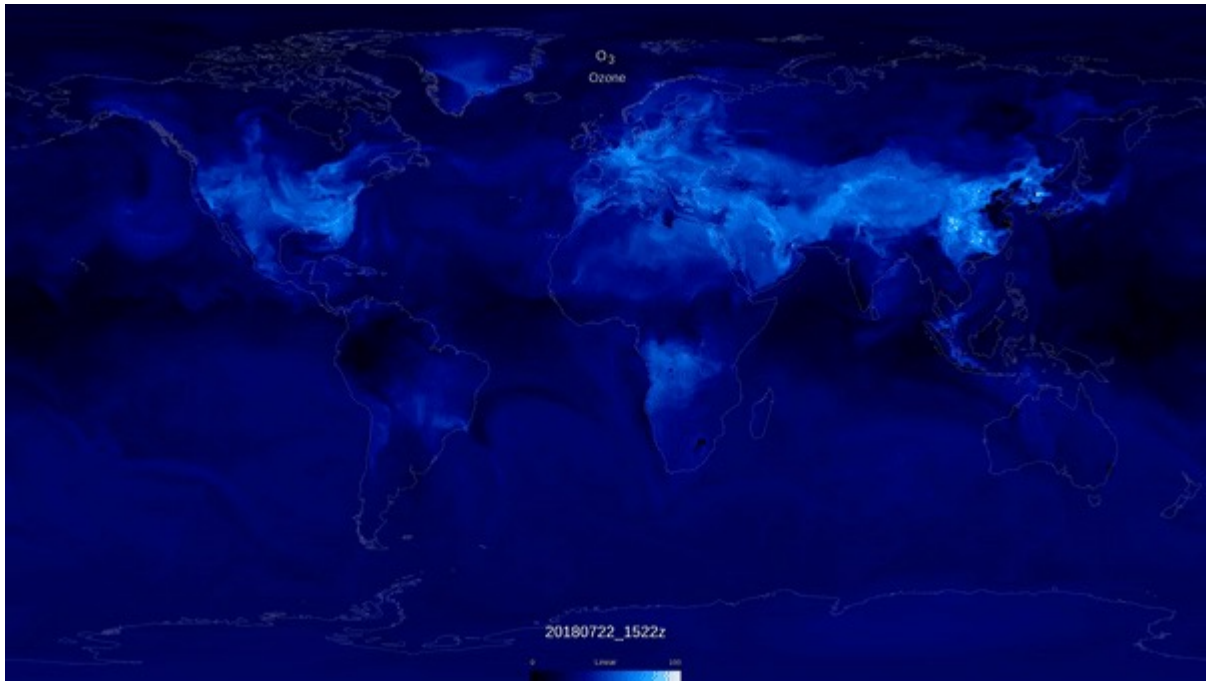


https://earthobservatory.nasa.gov/images/147293/a-meeting-of-smoke-and-storms

NASA Composition Forecasts (GEOS-CF)

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

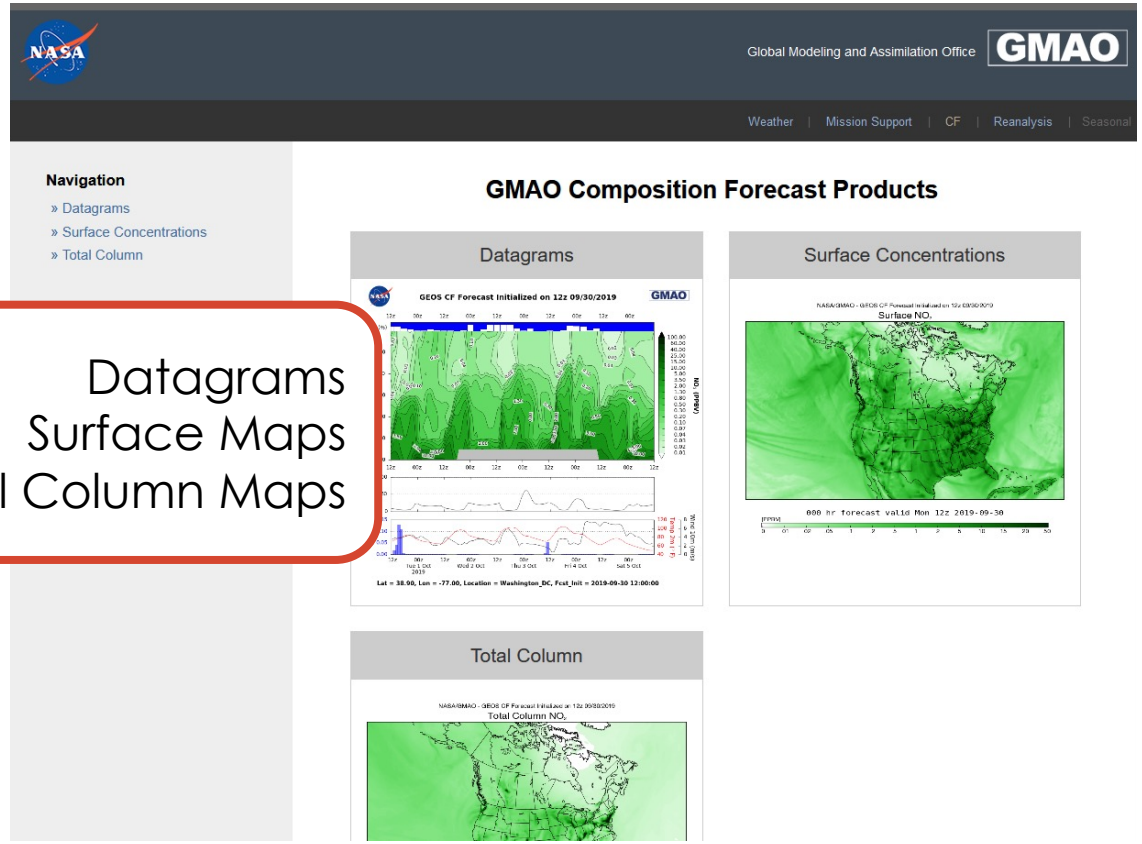
- The GEOS-Composition Forecast (CF) system forecasts trace gas and aerosol fields using constrained meteorology from the GEOS-FP system and the GEOS-Chem chemical mechanism.
- GEOS-Chem is a community-developed global 3-D model of atmospheric chemistry.
  - 250+ chemical species
  - 700+ chemical reactions
- One 5-day forecast per day
- O_3, NO_2, $PM_{2.5}$ …
- 15 min output for the surface
- Available since Jan 2018
- Uses QFED fire emissions



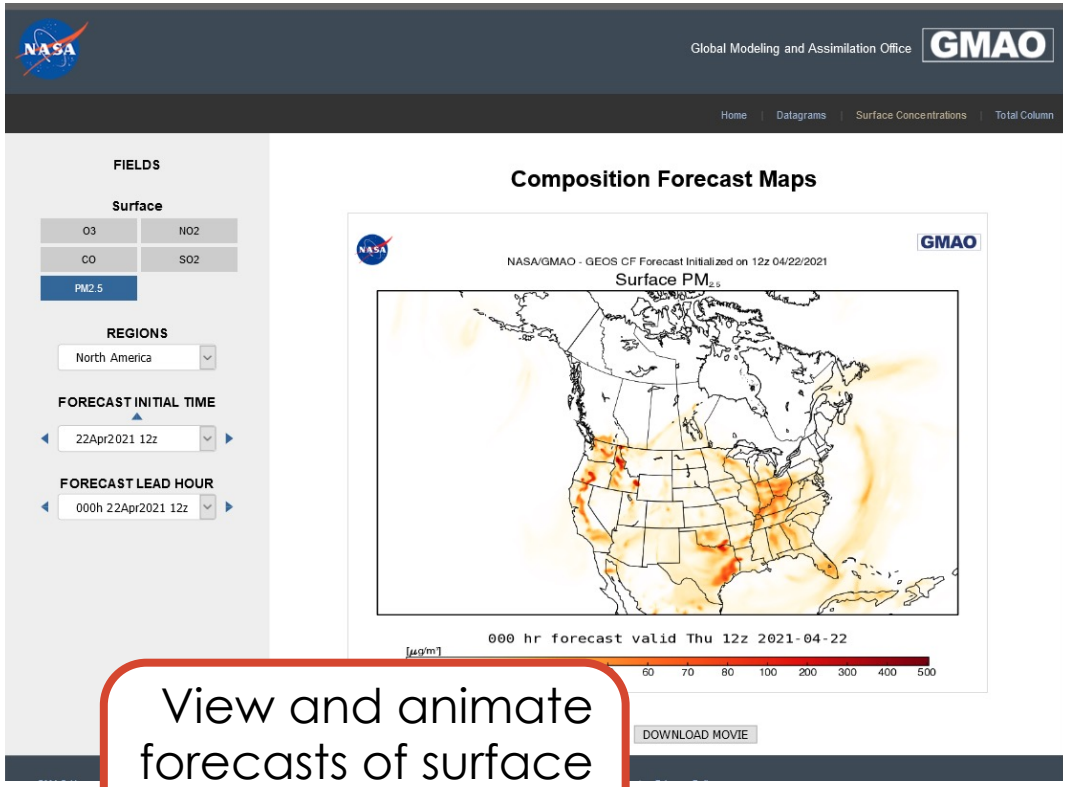
https://svs.gsfc.nasa.gov/4754

GEOS-CF

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



Datagrams
Surface Maps
Total Column Maps

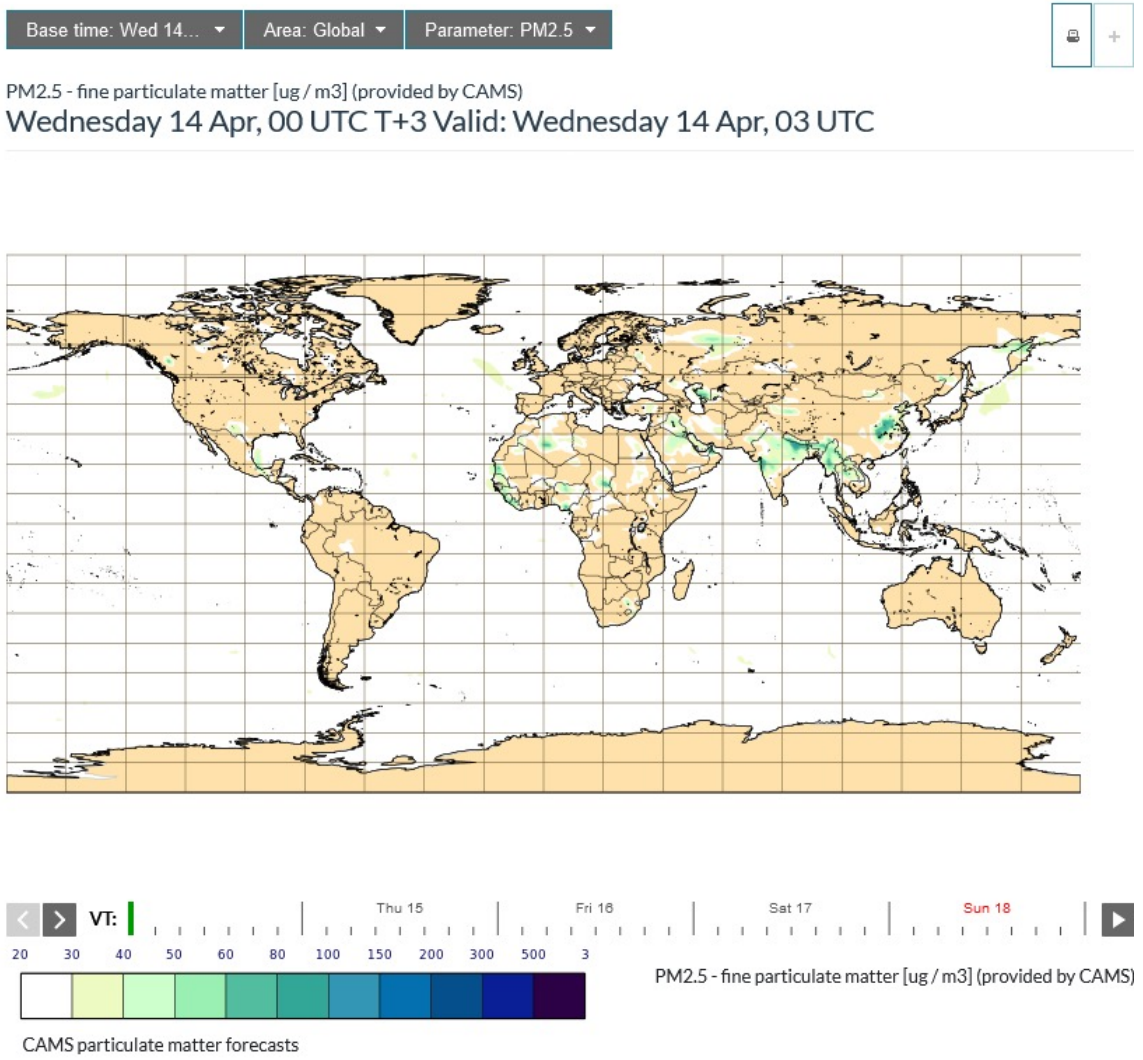


View and animate forecasts of surface O3, PM2.5, and other pollutants

ECMWF Copernicus Atmosphere Monitoring Service (CAMS)

https://atmosphere.copernicus.eu/

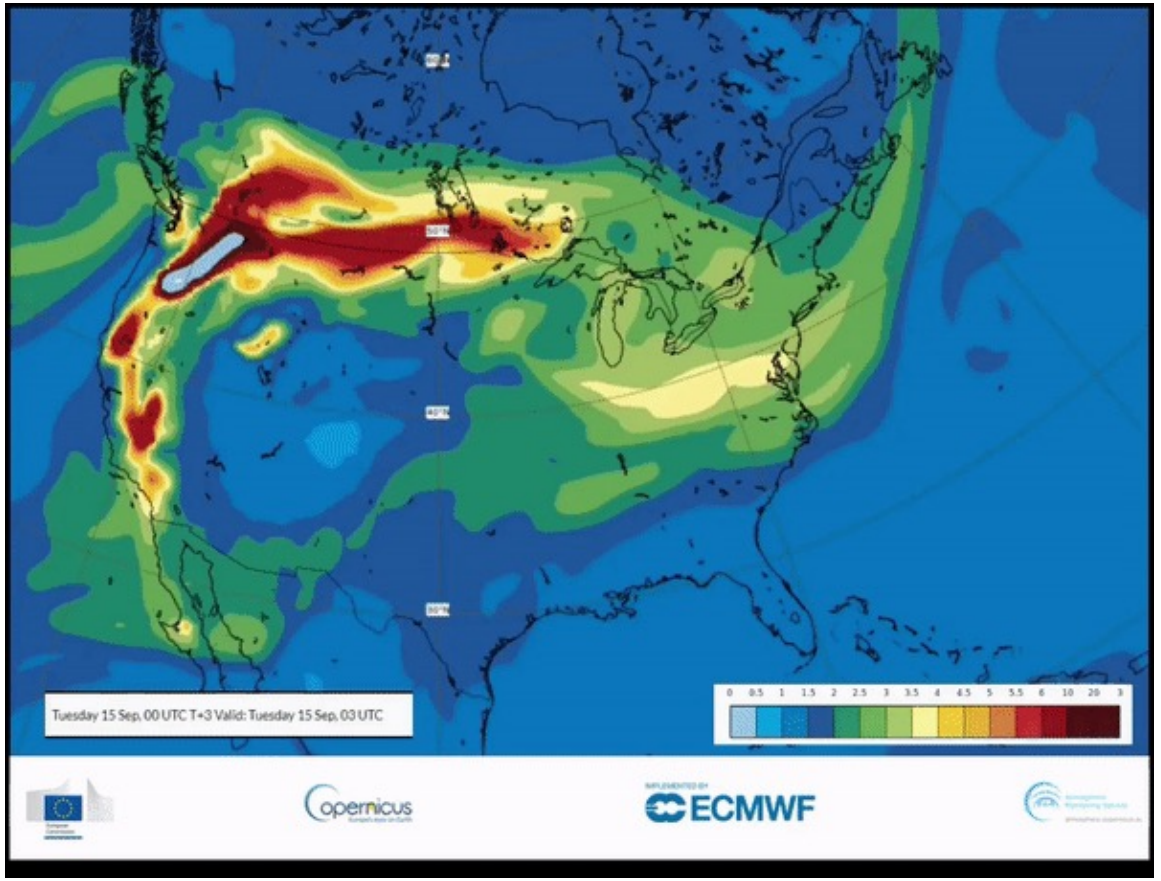
- CAMS provides five-day global composition forecasts of aerosols and other pollutants
- Data assimilation (including AOD)
- Initialized daily at 00Z and 12Z
- ~40 km Spatial Resolution
  - ~10 km for Europe-only
- GFAS fire emissions
- 2012-Present



https://atmosphere.copernicus.eu/charts/cams/

CAMS Forecast + GFAS Emissions: CA Fires, Sep 2020

- GFAS emissions in the CAMS forecast show the transport of smoke from fires across the US and forecasted to reach Europe days later.



Total column of carbon monoxide [10^{18} molecules / cm^2]

Source: Twitter

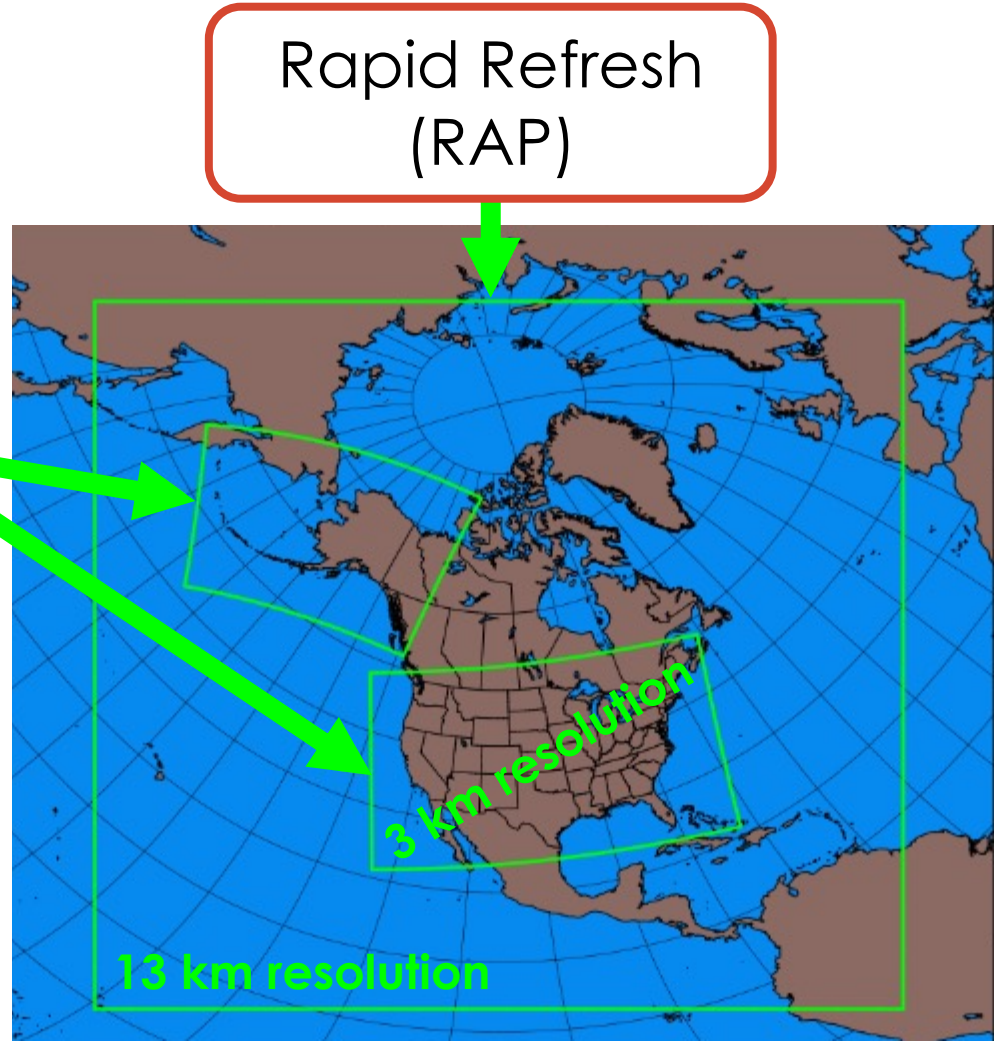
US Smoke Forecasts

NOAA Weather Models for Smoke Forecasts

https://rapidrefresh.noaa.gov/

https://rapidrefresh.noaa.gov/hrrr/

- The NOAA Rapid Refresh (RAP) is a continental-scale hourly weather forecast and data assimilation system.
- The NOAA High-Resolution Rapid Refresh (HRRR) model, is also updated hourly and covers a smaller geographic domain.
  - Assimilates radar data every 15 min



https://rapidrefresh.noaa.gov/pdf/Alexander_AMS_NWP_2020.pdf

NOAA Smoke Forecasts

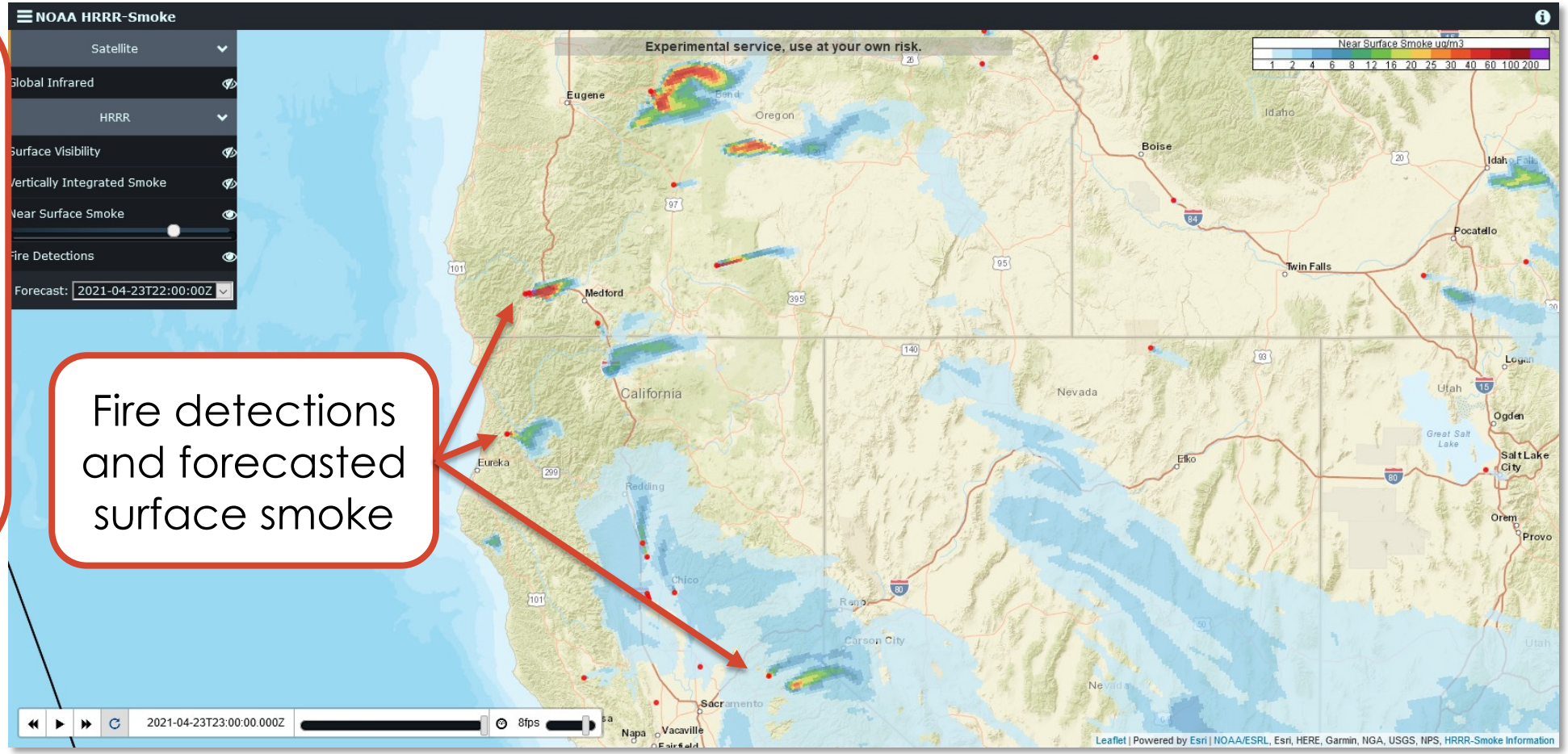
	RAP-Smoke	HRRR-Smoke
Spatial Resolution	13 km	3 km
Initialized	Hourly	Hourly
Domain	North America	CONUS/Alaska
Boundary Conditions	NOAA GFS	RAP-Smoke
Fire detections	MODIS + VIIRS	MODIS + VIIRS
Forecast	21 h	18 h
Website	https://rapidrefresh.noaa.gov/RAPsmoke/	https://rapidrefresh.noaa.gov/hrrr/HRRRsmoke/

RAP-Smoke and RAP-HRRR use fire emissions of $PM_{2.5}$ calculated using a method very similar to QFED, but not tuned to AOD.

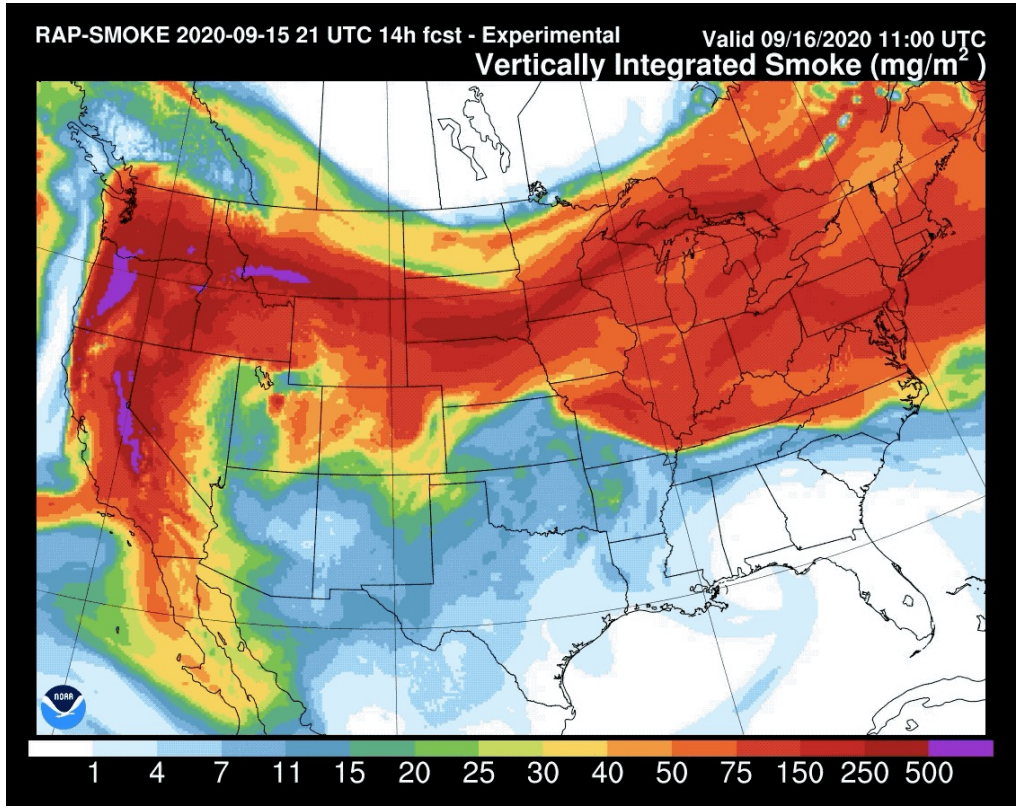
HRRR-Smoke Visualization

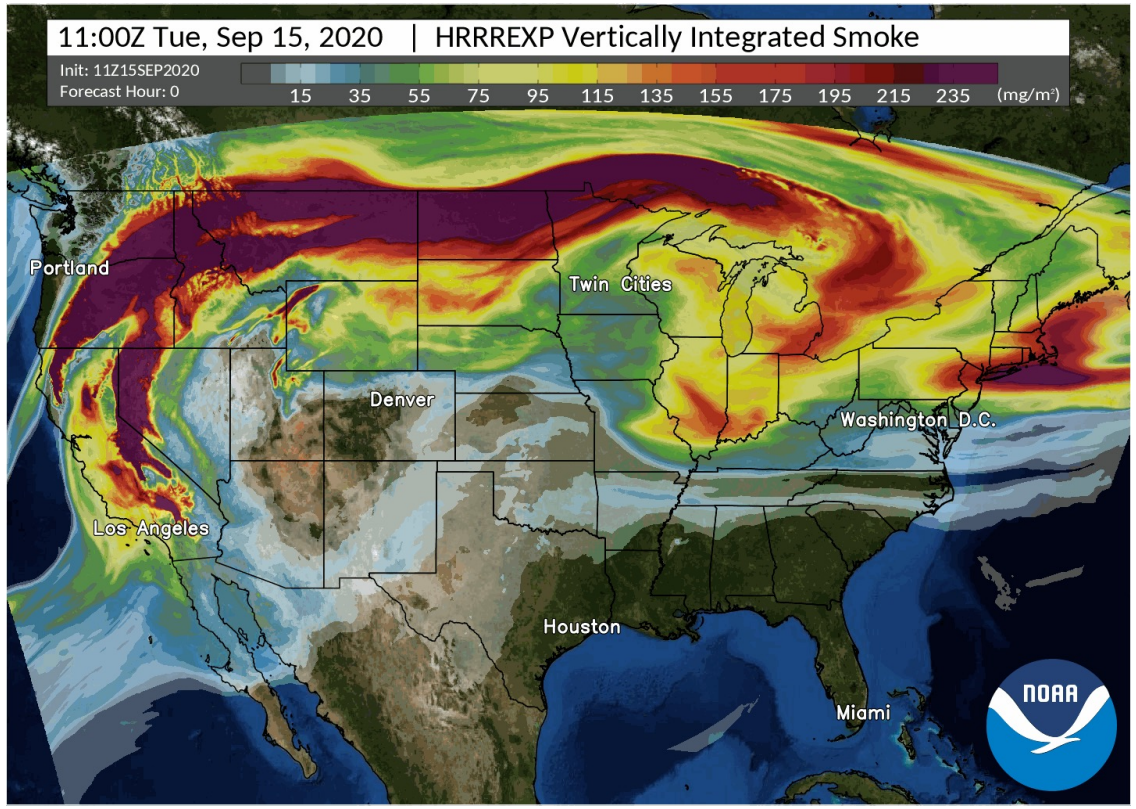
https://hwp-viz.gsd.esrl.noaa.gov/smoke/index.html

Layers include near-surface smoke ($PM_{2.5}$ [$\mu g/m^3$]), vertically integrated smoke (the amount of smoke in a 1 m^2 column of the atmosphere), and fire detections.



RAP-Smoke and HRRR-Smoke Forecasts – CA Fires, Sep 2020





RAP-Smoke and RAP-HRRR animations showing high resolution smoke transport. In the HRRR animation, individual plumes can be seen in Northern California.

Tool: U of Wisconsin RealEarth

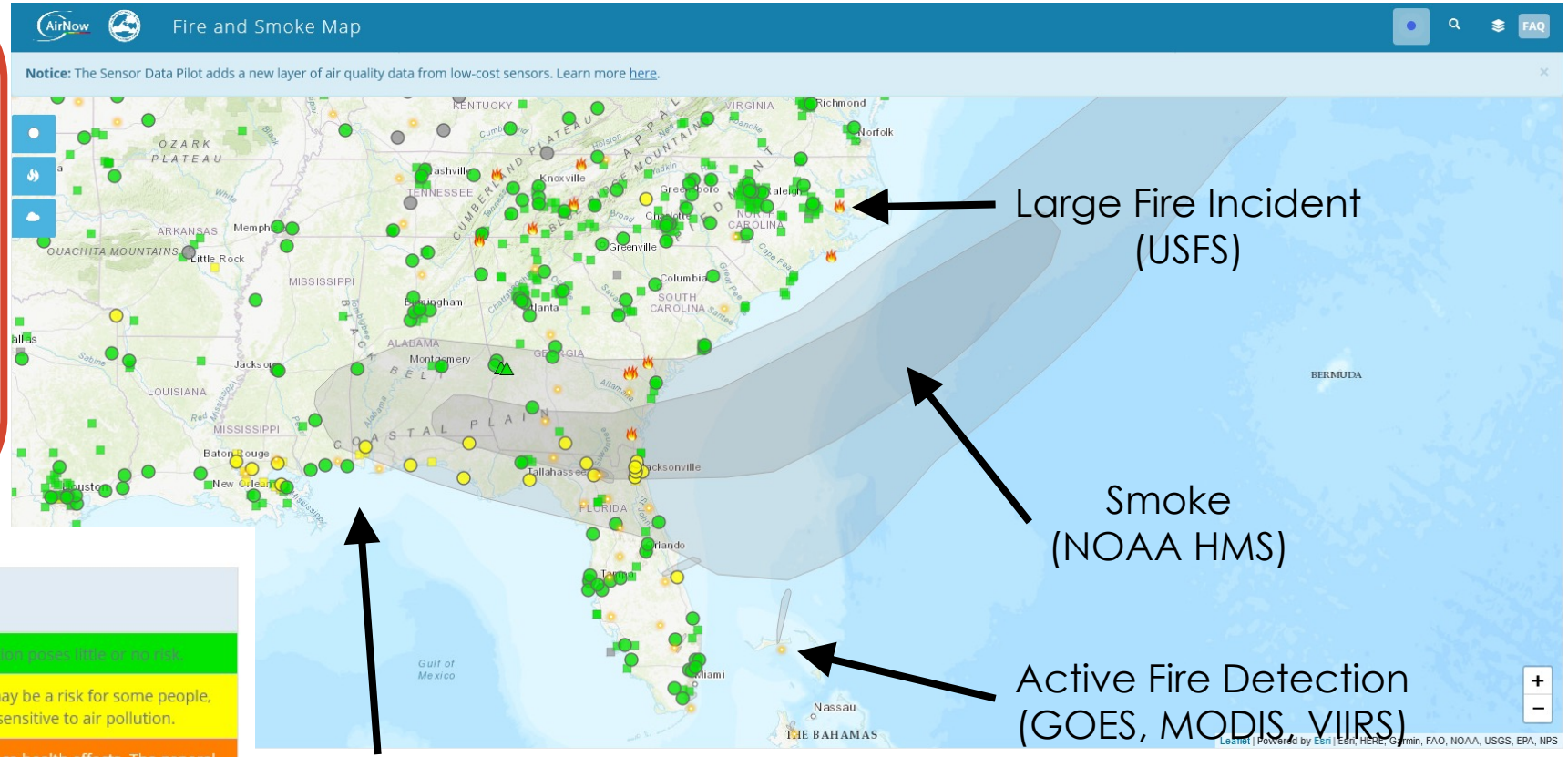
https://realearth.ssec.wisc.edu/

Real Earth is a visualization tool and app that animates fire-related model output, observations, and other Earth science data.

EPA AirNow Fire and Smoke Map

https://fire.airnow.gov/

Displays real-time information from ground monitors, fire detections and information, and smoke plume locations



AQI Basics for Ozone and Particle Pollution

Daily AQI Color	Levels of Concern	Values of Index	Description of Air Quality
Green	Good	0 to 50	Air quality is satisfactory, and air pollution poses little or no risk.
Yellow	Moderate	51 to 100	Air quality is acceptable. However, there may be a risk for some people, particularly those who are unusually sensitive to air pollution.
Orange	Unhealthy for Sensitive Groups	101 to 150	Members of sensitive groups may experience health effects. The general public is less likely to be affected.
Red	Unhealthy	151 to 200	Some members of the general public may experience health effects; members of sensitive groups may experience more serious health effects.
Purple	Very Unhealthy	201 to 300	Health alert: The risk of health effects is increased for everyone.
Maroon	Hazardous	301 and higher	Health warning of emergency conditions: everyone is more likely to be affected.

Contacts

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  - https://appliedsciences.nasa.gov/join-mission/training/english/arset-satellite-observations-and-tools-fire-risk-detection-and
- ARSET Website:
  - https://appliedsciences.nasa.gov/what-we-do/capacity-building/arset

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Homework and Certificate

- Three homework assignments:
  - Answers must be submitted via Google Form, accessed from the ARSET website.
  - Due date for all homework: June 10, 2021
- A certificate of completion will be awarded to those who:
  - Attend all live webinars
  - Complete the homework assignment by the deadline
  - You will receive a certificate approximately two months after the completion of the course from: marines.martins@ssaihq.com


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Thank You!