The chemistry of wildfire smoke

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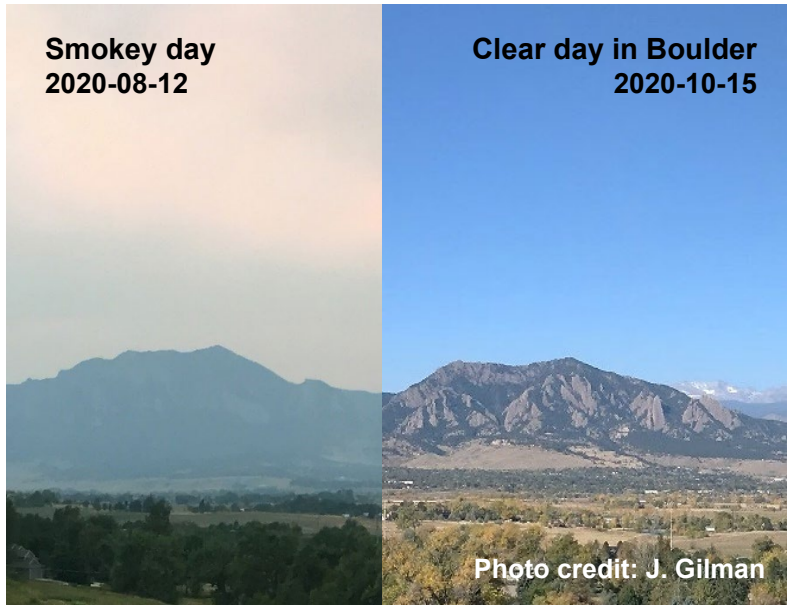
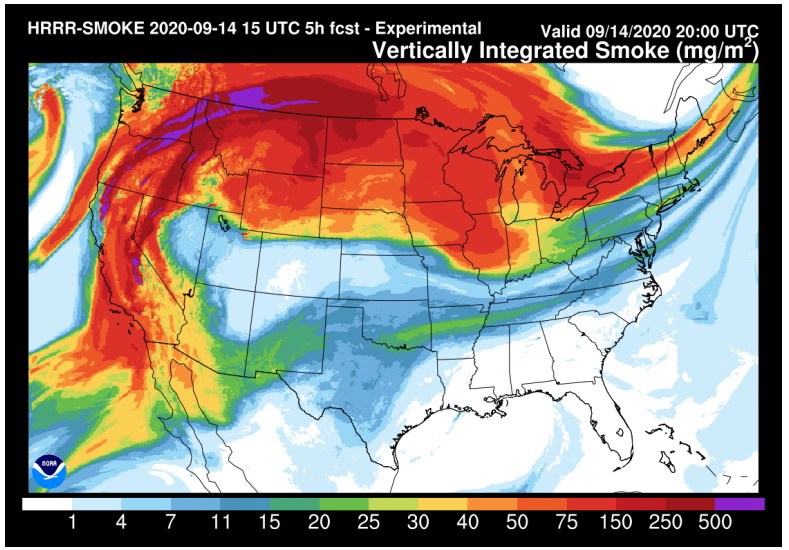
1) What is smoke made of?

2) How does smoke impact our health and the health of the atmosphere?

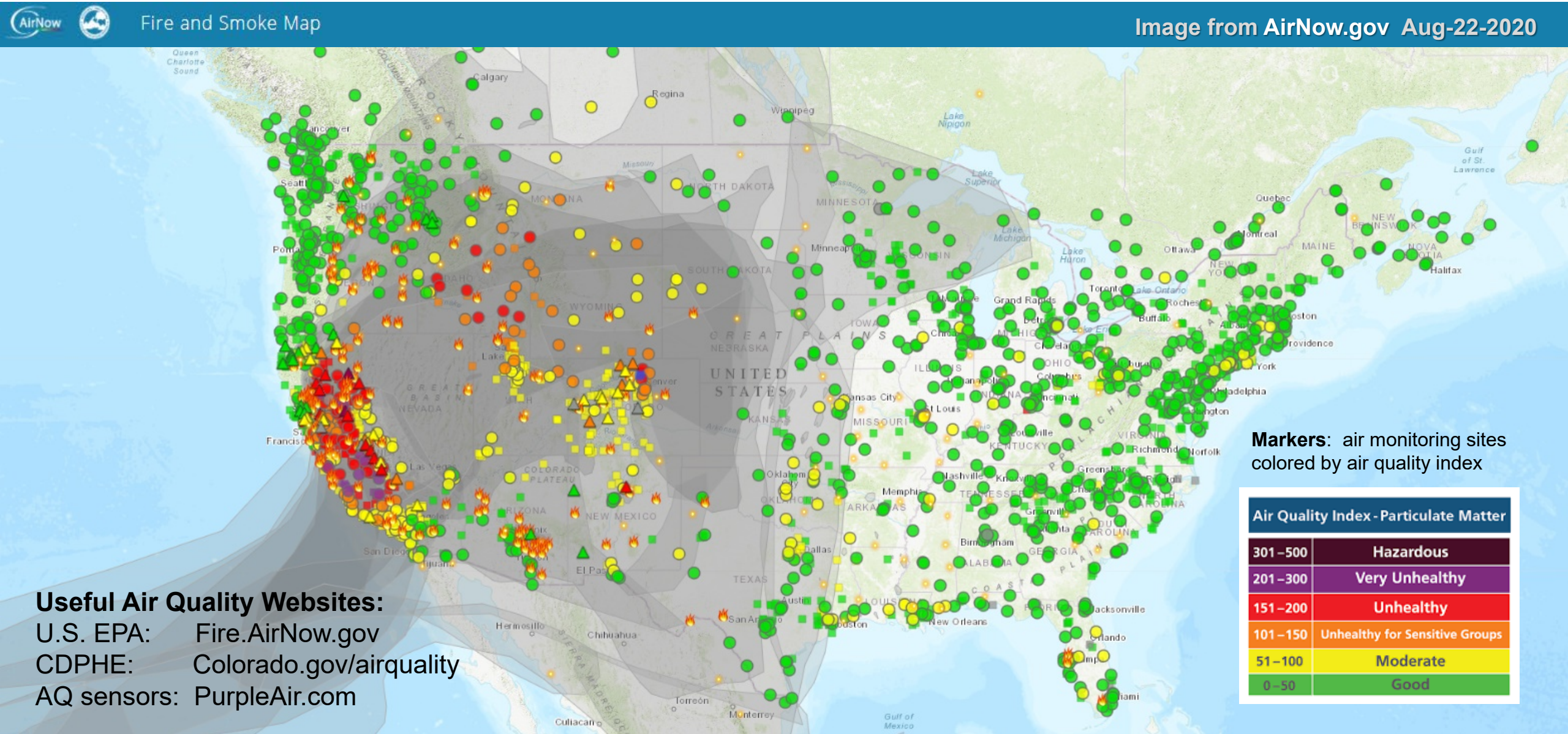


3) How and why do we measure smoke in the atmosphere?

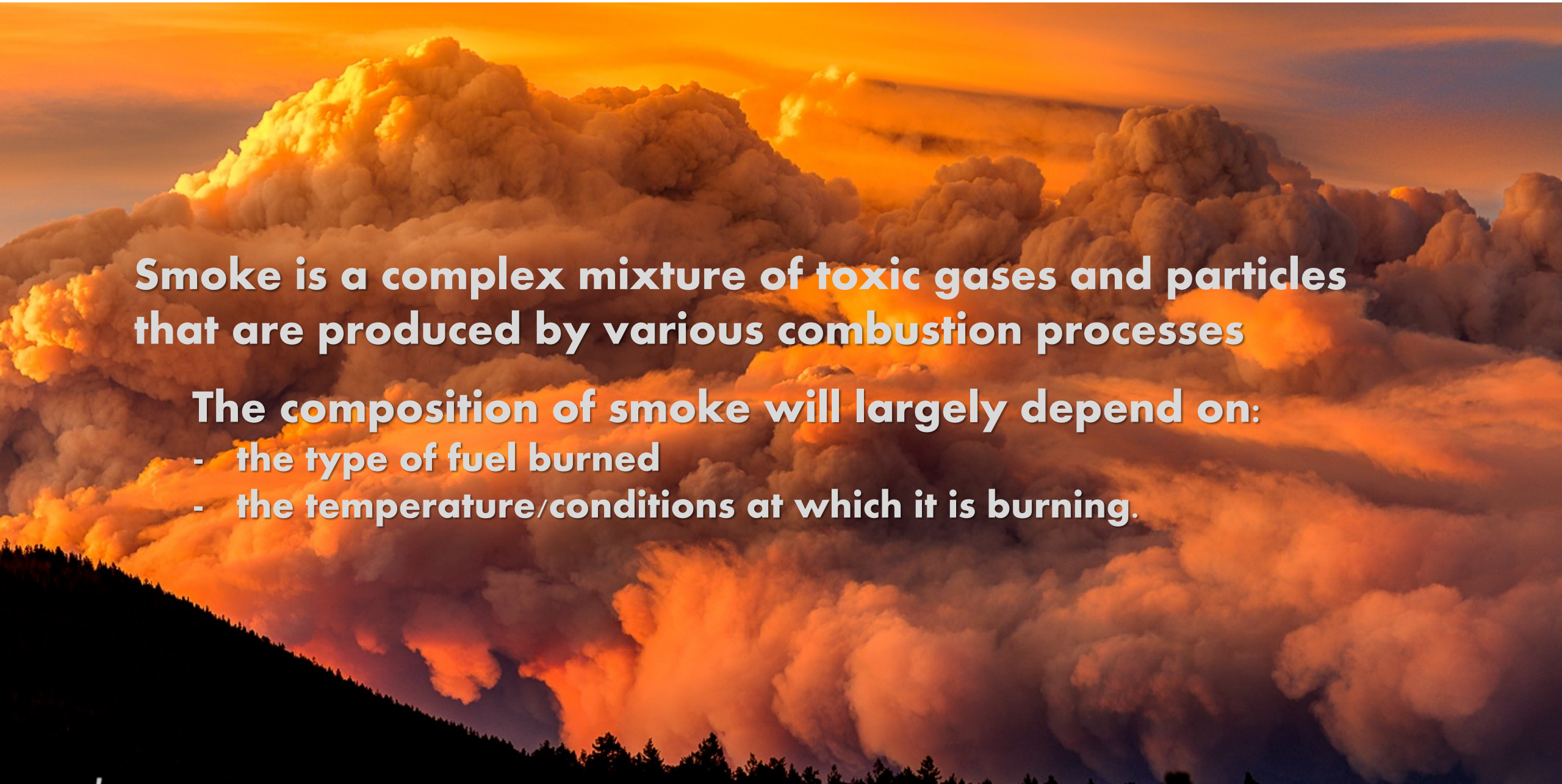


NOAA High Resolution Rapid Refresh – Smoke Model

Wildfire smoke can degrade air quality even at great distances from the ignition source impacting many more millions of people.



1. What is smoke made of?

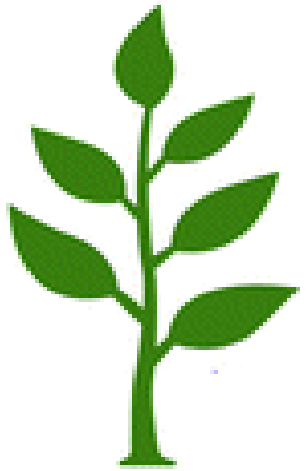


Smoke is a complex mixture of toxic gases and particles that are produced by various combustion processes

The composition of smoke will largely depend on:

- the type of fuel burned
- the temperature/conditions at which it is burning.

Biomass is composed of large organic structures. When burned, these chemical structures are broken down into thousands of different, smaller molecules.



From Naidjonoka et al. (2020)

+

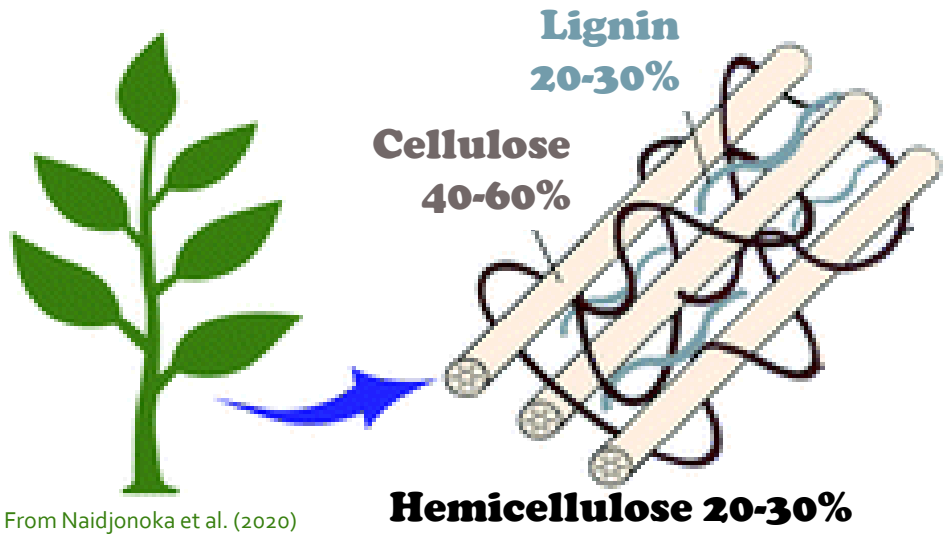
In Air (N_2 + O_2)

→

Composition of hardwood fuels by mass contribution (%)	
Carbon (C)	50 ± 3%
Oxygen (O)	44 ± 3%
Hydrogen (H)	6 ± 3%
Nitrogen (N)	< 5 %

Composition of wildfire smoke	Emissions g/kg fuel	Air Toxic	Air Quality Effects	Climate Effects
Carbon dioxide (CO_2)	1500			✓
Carbon monoxide (CO)	100	✓	✓	
Volatile Organic Compounds (VOCs)	25	✓ some	✓	
Particulate Matter (PM2.5 + PM10)	15	✓	✓	✓
Methane (CH_4)	5			✓
Nitrogen Oxides (NOx = NO + NO_2)	5	✓	✓	
Black Carbon (soot)	1		✓	✓
Other components	< 1 each	✓	✓	✓

Biomass is composed of large organic structures. When burned, these chemical structures are broken down into thousands of different, smaller molecules.



From Naidjonoka et al. (2020)

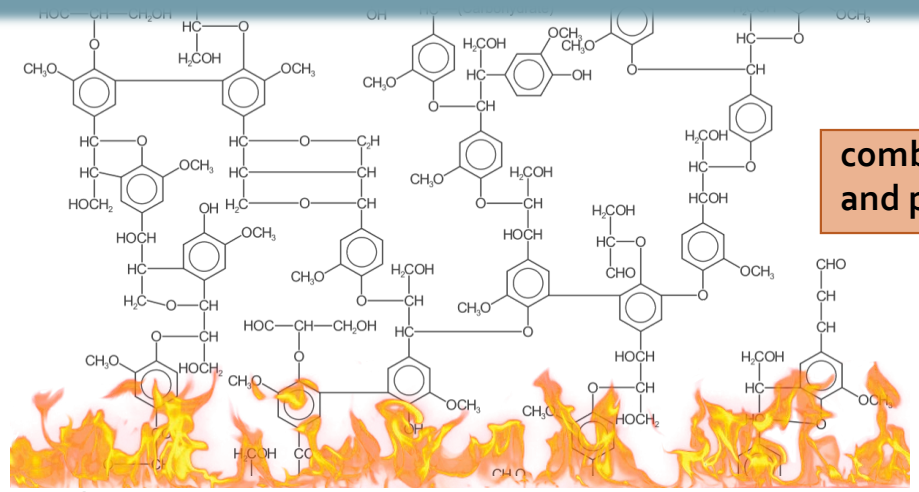
Cellulose: **provides structural support** and is composed of straight-chain polymer made of **10,000+ glucose units**

Hemicellulose: **provides a network of cross-linked fibers** made of planar/branched polymer made of **100+ sugar units (glucose and others)**

Lignin: resin-like polymer that decays slowly in rotting vegetation and gives smoke it's flavor when cooking over fire

Chlorophyll and amino acids: most of the biogenic-nitrogen resides in green plant material

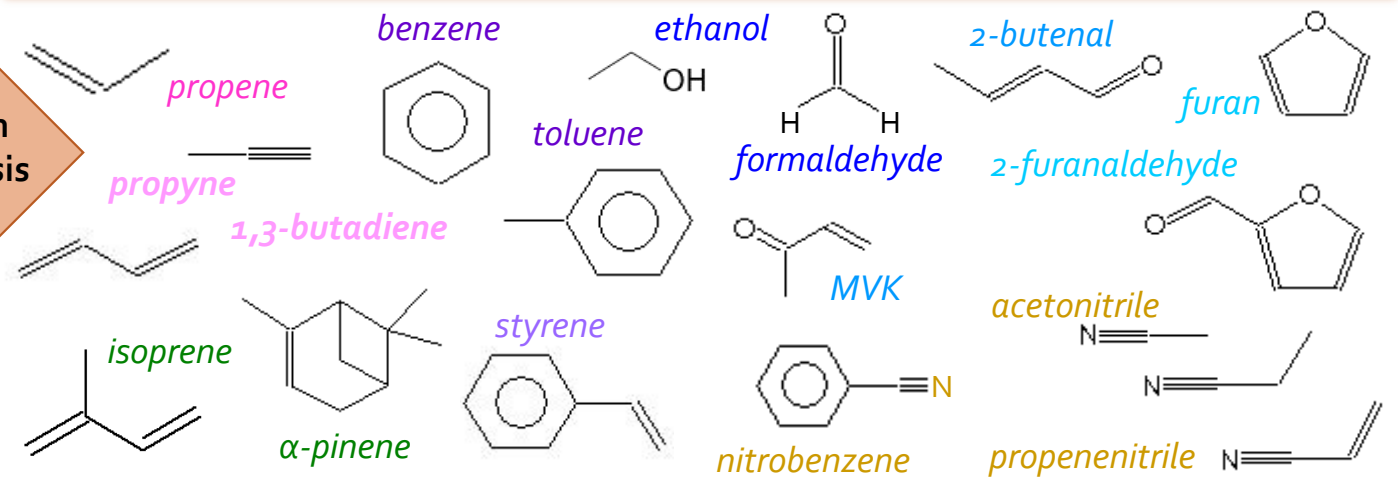
Example partial structure of lignin



Structure from Glazer et al. (1995) via Wikipedia

combustion and pyrolysis

Types of volatile organic compounds (VOCs) from biomass burning



Different fire processes will result in different gases being emitted.

Combustion:
Rapid chemical reaction with O_2 to produce CO_2 and heat

Fire Temperature

Flaming Combustion

- Temperature ~ 1200 °C, **flames**
- Occurs in the gas-phase
- **Large emissions of CO_2 and NOx**

Smoldering/Glowing Combustion

- Temperature ~ 600 °C, no flame
- Occurs at the surface of the material
- **Large emissions of CO and VOCs**

Rim Fire in California
Image credit: TheAtlantic.com

Complex organic molecules are created from smoldering combustion and pyrolysis.

Combustion:
Rapid chemical reaction with O_2 to produce CO_2 and heat

Pyrolysis:
Thermochemical process that occurs without the participation of O_2

Fire Temperature

Flaming Combustion
- Temperature ~ 1200 °C, **flames**
- Occurs in the gas-phase
- **Large emissions of CO_2 and NOx**

High-temperature Pyrolysis
- Temperature 850-1200 °C, no flame
- Occurs on or inside the material
- **Releases smaller organic molecules**

Smoldering/Glowing Combustion
- Temperature ~ 600 °C, no flame
- Occurs at the surface of the material
- **Large emissions of CO and VOCs**

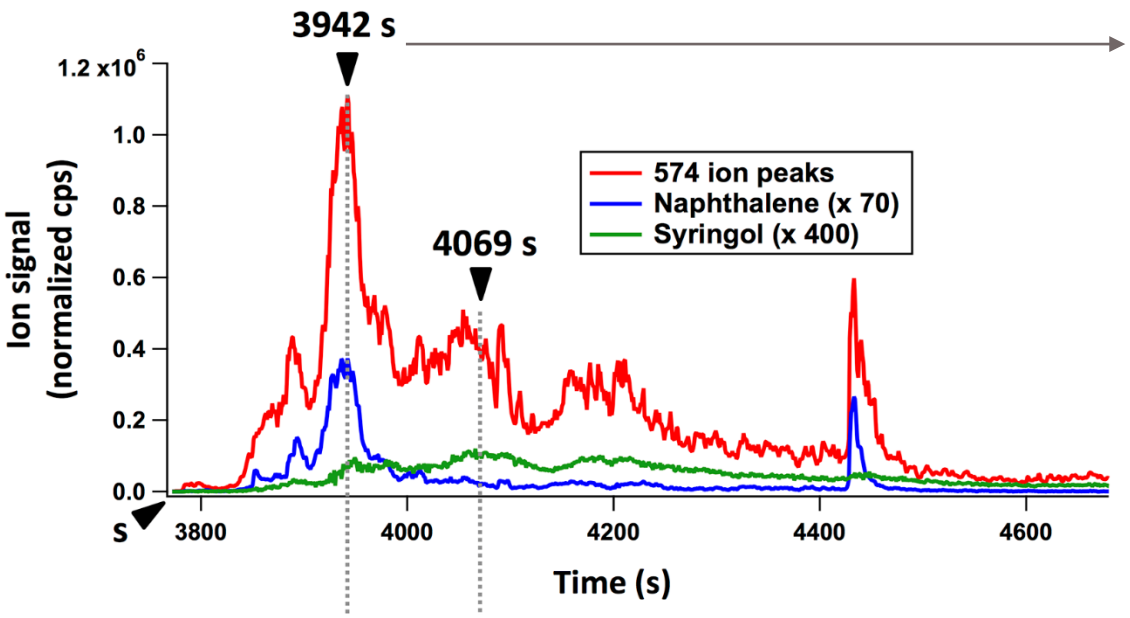
Low-temperature Pyrolysis
- Temperature 350 to 550 °C, no flame
- Occurs on or inside the material
- **Releases complex organic molecules**

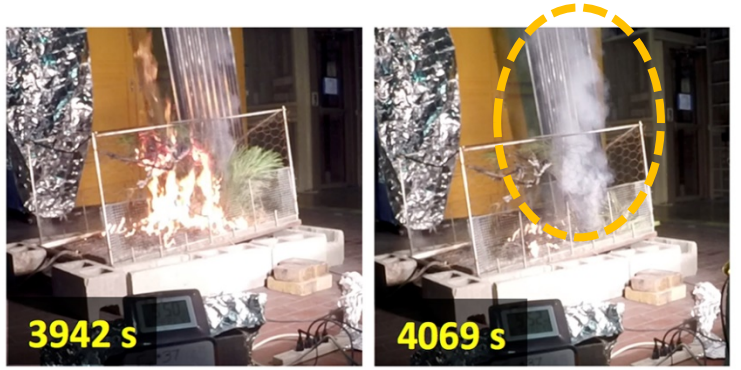
Biomass burns incompletely and unevenly. There are many different processes occurring all at once.

Rim Fire in California
Image credit: TheAtlantic.com

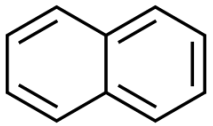
Temperature of a wildfire is a better predictor of smoke composition than fuel type.

Image credit: Henry Worobec

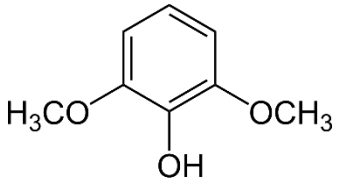




Naphthalene
a toxic PAH



Syringol
smokey smell

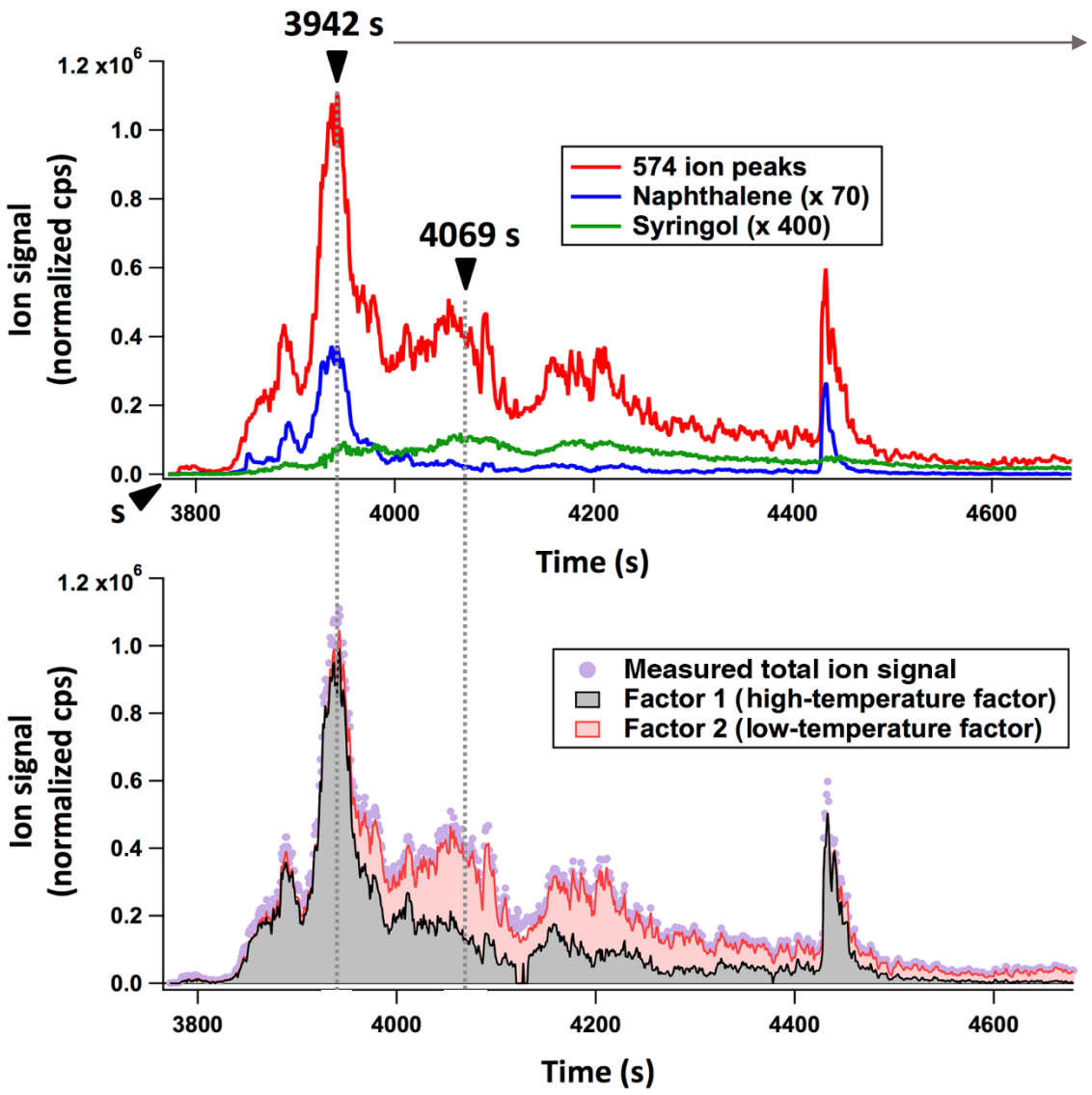


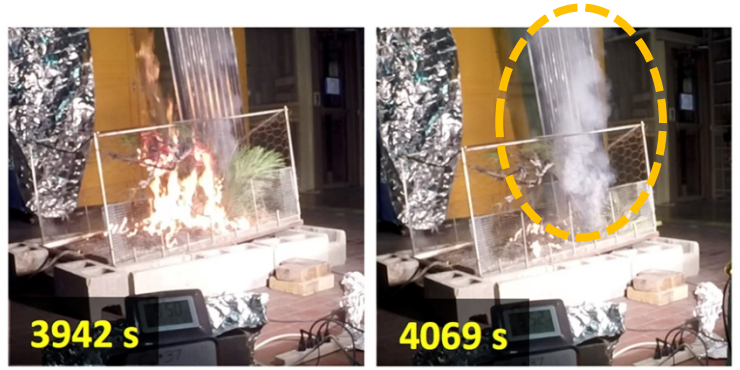
Sekimoto et al. (2018)

research.noaa.gov/article/ArtMID/587/ArticleID/2373/Wildfire-Temperatures-Key-to-Better-Understanding-Smoke-Impacts

Temperature of a wildfire is a better predictor of smoke composition than fuel type

Image credit: Henry Worobec





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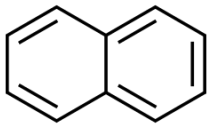

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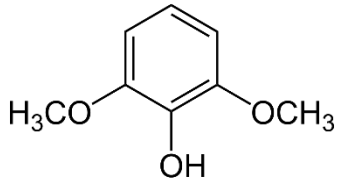


Key Finding:
85% of all VOC emissions across all western U.S. fuels studied could be predicted by this two factor solution which correlates with temperature.

Sekimoto et al. (2018)

research.noaa.gov/article/ArtMID/587/ArticleID/2373/Wildfire-Temperatures-Key-to-Better-Understanding-Smoke-Impacts

2. How does smoke impact our health and the health of the atmosphere?

Human Health:

Smoke contains toxic gases and particles that can be inhaled deeply into the lungs and cause a number of ailments.

Health of the Atmosphere:

Wildfire emissions can alter Earth's energy balance through the emission of greenhouse gases and scattering/absorption of sunlight by particulate matter.

Golden Gate Bridge under an orange smoke filled sky at midday in San Francisco, California on September 9, 2020

Image credit: AFP; Source: gulfnews.com/world/americas/

Smoke at any concentration is unhealthy to breathe.

Exposure Hazard = Pollutant x Concentration x Exposure Time

Pollutant: Gases & PM

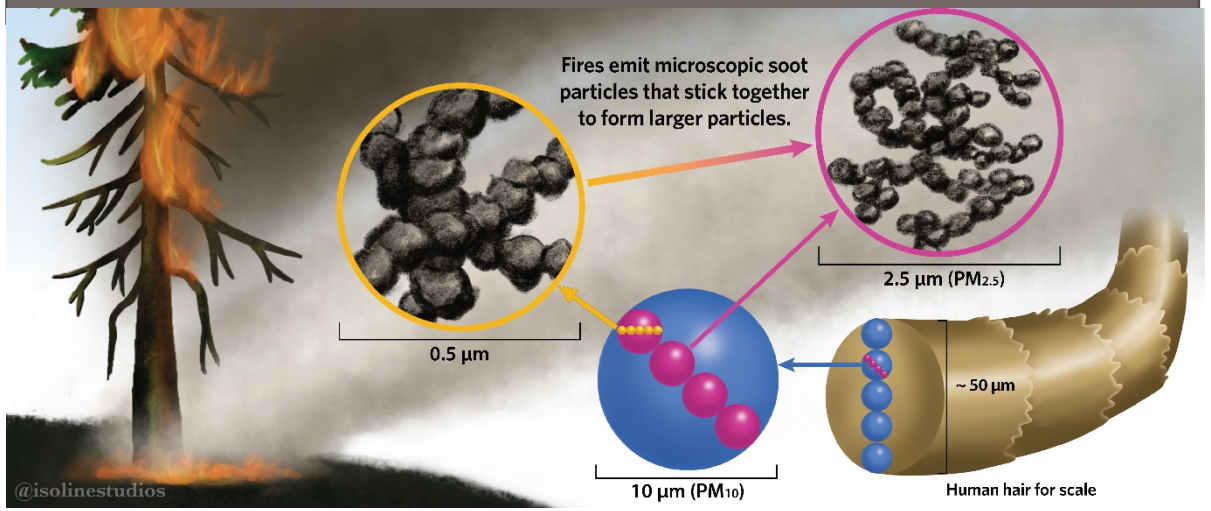
Concentration x Exposure Time: Acute vs. Chronic

Direct emission of toxic gases

- Carbon monoxide
- Air toxics such as formaldehyde and benzene, both known carcinogens

Inhalable particulate matter (PM)

- PM2.5 is "fine" particles that are 20 times thinner than a human hair (50 µm in diameter)
- Small particles can bend around corners and make their way deeper into your lungs



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Concentration x Exposure Time: Acute vs. Chronic

Direct emission of toxic gases

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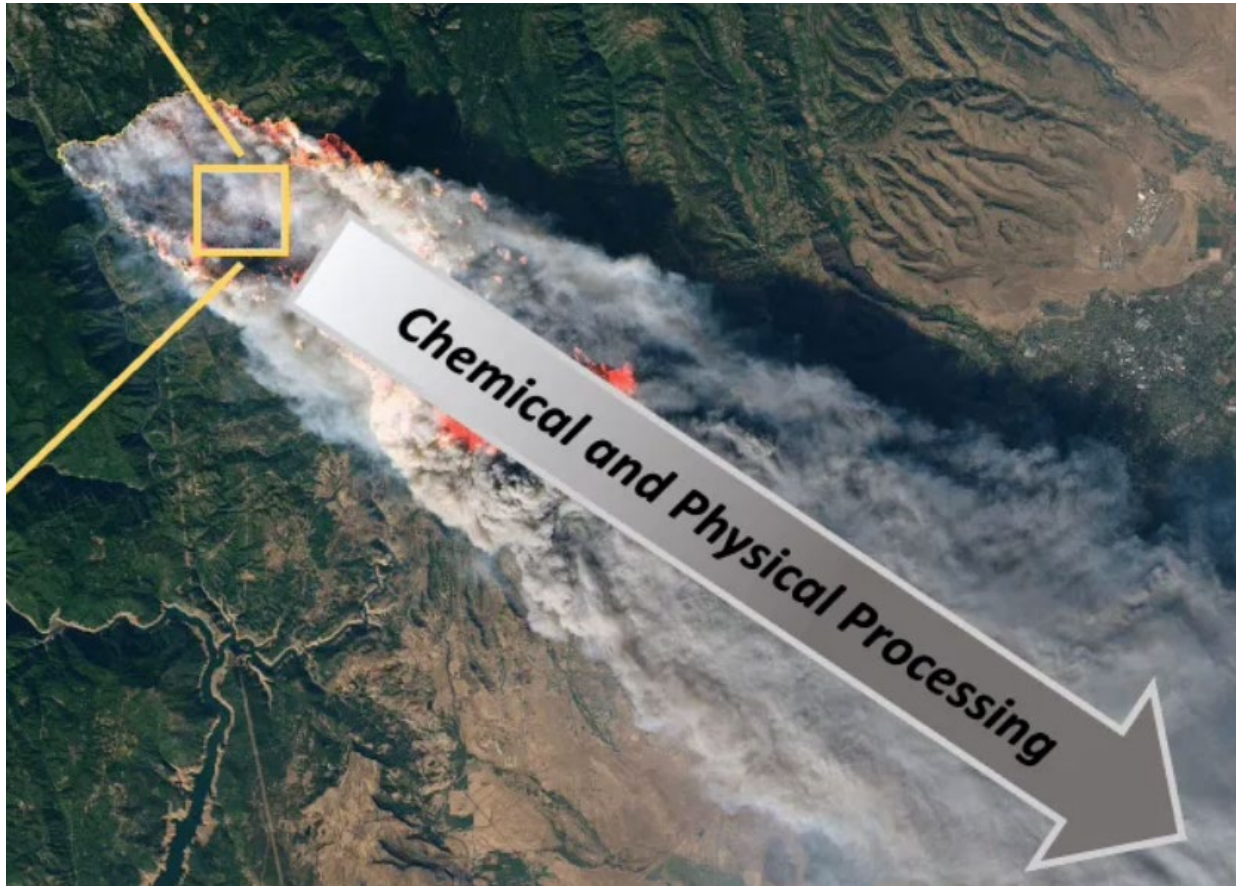
Formation of toxic gases and particles downwind of the emission source

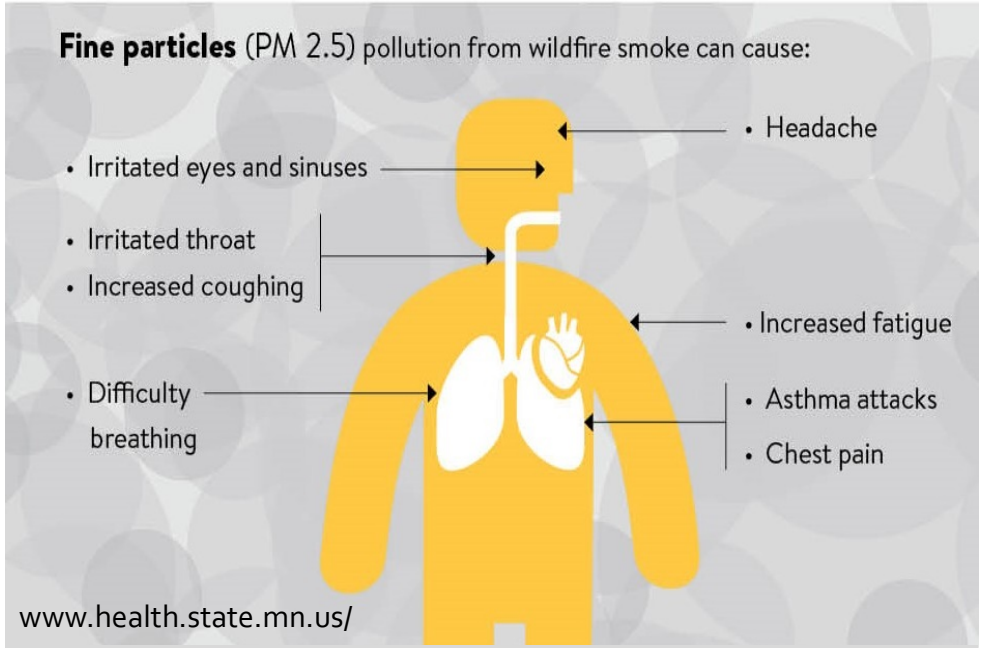
- Particles and ozone (O_3) can be formed in wildfire smoke as it ages in the atmosphere
- Both are air toxics and degrade air quality

VOC + NOx + sunlight → Ozone and Particles



$PM_{2.5}$ from wildfire smoke is particularly unhealthy and increasing across the west.

Wildfire Smoke Health Impacts

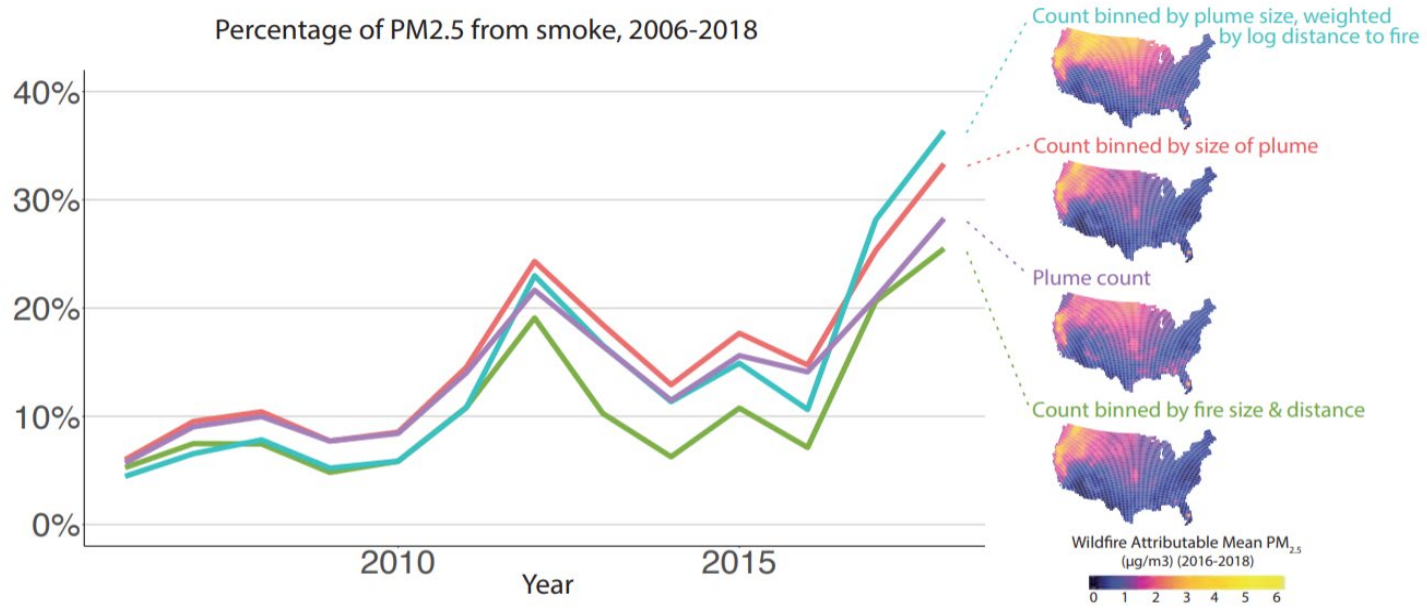


Health risks are higher for older adults, children, and those with preexisting health conditions.

Improve your health by limiting exposure!

For more info see:
www.cdc.gov/disasters/wildfires/smoke.html

Emission of PM2.5 from wildfires is increasing across the western U.S.

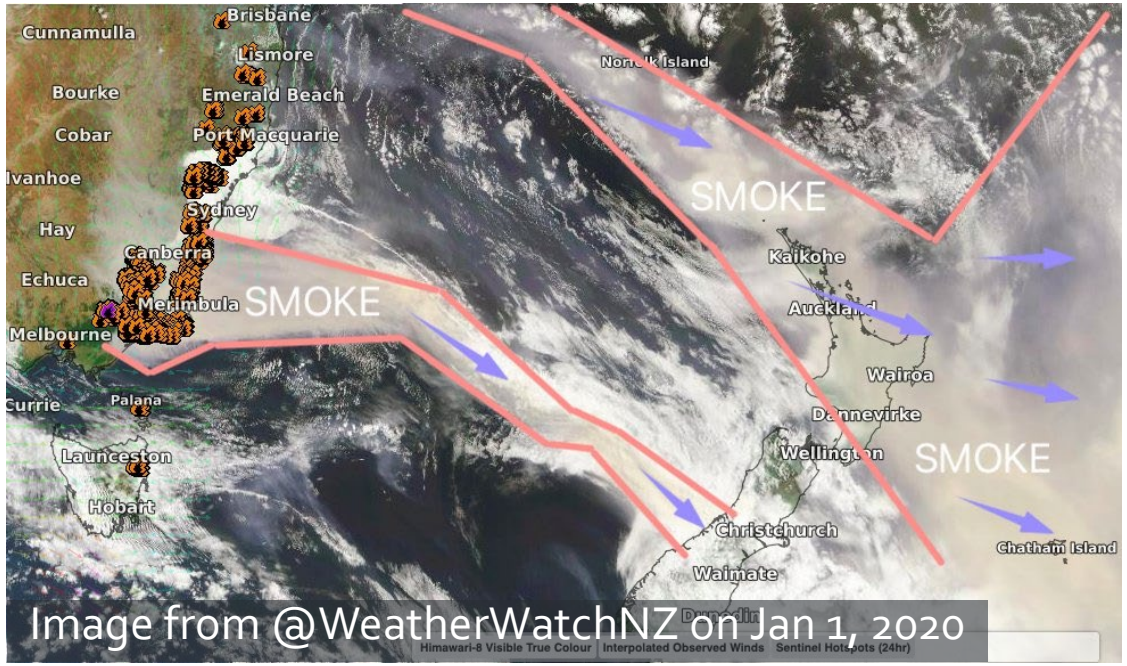


- PM2.5 in western U.S. = 11 µg/m^3; EPA limit is 12 11 µg/m^3
- Increasing wildfire smoke PM is erasing air quality gains
- Smokey days per year are increasing by 1.89 days per year
- Predicted PM2.5 from wildfires is increasing 1.36% per year

Burke et al. (2021). *The changing risk and burden of wildfire in the U.S.*

Wildfire smoke can have large and/or long-term effects on other Earth systems.

Historic wildfires in Australia in January 2021



"Caramelized" snow on NZ glaciers on Jan 1, 2020 @CNN

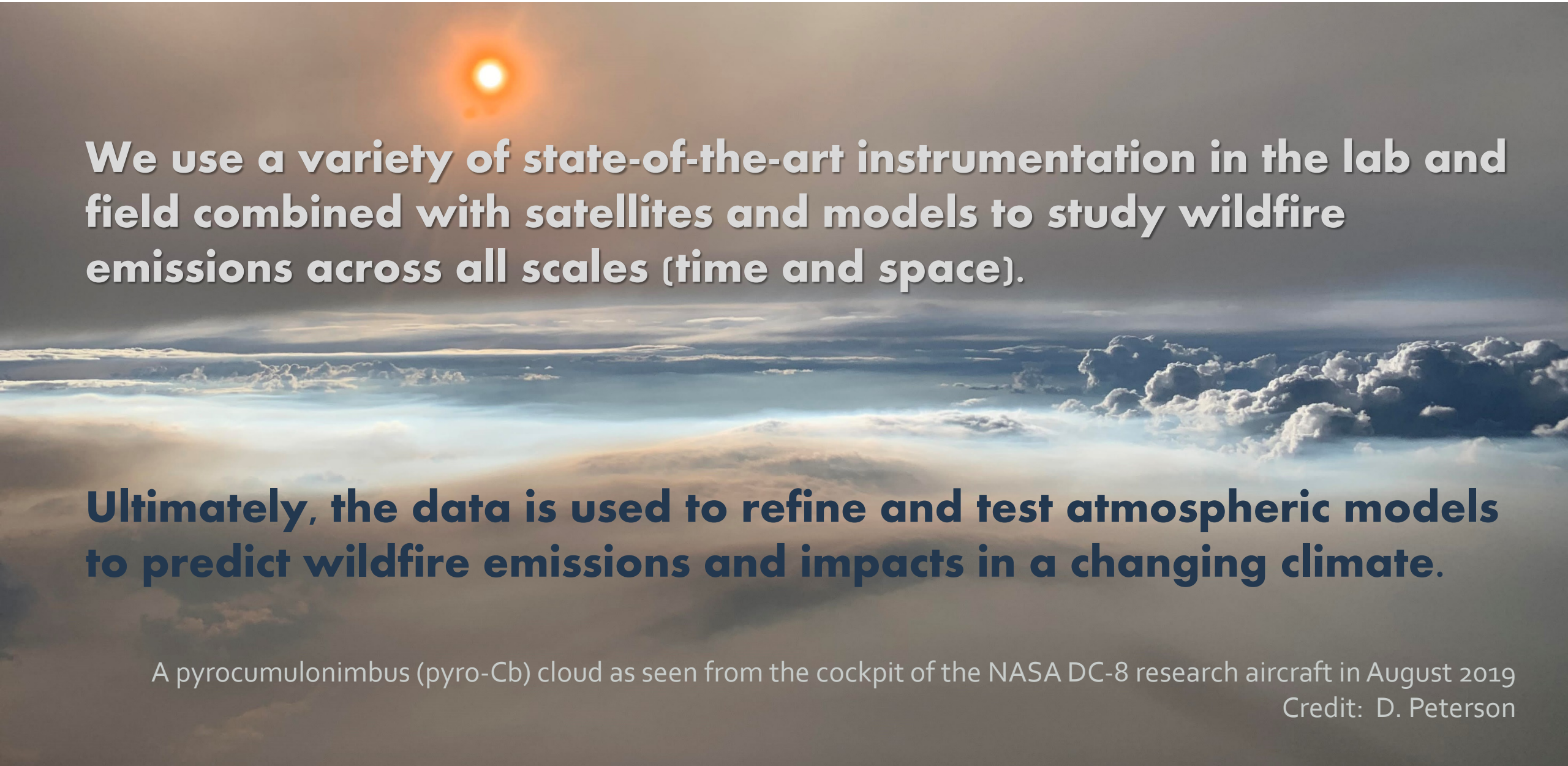
More than 70,000 square miles (75% of the state of Colorado) burned in Australia in 2019/2020 summer

The "New Year" brushfires produced the largest input of wildfire smoke – 1 million metric tons – to the stratosphere observed in the satellite era (Yu, et al. 2021).

Effects: **snow melt on glaciers to warming the stratosphere and changing Earth's energy balance**

https://research.noaa.gov/article/ArtMID/587/ArticleID/2745/Giant-Australian-bushfire-injected-1-million-tons-of-smoke-in-the-atmosphere

3. How and why do we still need to study biomass burning emissions?



We use a variety of state-of-the-art instrumentation in the lab and field combined with satellites and models to study wildfire emissions across all scales (time and space).

Ultimately, the data is used to refine and test atmospheric models to predict wildfire emissions and impacts in a changing climate.

A pyrocumulonimbus (pyro-Cb) cloud as seen from the cockpit of the NASA DC-8 research aircraft in August 2019
Credit: D. Peterson

Laboratory burns provide a controlled environment in which to measure smoke.

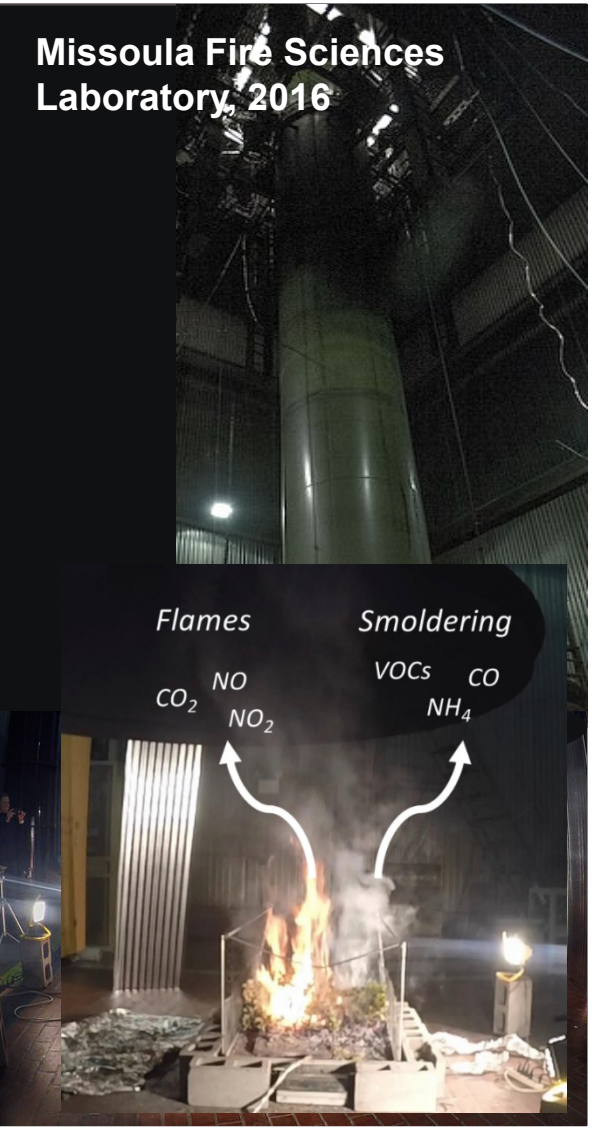
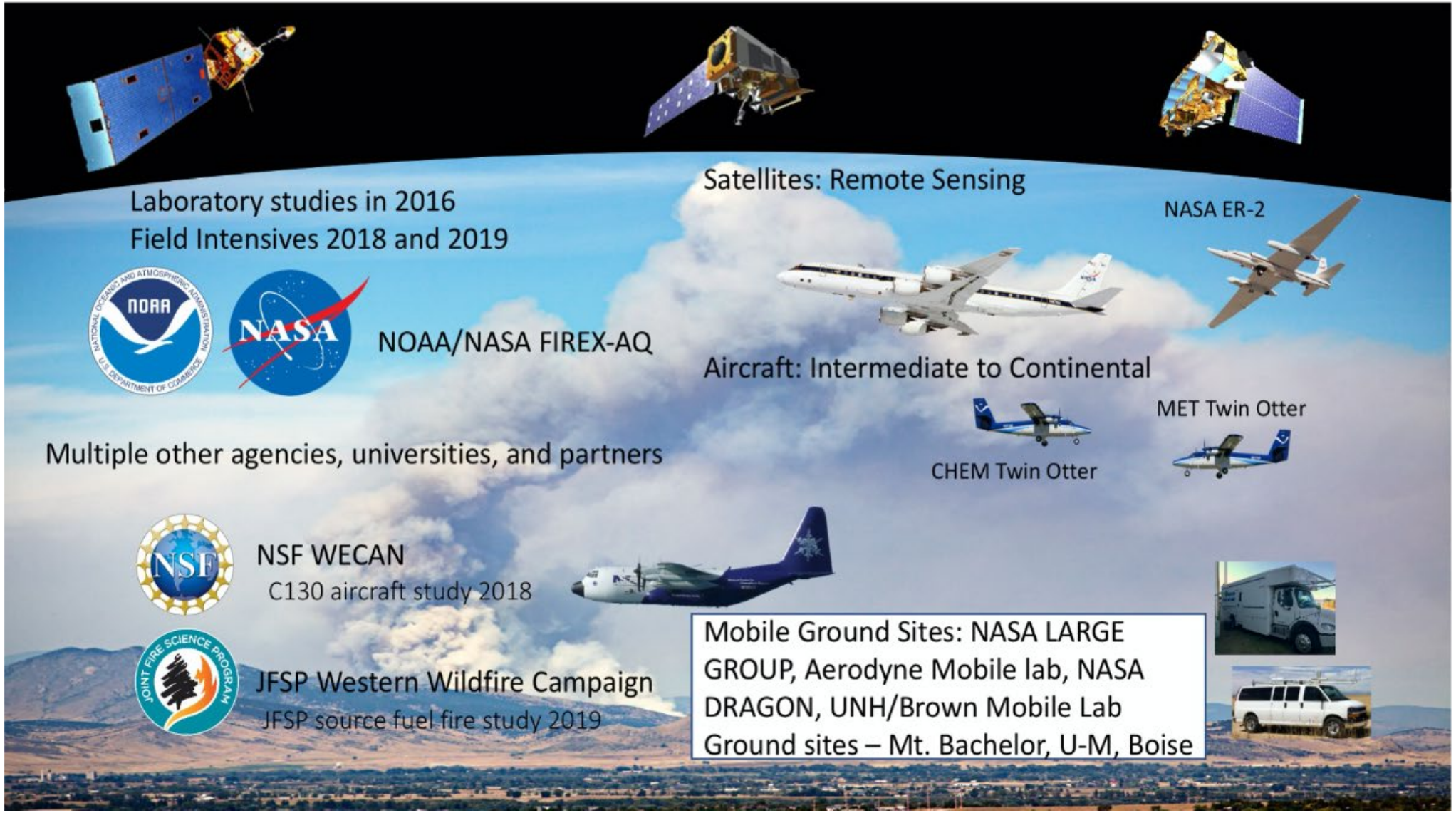


Image credit: Henry Worobec

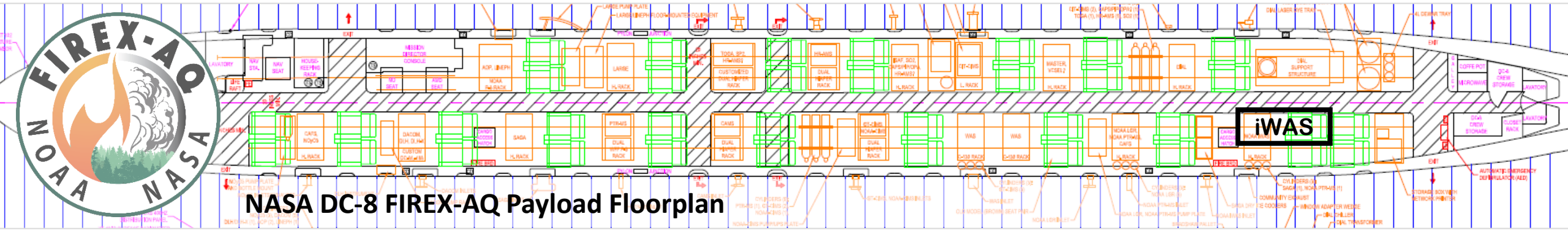
Image credit: Jessica Gilman

Field studies are used to study wildfire emissions in "real-world" conditions. NOAA, NASA, NSF and partners have completed the largest-scale field intensive.



NOAA FIREX-AQ information: https://csl.noaa.gov/projects/firex-aq

A number of state-of-the-art instruments are needed to fully characterize the complex chemical mixture of gases and particles emitted from biomass burning.



NASA DC-8 FIREX-AQ Payload Floorplan

For wildfires, we fly multiple transects at varying distance from the fire to characterize both near source emissions and during downwind plume transport

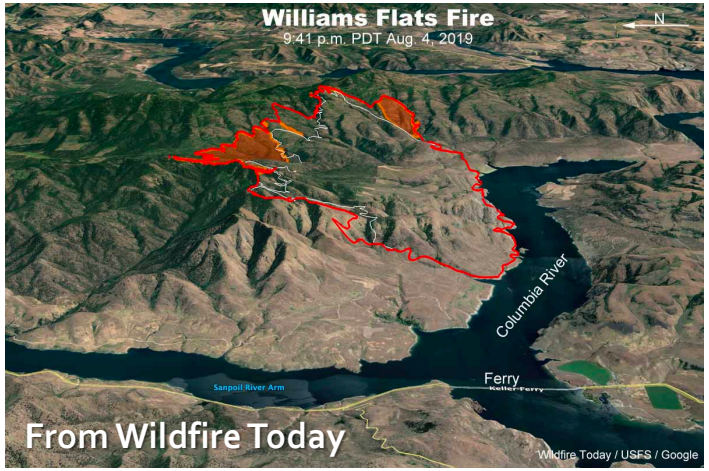
Williams Flats Fire

Date: 2019-08-03

Location: central Washington, U.S.

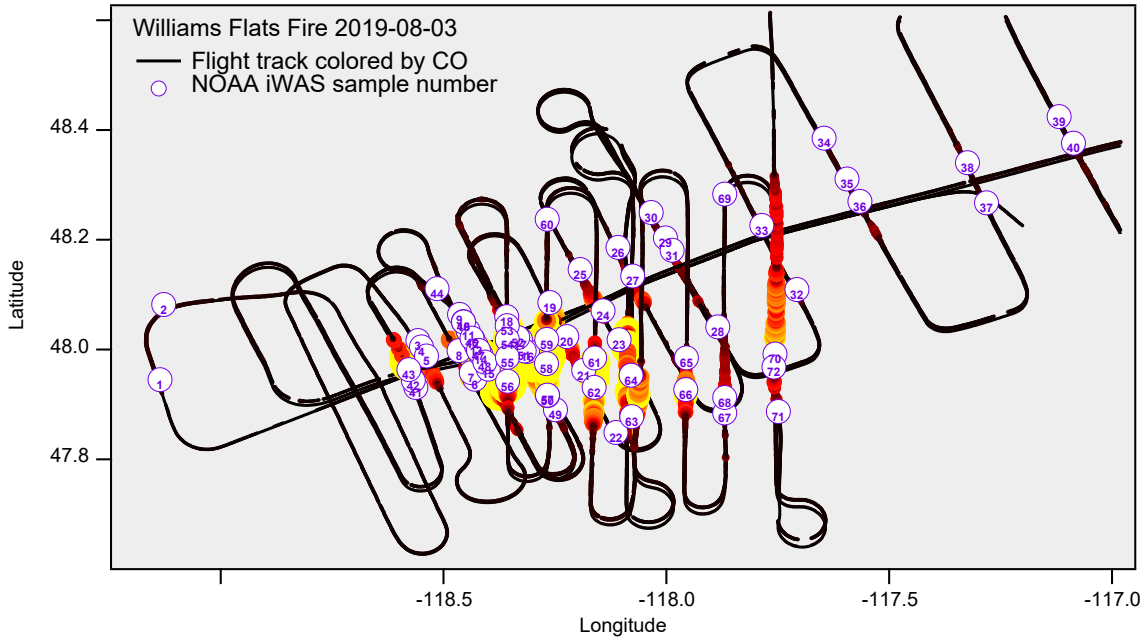
Fuel: Douglas Fir, Ponderosa Pine

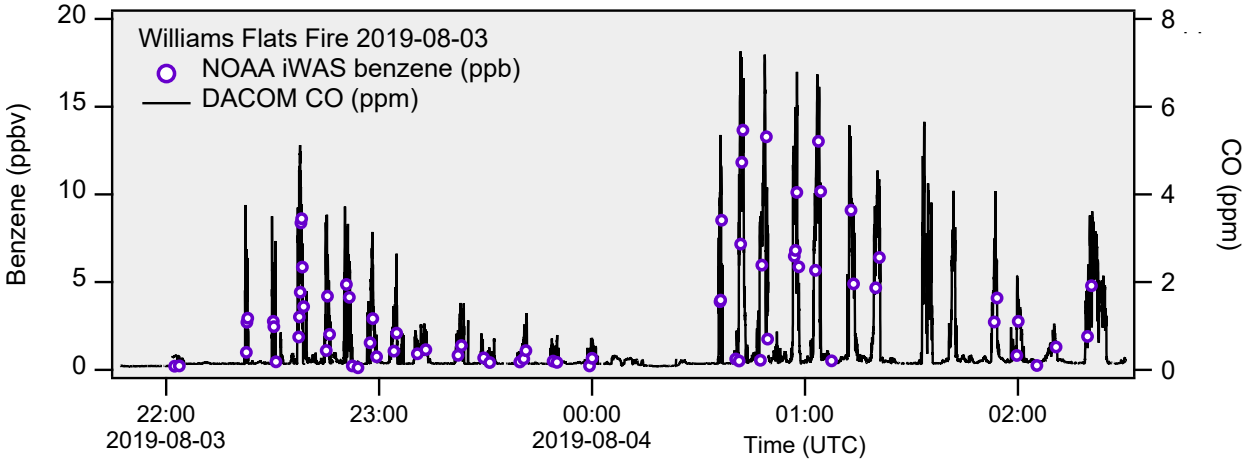
Area burned: 45,000 acres (180 km^2)



Satellite images and flight track compiled by Christopher Holmes

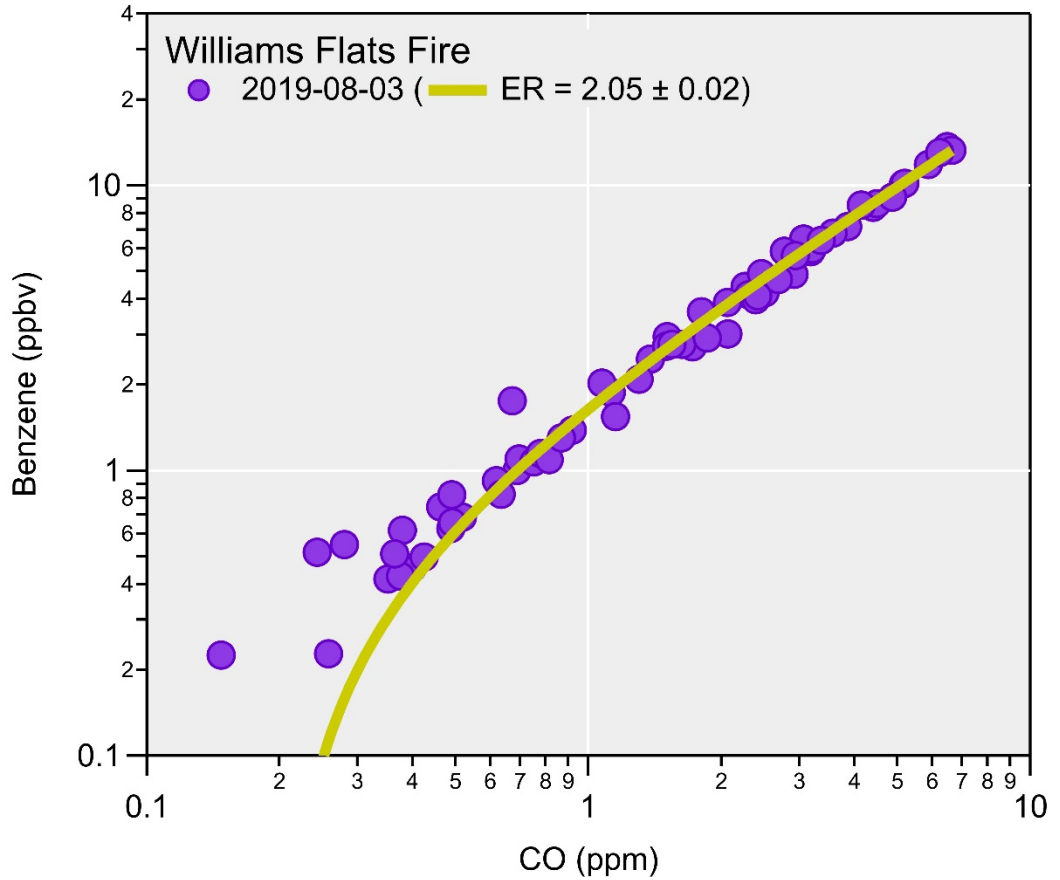
For wildfires, we fly multiple transects at varying distance from the fire to characterize both near source emissions and during downwind plume transport



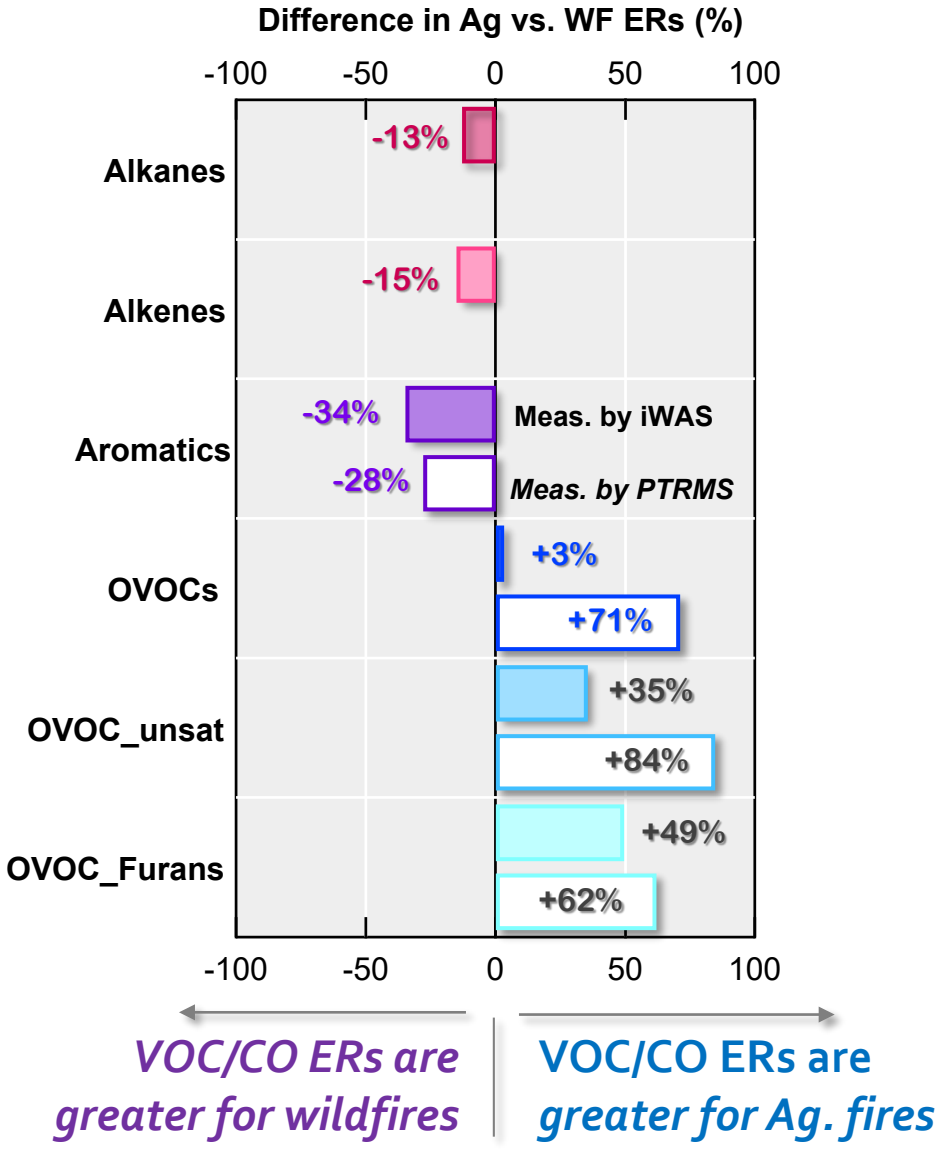


Enhancement ratio (ER) = VOC (ppbv) / CO (ppm)

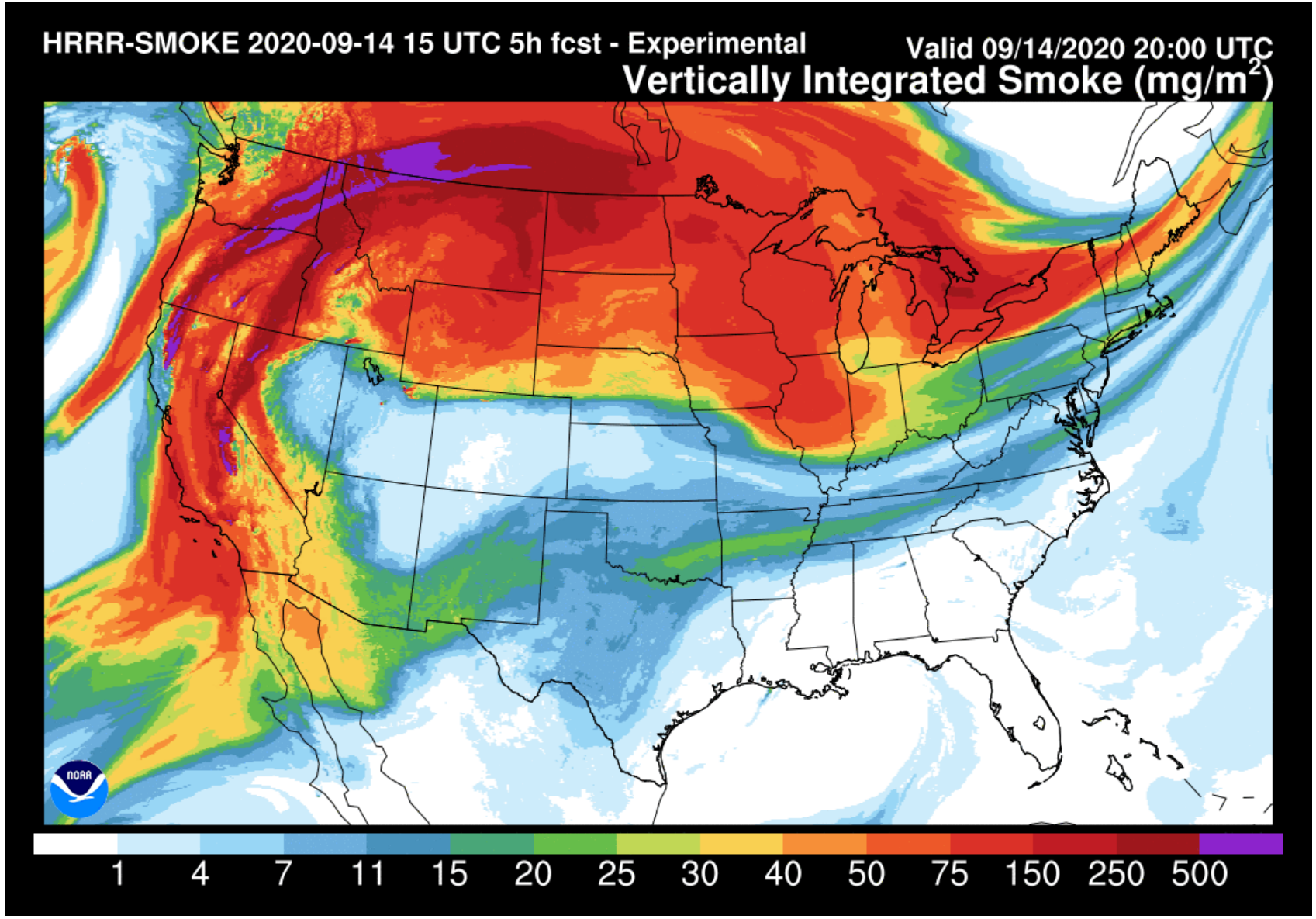
- Near source samples are proxies for emission ratios
  - Accounts for effects from mixing and dilution



Agricultural fires across the eastern/central plains are a significant source of smoke in the U.S. The chemical composition of wildfires and agricultural fires are different.



Biomass burning data to be integrated with weather models to predict where smoke will go and how it will impact local air quality

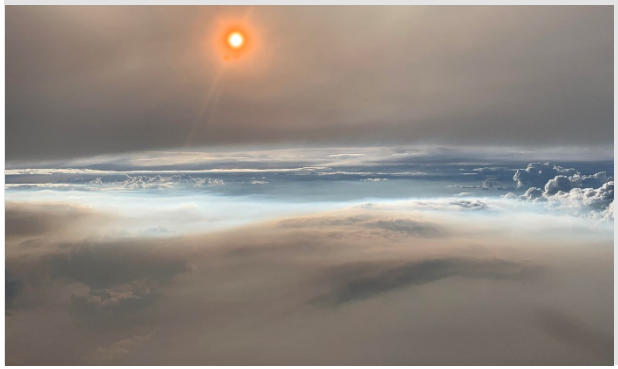


https://rapidrefresh.noaa.gov/hrrr/HRRRsmoke/

Summary

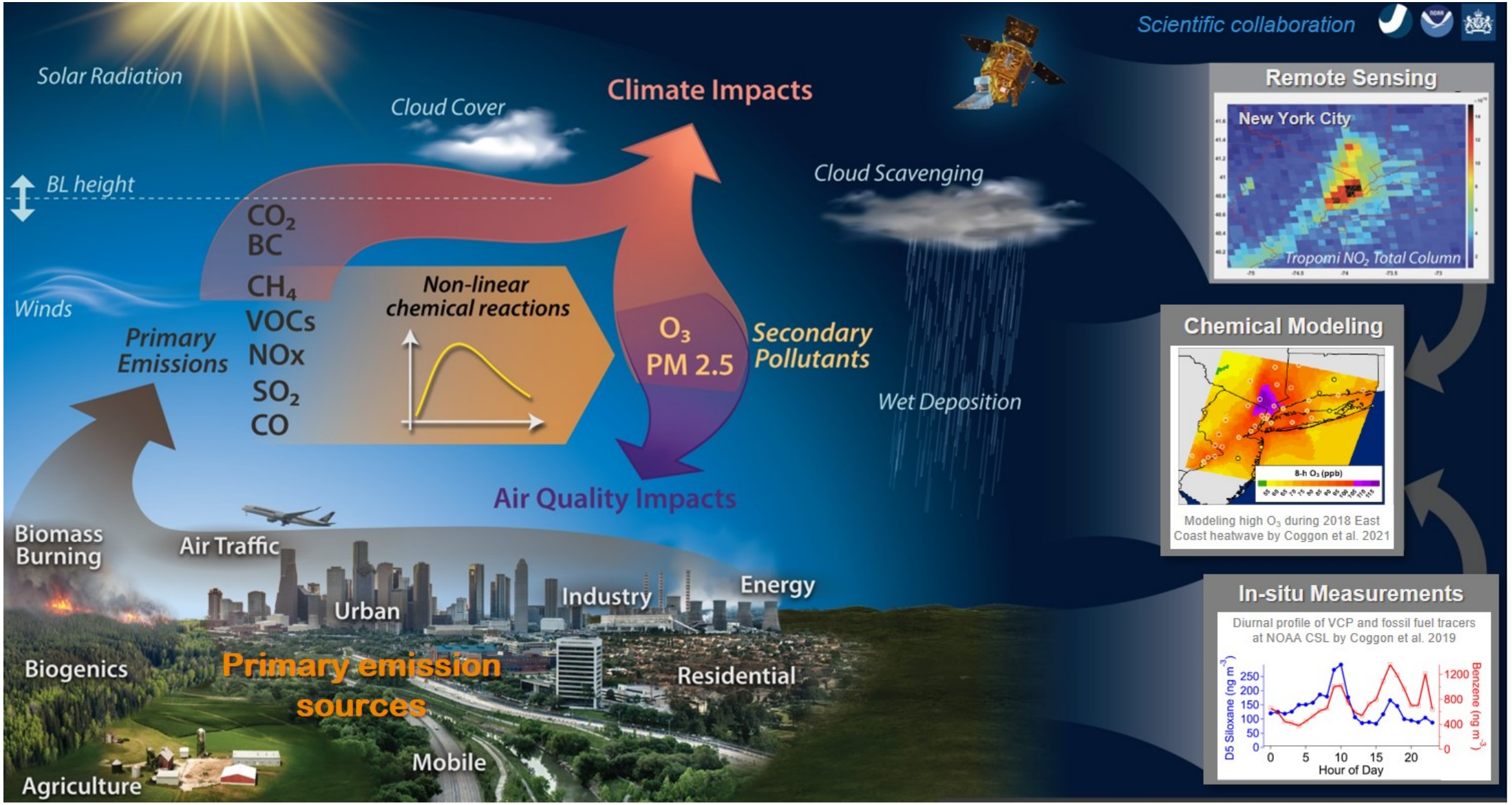
- Wildfire smoke is a complex mixture of toxic gases and particles that degrade air quality even at great distances from the ignition source.
- Wildfire smoke is harmful to human health. $PM_{2.5}$ from wildfires is increasing in the western U.S.
- Wildfire smoke can have large and/or long-term effects on other Earth systems.

Email: jessica.gilman@noaa.gov Twitter: @JBGilman

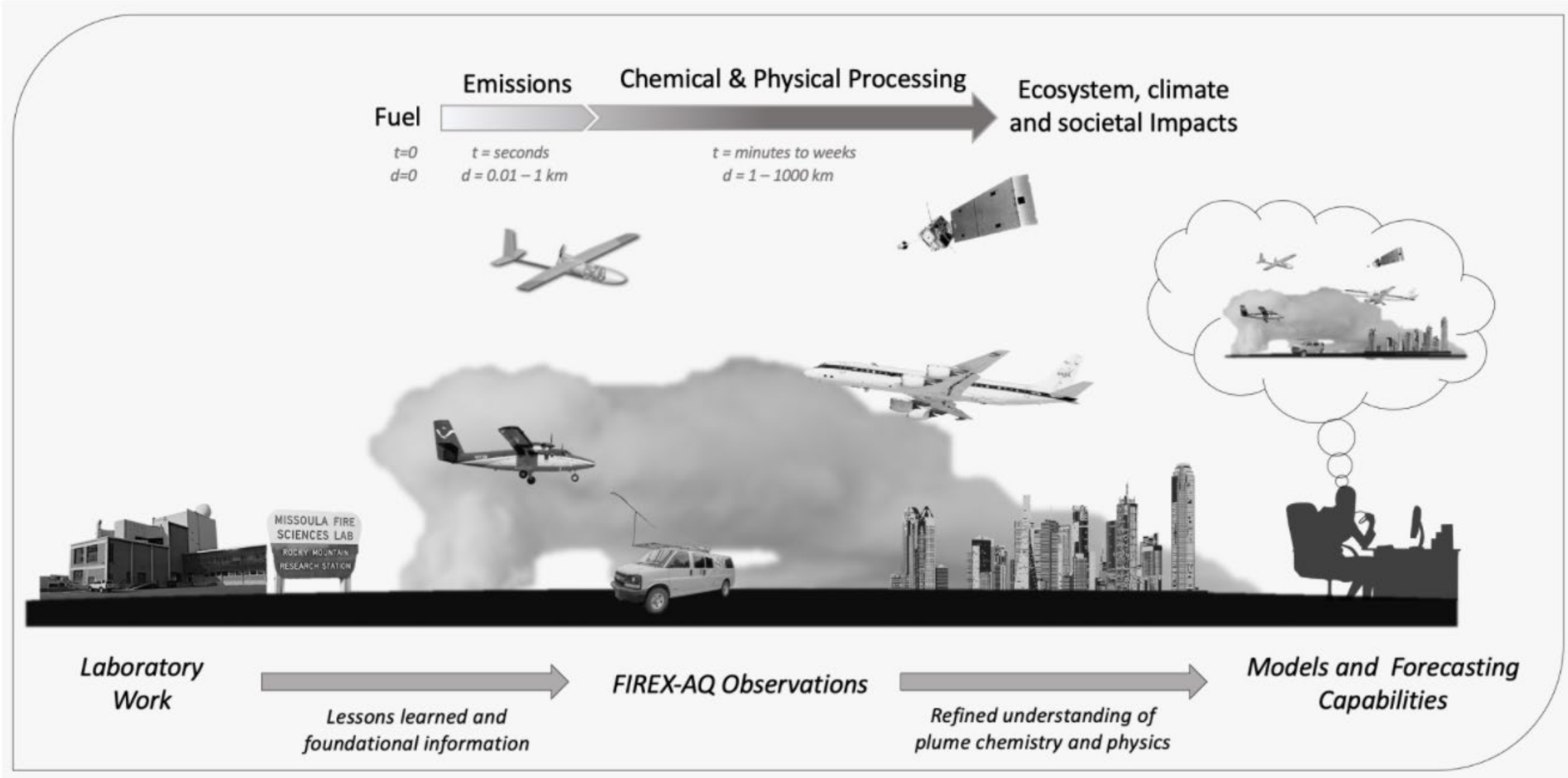


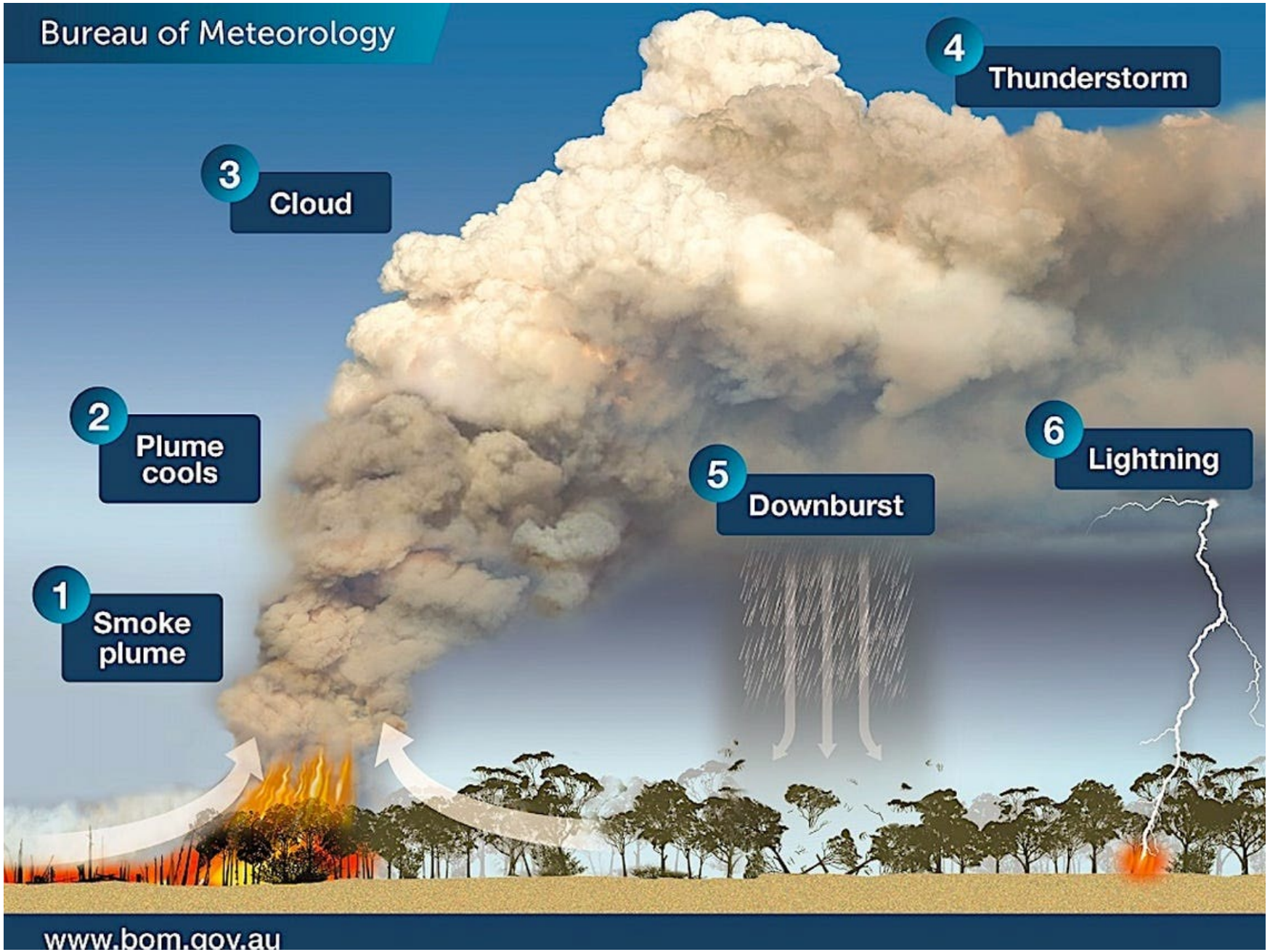
Thank you!

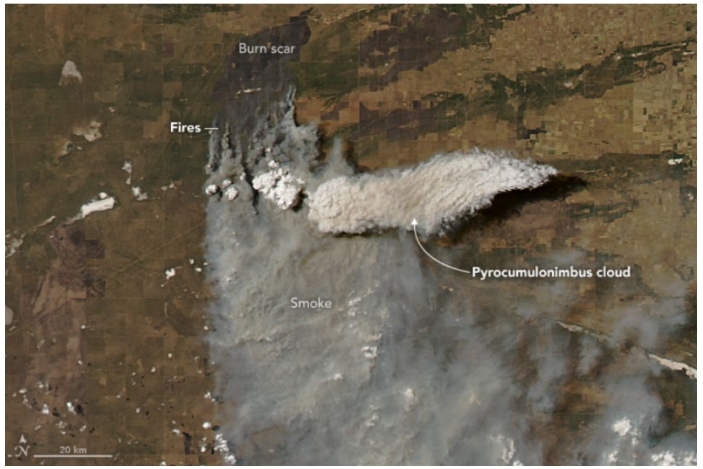
The atmosphere is a complex and dynamic system



Original figure by C. Thompson from Gkatzelis et al. 2021; Figure adapted by J. Gilman


Fuel
Emissions
Chemical & Physical Processing
Ecosystem, climate and societal Impacts
t=0
d=0
t = seconds
d = 0.01 – 1 km
t = minutes to weeks
d = 1 – 1000 km
MISSOULA FIRE SCIENCES LAB
ROCKY MOUNTAIN RESEARCH STATION
Laboratory Work
Lessons learned and foundational information
FIREX-AQ Observations
Refined understanding of plume chemistry and physics
Models and Forecasting Capabilities





Pyrocumulonimbus (pyro-Cb)

Pyrocumulus (pyro-Cu)

Research at the National Oceanic and Atmospheric Administration (NOAA)

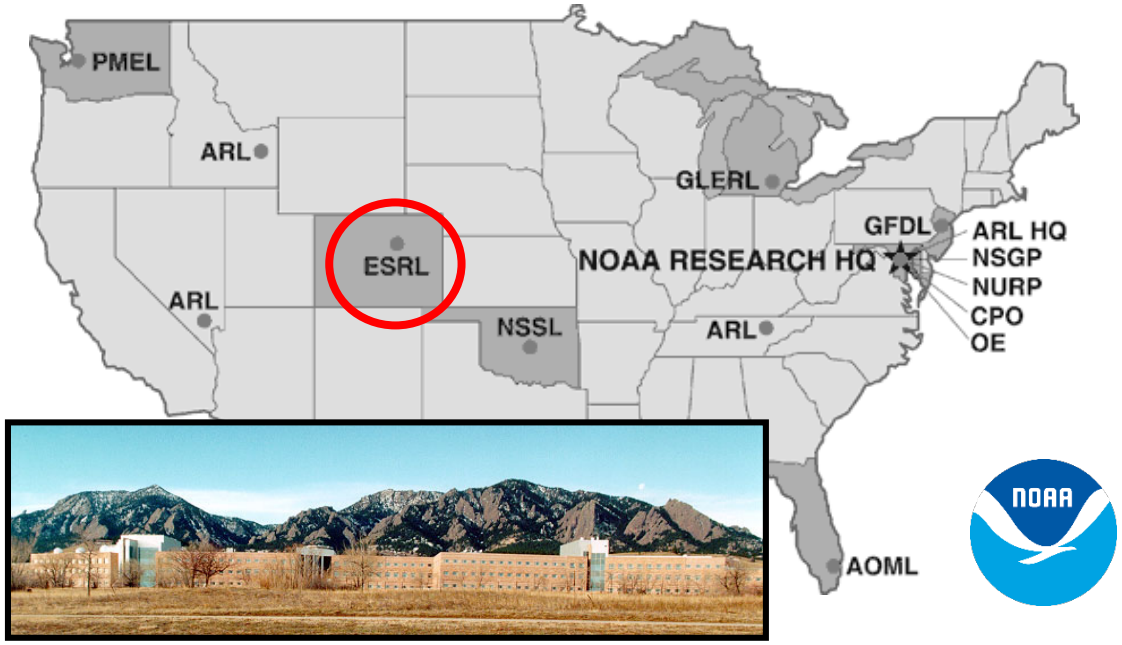
NOAA mandate:

- To document and understand changes in the Earth System in order to predict changes in the environment
- Provide decision makers with critical information to make effective judgements to prevent loss of life and property and manage natural resources while maintaining a strong economy
  - NOAA is part of the Dept. of Commerce
  - NOAA is NOT a regulatory agency

NOAA's research extends from the bottom of the ocean to the surface of the sun

Three main research topics:

- Ocean and Coastal Resources
- Weather (including space weather)
- Air Quality and Climate



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