Toward Understanding Aerosol Vertical Distribution and Boundary Layer Dynamics During Wildfire Events

Presenter

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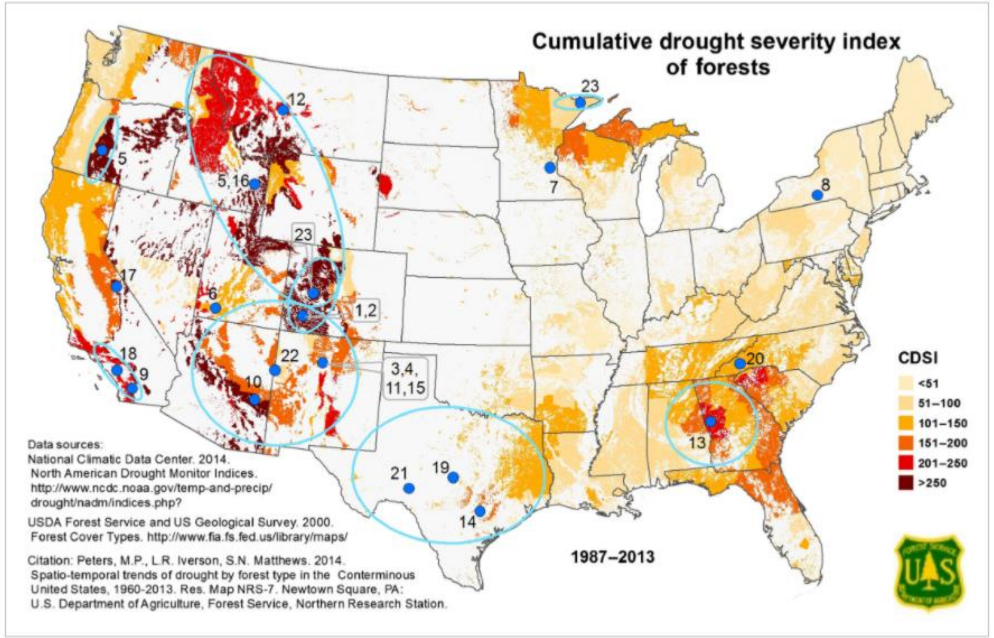
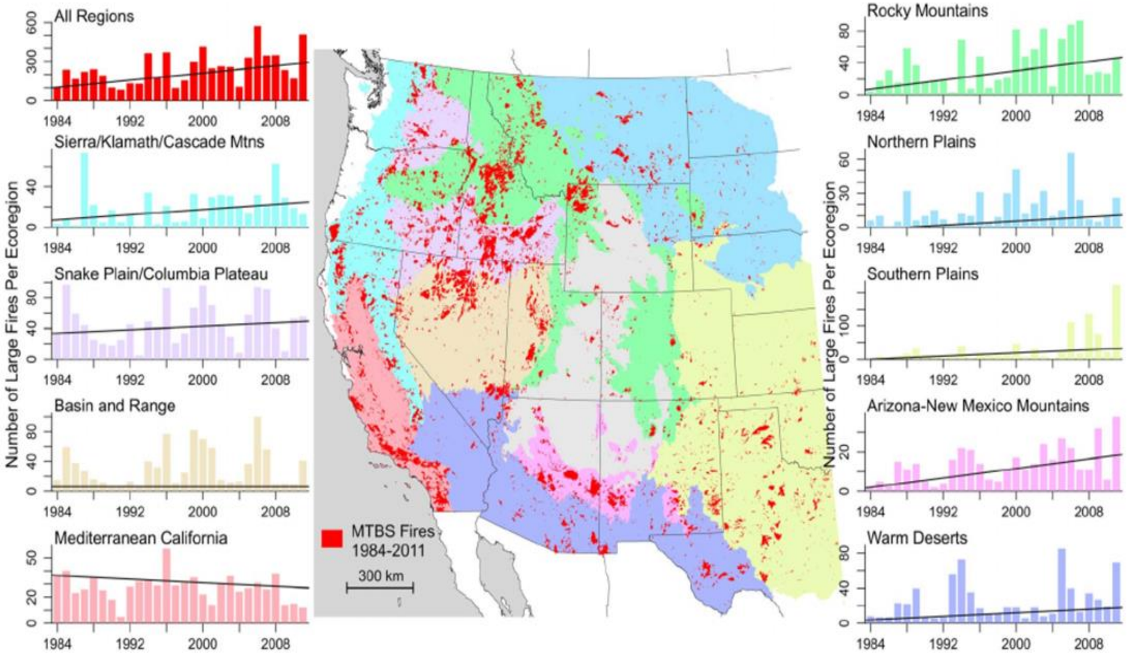
Background ***Intensifying Wildfires***

What changes in drought are in progress now?





Increasing drought conditions in western U.S.

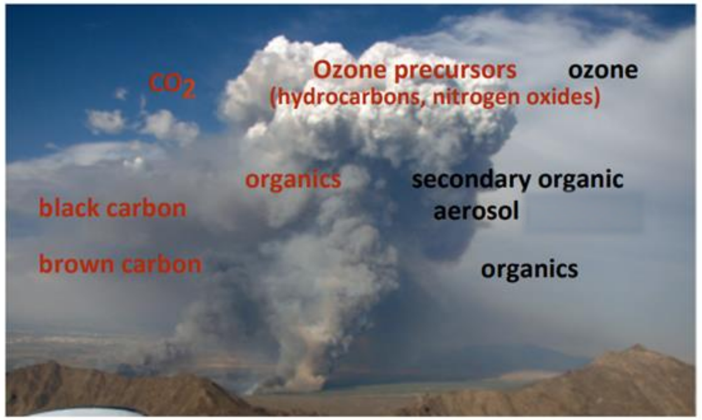
→ **Wildfires!**

Western U.S. trends for number of large fires in each ecoregion per year.
Dennison et al.(2014)

Background ***Vertical Distribution of Wildfire Emissions***

Wildfire Emission Inventory

- CO_2
- CO
- CH_4
- SO_2
- NH_3
- Nitrogen oxides (NOx)
- Water vapor
- Particulate matter (PM)
- Organic carbon
- Hydrocarbons
- Elemental carbon
- Volatile organic compounds (VOCs)

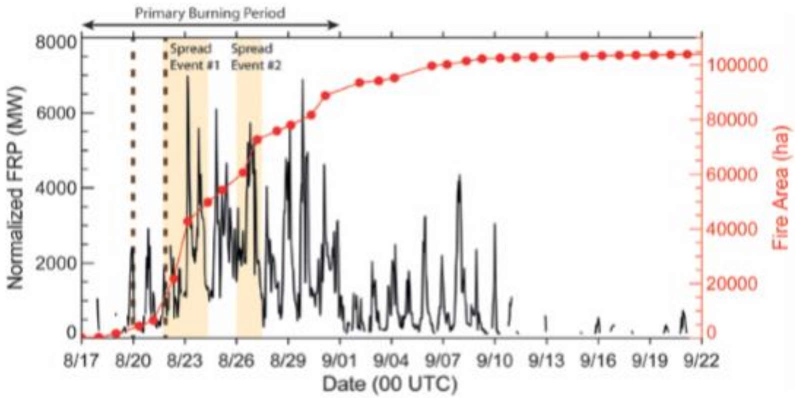


direct emissions → other pollutants formed downwind

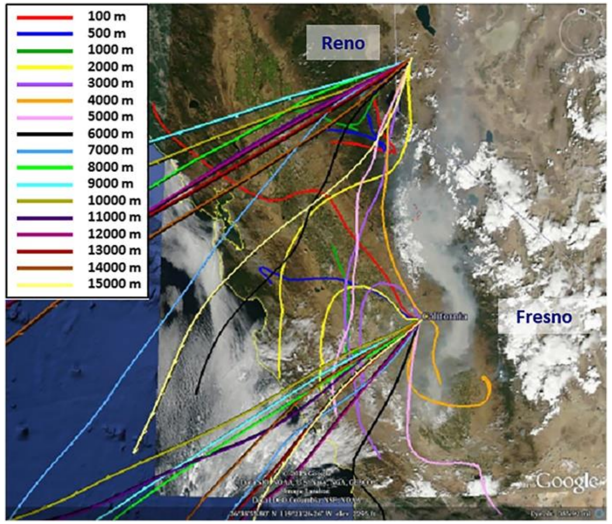
Plume **I**njection **H**eight (PIH)
Planetary **B**oundary **L**ayer **H**eight (PBLH)
Free **T**roposphere (FT)

Plumes inject into FT or reside in PBLH?

Case Study **2013 Rim Fire**



Peterson et al. (2015)



HySplit Backward air mass trajectories over visible satellite image (MODIS true color) of smoke plumes on 31 Aug 2013.

Loría-Salazar et al. (2021)

- As of 2013, the largest forest fire on record in the Sierra Nevada
- As of 2021, the 11th largest megafire in California history
- 104,131 ha of the Stanislaus National Forest and Yosemite National Park burned
- Cost $127.3 million to fight
- Widespread devastation
- Unhealthy air for hundreds of miles

- Two days of large fire growth occurred on August 22 (37,625 acres) and August 23 (51,793 acres).
- The primary burning period of 17-31 August was marked by the largest observed fire spread.

Method ***Wildfire Plume Rise Schemes***

- **Old but fundamental:** Briggs' solutions (1969, 1970, 1975, 1983, 1984)
  - A "old physics" of "turbulent fluid mechanics" model derived from chimney stacks as a function of atmospheric stability.
  - Adaptation for wildfires:

$$H_c = \begin{cases} 1.56\,[F_b/(Uu_*^2)] & \text{Neutral} \\ 2.6[F_b/(US)]^{\frac{1}{3}} & \text{Stable} \\ 30[F_b/U]^{0.6} & \text{Unstable} \end{cases}$$

H_c - final plume center-line height
F_b - buoyancy flux
U - near-surface wind velocity
u_* - friction velocity
S - static stability

  - Conversion to the plume top height $H_p = 1.5H_c$.
  - Inputs: 1) MODIS Fire Radiative Power (FRP);
    2) meteorological information from Weather Research and Forecasting Model (WRF) simulations co-located with active fire locations.
  - We used 10×FRP proposed by Val Martin et al. (2012) as total heat flux to estimate buoyancy flux.
  - We applied the layer-by-layer approach described by Turner (1985) for the determination of H_p based on the stability of each vertical layer.

Method ***Wildfire Plume Rise Schemes***

- **New:** Sofiev et al. (2012)

- An extended **semi-empirical** approach relies on energy balance and dimensional analysis.
- MISR satellite data used to both initialize and constrain the parameterization.
- Assume that the heat energy of the fire is spent only against buoyancy forces.
- **Inputs**: 1) MODIS FRP;
  2) meteorological information from WRF simulations co-located with active fire locations.
- Generic formula of final height of the plume top H_p :

$$H_p = \alpha H_{abl} + \beta \left(FRP/P_{f0}\right)^{\gamma} + exp(-\delta N_{FT}^2/N_0^2)$$

H_{abl} - PBLH
P_{f0} - reference FRP
$\alpha, \beta, \gamma, \delta$ - parameter sets
N_0 - reference Brunt Vaisala frequency
N_{FT} - Brunt Vaisala frequency at FT

calculation procedures:

1) use α = 0.15, β = 102 m, γ = 0.49, δ = 0 to calculate temporary plume injection height H_t.

2) to calculate final plume injection height H_p :
   if $H_t < H_{abl}$, use α = 0.24, β = 170 m, γ = 0.35, δ = 0.6 ;
   if $H_t > H_{abl}$, use α = 0.93, β = 298 m, γ = 0.13, δ = 0.7 .

Method ***Satellite Remote Sensing Observations***

- Multi-Angle Implementation of Atmospheric Correction (MAIAC)

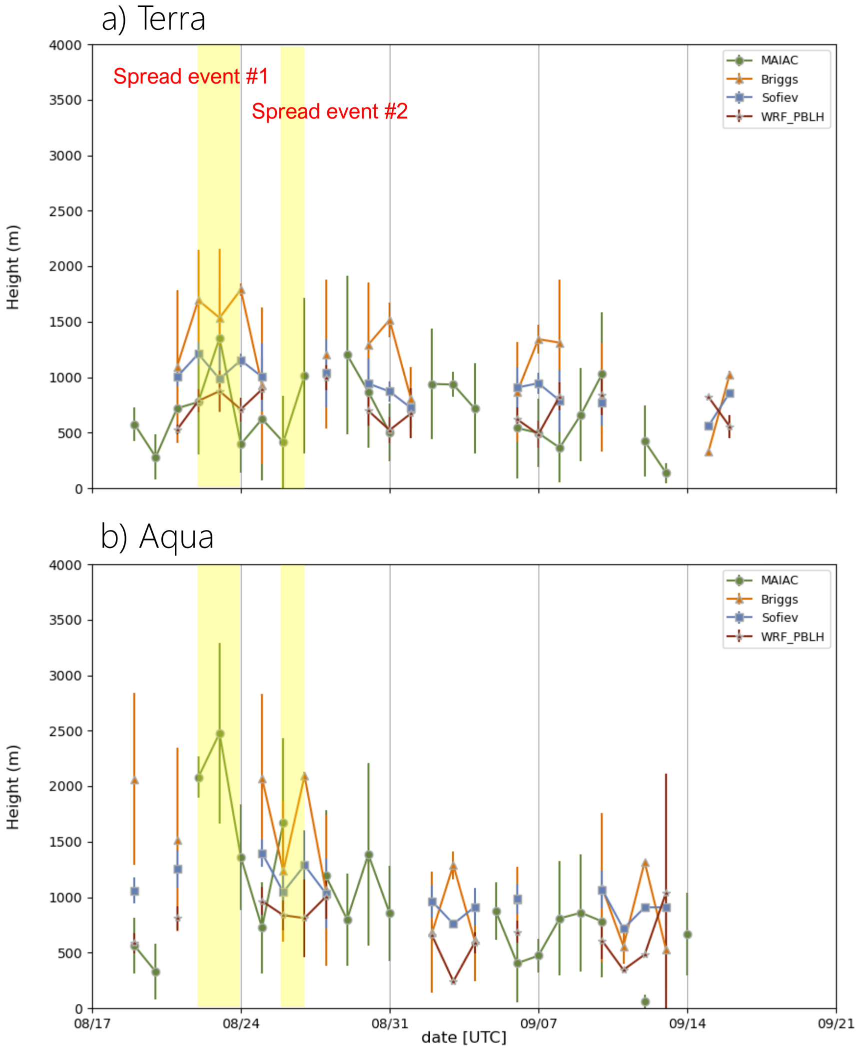
  - Fine-mode smoke aerosol is transparent at MODIS 11 μm channel. AOD > 0.8 (at 470 nm) indicates "thick" smoke.
  - Thermal technique for plume injection height from MODIS Terra and Aqua C6 datasets.
  - To compute an effective PIH:

    1) create thermal contrasts (11 μm) by the absorption of gases emitted during combustion phase and their entrainment into the rising plume between the smoke plume and smoke free background;

    2) assume an average lapse rate (6.5 C km^{-1}).
  - This method is only reliable for smoke transported near active fire sources but with higher resolution (Lyapustin et al., 2020).

Results ***Plume Injection Height Algorithm Comparison***

Daily Variation of PIH during 2013 Rim Fire



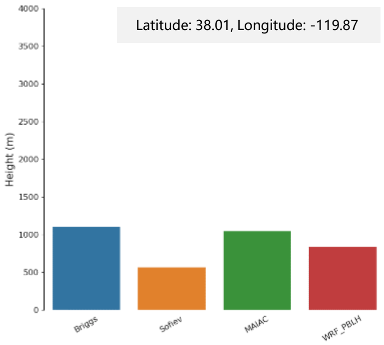
Spatial-Temporal Statistical Summary of PIH (in meters)

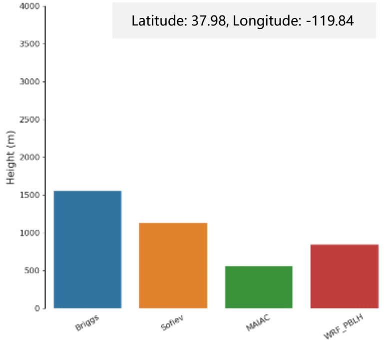
	Briggs/Terra	Briggs/Aqua	Sofiev/Terra	Sofiev/Aqua	MAIAC/Terra	MAIAC/Aqua
N	445	388	445	388	3618	3799
Min	195.14	163.77	405.79	500.59	0.75	0.10
Max	3388.91	3212.70	1589.39	1749.41	2587.42	3748.61
Mean	1251.86	1196.09	969.79	1068.89	771.72	1144.61
Median	1256.09	993.19	1037.42	1117.15	649.60	985.35
Std(±)	643.24	743.52	276.62	260.94	556.22	850.26
P25	646.36	570.21	680.01	905.83	325.77	474.64
P75	1721.41	1808.57	1187.58	1270.71	1156.57	1579.50

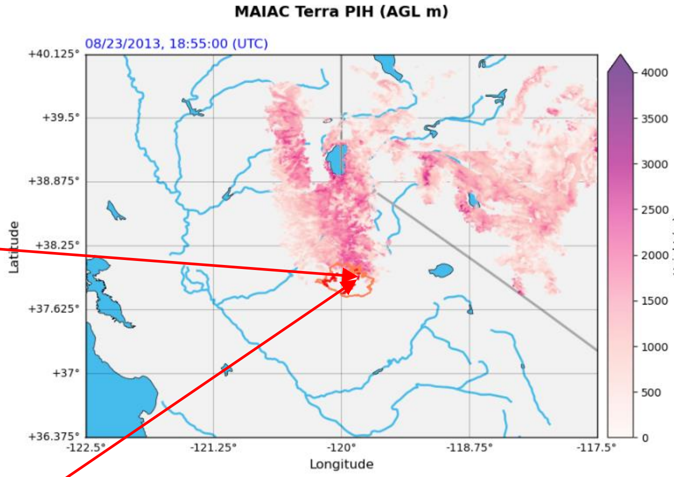
- Briggs overestimates PIH values when fire becomes contained but close to satellite observations for extreme wildfires that spread rapidly.
- Sofiev shows stable performance in PIH predictions; however, Briggs has more daily variations of PIH.
- Aqua (local afternoon) MODIS FRP data is a better fit as inputs used in PIH algorithms.

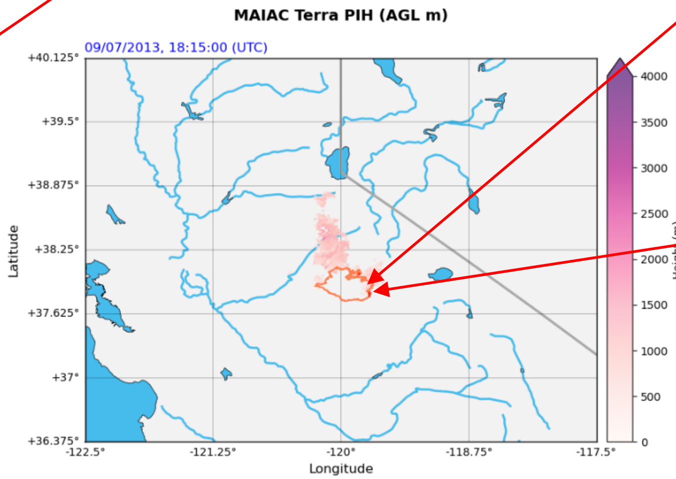
Results ***Evaluation of Plume Rise Schemes***

- Large fire day: Aug 23, 2013
  Briggs tends to reach the maximum PIH value observed by satellite.

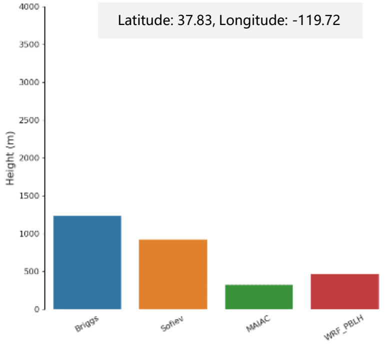


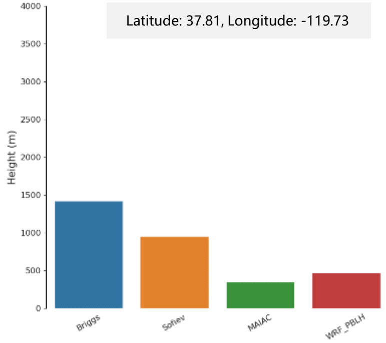




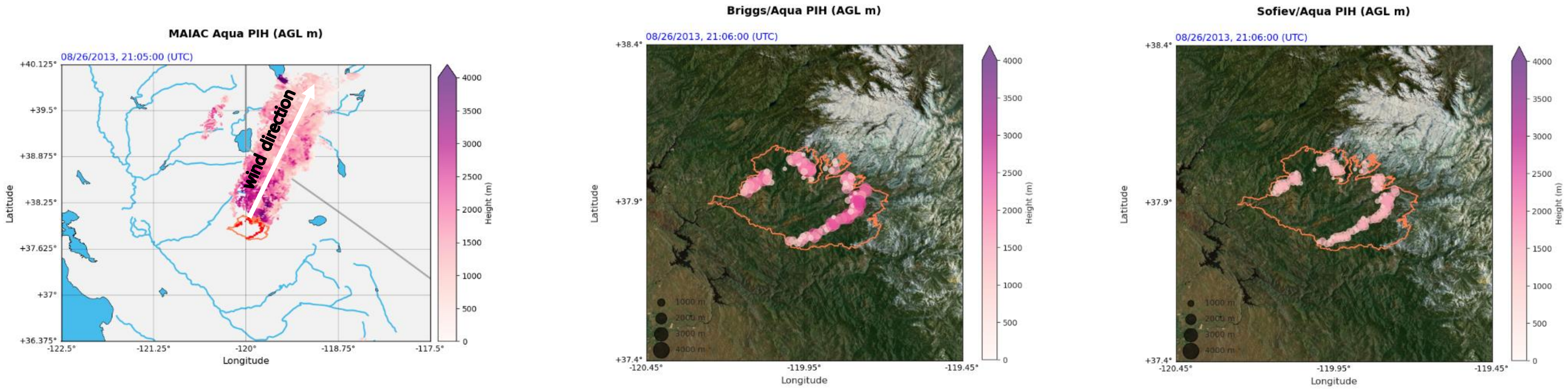


- Small fire day: Sep 7, 2013
  Briggs is too high to capture small fire behaviors; Sofiev is then preferred.



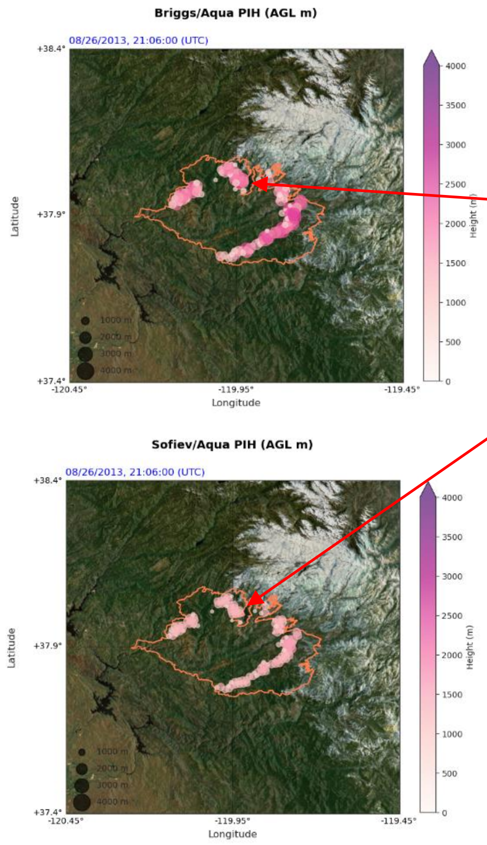


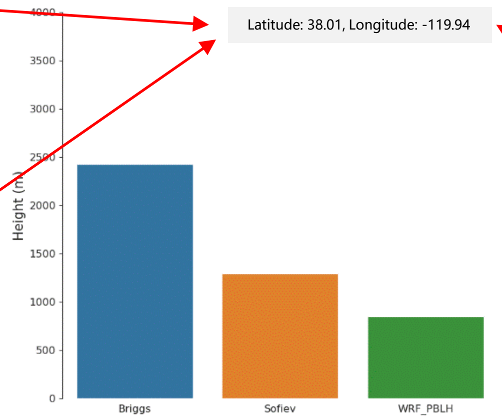
Results ***Evaluation of Plume Rise Schemes***

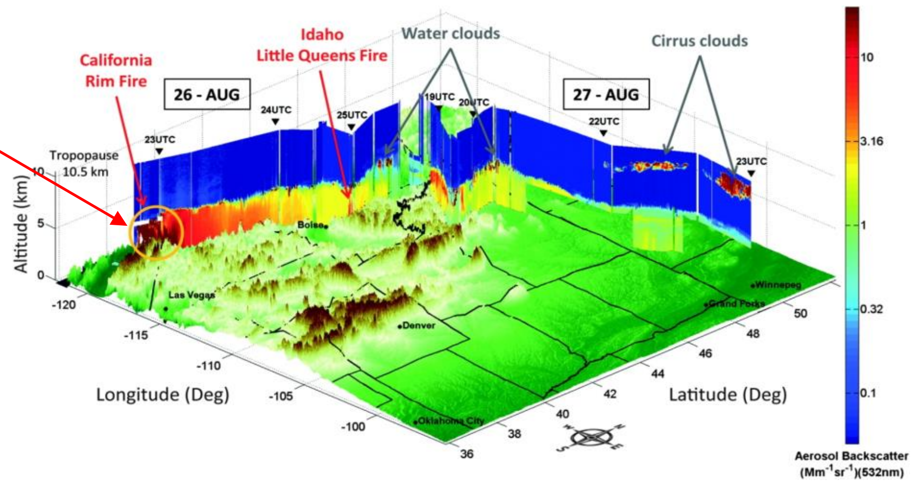


- Briggs can reflect the general trend that fire progresses due to highly spatial – temporal variability in the predicted PIH values.
- Sofiev will be a prudent choice to estimate average PIH value over the region where wildfire happens.

Results Evaluation of Plume Rise Schemes







Atmospheric backscatter observed by DIAL/HSRL from the surface (sea level) to the mean height of the tropopause (10.5 km) during the two Rim Fire DC-8 flights on 26 and 27 Aug 2013. *(Peterson,2015)*

- The plume injection height differences among these two schemes are not trivial for large wildfire events.
- Briggs has a good agreement with Lidar observations near active fire sources.

Conclusion & Future Work

- Two PIH algorithms have been evaluated by MAIAC satellite PIH retrievals and Lidar observations.
- Briggs' solutions predict higher PIH than Sofiev plume scheme and the calculated PIH values vary greatly over location and time.
- Conservative forecast dominates in Sofiev plume scheme that is not suitable for megafire events.
- Both algorithms significantly rely on satellite FRP data. Large uncertainties in PIH simulations can be affected by PyroCb formed during large wildfire period.
- To develop a new smoke PIH model embedded in air quality models, consider using remote sensing data from geostationary satellites (i.e., GEOS-17, resolution: 2 km, 5 mins) and evaluating the results using data from recent fire field campaigns.

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