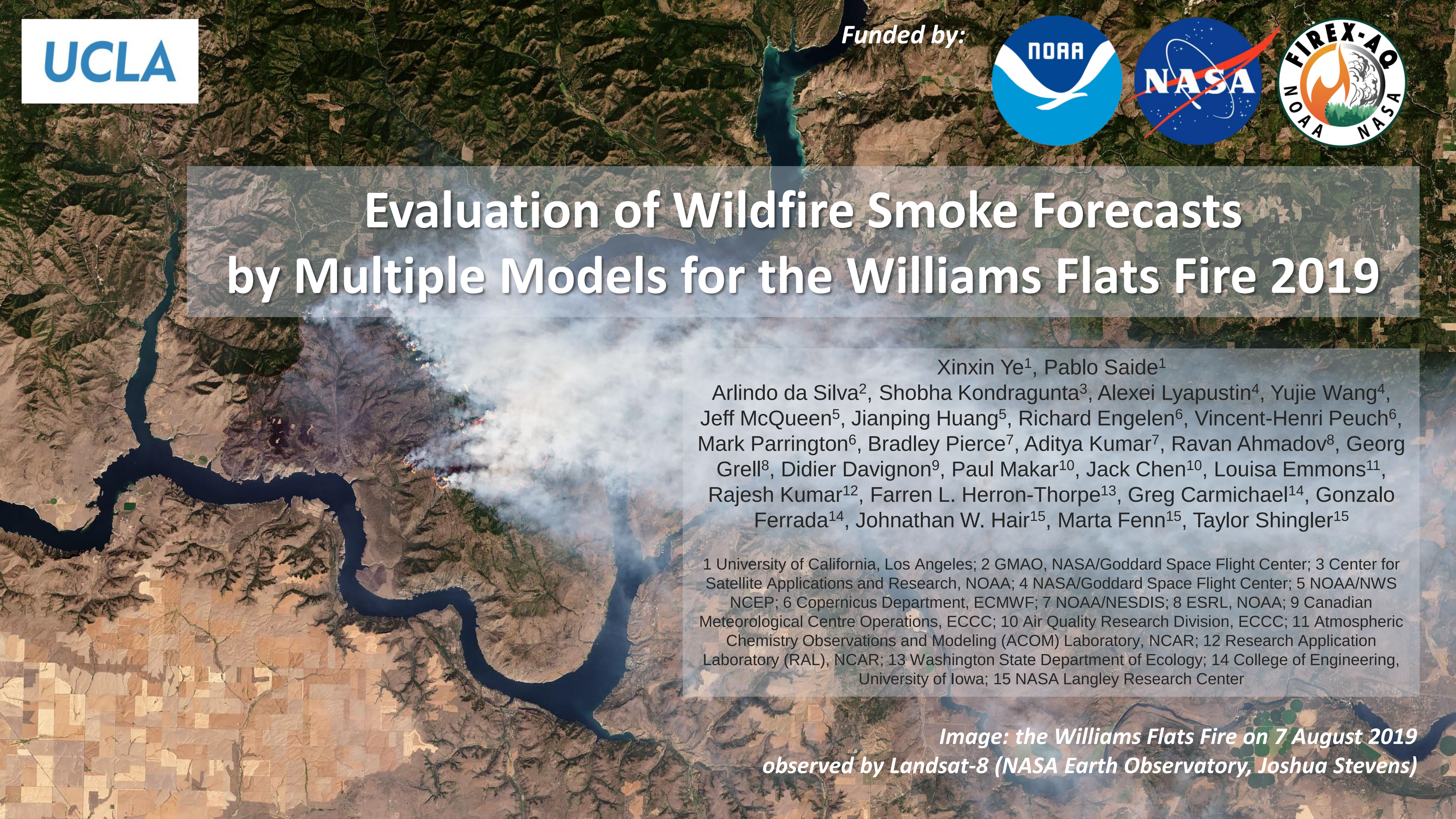

UCLA

Funded by: NOAA NASA FIREX-AQ NOAA NASA

Evaluation of Wildfire Smoke Forecasts by Multiple Models for the Williams Flats Fire 2019

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Image: the Williams Flats Fire on 7 August 2019 observed by Landsat-8 (NASA Earth Observatory, Joshua Stevens)

Motivations

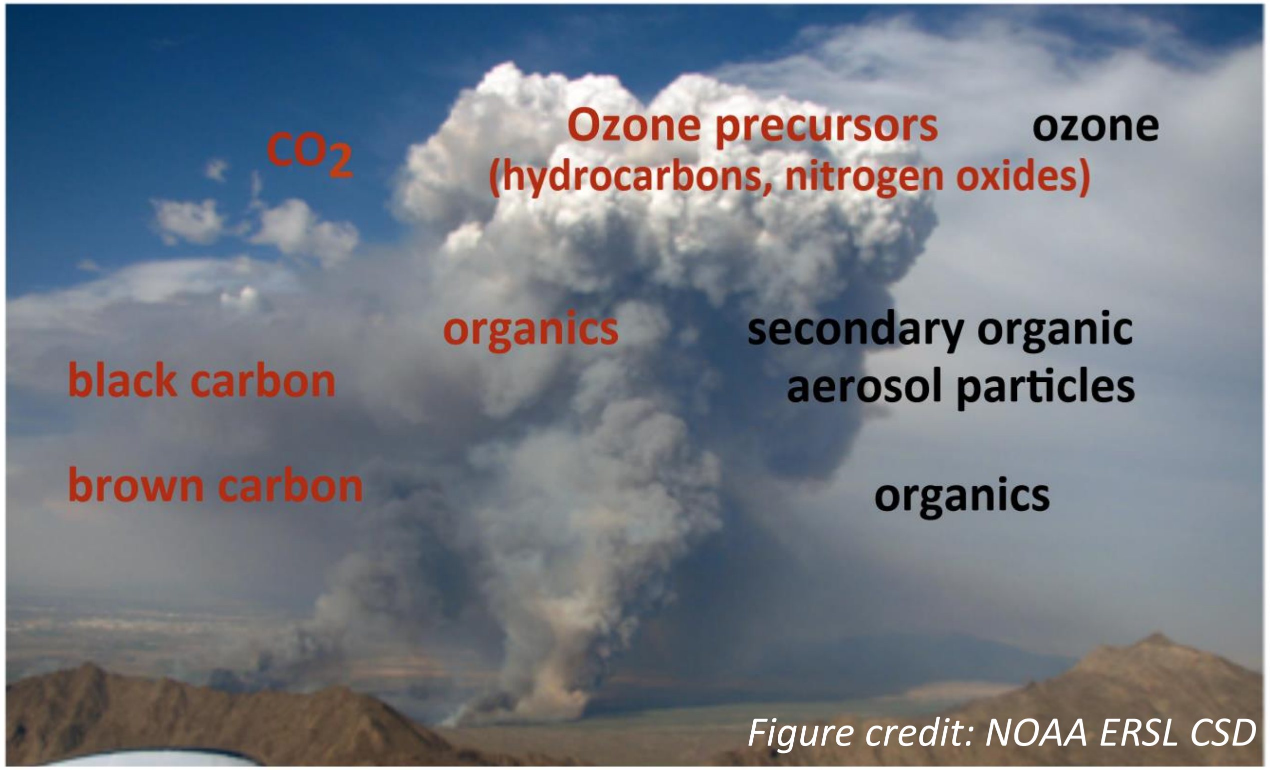


Figure credit: NOAA ERSL CSD

direct emissions → other pollutants formed downwind

Wildfire Smoke

- The western U.S. has seen **substantial increase of frequency and size of wildfires** in recent decades
- Impacts on **air quality, weather, and climate.**
- Predictions of wildfire emissions and smoke are within the **largest uncertainties of air quality forecasts**

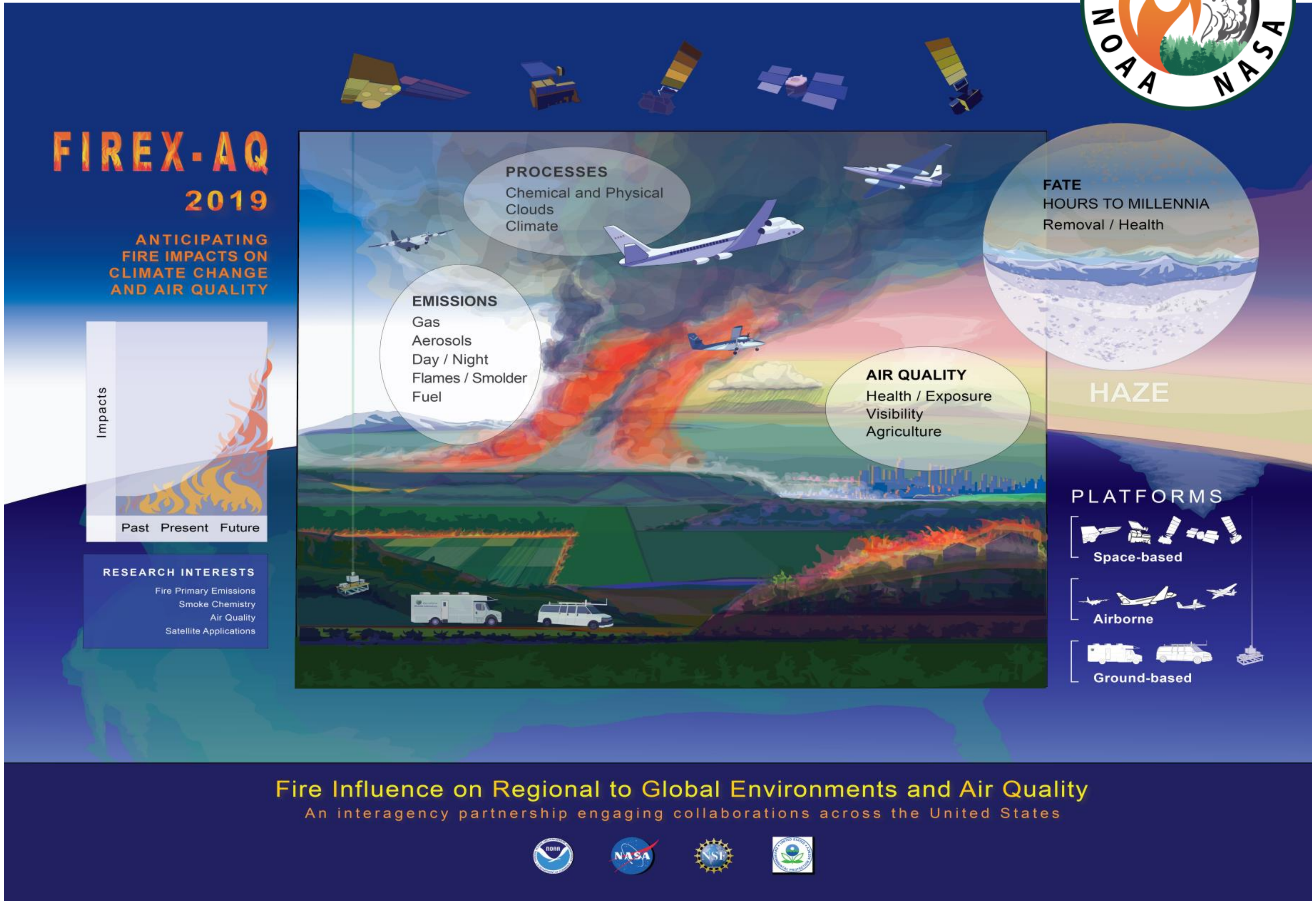
Challenges for Smoke Forecasting

- **Persistency** of fire activity throughout forecasting period?
- **Prescribed diurnal cycle** for fire emissions
- **Plume rise (emission injection)** parameterization

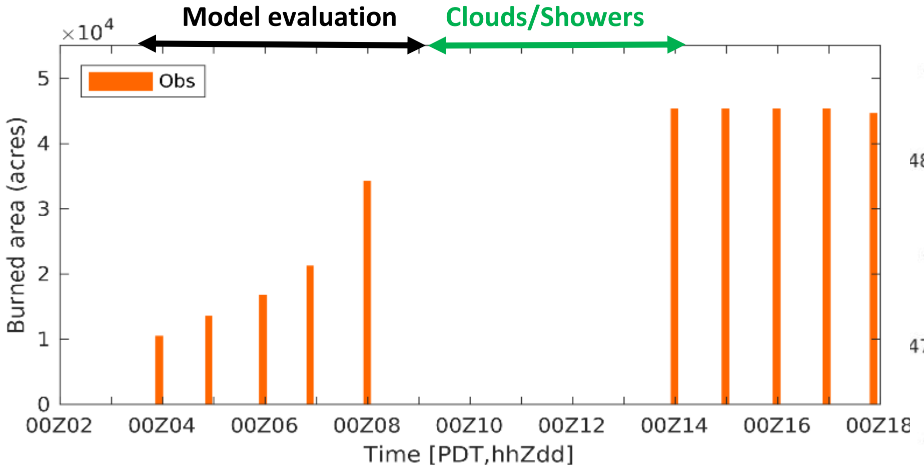
Where are we standing? How to improve smoke forecasting performance?

Fire Influence on Regional to Global Environments and Air Quality (FIREX-AQ)

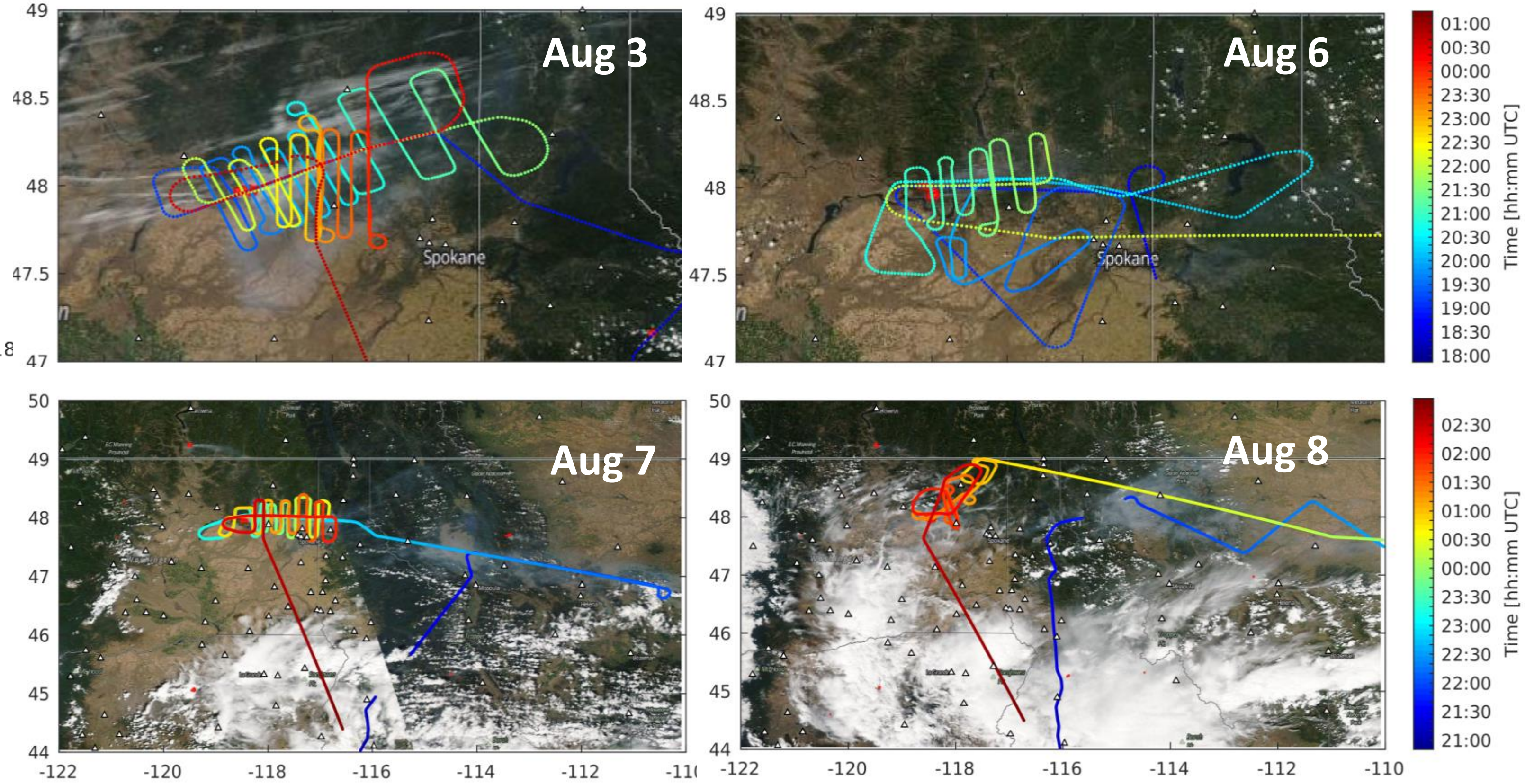
- A joint project led by NOAA and NASA
  - July-August 2019: Boise, ID
  - August-Sept 2019: Salina, KS
- Comprehensive observations and forecasts are collected; coordination between platforms
- Composition and chemistry of smoke from wildfires and agricultural fires in the continental U.S.; ignition to transport
- Investigate the impact on air quality and climate



Williams Flats Fire (2-14 August 2019)



DC-8 flights that sampled the Williams Flats Fire



(*Background*: MODIS AQUA true color image
Source: NASA WorldView)

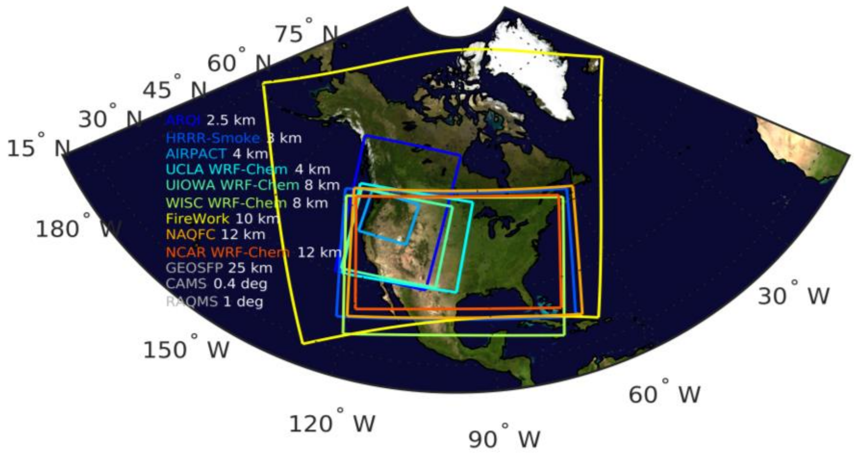
Objectives

- Spatial and temporal evolution of the fire event
- Evaluate performance of models forecasts for fire smoke plume from different dimensions
- Provide implications for future development and improvement of smoke forecasting

Wildfire Smoke Forecasting Systems

Model	Forecast domain	Institution	Grid resolution	Initial time (UTC)	Chemical mechanism	Fire emission key parameter (inventory)	Plume injection	Assim. of satellite data
GEOSFP	Global	NASA/GMAO	5/16×1/4 deg	00	Simplified	FRP (QFED)	No	Yes
CAMS	Global	ECMWF	0.4 deg	00	Full	FRP (GFASv1.2)	Yes	Yes
RAQMS	Global	University of Wisconsin	1.0 deg	12	Full	hotspots (RAQMS)	No	Yes
ARQI (FireWork experimental)	NW US & SW Canada	ECCC	2.5 km	12	Full	hotspots (CFFEPSv4.0)	Yes	No
HRRR-Smoke	CONUS	NOAA/ESRL/ GSD	3 km	00	Smoke tracer	FRP	Yes	No
AIRPACT	NW US	Washington State University	4 km	08	Full	hotspots (SMARTFIRE/ Bluesky)	Yes	No
UCLA WRF-Chem	W US	UCLA	4 km	00	Smoke tracer	FRP (QFED, with inversion)	Yes	Yes (constrain emis.)
UIWOA WRF-Chem	W US	University of Iowa	8 km	12	Full	FRP (QFED)	Yes	No
WISC WRF-Chem	CONUS	University of Wisconsin	8 km	12	Simplified	hotspots (PREP-CHEM)	Yes	Yes (IC)
FireWork	North America	ECCC	10 km	12	Full	hotspots (CFFEPSv2.1)	Yes	No
NAQFC	CONUS	NOAA/NCEP	12 km	12	Full	hotspots (HMS/Bluesky)	Yes	No
NCAR WRF-Chem	CONUS	NCAR/ACOM	12 km	00	Full	hotspots (FINN)	Yes	No

- 12 models are incorporated
- Differences among models in terms of:
  - Fire emissions
  - Plume injection parameterization
  - Assimilation of satellite AOD retrievals
  - Complexity of chemistry
  - Dynamic core and meteorology
  - Time of initialization
  - Domain resolution
  - …



Observations

GOES-17 fire detections and FRP

- Wildfire Automated Biomass Burning Algorithm (WFABBA)

MAIAC AOD

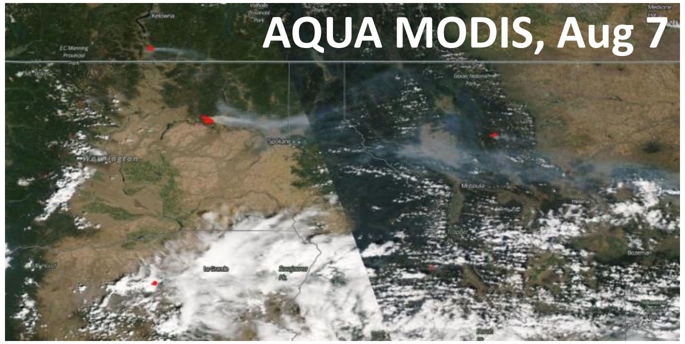
- **MCD19A2 Version 6** (Lyapustin and Wang, 2018)
- **MODIS** Terra and Aqua data using Multi-Angle Implementation of Atmospheric Correction (**MAIAC**)
- Gridded Level 2 product produced daily at 1-km pixel resolution
- Green band AOD (at 550 nm) is used for model evaluation

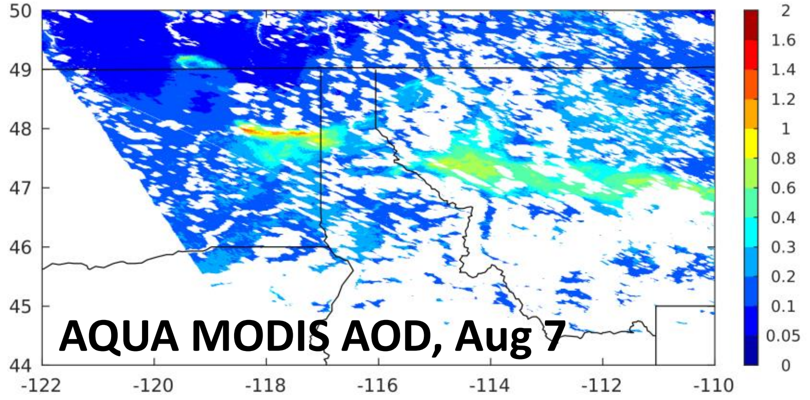
Surface PM2.5

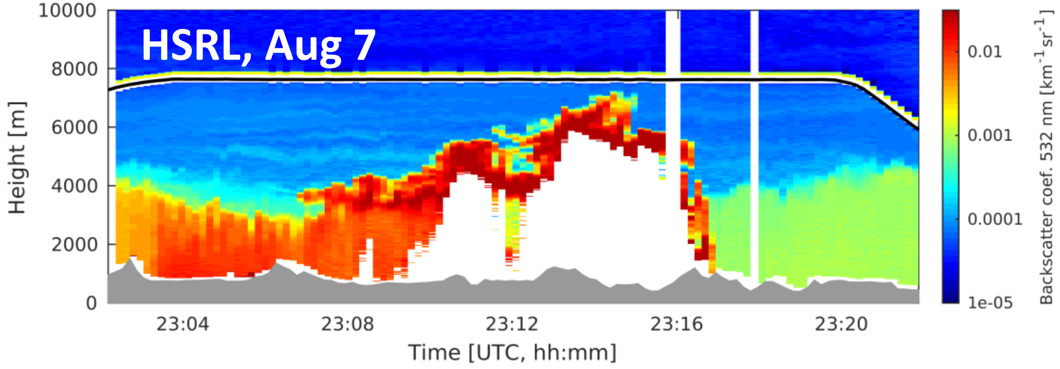
- Collected by Openaq and EPA's Air Data

DIAL-HSRL

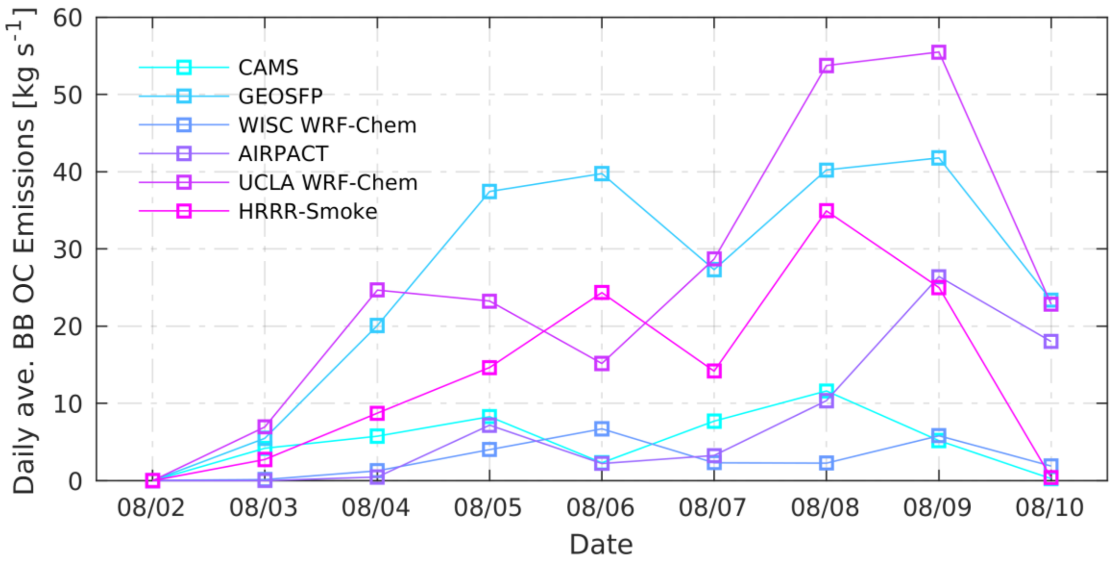
- Airborne Differential Absorption Lidar (**DIAL**) – High Spectral Resolution Lidar (**HSRL**) observations on board NASA's DC-8, collected by NASA Langley Research Center (Hair et al.)
- Provides simultaneous aerosol and ozone profiles above and below DC-8
- Data version: R0

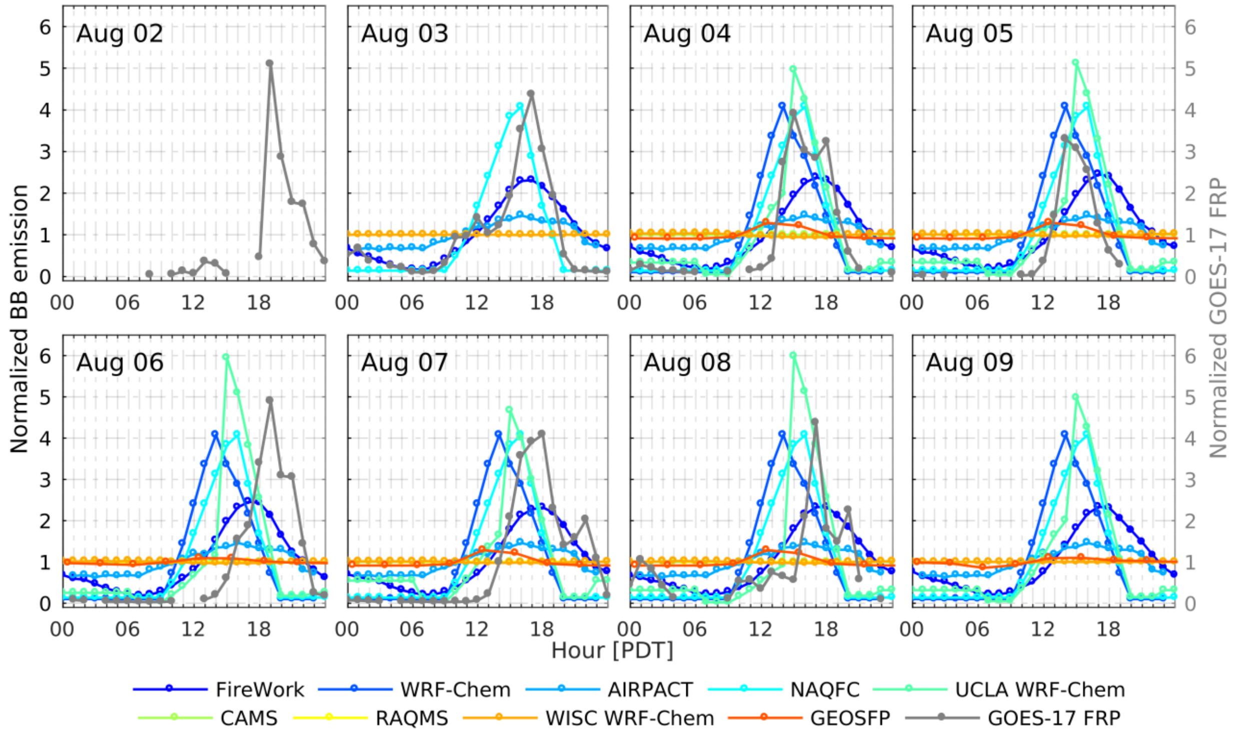






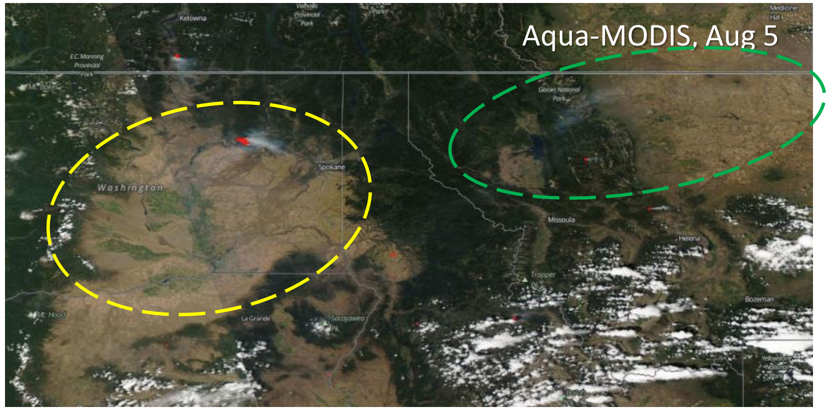
Daily emissions and diurnal variation pattern



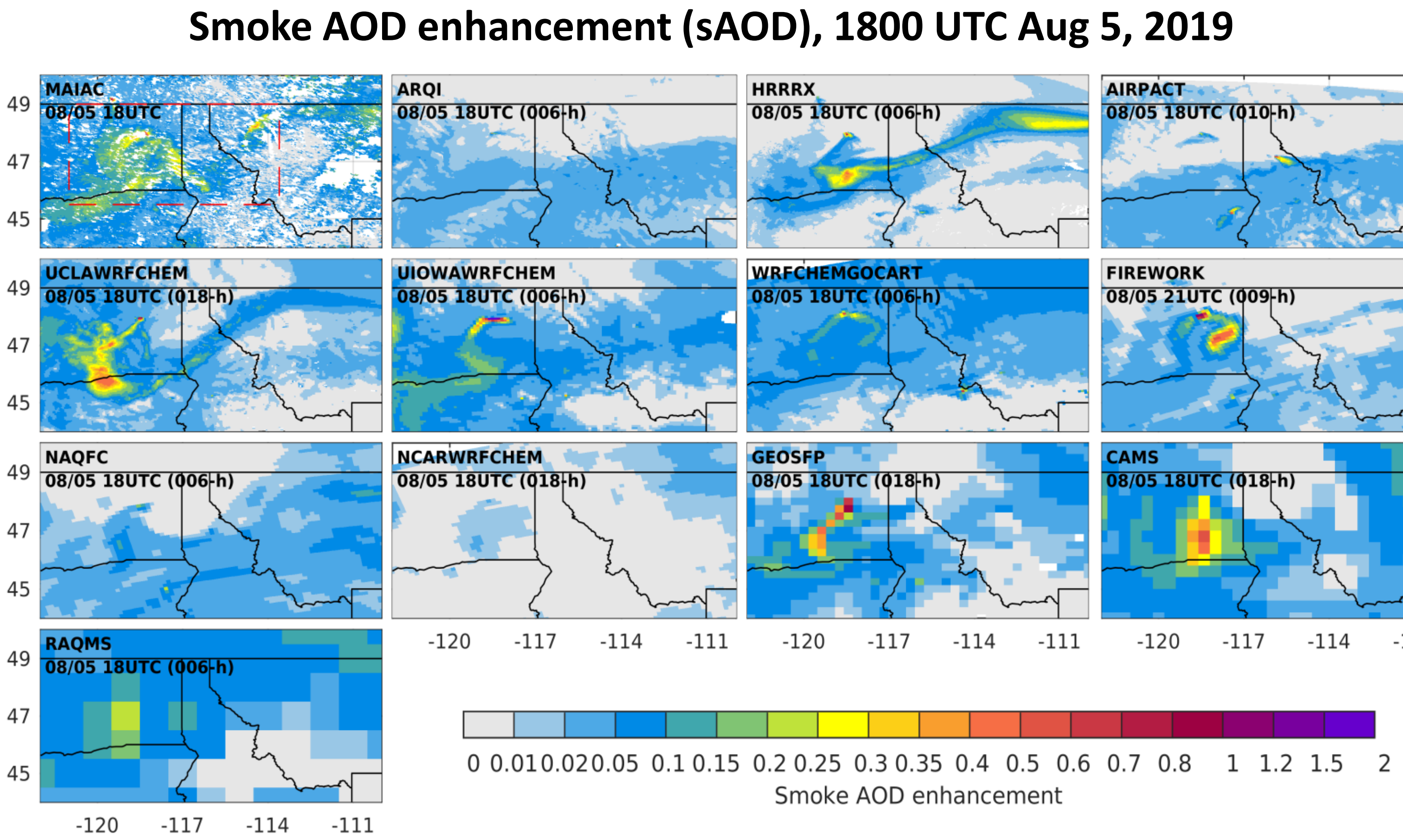


- **Large spread of daily average BB OC emissions** (~×10)
- **FRP-based emissions** are relatively higher than hotspot-based (bottom-up) emissions
- GOES-17 FRP (WFABBA) product shows fire activity **peaking at about 14-19 PDT**
- Models usually assume fixed diurnal factors
- Various diurnal patterns among the models; most patterns deviate from observed FRP
- Nighttime fire activity is not well described by most models (3-4 Aug and 7-8 Aug)

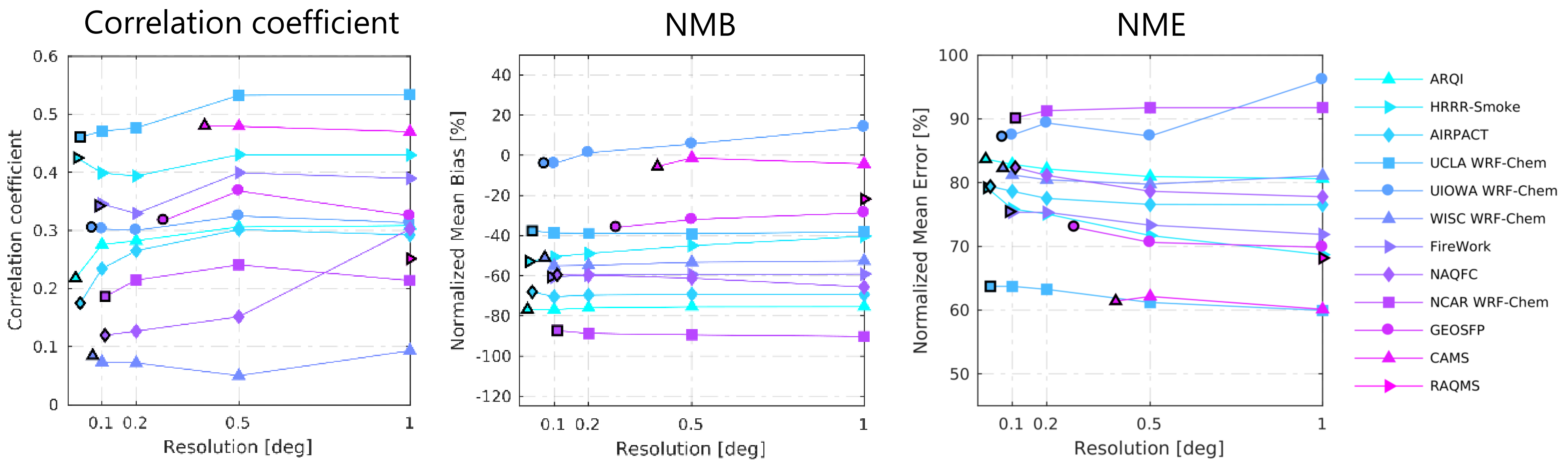
Comparing AOD forecasts against MODIS MAIAC AOD (550 nm)



- Background AOD has been subtracted (using average of the lowest 20% AOD values) for each map of snapshot.
- Grid cells with valid model and obs. data are filtered for statistics.
- MODIS MAIAC AOD data are re-gridded onto the grid of each model for apple-to-apple comparisons.

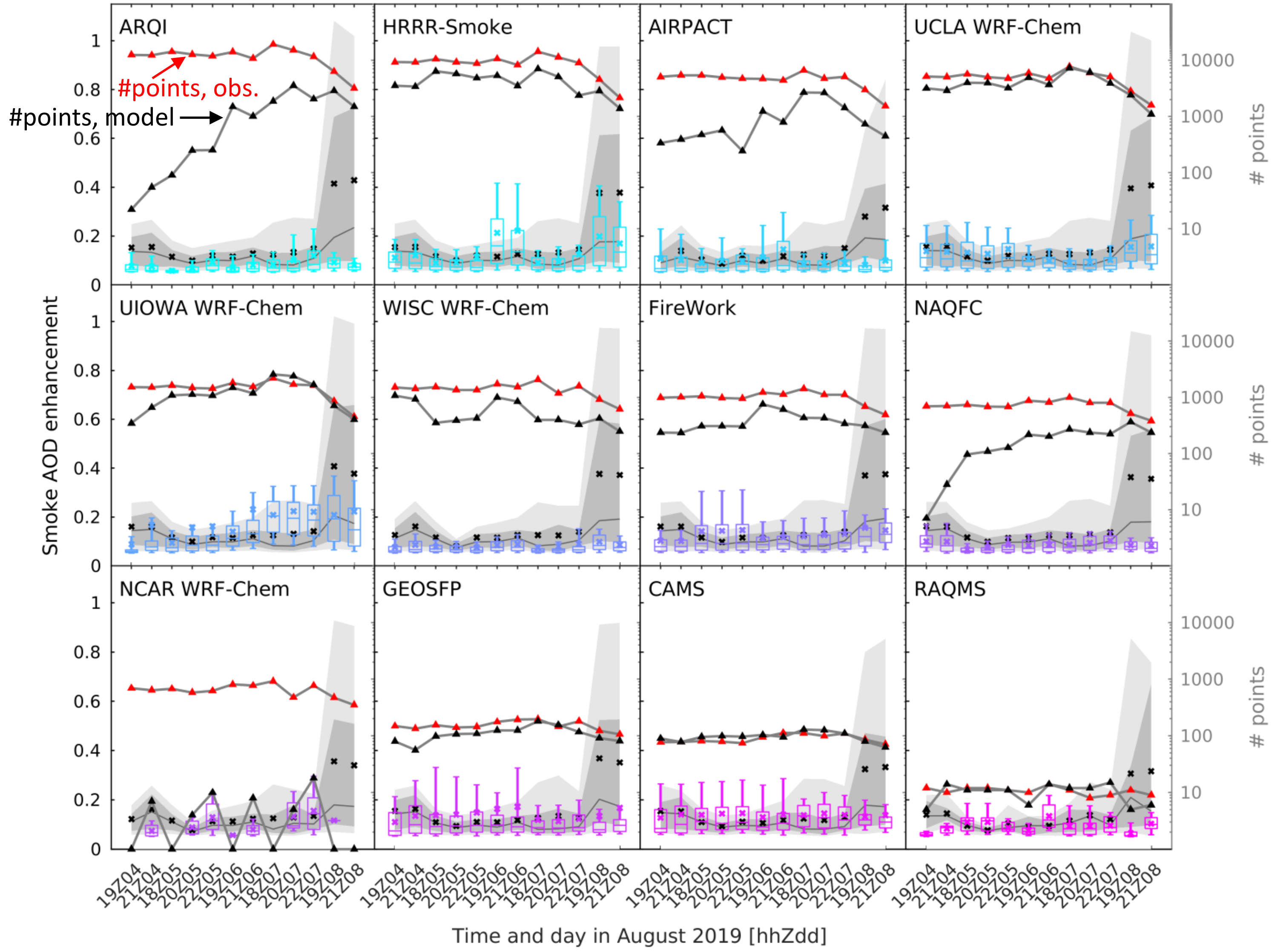


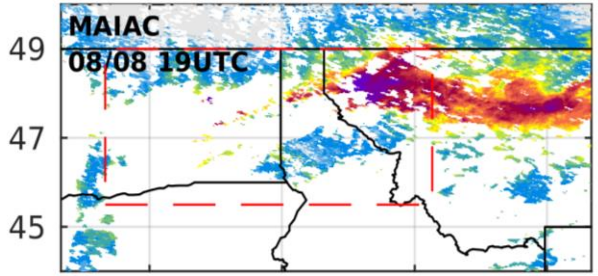
Model performance (at different regridding resolution)

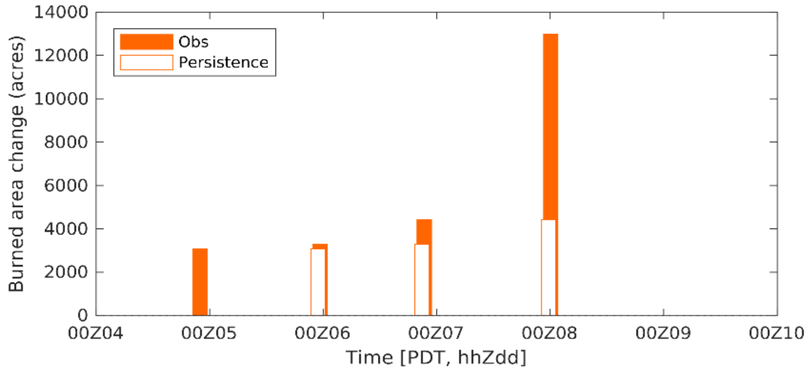


- General **underestimation** of sAOD for nearly all models; **NME>60%; r<0.55**
- Some models show **nearly unbiased** predictions (UIOWA WRF-Chem and CAMS)
- How do the model performance relate to re-gridding resolution?
  - NMB: no significant difference regarding relative performance among the models
  - NME and r: mixed features for different models
- Models driven by FRP-based fire emissions and/or assimilate satellite AOD data have relatively better performance.

Comparing spread of sAOD



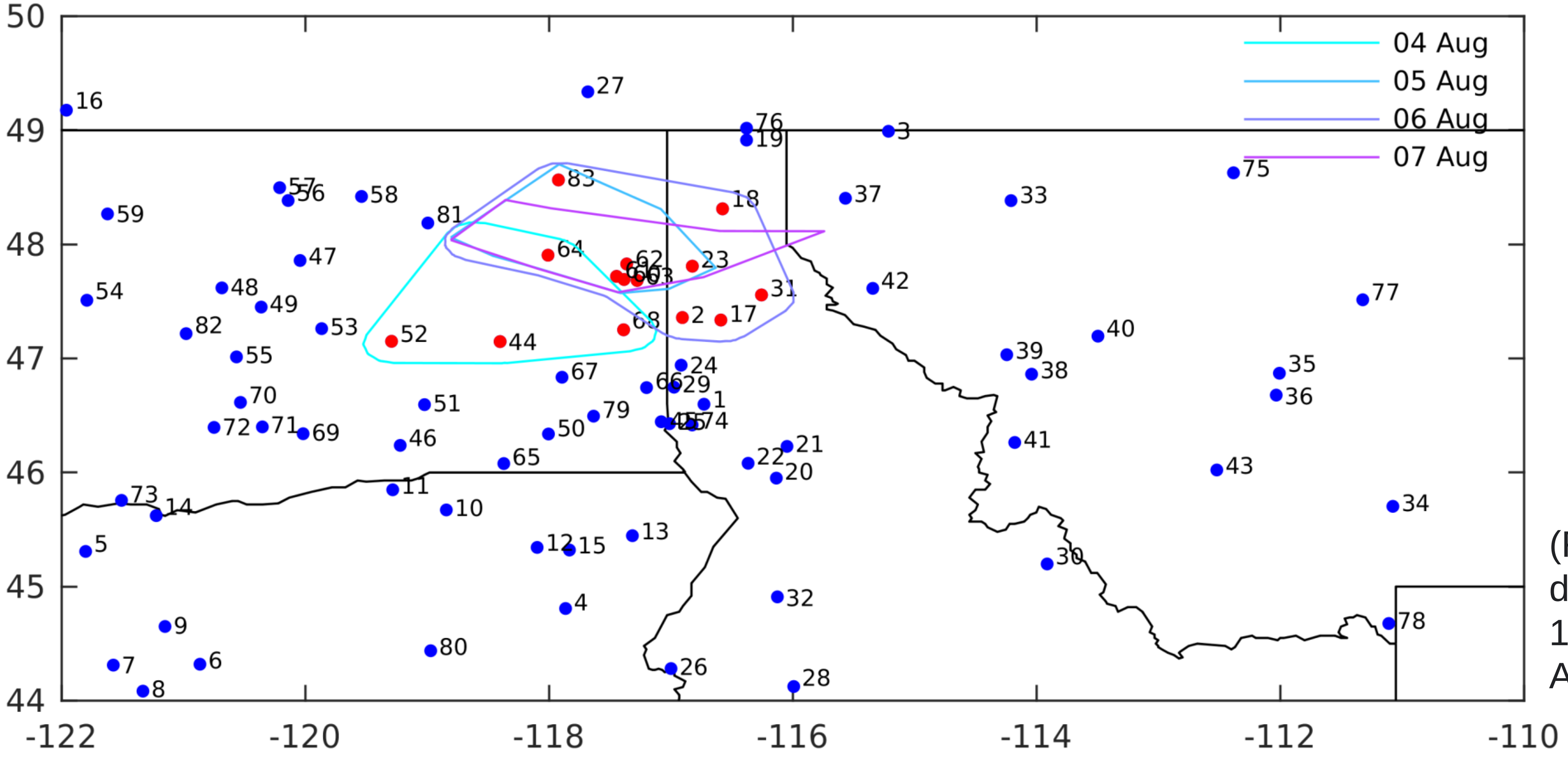




- **Distribution of sAOD (>=0.05)**
- **Boxplots: model; Shading: obs.**
- Filtered within the red box to avoid including other small fires
- Box: 25~75%, whiskers: 10~90%, line: median, x: mean
- Underestimation on Aug 8, related to lower emissions on Aug 7 estimated by persistency

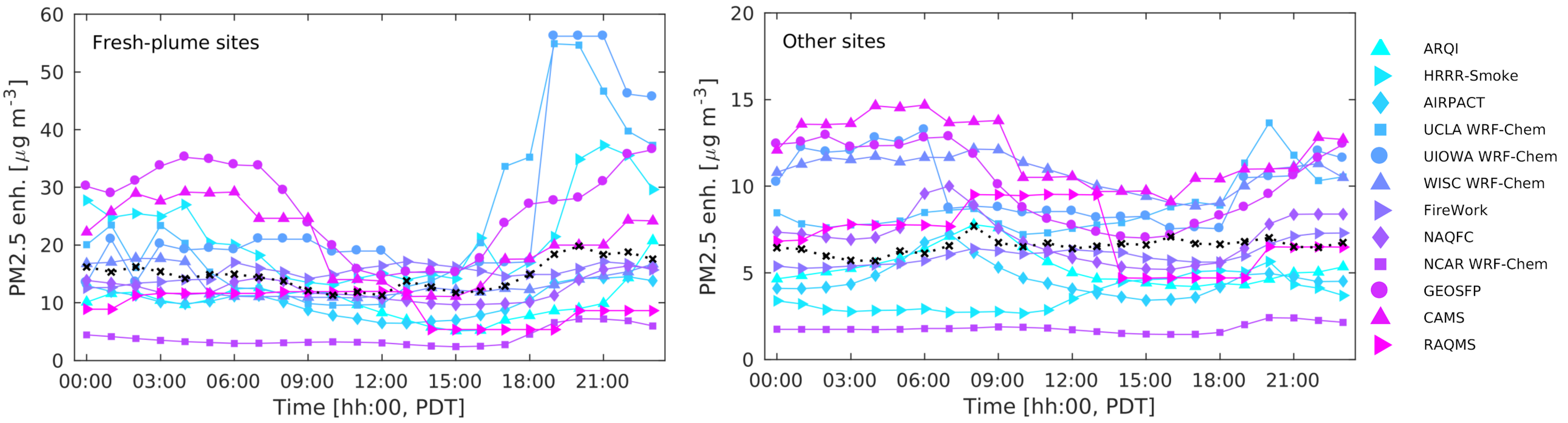
Evaluation of surface PM2.5 forecasts

- Surface PM2.5 measurements by AirNow network (from OpenAQ and EPA's Air Data)
- **83 sites** in the region of analysis; **14 sites** (red dots) with immediate impact by fresh plumes



(Fresh plume boundaries are determined based on GOES-17 visible images and MAIAC AOD by *Pargoal Arab*)

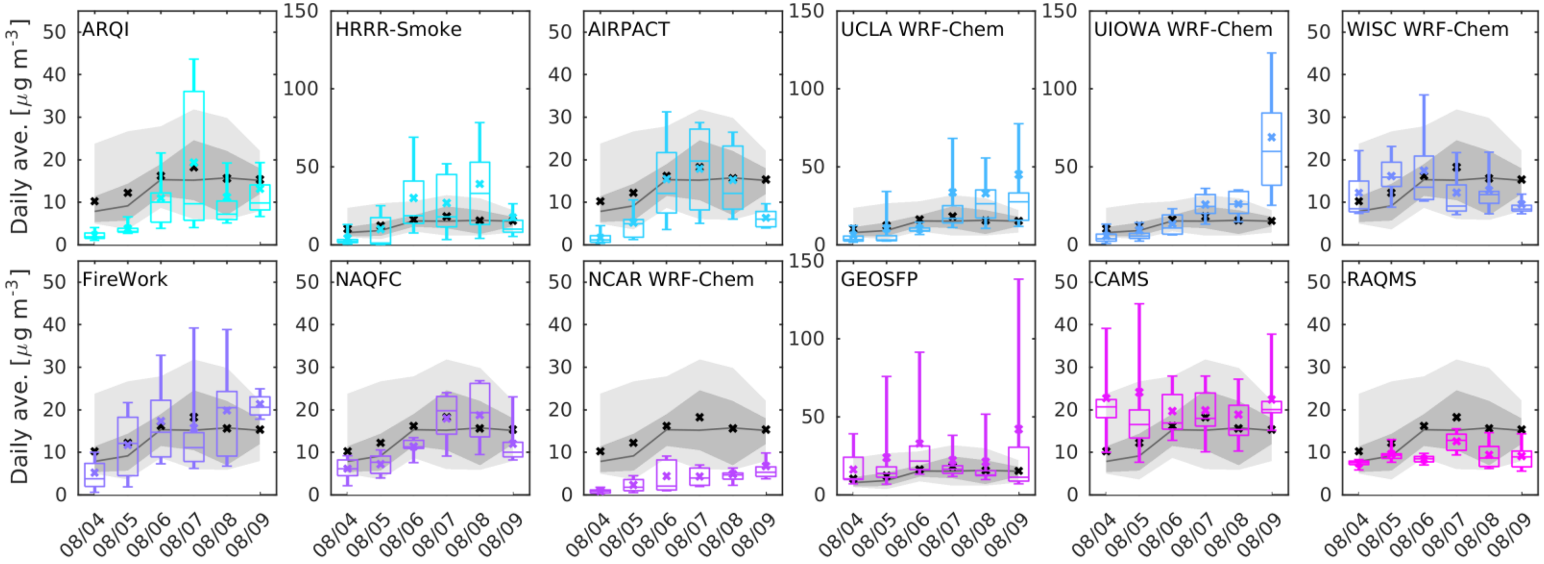
Comparing diurnal variation of PM2.5 enhancements



- Diurnal profile of mean PM2.5 enhancements over different groups of sites
- Most models show **stronger diurnal variations** compared to observations over both groups of sites
- **FireWork** and **NAQFC** show overall good performance.
- Models with **FRP-based fire emissions** show generally **over-estimations**, especially in **late afternoon or nighttime**
- Discrepancies compared to sAOD performance suggest deficiencies in vertical emission allocation, PBL evolution, and nighttime emissions.

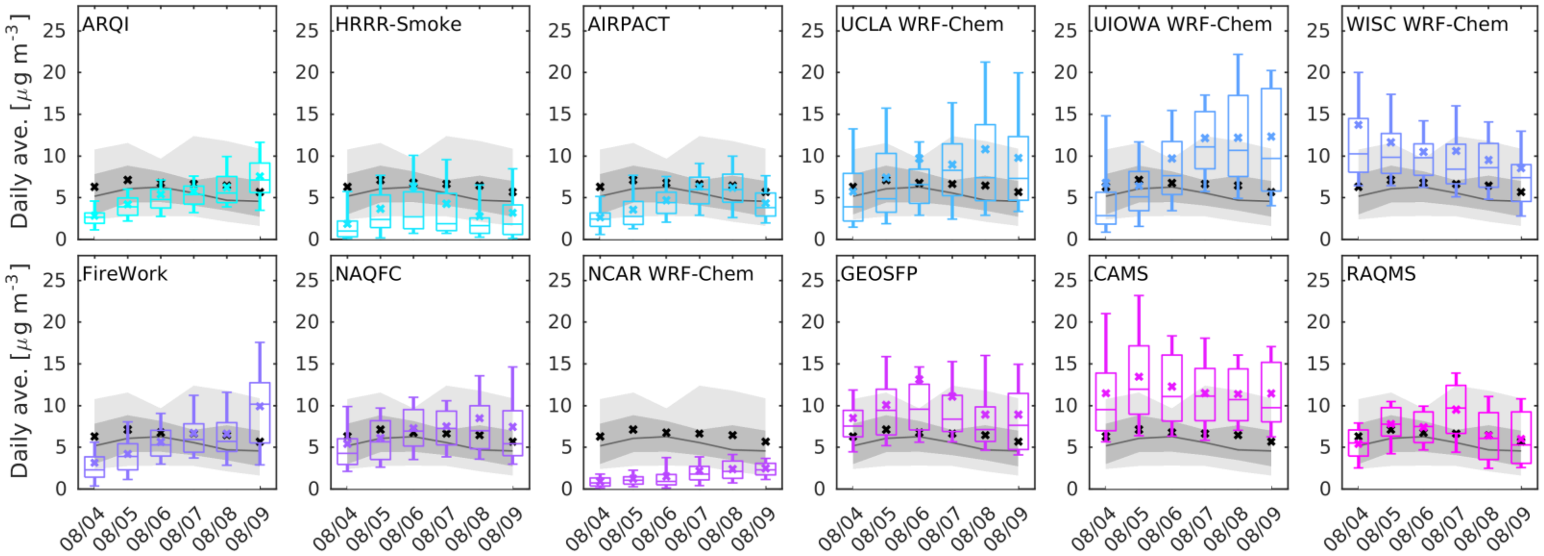
Daily average PM2.5 enhancements on 4-9 August

▪ Fresh-plume sites



- Magnitude of daily average PM2.5 enhancements over two groups of sites
- **Box**: model; **Shading**: obs.
- Fresh-plume sites show an increasing trend, and a peak of mean values ("**x**") on Aug 7.
- Most models captured the trend.

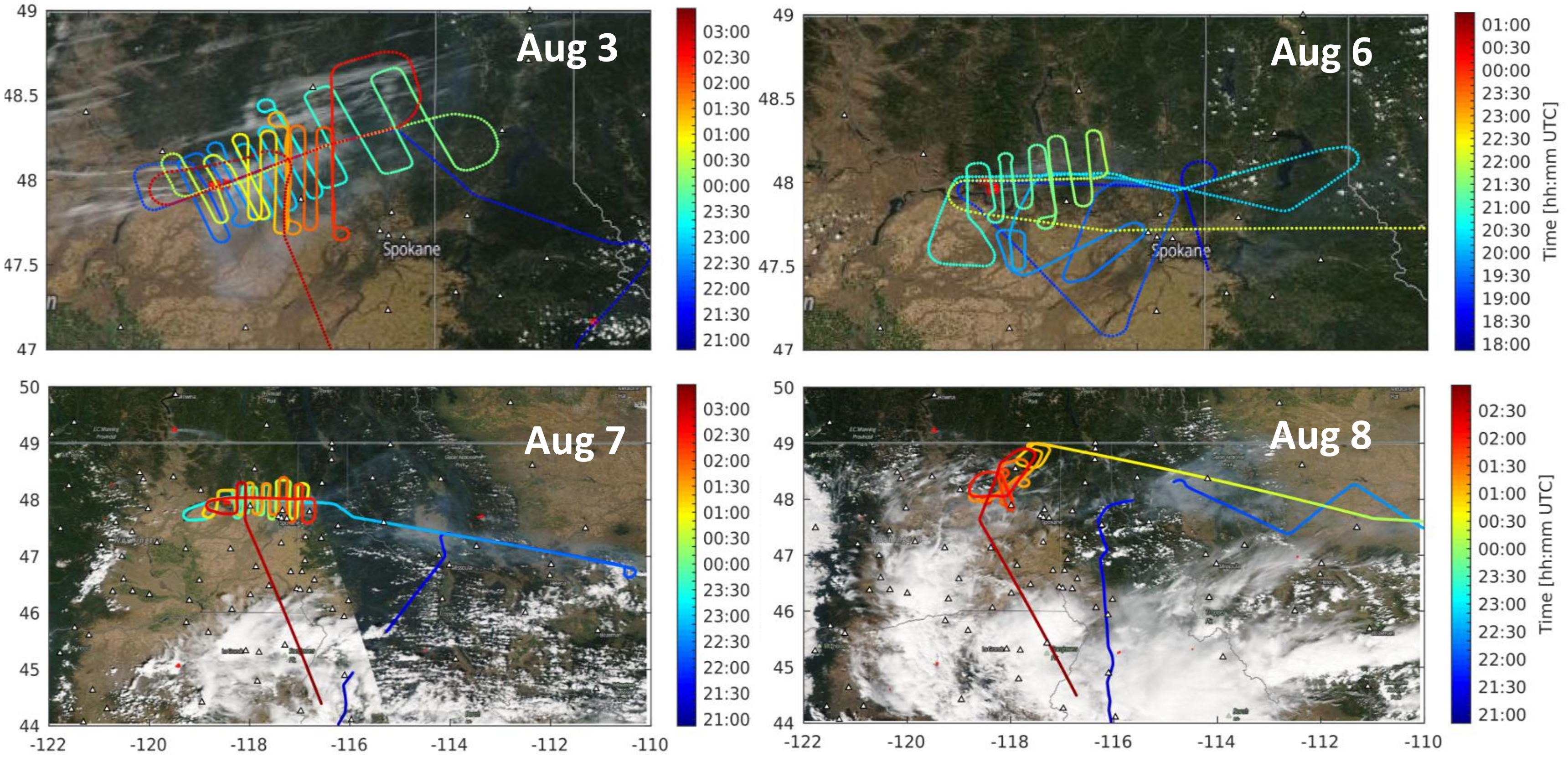
▪ Other sites



- Other sites show a slightly decreasing trend, due to probably the large portion of injected emissions, thus lofted smoke on Aug 8 to 9.

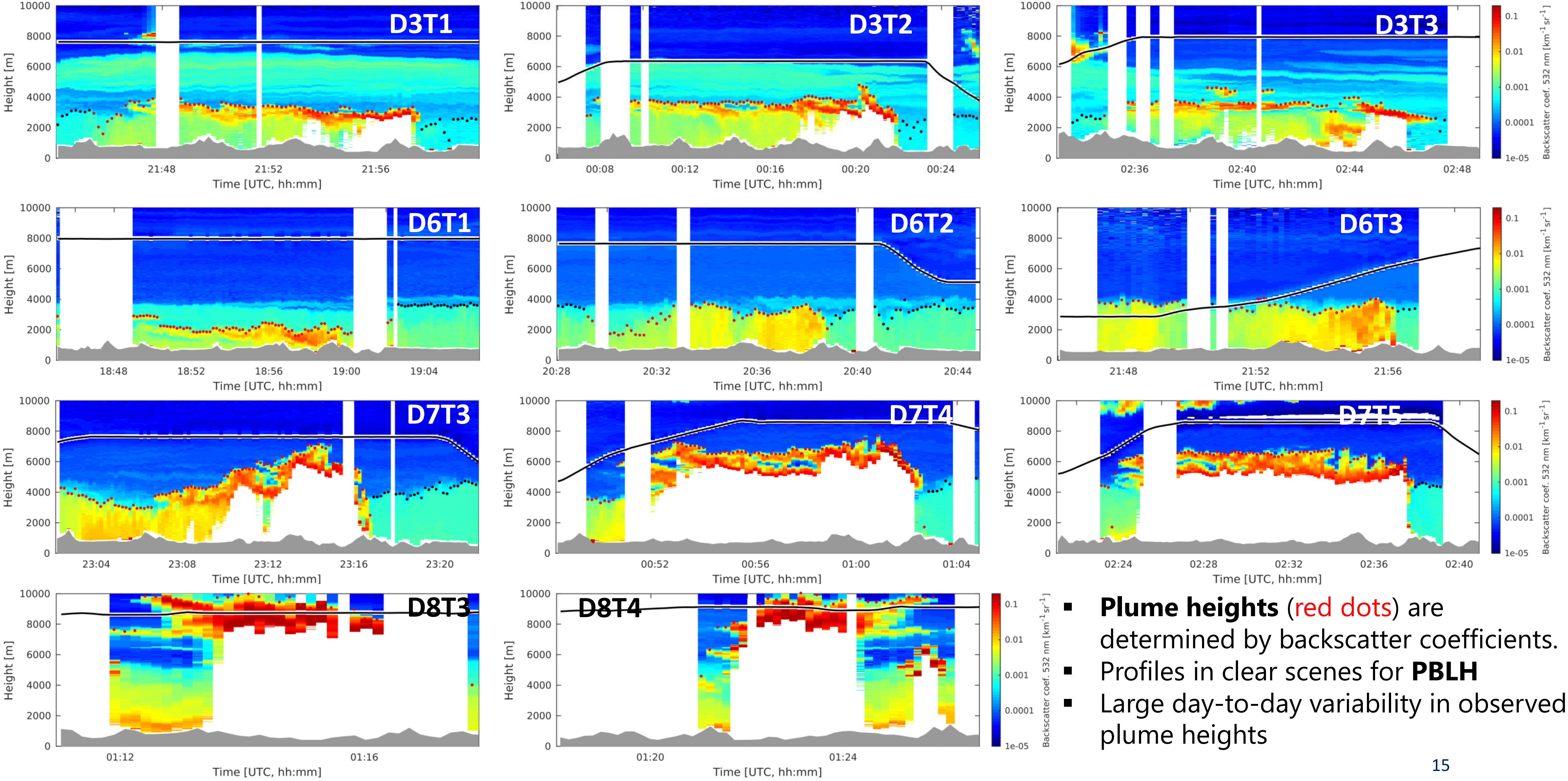
Evaluating plume injection and vertical structure

Flight transect	Date (Aug 2019)	Start time (hh:mm UTC)	End time (hh:mm UTC)	Plume sampled (F: fresh A: aged)
D3T1	03	21:44	22:99	F
D3T2		00:06	00:26	F
D3T3		02:33	02:49	F
D6T1	06	18:45	19:07	F
D6T2		20:28	20:45	F
D6T3		21:46	21:59	F
D7T1	07	21:34	22:10	A
D7T2		22:10	22:55	A
D7T3		23:02	23:22	F
D7T4		00:48	01:05	F
D7T5		02:21	02:41	F
D8T1	08	21:35	22:07	A
D8T2		00:09	00:36	A
D8T3		01:11	01:18	F
D8T4		01:18	01:27	F



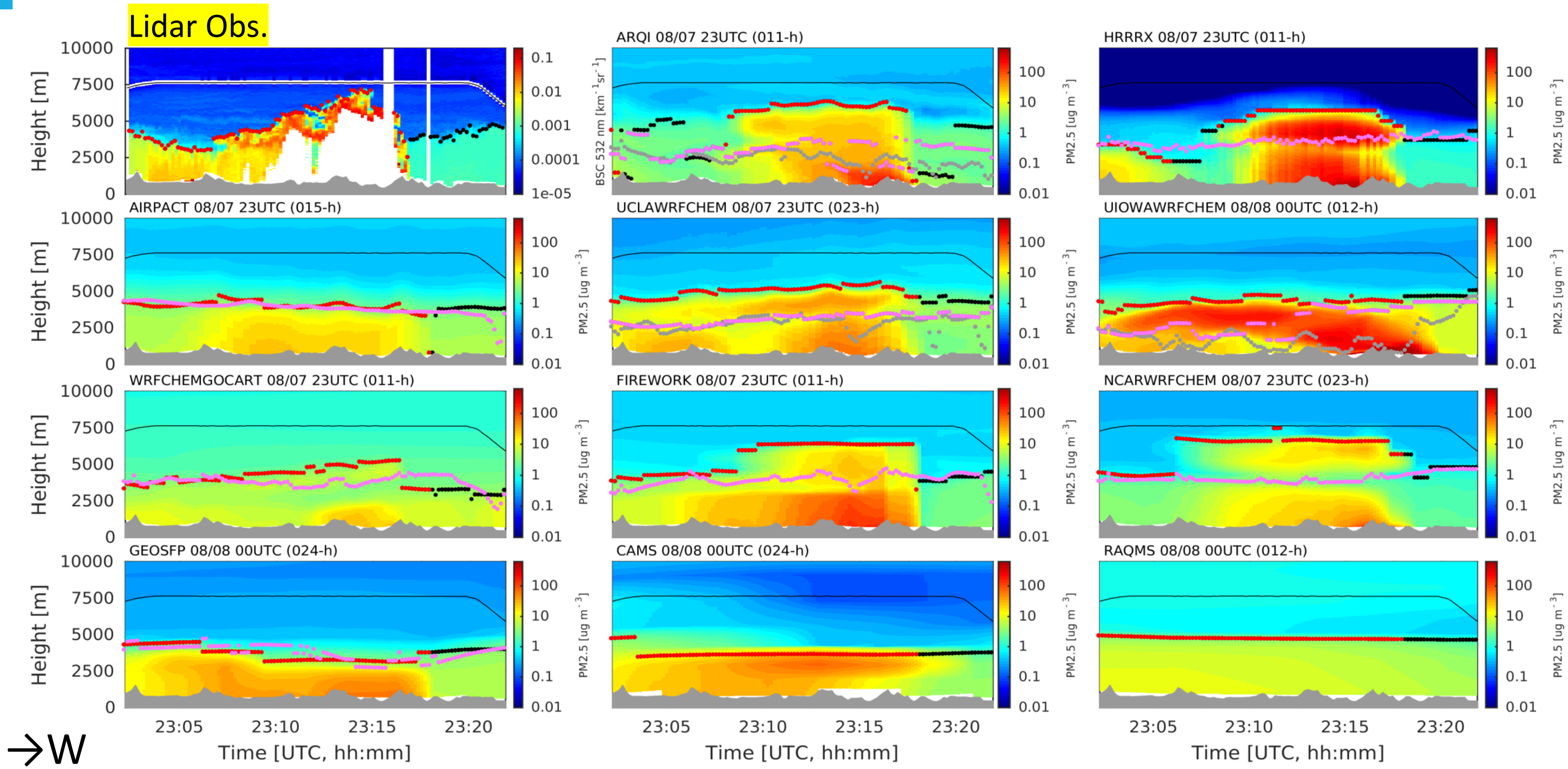
- Select flight transects that sampled straight through the smoke plume
- 16 transects were examined
- 12 for fresh plumes and 4 for aged plumes

BSC (532nm) along flight transects and plume heights



- **Plume heights** (red dots) are determined by backscatter coefficients.
- Profiles in clear scenes for **PBLH**
- Large day-to-day variability in observed plume heights

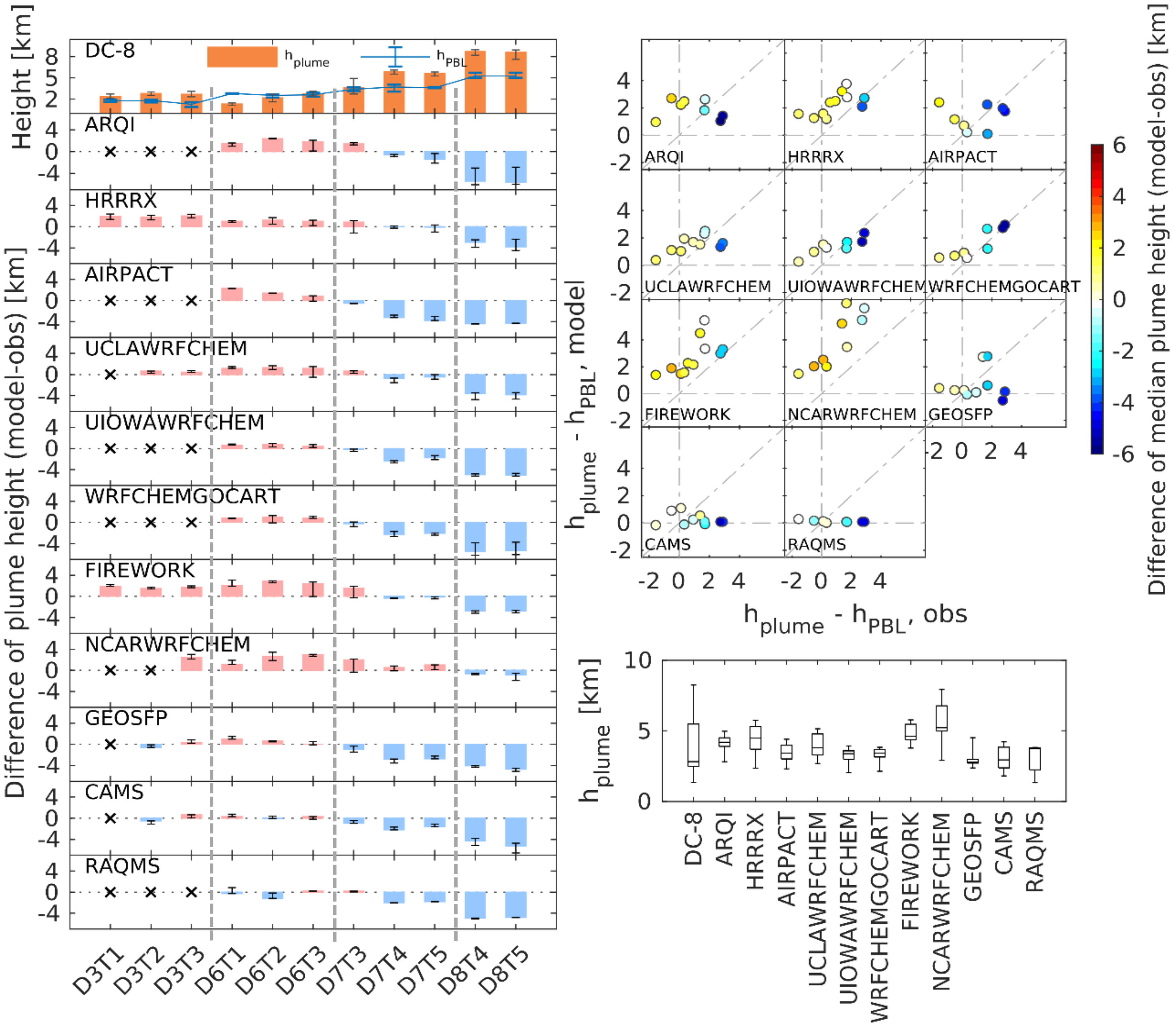
DIAL-HSRL bsc vs. model PM2.5 forecasts, 23:02-23:22 UTC Aug 7 (D7T3)



Red: plume height by pm2.5 **Black**: PBLH, out-of-plume by pm2.5

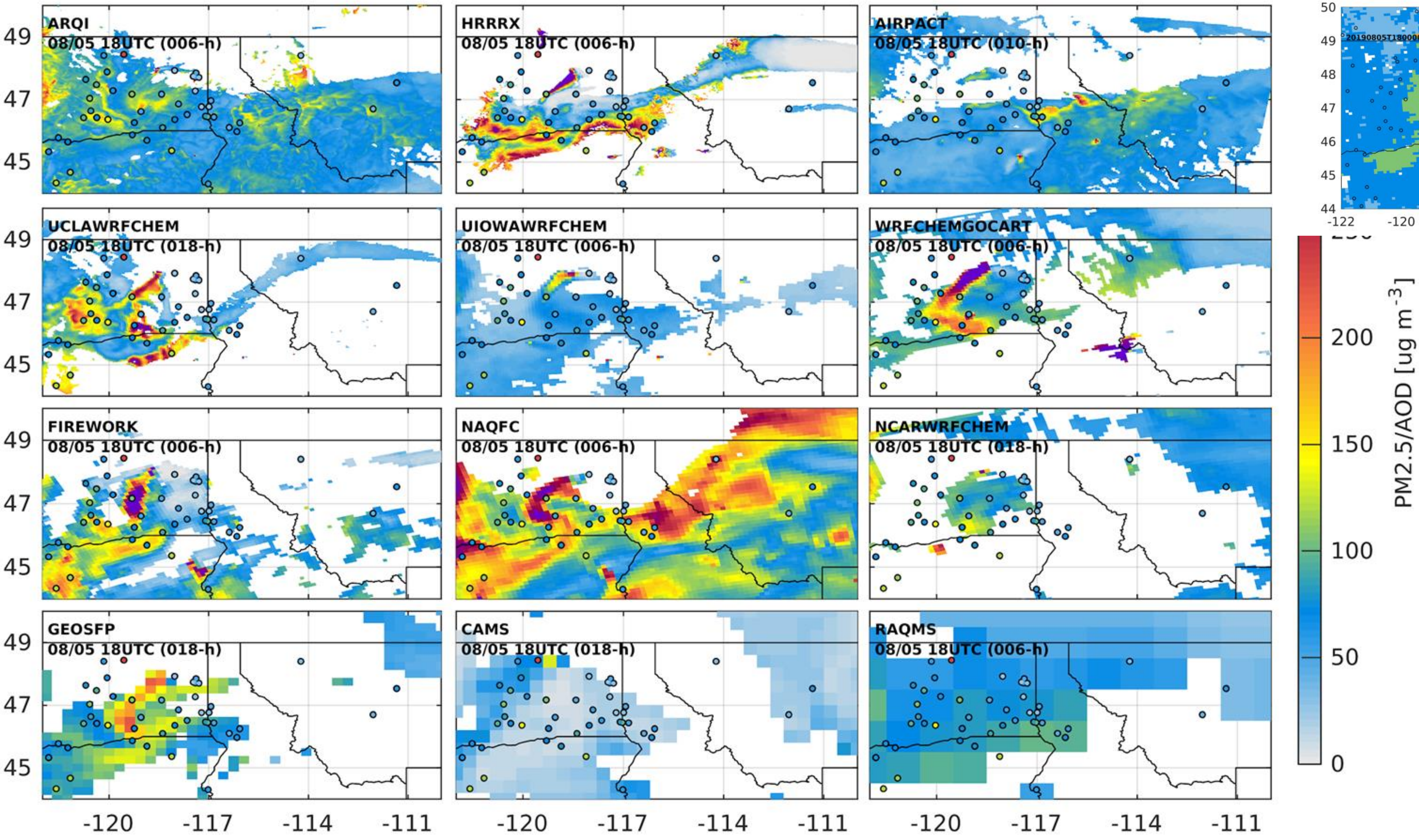
Grey: PBLH by model **Pink**: PBLH estimated by θ_v profile

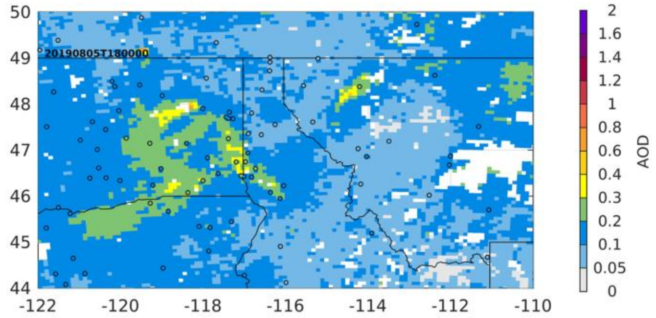
Evaluating plume heights and plume injection



- Plume heights and PBL heights estimated using observations indicate day-to-day variations in emission injection
- Most models show over-injection on Aug 3 and 6, and under-injection on Aug 7 and 8
- Scatter plots show observed and modeled difference between median plume height and median PBL height, colored by bias of modelled plume heights.
- Box plot is spread of median plume heights of all the transects. Box borders are 25th and 75th percentiles, whiskers represent minimum and maximum.

Map of PM2.5/AOD ratio, 18 UTC Aug 5

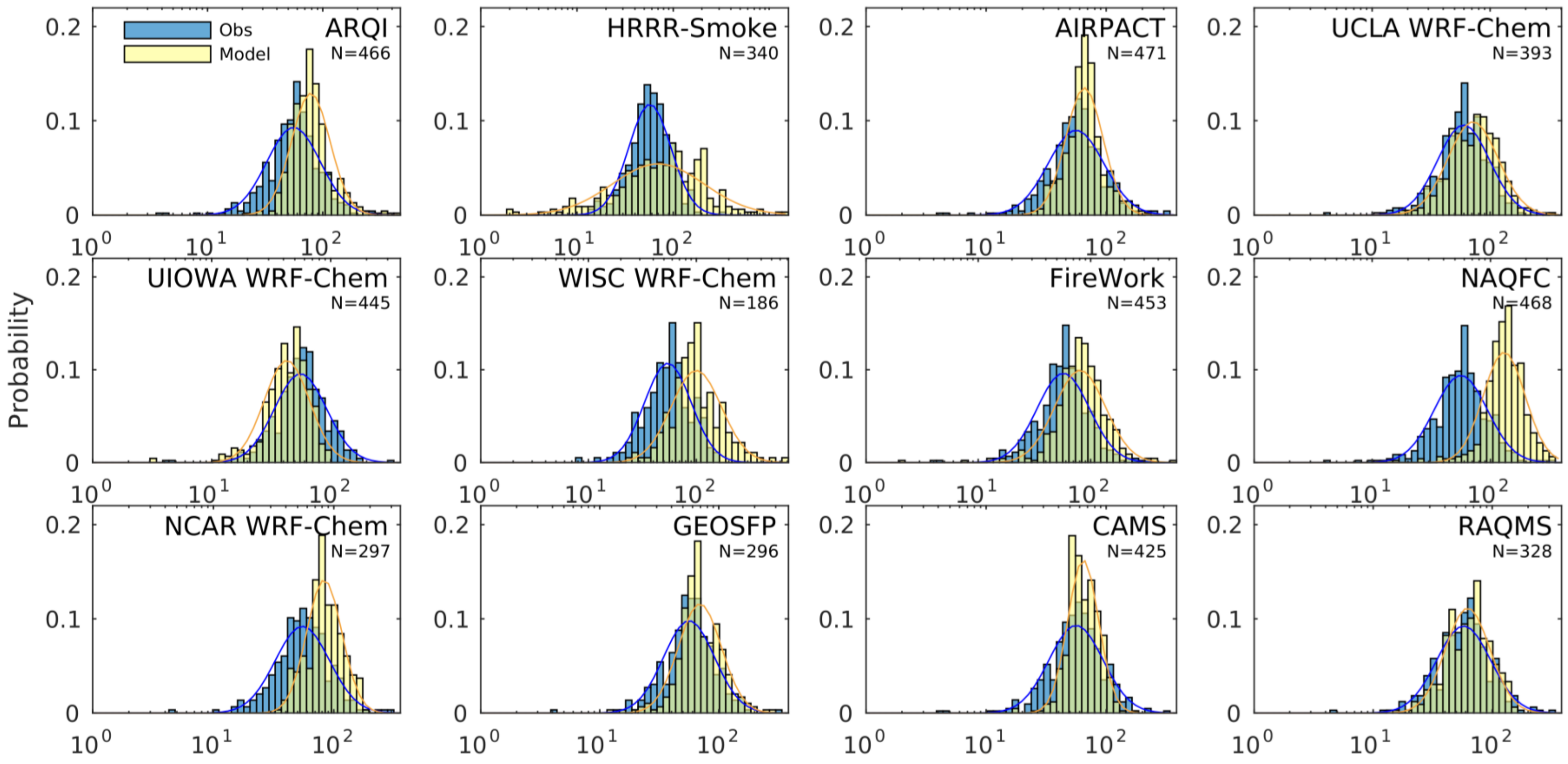




Filter for Obs:
AOD enh > 0.05

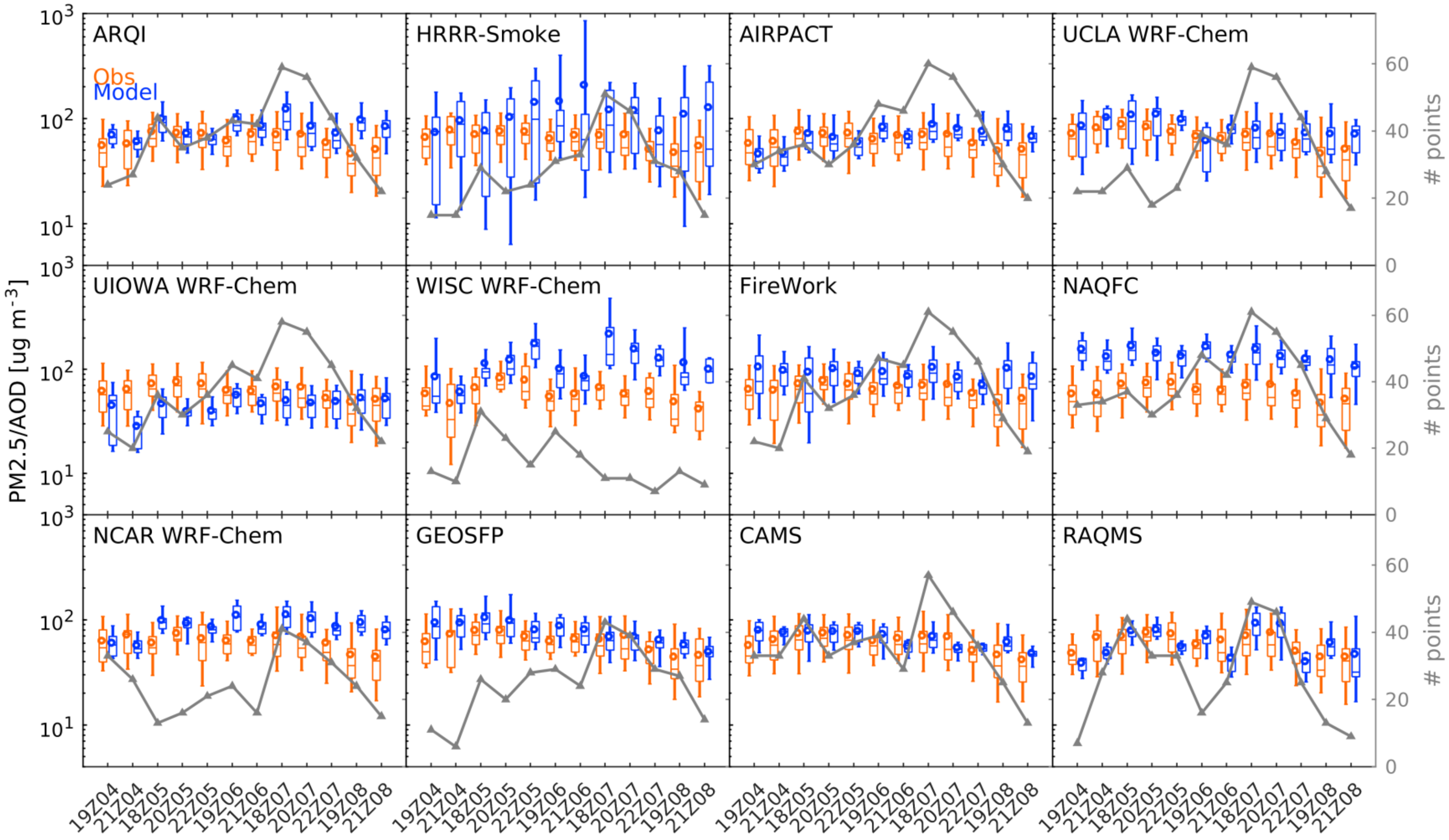
Filter for Model:
hrrrx, firework:
AOD enh > 0.02
ncarwrfchem,
airpact, arqi, naqfc:
AOD enh > 0.01
Other models:
AOD enh > 0.05

Comparison of observed and modeled PM2.5/AOD ratio



- Probability distribution of PM2.5/AOD over selected sites that are collocated within both predicted and observed smoke plumes. The curves are log-normal fitting distributions.
- Lower-end ratios generally correspond to lofted smoke above PBL, while upper-end ratios stand for smoke close to the ground.
- Most models show positively biased distributions (except for UIOWA WRF-Chem)

Day-to-day variation of PM2.5/AOD ratio distribution



Decreasing trend in observed PM2.5/AOD ratios likely corresponds to the stronger plume injections and lofted smoke on Aug 8 and 9.

Summary and future work

Summary

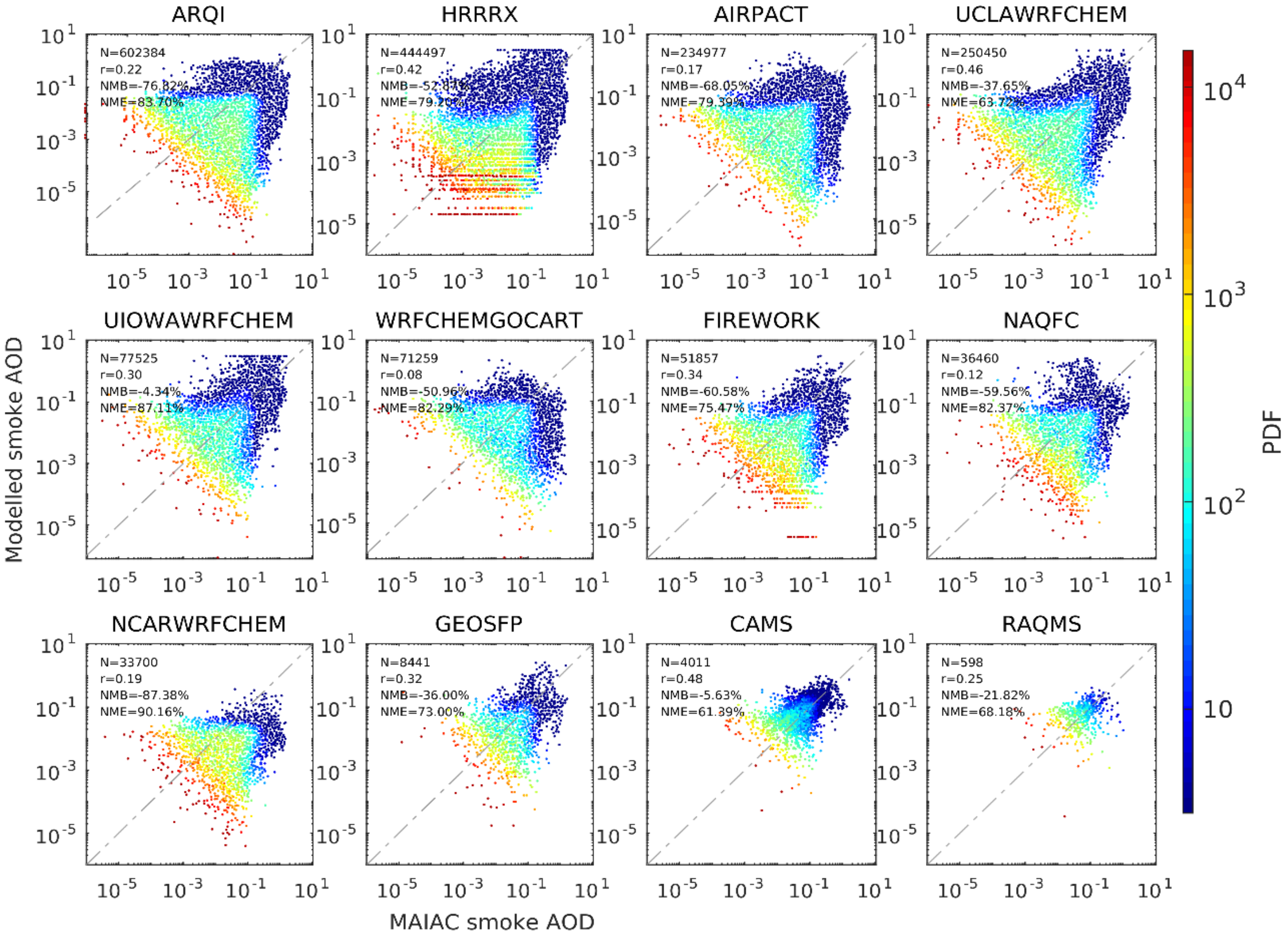
- The **diurnal variation pattern and nighttime fire activities** are yet to be improved.
- Some models show nearly unbiased predictions of sAOD and smoke PM2.5 enhancements, but the **low correlation coefficients and discrepancies in performance** calls for further model improvements (PBL, emission injection, aerosol optical properties, etc.)
- **Persistent burning** is used for predicted emissions by all models, which led to **underestimated AOD** by all the models on the day with dramatical fire evolution.
- **Large day-to-day variability in plume injection heights** is seen in observations, but generally **not captured** by the forecasting systems.

Future work

- Analysis of aerosol components, optical properties, and their representation in models would help to identify key factors affecting model performance.
- Retrospective runs would help to identify contributions of factors to the forecasts, e.g. chemistry mechanisms, meteorology, emissions, plume injection, etc.

Thanks!

Statistics of smoke AOD enhancements (sAOD)



- Comparing sAOD on 4-8 August 2019
- General **underestimation** of sAOD for all models
- Some models show **nearly unbiased** predictions (UIOWA WRF-Chem and CAMS)
- Linear correlation coefficients (*r*) are low, and Normalized Mean Error (NME) is above 60% for all models, owing to spatial displacement of smoke plume.

Evaluating spatial extent of smoke plume (sAOD>0.05)

- For each map of sAOD snapshot, **FMS** and **FAR** are used to quantify spatial coverage of plume based on exceedance of a threshold (sAOD>0.05).
- Due to cloud contaminations, the filtered grid cells do not necessarily indicate the exact coverage and realistic outline of a plume.
- Figure of Merit in Space (**FMS**) (Boybeyi et al., 2001; Rolph, et al., 2009) (best: 100%; equivalent to the threat score or critical success index (CSI)):

$$FMS = \frac{a}{a+b+c} \times 100\%$$

- False Alarm Ratio (**FAR**) (best: 0%):

$$FAR = \frac{b}{a+b} \times 100\%$$

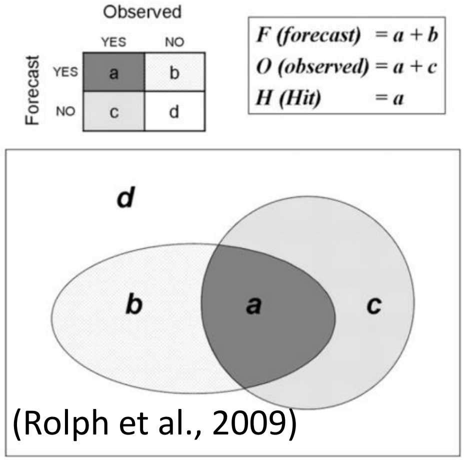


FIG. 12. The definitions of forecast (F), observed (O), and hit (H) in the NCEP FVS.