EARTH SCIENCE
APPLIED SCIENCES

HEALTH & AIR QUALITY

Improving Air Quality State Implementation Plans (SIPs) using Land Surface Remote Sensing

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Pennsylvania Department of Environmental Protection Citizen's Advisory Council meeting
Harrisburg, Pennsylvania 12 May, 2026

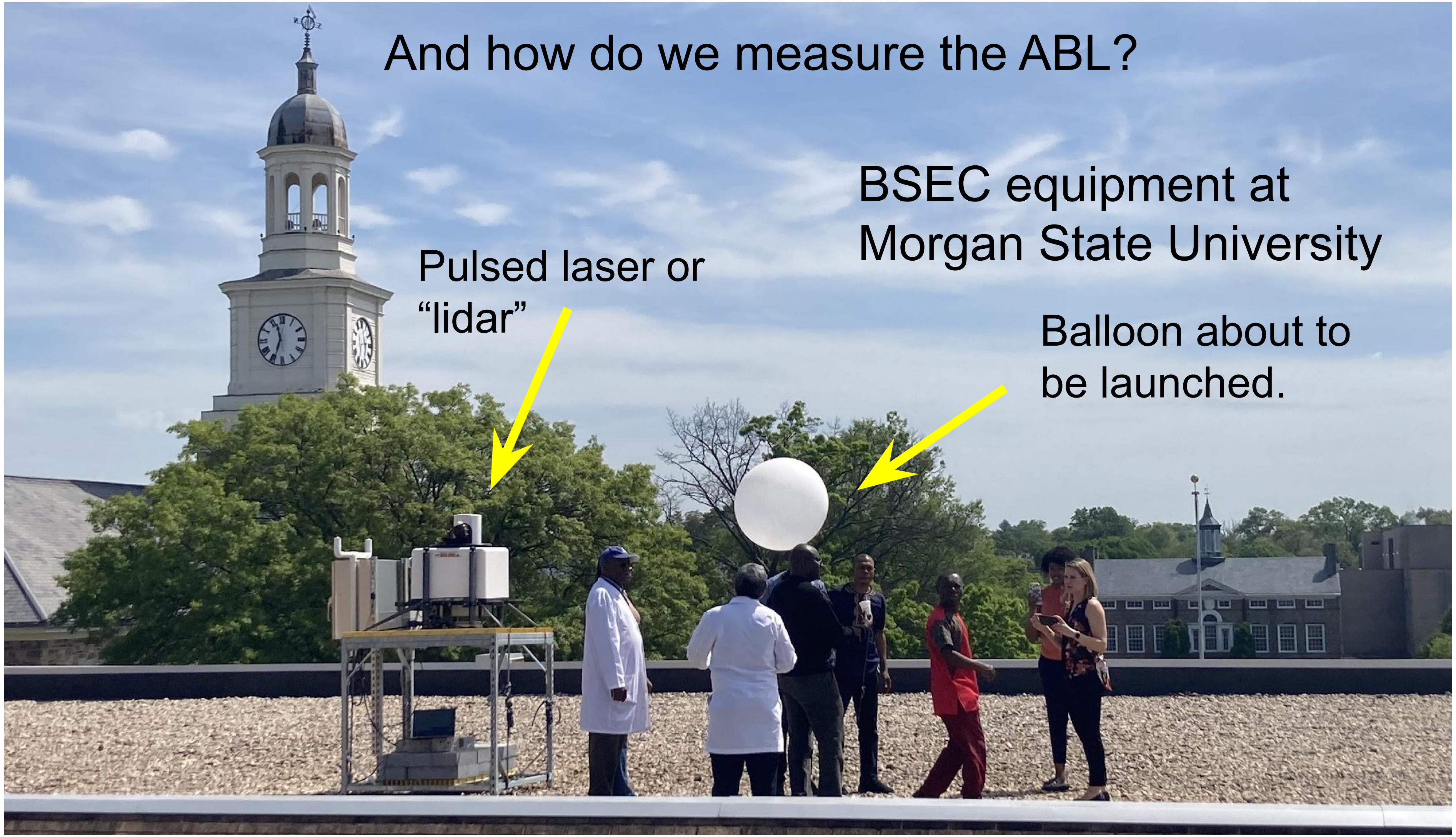
Outline

1. Background on how understanding the **atmospheric boundary layer (ABL)** is relevant to understanding regional air quality.

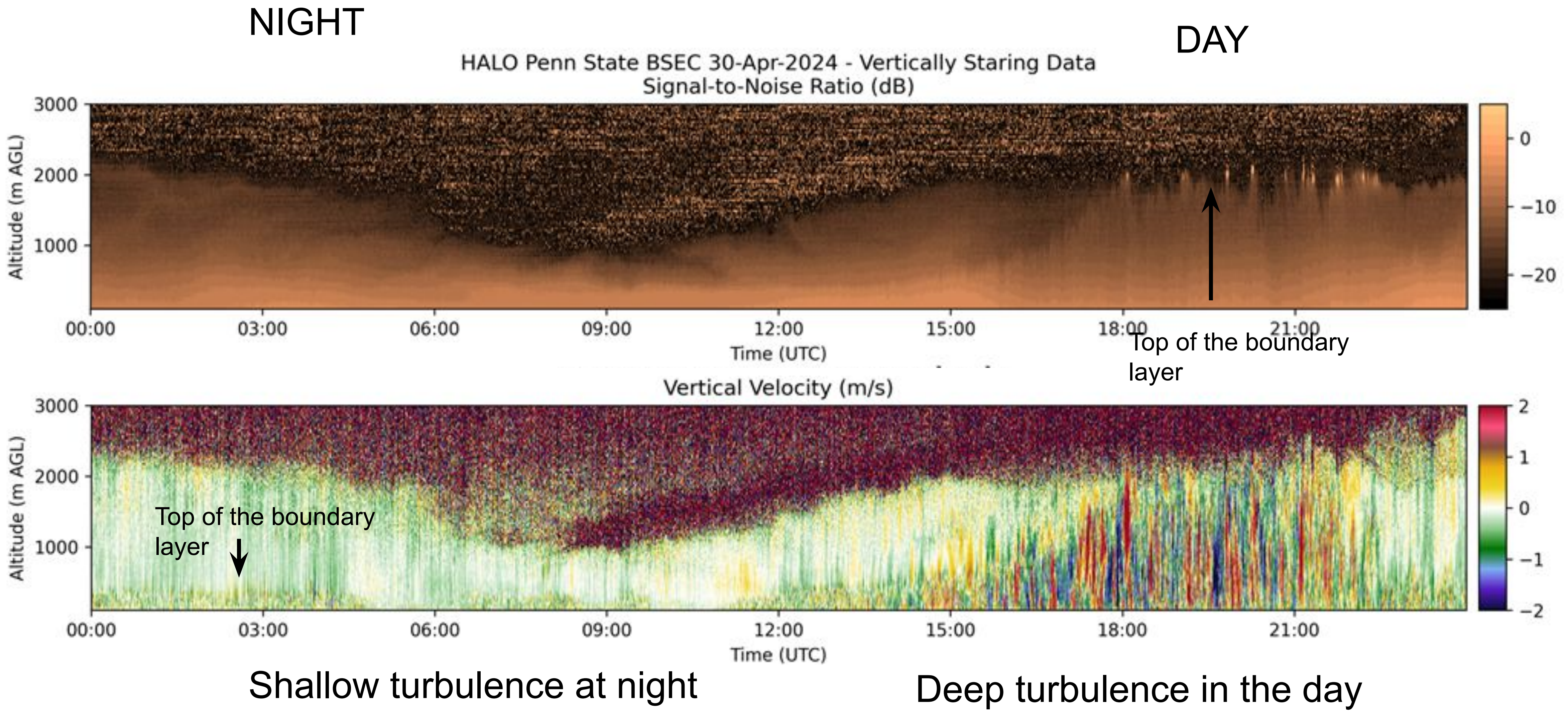
2. Results from the San Joaquin Valley.

3. The role of atmospheric transport uncertainty on Pennsylvania air quality simulations.

What is the Atmospheric Boundary Layer (ABL)?

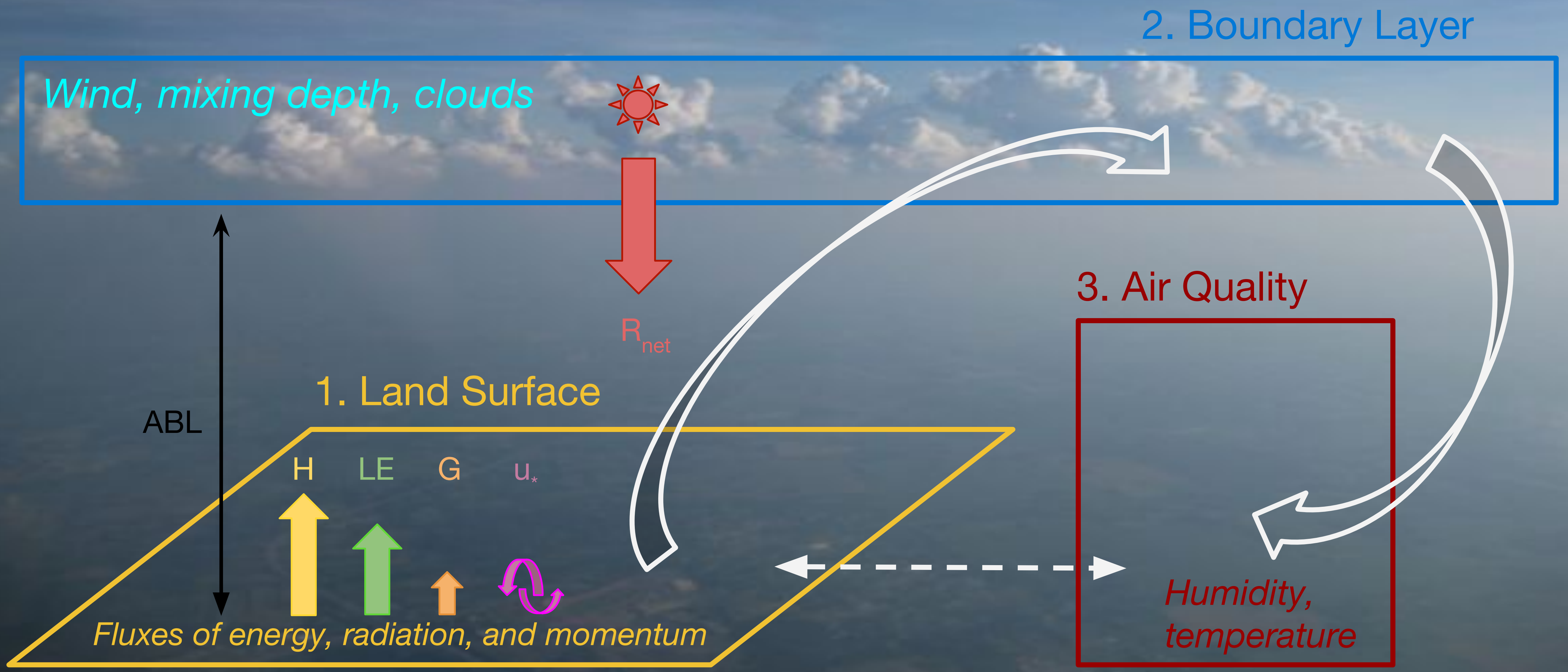


An example of the ABL on a typical day.



A hot hazy summer ABL over Maryland
Photo credit: W.Brune

The properties of the ABL are tightly coupled with the land surface, and fluxes of energy, radiation and momentum at the land surface.



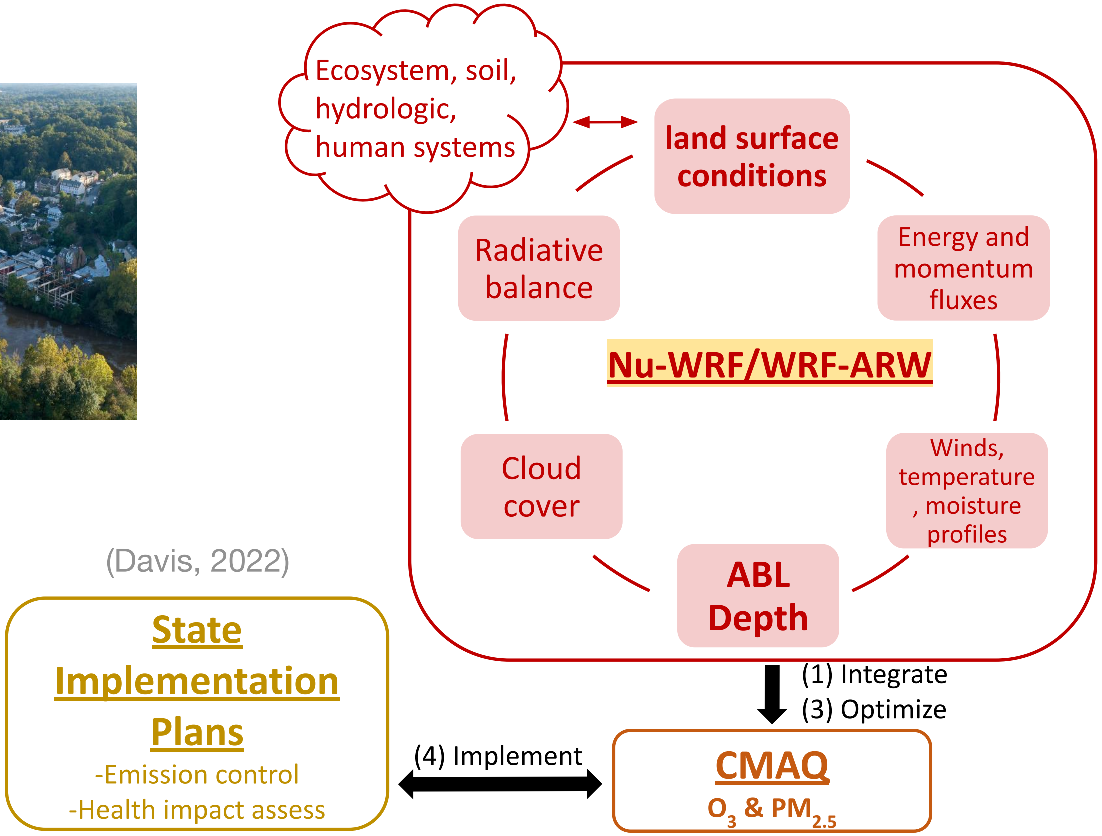
Areas of Interest

California and Mid-Atlantic

California and Pennsylvania are two states whose SIP modeling systems could benefit substantially from the use of the NASA LIS / NU-WRF system.

CALIFORNIA AIR RESOURCES BOARD

pennsylvania DEPARTMENT OF ENVIRONMENTAL PROTECTION



(Davis, 2022)

Simulation of the **ABL** is central to meteorological and air quality modeling and therefore is critically important for the development of a high-quality **SIP**.

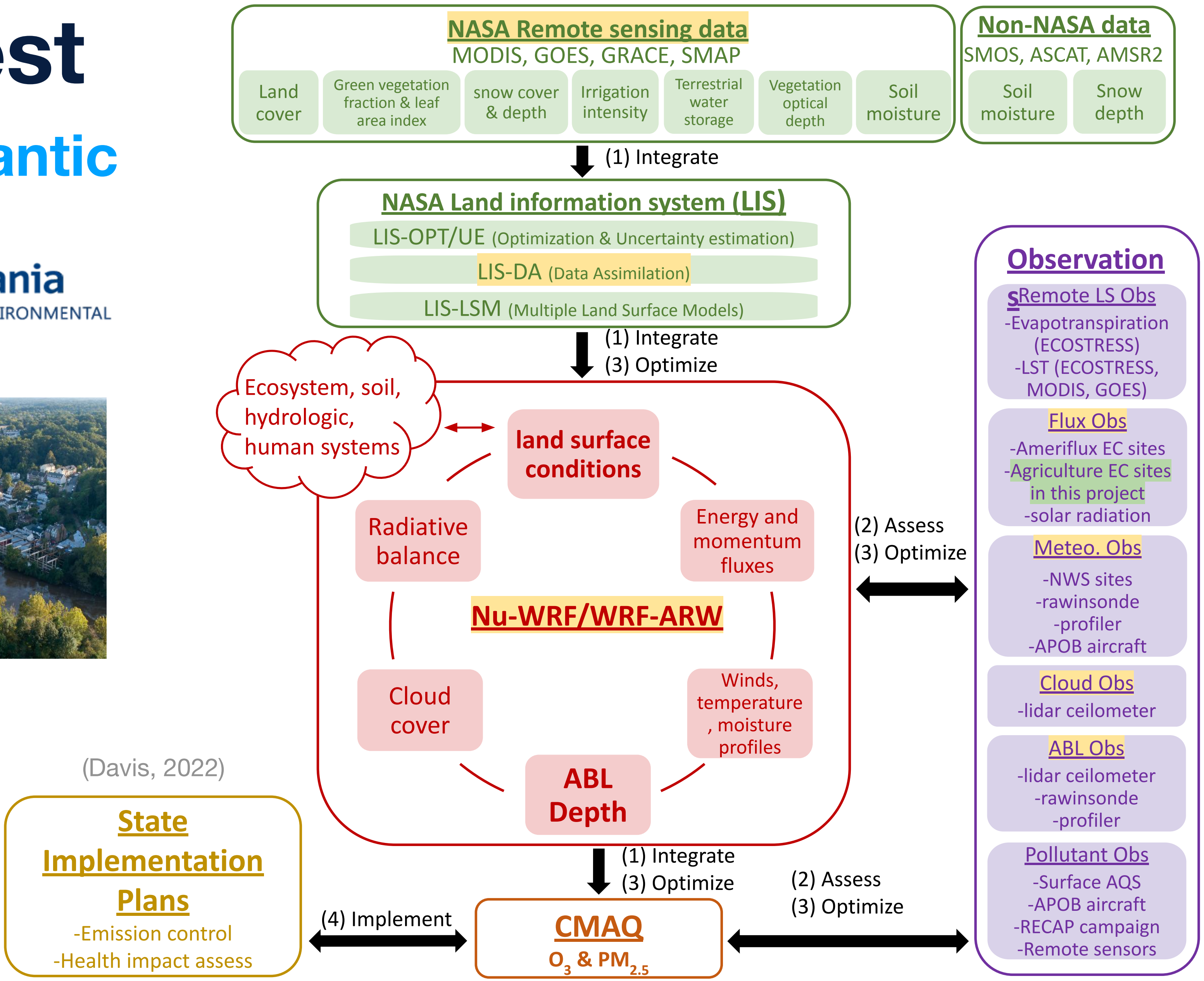
- Red subset: ABL properties
  - “wheel of interaction”: the coupled land surface - boundary layer system

Areas of Interest

California and Mid-Atlantic

- For regions that do not meet EPA AQ standards: must develop Plans
  - CA and PA: strong AQ concerns
  - CARB has trouble simulating AQ

(Davis, 2022)



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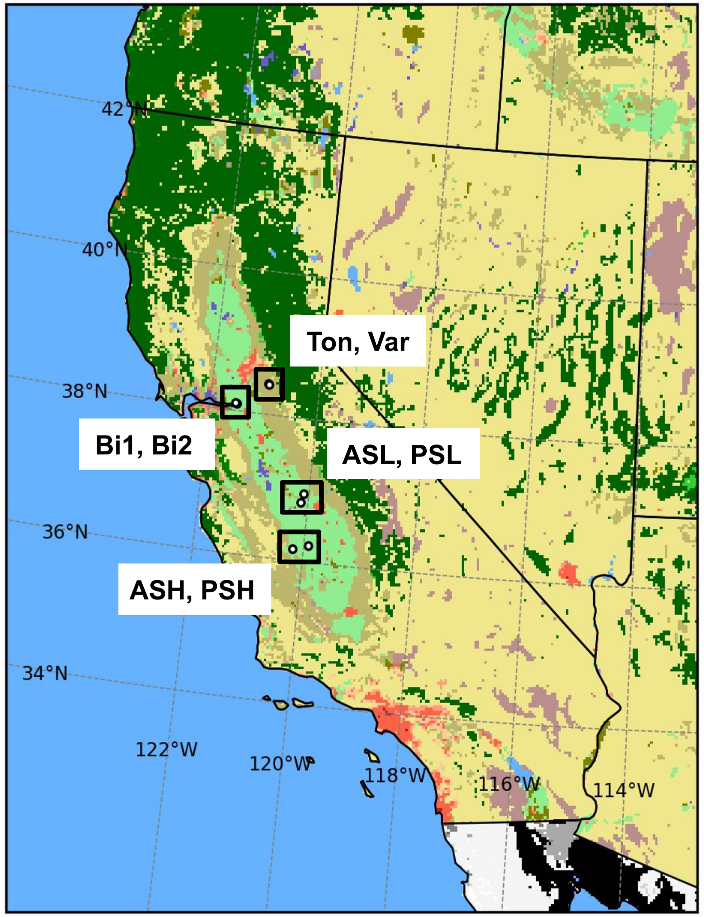
PX LSM

We follow EPA's choice on the land surface model.

AmeriFlux

17 IGBP Water
23 Developed Open Space
24 Developed Low Intensity
25 Developed Medium Intensity
26 Developed High Intensity
27 Barren Land (Rock/Sand/Clay)
28 Deciduous Forest
29 Evergreen Forest
30 Mixed Forest
32 Shrub/Scrub
33 Grassland/Herbaceous
37 Pasture/Hay
38 Cultivated Crops
39 Woody Wetlands
40 Emergent Herbaceous Wetlands



CA central valley: cultivated crops

AmeriFlux
- 2 crops
- 2 savannas
- 4 orchards

Physical scheme	SJV	Reference
Land-surface	Pleim-Xiu	*Xiu and Pleim (2001)*

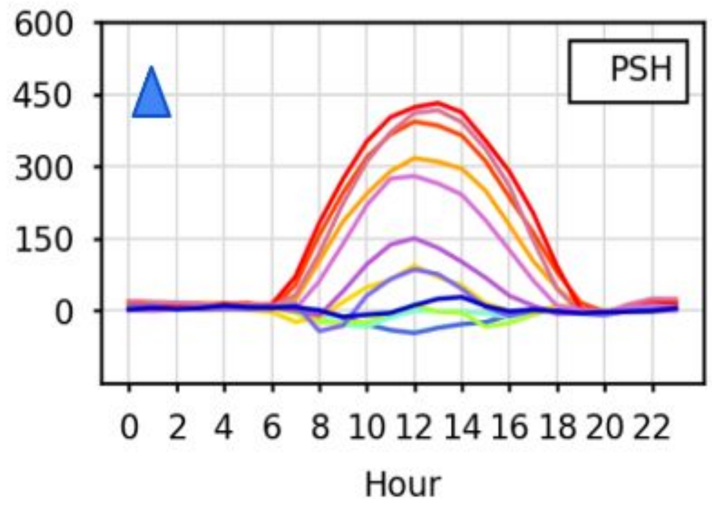
Site ID	Vegetation	Irrigation	Reference
US-Ton	Savanna	Non-irrigated	*Ma et al. (2021)*
US-Var	Grassland		*Ma et al. (2021)*
US-Bi1	Alfalfa	**Irrigated**	*Rey-Sanchez et al. (2022)*
US-Bi2	Corn		*Rey-Sanchez et al. (2022)*
US-ASH	Almond		*Anderson (2020)*
US-ASL	Almond		*Anderson (2020)*
US-PSH	Pistachio		*Anderson (2020)*
US-PSL	Pistachio		*Anderson (2020)*

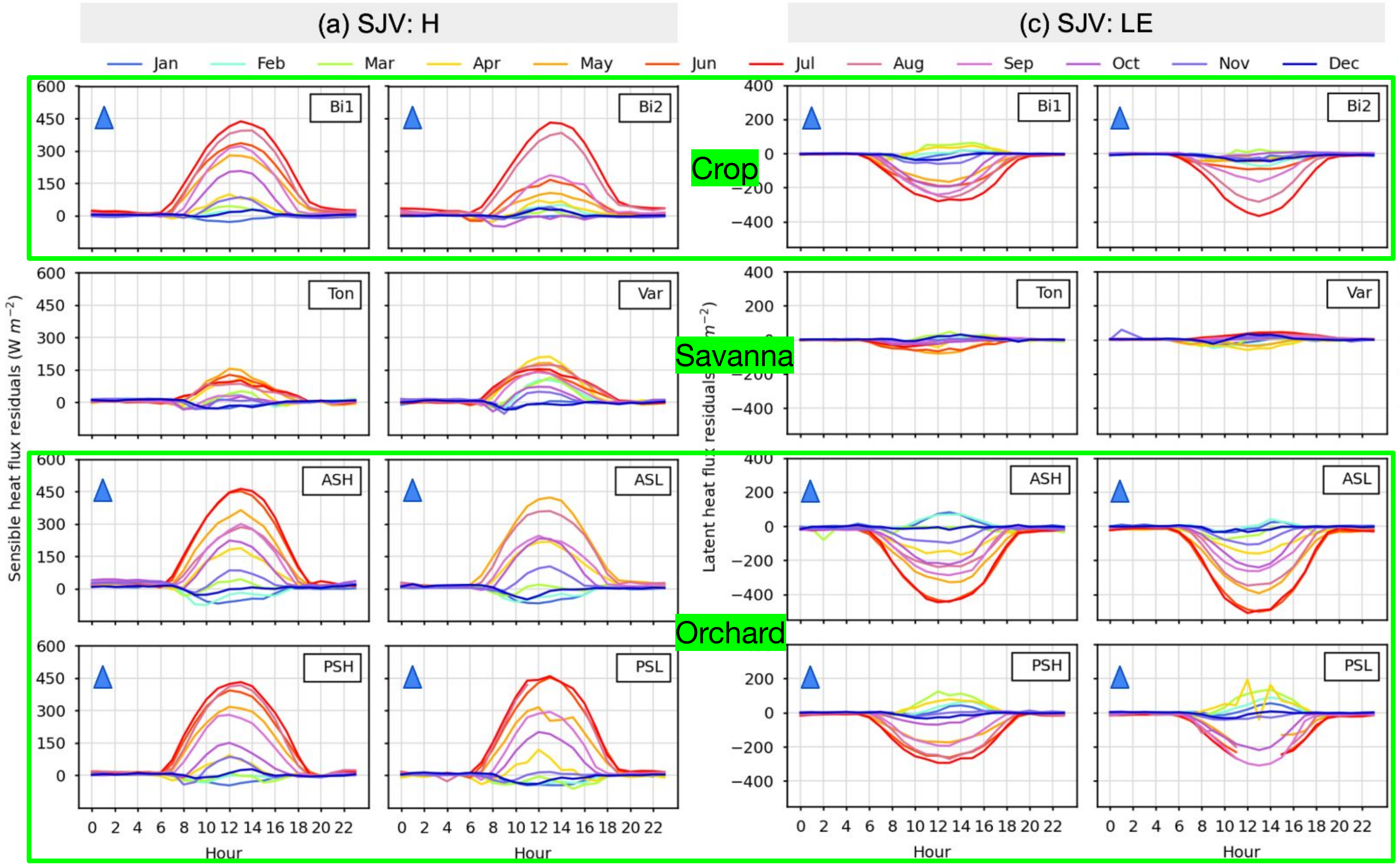
Flux biases

$$Residuals = \frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)$$

In the model:
Too much energy goes into heating, not enough into ET.

The model overestimates H and underestimates LE.



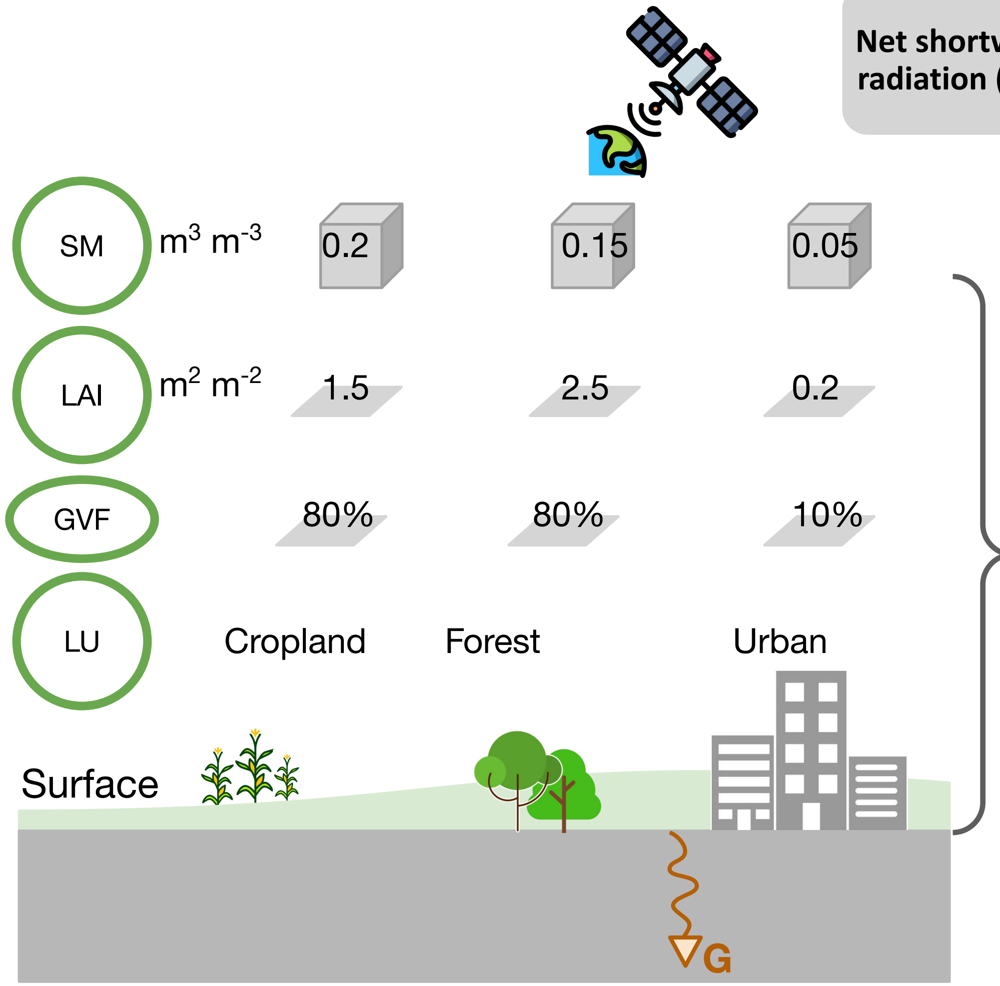


WRF PX has a strong energy partitioning bias over irrigated land in CA.
Physically consistent with missing irrigation.

We can improve H/LE simulations

Remote sensing of vegetation. Irrigation estimates.

Net shortwave radiation (SW) + Net longwave radiation (LW) = Sensible heat flux (H) + Latent heat flux (LE) + Ground heat flux (G)



Available energy → H or LE

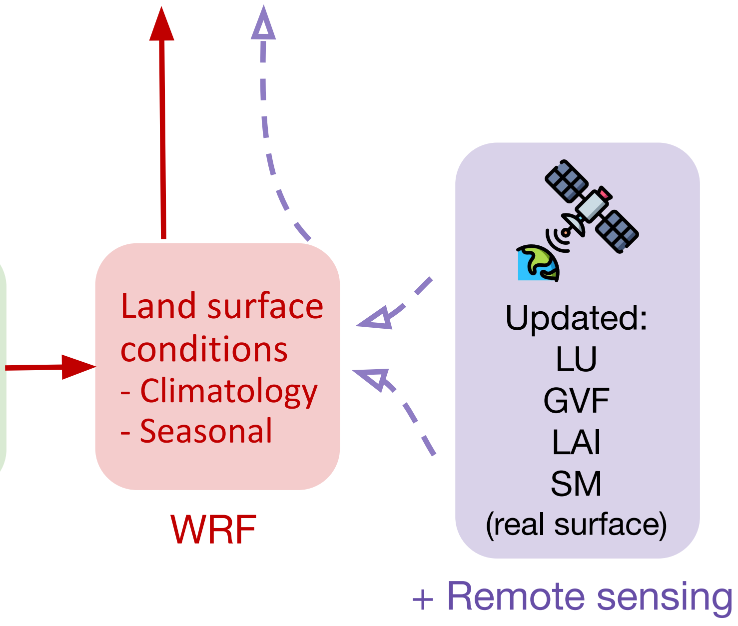
$$R_n = (1-\alpha)SW_\downarrow + LW_\downarrow - \varepsilon\sigma T_s^4$$

$$LE = \lambda E$$

Parameters: roughness, canopy resistance, albedo, emissivity

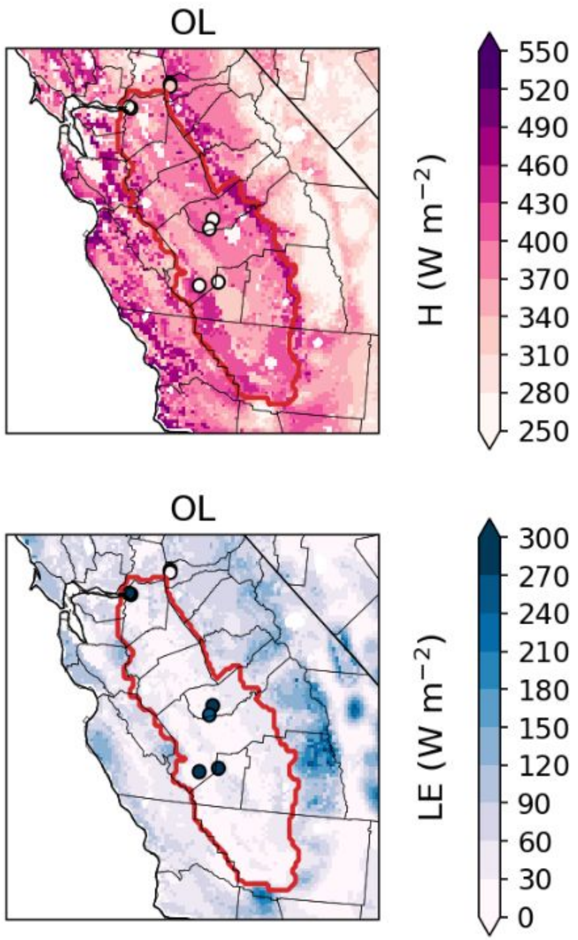
- Green vegetation
- Canopy density
- Soil water available

Surface controls



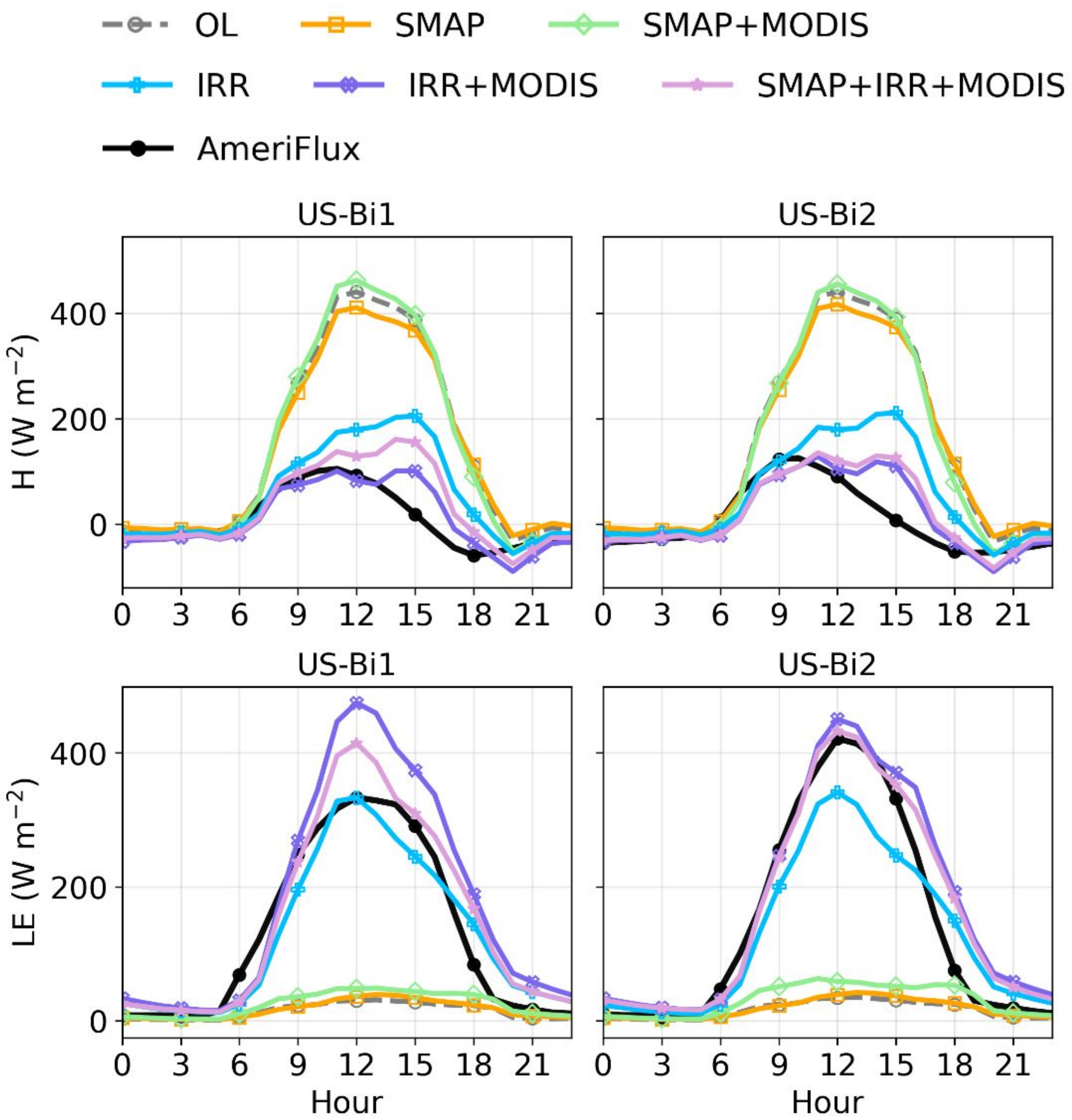
Heat fluxes

Improvements come from irrigation scheme.



July 2021

- US-Bi1: Alfalfa, US-Bi2: Corn
- Experiments with irrigation substantially corrects H and LE at irrigated croplands
- Remote Sensing alone does not fix the problem.

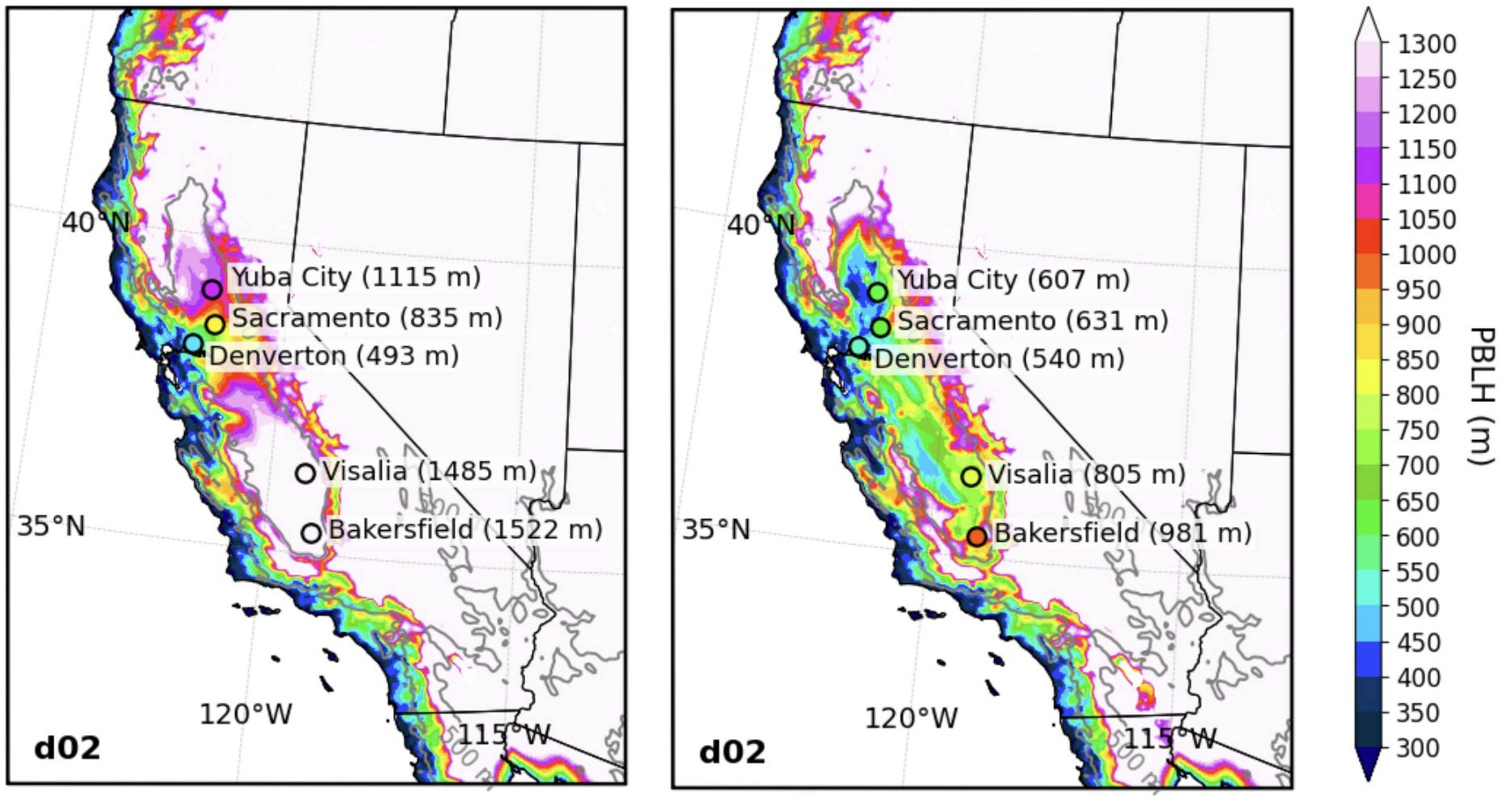


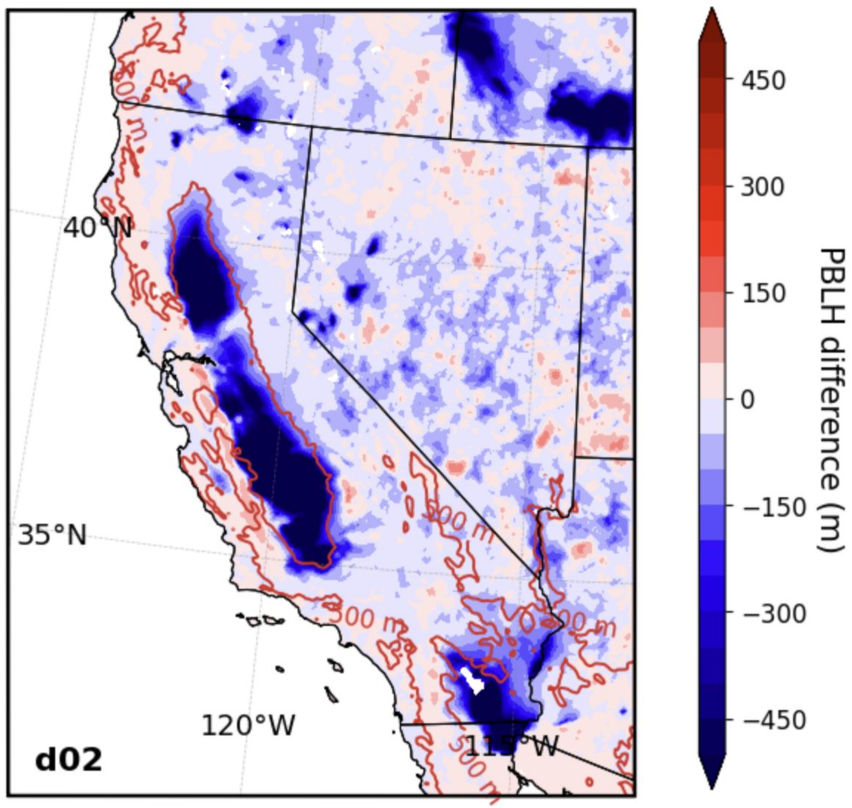
PBLH simulations

Noah-MP irrigation scheme decreases daytime PBLH by 500 m.

- Irrigation has a direct effect on the lower atmosphere in the valley.

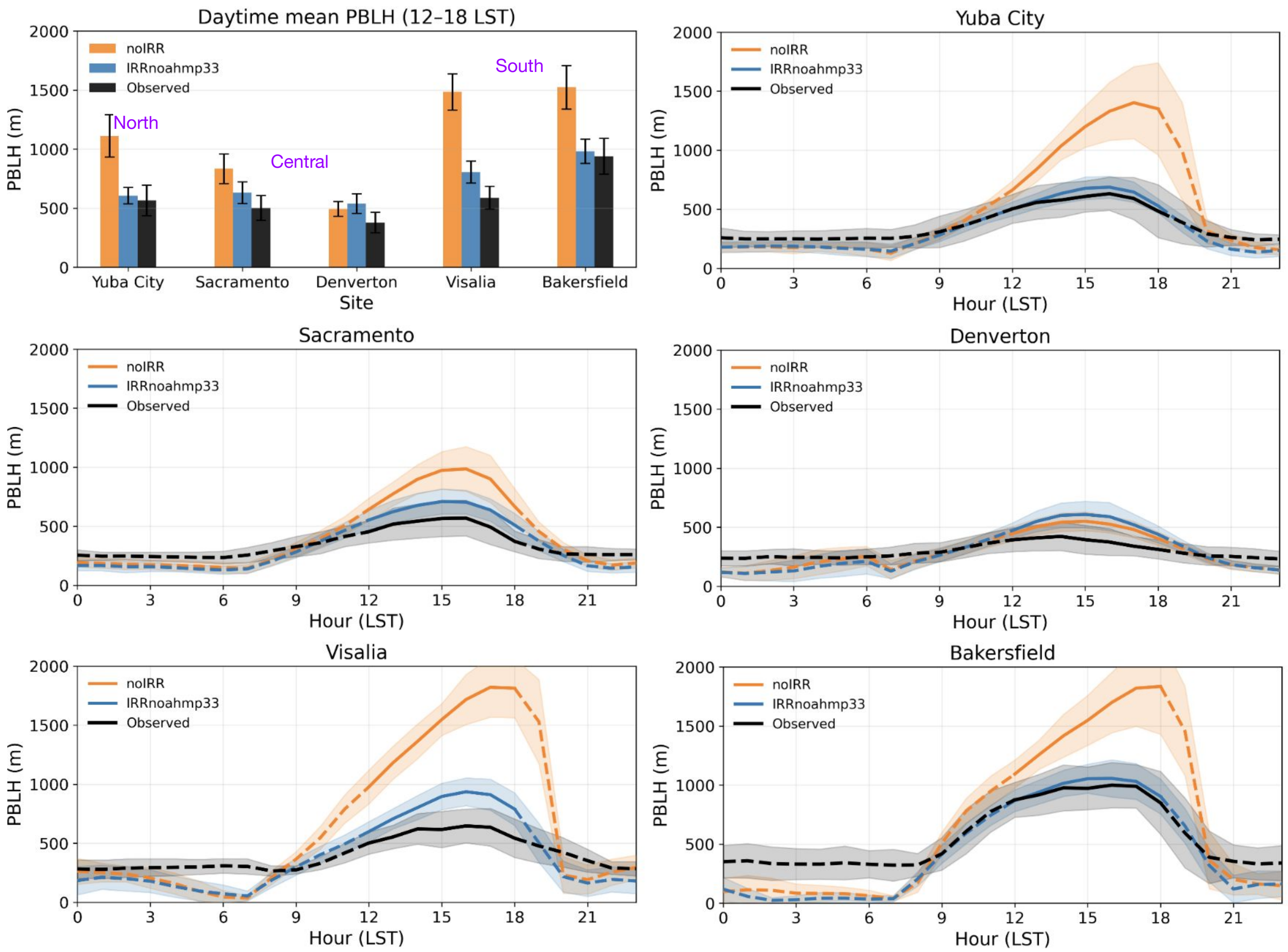
WRF NP baseline WRF NP with irrigation





PBLH evaluations

We use ceilometer observations from CARB ceilometer network.



Observations (**black**)

- Lower near the Delta, higher toward the south

WRF Noah-MP baseline (**orange**)

- Produce ABL that are too deep

WRF Noah-MP with irrigation (**blue**)

- Simulated PBLH decreases and agrees better with the observations

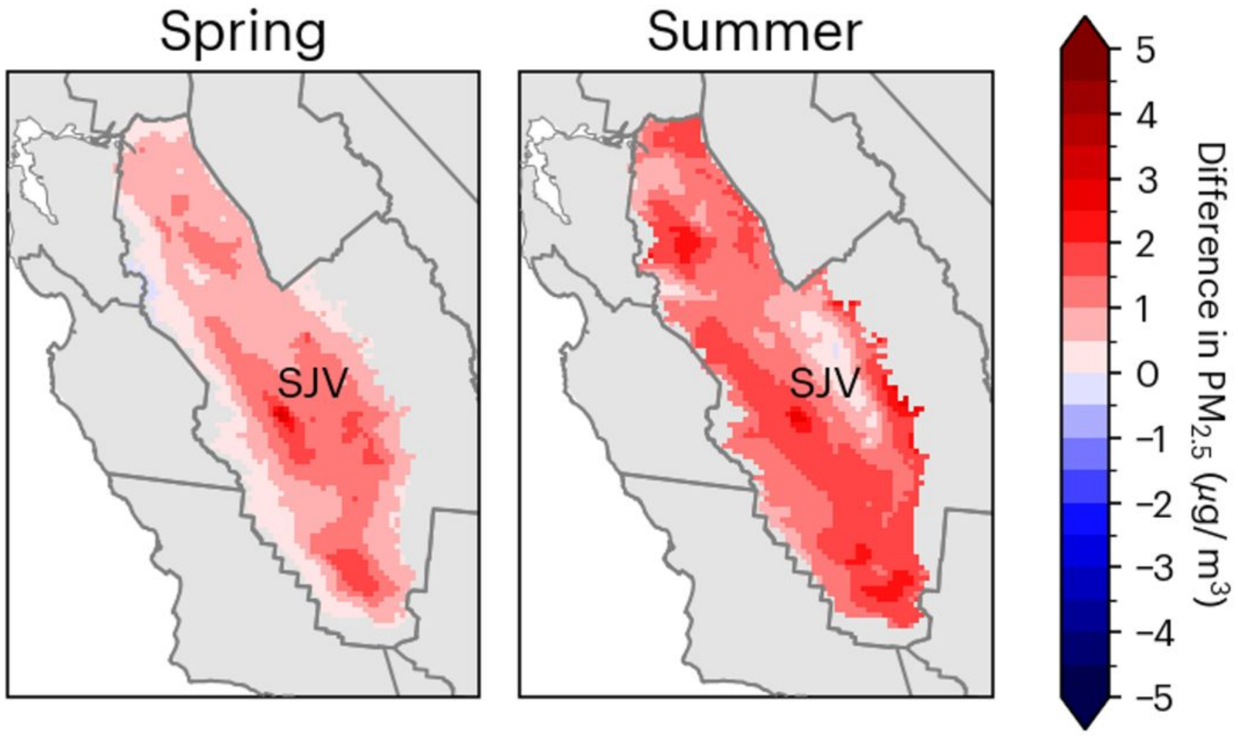
Irrigation helps close the loop from land surface states, to fluxes, to ABL development in the CCV.

Improvement in air quality simulation

Air quality simulation with data informed NU-WRF

- predicted higher $PM_{2.5}$ ↑ ~2 μg/m^3
- reduced model biases by ~ 40% in the SJV.

Seasonal differences in simulated $PM_{2.5}$
(NUWRF/LIS CMAQ minus WRF_NoahMP CMAQ)



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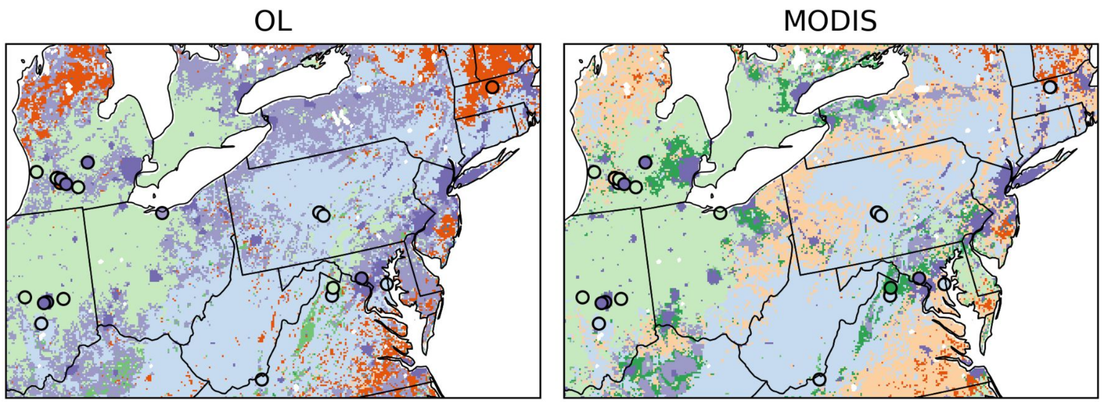
Surface fluxes

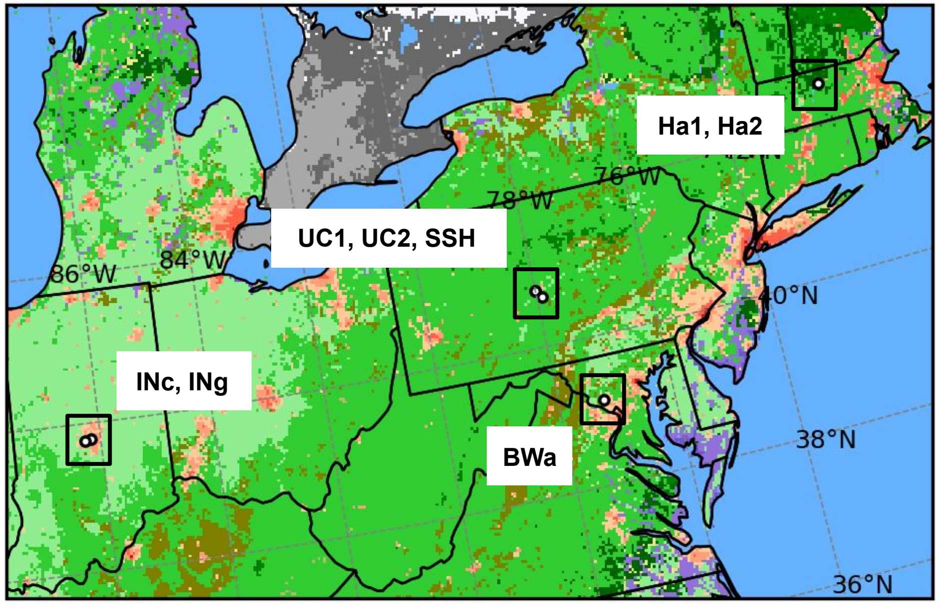
PX LSM works well in the MidAtlantic.

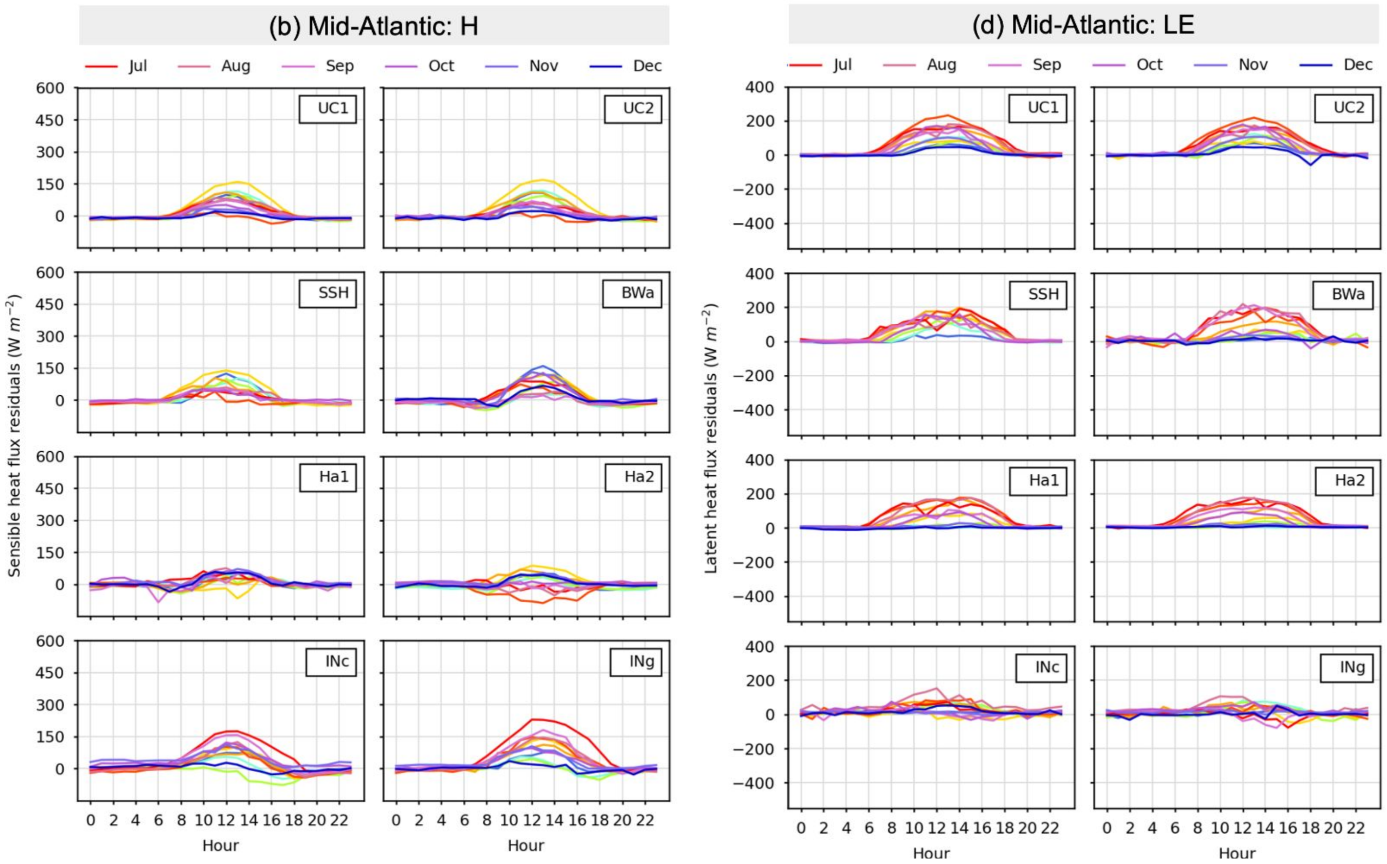
Mid-Atlantic PX: Deciduous forest, cultivated crops, developed low/medium/high intensity

- 2 urban, 2 crops, 1 turfgrass, 3 forests
- Modest errors

MODIS land cover: questionable woody savannas





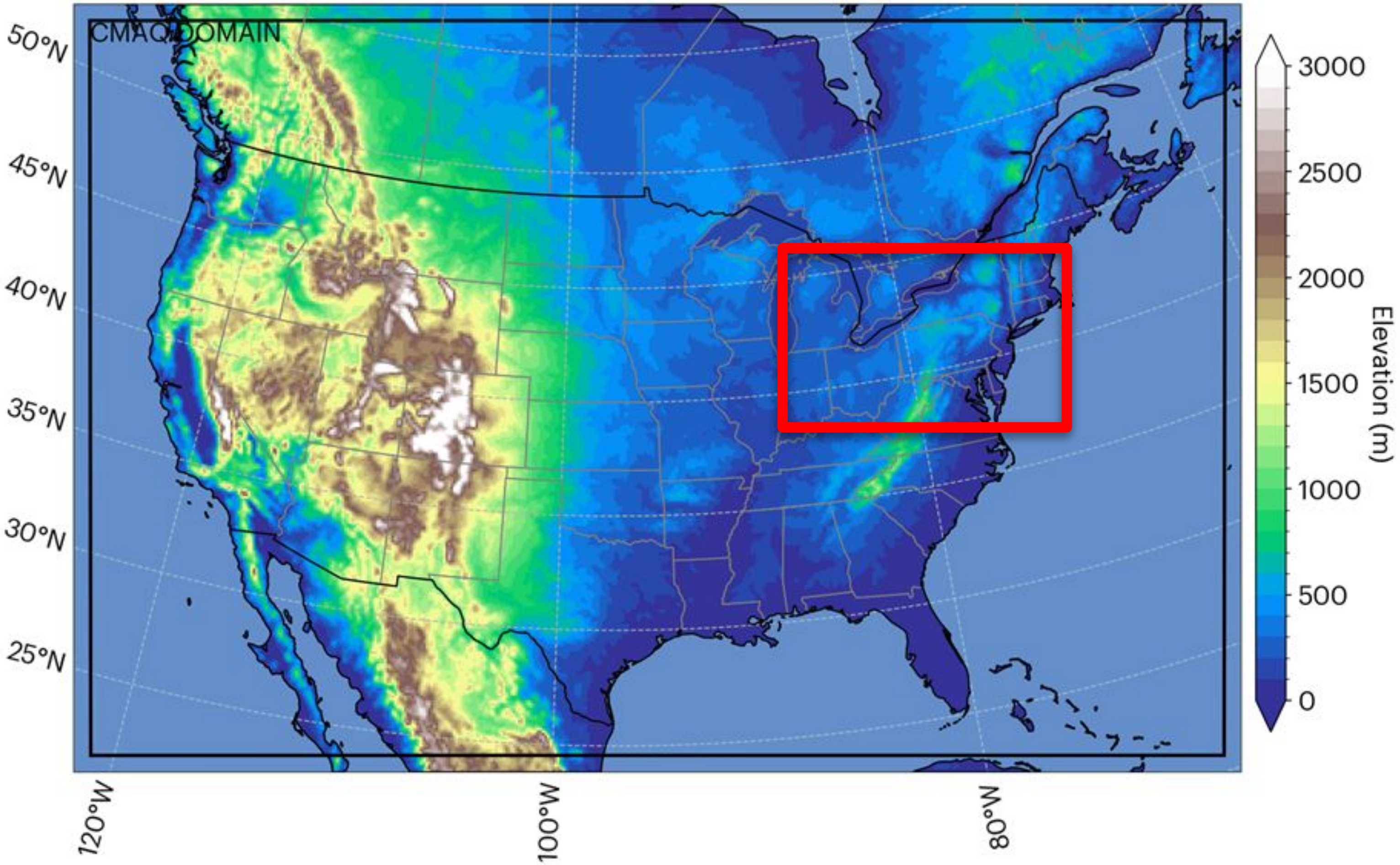


We are exploring the influence of meteorological uncertainty on air quality with an atmospheric model ensemble.

➢ **Configurations**

Nested domain: 12km; 4km
Meteorology model: WRF v4.3
- 15 members

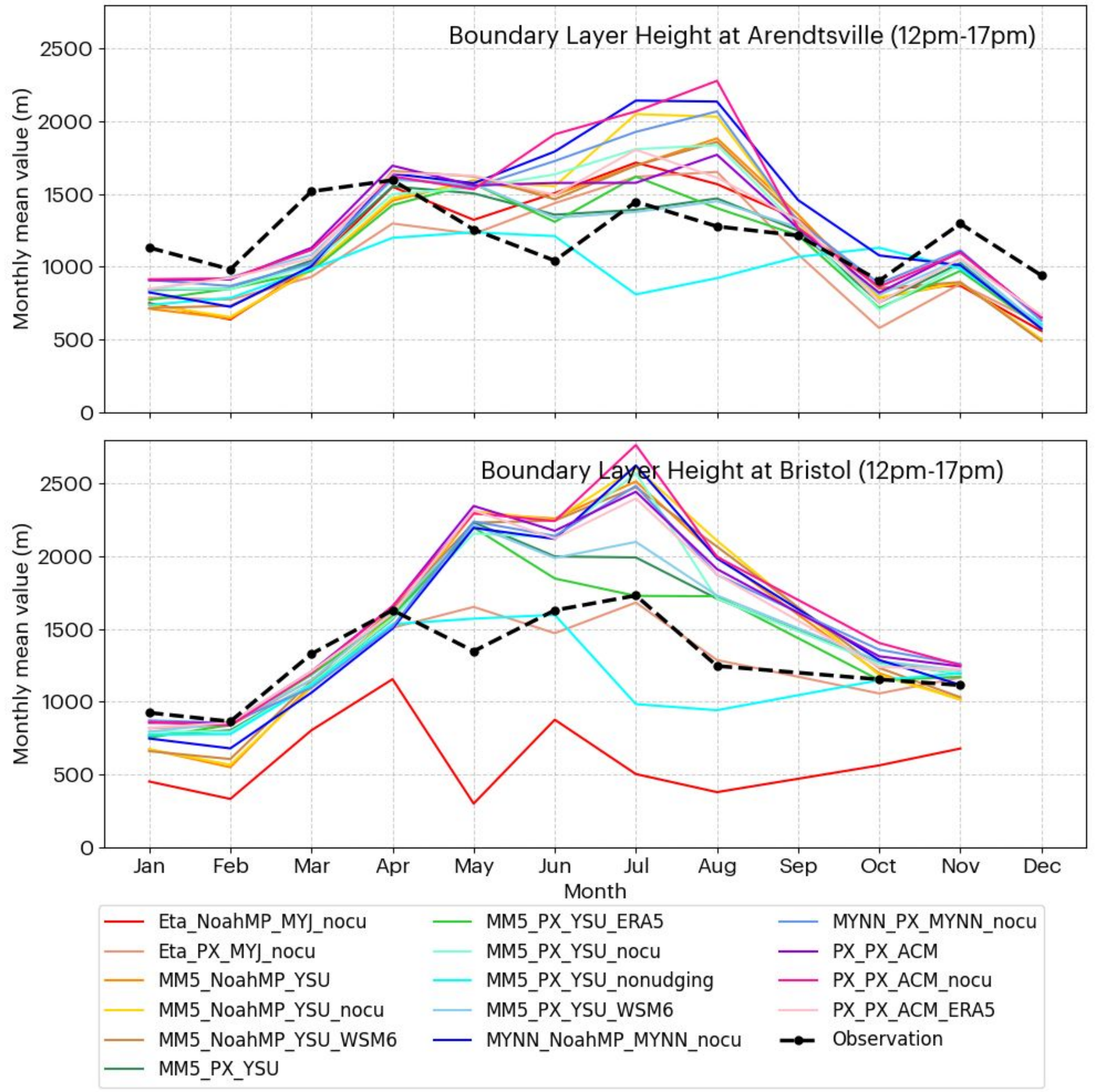
Air quality model: CMAQ v5.4
- 2021 winter and summer
- Emissions: EPA 2021 NEI + Beis4 online
- Mechanism: CB6; AERO7
- Meteo: selected 5 members



The ensemble encompasses observed atmospheric properties

- Most of ensemble members overestimated summer ABLH, underestimated winter ABLH.
- No model simulated ABLH perfectly.
- We select a subset of these models that encompass the observations.
- We attempt to minimize the bias in representing boundary layer height, winds, temperature and relative humidity.

Monthly comparison of afternoon ABLH

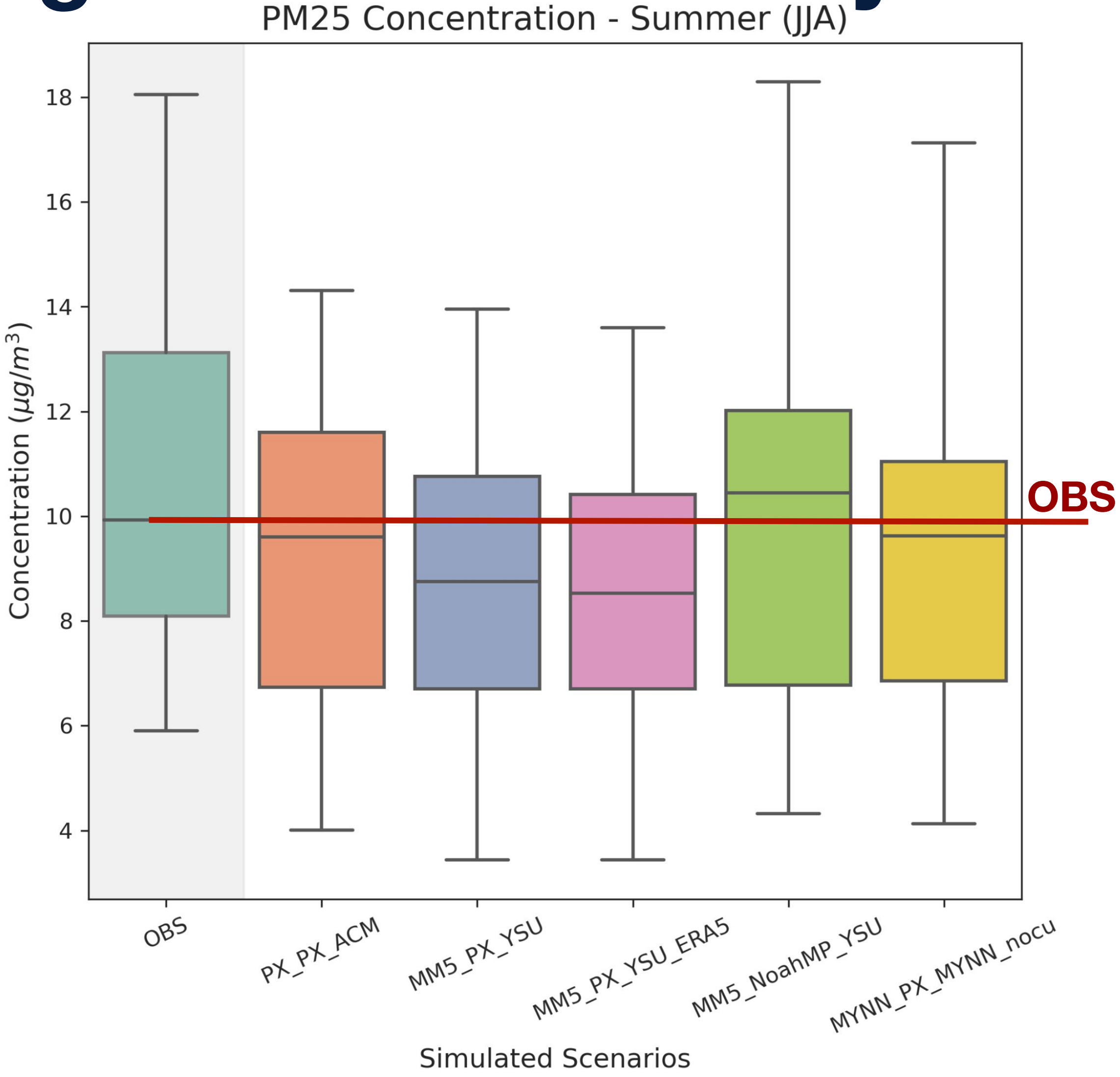


No	Reanalysis	Microphysics scheme	Cumulus scheme	Land-surface physics	PBL scheme (& Surface layer)	Grid nudging
1	NARR	Morrison 2-mom	Kain-Fritsch	Pleim-Xiu	ACM2 (Pleim-Xiu)	ON
2	NARR	Morrison 2-mom	OFF	Pleim-Xiu	ACM2 (Pleim-Xiu)	ON
3	NARR	Morrison 2-mom	Kain-Fritsch	Pleim-Xiu	YSU (MM5)	ON
4	NARR	Morrison 2-mom	Kain-Fritsch	Pleim-Xiu	YSU (MM5)	OFF
5	NARR	Morrison 2-mom	OFF	Pleim-Xiu	YSU (MM5)	ON
6	NARR	Morrison 2-mom	Kain-Fritsch	NoahMP	YSU (MM5)	ON
7	NARR	Morrison 2-mom	OFF	NoahMP	YSU (MM5)	ON
8	NARR	Morrison 2-mom	OFF	Pleim-Xiu	MYNN (MYNN)	ON
9	NARR	Morrison 2-mom	OFF	NoahMP	MYNN (MYNN)	ON
10	NARR	Morrison 2-mom	OFF	Pleim-Xiu	MYJ (Eta)	ON
11	NARR	Morrison 2-mom	OFF	NoahMP	MYJ (Eta)	ON
12	NARR	WSM-6	Kain-Fritsch	Pleim-Xiu	YSU (MM5)	ON
13	NARR	WSM-6	Kain-Fritsch	NoahMP	YSU (MM5)	ON
14	ERA5	Morrison 2-mom	Kain-Fritsch	Pleim-Xiu	YSU (MM5)	ON
15	ERA5	Morrison 2-mom	Kain-Fritsch	Pleim-Xiu	ACM2 (Pleim-Xiu)	ON

EPA suggested

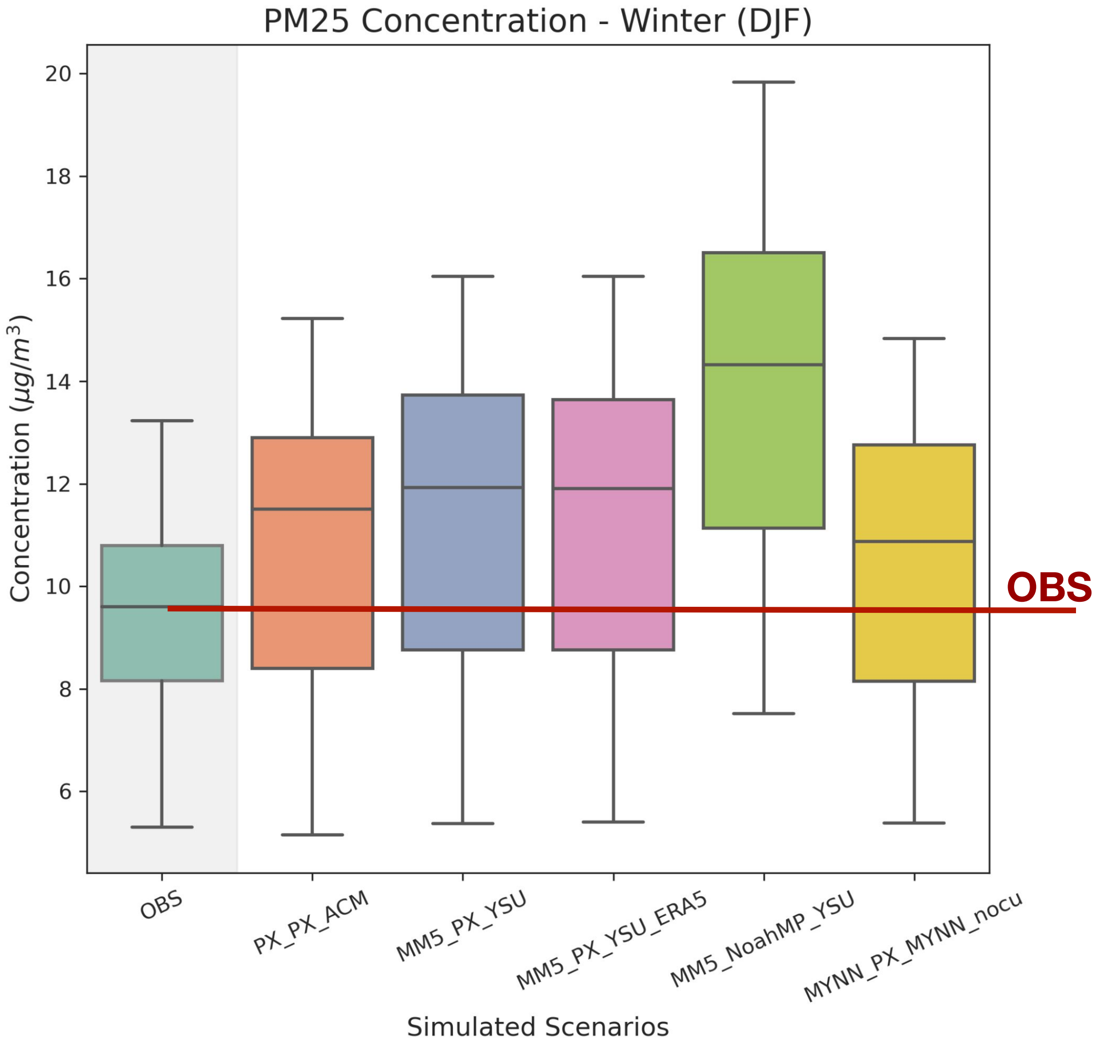
WRF ensemble members

Simulation of regionally-averaged PM2.5 yield significant variability among ensemble members



- Variability in the summer, regional mean PM2.5 concentration is roughly 3 micrograms per cubic meter.
- This is a substantial fraction of the mean concentration even when highly averaged.

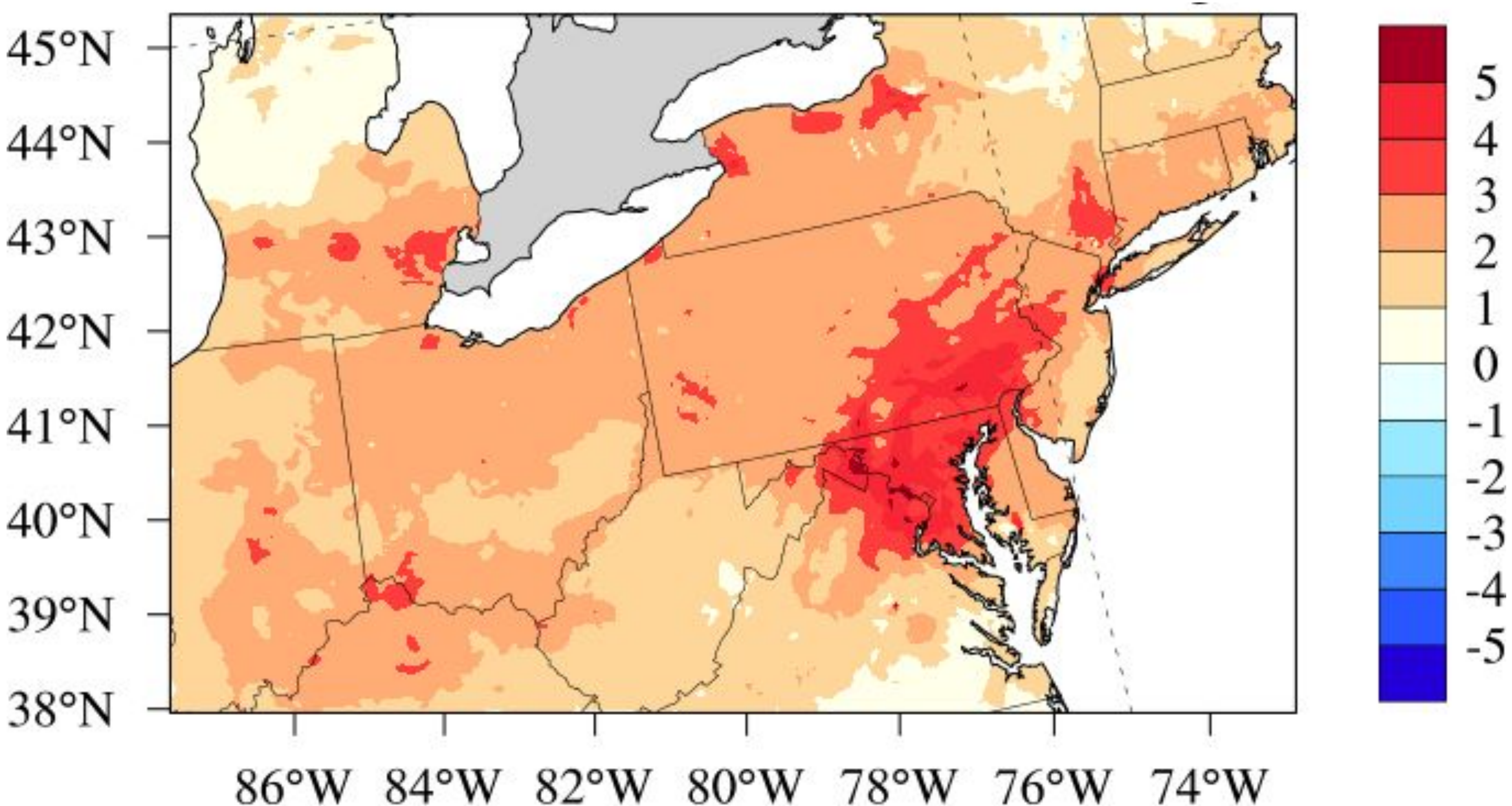
Simulation of regionally-averaged PM2.5 yield significant variability among ensemble members



- Winter regional mean PM2.5 concentrations are biased high with respect to observations, in addition to having fairly large variability.
- The cause of the bias is not clear.

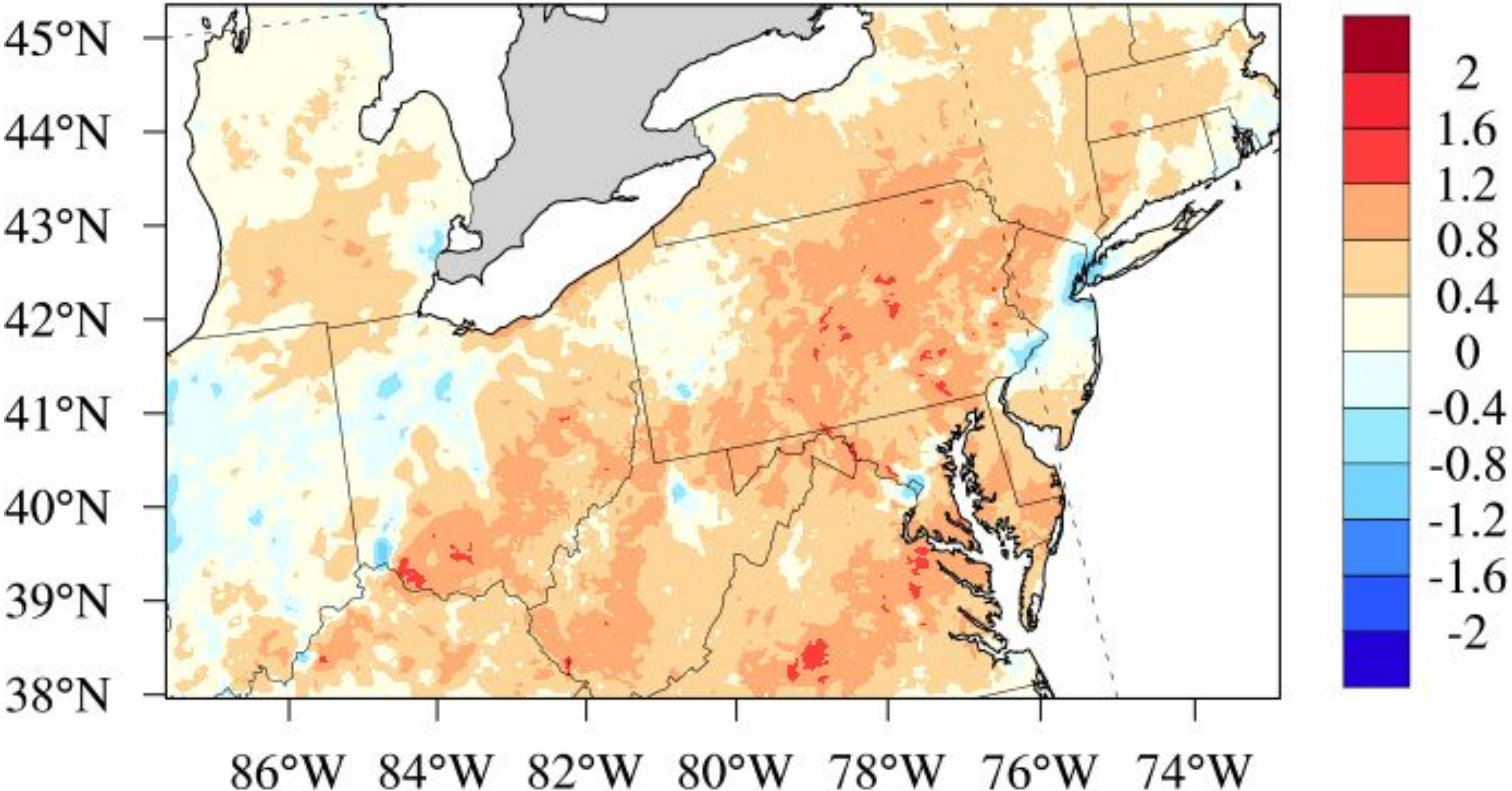
Spatial variability among members is also significant

$PM_{2.5}$ concentration in Jan. Unit: ug/m^3
MM5_NoahMP_YSU minus PX_PX_ACM

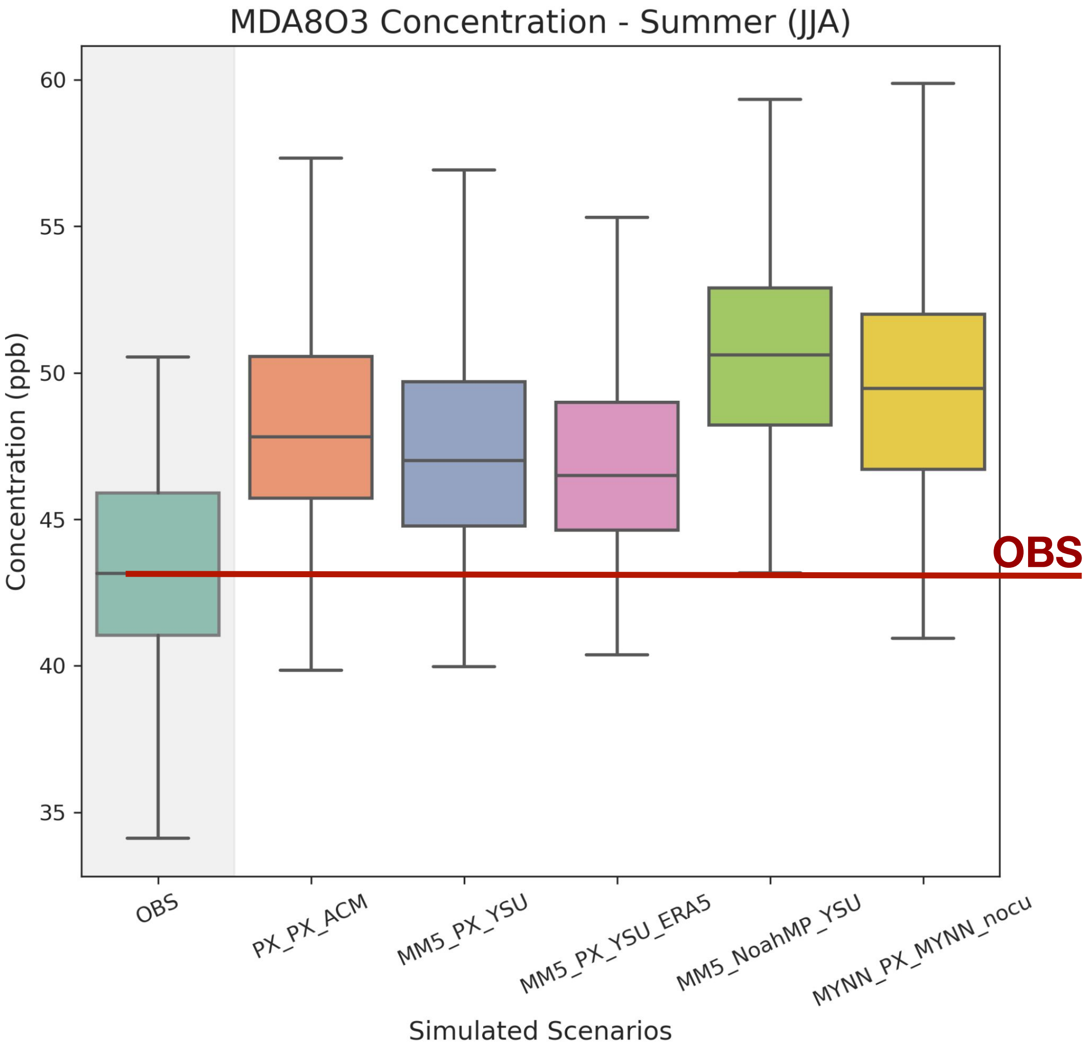


Spatial variability among members is also significant

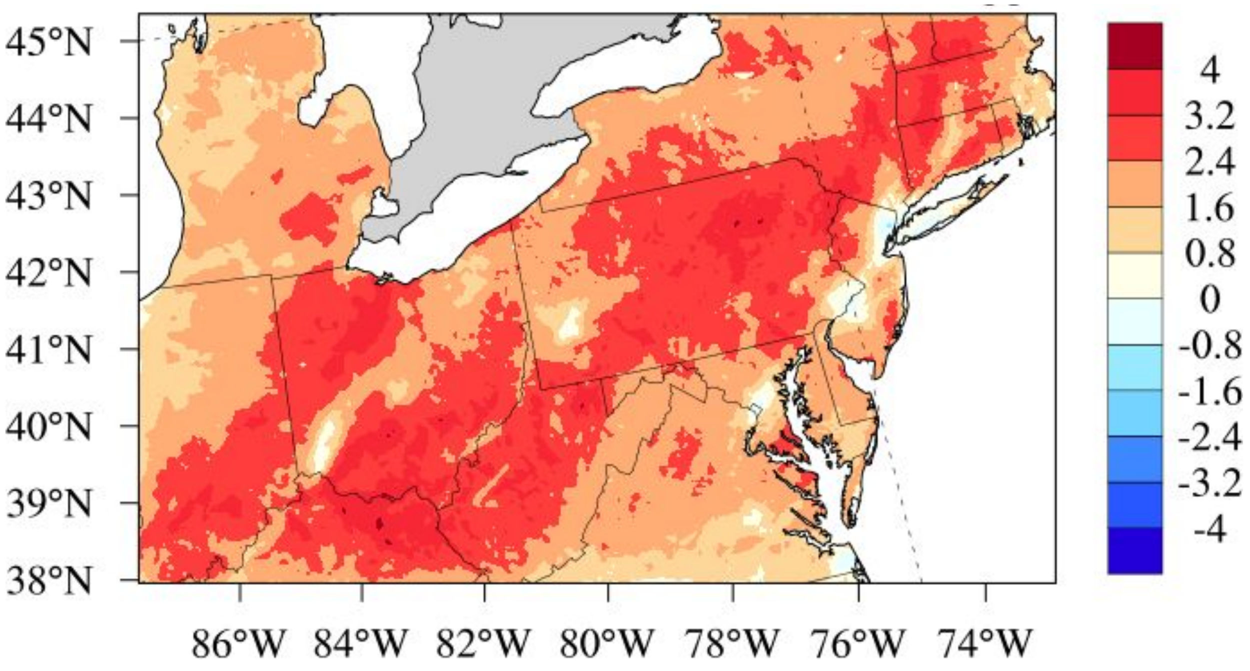
$PM_{2.5}$ concentration in July. Unit: ug/m^3
MM5_NoahMP_YSU minus PX_PX_ACM



Summer ozone is biased and variability amont the members is roughly 5 ppb



Daytime O_3 in July. Unit: ppb
MM5_NoahMP_YSU minus PX_PX_ACM



Conclusions

1. We can reduce identify and reduce atmospheric transport biases (e.g. CA central valley).

2. Flux biases in the Mid-Atlantic are small, but atmospheric models still show biases. We have just begun to explore the atmospheric transport ensemble.

3. The impact of transport uncertainties is significant. Biases can also be caused by emission and chemistry.

Publications

Wu, F., Davis, K. J., Zhang, L., Anderson, R. G., Horne, J. P., Goslee, S., Munger, W., Cai, C., Cui, Y. Y., Zhao, Z., & Zhong, M. (2026). Evaluating surface fluxes in WRF using eddy-covariance flux measurements in the Western and Eastern U.S. *Agricultural and Forest Meteorology*, *379*, 111029. https://doi.org/10.1016/j.agrformet.2026.111029

Jiang, Y., Zhang, L., Wu, F., Kulkarni, S., Cui, Y. Y., Cai, C., et al. (2026). Improving air quality simulations in California's San Joaquin Valley using land surface remote sensing. Journal of Geophysical Research: Atmospheres, 131, e2025JD045616. https://doi.org/10.1029/2025JD045616

Davis, K. J., Wu, F., Richardson, S., Ahlswede, B (2025), AmeriFlux BASE US-NSa NASA HAQ - SJV East Irrigated Vineyard, Ver. 1-5, AmeriFlux AMP, (Dataset). https://doi.org/10.17190/AMF/2574379

Davis, K. J., Wu, F., , Richardson, S., Ahlswede, B (2025), AmeriFlux BASE US-NSb NASA HAQ - SJV West Irrigated Cotton, Ver. 1-5, AmeriFlux AMP, (Dataset). https://doi.org/10.17190/AMF/2574380

Wu, F., Davis, K. J., Lawston-Parker, P., Zhang, L., Jiang, Y., Zhong, M. Improving Regional Surface Energy Partitioning through Remote Sensing Data Assimilation and Irrigation Representation. Preprint available at http://ssrn.com/abstract=6448780

Wu, F., Davis, K. J., Lawston-Parker, P., Jiang, Y., Zhang, L. Noah-MP Irrigation Improves Boundary Layer Height Simulations in the Central Valley of California. *In preparation.*

Jiang, Y., Davis, K. J., Wu, F., Zhong, M., Zhang, L., Peng, W. Quantifying the Influence of Meteorological Uncertainty on Pennsylvania Air Quality via Ensemble Modeling. *In preparation*

Air quality simulation

$PM_{2.5}$ concentration in July. Unit: ug/m^3
MM5_NoahMP_YSU minus PX_PX_ACM