# Deterministic and Probabilistic Short-Term Air Quality Predictions

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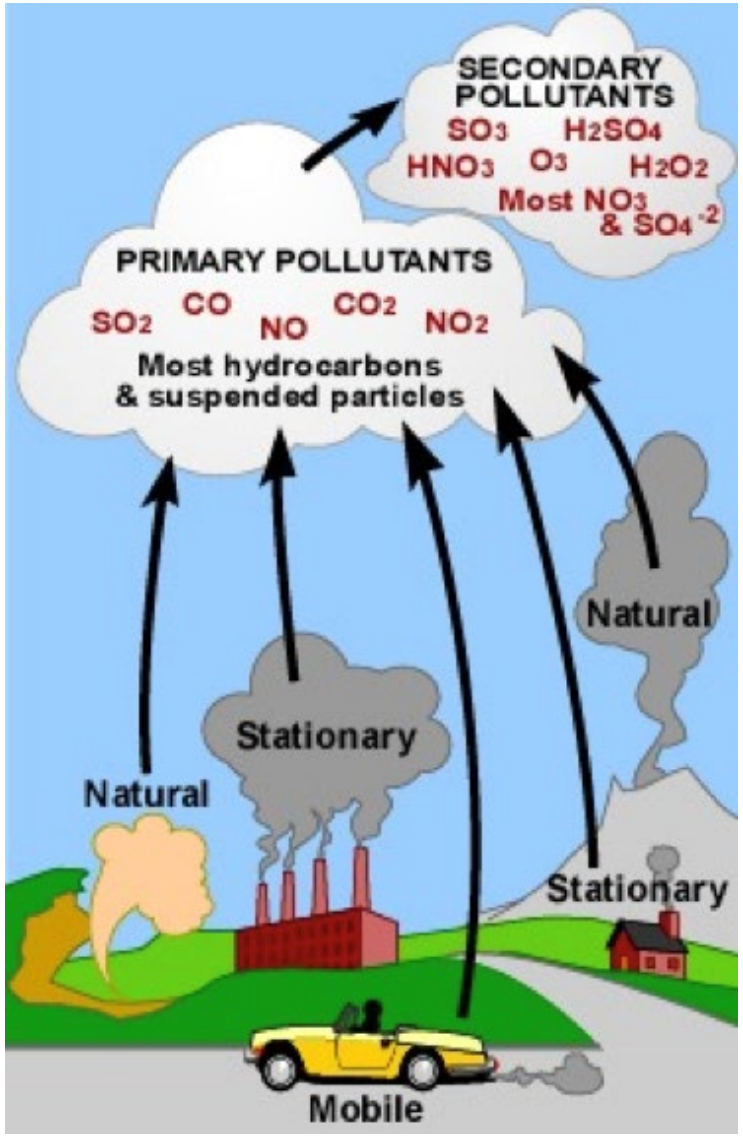
# What is Air Pollution?

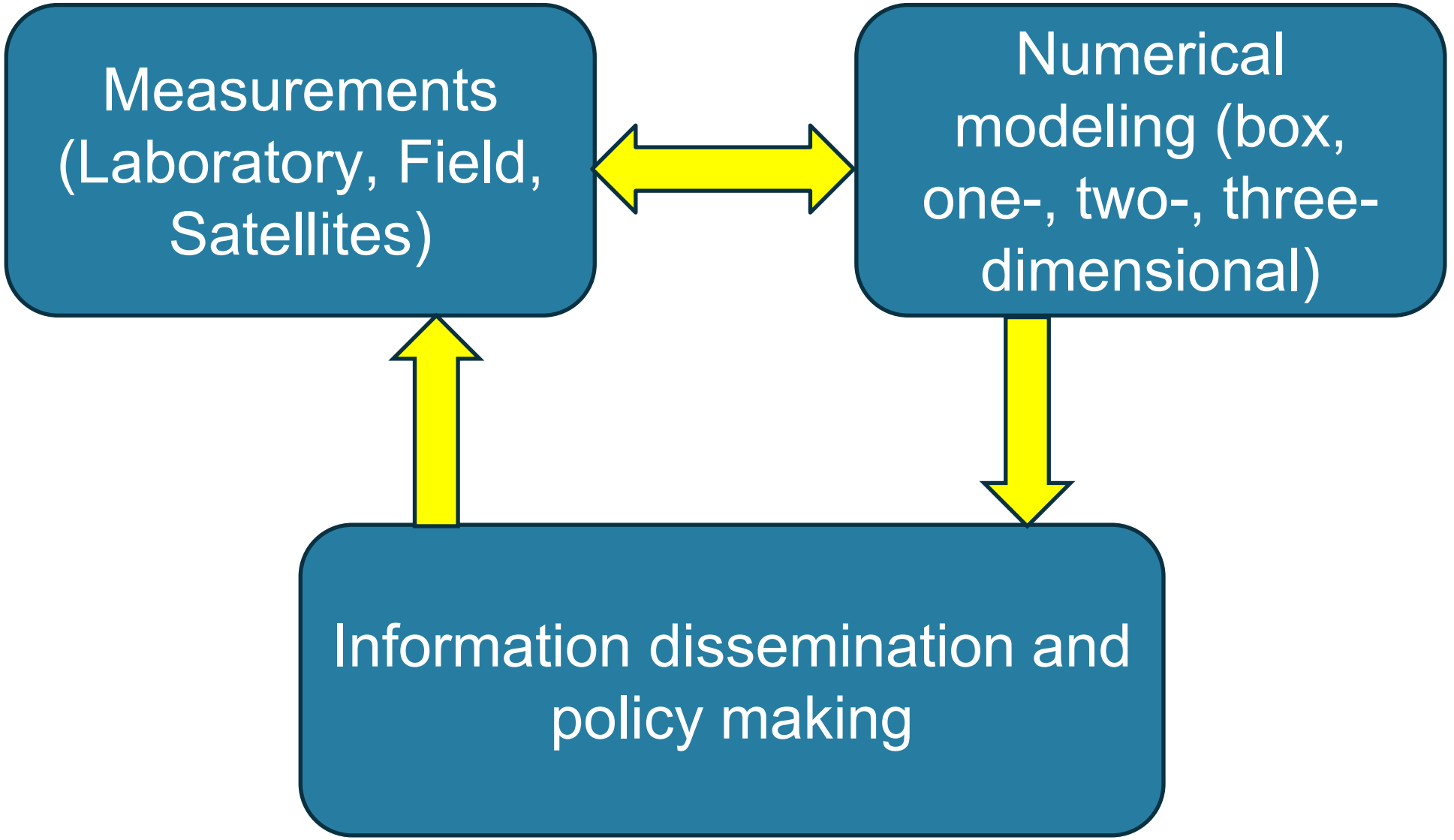
- Air Pollution represents the presence of chemicals and particles in the atmosphere above a certain threshold that cause health hazards and damage ecosystems.
- In UK, the Department for Environment, Food and Rural Affairs defines these thresholds in terms of National Ambient Air Quality Standards (NAAQS):
  - Maximum daily 8 hour average ozone NAAQS: 100 μg/$m^3$
  - 24-h average PM2.5 NAAQS: 20 μg/$m^3$
- Air pollutants are either emitted directly to the atmosphere or form via chemical reactions in the atmosphere.
- Air pollution cause huge losses in the UK
  - 28,000-36,000 premature deaths
  - Economic loss: ~ £20 billion per year



# Air Pollution is a global threat


- 7 million premature deaths [WHO, 2018]
- US$5 trillion economic loss [World Bank, 2015]
- 79-121 million tones of lost crop produces globally [Avnery et al., 2011]
- 94 million people can be fed in India by saving crops from ozone damage [Ghude et al., 2014]

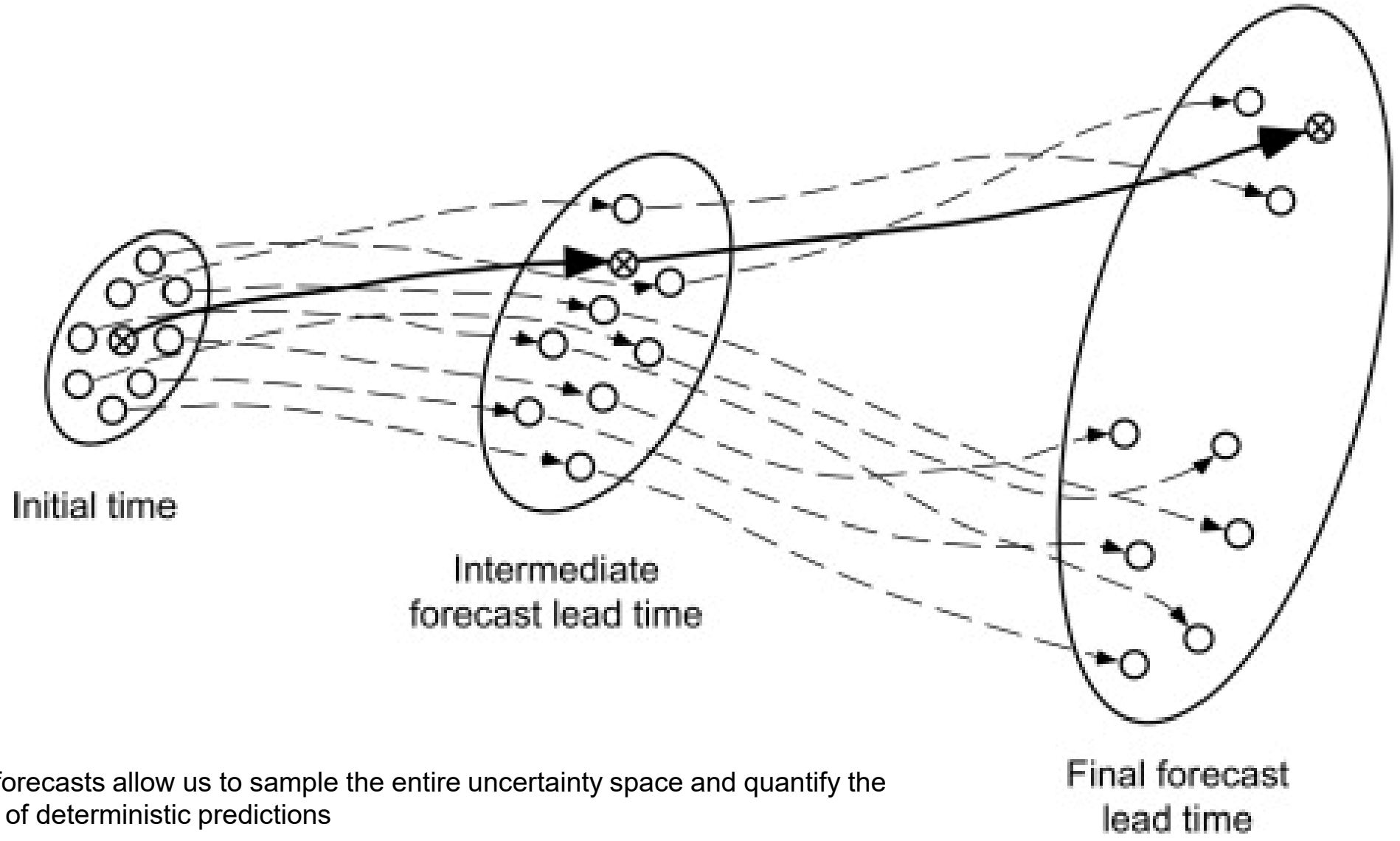
# Framework to address air pollution



# Why do we need air pollution forecasts?

1) Protecting public health through air quality warnings and alerts
2) Protecting ecosystems
3) Short-term temporary regulatory actions and urban planning including monitoring networks
4) Medical infrastructure management
5) Increased public productivity through healthier population -> economic benefits
6) Public awareness and education that is vital for mitigation

# Deterministic and Probabilistic forecasts




Ensemble forecasts allow us to sample the entire uncertainty space and quantify the uncertainty of deterministic predictions

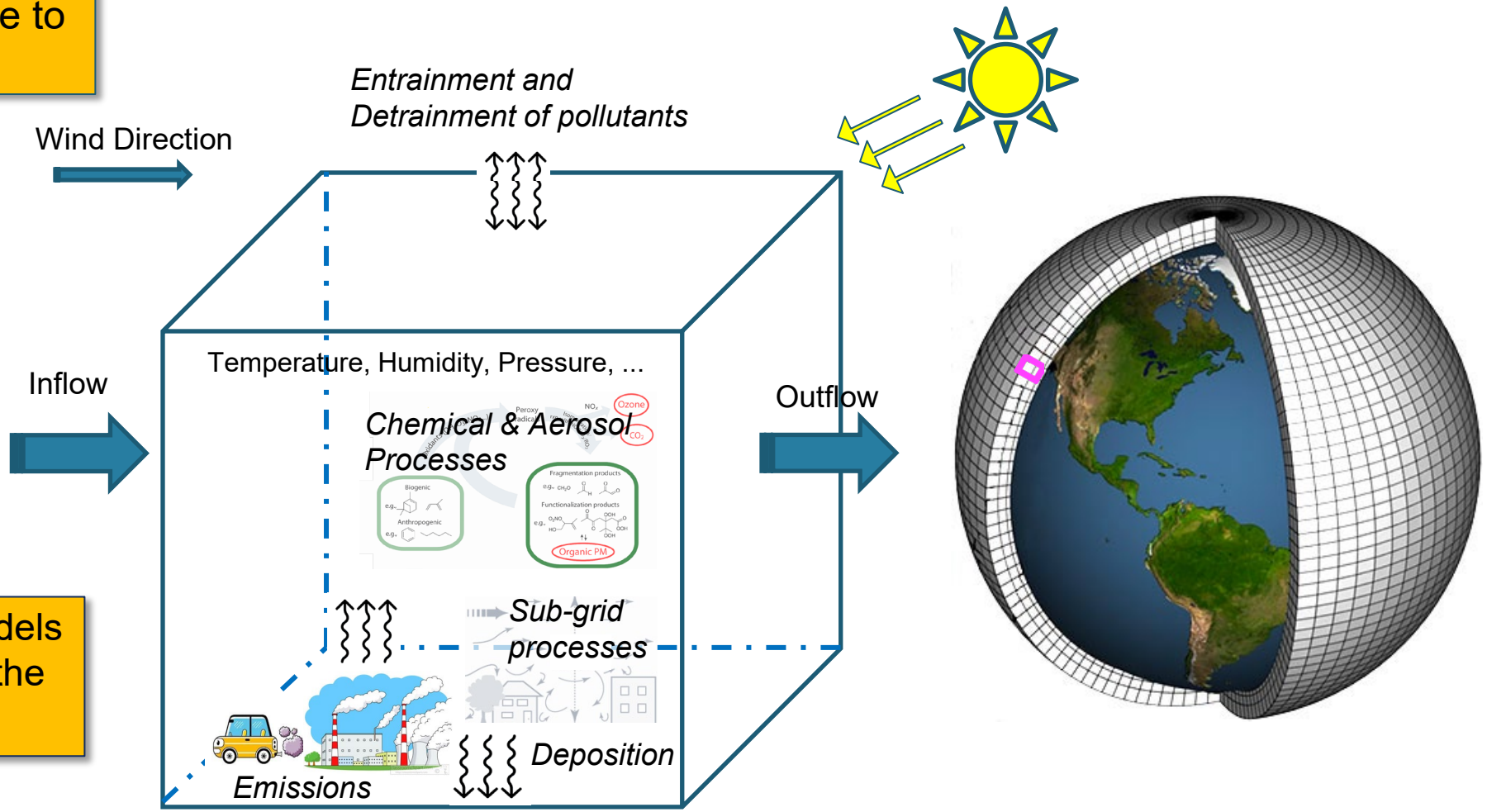
[Wilks, 2011]

# What is a model?

Model = Simplified representation of complex systems amenable to analysis

# What is an air quality model?

Model = Simplified representation of complex systems amenable to analysis




Weather/Climate/Air Quality Models = Simplified representation of the complex Earth System

# Modeling Applications

- Predicting past, current and future air quality/atmospheric composition
- Air Quality Forecasting
- Exploring the interactions between weather and atmospheric chemistry
- Studying the role of chemistry in climate and the feedback of climate on chemistry
- Understanding the biogeochemical processes that govern the composition of and changes to the natural environment
- Aiding in the interpretation of observations
- Assessing the value of current and future observational systems
- …….

We need models to increase our understanding of atmospheric chemistry/air quality and to develop tools to provide societal relevant information

# NSF NCAR Atmospheric Chemistry Modeling Ecosystem

**Understanding Air Quality and Chemistry in Detail**

Chemical Box Models (BOXMOX)
Column Models (SCAM)
LES models (WRF-LES, NCAR-LES)

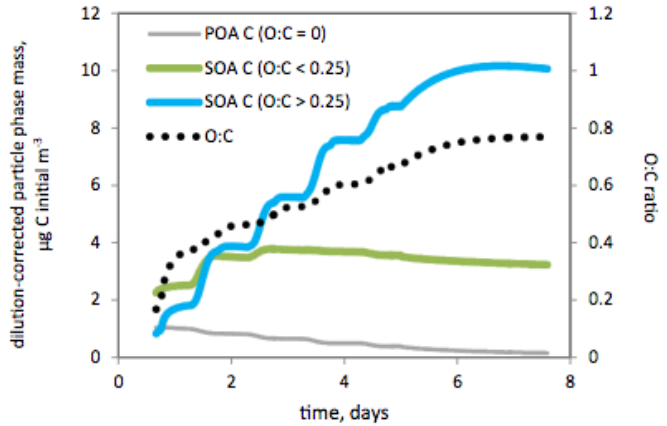
Radiative Transfer models (TUV)
Hyper-explicit models (GECKO-A)

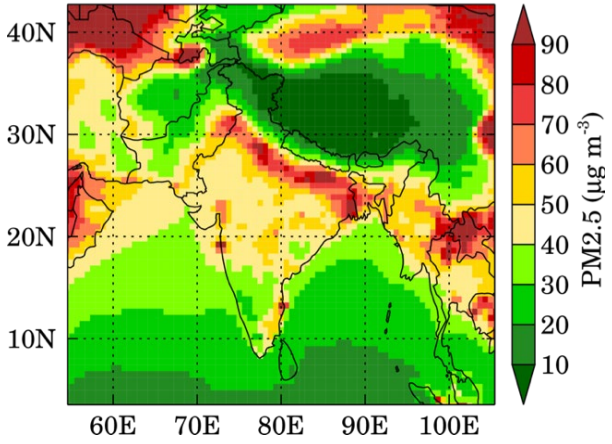
**Examining the Urban/Cloud Resolving to Regional Scales**

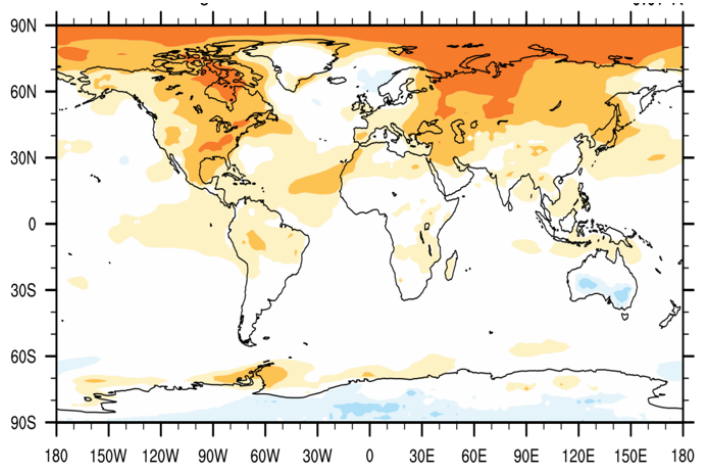
Regional Chemical Transport models (WRF-Chem)

**Global Scale Impacts of Atmospheric Chemistry**

Global Chemical Transport Models & Earth System Models (CAM-Chem, WACCM - *part of CESM*)

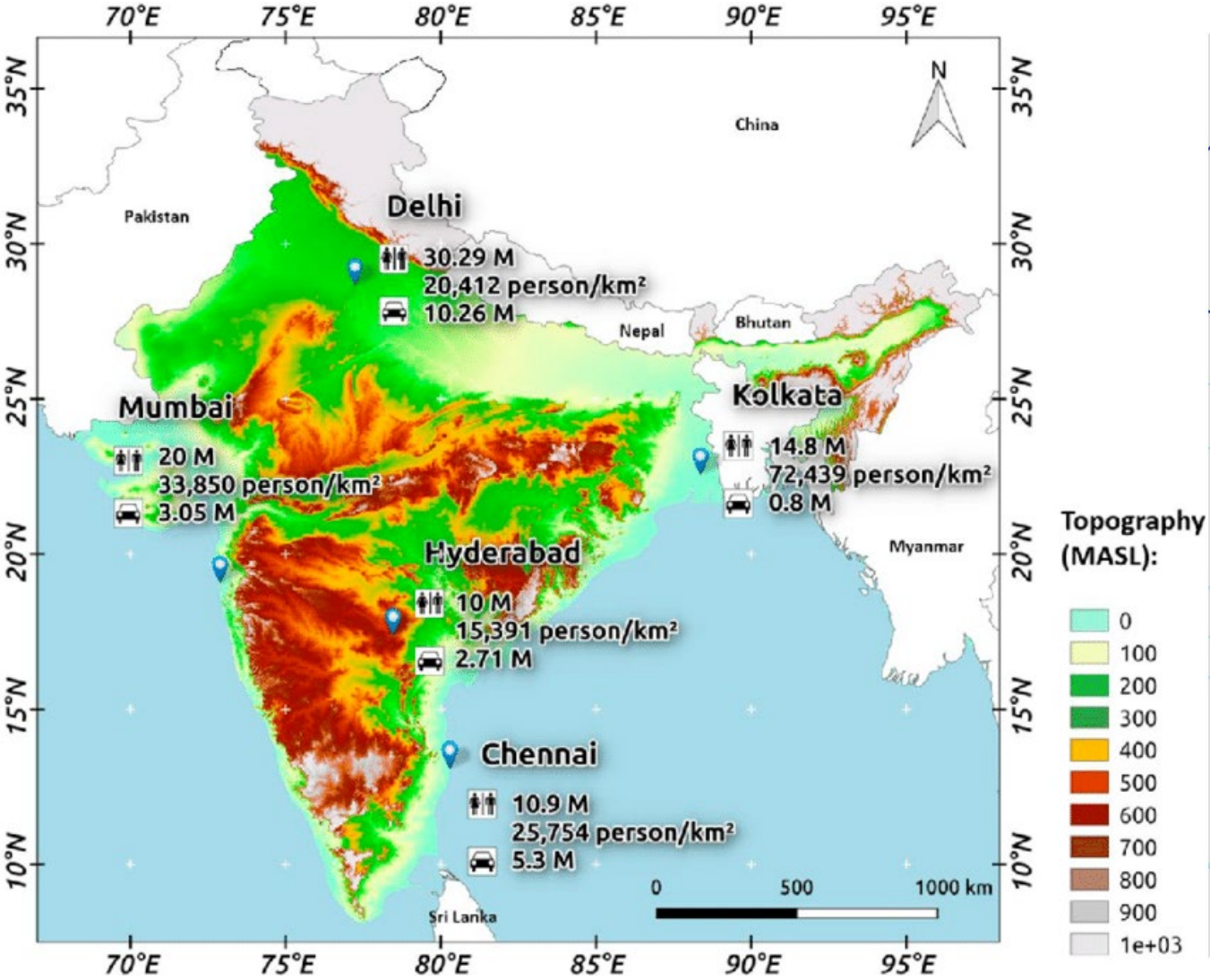


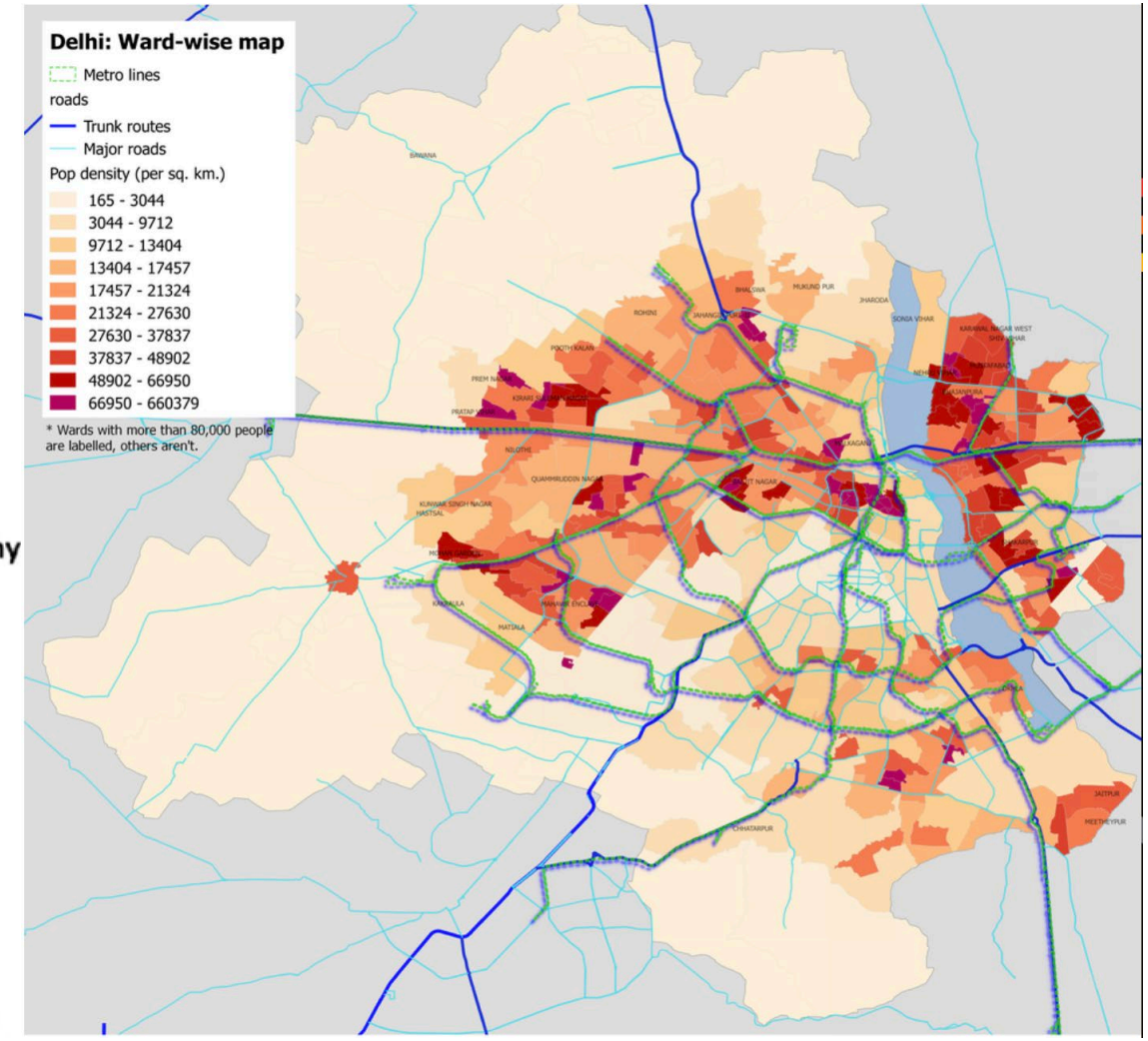
# Deterministic air quality forecasting system development
# Delhi example

# Delhi topography and population







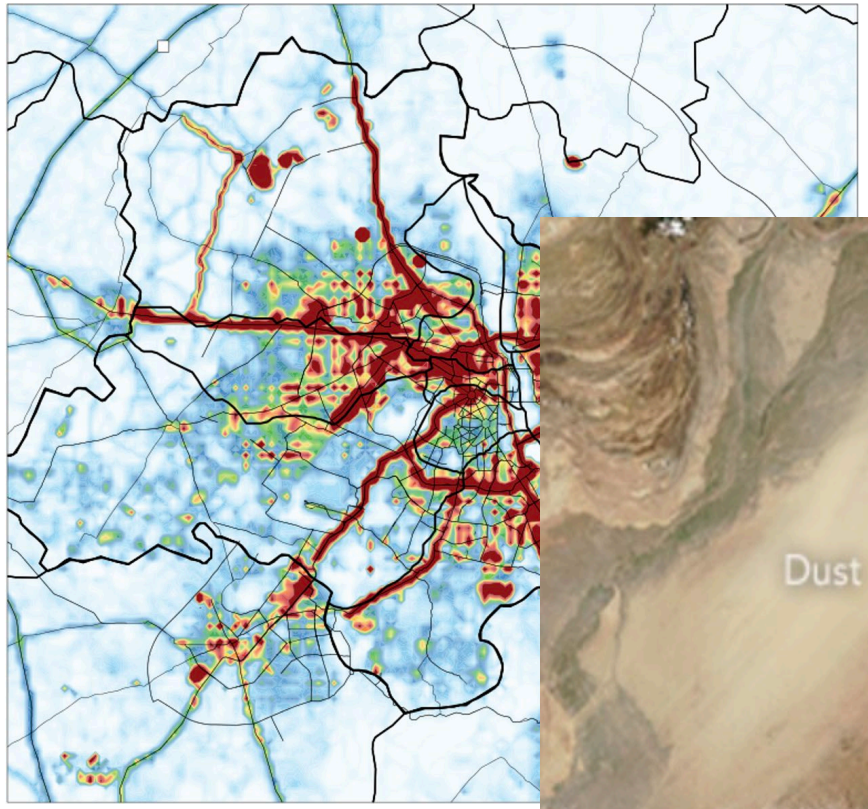



P. Kumar et al., [2020]

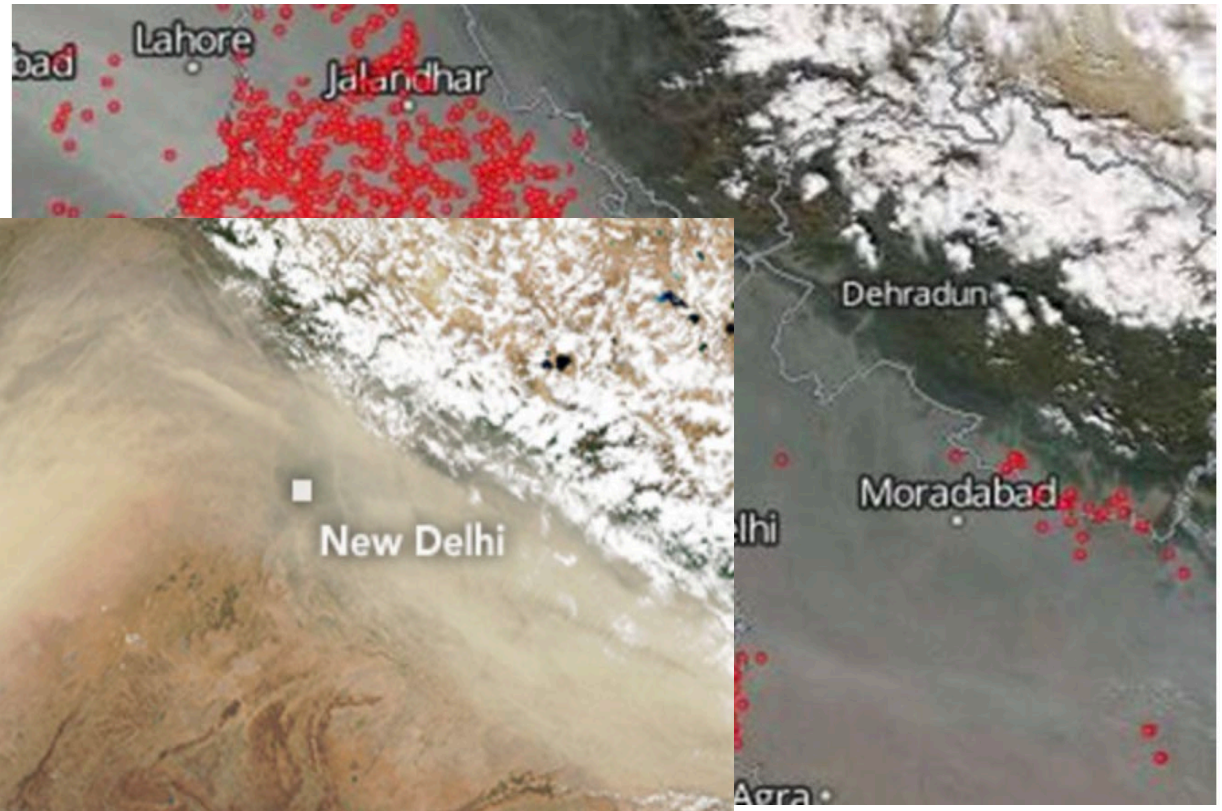
Image from reditt.com

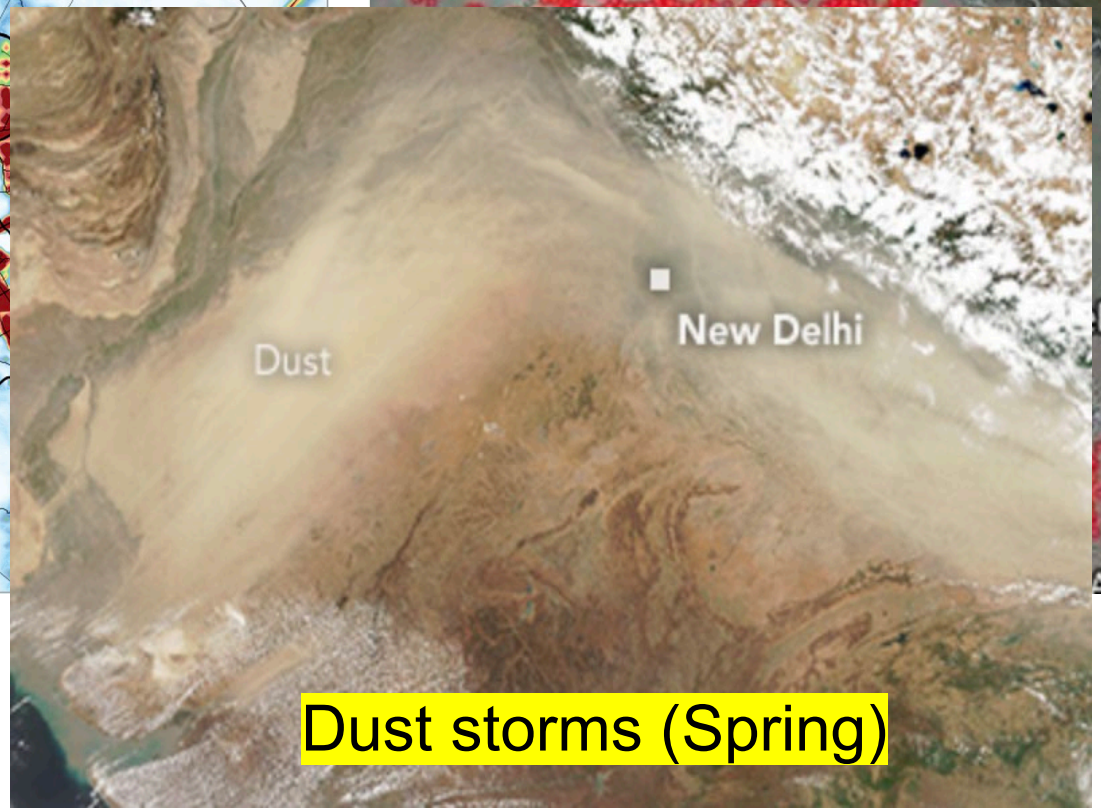
# Major emission sources affecting Delhi

Anthropogenic emissions (All year)

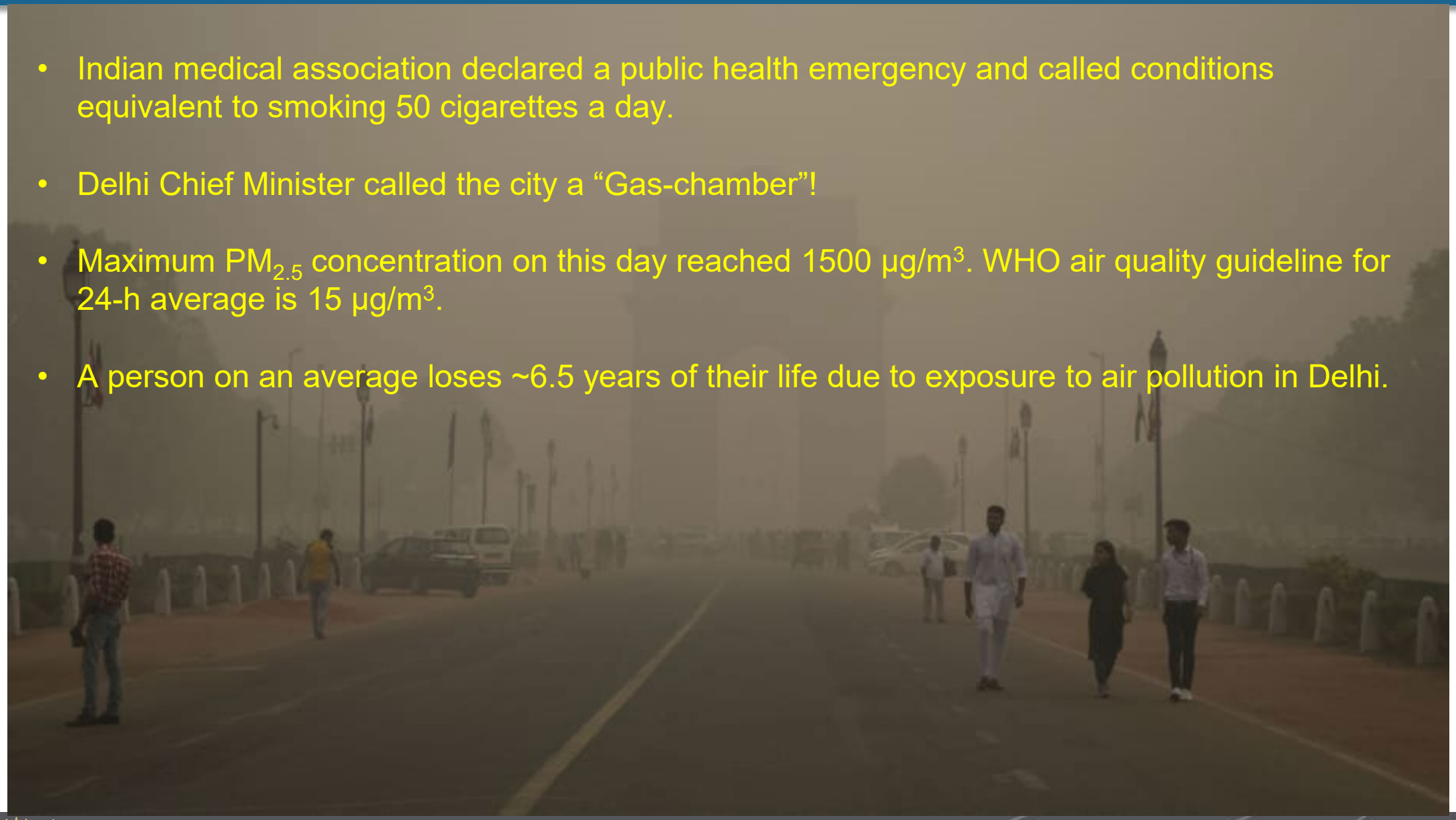


Crop residue burning (Spring and Fall)



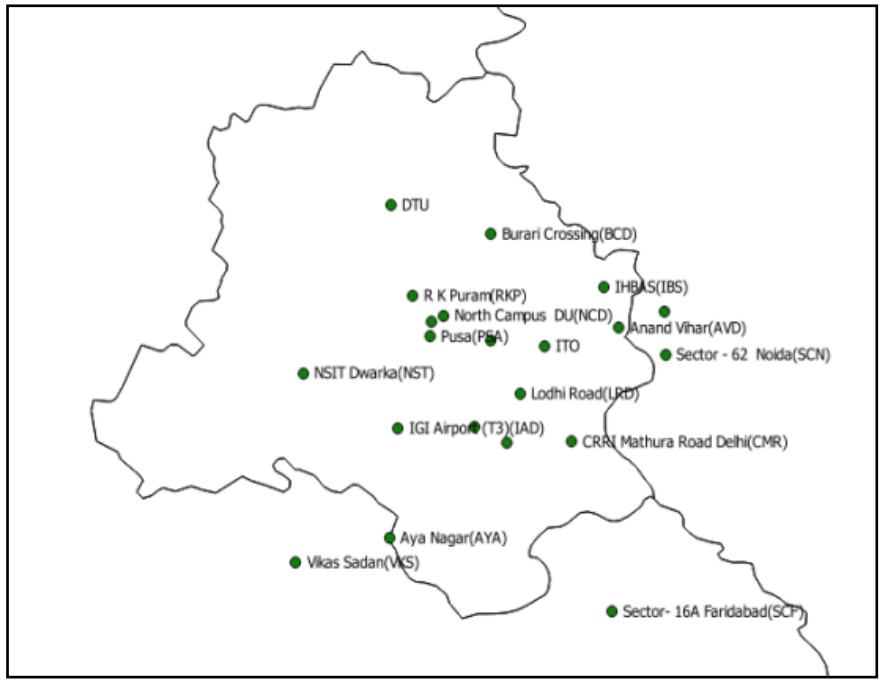
# 08 Nov 2017: Red Letter Day in Delhi (AQI = 999)



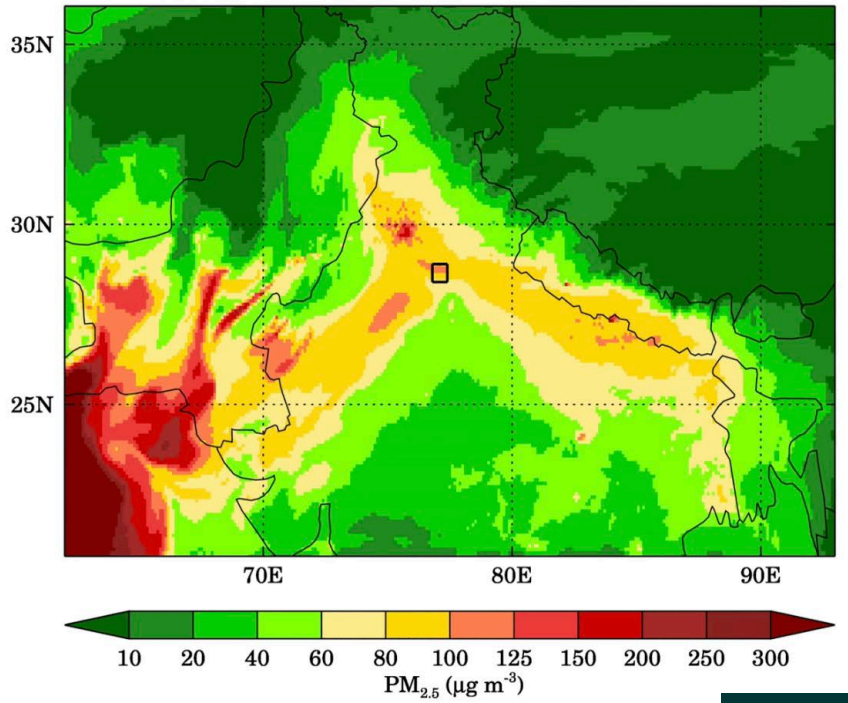
- Indian medical association declared a public health emergency and called conditions equivalent to smoking 50 cigarettes a day.
- Delhi Chief Minister called the city a “Gas-chamber”!
- Maximum $PM_{2.5}$ concentration on this day reached 1500 μg/$m^3$. WHO air quality guideline for 24-h average is 15 μg/$m^3$.
- A person on an average loses ~6.5 years of their life due to exposure to air pollution in Delhi.

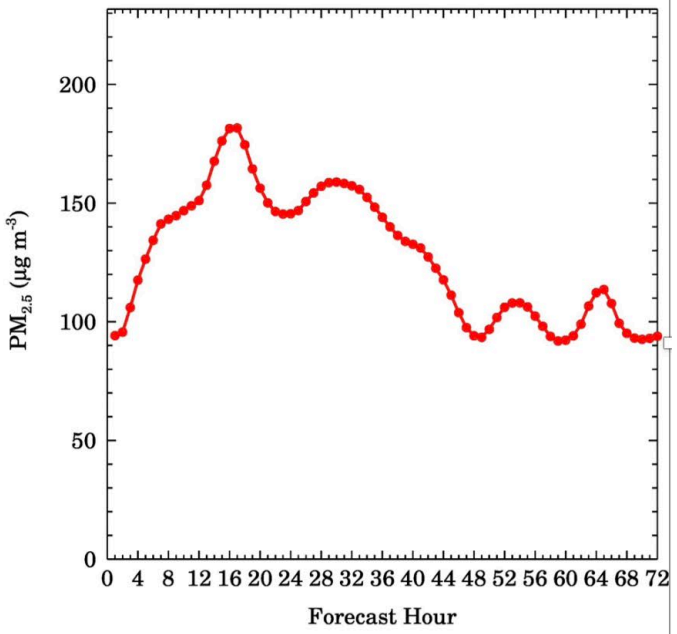
# Government (Ministry of Earth Sciences), India Initiatives

**Air Quality Monitoring Network (Delhi-NCR)**

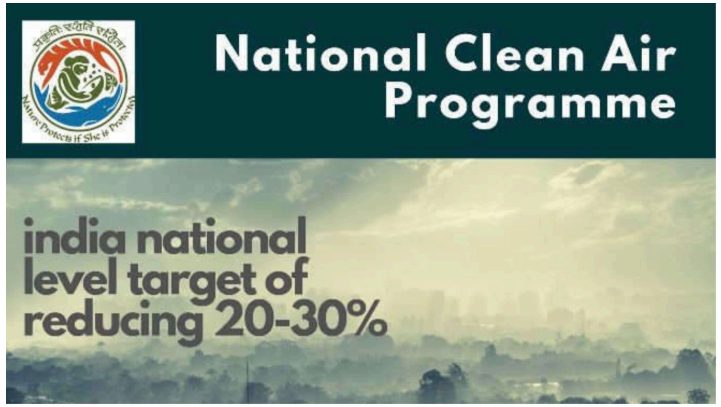



**Air Quality Forecasts**

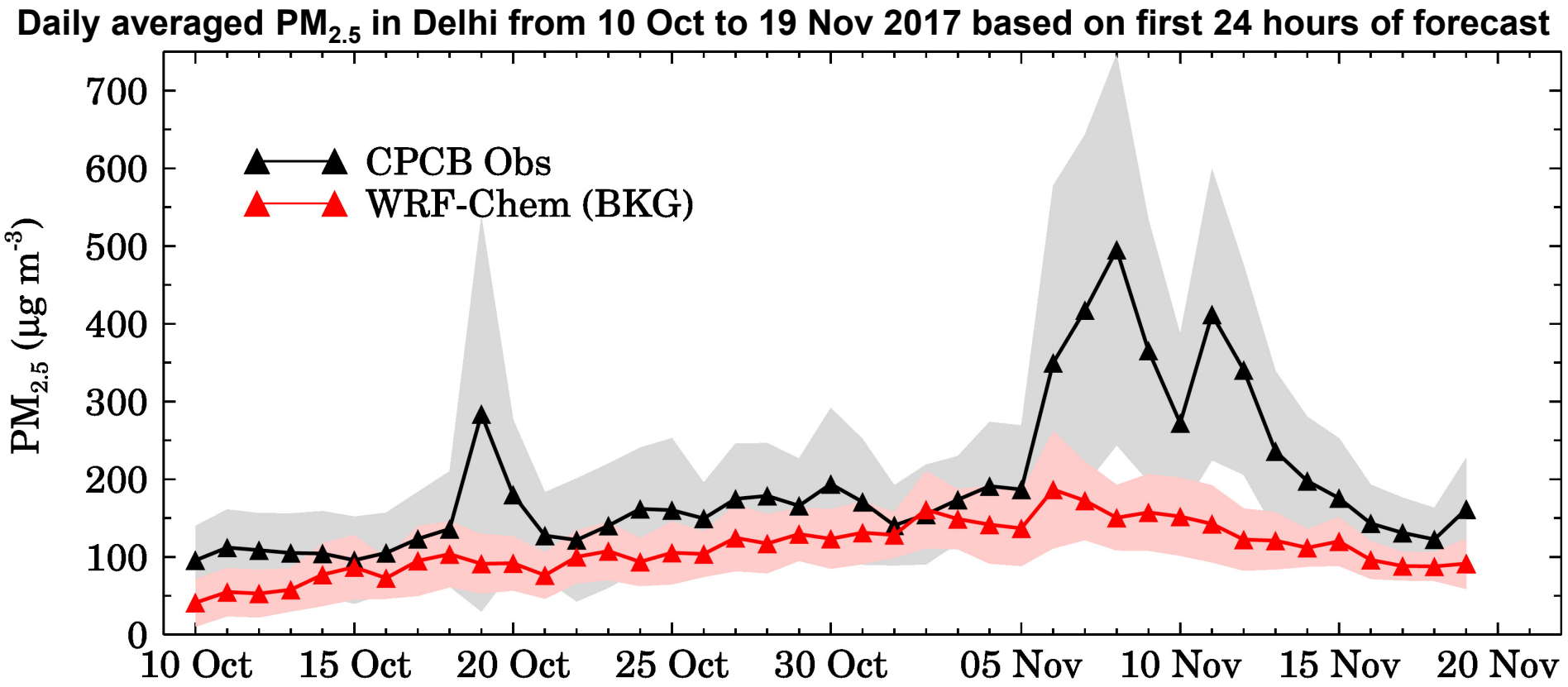



**Information Dissemination:**
Digital boards
SMS
Mobile Apps
Websites

# Did Delhi residents get an early warning?




WRF-Chem based forecasting system could not predict the pollution event.

# Race against time to develop a new AQEWS

**Dec 2017**
First NSF NCAR-IITM conversation

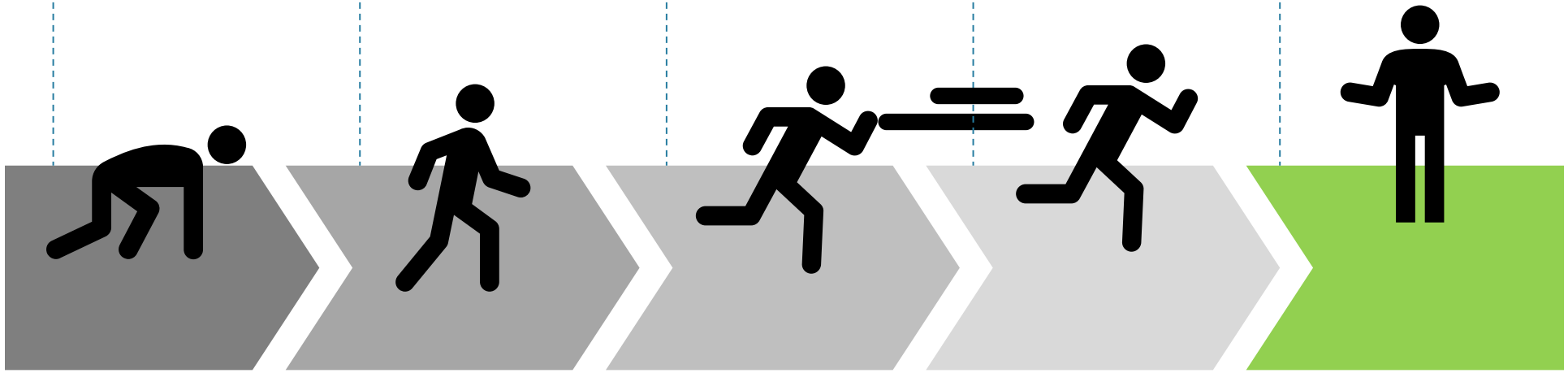
**Feb 2018**
NSF NCAR proposal sent to IITM

**Mar 2018**
NSF NCAR proposal accepted by IITM

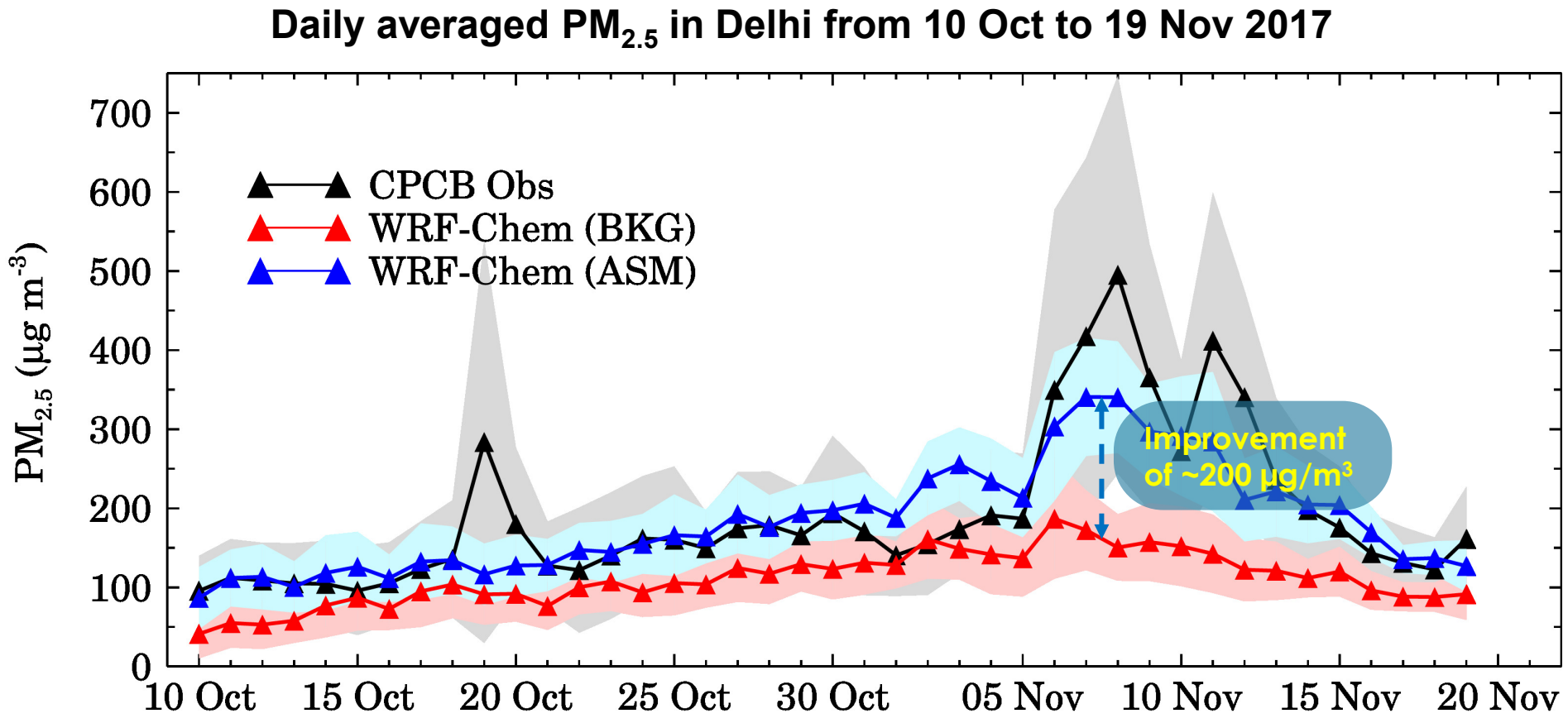
**Mar-Sep 2018**
System development and testing

**Oct 2018**
Operational predictions started at NSF NCAR

**Jan 2019**
Operational system transitioned to IITM

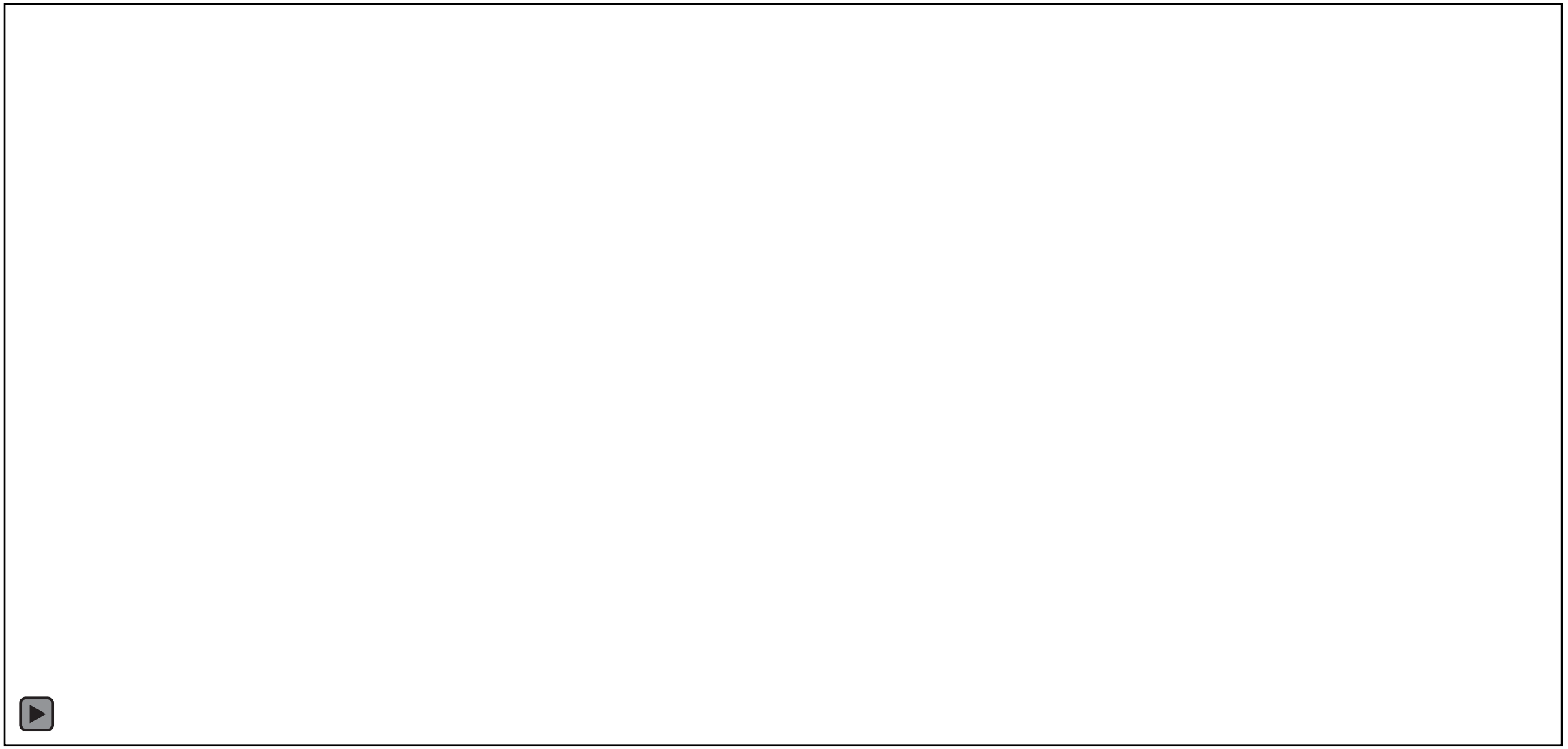


# Improved predictions of 2017 event

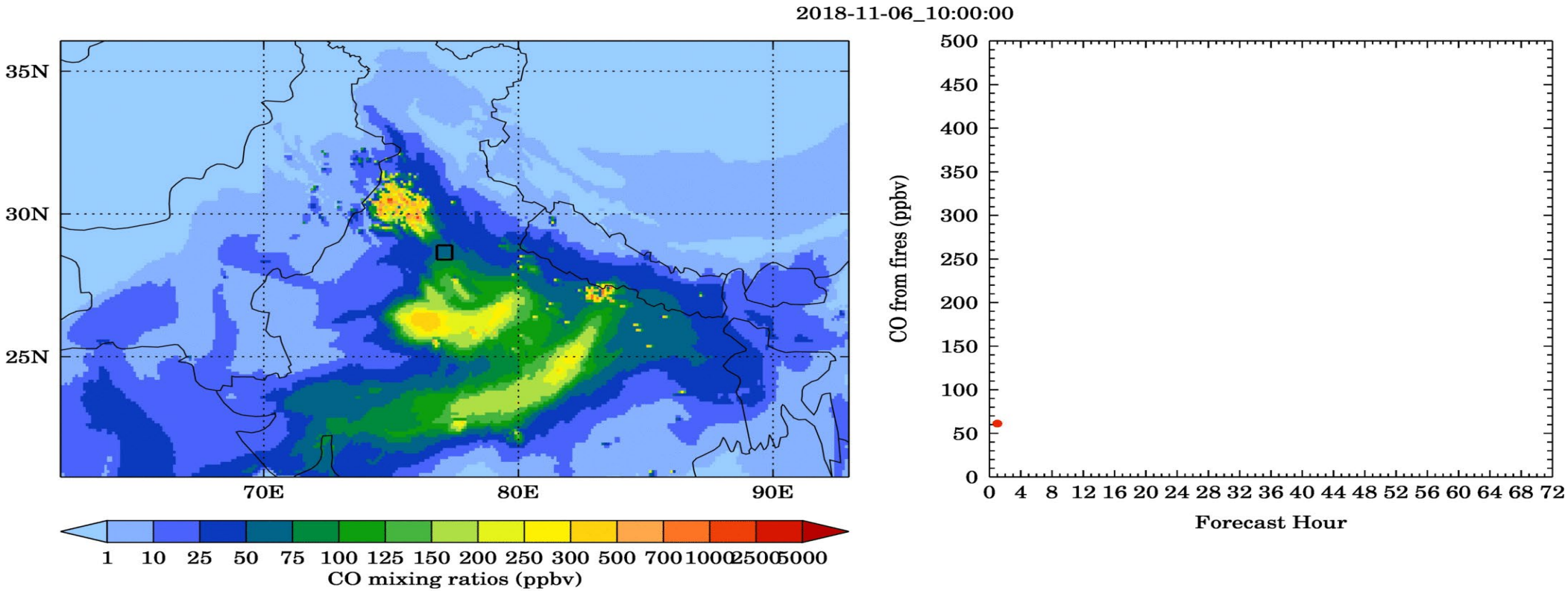



Mean bias reduction over the entire period: 86% [Kumar et al., 2020]

# Overview of the Forecast Products



# Forecasting Crop-residue burning influence in Delhi



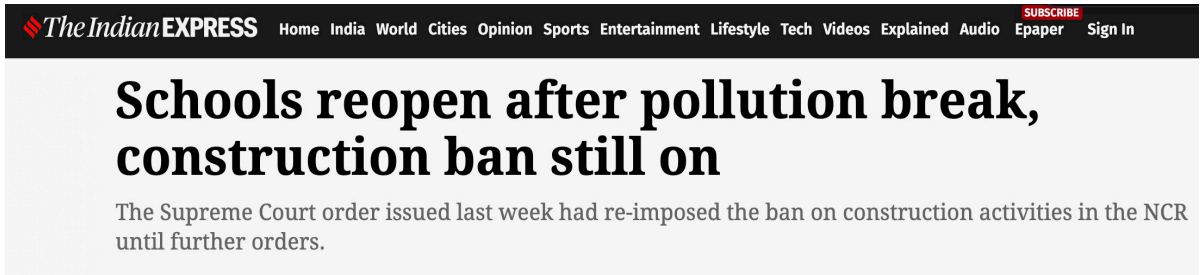
# Empowering decision-makers!!


**Delhi air pollution: NCR schools, colleges shut, construction at a halt till November 21**

Delhi Air Quality Information → Commission for Air Quality Management

Commission for Air Quality Management → (Polluted air) → Restricted Activities

Commission for Air Quality Management → (Cleaner air) → Normal Operation

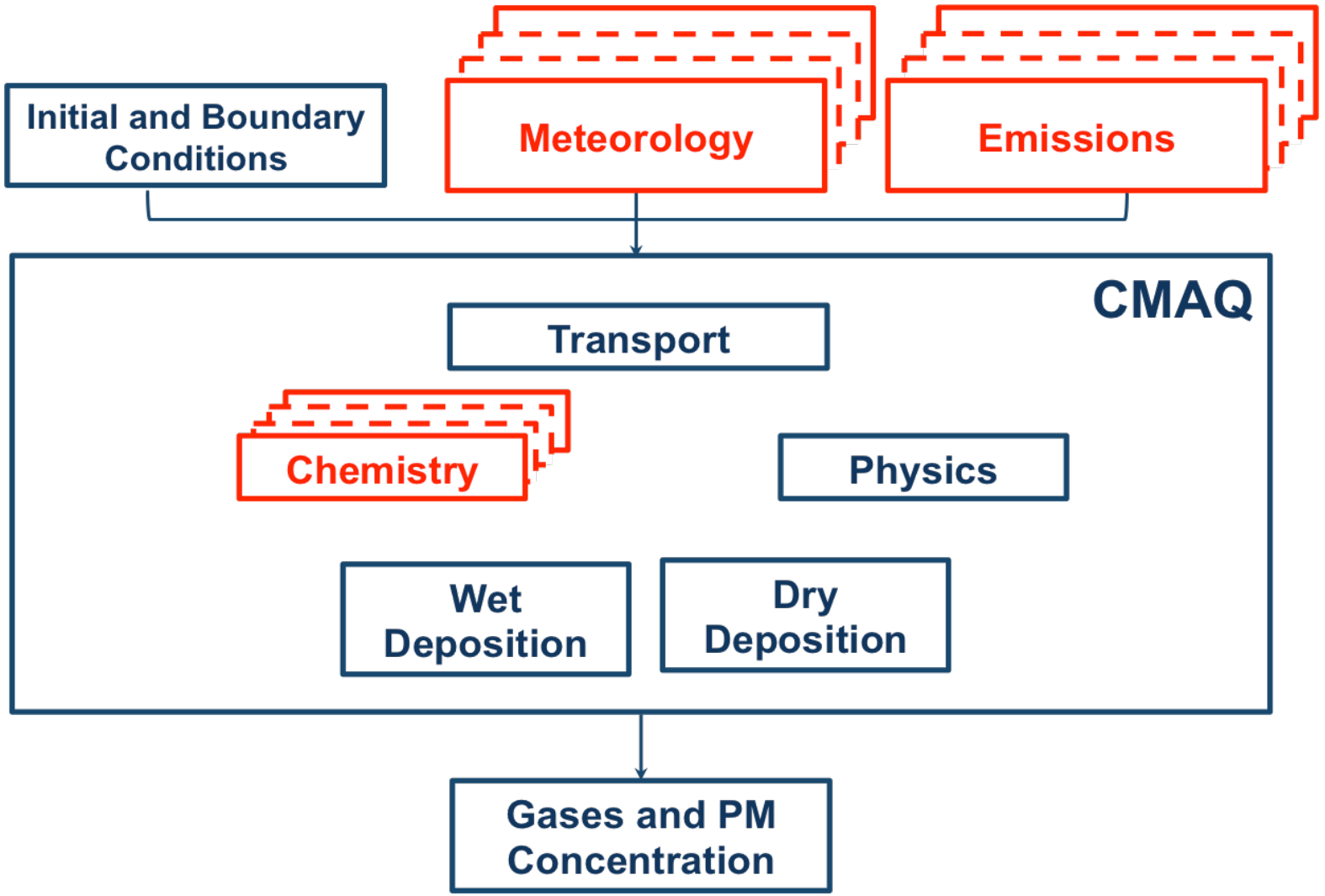



[Ghude, Kumar et al., Nature, 2022]

# Probabilistic air quality forecasting system development USA example

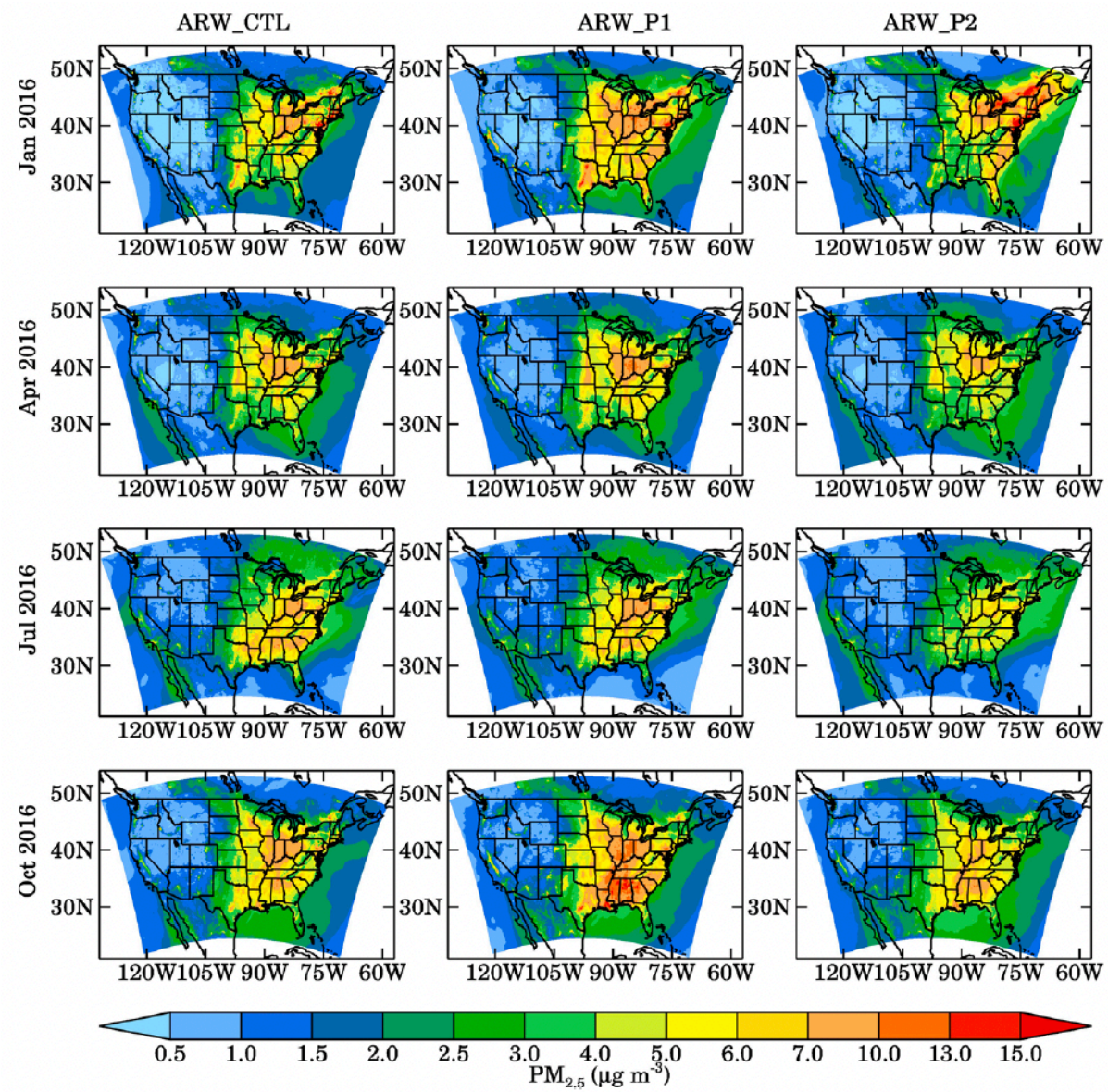
# Ensemble design

## Air Quality Modeling Process and Ensemble design



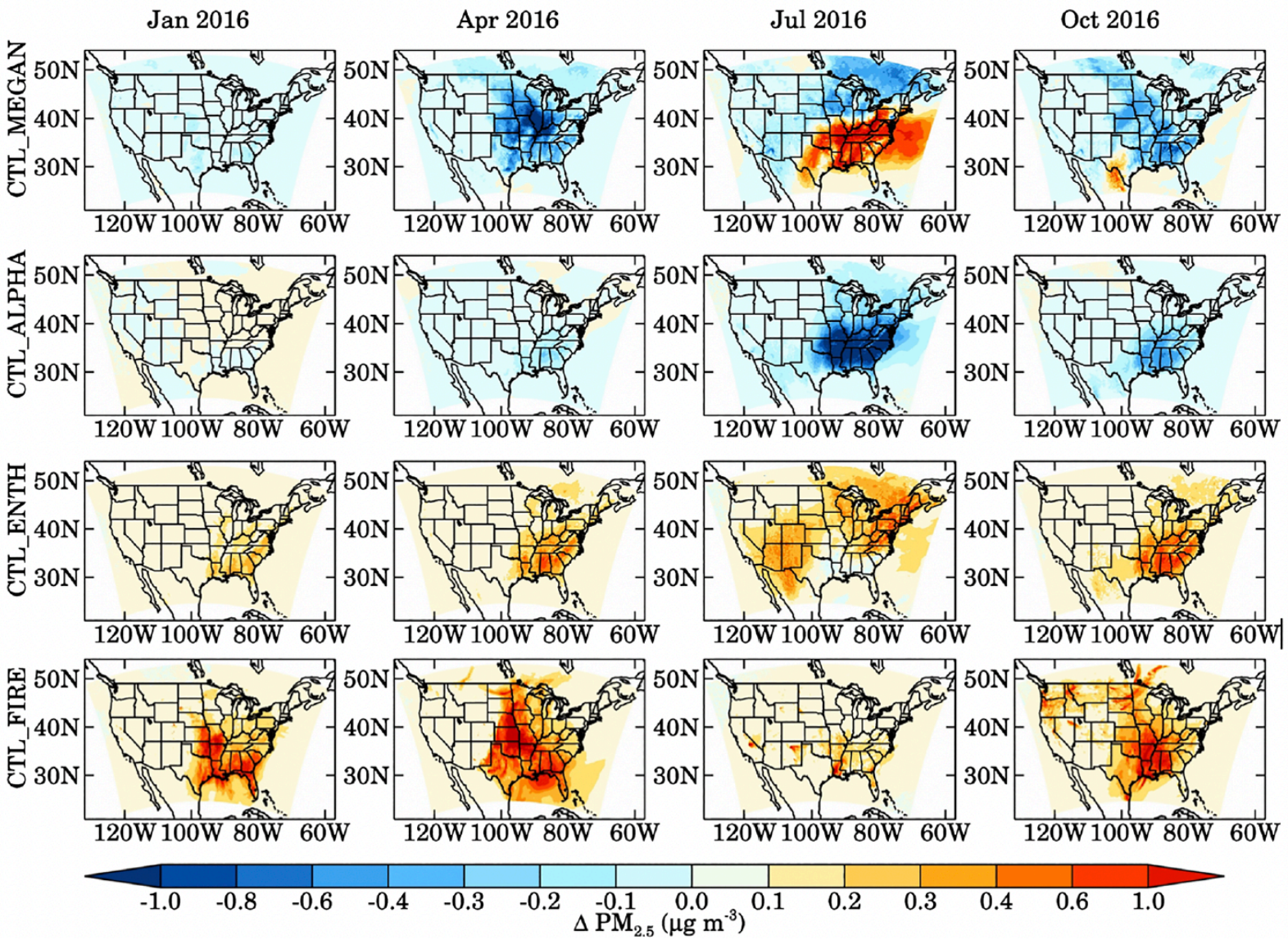

- Our ensemble design will capture three major sources of uncertainties in $PM_{2.5}$ predictions.

# Changes in $PM_{2.5}$ due to Meteorological Variability



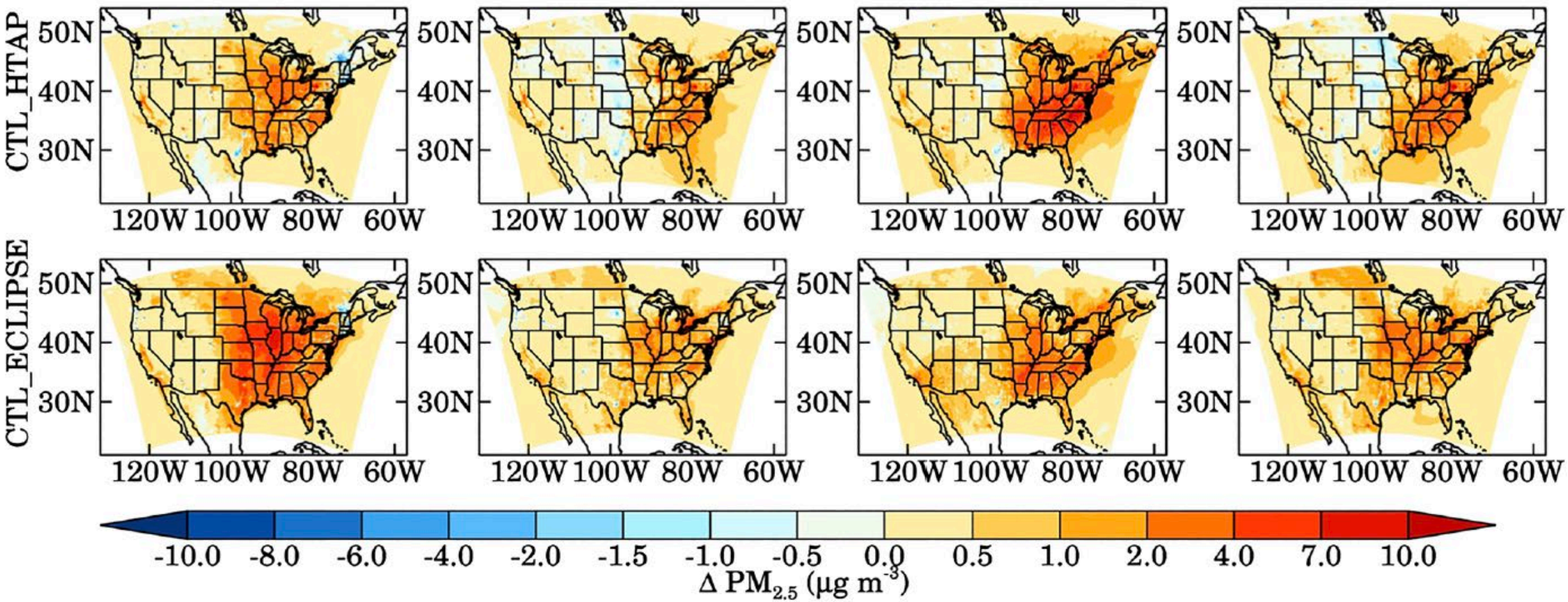

- Higher PM2.5 mass concentrations over the eastern United States.
- Arw_p1 shows the highest concentrations in most parts of the domain in January except for some areas in the northeastern part of the domain where arw_p2 shows the highest concentrations.
- PM2.5 mass concentrations decrease in April and July relative to January especially over the eastern United States and increase again in October.
- PM2.5 mass concentrations increase over the western United States in July likely because of the wildfires.

# Changes in $PM_{2.5}$ due to Biogenic, Fire, and SOA perturbations



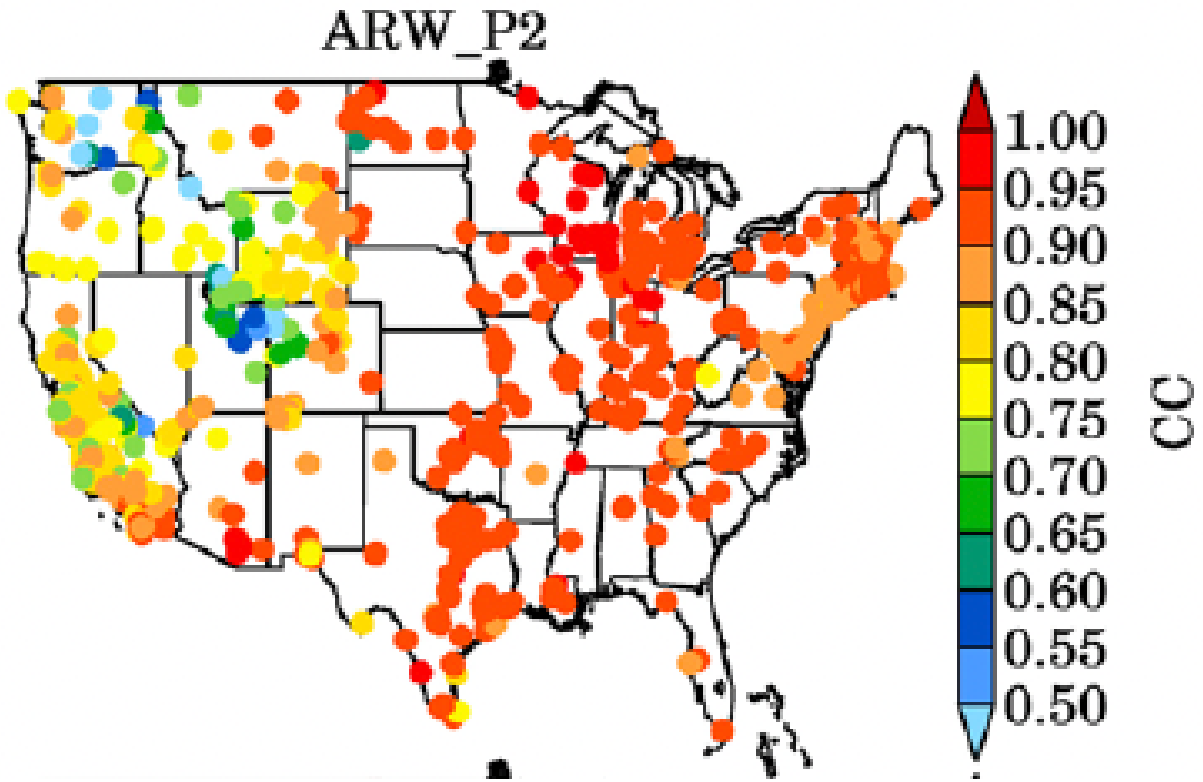

- Biogenic emission perturbation decrease $PM_{2.5}$ in all seasons except during summer over Southeast US.
- Enthalpy perturbation increase PM2.5 in all the seasons.
- Perturbations in SOA mass yields decreases PM2.5 everywhere except during winter.
- Fire emission perturbations increases PM2.5 in all seasons.

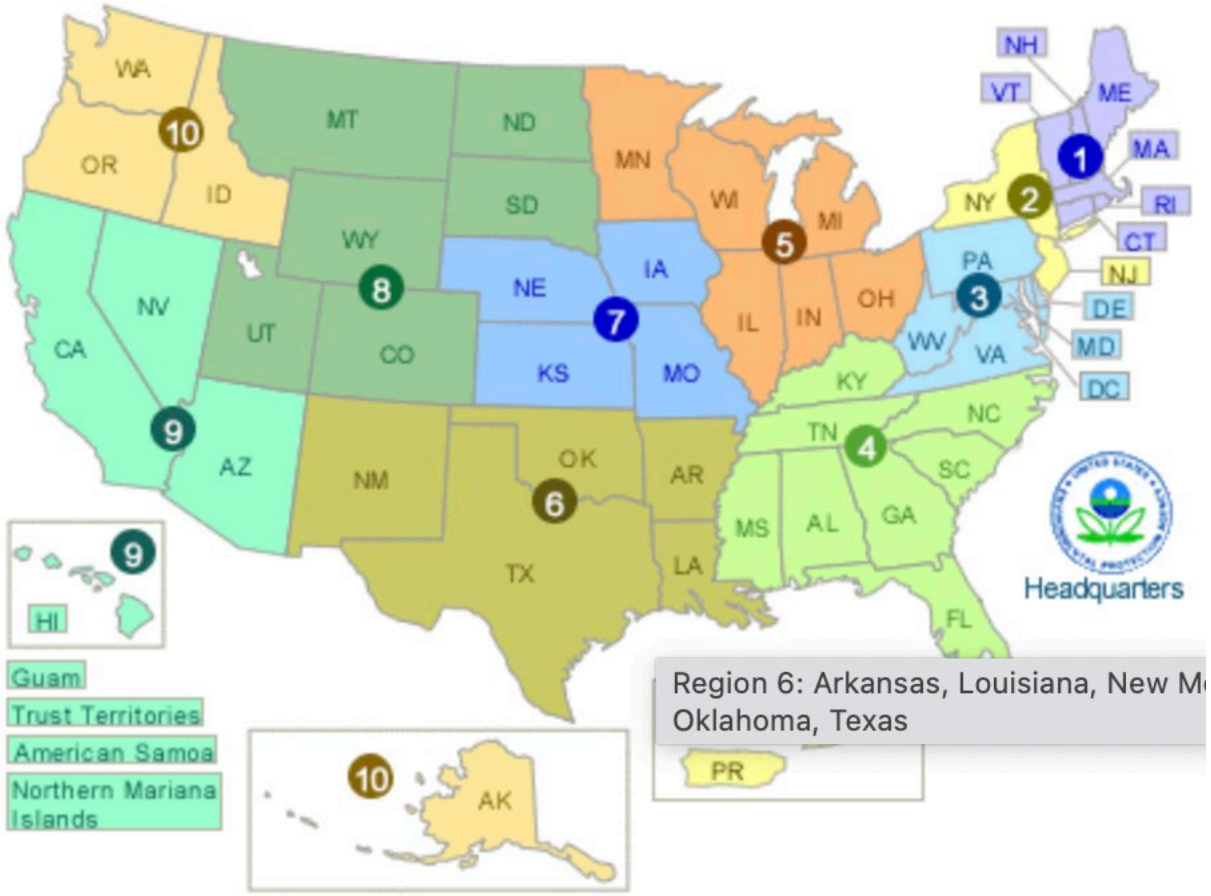
# Changes in $PM_{2.5}$ due to Anthropogenic emission perturbations



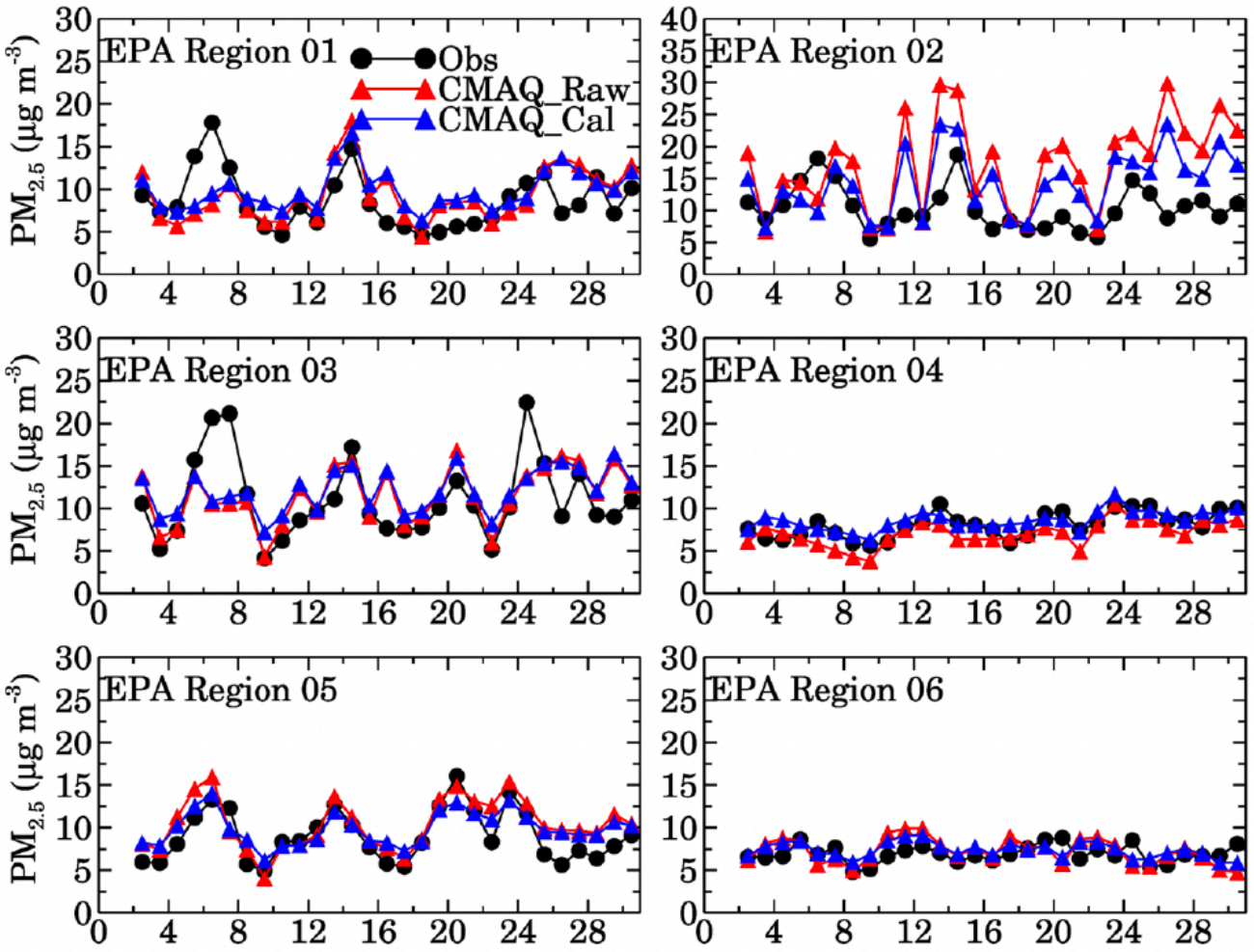

- Anthropogenic emissions lead to the largest changes in PM2.5 across the CONUS.

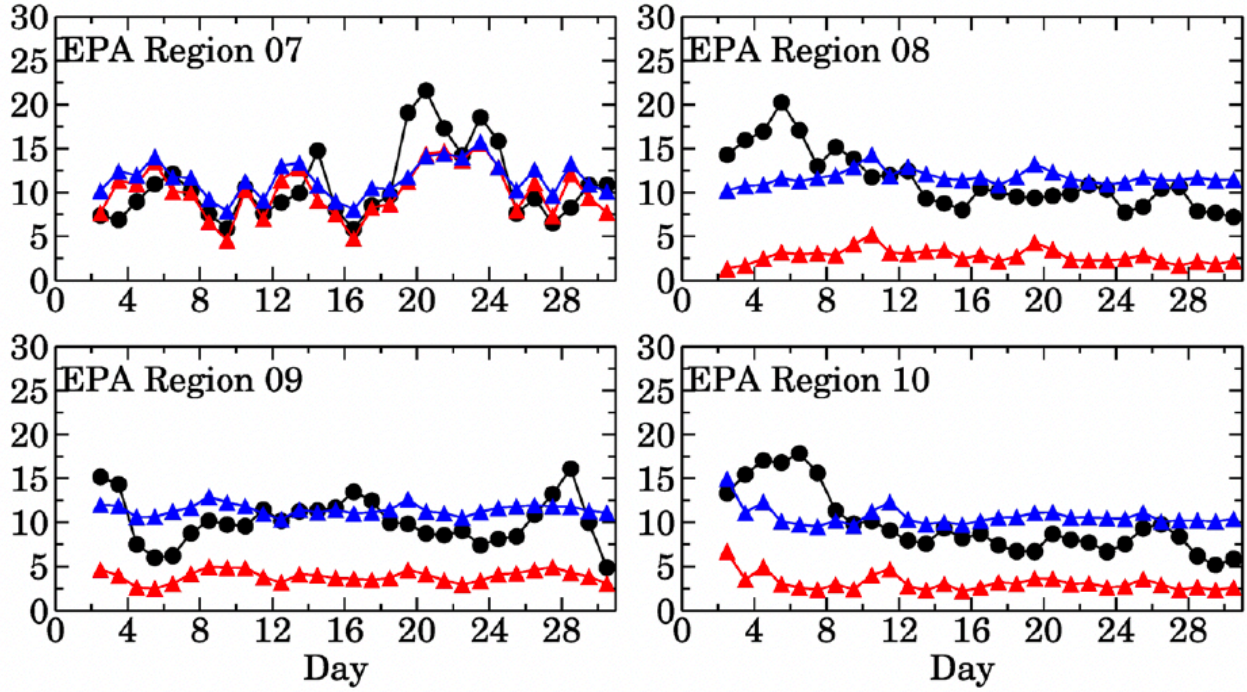
# Observations site over CONUS and EPA regions



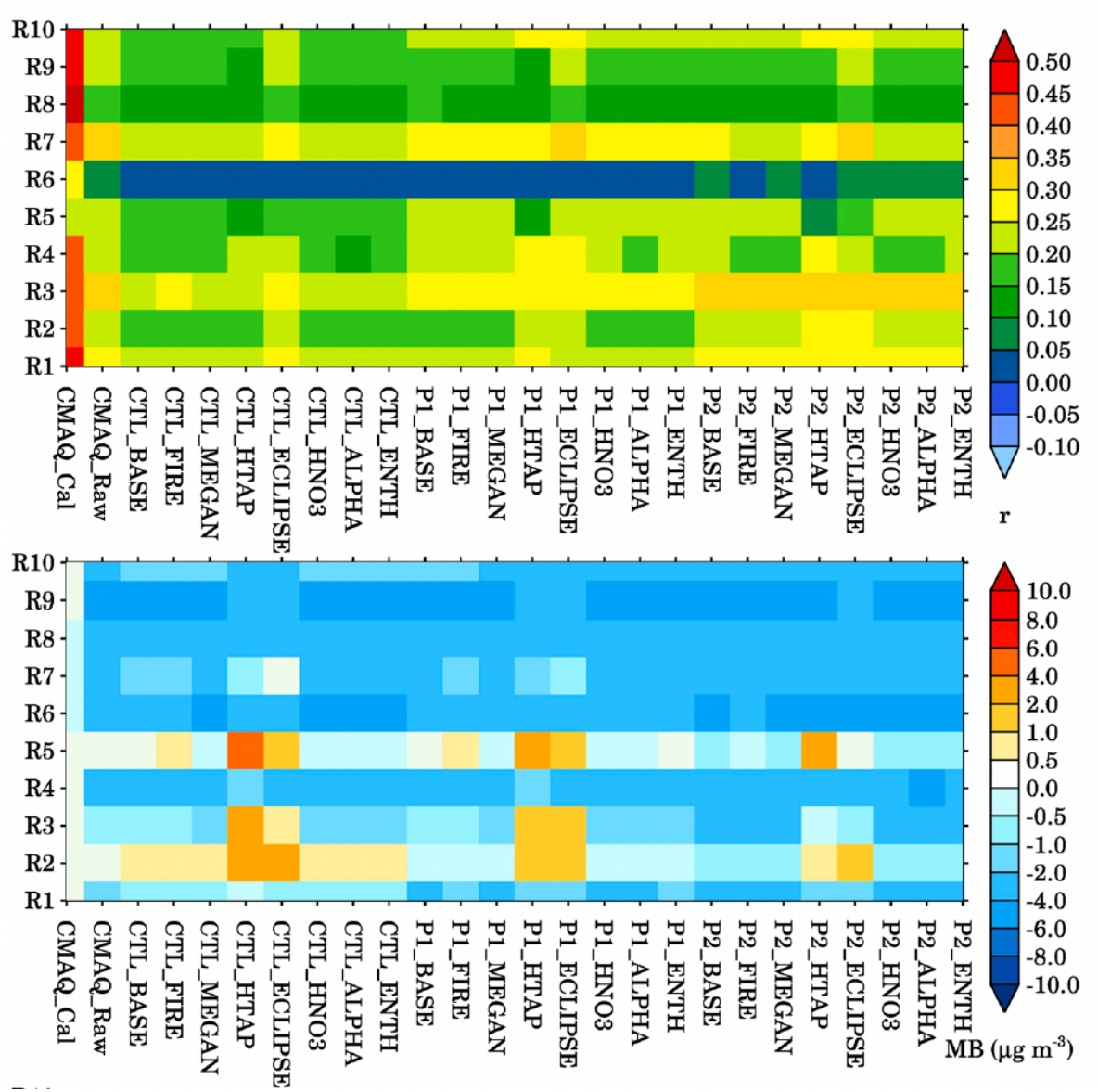
# Model validation

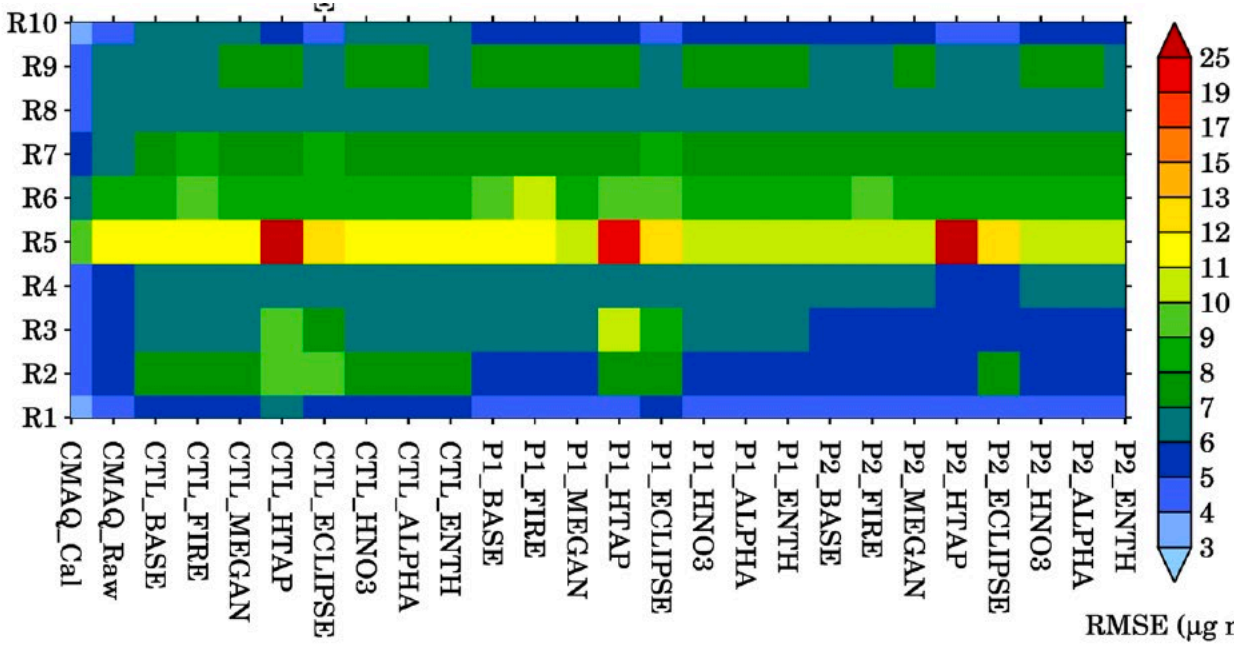



- Raw ensemble average captures PM2.5 in most of the CONUS regions except in Regions 8-10. Ensemble calibration was needed to improve the accuracy of PM2.5 predictions in those regions.

# Calibrated ensemble shows the best performance



But Dynamical ensembles are very expensive and sometime impractical for operations….

# The Analog Ensemble (1)

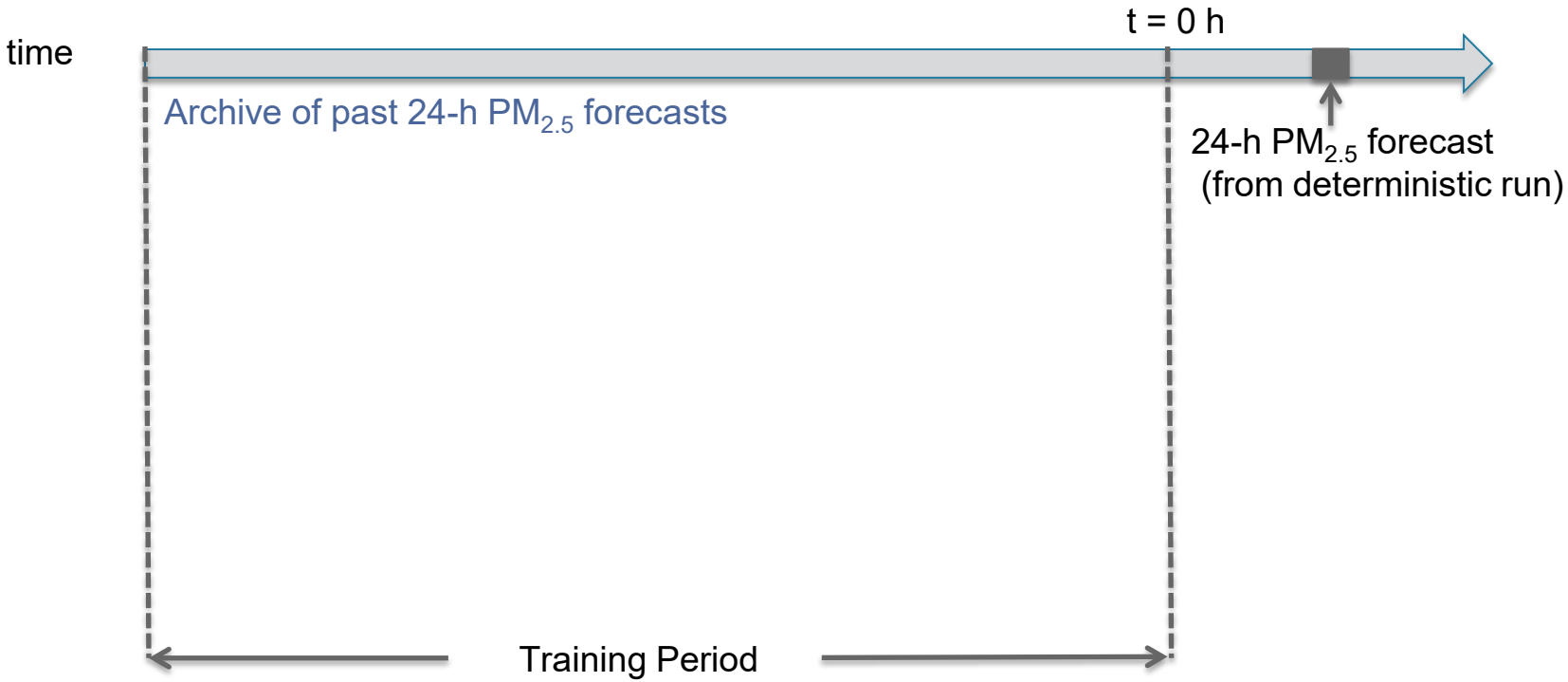



Figure adapted from Delle Monache et al. (2013)

# The Analog Ensemble (2)

Find set number of analogs based on certain predictors

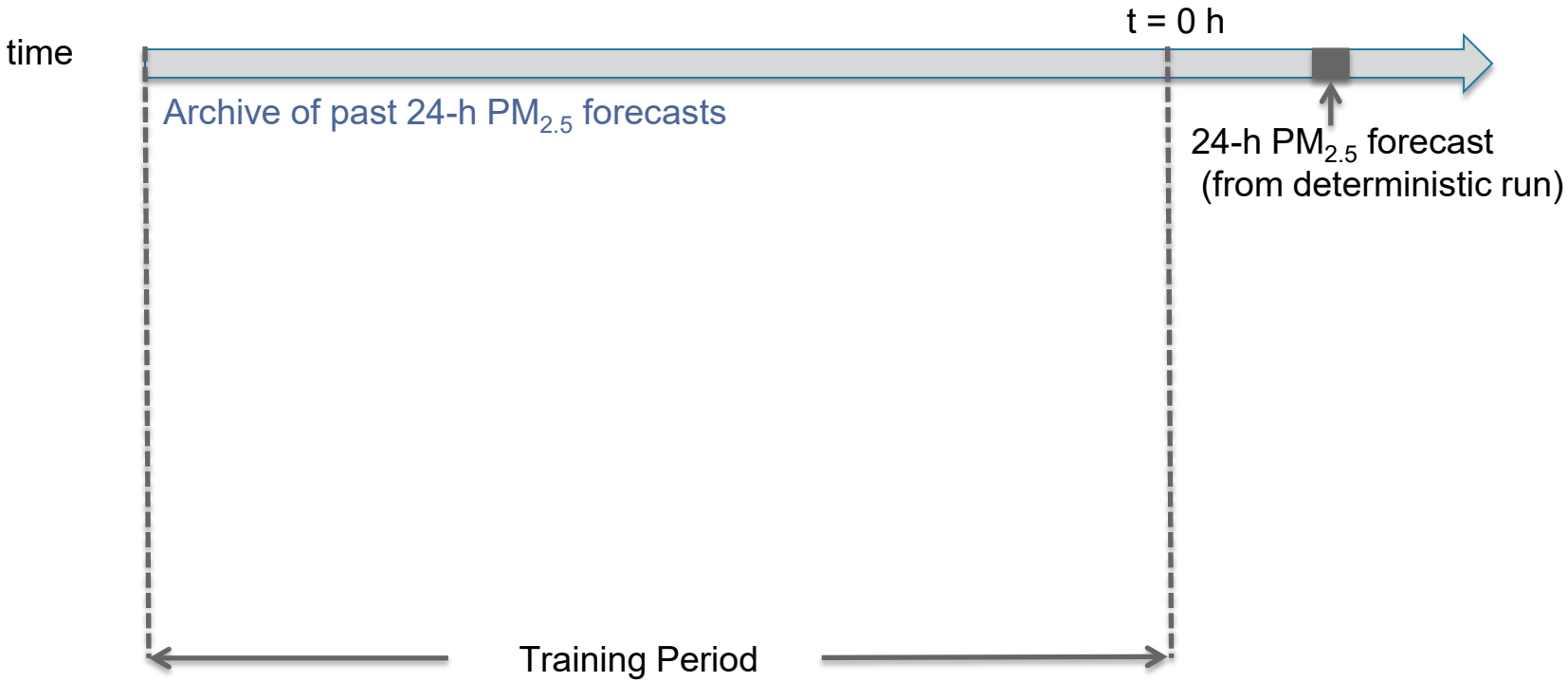



Figure adapted from Delle Monache et al. (2013)

# The Analog Ensemble (3)

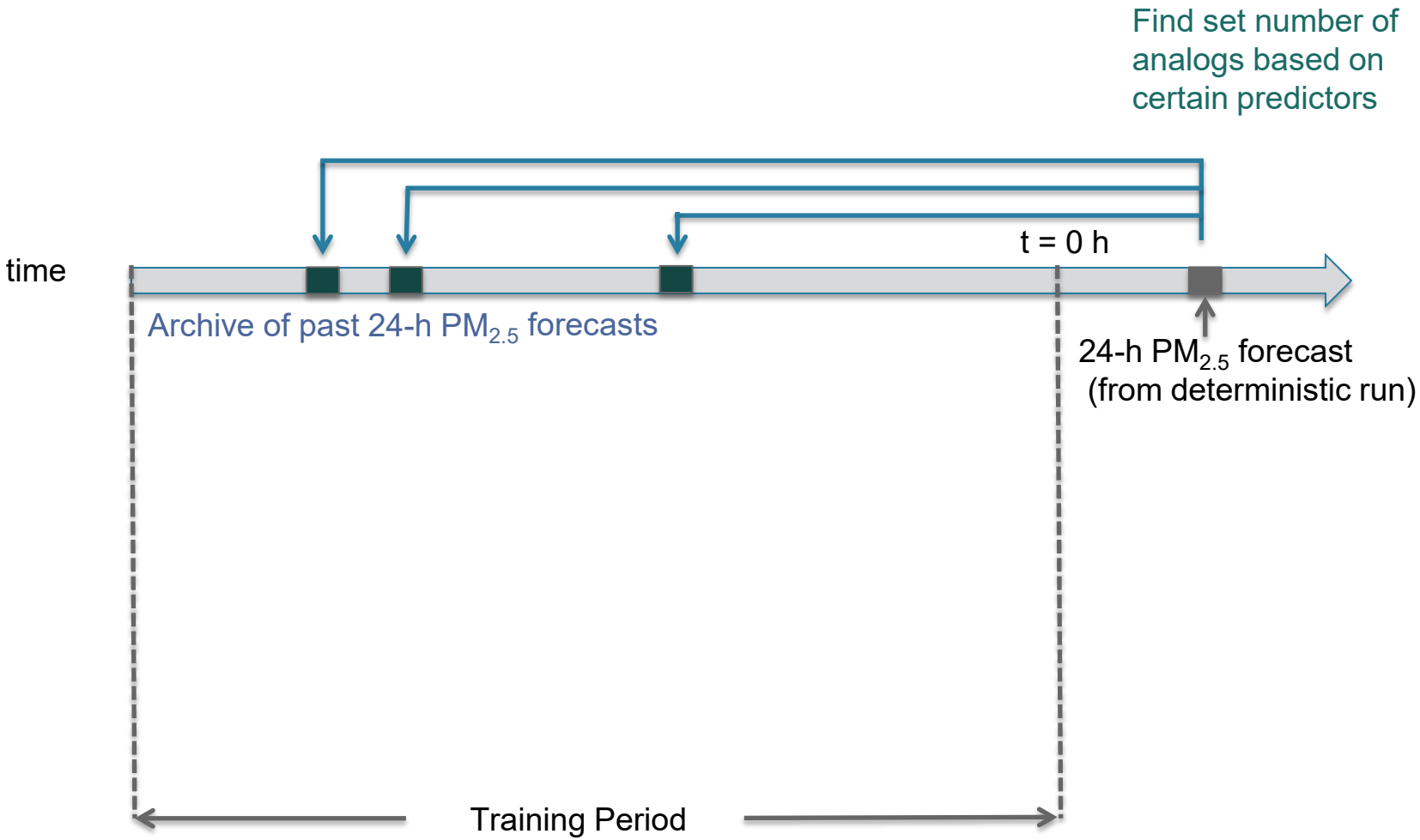



Figure adapted from Delle Monache et al. (2013)

# The Analog Ensemble (4)

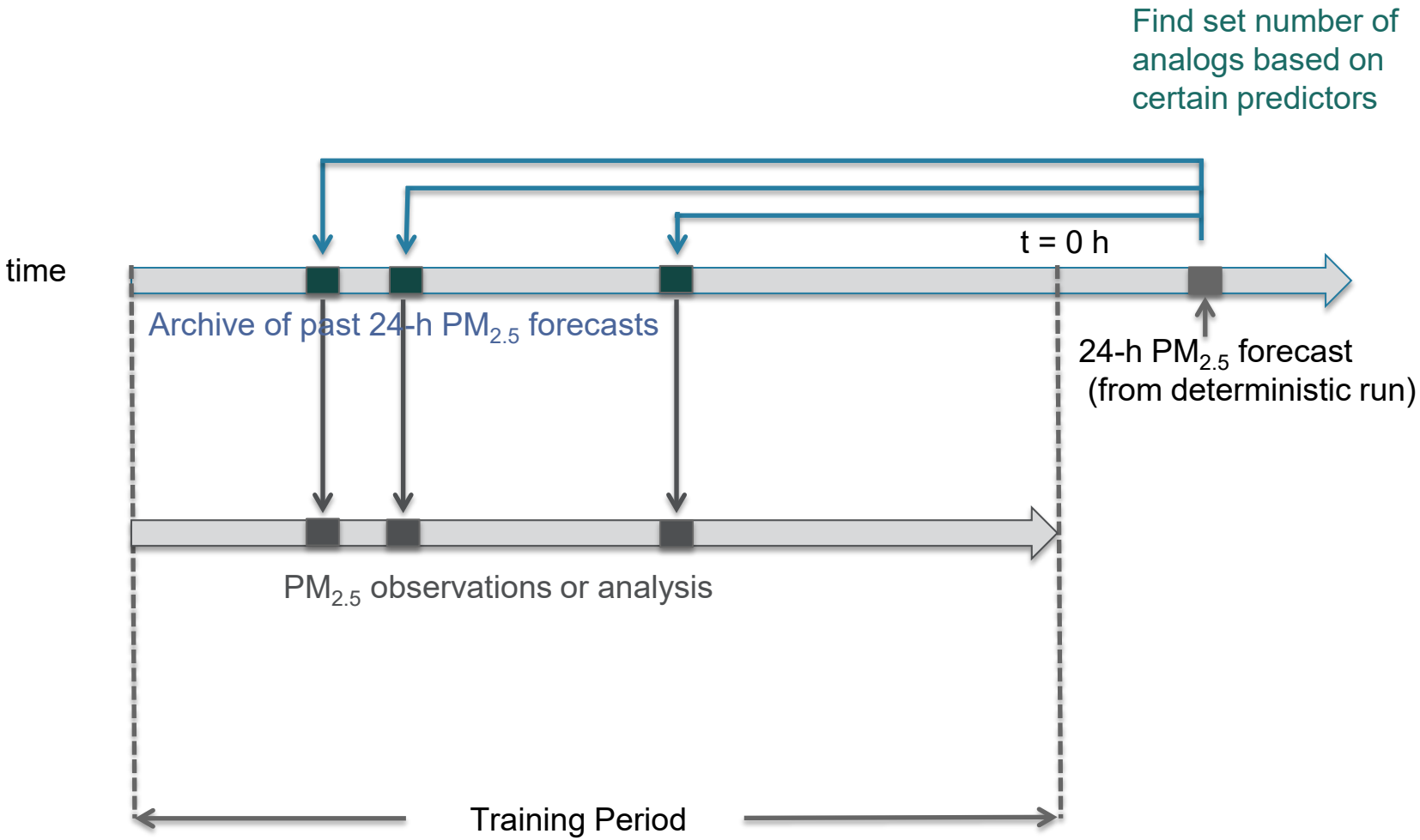



Figure adapted from Delle Monache et al. (2013)

# The Analog Ensemble (5)

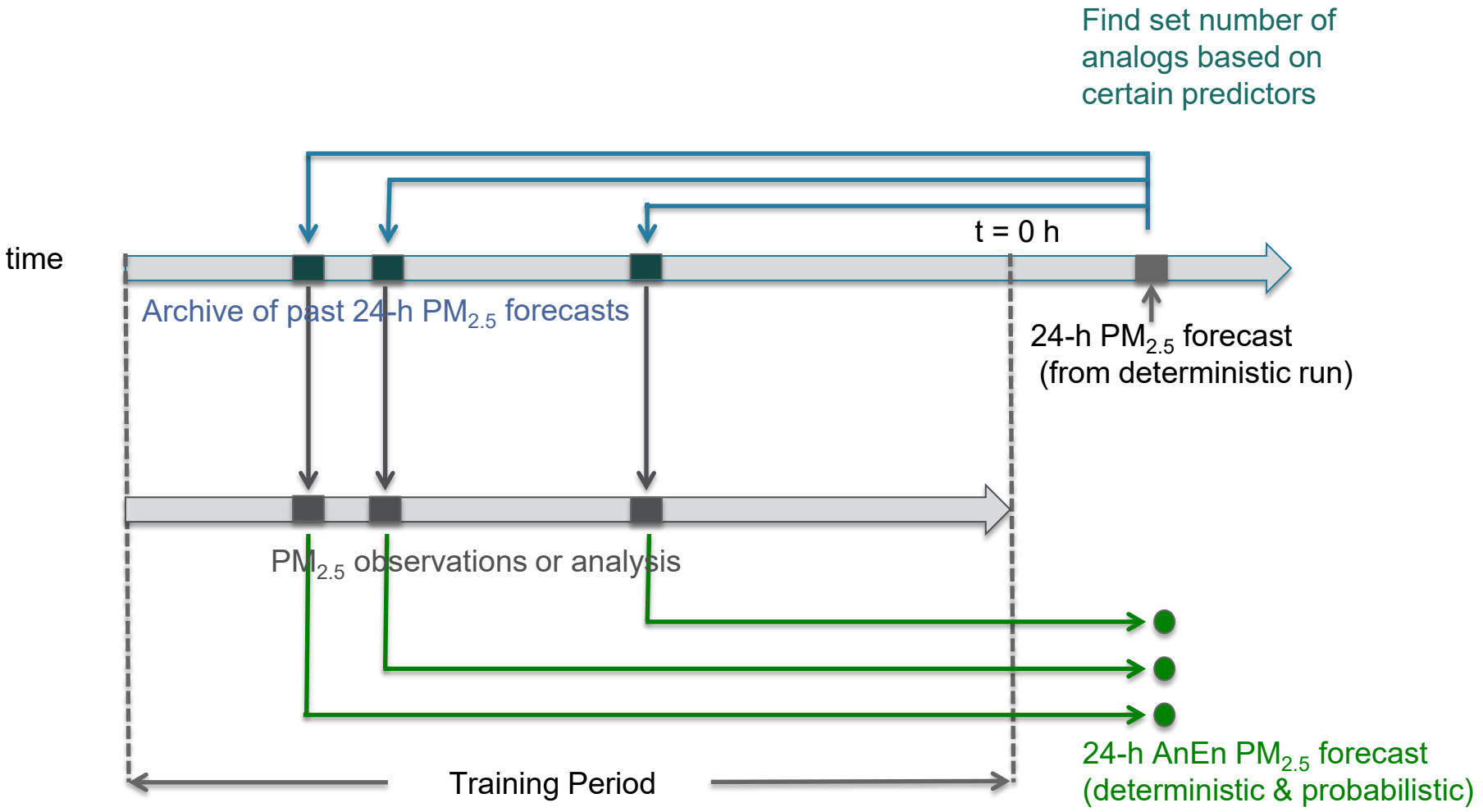
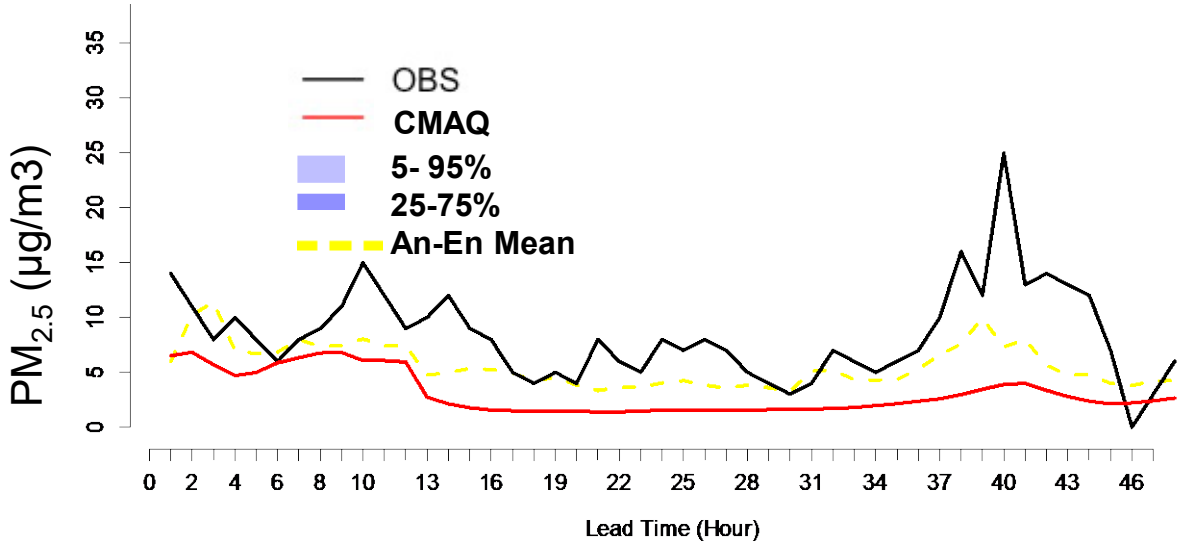
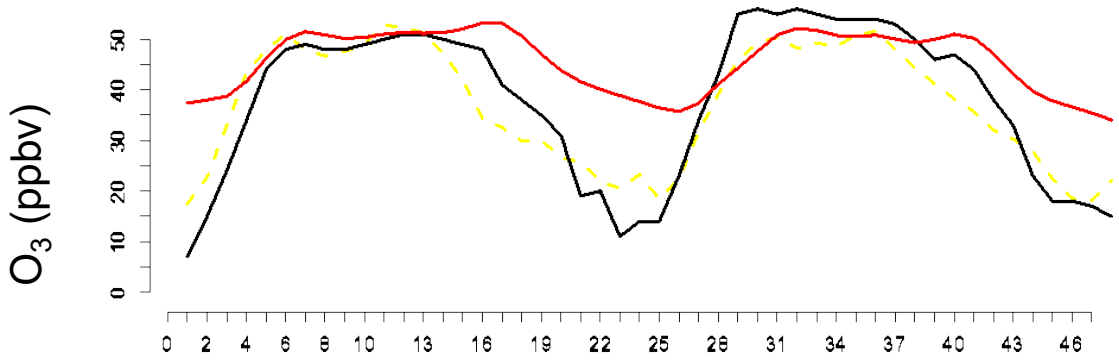


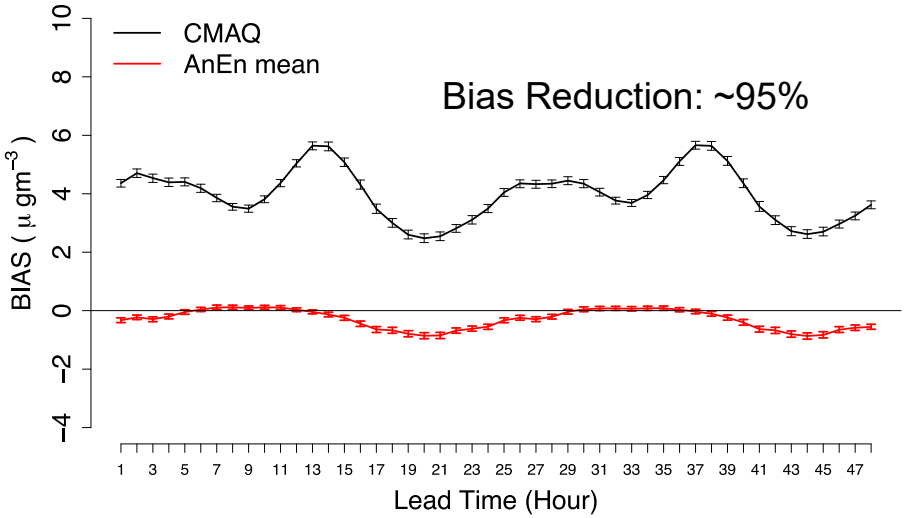

Figure adapted from Delle Monache et al. (2013)

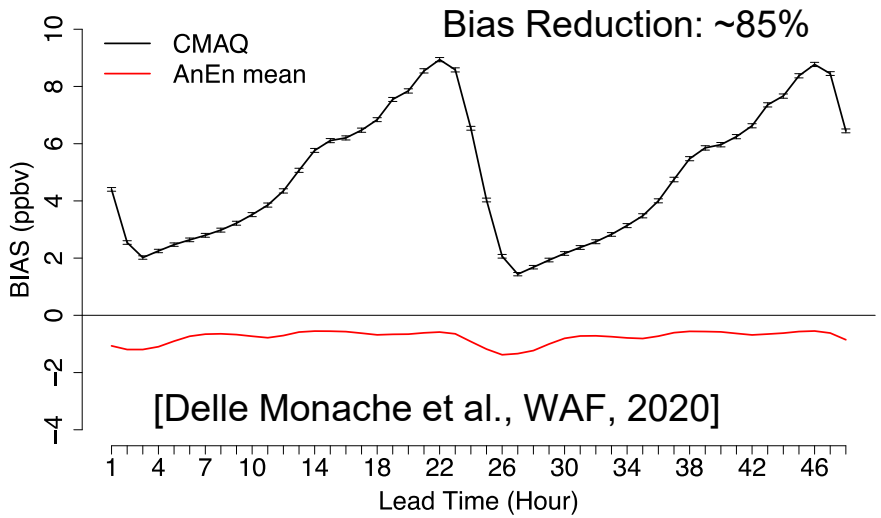
# Quantifying uncertainties in Air Quality Forecasts (AnEn)




## AnEn generates forecast quantiles that provide uncertainty quantification



# Summary

- Air pollution is one of the most important environmental problems facing the society.
- We have capabilities to predict air pollution 3-5 days in advance so that decision-makers can alert the public of any forthcoming air pollution episode.
- Deterministic forecasts constrained by multi-platform observations are found to be very helpful in Delhi.
- Probabilistic forecasts allow decision-makers evaluate the uncertainties and understand their value in the decision-making process.

**Thank You !**