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Numerical simulation of an extreme haze pollution event over North China Plain based on initial and boundary condition ensembles

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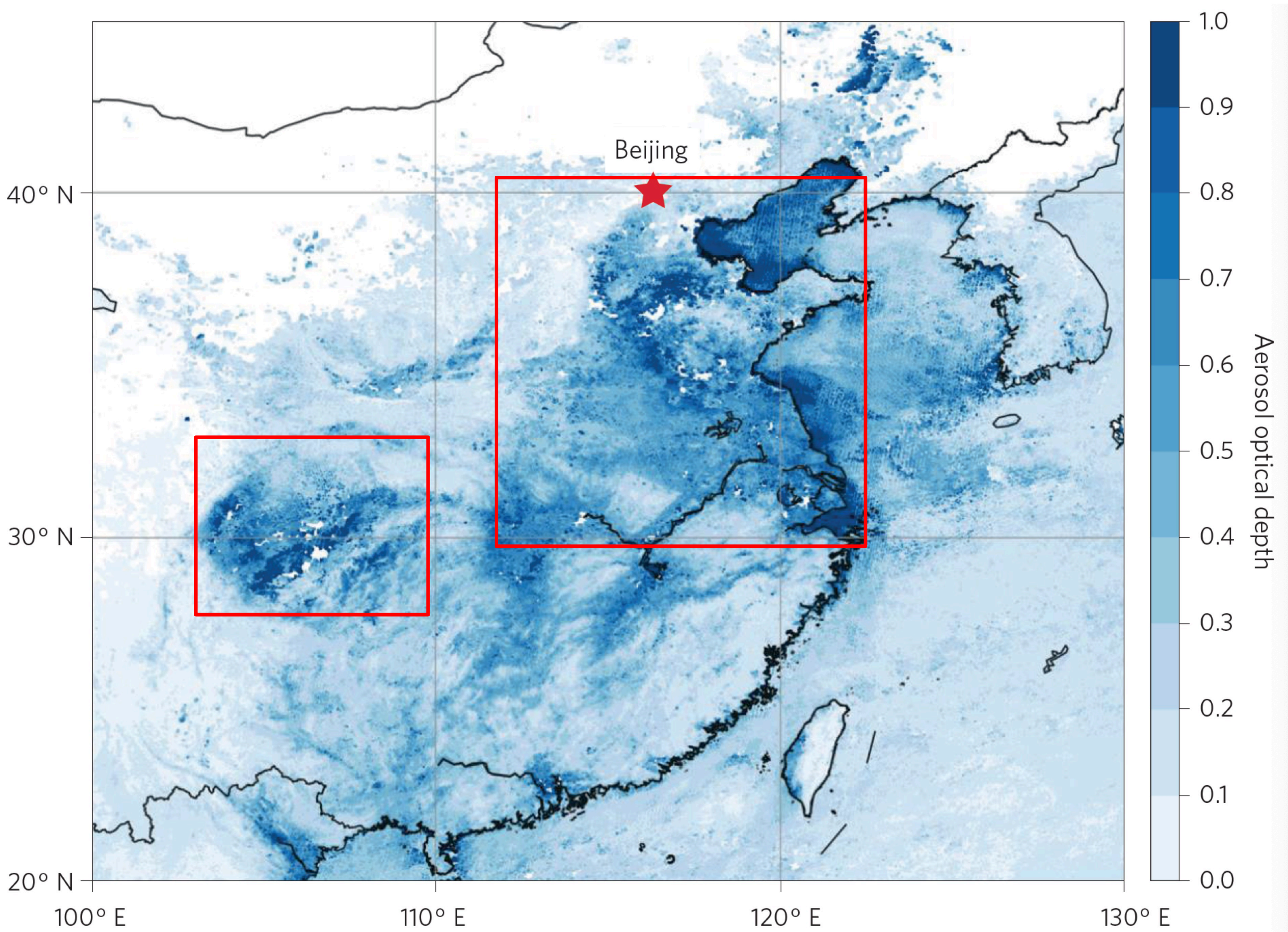
Outline

- Introduction
- Case analysis
- Experiment design
- Model verification and ensemble results
- Summary

Introduction: haze pollution over China

Aerosol optical depth (AOD) over China (Dec. 2016 – Jan. 2017)

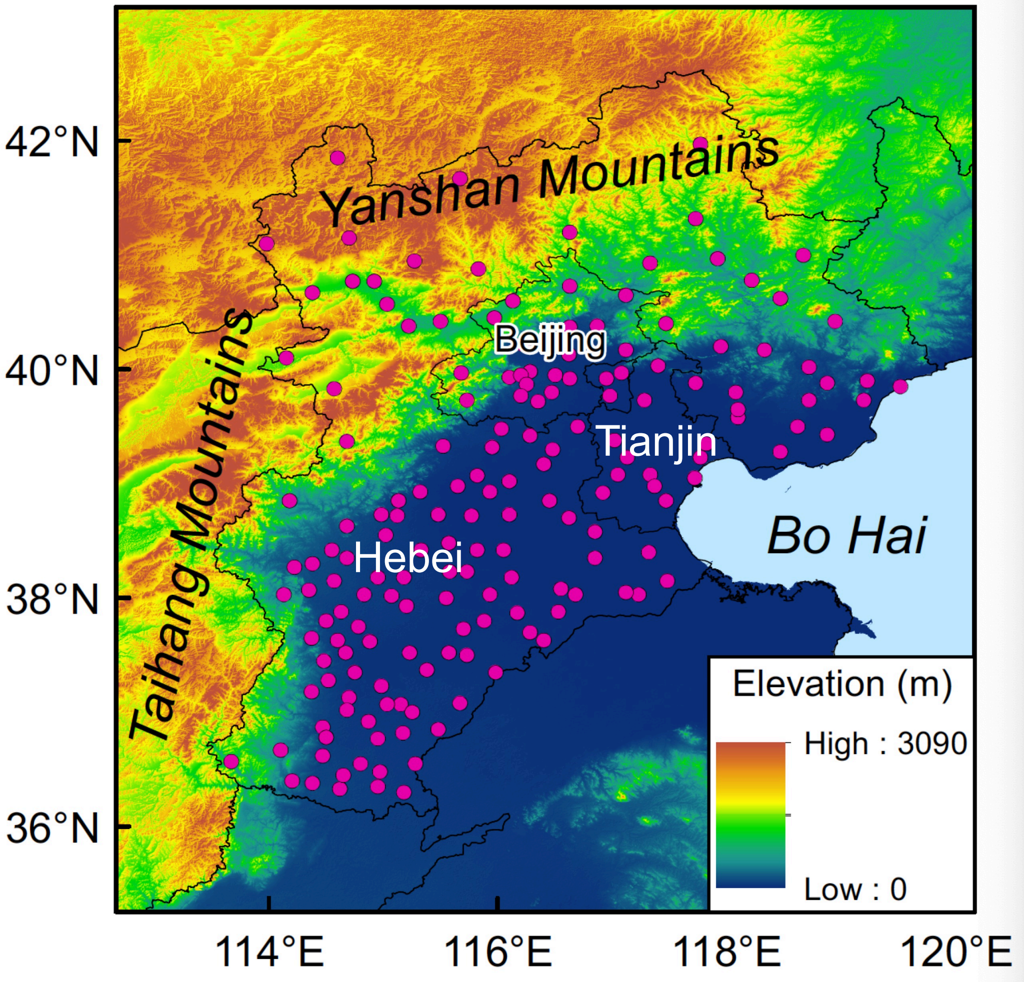


The higher the AOD, the more turbid the atmosphere.

(Zhang 2017)

Introduction: haze pollution over BTH

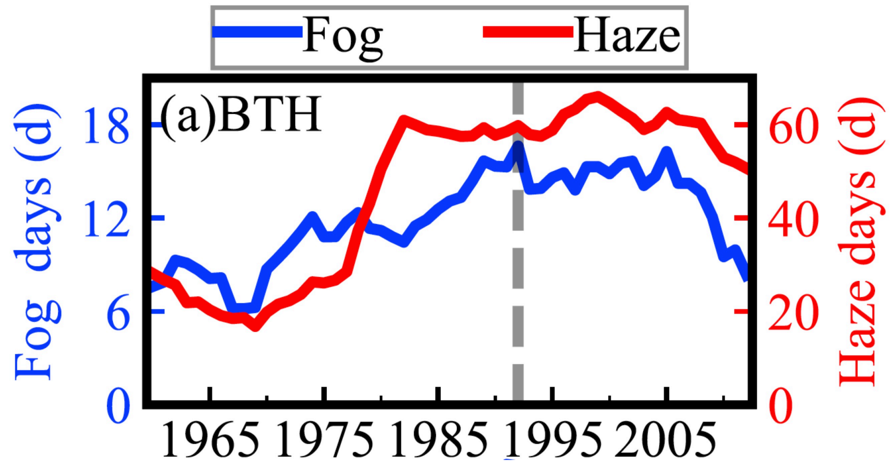
Topographic map of the BTH region



Red dots: the meteorological sites (Wu et al. 2017)

BTH: Beijing-Tianjin-Hebei area

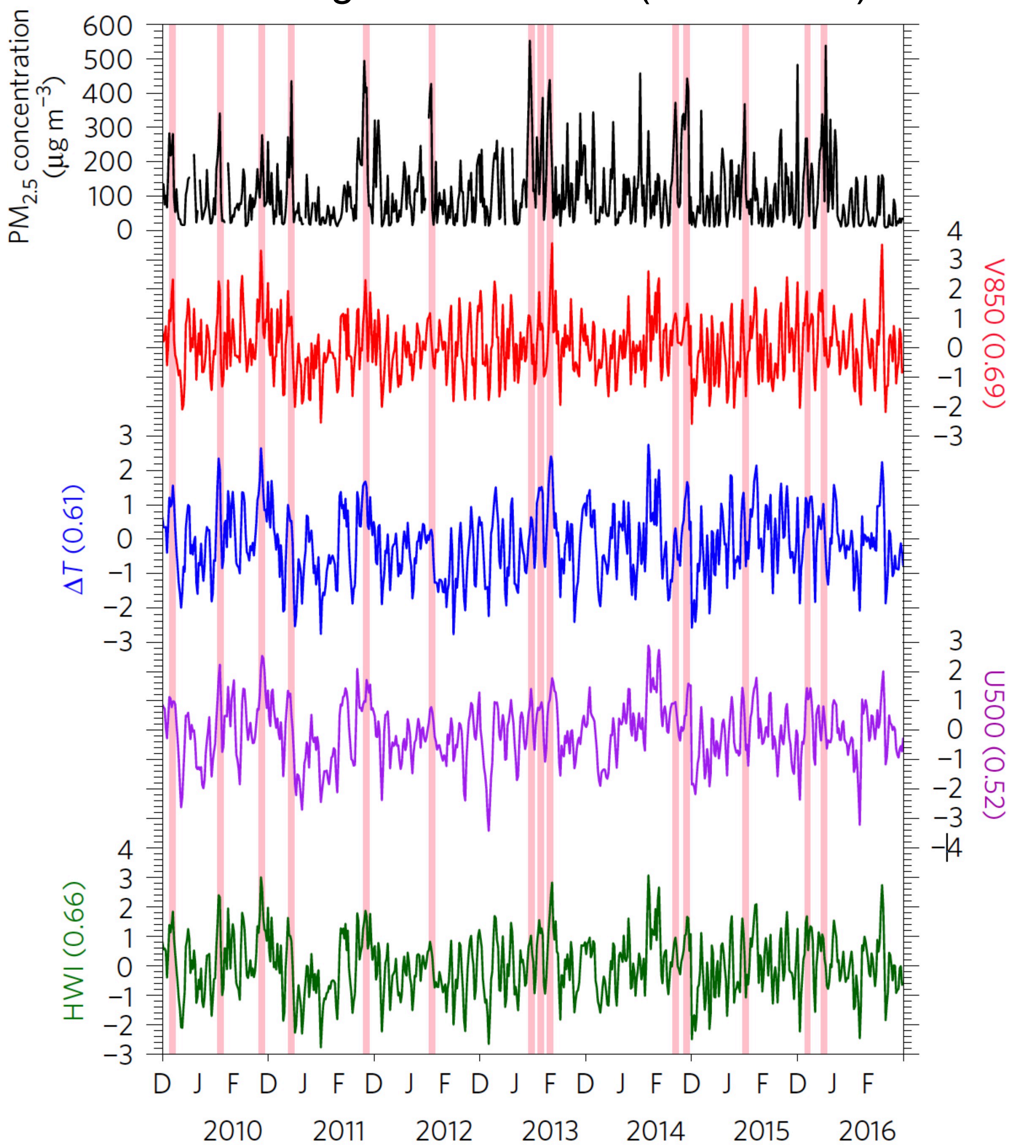
Annual variations of fog days and haze days from 1960 to 2012 over BTH



(Yan et al. 2019)

Introduction: haze pollution over BTH

Beijing winter daily PM2.5 (black curve) and meteorological anomalies (2009-2015)



BTH haze events happen under <u>favorable weather conditions</u>: increased low-level southerly winds, warm surface, and strong mid-level westerly winds.

(Cai et al. 2017)

Introduction: haze pollution simulation or prediction

https://ruc.noaa.gov/wrf/WG11/

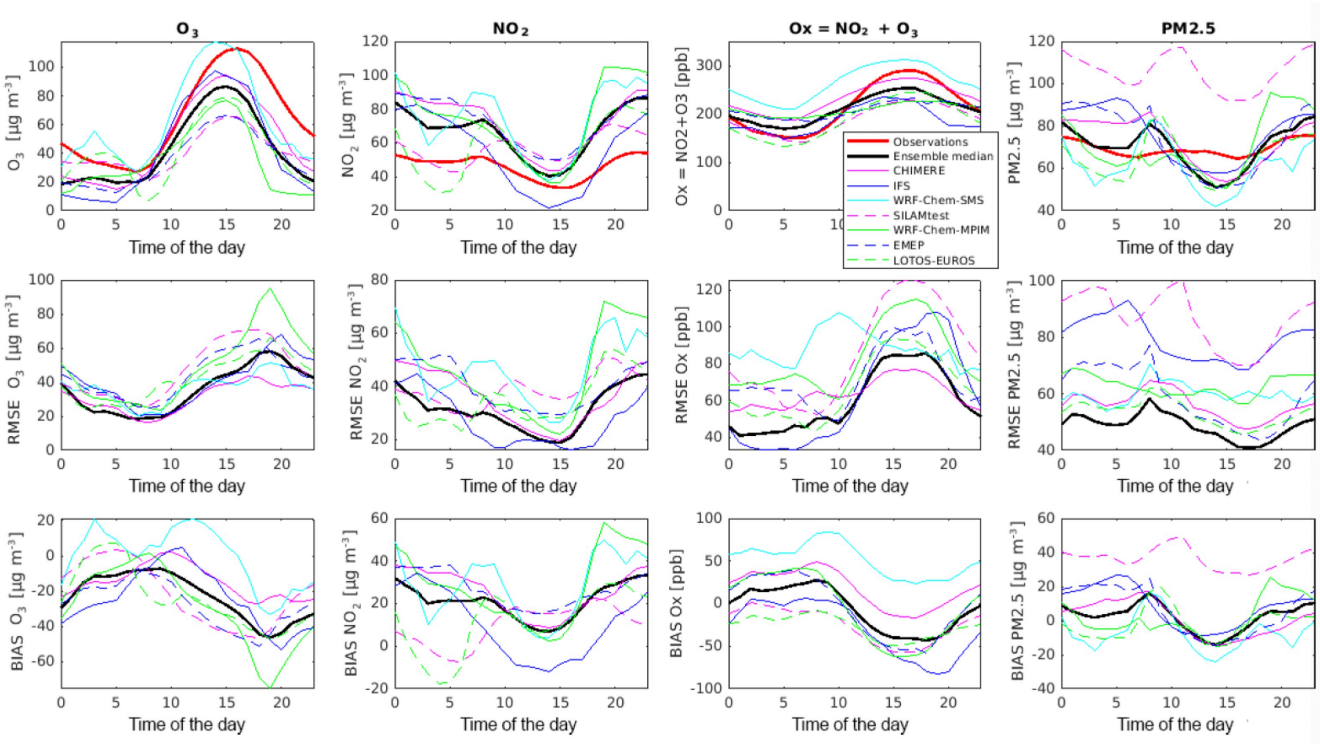
Accurate air quality prediction is demanding:
regional/global weather/climate models coupled with chemistry are the main tools for air quality research and prediction.

However, large biases exists because of:

a. uncertainties in emissions
b. high-complexities of physical and chemical processes in numerical models
c. uncertainties in meteorological conditions
……

(Grell et al.2005; Wang et al. 2016; Zhang et al. 2017)

Ensemble method is an effective way to reduce model biases



- **Multi-models**
  Huang et al. (2015)
  Zhai et al. (2018)
  Brasseur et al. (2019)
  Petersen et al. (2019)
- **Multi-physics schemes**
  Cai et al. (2017)
- **Multi-emissions**
  Tang et al. (2010)

Diurnal variations in the concentrations and of the RMSE and BIAS of O3, NO2, Ox, and PM2.5 from different models for Beijing during Apr. 2016-Jun. 2017 (Petersen et al. 2019)

Introduction: ensemble forecast of air quality

Limitations:

Multi-model or multi-physics ensembles pay attention to physical or chemical uncertainties within or across models. In fact, meteorological conditions also introduce large uncertainties in air quality simulation or prediction.

Objectives of this study:

- **Explore the effects of varying initial and lateral boundary values of meteorological field on the generation and transmission of $PM_{2.5}$ through ensemble of runs with WRF-Chem model;**
- **Evaluate whether the ensemble experiments can effectively improve the simulation of $PM_{2.5}$ concentration in regional air quality model.**

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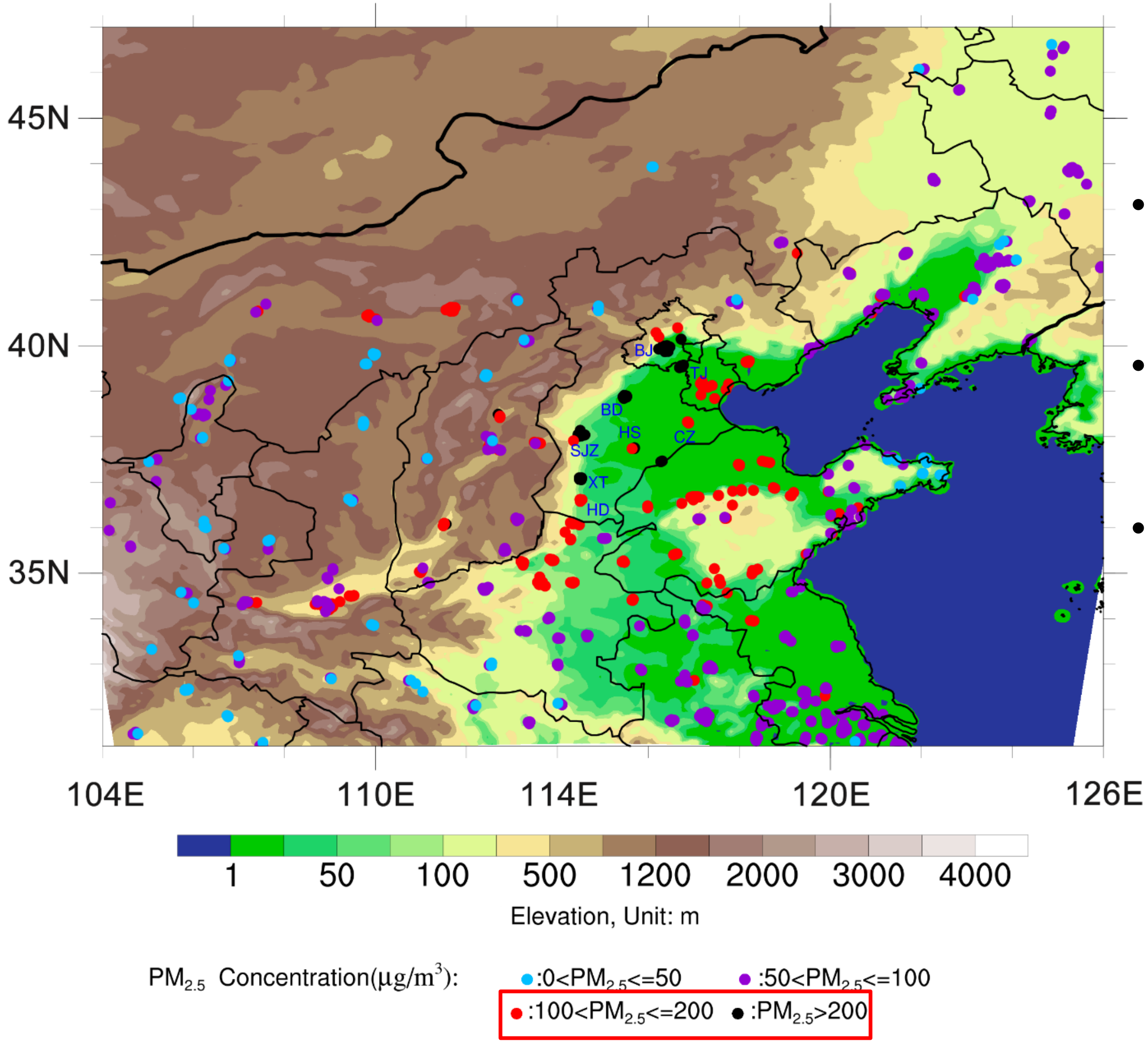
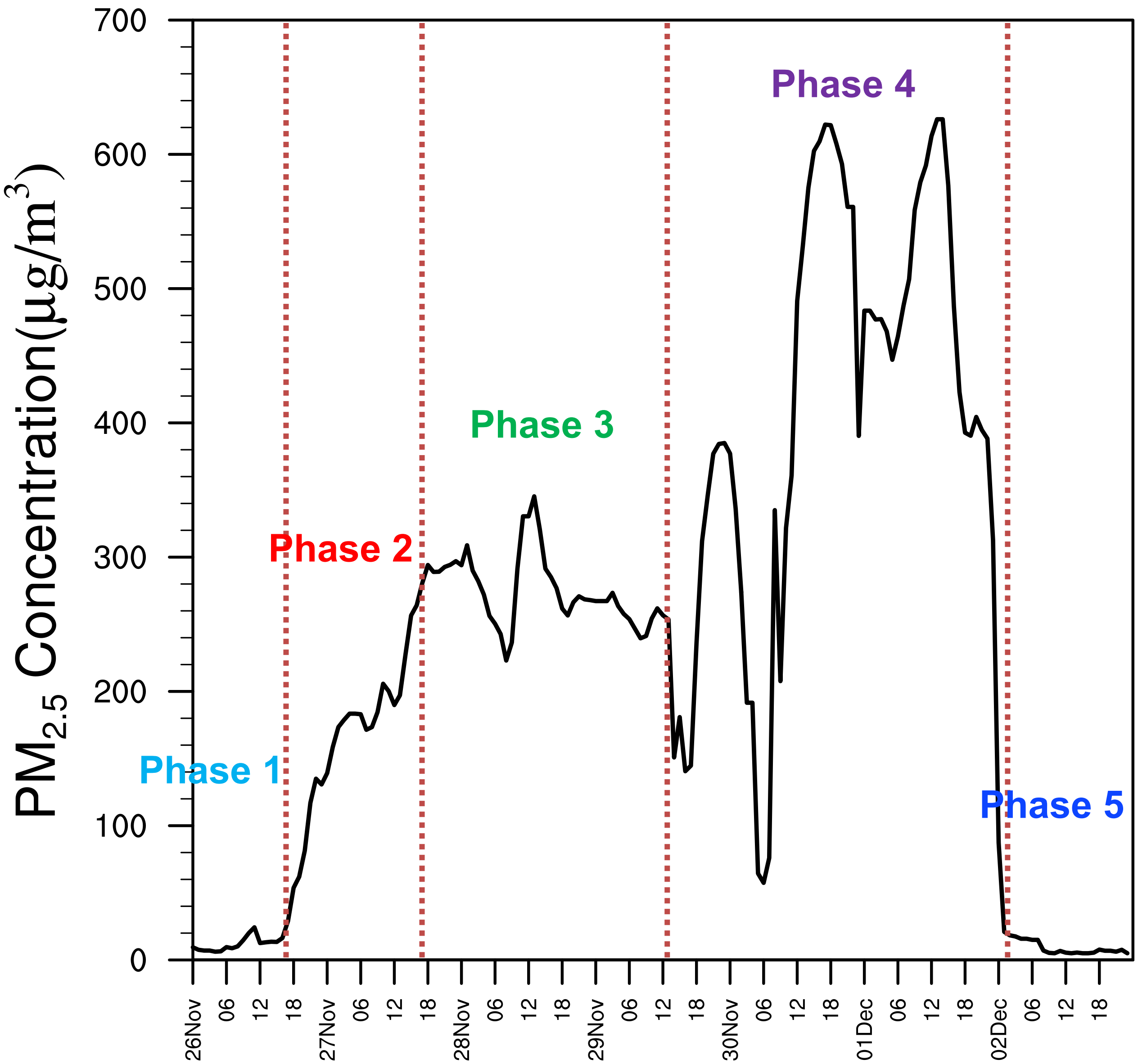
Case analysis

Topographic map and hourly averaged $PM_{2.5}$ concentration



- **Haze episode duration:**
  Nov. 26 – Dec. 2, 2015
- **Extreme $PM_{2.5}$ concentration:**
  727μg/m³
- **Eight Highly polluted cities:**
  BJ, TJ, BD, HS, CZ, SJZ, XT, HD

Case analysis: Beijing

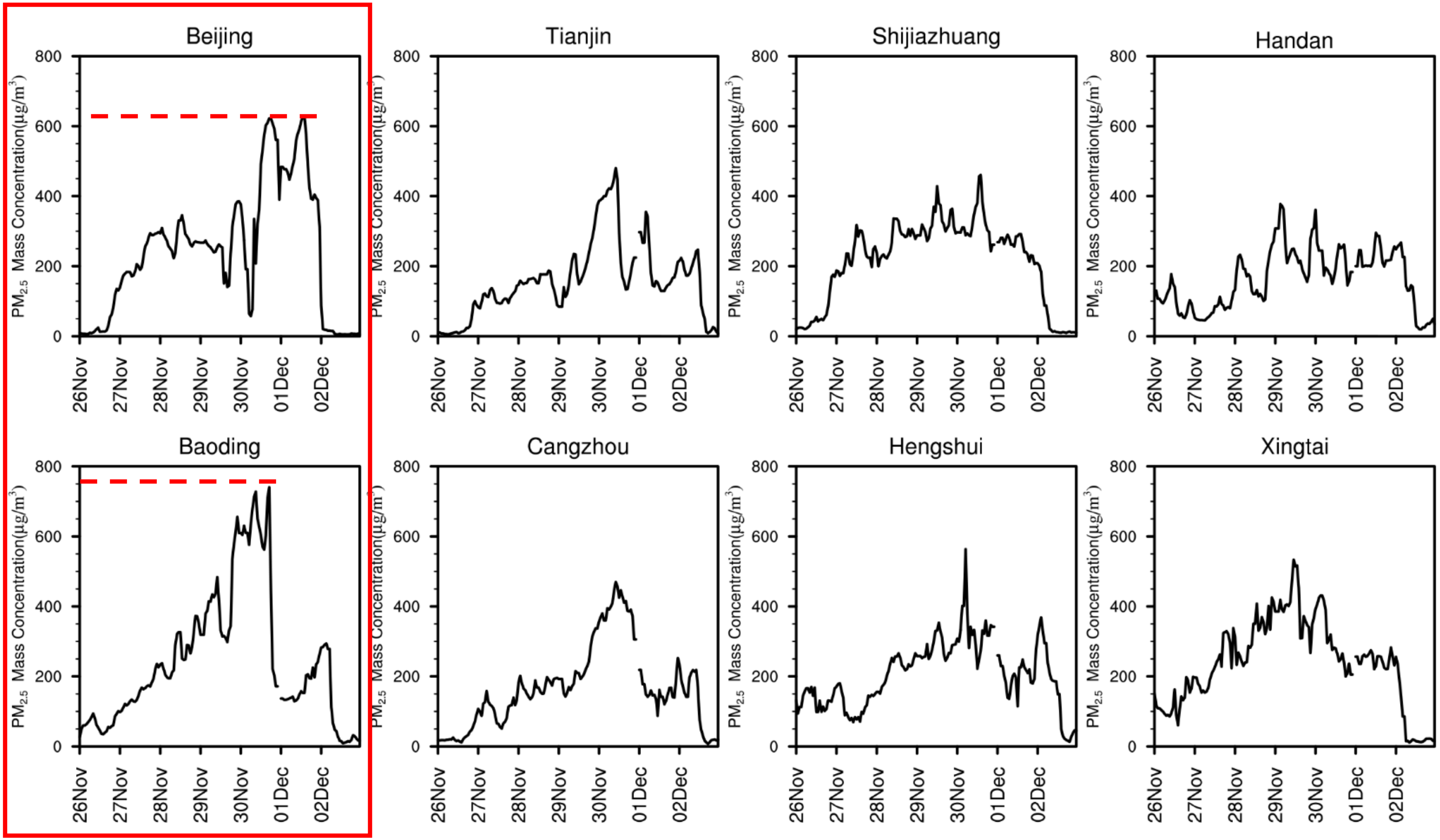


Observational $PM_{2.5}$ concentration time series at Beijing

- **Phase 1:**
  Clean period
- **Phase 2:**
  $PM_{2.5}$ rapid accumulation
- **Phase 3:**
  High PM2.5 maintenance
- **Phase 4:**
  Great fluctuation
- **Phase 5**
  Clean period

Case analysis: eight highly polluted cities

Time series of observed $PM_{2.5}$ concentrations for eight highly polluted cities



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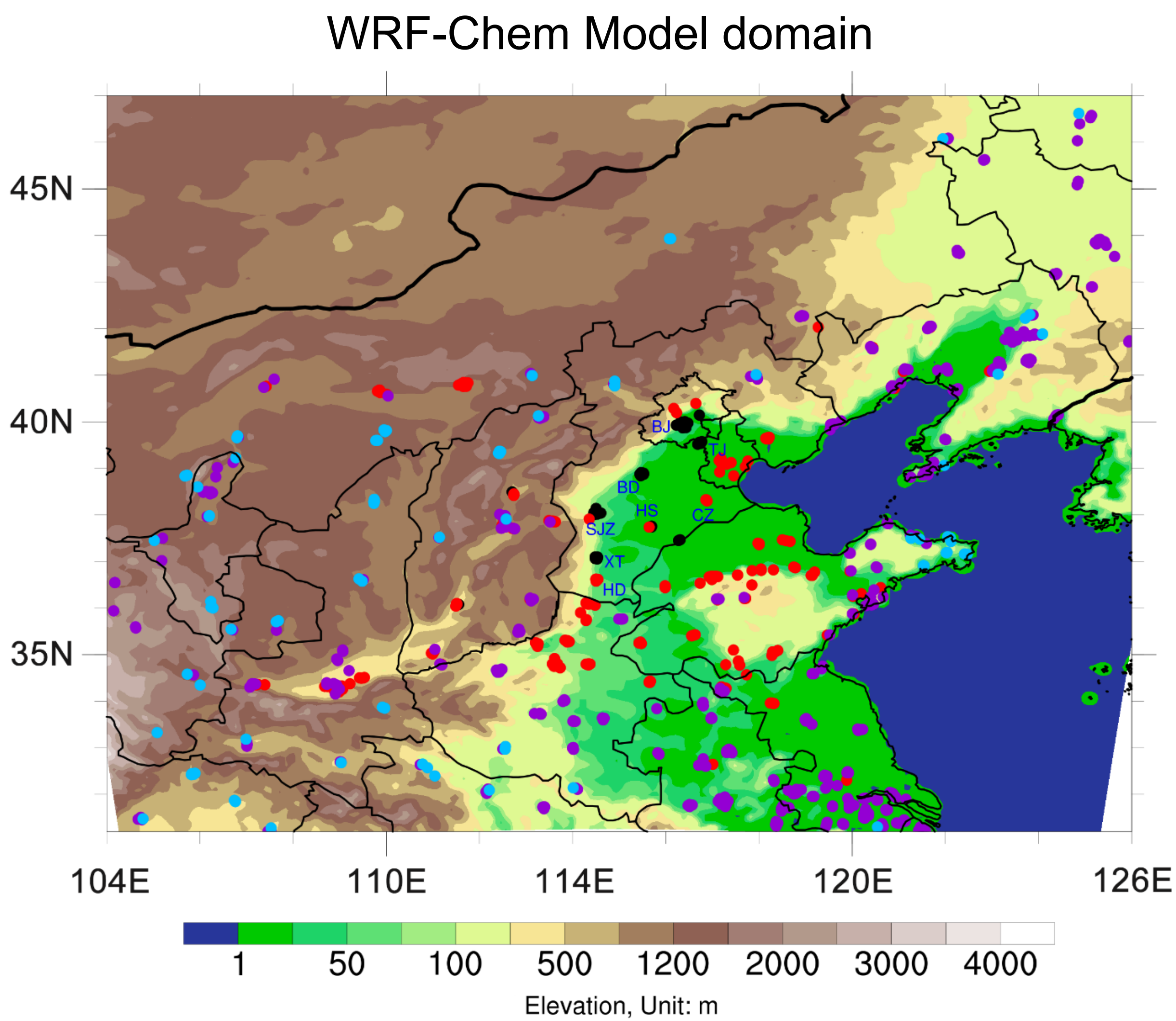
Experiment design



Grid size: 9 km

Experiment design

WRF-Chem model configuration

Items	Details
Basic configurations	Model version: WRF-ChemV3.9.1.1 Vertical layers: 30 layers Model top: 50 hPa Simulation period: 00UTC25November – 00UTC3December, 2015
Physical parameterization schemes	Microphysics: Morrison double-moment Longwave and shortwave Radiation: RRTMG Land Surface: Noah Land Surface, Revised MM5 Monin-Obukhov Planetary Boundary Layer: Yonsei University PBL Cumulus Parameterization: Grell-Freitas
Chemical parameterization schemes	Chemical Mechanism: CBMZ including aqueous-phase chemical reaction Aerosol Scheme: 8 bins MOSAIC Photolysis Scheme: Fast-J Dry Deposition: On Wet Deposition: On Aerosol Direct Effect: On
Emission source field	MEIC_base2012 (Tsinghua University)

Experiment design

ERA5: the latest generation of atmospheric reanalysis released by ECMWF in 2017

HRES: hourly, 0.25 degree

10 EDA members: 3 hourly, 0.25 degree

Experiment	Initial condition	Lateral boundary conditions	Experiment numbers
CTRL	HRES	HRES	1
INDE	10 EDA members	HRES	10
BDDE	HRES	10 EDA members	10
INBDDE	10 EDA members	10 EDA members	10

Mathematical methods

The systematic bias is defined as: bias = $\frac{\sum_{i=1}^{n}(c_{im} - c_{iobs})}{n}$

RMSE is defined as: $RMSE = \sqrt{\frac{\sum_{i=1}^{n}(diff(i) - bias)^2}{n}}$

where $diff(i) = c_{im} - c_{iobs}$

The ensemble efficiency (EE) is defined as:

$$\mathrm{EE} = \frac{RMSE_{ens} - RMSE_{CTRL}}{RMSE_{CTRL}} \times 100\%$$

where, $RMSE_{CTRL}$ refers to the computed RMSE in CTRL, $RMSE_{ens}$ refers to $RMSE_{INDE}$, or $RMSE_{BDDE}$ and $RMSE_{INBDDE}$ when we compute EE for INDE, BDDE, INBDDE, respectively.

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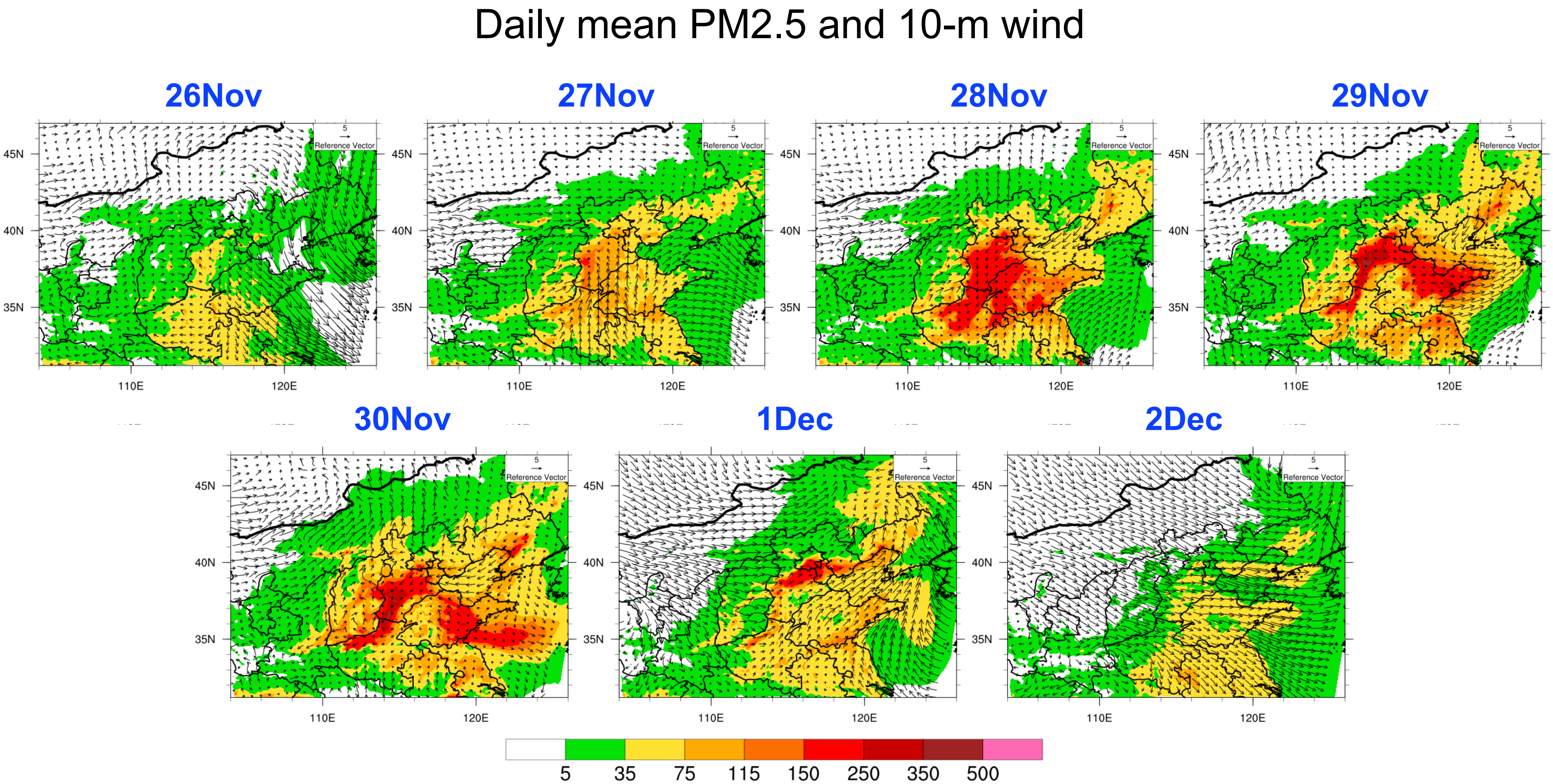
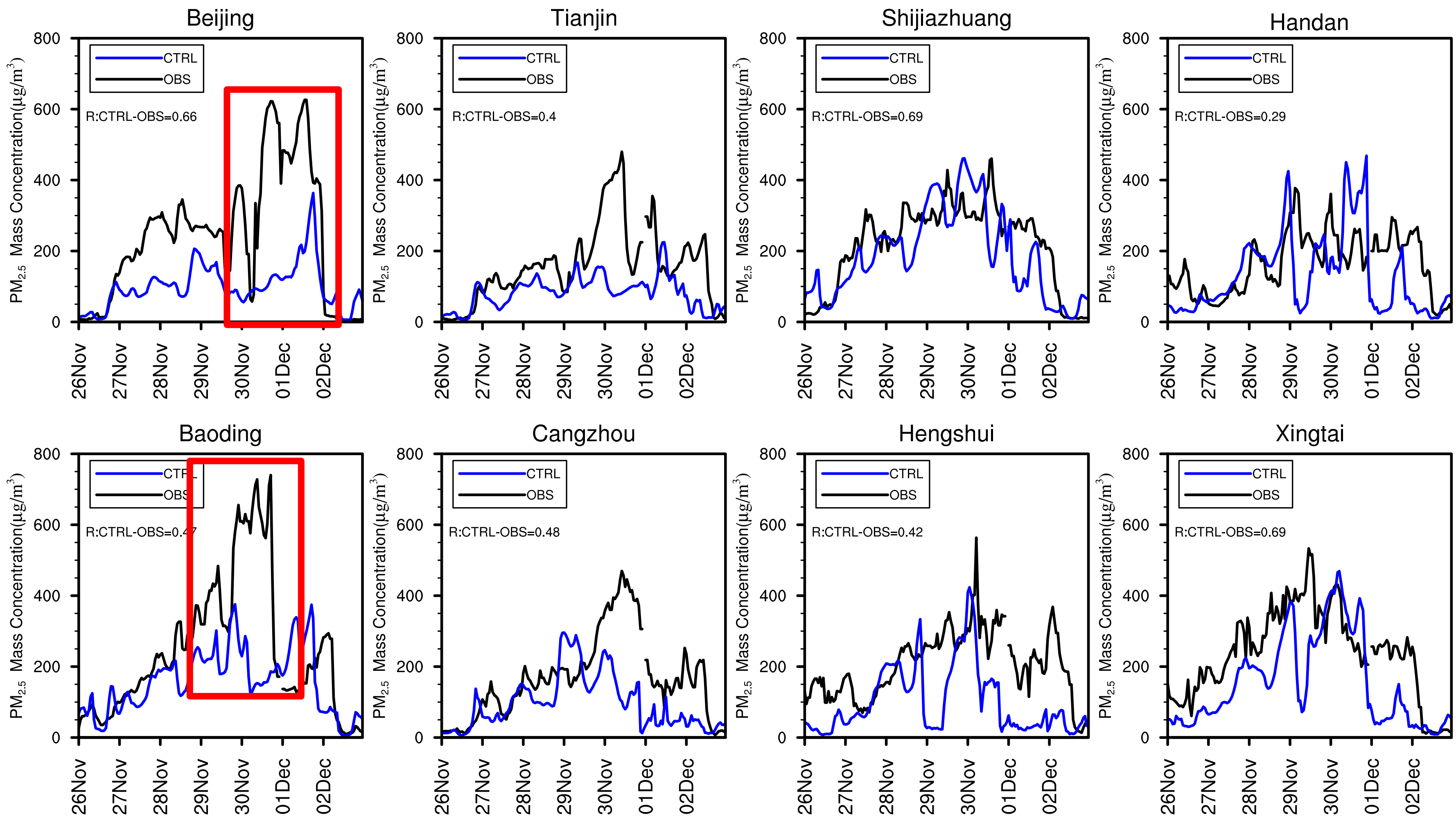
Model verification：CTRL run



CTRL run reproduces the overall life cycle of the haze event over BTH region.

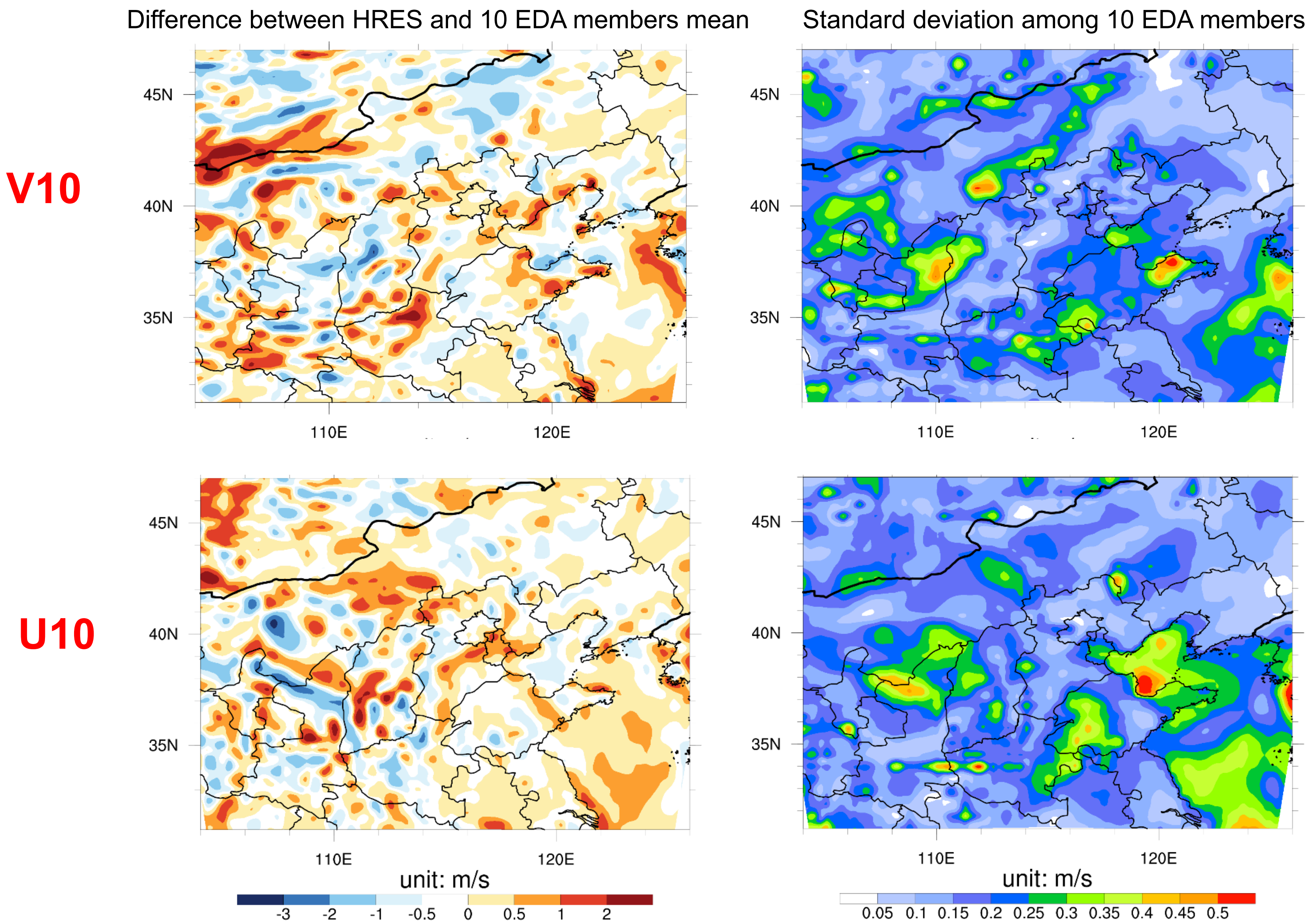
Model verification：CTRL run

$PM_{2.5}$ Mass Concentration ($\mu g/m^3$)

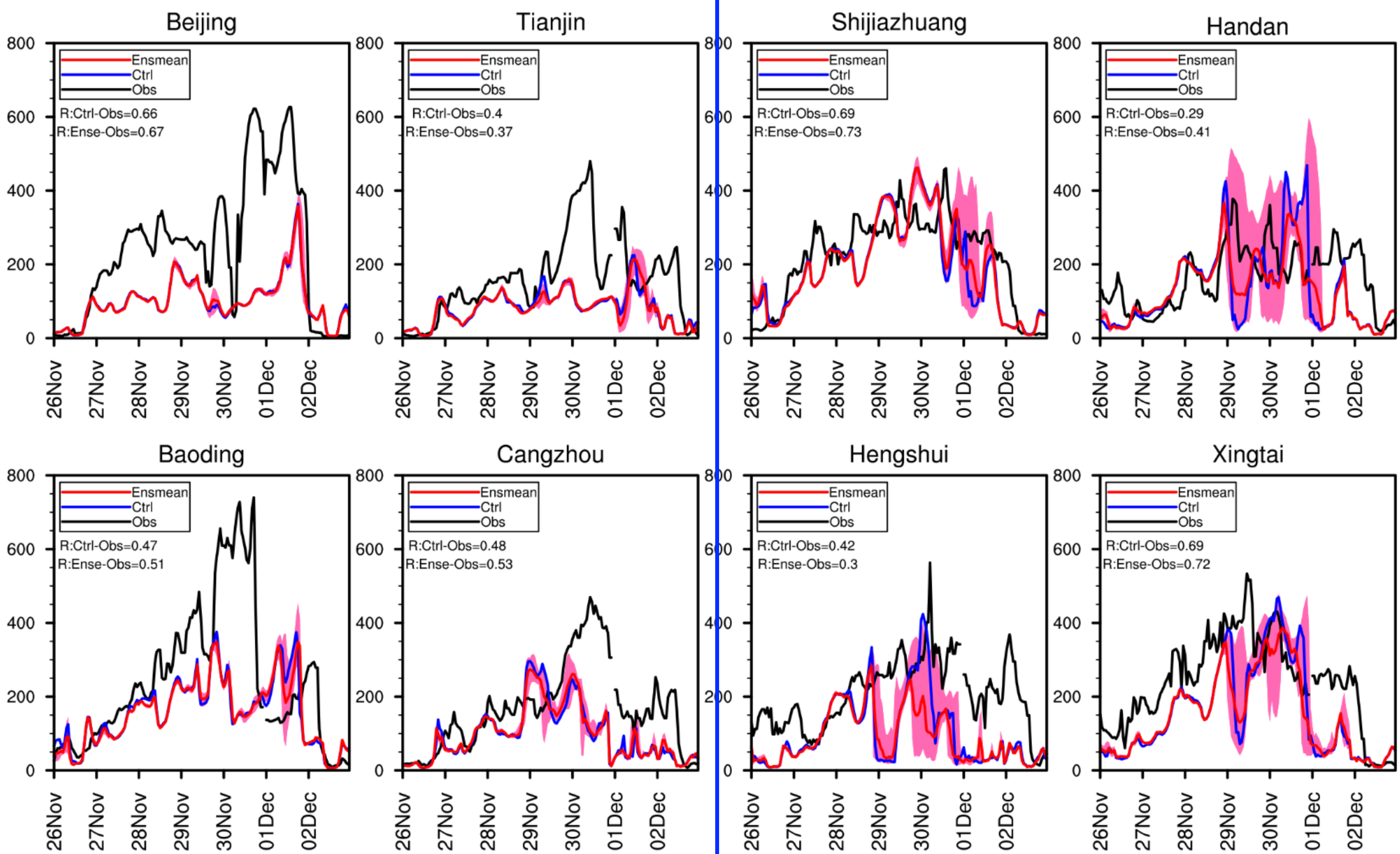


WRF-Chem fails to capture the large fluctuations of instantaneous $PM_{2.5}$ concentration

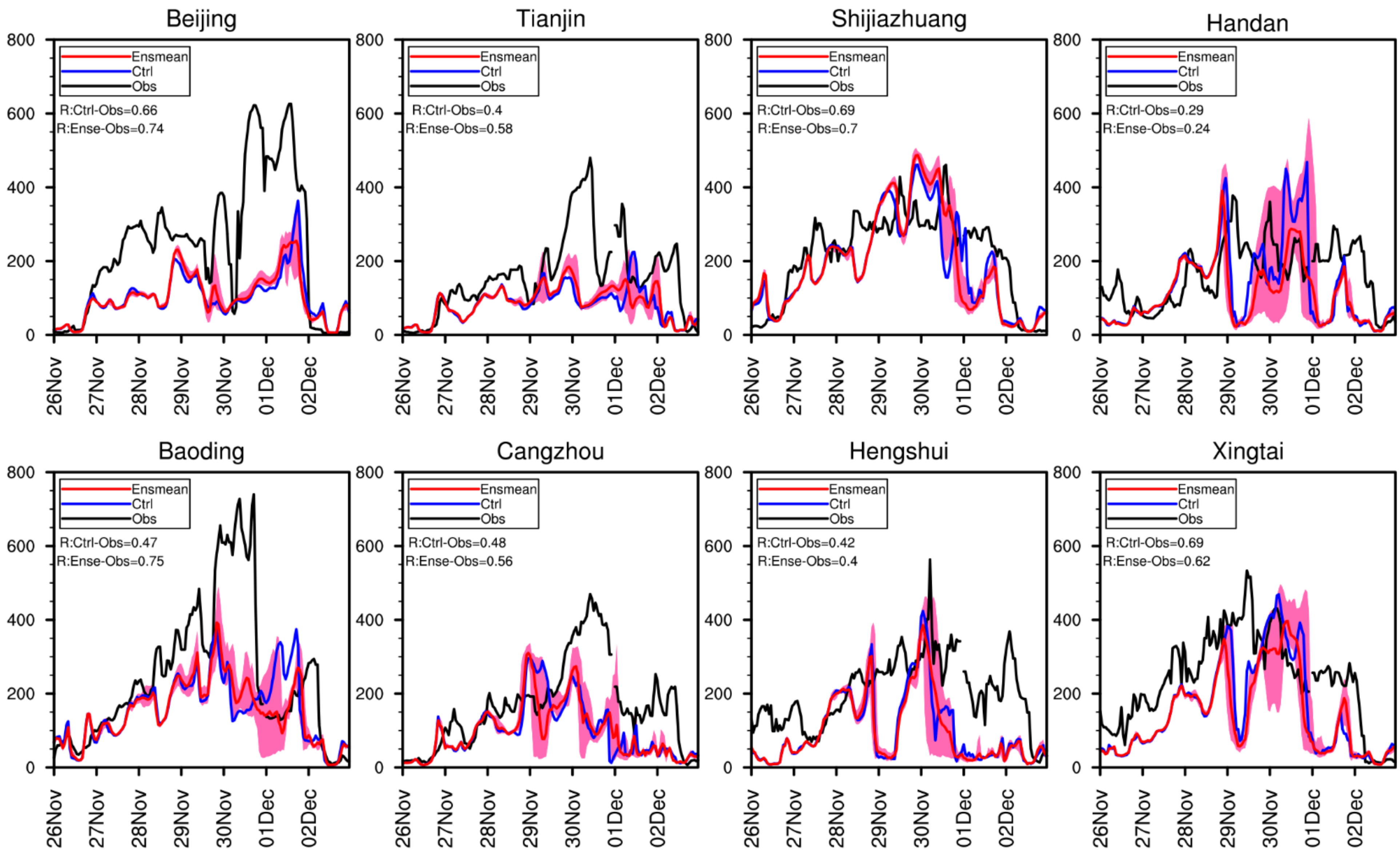
Initial condition analysis: V10 & U10 at 00UTC25Nov



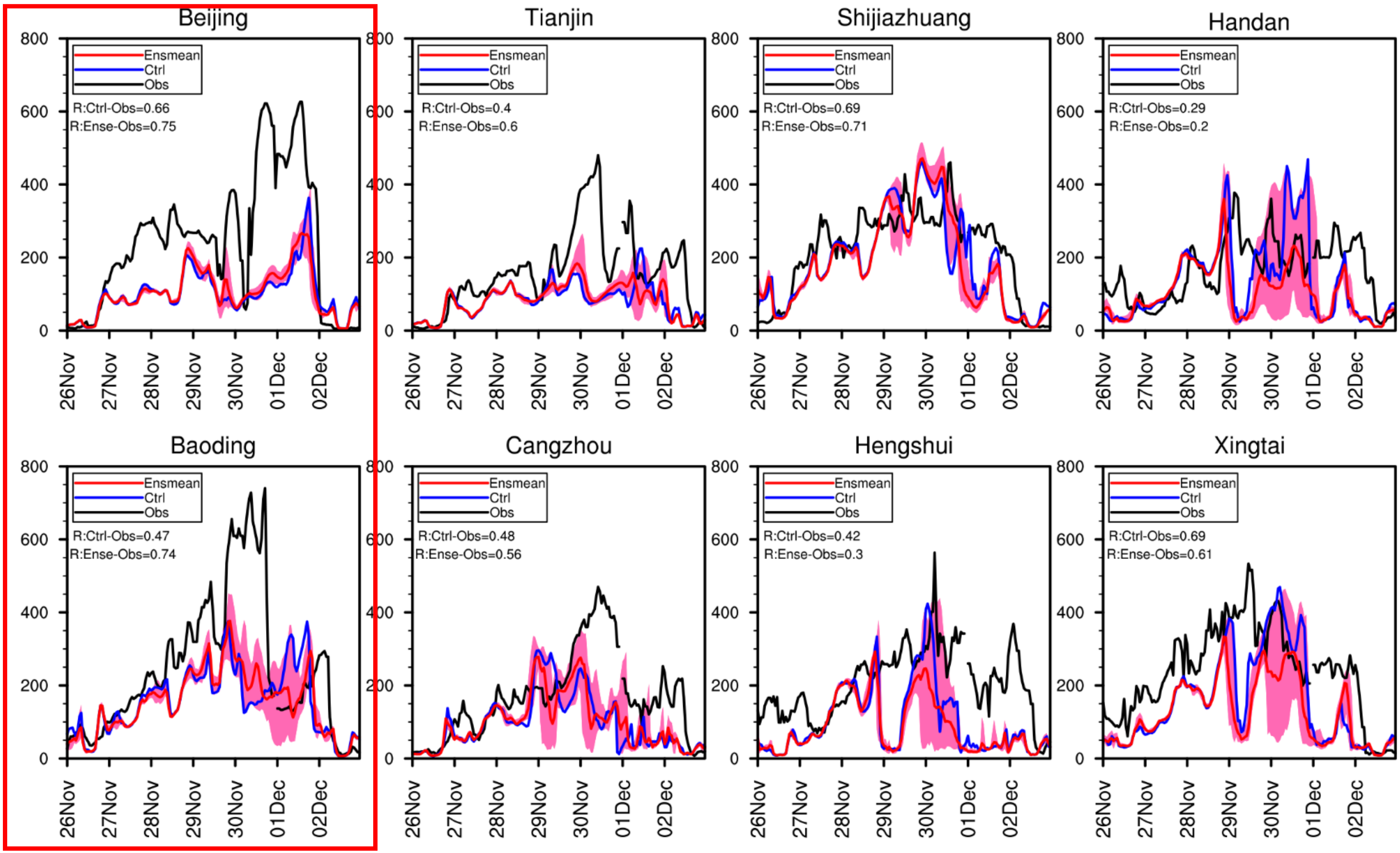
$PM_{2.5}$: CTRL VS INDE (Initial condition ensemble)



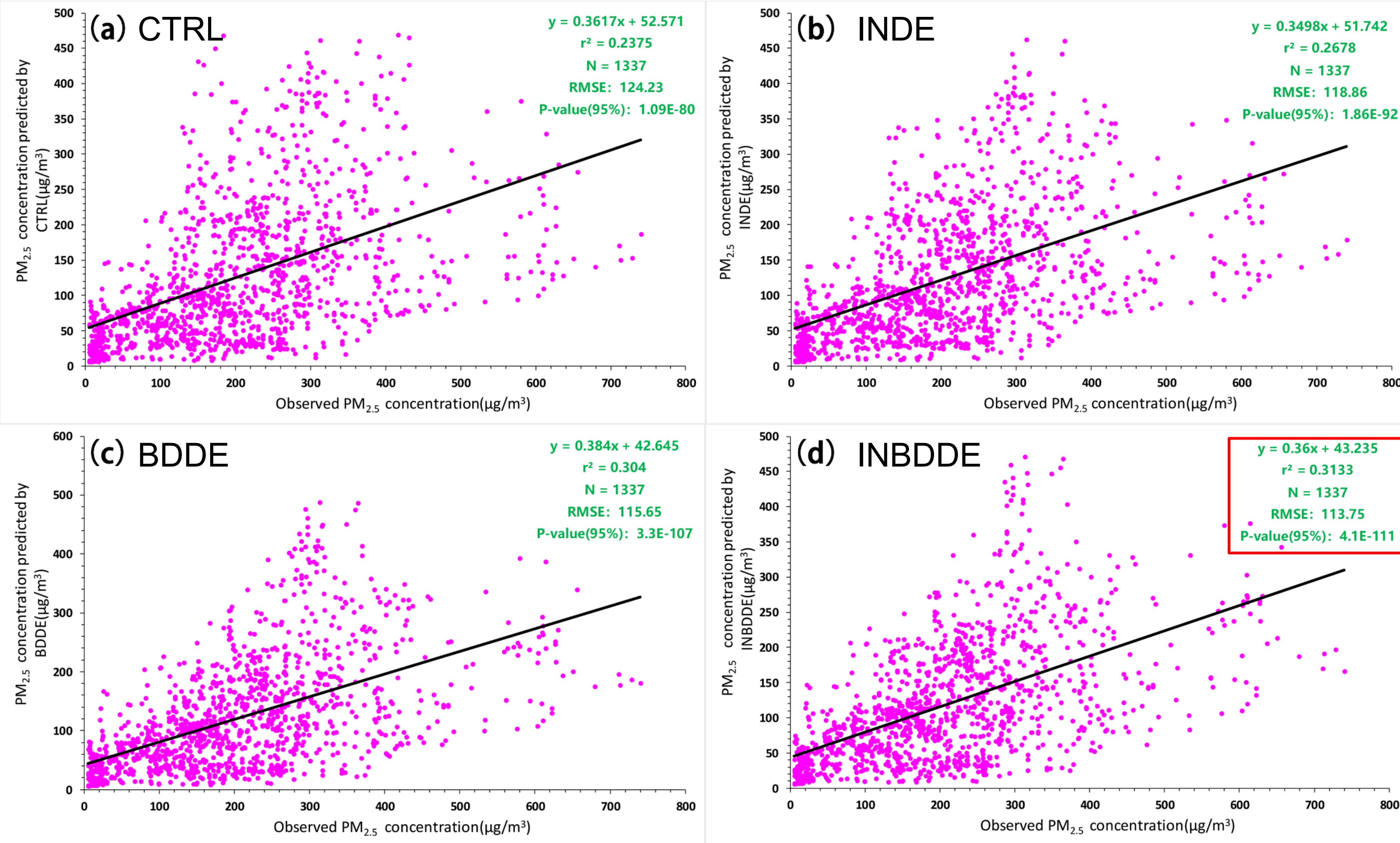
$PM_{2.5}$: CTRL VS BDDE (LBCs ensemble)



PM$_{2.5}$: CTRL VS INBDDE (Initial and LBCs ensemble)



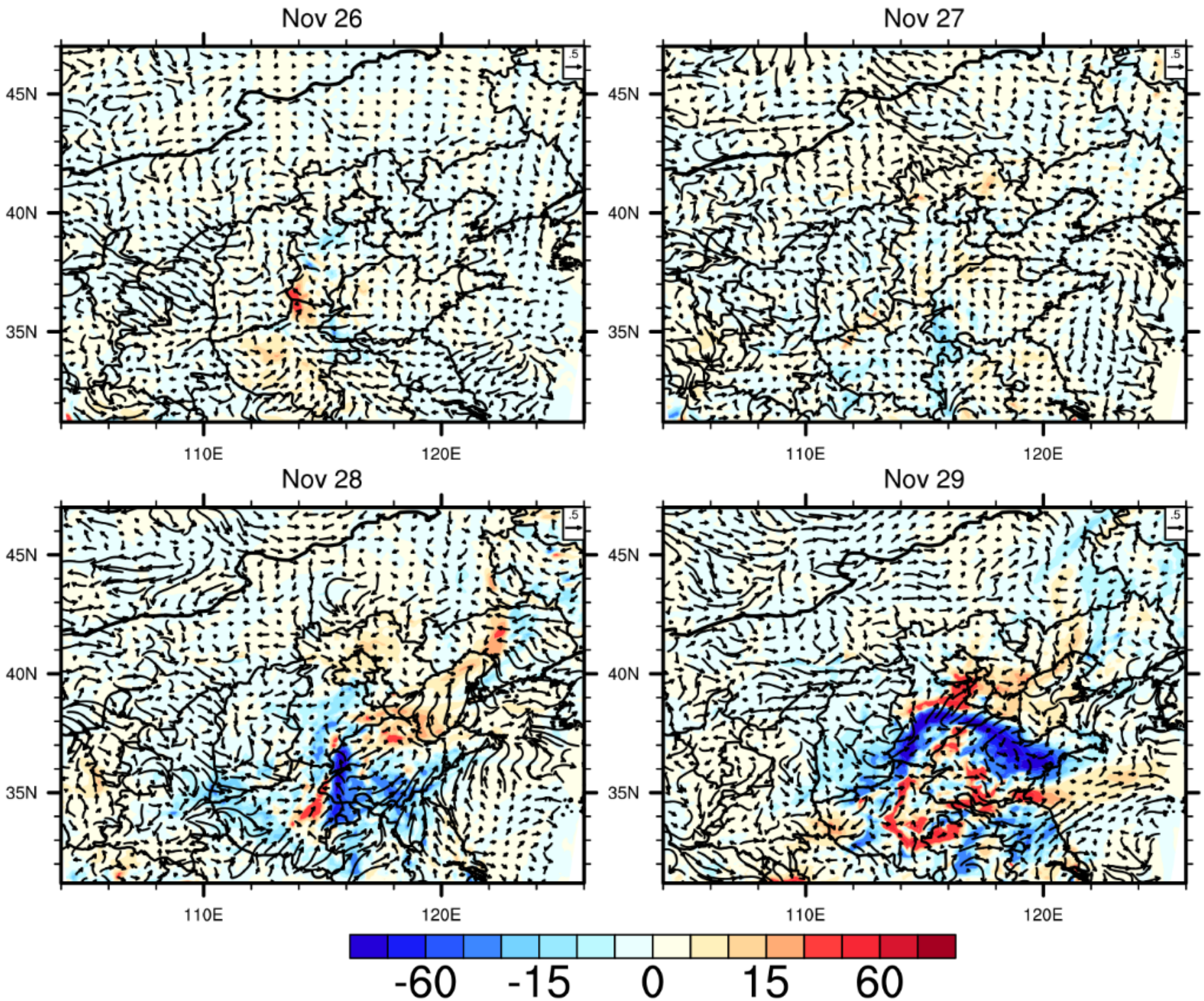
Regression Analysis



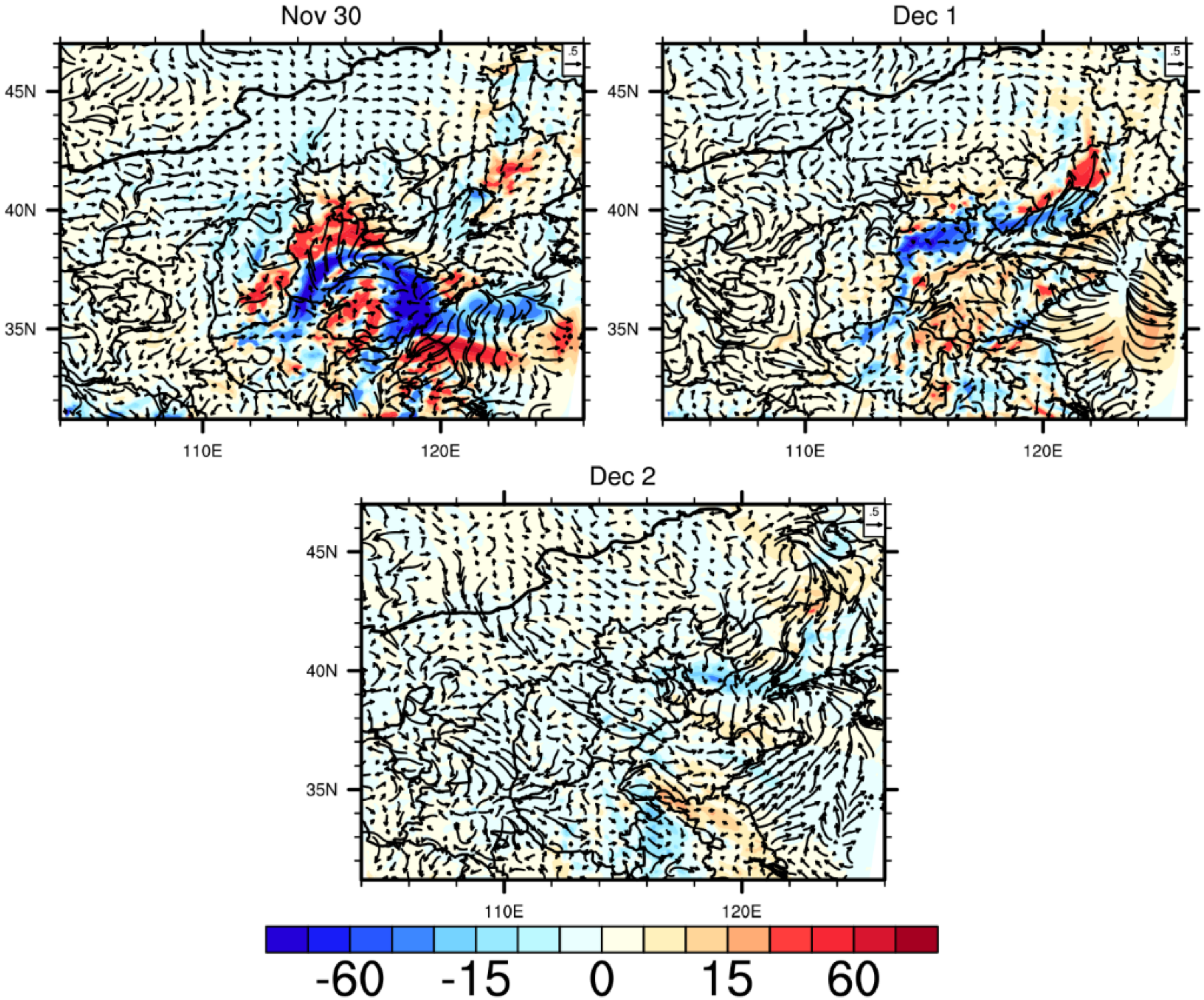
Near surface meteorological factors

Variable	Number of samples	Expt	bias	R	RMSE	EE
$PM_{2.5}$ (μg/m³)	1337	CTRL	-77.95	0.49	124.23	0
		INDE	-81.20	0.52	118.86	-4.33%
		BDDE	-83.32	0.55	115.65	-6.91%
		INBDDE	-87.63	0.56	113.75	-8.44%
RH2M (%)	1337	CTRL	-7.24	0.78	13.38	0
		INDE	-7.84	0.79	13.23	-1.10%
		BDDE	-6.85	0.78	13.47	0.70%
		INBDDE	-7.48	0.79	13.49	0.81%
T2M (℃)	1336	CTRL	0.26	0.83	2.04	0
		INDE	0.41	0.83	2.01	-1.20%
		BDDE	0.24	0.83	2.04	0.13%
		INBDDE	0.37	0.83	2.04	0.03%
WS10 (m/s)	1336	CTRL	1.31	0.61	1.47	0
		INDE	1.32	0.62	1.46	-0.75%
		BDDE	1.29	0.64	1.48	0.56%
		INBDDE	1.30	0.64	1.50	2.32%
WD10 (°)	1336	CTRL	-16.84	0.26	133.29	0
		INDE	-18.89	0.27	126.37	-5.19%
		BDDE	-14.74	0.29	121.45	-8.89%
		INBDDE	-15.73	0.29	120.49	-9.61%

Difference field between INBDDE and CTRL



Difference field between INBDDE and CTRL



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Summary

- **WRF-Chem** reproduces the overall life cycle of the haze event over BTH region but fails to capture the large fluctuations of $PM_{2.5}$ concentration in the eight selected cities.
- In general, the ensemble experiments can improve the simulation skill of $PM_{2.5}$ concentration in this case, especially in INBDDE runs.
- 10-m wind direction (-5.19%, -8.89% and -9.61%) seem to be the dominant reason for the improvement of $PM_{2.5}$ in ensemble runs.

Thanks !

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X. Li, H. Liu*, Z. Zhang, and J. Liu, Numerical simulation of an extreme haze pollution event over North China Plain based on initial and boundary condition ensembles. Atmospheric and Oceanic Science Letters, in press.