Response to Reviewers

No.: ACP-2025-10

Title: Anthropogenic and Natural Causes for the Interannual Variation of $PM_{2.5}$ in East Asia During Summer Monsoon Periods From 2008 to 2018

Anonymous referee #3:

The manuscript "Anthropogenic and Natural Causes for the Interannual Variation of $PM_{2.5}$ in East Asia During Summer Monsoon Periods From 2008 to 2018" by Ma et al. used a regional climate chemistry-ecosystem coupled model to investigate interannual variations in $PM_{2.5}$ across East Asia from 2008 to 2018 and investigates the drivers. This has been an important topic in the past years, and this work improves over previous studies by exploring the impact of CO_2. I feel this point is of interest to the community and falls within the scope of ACP. The manuscript is also well written and easy to follow. I recommend publication after addressing the following points.

Response: We thank referee #3 for careful reading and valuable comments. We have responded to each specific comment in blue below. Please note that the line numbers given below refer to the clean version of the manuscript.

1. My major concern is the boundary between CO_2 change and meteorology change in the work. As mentioned in the text, CO_2 could influence PM via changing radiation, temperature, and precipitation. Aren't these already counted in the meteorology change? This needs to be explained clearer.

Response: Thanks. As shown in Table 1, the difference between SIM_{Base} and $SIM_{MET=2008}$ (SIM_{Base} - $SIM_{MET=2008}$) quantifies the impact of meteorological variability on $PM_{2.5}$ concentrations. Here, "meteorological variability" refers to the year-to-year changes in weather relative to the fixed 2008 baseline. In contrast, the difference between SIM_{Base} and $SIM_{CO2=2008}$ (SIM_{Base} - $SIM_{CO2=2008}$) isolates the effect of CO_2 emission changes on $PM_{2.5}$. As a principal greenhouse gas, CO_2 modifies meteorological parameters—such as radiation, temperature, and precipitation—which in turn influence $PM_{2.5}$ levels. In this comparison, all meteorological changes derive solely from variations in CO_2 concentration, a mechanism fundamentally different from the meteorological influences identified in Experiments SIM_{Base} and $SIM_{MET=2008}$.

We have added some discussions on this aspect.

Table 1. The Numerical experimental in this study.

Experiment	Time	Meteorological fields	CO_2 emissions	Anthropogenic pollutant emissions
SIM_{2008}	2008	2008	2008	2008
SIM_{Base}	2009-2018	2009-2018	2009-2018	2009-2018

$SIM_{MET=2008}$	2009-2018	2008	2009-2018	2009-2018
$SIM_{CO2=2008}$	2009-2018	2009-2018	2008	2009-2018

Changes in manuscript:

2.1 Model description

(L141–148): "In the RegCM-Chem-YIBs model, changes in CO_2 concentrations affect $PM_{2.5}$ primarily via two mechanisms: first, CO_2-induced radiative forcing alters the atmospheric radiation balance, leading to shifts in temperature, precipitation, and boundary-layer structure that modulate $PM_{2.5}$ formation, transport, and removal(Li and Mölders, 2008; Matthews, 2007); And second, through the YIBs module, changes in CO_2 concentration modulate photosynthetic activity and stomatal behavior, altering BVOCs emissions that undergo atmospheric photochemical oxidation to form secondary organic aerosols, a significant fraction of $PM_{2.5}$ (Kergoat et al., 2002; Kellomaki and Wang, 1998)."

2.3 Experiment settings

(L189–193): "It is noteworthy that, as a principal greenhouse gas, CO_2 modifies meteorological parameters—such as radiation, temperature, and precipitation—which in turn influence $PM_{2.5}$ levels. In this comparison, all meteorological changes derive solely from variations in CO_2 emissions, a mechanism fundamentally different from the meteorological influences identified in experiments SIM_{Base} and $SIM_{MET=2008}$."

References

Kellomaki, S. and Wang, K. Y.: Growth, respiration and nitrogen content in needles of Scots pine exposed to elevated ozone and carbon dioxide in the field, Environmental pollution (Barking, Essex : 1987), 101, 263-274, 10.1016/s0269-7491(98)00036-0, 1998.

Kergoat, L., Lafont, S., Douville, H., Berthelot, B., Dedieu, G., Planton, S., and Royer, J. F.: Impact of doubled CO₂ on global-scale leaf area index and evapotranspiration:: Conflicting stomatal conductance and LAI responses -: art. no. 4808, Journal of Geophysical Research-Atmospheres, 107, 10.1029/2001jd001245, 2002.

Li, Z. and Mölders, N.: Interaction of impacts of doubling CO₂ and changing regional land-cover on evaporation, precipitation, and runoff at global and regional scales, International Journal of Climatology, 28, 1653-1679, 10.1002/joc.1666, 2008.

Matthews, H. D.: Implications of CO₂ fertilization for future climate change in a coupled climate-carbon model, Global Change Biology, 13, 1068-1078, 10.1111/j.1365-2486.2007.01343.x, 2007.

2. Another important concern is for Section 3.2 and 3.3: I would suggest present some statistics other than just make the conclusions by spatial distribution plots. e.g., when you say a reduction of $PM_{2.5}$ is associated with an increase of a certain factor, did you find a correlation? We cannot simply say a decrease of A is due to an increase of B and a decrease of C, they may just not relate to each other with small correlation.

Response: Thanks. We have provided the relevant statistical data in the supplementary information and have incorporated Tables S1–S4 into the main manuscript (Tables 3–6) to facilitate easier access for readers.

We attribute changes in $PM_{2.5}$ concentrations to three primary factors: meteorological variability, CO_2 emission changes, and anthropogenic pollutant emissions changes. In Section 3.2, we assessed the combined effects of meteorological factors—including temperature, precipitation, wind speed, and planetary boundary layer height—on $PM_{2.5}$ concentrations, without isolating the individual contributions of each factor. As illustrated in Figure 4 and Table 4, $PM_{2.5}$ concentrations exhibit a negative correlation with precipitation and a positive correlation with temperature, elucidating the mechanisms by which meteorological conditions influence $PM_{2.5}$ levels.

Similarly, in Section 3.3, we quantified the integrated impact of CO_2 on atmospheric $PM_{2.5}$ concentrations through its modulation of biogenic volatile organic compound (BVOC) emissions and alteration of meteorological conditions.

Your insightful suggestion has provided us with a new perspective. In our forthcoming research, we plan to conduct sensitivity experiments by individually fixing specific meteorological variables. This approach will enable us to independently assess the impact of temperature, precipitation, wind speed, and other factors on $PM_{2.5}$ concentrations. Additionally, we aim to distinguish the respective impacts of CO_2-induced meteorological changes and CO_2-driven alterations in BVOC emissions on $PM_{2.5}$ levels. This line of inquiry represents a deeper exploration of the subject and promises to yield valuable insights.

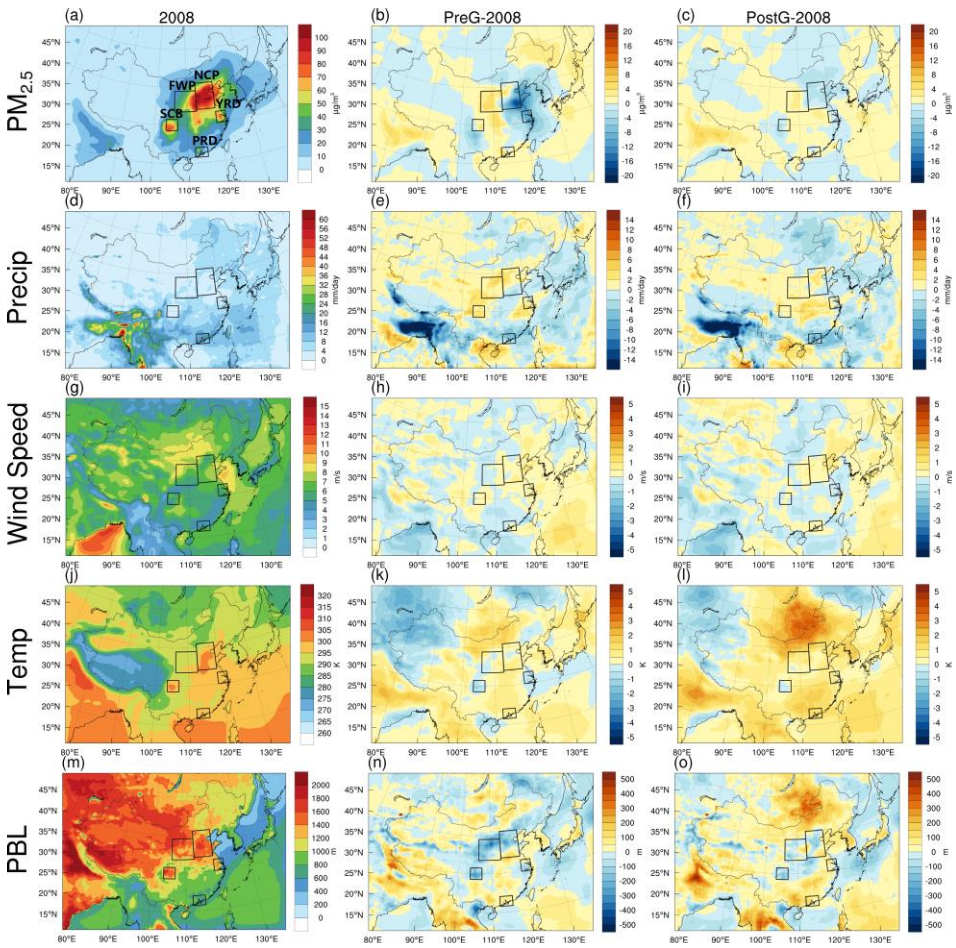

Figure 4. The $PM_{2.5}$ (a–c, μg/m^3), precipitation (d–f, mm/day), wind speed (g–i, m/s), temperature (j–l, K), and Planetary Boundary Layer (PBL) height (m–o, m) during the EASM period in 2008 (left), and their mean changes due to meteorological variations in PreG (2009–2013, center) and PostG (2014–2018, right) phase relative to 2008 (SIM_{Base} - $SIM_{MET=2008}$).

Table 4. Impact of meteorological condition changes on $PM_{2.5}$ (μg/m^3), precipitation (mm/day), wind speed (m/s), near-surface temperature (K), and Planetary Boundary Layer (PBL) height (m) during the EASM period in PreG (2009–2013) and PostG (2014–2018) phase relative to 2008 (SIM_{Base} - $SIM_{MET=2008}$).

Region	Period	$PM_{2.5}$ (μg/m^3)	Precipitation (mm/day)	Wind Speed (m/s)	Near-Surface Temperature (K)	PBL (m)
NCP	PreG	-4.01	0.58	0.17	0.32	-46.8
	PostG	-1.6	0.6	0.26	0.6	-14.5
FWP	PreG	2.32	1.68	-0.06	0.1	-108.5
	PostG	1	0.81	0.05	0.46	-15.3
YRD	PreG	-6.31	1.02	0.18	-0.29	-33.9
	PostG	-0.43	0.48	-0.08	0.45	21.9
PRD	PreG	1.49	-2.39	-0.02	0.36	29.6
	PostG	0.11	-3.24	0.18	1.00	52.2

SCB	PreG	0.29	1.81	0.13	-0.58	-136.5
	PostG	-1.14	0.37	-0.03	-0.14	-76

Changes in manuscript:

Table 3. Changes in near-surface $PM_{2.5}$ concentrations (μg/m³) during the EASM period from 2009 to 2018 relative to 2008 in the North China Plain (NCP), Fen-Wei Plain (FWP), Yangtze River Delta (YRD), Pearl River Delta (PRD), and Sichuan Basin (SCB) (SIM_{Base} - SIM_{2008}).

Year	NCP	FWP	YRD	PRD	SCB
2009	-11.24	-1.29	-11.37	1.41	-3.16
2010	-3.87	1.9	-15.2	-3.57	-4.79
2011	-6.27	0.22	-14.76	0.13	-8.65
2012	-7.42	1.69	-17.61	2.35	-15.99
2013	-14.67	-15.49	-14.9	-6.34	-20.37
2014	-24.26	-15.36	-19.95	-6.72	-22.87
2015	-31.41	-16.9	-27.76	-9.91	-31.75
2016	-38.5	-25.23	-32.43	-8.18	-35.58
2017	-40.69	-25.49	-26.21	-5.82	-37.43
2018	-48.96	-27.83	-33.08	-9.53	-42.19
PreG	-8.69	-2.59	-14.77	-1.20	-10.59
PostG	-36.76	-22.16	-27.89	-8.03	-33.96

Table 4. Impact of meteorological condition changes on $PM_{2.5}$ (μg/m^3), precipitation (mm/day), wind speed (m/s), near-surface temperature (K), and Planetary Boundary Layer (PBL) height (m) during the EASM period in PreG (2009–2013) and PostG (2014–2018) phase relative to 2008 (SIM_{Base} - $SIM_{MET=2008}$).

Region	Period	$PM_{2.5}$ (μg/m^3)	Precipitation (mm/day)	Wind Speed (m/s)	Near-Surface Temperature (K)	PBL (m)
NCP	PreG	-4.01	0.58	0.17	0.32	-46.8
	PostG	-1.6	0.6	0.26	0.6	-14.5
FWP	PreG	2.32	1.68	-0.06	0.1	-108.5
	PostG	1	0.81	0.05	0.46	-15.3
YRD	PreG	-6.31	1.02	0.18	-0.29	-33.9
	PostG	-0.43	0.48	-0.08	0.45	21.9
PRD	PreG	1.49	-2.39	-0.02	0.36	29.6
	PostG	0.11	-3.24	0.18	1.00	52.2
SCB	PreG	0.29	1.81	0.13	-0.58	-136.5
	PostG	-1.14	0.37	-0.03	-0.14	-76

Table 5. Impact of CO_2 emission changes on $PM_{2.5}$ (μg/m^3), CO_2 (ppm), precipitation (mm/day), and isoprene (μg/m^3) during the EASM period in PreG (2009–2013) and PostG (2014–2018) phase relative to 2008 (SIM_{Base} - $SIM_{CO2=2008}$).

Region	Period	$PM_{2.5}$ ($\mu g/m^3$)	CO_2 (ppm)	Precipitation (mm/day)	Isoprene ($\mu g/m^3$)
NCP	PreG	0.6	3.19	0.27	-0.1
	PostG	-1.3	4.24	0.13	0.26
FWP	PreG	0.84	1.70	0.21	-0.16
	PostG	-0.98	2.05	0.06	0.33
YRD	PreG	-0.02	4.1	0.13	-0.32
	PostG	-0.05	6.2	0.09	-0.58
PRD	PreG	1.13	1.97	-1.02	0.31
	PostG	0.31	3.20	-0.33	0.92
SCB	PreG	-0.49	2.80	0.64	-0.78
	PostG	-0.73	2.78	0.21	0.69

Table 6. Changes in total $PM_{2.5}$ concentrations (ALL, SIM_{Base} - SIM_{2008}) and the impacts of anthropogenic pollutant emissions (Emis, All-Met-CO_2), meteorological conditions (Met, SIM_{Base} - $SIM_{MET=2008}$), and CO_2 emission (CO_2, SIM_{Base} - $SIM_{CO2=2008}$) variations on $PM_{2.5}$ concentrations ($\mu g/m^3$) during the EASM period in PreG (2009–2013) and PostG (2014–2018) phase relative to 2008.

Region	Period	ALL	Emis	Met	CO_2
NCP	PreG	-8.69	-5.28	-4.01	0.6
	PostG	-36.76	-33.86	-1.6	-1.3
FWP	PreG	-2.59	-5.75	2.32	0.84
	PostG	-22.16	-22.18	1	-0.98
YRD	PreG	-14.77	-8.44	-6.31	-0.02
	PostG	-27.89	-27.41	-0.43	-0.05
PRD	PreG	-1.2	-3.82	1.49	1.13
	PostG	-8.03	-8.45	0.11	0.31
SCB	PreG	-10.59	-10.39	0.29	-0.49
	PostG	-33.96	-32.09	-1.14	-0.73

Other comments:

3. Section 2.3 and Table 1: Can you introduce a bit more detail of what processes CO_2 will influence in your model? Are the meteorological fields used in SIM_{Base} and $SIM_{CO2=2008}$ the same or SIM_{Base} also reflect the meteorology change due to CO_2? In Fig 1, it seems that meteorology responses to YIBs that changes with CO_2, then how do you apply the fixed meteorological field for $SIM_{MET=2008}$? ignoring the response of CO_2 variation?

Response: Thanks. We added some descriptions of what processes CO_2 will influence in our model.

To clarify the experimental design, we have revised Table 1 and its description in the revised manuscript. The SIM_{2008} experiment represents the baseline conditions for the year 2008. In the SIM_{Base} experiment, interannual variations in meteorological fields, CO_2 emissions, and anthropogenic pollutant emissions (excluding CO_2 emissions) were considered for simulations spanning 2009–2018, representing the baseline conditions for 2009–2018. Additionally, the $SIM_{MET=2008}$ and $SIM_{CO2=2008}$ experiments were designed, where meteorological fields and CO_2 emissions were fixed at their 2008 levels, respectively, while simulations were conducted for 2009–2018.

As shown in Table 1,SIM_{2008} and SIM_{Base} serve as baseline experiments that collectively capture the evolution of $PM_{2.5}$ concentrations under the combined influences of meteorological variability, CO_2 emission changes, and anthropogenic pollutant emissions changes (SIM_{Base} - SIM_{2008}).

The SIM_{Base} and $SIM_{CO2=2008}$ experiments share identical meteorological conditions, differing only in their CO_2 emission datasets; by comparing SIM_{Base} and $SIM_{CO2=2008}$ (SIM_{Base} - $SIM_{CO2=2008}$), we isolate the impact of CO_2 emission changes on $PM_{2.5}$. Likewise, since SIM_{Base} and $SIM_{MET=2008}$ use the same CO_2 emission inputs and differ only in meteorological fields, their comparison (SIM_{Base} - $SIM_{MET=2008}$) quantifies the effect of meteorological variability on $PM_{2.5}$

Table 1. The Numerical experimental in this study.

Experiment	Time	Meteorological fields	CO_2 emissions	Anthropogenic pollutant emissions
SIM_{2008}	2008	2008	2008	2008
SIM_{Base}	2009-2018	2009-2018	2009-2018	2009-2018
$SIM_{MET=2008}$	2009-2018	2008	2009-2018	2009-2018
$SIM_{CO2=2008}$	2009-2018	2009-2018	2008	2009-2018

Changes in manuscript:

2.1 Model description

(L141–148): "In the RegCM-Chem-YIBs model, changes in CO_2 concentrations affect $PM_{2.5}$ primarily via two mechanisms: first, CO_2-induced radiative forcing alters the atmospheric radiation balance, leading to shifts in temperature, precipitation, and boundary-layer structure that modulate $PM_{2.5}$ formation, transport, and removal(Li and Mölders, 2008; Matthews, 2007); And second, through the YIBs module, changes in CO_2 concentration modulate photosynthetic activity and stomatal behavior, altering BVOCs emissions that undergo atmospheric photochemical oxidation to form secondary organic aerosols, a significant fraction of $PM_{2.5}$ (Kergoat et al., 2002; Kellomaki and Wang, 1998)."

2.3 Experiment settings:

(L169–175): "The numerical experiments are presented in Table 1. The SIM_{2008} experiment represents the baseline conditions for the year 2008. In the SIM_{Base} experiment, interannual variations in meteorological fields, CO_2 emissions, and anthropogenic pollutant emissions (excluding CO_2 emissions) were considered for simulations spanning 2009–2018, representing the baseline conditions for 2009–2018. Additionally, the $SIM_{MET=2008}$ and $SIM_{CO2=2008}$ experiments were designed, where meteorological fields and CO_2 emissions were fixed at their 2008 levels, respectively, while simulations were conducted for 2009–2018."

(L179–188): "By comparing the simulation results from different years in the SIM_{Base} experiment to SIM_{2008} (SIM_{Base} - SIM_{2008}), we quantified changes in $PM_{2.5}$ concentrations relative to 2008 for the period 2009–2018. To evaluate the impact of meteorological conditions on $PM_{2.5}$ concentrations, we compared the results of the SIM_{Base} experiment with those of the $SIM_{MET=2008}$ experiment for the same year (SIM_{Base} - $SIM_{MET=2008}$). Similarly, the contribution of CO_2 emission changes to $PM_{2.5}$ variations was assessed by comparing the SIM_{Base} experiment with the $SIM_{CO2=2008}$ experiment (SIM_{Base} - $SIM_{CO2=2008}$) in the same year. The contribution of anthropogenic pollutant emissions was then determined by subtracting the effects of meteorological and CO_2 emission changes from the total $PM_{2.5}$ variation."

References

Kellomaki, S. and Wang, K. Y.: Growth, respiration and nitrogen content in needles of Scots pine exposed to elevated ozone and carbon dioxide in the field, Environmental pollution (Barking, Essex : 1987), 101, 263-274, 10.1016/s0269-7491(98)00036-0, 1998.

Kergoat, L., Lafont, S., Douville, H., Berthelot, B., Dedieu, G., Planton, S., and Royer, J. F.: Impact of doubled CO₂ on global-scale leaf area index and evapotranspiration:: Conflicting stomatal conductance and LAI responses -: art. no. 4808, Journal of Geophysical Research-Atmospheres, 107, 10.1029/2001jd001245, 2002.

Li, Z. and Mölders, N.: Interaction of impacts of doubling CO₂ and changing regional land-cover on evaporation, precipitation, and runoff at global and regional scales, International Journal of Climatology, 28, 1653-1679, 10.1002/joc.1666, 2008.

Matthews, H. D.: Implications of CO₂ fertilization for future climate change in a coupled climate-carbon model, Global Change Biology, 13, 1068-1078, 10.1111/j.1365-2486.2007.01343.x, 2007.

4. line 148: as the impact of meteorological conditions is calculated by SIMbase-SIMmet=2008, it is likely to also include influences of CO_2.

Response: Thanks. SIM_{Base} and $SIM_{MET=2008}$ use the same CO_2 emission inputs and differ only in meteorological fields, their comparison (SIM_{Base} - $SIM_{MET=2008}$) quantifies the effect of meteorological variability on $PM_{2.5}$. Please refer to comment 3 for a detailed response.

5. line 154-158: it would be better to bring some information of model evaluation to the text instead of letting the audience check all the information in other references. e.g., you might also show numbers for measured $PM_{2.5}$ trend when discussing the simulation results in Section 3.1, or include figures to compare with observations in

supplements.

Response: Thank you for your invaluable suggestions. We have incorporated the model evaluation results into the manuscript and expanded the corresponding descriptions.

Changes in manuscript:

2.4 Model evaluations

(L198–207): "Observed $PM_{2.5}$ data were obtained from the China National Environmental Monitoring Center (CNEMC). This study used hourly $PM_{2.5}$ concentrations during the summer monsoon period (May 1 to August 31) from 2015 to 2018. A total of 366 monitoring stations across Chinese cities, selected based on data completeness and representativeness, were used for model validation. The locations of these stations are shown in Fig. S5. CO_2 observations were sourced from the World Data Centre for Greenhouse Gases (WDCGG), including all seven sites in East Asia: Waliguan, Korea Tae-ahn Peninsula, Ulaanbaatar in Mongolia, Lulin, Yonagunijima, Cape D'Aguilar (Hong Kong), and King's Park. Detailed station locations are shown in Fig. S6. Reanalysis data for temperature, wind fields, and relative humidity were obtained from the ERA-Interim dataset."

(L208–21): "As shown in Table 2 and Figures S1–S6, the SIM_{Base} experiments reproduce 2015–2018 $PM_{2.5}$ and CO_2 concentrations with high correlations and low biases relative to observations, while their simulated meteorological fields closely match reanalysis data. Overall, the RegCM-Chem-YIBs model effectively captures the fundamental characteristics and temporal trends of meteorological factors, $PM_{2.5}$, and CO_2 concentrations in East Asia."

Table 2. Evaluations of the near-surface CO_2 and $PM_{2.5}$ in East Asia.

Species	Year	Observation	Simulation	Bias	RMSE	R
CO_2 (ppm)	2015	402.82	406.98	4.16	9.37	0.44
	2016	407.12	410.44	3.32	8.22	0.69
	2017	408.35	413.62	5.27	11	0.39
	2018	409.61	416.68	7.07	11.32	0.41
$PM_{2.5}$ (ug/m^3)	2015	36.6	25.57	-11.03	12.99	0.71
	2016	31.03	22.91	-8.12	10.31	0.64
	2017	29.61	24.02	-5.59	10.57	0.71
	2018	27.18	19.04	-8.14	11.62	0.61

RMSE: root mean square error; R: correlation coefficient.

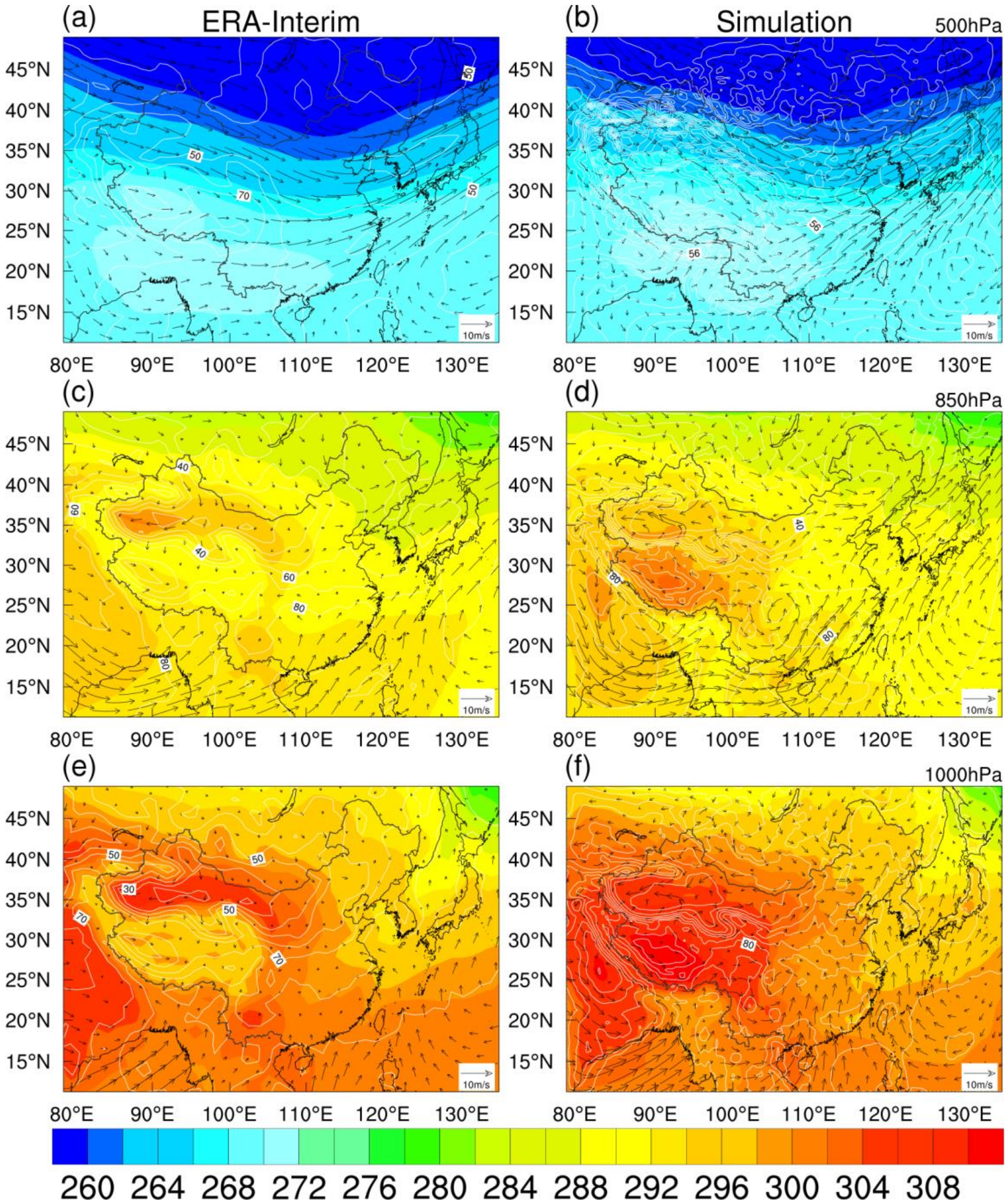

Figure S1. Comparisons between the simulated (right) and reanalysis (left) mean temperature (shading, units: K), wind (vectors, units: m/s), and relative humidity (contours, units: %) at 500 hPa (a, b), 850 hPa (c, d) and 1000 hPa (e, f) during the EASM period in 2015.

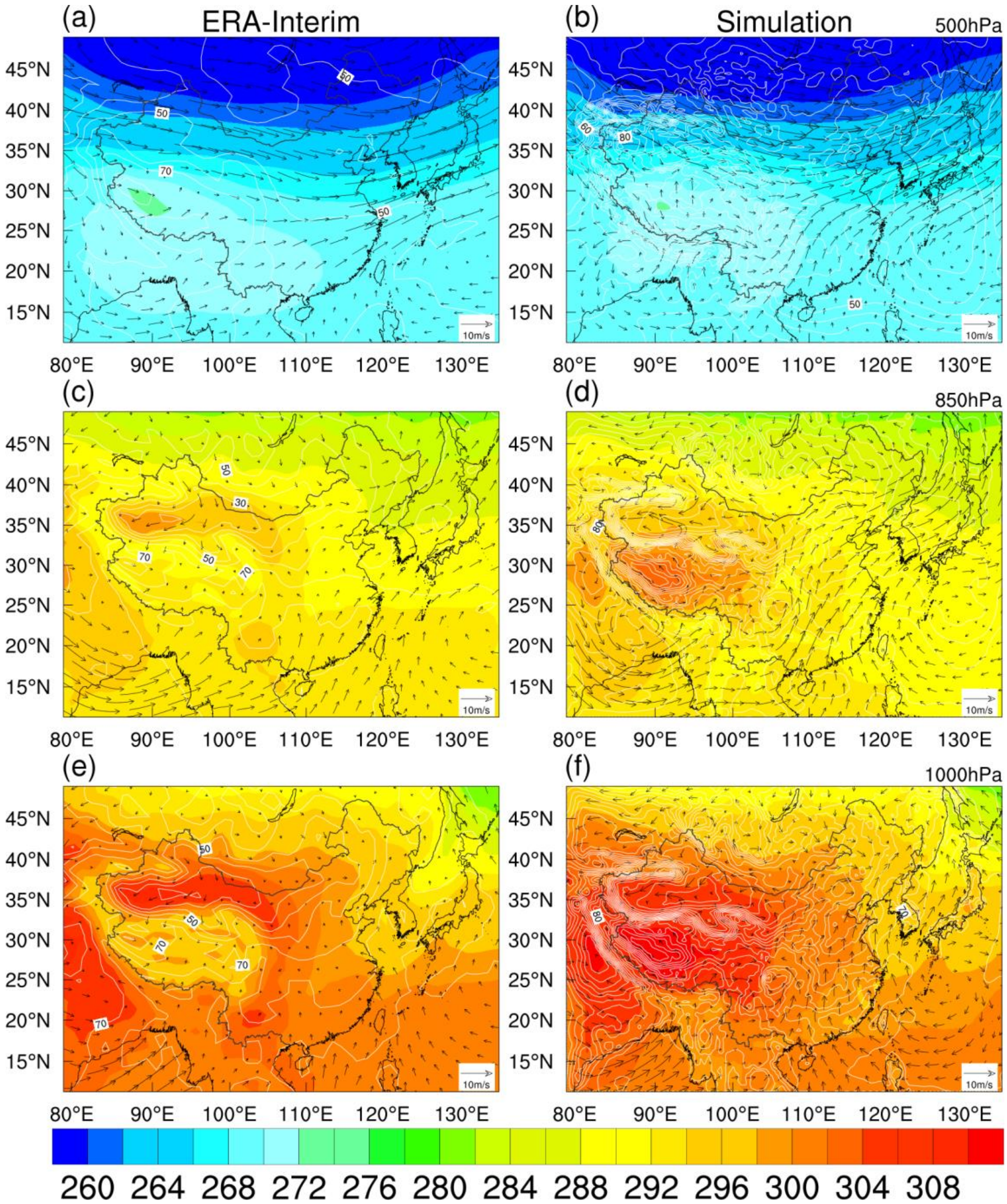

Figure S2. Comparisons between the simulated (right) and reanalysis (left) mean temperature (shading, units: K), wind (vectors, units: m/s), and relative humidity (contours, units: %) at 500 hPa (a, b), 850 hPa (c, d) and 1000 hPa (e, f) during the EASM period in 2016.

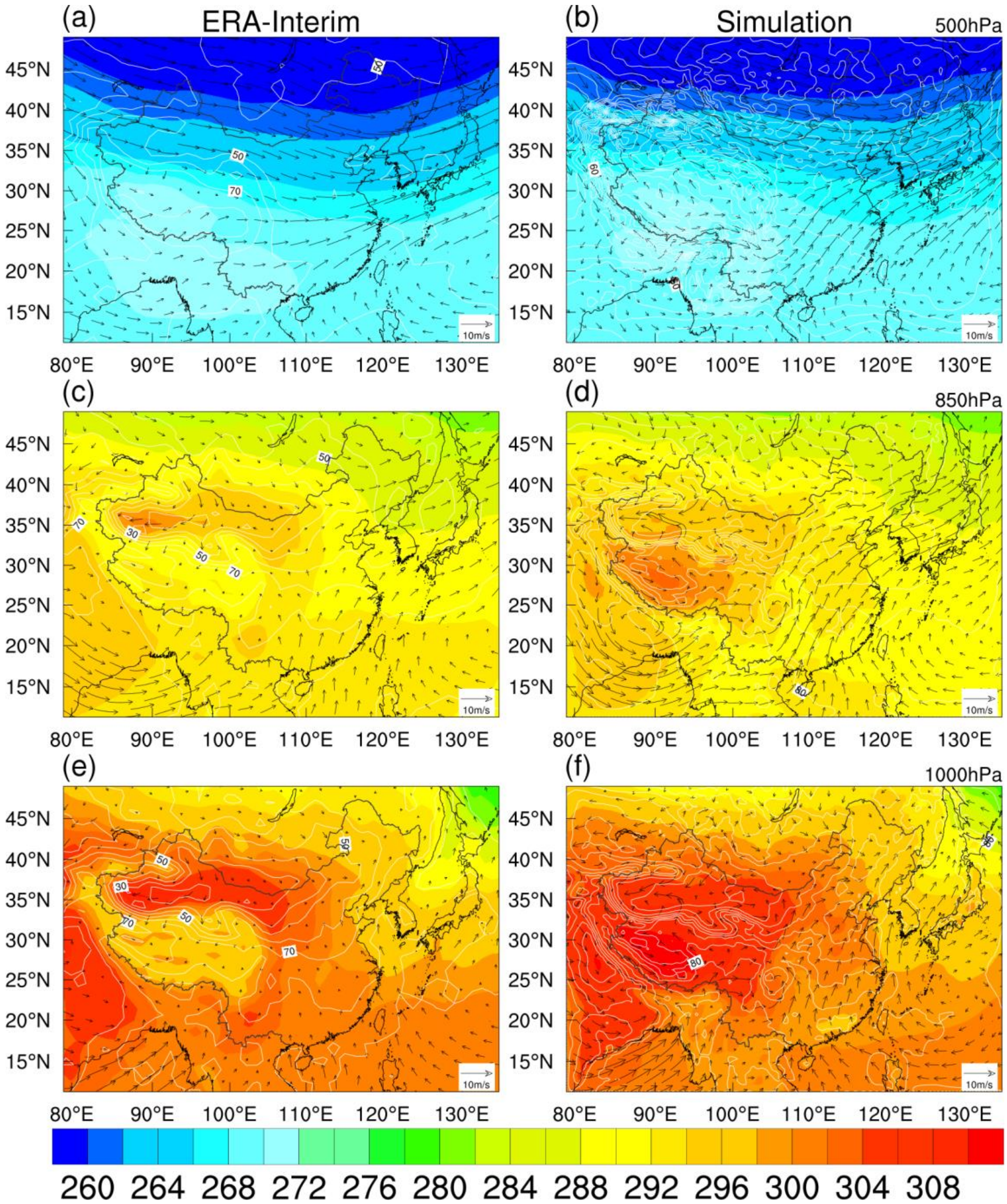

Figure S3. Comparisons between the simulated (right) and reanalysis (left) mean temperature (shading, units: K), wind (vectors, units: m/s), and relative humidity (contours, units: %) at 500 hPa (a, b), 850 hPa (c, d) and 1000 hPa (e, f) during the EASM period in 2017.

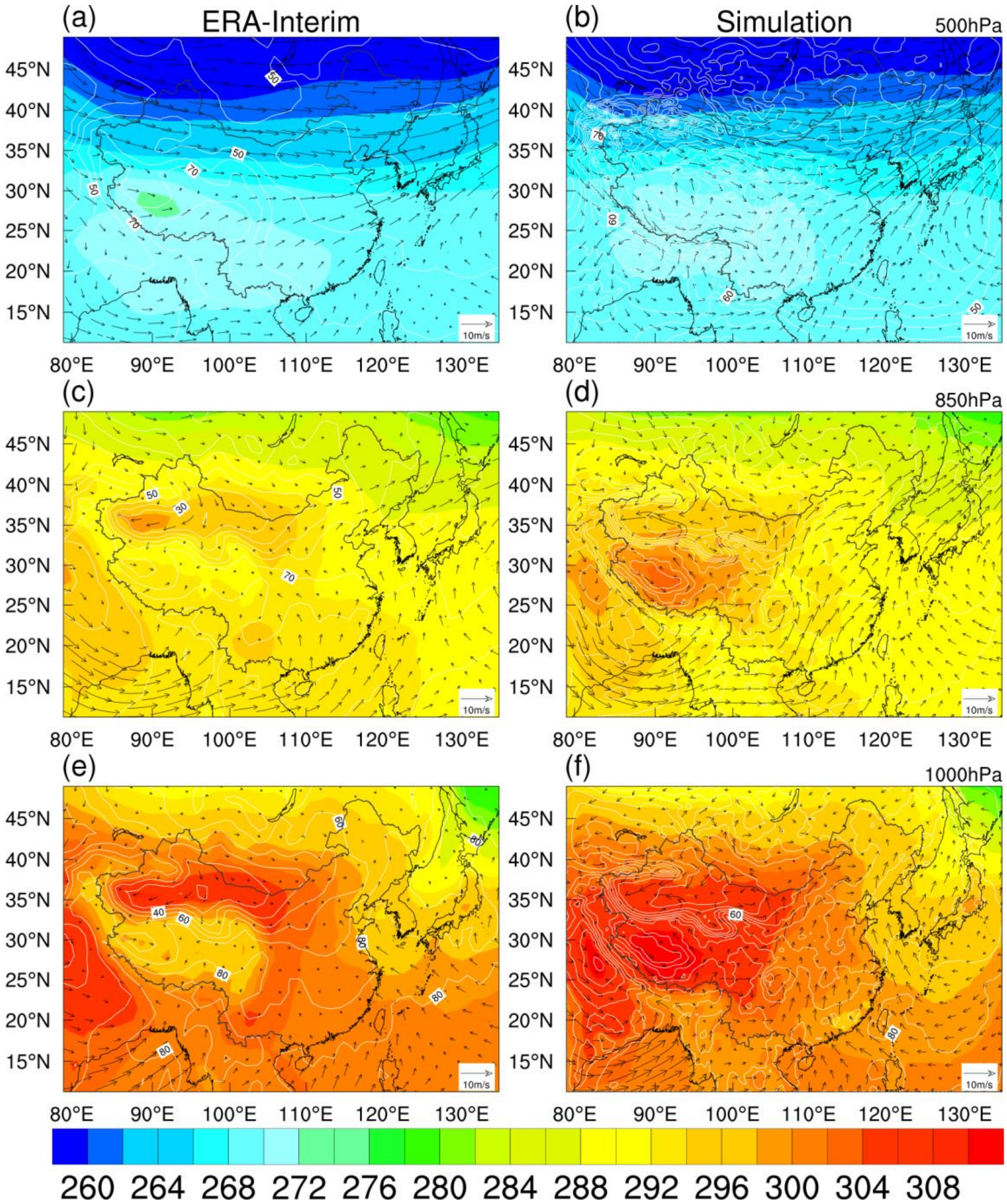

Figure S4. Comparisons between the simulated (right) and reanalysis (left) mean temperature (shading, units: K), wind (vectors, units: m/s), and relative humidity (contours, units: %) at 500 hPa (a, b), 850 hPa (c, d) and 1000 hPa (e, f) during the EASM period in 2018.

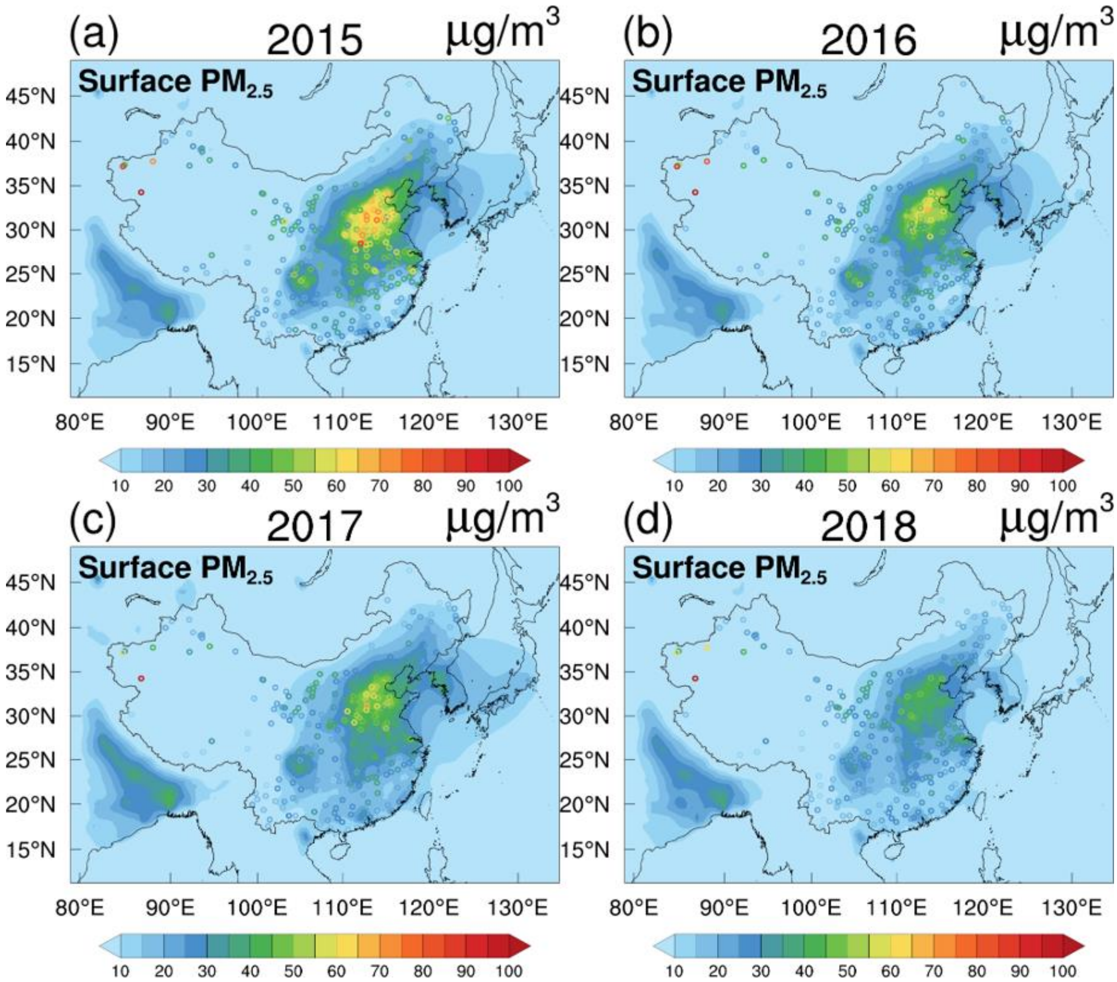

Figure S5. Comparisons between the simulated and observed near-surface $PM_{2.5}$ concentrations (units: μg/m³) during the EASM period in (a)2015, (b)2016, (c)2017, (d)2018. Colored circles represent the observations.

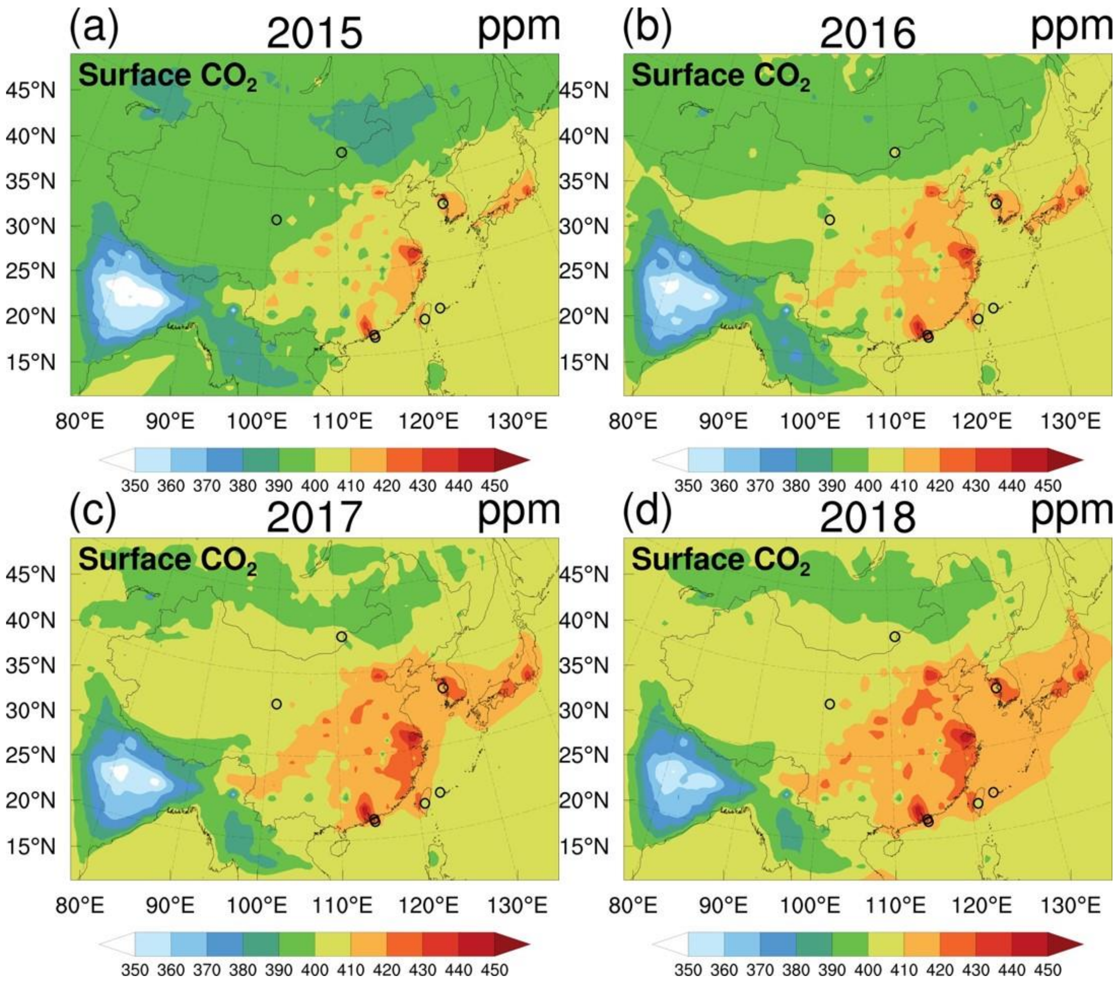

Figure S6. Comparisons between the simulated and observed near-surface CO_2 concentrations (units: ppm) during the EASM period in (a)2015, (b)2016, (c)2017, (d)2018. Colored circles represent the observations.

6. The wording of "anthropogenic emissions" driver in many places of the manuscript might need to be clearer. One key question is whether it is also the anthropogenic emissions contributing to the CO_2 changes. If so, the "anthropogenic emissions" in the text should means non-CO_2 emissions.

Response: Thank you for highlighting this critical issue. In response, we have revised the manuscript to replace all instances of "anthropogenic emissions" with "anthropogenic pollutant emissions". Additionally, in Section 2.3 Experiment settings, we have clarified that "anthropogenic pollutant emissions" exclude CO_2 emissions.

2.3 Experiment settings:

(L170–173): "In the SIM_{Base} experiment, interannual variations in meteorological fields, CO_2 emissions, and anthropogenic pollutant emissions (excluding CO_2 emissions) were considered for simulations spanning 2009–2018, representing the baseline conditions for 2009–2018."

7. Section 3.3: Will CO_2 also change temperature and cloud due to its effects on

radiation balance? Are those negligible factors comparing to those shown in Fig 5?

Response: Thanks. CO_2 alters atmospheric radiative properties, thereby influencing meteorological factors such as temperature, cloud cover, and precipitation. Our analysis of the relationships between temperature, cloud cover, and $PM_{2.5}$ concentrations indicates that their direct effects are insignificant. Specifically, cloud cover affects $PM_{2.5}$ primarily through indirect mechanisms, including modulation of solar radiation and changes in planetary boundary layer height. Temperature influences $PM_{2.5}$ via multiple complex pathways, such as regulating secondary organic aerosol formation, vertical convection, and boundary layer dynamics. In contrast, precipitation directly removes $PM_{2.5}$ through wet deposition processes. Therefore, the primary pathways through which CO_2 impacts $PM_{2.5}$ concentrations are its modulation of precipitation patterns and its influence on biogenic volatile organic compound (BVOC) emissions from vegetation.