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Assessment of future solar energy potential changes under the shared socio-economic pathways scenario 2–4.5 with WRF-chem: The roles of meteorology and emission

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- ✓ Solar radiation is the primary source of energy for life on Earth, driving the water, carbon, and energy cycles of the Earth system, while providing energy for solar generation and solar batteries as a renewable, clean energy source.
- ✓ In recent years, changes in surface solar energy have been observed globally, but the causes of solar energy changes remain highly controversial, especially the relative impact of aerosols and clouds on surface solar energy remains to be studied.

- ✓ The aerosol direct effect (ADE) is the mechanism by which aerosols scatter and absorb shortwave and longwave radiation, thereby altering the radiative balance of the Earth-atmosphere system.
- ✓ The aerosol indirect effect (AIE) is the mechanism by which aerosols modify the microphysical and hence the radiative properties, amount and lifetime of clouds.
    - aerosols increase cloud reflectivity and cool the surface by increasing the number of clouds droplets;
    - the size of cloud droplets decrease as more aerosols are activated, which inhibits the collision and auto-conversion of cloud droplets, thereby inhibiting the warm cloud process.

Model evaluations: aerosol direct and indirect effects on meteorology and solar energy

- Large uncertainties in the interactions of aerosols-clouds-climate/meteorology.
- A challenge in the representation of aerosol–cloud interaction and its impacts in the current climate or weather models.
- Future meteorological conditions and emission reductions are expected to impact on solar energy potential.

Sensitivity experiments

Photovoltaic power potential (PVpot):

- surface solar radiation (SSR)

$$PVpot = \alpha_1 \times SSR + \alpha_2 \times SSR^2 + \alpha_3 \times SSR \times T_2 + \alpha_4 \times SSR \times WS10$$

WRF-Chem evaluation: aerosol direct and aerosol indirect effects

Impacts of aerosol direct (ADE) and aerosol indirect (AIE) on an extreme rainfall event over Beijing on 19–21 July 2016 were analyzed by conducting <u>four numerical experiments</u> with WRF-Chem

Experimental design.

	Aerosol–radiation feedback	Aerosol–cloud interactions
EXP_CTRL	On	On
EXP_NOADE	Off	On
EXP_NOAIE	On	Off
EXP_NOAE	Off	Off

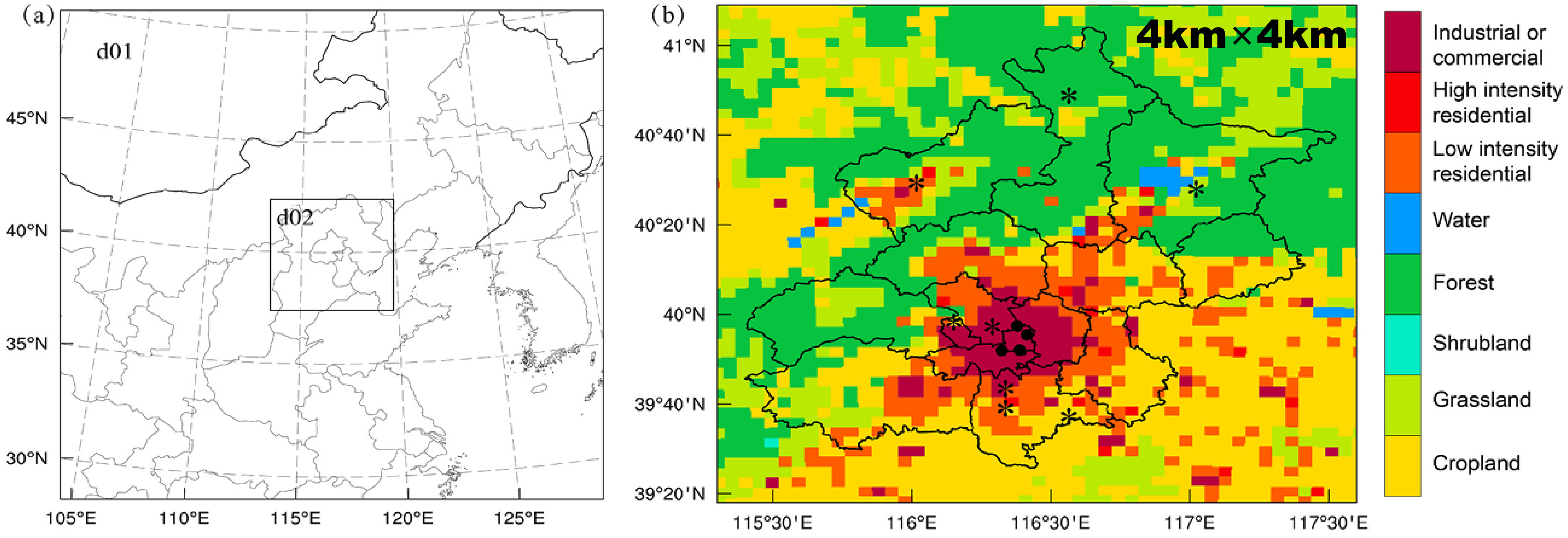


Fig. 1. (a) Study domain and (b) land use in Beijing. The asterisks represent the locations of the weather stations and the dots represent the locations of the $PM_{2.5}$ stations.

Comparison between the simulated and observed temperature (°C) and $PM_{2.5}$ (μg m^{-3}) from 1800 BJT on 18 July to 0800 BJT on 21 July 2016.

Variable	Station	*N*	SIM	OBS	*R*	RMSE	MB	NMB (%)	MFB (%)	MFE (%)
Temperature	Labagoumen	57	20.3	20.3	0.91	0.6	–0.1	0	2	0
	Yudushan	57	18.5	18.6	0.86	0.7	–0.1	–1	3	0
	Yaoshang	57	21.1	20.7	0.91	0.7	0.4	2	2	1
	Taishitun	57	22.8	22.8	0.83	0.9	0.0	0	3	0
$PM_{2.5}$	Wanshouxigong	57	43.4	71.8	0.82	44.6	−28.4	−40	45	−29
	Dongsi	57	42.7	71.2	0.83	42.3	−28.5	−40	44	−30
	Tiantan	57	46.1	72.6	0.88	39.2	−26.5	−37	40	−18
	Olympic Center	57	38.6	63.1	0.91	32.5	−24.5	−39	41	−37

N: number of paired samples; SIM and OBS: average values of the model and observational results sampled at the observation site and time, respectively; *R*: correlation coefficient between the observations and model results; RMSE, MB and NMB: root mean square error, mean bias and normalized mean bias between the observations and model results; MFB and MFE: mean fractional bias and mean fractional error between the observations and model results.

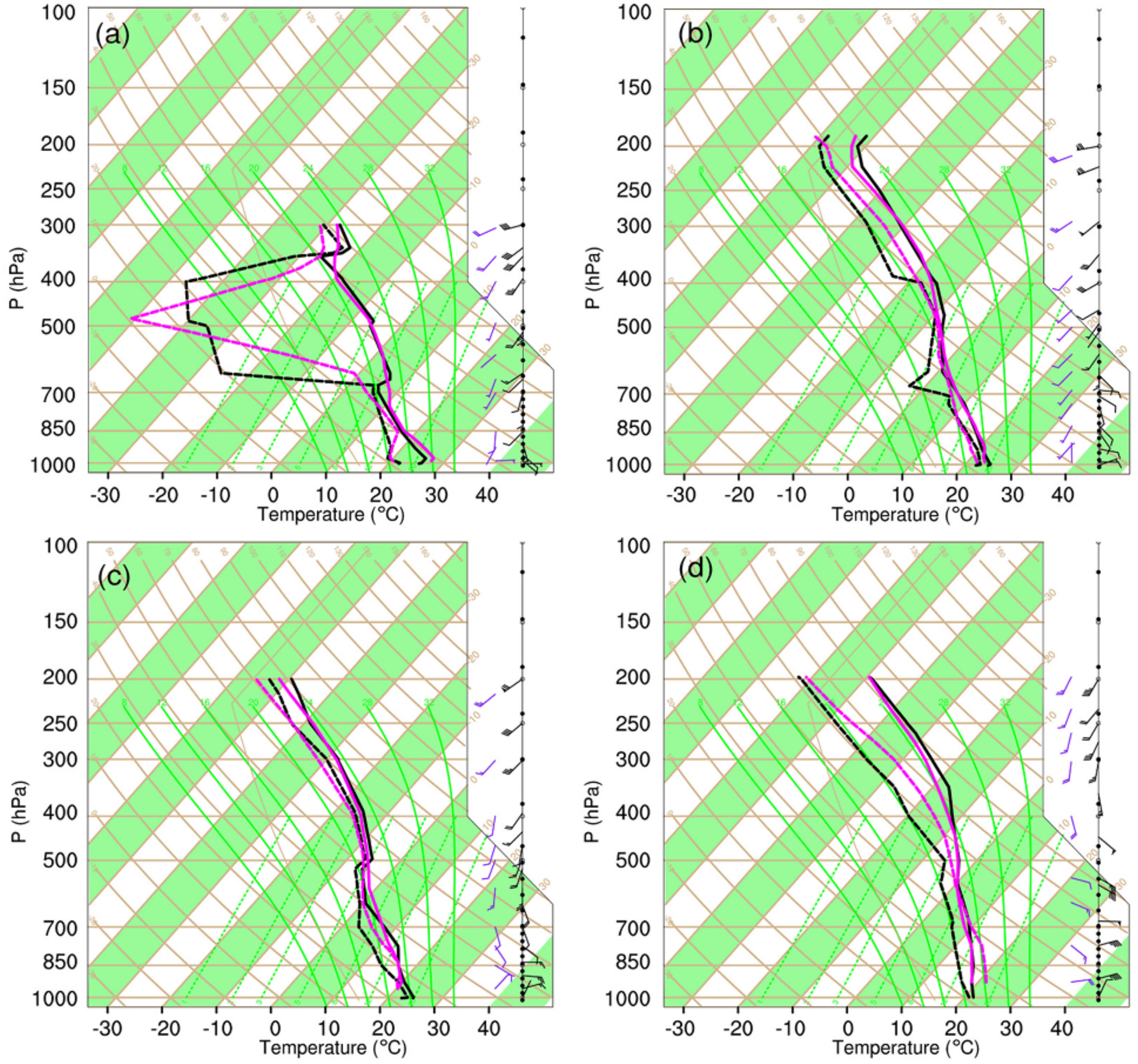


Fig. 2. The Skew-T Log-P diagram for radiosonde (black color) and model (purple color) in Beijing at (a) 2000 BJT on 18 July, (b) 0800 BJT on 19 July, (c) 2000 BJT on 19 July, and (d) 0800 BJT on 20 July. Note the solid and dash lines indicate the profiles of temperature and dew-point temperature. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

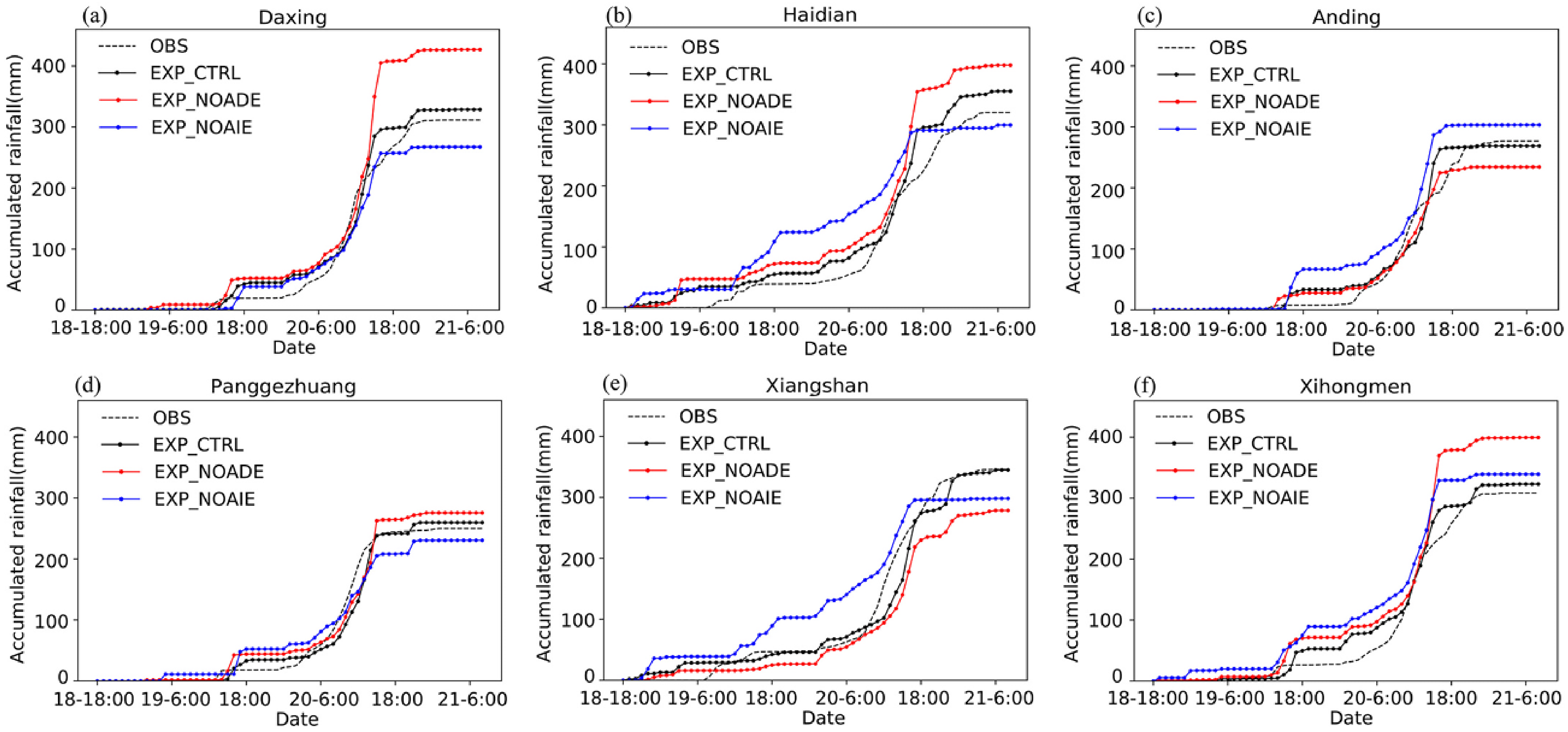


Fig. 4. Comparison of observed (OBS, black dashed lines) and simulated (EXP_CTRL, black solid lines with dots; EXP_NOADE, red solid line with dots; EXP_NOAIE, blue solid line with dots) accumulated rainfall at (a) Daxing, (b) Haidian, (c) Anding, (d) Panggezhuang, (e) Xiangshan and (f) Xihongmen from 1800 BJT on 18 July to 0800 BJT on 21 July 2016. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

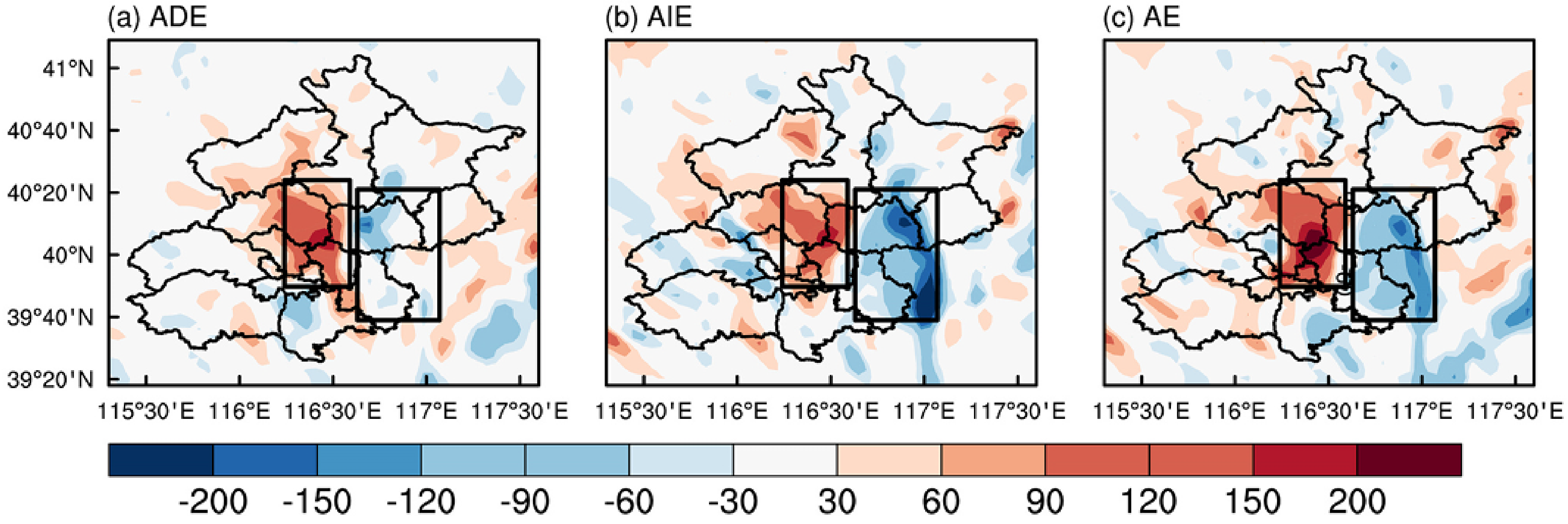


Fig. 6. Horizontal distribution of the change in accumulated rainfall (mm) induced by the (a) ADE, (b) AIE and (c) AE from 1800 BJT on 18 July to 0800 BJT on 21 July 2016. The black boxes represent central (left) part of the Beijing and eastern (right) part of the Beijing, which show large differences.

- ✓ ADE and AIE change the distribution of the accumulated rainfall centers and increase the amount of accumulated rainfall in central part of Beijing, with a maximum value of 200 mm. In eastern part of Beijing, the ADE- and AIE-induced accumulated rainfall decrease by up to 90 and 200 mm, respectively.
- ✓ ADE and AIE have different impacts on the hourly rainfall in tensity in different periods of the rainfall event and in different regions. During 1200–1800 BJT on 19 July, the impacts of the ADE and AIE are the opposite in Beijing, with the ADE-induced hourly rainfall intensity increasing by about 1 mm h^{-1} , whereas AIE-induced hourly rainfall intensity decreases by about 1.4 mm h^{-1} .
- ✓ ADE and AIE affect rainfall through different physical processes.

Numerical analysis of aerosol direct and indirect effects on an extreme rainfall event over Beijing in July 2016, *Atmospheric Research*, 2021

WRF-Chem evaluation: aerosol and cloud effects on solar energy over China

Aerosol concentrations in China gradually decreased during the period of 2016–2020 in association with strict pollutant control measures. WRF-Chem is applied to access aerosol direct effect (ADE), aerosol indirect effect (AIE), and cloud radiation effect (CRE) to solar energy by conducting sensitivity experiments.

Configurations of the

Experiments
EXP_CTRL
EXP_NOADE
EXP_NOAIE
EXP_NOCRE

Eq. (1) was used to calculate the contributions of the ADE, AIE, and CRE to solar energy trends:

$$Relative\ Contribution\ Percent = \frac{\Delta Trend_i}{\sum|\Delta Trend_i|} \times 100\%, \tag{1}$$

where $\Delta Trend_i$ is the change in the solar energy trends due to the ADE, AIE, and CRE. When the relative contribution percent is higher than 0, it represents a positive contribution, which means that the solar trends increase when ADE, AIE or CRE is turned on. When the relative contribution percent is below 0, it represents a negative contribution, which means that the solar trends decrease when ADE, AIE, or CRE is turned on.

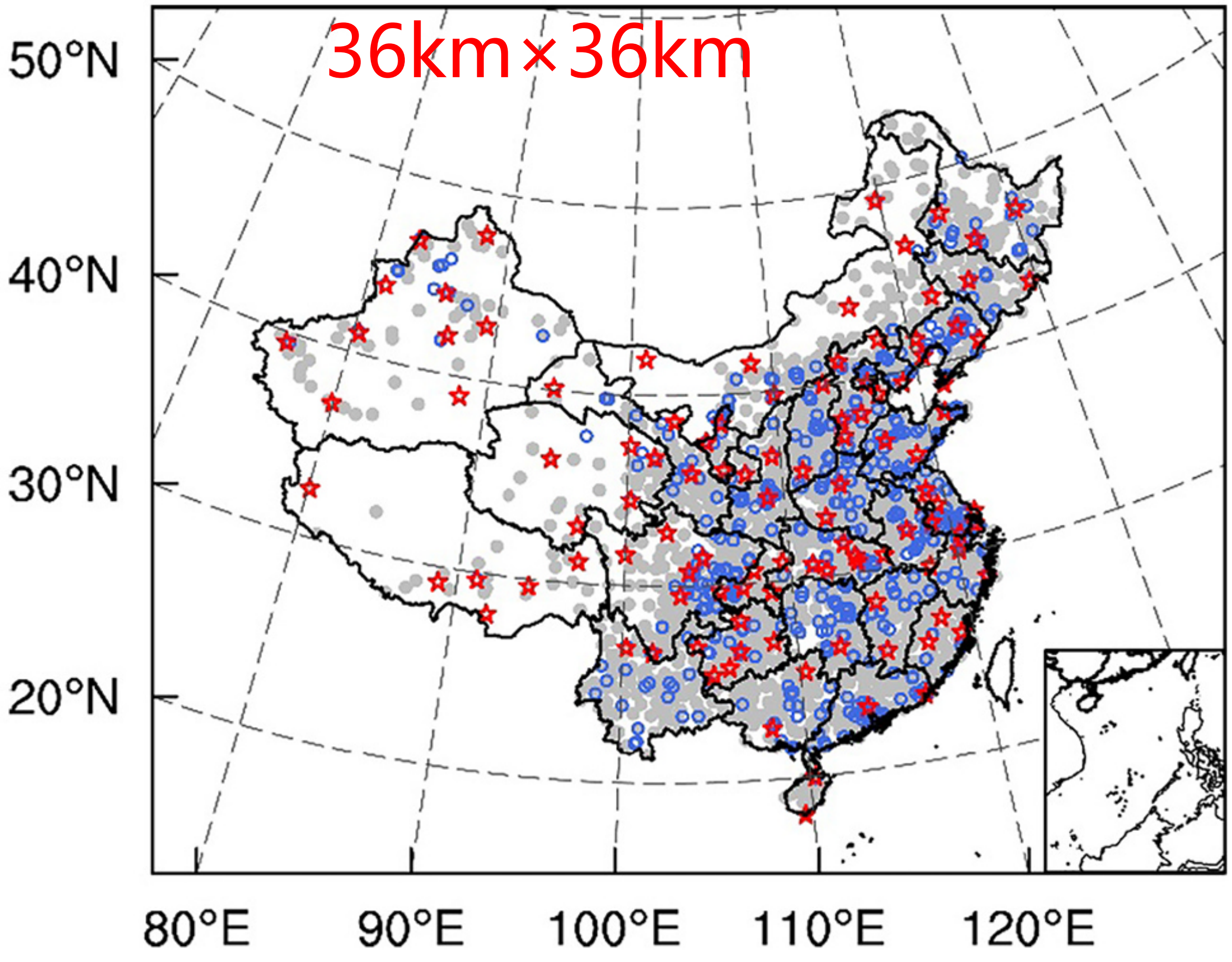


Fig. 1. Model domain and observation station distribution (grey dots are meteorological stations, blue dots are pollution stations, and red pentagrams are radiation stations).

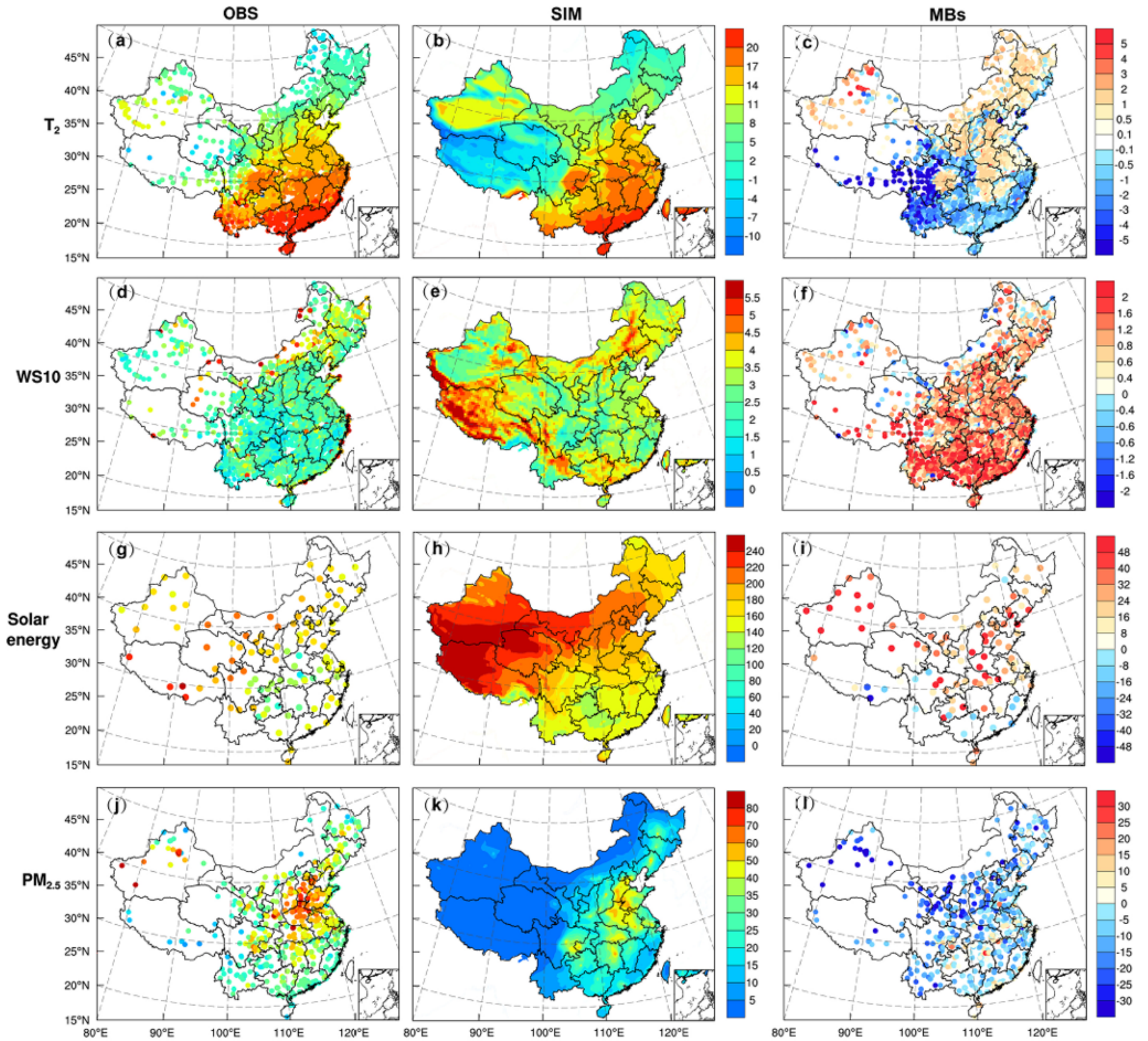
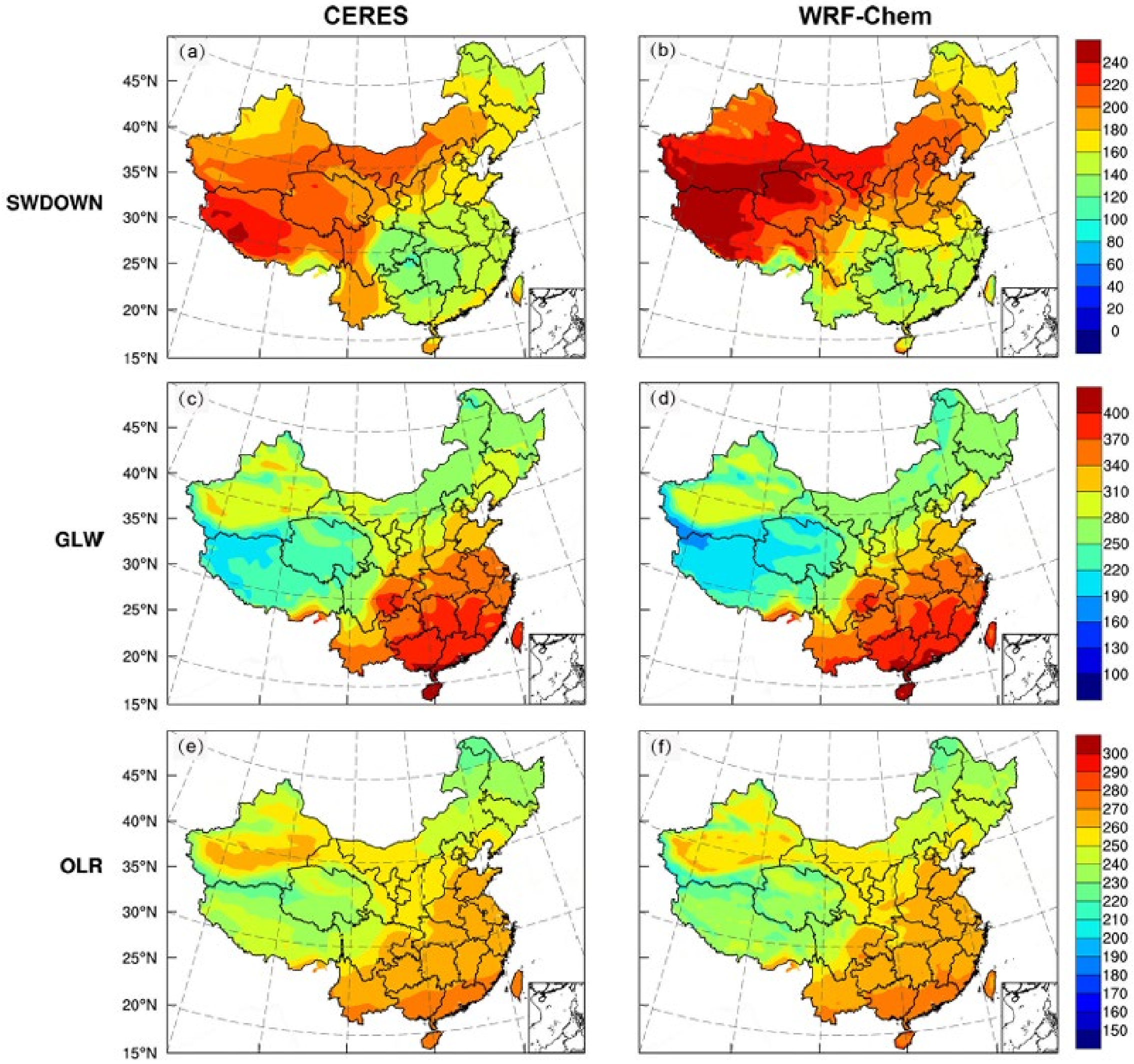
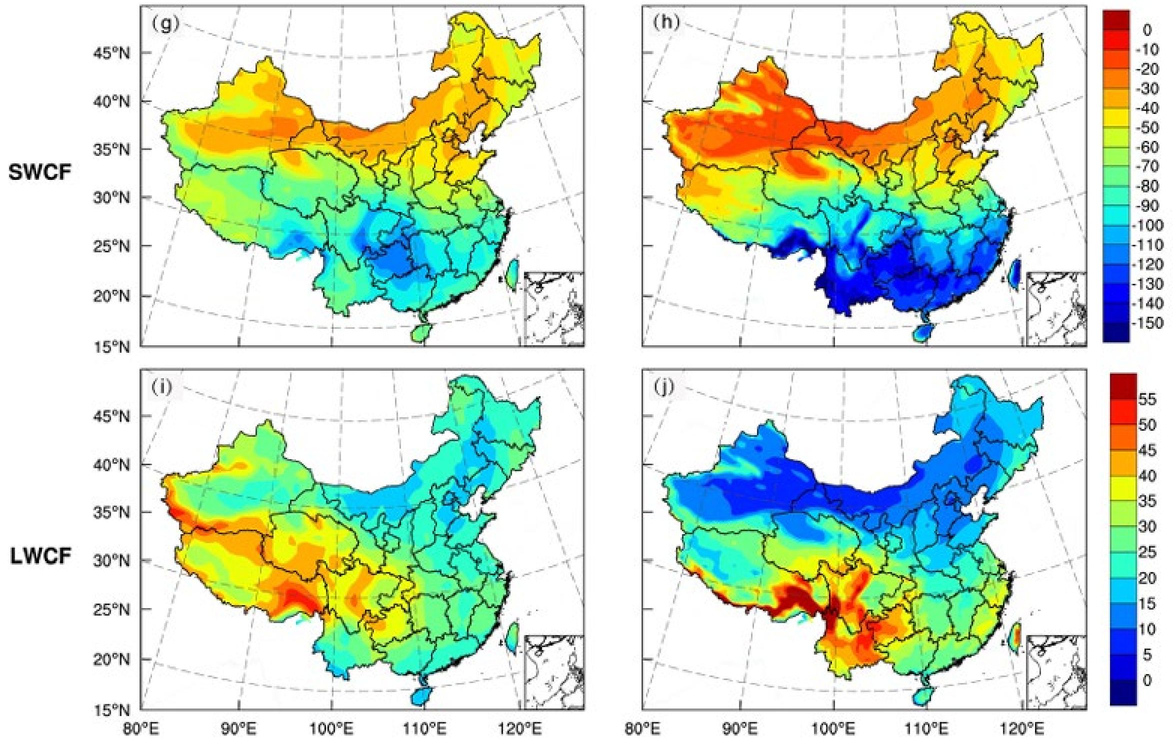


Fig. 2. Spatial distribution of observed (OBS, first column), simulated (SIM, second column) and mean bias between simulation and observation (MBs, third column) for T_2 (°C), WS10 (m s^{-1}), solar energy (W m^{-2}) and $PM_{2.5}$ (μg m^{-3}) at each site in China during 2016–2020.



Horizontal distribution of five-year average downward shortwave radiation at the surface (SWDOWN, W m^{-2}), downward longwave radiation at the surface (GLW, W m^{-2}), outgoing longwave radiation at the top of the atmosphere (OLR, W m^{-2})



Horizontal distribution of five-year average shortwave cloud forcing (SWCF, W m^{-2}) and longwave cloud forcing (LWCF, W m^{-2}) from simulations and CERES satellite observations for 2016–2020.

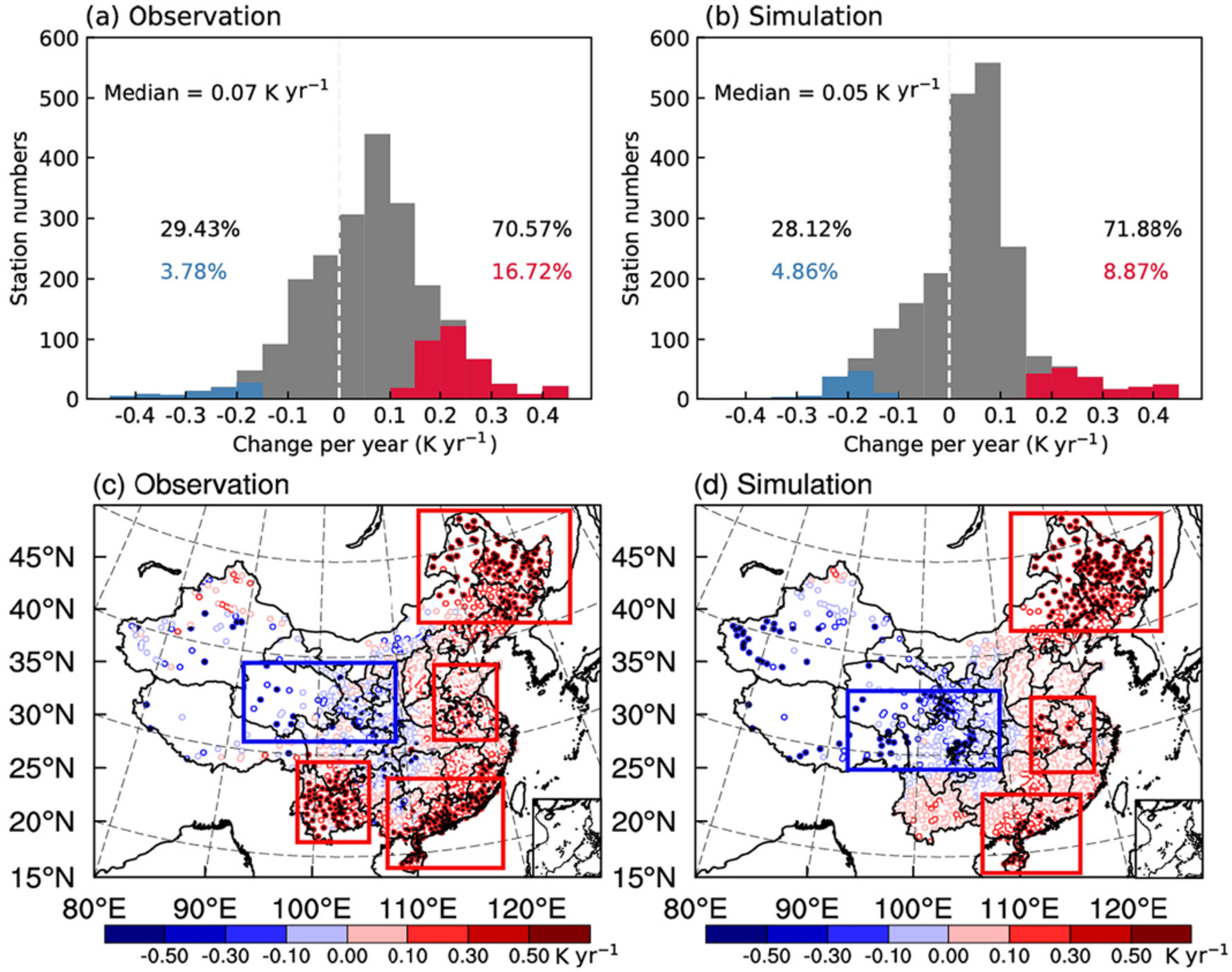


Fig. 5. (a) and (b) Station frequencies and (c) and (d) spatial distribution of observed and modeled T_2 trends (K yr^{-1}) during 2016–2020. The grey color in the upper histograms represents all stations, red represents a significant increasing trends, and blue represents a significant decreasing trends. The median trend is shown in each histogram along with the percentage of sites with increasing/decreasing trends (black) and significant increasing/decreasing trends in increasing/decreasing trends (red or blue). The red circles in the two panels represent an increase, blue circlec represent a decrease, black dots in circles represent significant trends, and white dots in circles represent insignificant trends. Red and blue boxes indicate areas with significant increasing and decreasing trends, respectively.

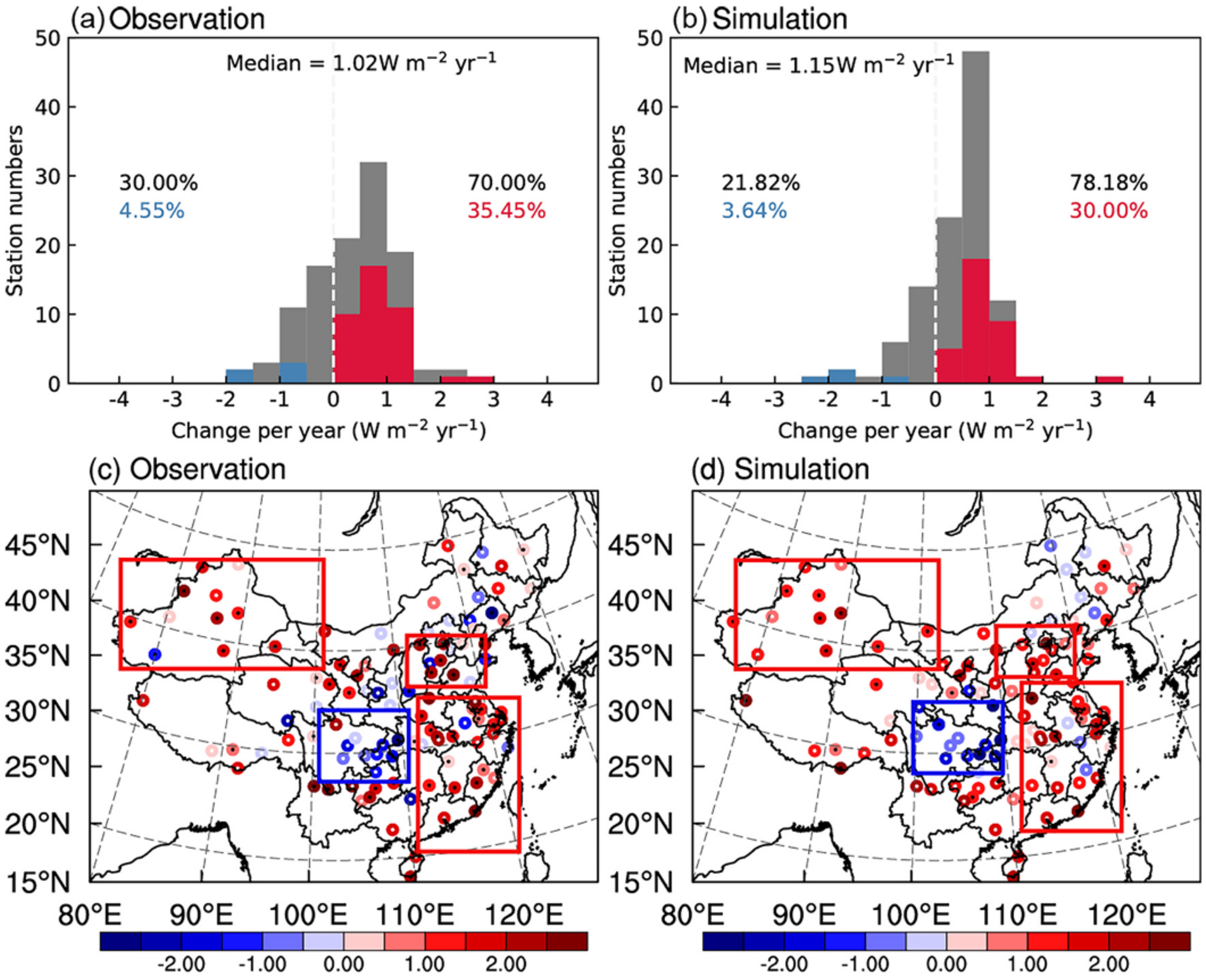


Fig. 8. Same as Fig. 5, but for solar energy (W m^{-2} yr^{-1}).

- ✓ Based on the observations and simulations, the T2 increases at 70.6% and 71.9% of the sites in the period 2016–2020, with a median trend of 0.07 and 0.05 K yr^{-1}, respectively. The WRF-Chem captured significant increases in the T2 in the Northeast China, North China, and Pearl River Delta regions and a significant decrease in the Sichuan Basin.
- ✓ The PM2.5 gradually decreased from 2016 to 2020, with a median trend of 3.24 and 2.24 μg m^3 yr^{-1} for observations and simulations, respectively.
- ✓ ADE, AIE, and CRE differently affect the solar energy in the period 2016–2020 in different regions of China. The ADE positively affects the solar energy in China, with a maximum contribution exceeding 70% in northern China and ~ 60% in several regions of Xinjiang. A positive contribution of the AIE to solar energy trends was mainly observed in Guangxi and the southern Qinghai–Tibet Plateau, with a maximum contribution of 60%. A positive contribution of the CRE to the solar energy was mainly observed in Guangdong, Xinjiang, and Tibet, with maximum contributions of 60%, 70%, and 80%, respectively.

Quantification of aerosol and cloud effects on solar energy over China using WRF-Chem, *Atmospheric Research*, 2024

WRF-Chem application: future solar energy potential changes under the shared socio-economic pathways scenario 2–4.5

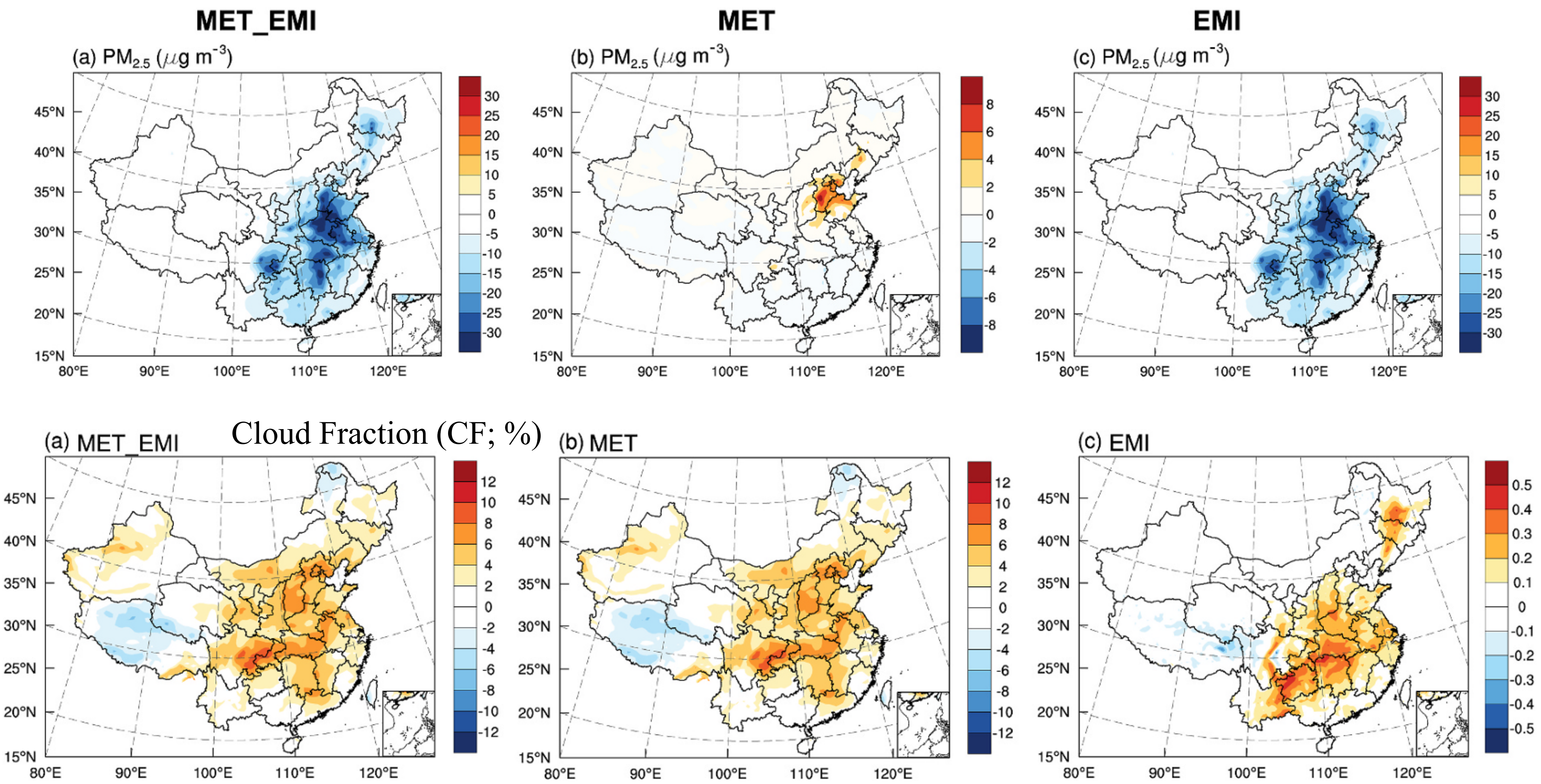
current (2016–2020) + future (2046–2050) under SSP 2–4.5

✓ CMIP6
✓ Dynamic Projection model for Emissions in China (DPEC) emissions

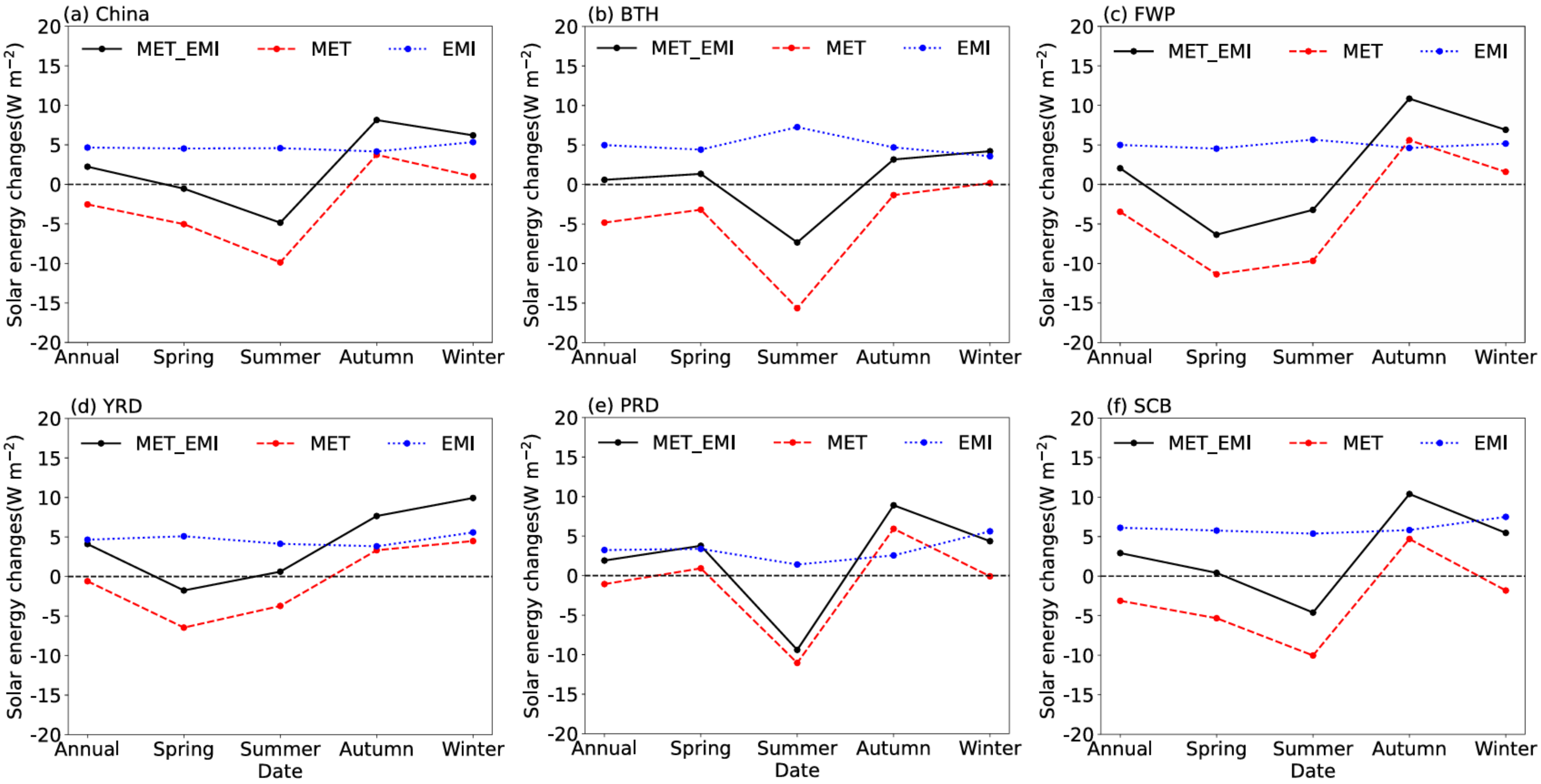
Numerical experimental design.

	Experiments	Meteorology	Anthropogenic emissions
1	CuMet_CuEmi	Current	Current
2	FuMet_CuEmi	Future	Current
3	CuMet_FuEmi	Current	Future
4	FuMet_FuEmi	Future	Future

Impacts of meteorology and emission on solar energy potential



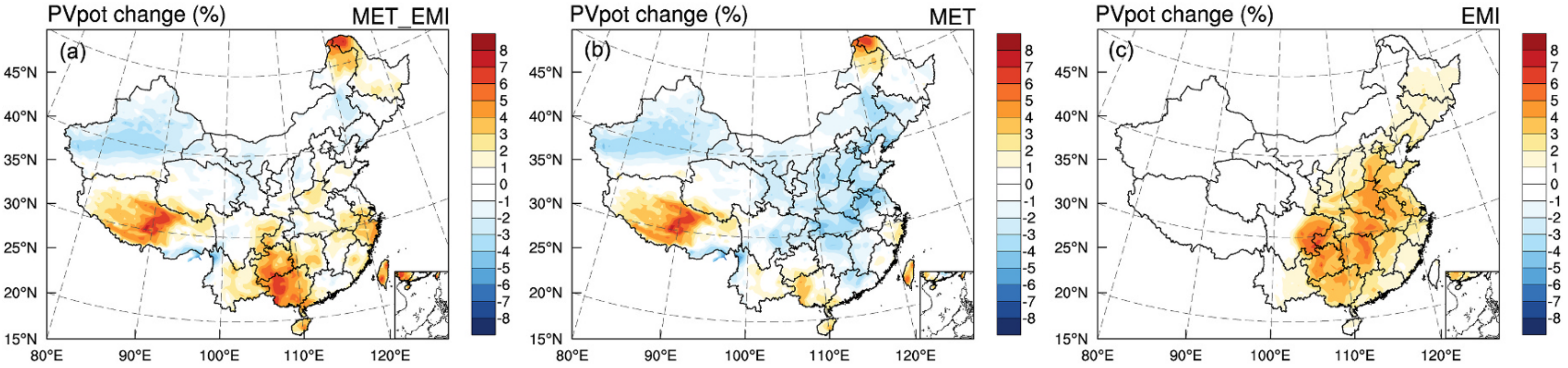
MET_EMI
MET
EMI
(a) $PM_{2.5}$ ($\mu g\ m^{-3}$)
(b) $PM_{2.5}$ ($\mu g\ m^{-3}$)
(c) $PM_{2.5}$ ($\mu g\ m^{-3}$)
Cloud Fraction (CF; %)
(a) MET_EMI
(b) MET
(c) EMI



Effects of future meteorological conditions and emission reduction on annual and seasonal mean solar energy (W m^{-2})

Correlation of future meteorological (R_MET) and emission reduction (R_EMI) induced surface solar energy changes with combination of meteorological and emission reduction induced solar energy changes in different regions of China.

R	China	BTH	FWP	YRD	PRD	SCB
R_MET	0.99	0.98	0.98	0.98	0.99	0.99
R_EMI	0.07	0.08	0.17	0.11	0.22	0.22



- Future annual average solar energy increases by 2.2, 0.1, 2, 4.1, 1.9, and 2.9 W m^{-2} for China, Beijing-Tianjin-Hebei, Fenwei Plain, Yangtze River Delta, Pearl River Delta, and Sichuan Basin, respectively.
- Future annual average photovoltaic potential increase by 1–4% in these regions. This increase is primarily attributed to the increase in solar energy resulting from emission reductions (4.7, 5.1, 5.0, 4.7, 3.2, and 6.1 W m^{-2}), which outweighs the decrease caused by meteorological conditions (2.5, 5.0, 2.0, 4.1, 1.9, and 2.9 W m^{-2})

Assessment of future solar energy potential changes under the shared socio-economic pathways scenario 2–4.5 with WRF-chem: The roles of meteorology and emission, *Atmospheric Environment*, 2024


Thanks for your attention!