Supplementary Information to "Meteorologocal Change and Impacts on Air Pollution – Results from North China"

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A Economic and Energy Statistics

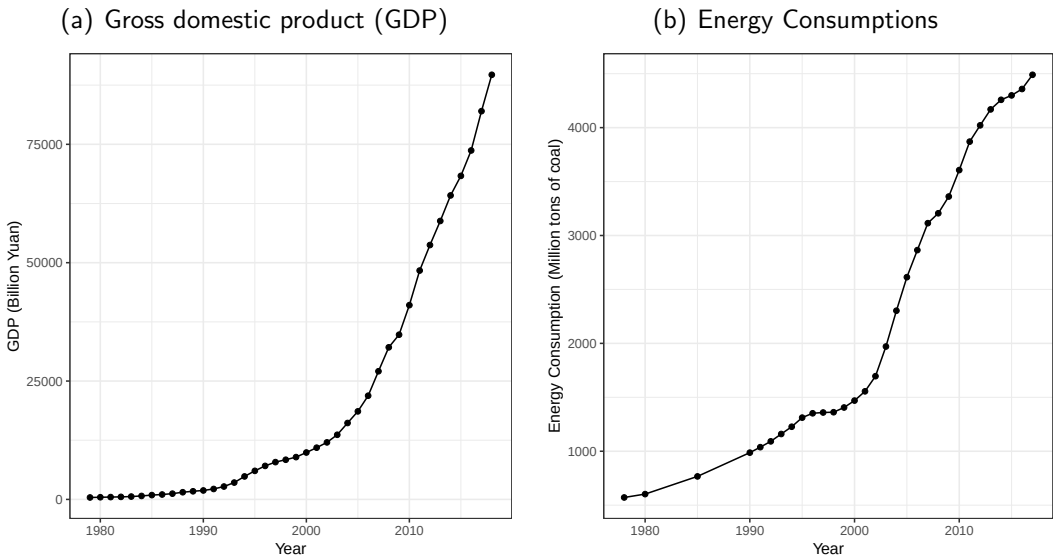


Figure S1: Chinese economic growth in terms of the gross domestic product (in billion Yuan) and national energy consumptions (in million tons of coal) from 1978 to 2017.

B Boundary Layer Height Distribution

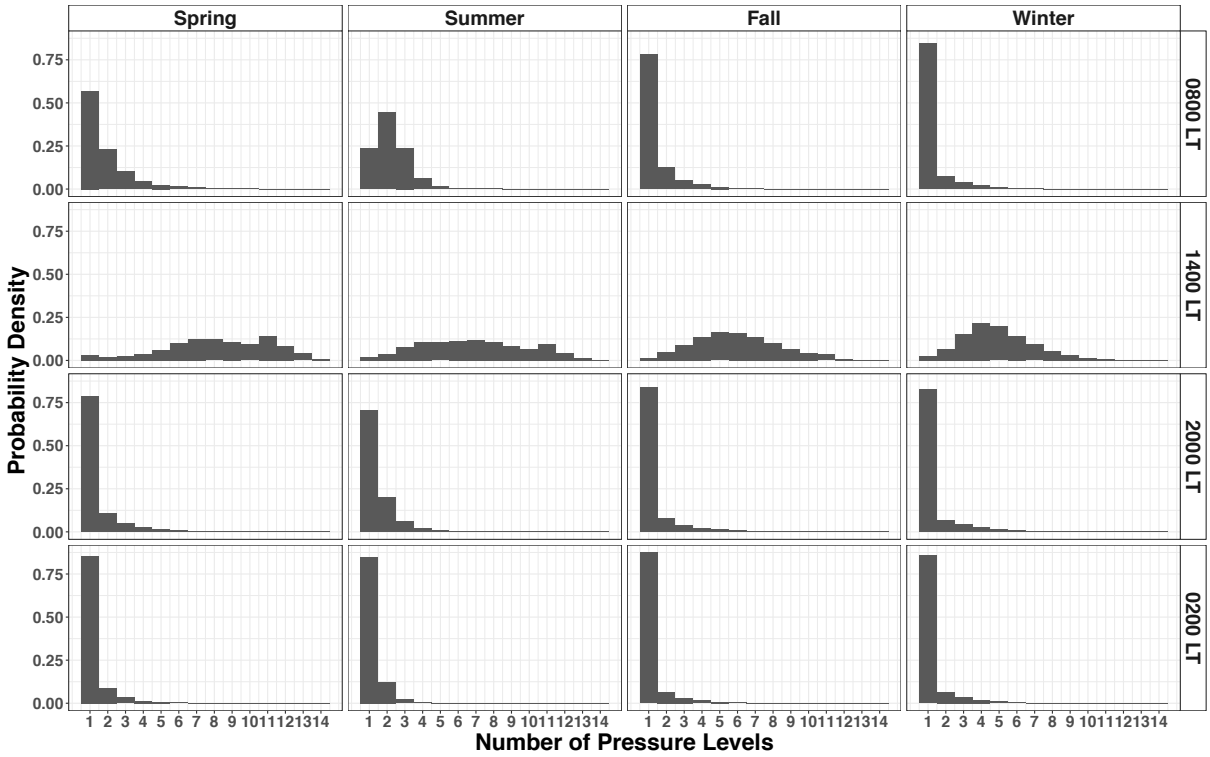
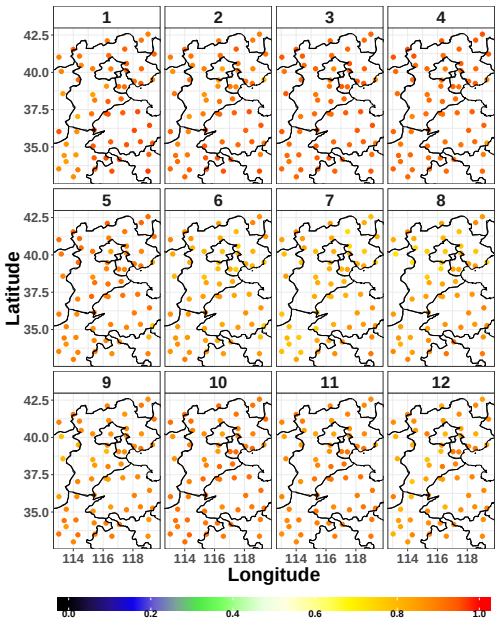


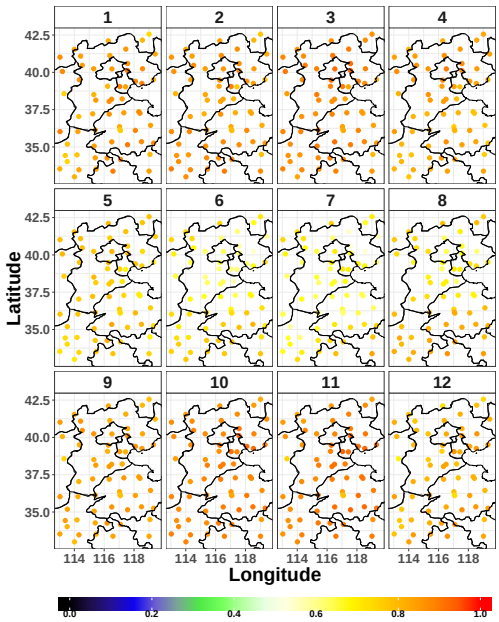
Figure S2: Histograms for the number of pressure layers at the four observation hour and the four seasons: Spring: March to May, Summer: June to August, Fall: September to November and Winter: December to February, based on BLH data at the 261 grids in the study region.

C Correlations between assimilated data and site observations

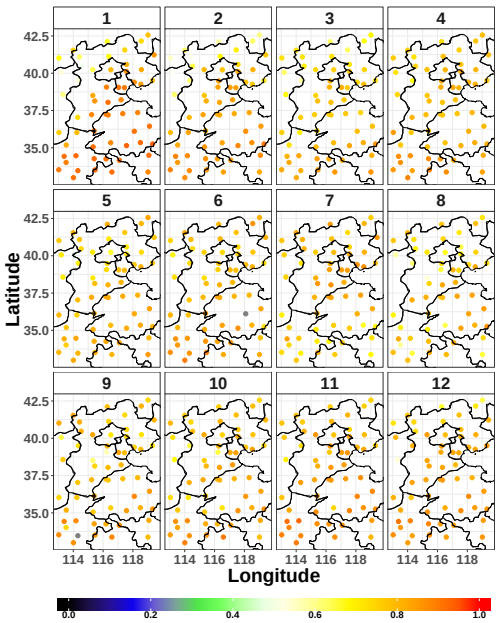
(a) T2M (ECMWF and CMA)



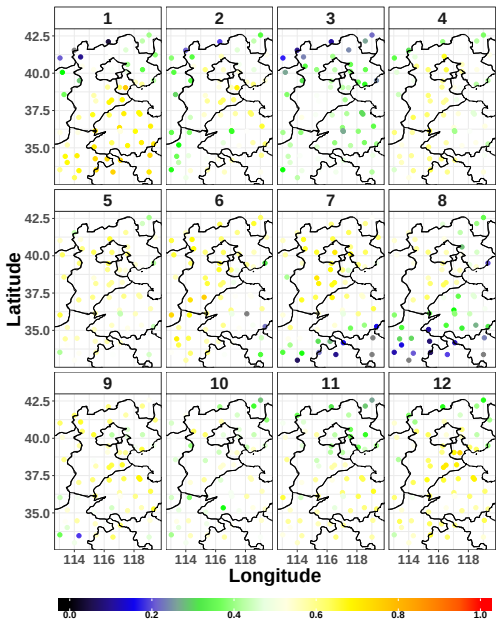
(b) T2M (MERRA2 and CMA)



(c) RH (ECMWF and CMA)



(d) RH (MERRA2 and CMA)



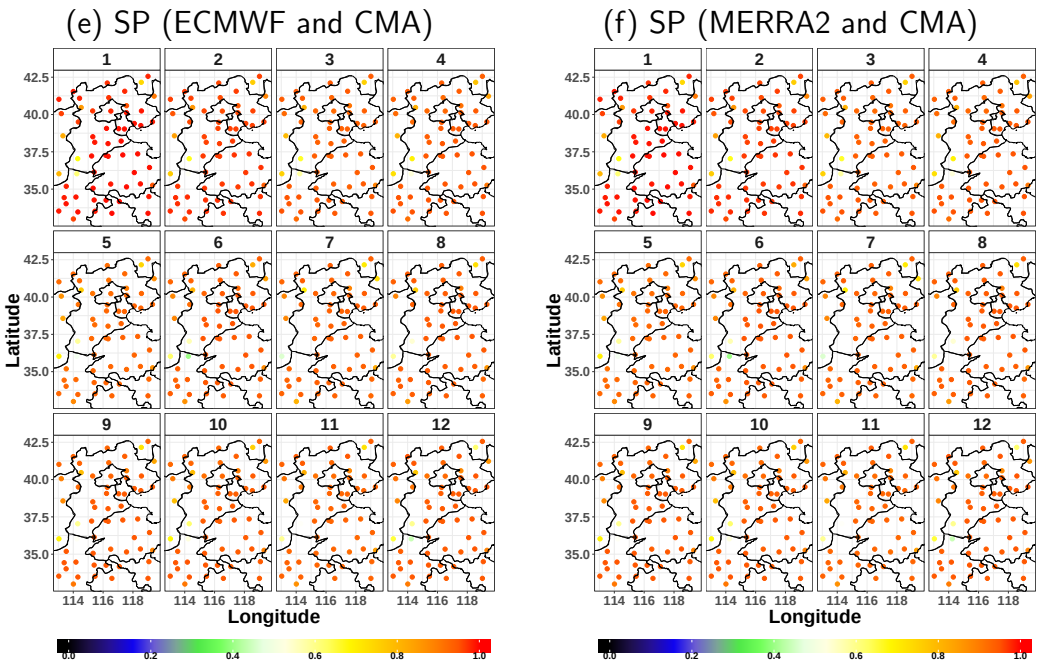


Figure S3: Correlation coefficients in T2M ((a) and (b)) , RH ((c) and (d)) and SP ((e) and (f)) between ECMWF and China Meteorological Agency site data (CMA) and between MERRA2 and CMA, respectively.

Table S1: Monthly average correlation coefficients over all the grids between between ECMWF and CMA in (a) and MERRA2 and CMA site data in (b). The "Avg" denotes averages over the 12 months.

(a) ECMWF and CMA

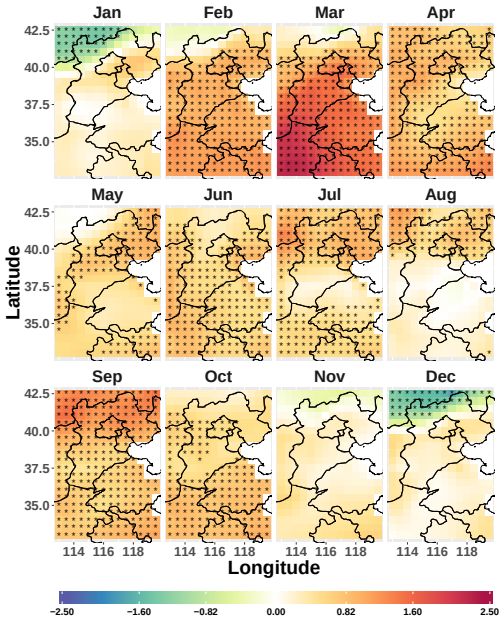
Month	SP	T2M	RH
1	0.965	0.915	0.829
2	0.947	0.911	0.786
3	0.916	0.930	0.763
4	0.918	0.924	0.800
5	0.898	0.892	0.785
6	0.911	0.834	0.784
7	0.908	0.818	0.783
8	0.916	0.832	0.748
9	0.911	0.874	0.777
10	0.909	0.903	0.799
11	0.905	0.886	0.826
12	0.909	0.856	0.815
Avg	0.918	0.881	0.791

(b) MERRA2 and CMA

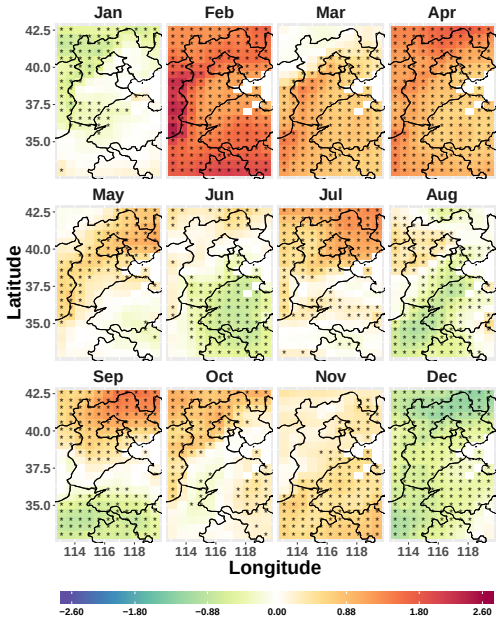
Month	SP	T2M	RH
1	0.943	0.841	0.562
2	0.948	0.848	0.493
3	0.946	0.874	0.387
4	0.944	0.826	0.531
5	0.943	0.763	0.546
6	0.946	0.691	0.567
7	0.939	0.672	0.502
8	0.953	0.749	0.397
9	0.950	0.831	0.557
10	0.946	0.881	0.492
11	0.937	0.883	0.512
12	0.944	0.808	0.571
Avg	0.945	0.806	0.510

D Comparison between ECMWF and MERRA2

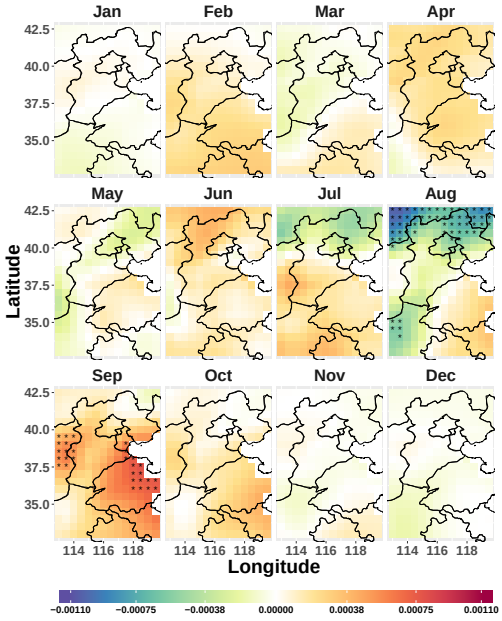
(a) T2M ECMWF



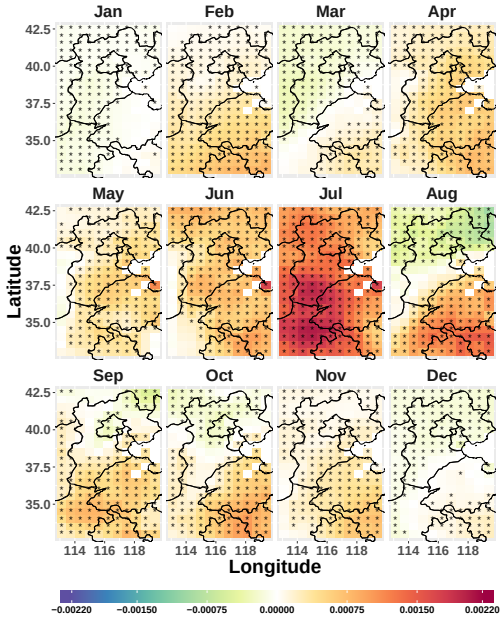
(b) T2M MERRA2



(c) SH ECMWF



(d) SH MERRA2



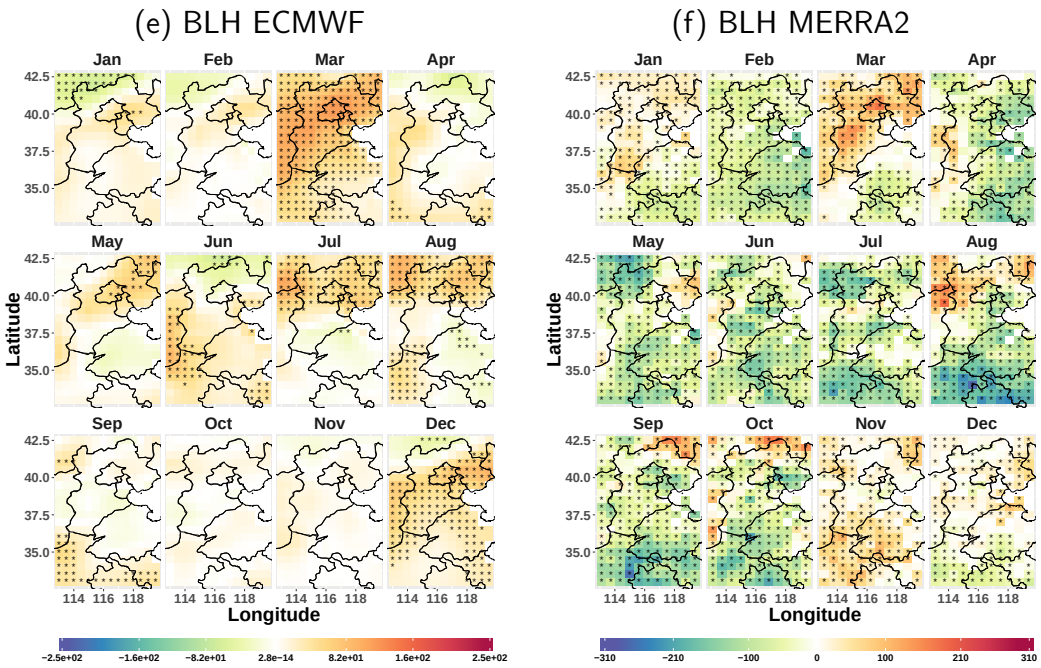


Figure S4: Comparisons of average changes for the 2-meter temperature (a and b), specific humidity (c and d) and boundary layer height (e and f) estimated using assimilated data from ECMWF and MERRA2, respectively, for the twelve months at the 261 grids between the two 19-year periods. Redness (blueness) indicate increase (decrease) in the variable while stars mark significance changes after controlling the FDR at 5%. Black lines mark the provincial borders.

E Air Quality Monitoring Sites Overlaid with the Grids

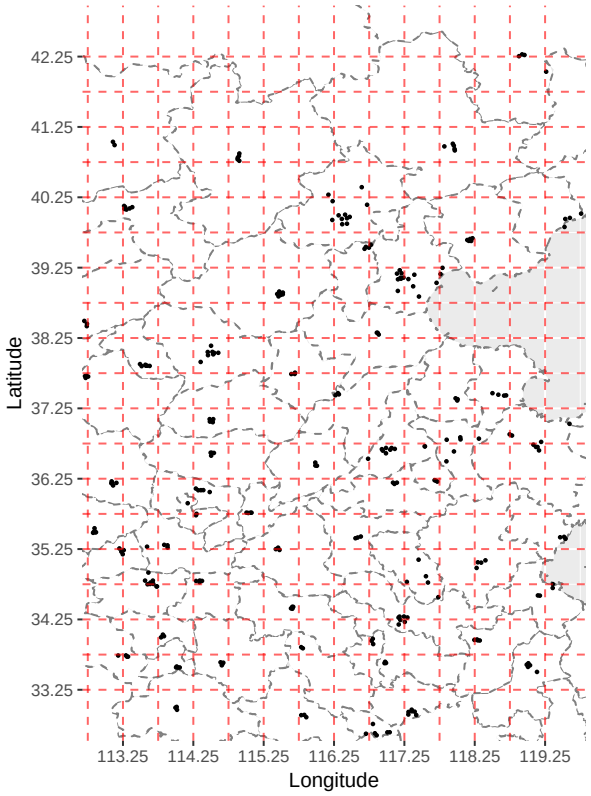
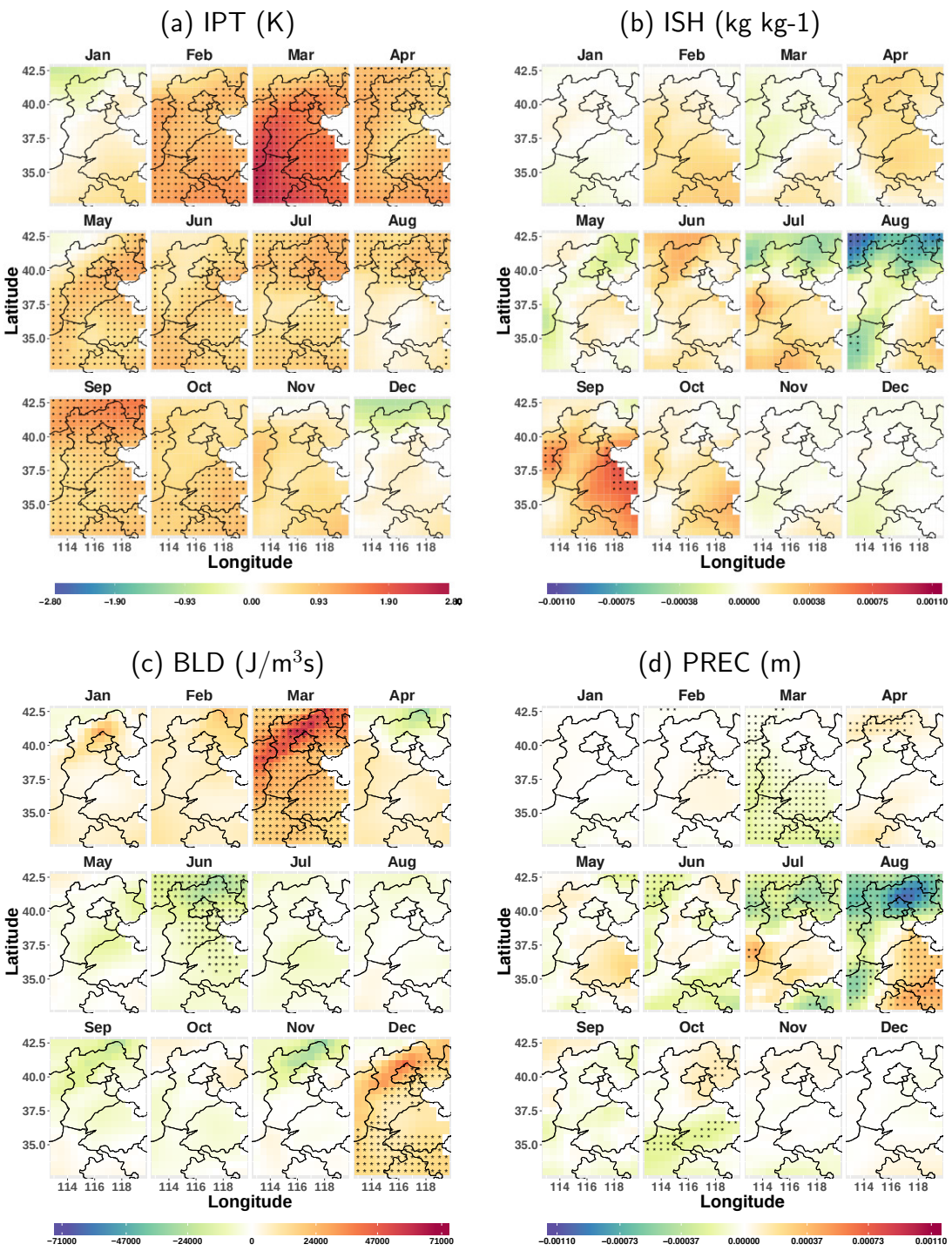


Figure S5: Locations of the Guokong observation stations (black points) over the study area, and the grids they belong to. Crossing points of red dashed lines are the grid points with renanlysis data from ECMWF.

F Extra Testing Results for Climate Change



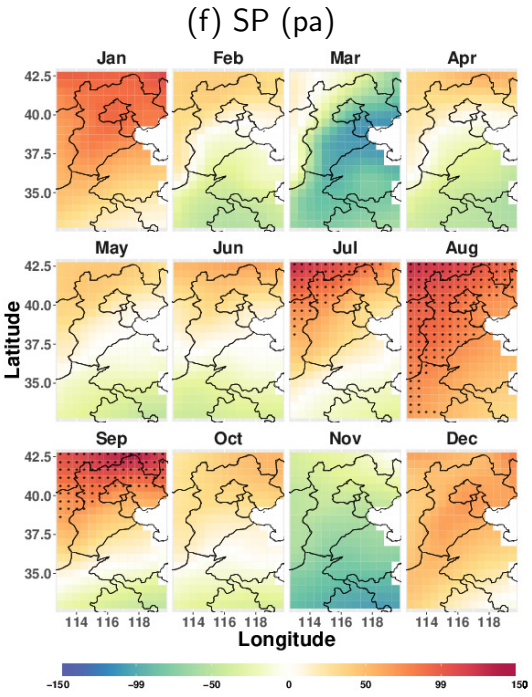


Figure S6: Average changes between two 19-year periods for the integrated potential temperature (Kelvin) (a), integrated specific humidity (kg kg^{-1}) (b), boundary layer dissipation (BLD in J/m^{3}s) (c), total precipitation (d) and surface pressure (hpa) (e) for the twelve months at the 261 grids between the two time periods. Redness (blueness) indicate increase (decrease) in the variable while stars mark significance change by controlling the FDR at 5%. Black lines mark the provincial borders.

G Comparisons between D2M, IRH, ISH, IPT

Table S2: Estimated regression coefficients of Model (6) and their statistical significance that replaces D2M with IRH as covariate in two heating seasons.

(a) November 15th 2014 to March 15th 2015

	Beijing	Dezhou	Handan	Jinan	SJZ	Zhengzhou
SP	-0.14***	-0.07**	-0.065.	-0.12***	-0.201***	0.14***
T2M	0.05**	0.19***	0.158***	0.14***	0.008	0.15***
IRH	0.1***	0.14***	0.157***	0.08***	0.067***	0.05***
LogBLD	-0.04**	-0.09***	0.001	-0.04**	-0.012	-0.02
LogBLH	-0.22***	-0.18***	-0.088**	-0.28***	-0.205***	-0.21***
INW	-0.06**	-0.1**	0.021	-0.11***	-0.129***	0.03
INE	0.05***	0.12***	0.075**	0.08***	-0.07***	-0.05**
ISW	0.14***	0.03	0.044*	0.13***	0.065***	0.06***
ISE	0.1***	0.08***	0.063***	0.04***	0.004	-0.01
Lagged Y	0.63***	0.51***	0.478***	0.65***	0.547***	0.61***
R^2	0.580	0.473	0.335	0.590	0.583	0.542

(b) November 15th 2015 to March 15th 2016

SP	-0.088***	-0.04*	-0.005	-0.0246*	-0.187***	0.11***
T2M	0.002	0.04.	0.078**	0.0501***	-0.009	0.09***
IRH	0.04***	0.08***	0.061**	0.034**	-0.018	0.03*
LogBLD	-0.02.	-0.05*	-0.035.	-0.0026	0.075***	-0.01
LogBLH	-0.226***	-0.05*	-0.093***	-0.2452***	-0.295***	-0.23***
INW	0.012	-0.14***	-0.173***	0.0128	-0.159***	-0.05*
INE	0.033**	-0.11**	-0.107***	0.0066	-0.062***	-0.04**
ISW	0.083***	-0.09***	-0.079***	0.0436***	0.07***	0.02
ISE	0.042***	-0.02	-0.037**	-9e-04	0.023*	-0.1***
Lagged Y	0.693***	0.68***	0.671***	0.7275***	0.607***	0.62***
R^2	0.643	0.690	0.667	0.6874	0.660	0.62

Note: *p<0.05; **p<0.01; ***p<0.001

Table S3: Estimated regression coefficients of Model (6) and their statistical significance with D2M as covariate in two heating seasons.

(a) November 15th 2014 to March 15th 2015

	Beijing	Dezhou	Handan	Jinan	SJZ	Zhengzhou
SP	-0.060***	-0.093***	-0.051**	-0.055**	-0.015	-0.006
T2M	0.115***	0.000	-0.089**	0.014	-0.062**	0.077***
D2M	0.070***	0.182***	0.109***	0.254***	0.029.	0.060***
LogBLD	-0.065***	-0.099***	-0.121***	-0.076***	0.002	0.036**
LogBLH	-0.241***	-0.257***	-0.012	-0.162***	-0.195***	-0.119***
INW	-0.032 *	0.111**	-0.111**	0.147***	-0.210***	-0.155***
INE	-0.062***	0.139***	-0.018	0.133***	-0.031.	-0.022*
ISW	0.069***	0.066 **	-0.085**	0.048 **	0.074***	-0.095***
ISE	0.053***	0.0399*	-0.010	0.067***	0.028 *	-0.059***
Lagged Y	0.563***	0.495***	0.550***	0.512***	0.547***	0.691***
R^2	0.635	0.559	0.433	0.507	0.580	0.613

(b) November 15th 2015 to March 15th 2016

SP	-0.056***	-0.064 *	-0.062**	-0.033 *	0.014	-0.015.
T2M	0.109***	-0.146***	-0.162***	-0.048 **	-0.021	-0.040 *
D2M	0.047**	0.175***	0.150***	0.117***	0.080***	0.070***
LogBLD	-0.061***	-0.095***	0.035.	-0.060***	0.050***	-0.001
LogBLH	-0.194***	-0.124***	-0.041.	-0.077***	-0.235***	-0.051***
INW	-0.051**	0.018	-0.372***	-0.106***	-0.238***	-0.192***
INE	-0.030**	-0.056*	-0.105***	-0.094***	-0.087***	-0.110***
ISW	0.048***	0.033	-0.131***	-0.064***	0.015	-0.078***
ISE	-0.002	0.025.	-0.113***	-0.015	-0.025***	-0.066***
Lagged Y	0.610***	0.633***	0.569***	0.694***	0.551***	0.767***
R^2	0.703	0.666	0.624	0.707	0.635	0.739

Note: *p<0.05; **p<0.01; ***p<0.001

Table S4: Estimated regression coefficients of Model (6) and their statistical significance that replaces ISH with D2M as covariate in two heating seasons.

(a) November 15th 2014 to March 15th 2015

	Beijing	Dezhou	Handan	Jinan	Shijiazhuang	Zhengzhou
SP	-0.12***	-0.08**	-0.047	-0.12***	-0.201***	0.14***
T2M	-0.04*	0.11**	0.007	0.08**	-0.064***	0.12***
ISH	0.13***	0.12***	0.158***	0.08***	0.108***	0.05***
LogBLD	-0.05***	-0.11***	-0.01	-0.04**	-0.014	-0.02
LogBLH	-0.21***	-0.18***	-0.084**	-0.28***	-0.197***	-0.21***
INW	0.06***	0.09**	0.016	0.11***	-0.134***	0.03
INE	0.05***	0.13***	0.073**	0.08***	-0.072***	-0.05***
ISW	0.14***	0.03	0.043*	0.13***	0.062***	0.06***
ISE	0.1***	0.08***	0.065***	0.04**	0.004	-0.01
Lagged Y	0.63***	0.53***	0.484***	0.65***	0.545***	0.61***
R^2	0.591	0.473	0.332	0.597	0.593	0.545

(b) November 15th 2015 to March 15th 2016

SP	-0.08***	-0.03	-0.003	-0.018	-0.189***	0.11***
T2M	-0.04*	-0.02	0.017	0.013	-0.006	0.08***
ISH	0.07***	0.1***	0.073***	0.054***	-0.004	0.03
LogBLD	-0.02	-0.06**	-0.037*	-0.002	0.077***	-0.01
LogBLH	-0.22***	-0.05*	-0.095***	-0.243***	-0.287***	-0.24***
INW	0.01	-0.15***	-0.174***	0.013	-0.159***	-0.05*
INE	0.03*	-0.11***	-0.107***	0.004	-0.066***	-0.03*
ISW	0.08***	-0.08***	-0.078***	0.043***	0.068***	0.02
ISE	0.04***	-0.03	-0.039**	-0.002	0.023*	-0.09***
Lagged Y	0.69***	0.69***	0.672***	0.728***	0.606***	0.62***
R^2	0.646	0.691	0.672	0.694	0.663	0.622

Note: *p<0.05; **p<0.01; ***p<0.001

Table S5: Estimated regression coefficients of Model (6) and their statistical significance that replaces T2M with IPT as covariates in two heating seasons.

(a) November 15th 2014 to March 15th 2015

	Beijing	Dezhou	Handan	Jinan	Shijiazhuang	Zhengzhou
SP	-0.18***	-0.04.	-0.1051**	-0.11***	-0.2089***	0.175***
IPT	-0.06***	0.04	-0.0241	0.03.	-0.0373*	0.122***
D2M	0.15***	0.27***	0.26***	0.15***	0.0805***	0.06***
LogBLD	-0.04**	-0.07**	5e-04	-0.03*	-0.0085	-0.02
LogBLH	-0.23***	-0.12***	-0.0991***	-0.25***	-0.2287***	-0.153***
INW	0.07***	0.14***	0.0672*	0.12***	-0.1197***	0.007
INE	0.05***	0.12***	0.0849***	0.08***	-0.0708***	-0.052***
ISW	0.14***	0.03	0.0561**	0.13***	0.0621***	0.052**
ISE	0.1***	0.05*	0.0501**	0.03**	8e-04	-0.017
Lagged Y	0.63***	0.49***	0.4653***	0.63***	0.5511***	0.6***
R^2	0.586	0.490	0.337	0.593	0.582	0.534

(b) November 15th 2015 to March 15th 2016

SP	-0.12***	-0.05*	-0.008	-0.026*	-0.19***	0.13***
IPT	-0.06***	-0.07*	0.002	-0.0079	-0.011	0.08***
D2M	0.1***	0.13***	0.078**	0.0768***	0.004	0.04*
LogBLD	-0.02.	-0.06**	-0.038*	7e-04	0.078***	-0.01
LogBLH	-0.24***	-0.07***	-0.094***	-0.2403***	-0.289***	-0.2***
INW	0.03*	-0.12***	-0.167***	0.0172	-0.156***	-0.06*
INE	0.03*	-0.11**	-0.105***	4e-04	-0.067***	-0.04**
ISW	0.09***	-0.07***	-0.077**	0.0432***	0.069***	0.02
ISE	0.04***	-0.02	-0.037*	-0.0036	0.024*	-0.1***
Lagged Y	0.69***	0.68***	0.675***	0.7248***	0.606***	0.62***
R^2	0.651	0.690	0.677	0.693	0.661	0.623

Note: *p<0.05; **p<0.01; ***p<0.001

Table S6: Comparison of R^2 between Model (6) (Original) and those which replace D2M with RH or ISH, and that replaces T2M with IPT, respectively, in the six cities.

	Year	Beijing	Dezhou	Handan	Jinan	SJZ	Zhengzhou	Average
Original	2015	0.64	0.56	0.43	0.51	0.58	0.61	0.56
	2016	0.70	0.67	0.62	0.71	0.64	0.74	0.68
RH	2015	0.58	0.47	0.34	0.59	0.58	0.54	0.52
	2016	0.64	0.69	0.68	0.69	0.66	0.62	0.66
ISH	2015	0.59	0.47	0.33	0.59	0.59	0.54	0.52
	2016	0.64	0.69	0.67	0.69	0.66	0.62	0.66
IPT	2015	0.59	0.49	0.34	0.59	0.58	0.53	0.52
	2016	0.65	0.69	0.67	0.69	0.66	0.62	0.66

H Pairwise Scattered Plots and Fitted Regression Lines

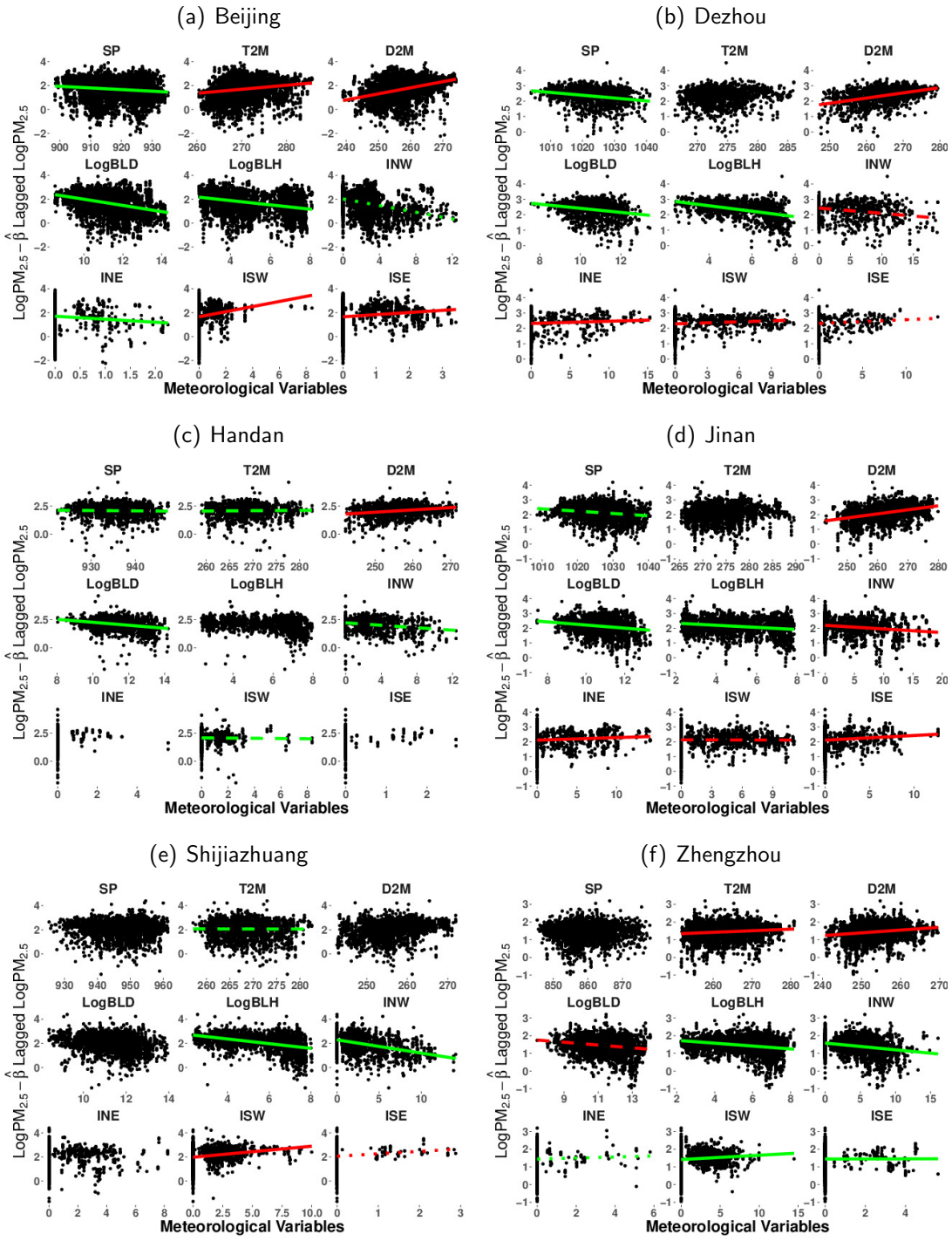


Figure S7: Pairwise scattered plots between $\text{LogPM}_{2.5}$ - $\hat{\beta}$ Lagged $\text{LogPM}_{2.5}$ and the nine meteorological variables for the six cities with the fitted lines for those significant climate variables shown in Table 1 based on data are from November 15th 2014 to March 15th, 2015. Here, $\hat{\beta}$ denotes the estimated coefficient to the lagged $\text{PM}_{2.5}$ term. Red (Green) lines indicates significant positive (negative) effects with dotted, dashed and solid lines for significance with p-values less than 0.05, 0.01 and 0.001 respectively.

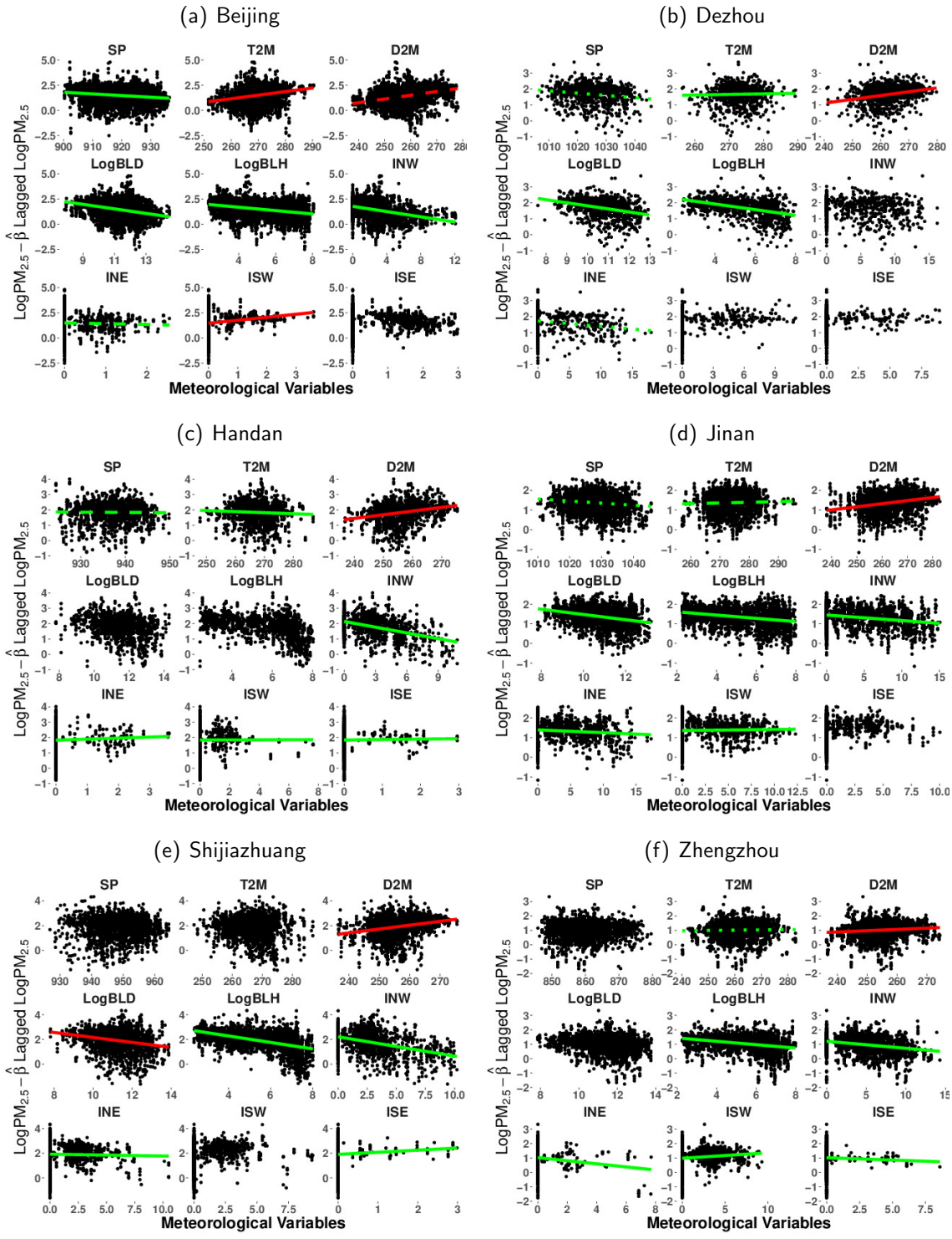


Figure S8: Pairwise scattered plots between $\text{LogPM}_{2.5}$ - $\hat{\beta}$ Lagged $\text{LogPM}_{2.5}$ and the nine meteorological variables for the six cities with the fitted lines for those significant climate variables shown in Table 1 based on data are from November 15th 2015 to March 15th, 2016. Here, $\hat{\beta}$ denotes the estimated coefficient to the lagged $\text{PM}_{2.5}$ term. Red (Green) lines indicates significant positive (negative) effects with dotted, dashed and solid lines for significance with p-values less than 0.05, 0.01 and 0.001 respectively.

I Absolute Climate Change Effects for Significant Cities

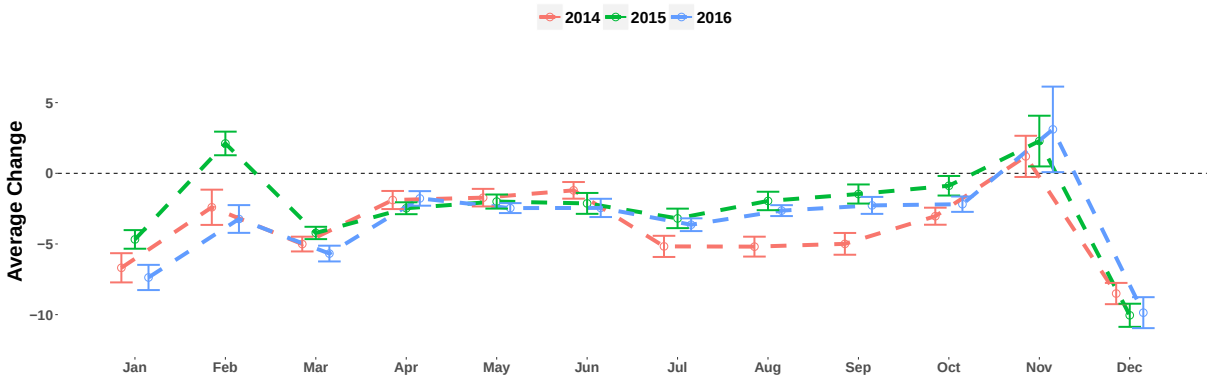


Figure S9: Absolute average $PM_{2.5}$ changes in the cities with significant climate change effects. The error bars are 95% confidence.

J Monthly averaged time series plots

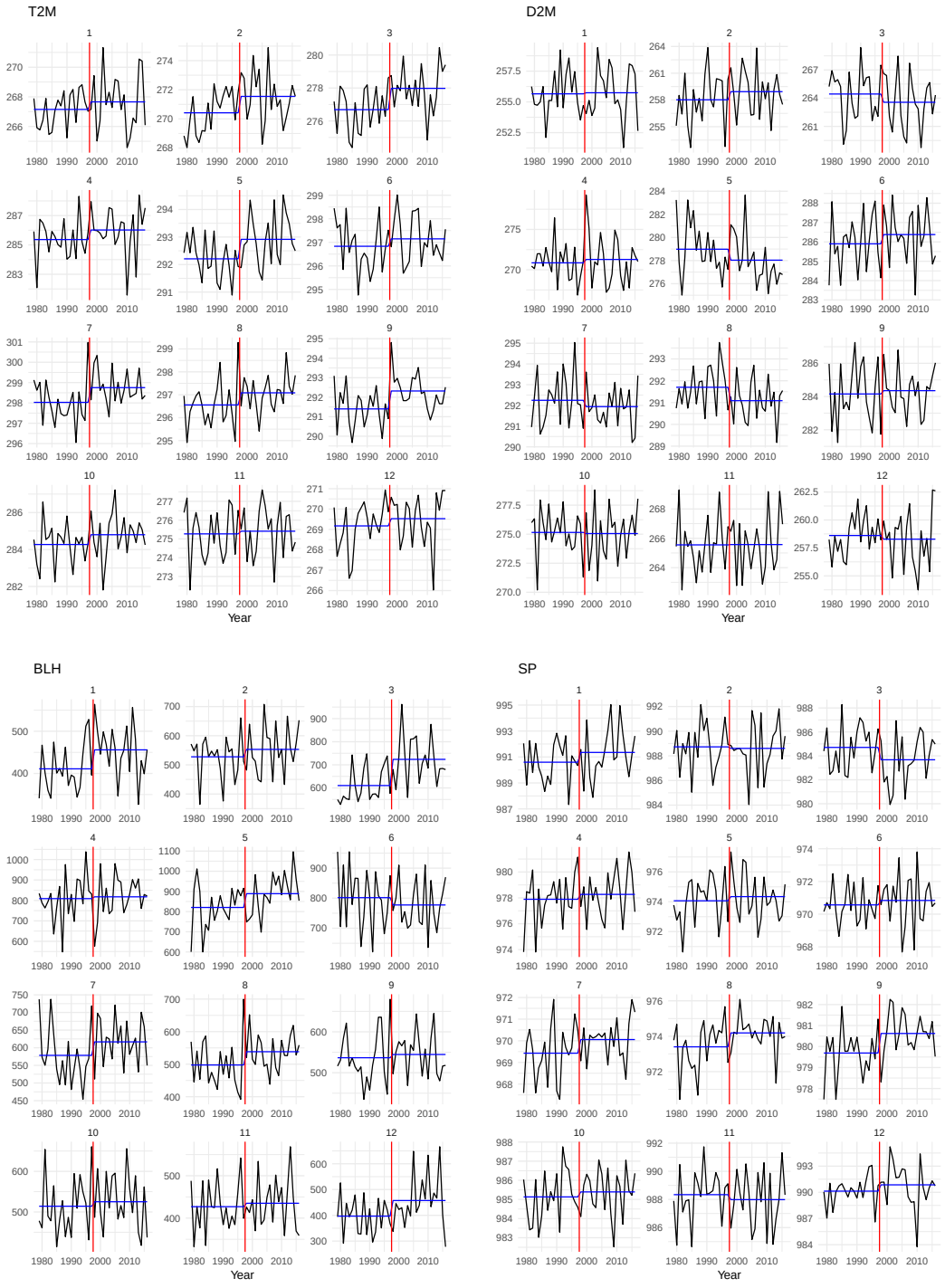


Figure S10: Monthly averaged time series plots in Beijing for T2M, D2M, BLH and BLD. The vertical red line is between 1997 and 1998, the boundary of two periods. The blue lines are averge of the 19 years in each period.

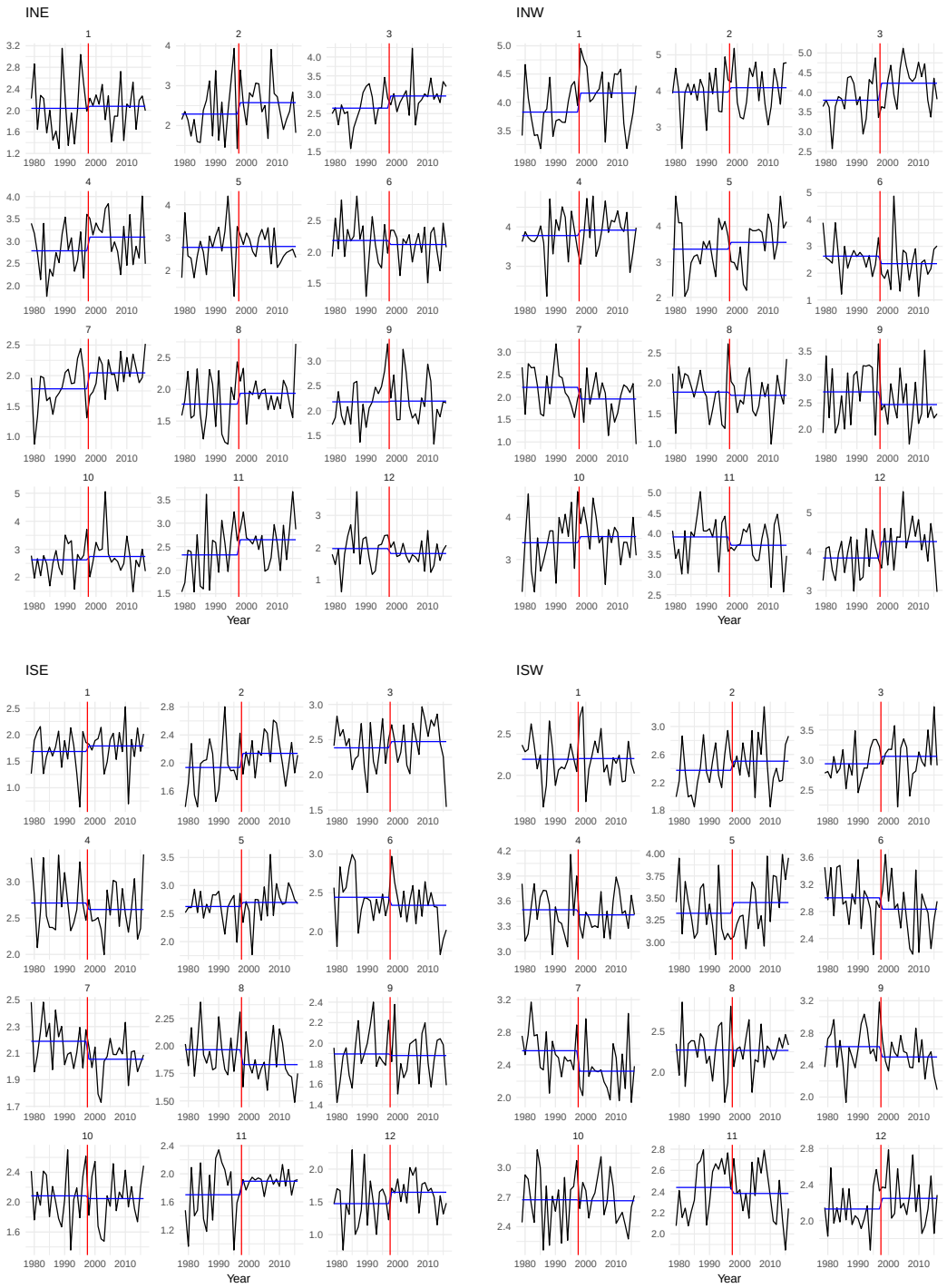
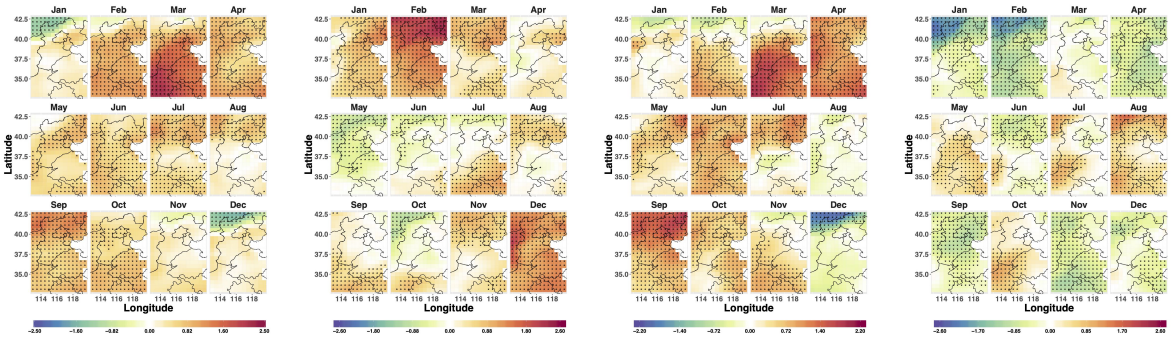


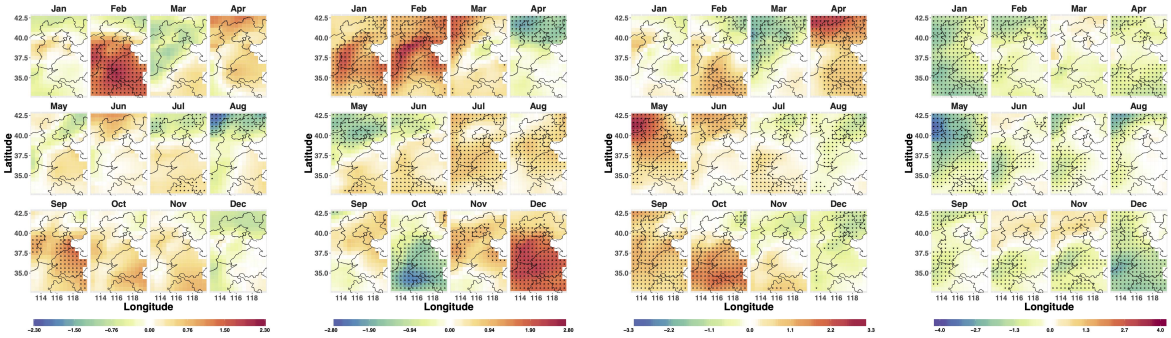
Figure S11: Monthly averaged time series plots in Beijing for INE, INW, ISE and ISW. The vertical red line is between 1997 and 1998, the boundary of two periods. The blue lines are averge of the 19 years in each period.

K Test Results with Nine-Year Bins

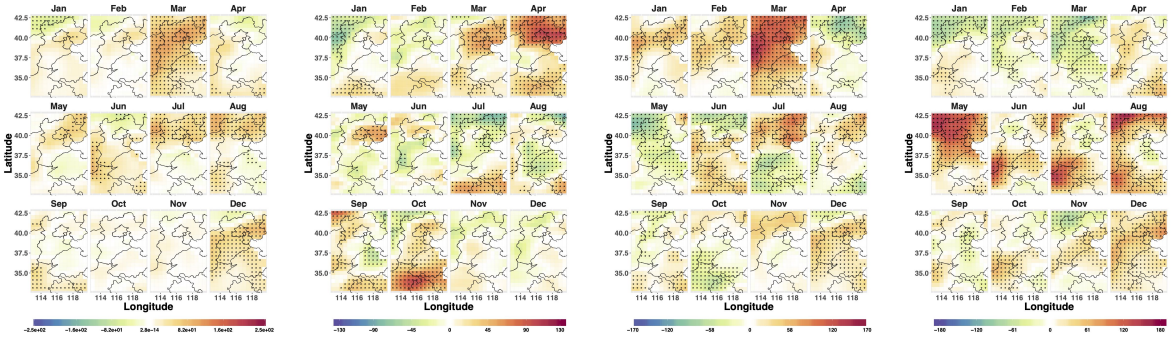
T2M: 1979-2016, 1979-1997, 1989-2007 and 1998-2016



D2M: 1979-2016, 1979-1997, 1989-2007 and 1998-2016



BLH: 1979-2016, 1979-1997, 1989-2007 and 1998-2016



NW: 1979-2016, 1979-1997, 1989-2007 and 1998-2016

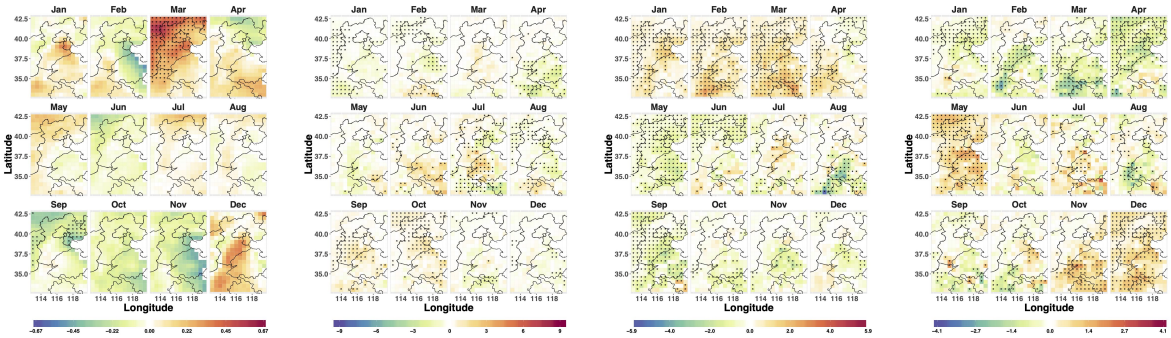


Figure S12: Test results for temporal bins of different sizes. The subfigures in each panel from left to right are test results for 1979-2016 (19 years bins), 1979-1997, 1989-2007 and 1998-2016 (9 years bins).