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Supplement of

Seesaw haze pollution in North China modulated by the sub-seasonal variability of atmospheric circulation

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S1. Supplementary Figures S1-S6

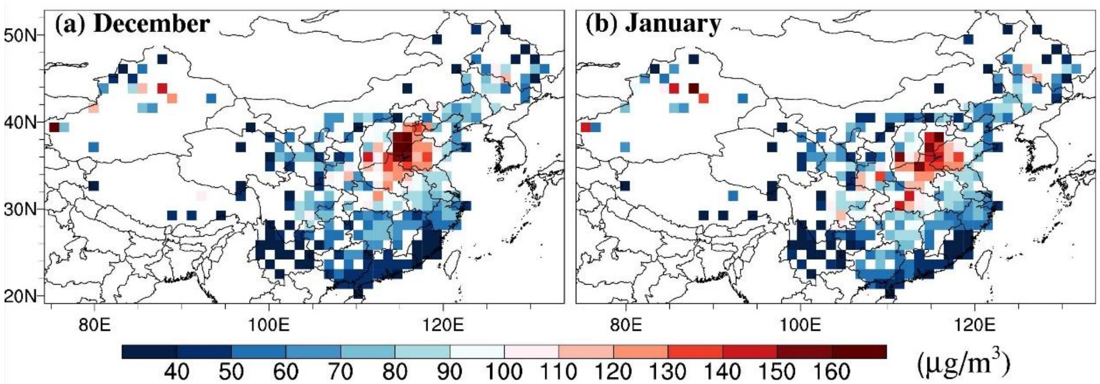

Figure S1. Three-year average of monthly mean $PM_{2.5}$ in December (2014-2016; Fig. S1a) and January (2015-2017; Fig. S1b)

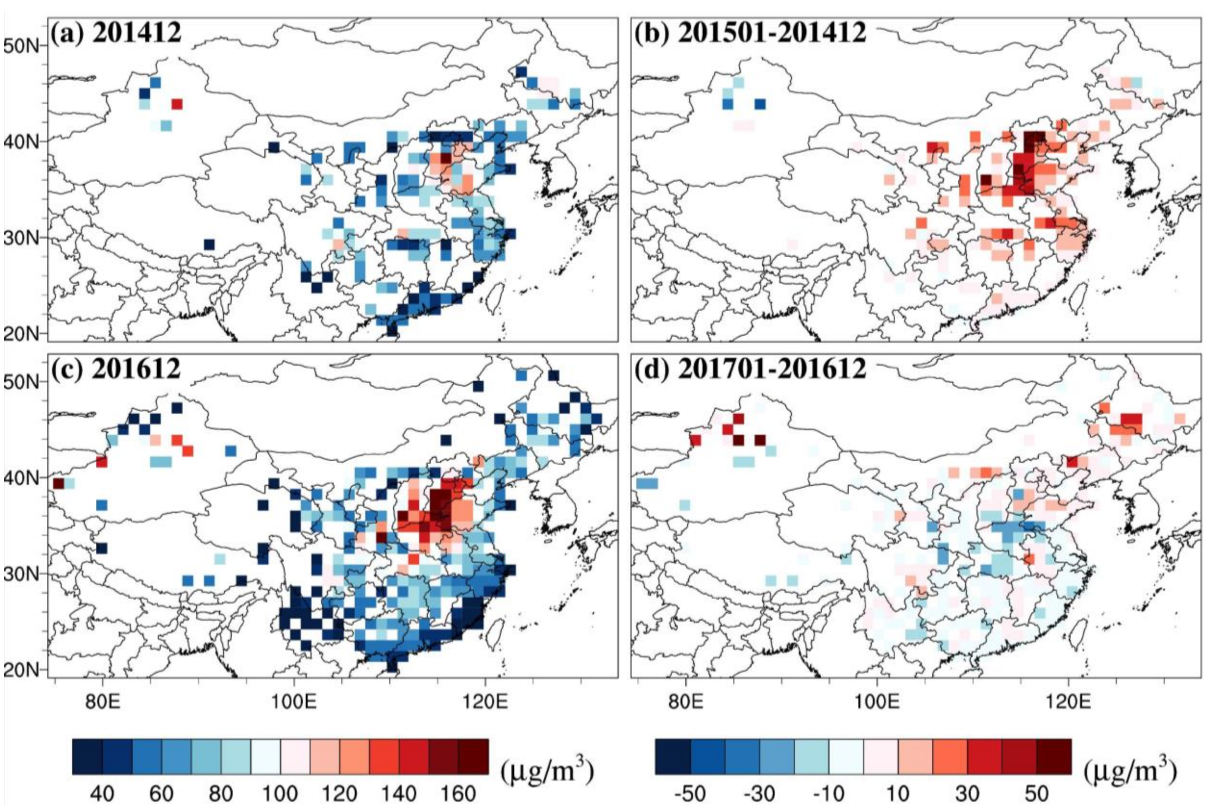

Figure S2. Monthly mean $PM_{2.5}$ in December 2015 (Fig. S2a) and 2016 (Fig. S2c), and the difference between the anomaly of January 2016 (Fig. S2b) and 2017 (Fig. S2d) (relative to January from 2015-2017) and the previous December anomaly

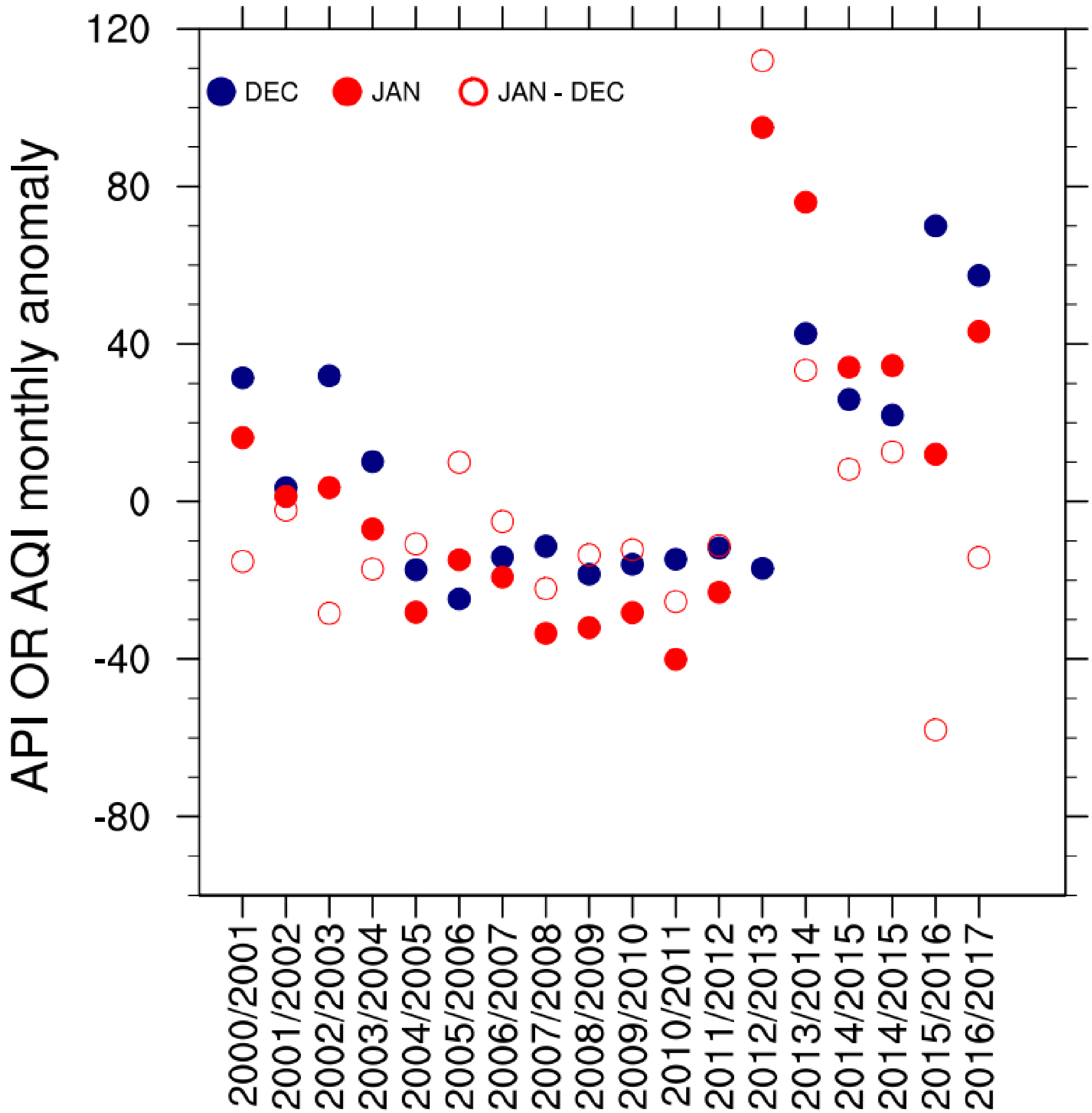

Fig. S3. Monthly mean anomaly of $PM_{2.5}$ between the adjacent December (solid blue) and January (solid red) as well as the change (hollow red circle) from December to January during 2000-2017 over North China. The data from 2000-2014 was based on air pollution index (API; http://datacenter.mep.gov.cn/), and the data for 2014-2017 was based on air quality index (AQI; http://www.pm25.in). For December (January), the anomaly is relative to 2000-2014 (2001-2015) fifteen-year respective monthly mean value. The data for December 2014 and January 2015 was shown twice, with the former one from API, and the latter one from AQI, and they are relatively comparable.

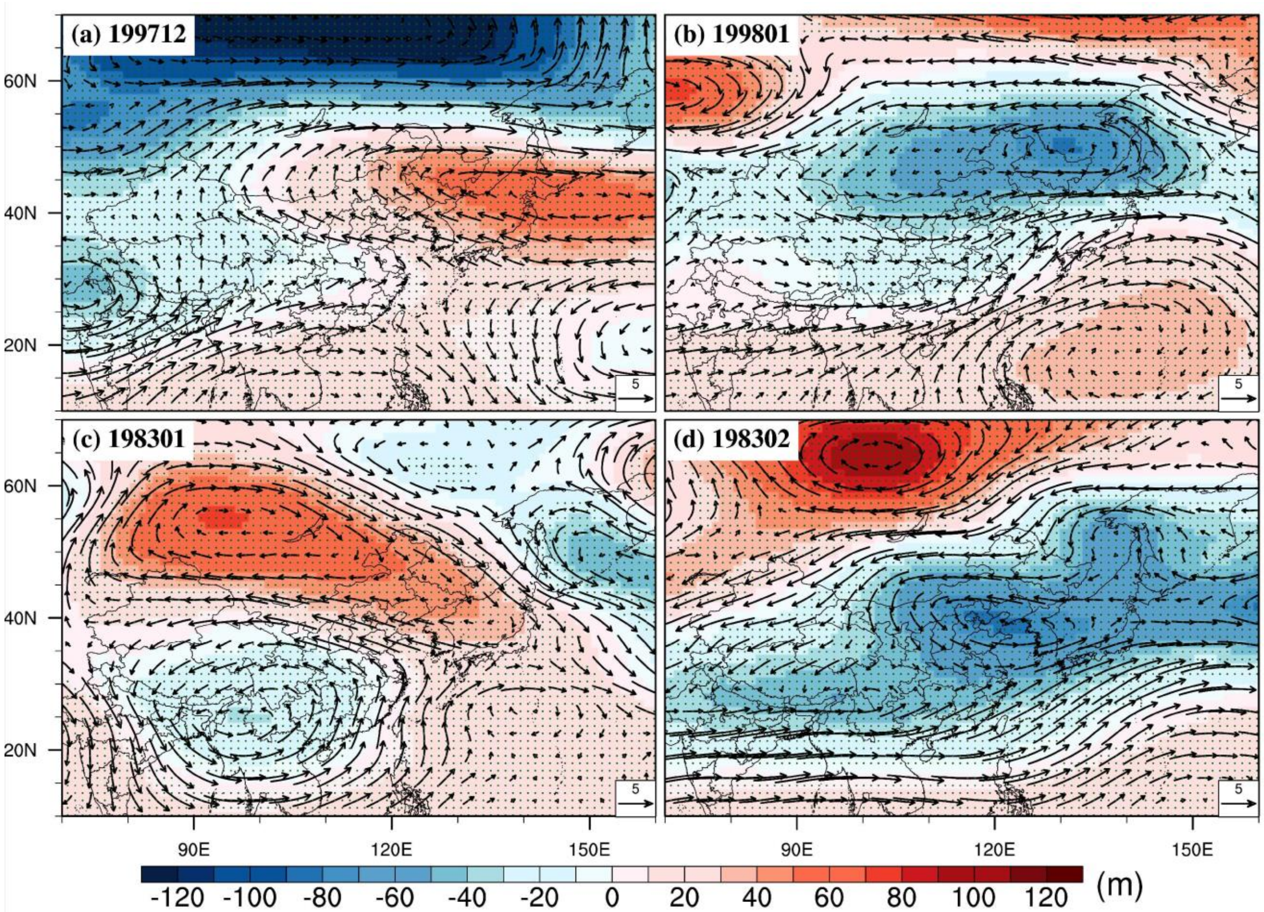

Fig. S4. Anomaly of geopotential height and wind vector at 500 hPa. (The anomaly is relative to 1987-2016). Areas within 90% of confidence interval are masked in white.

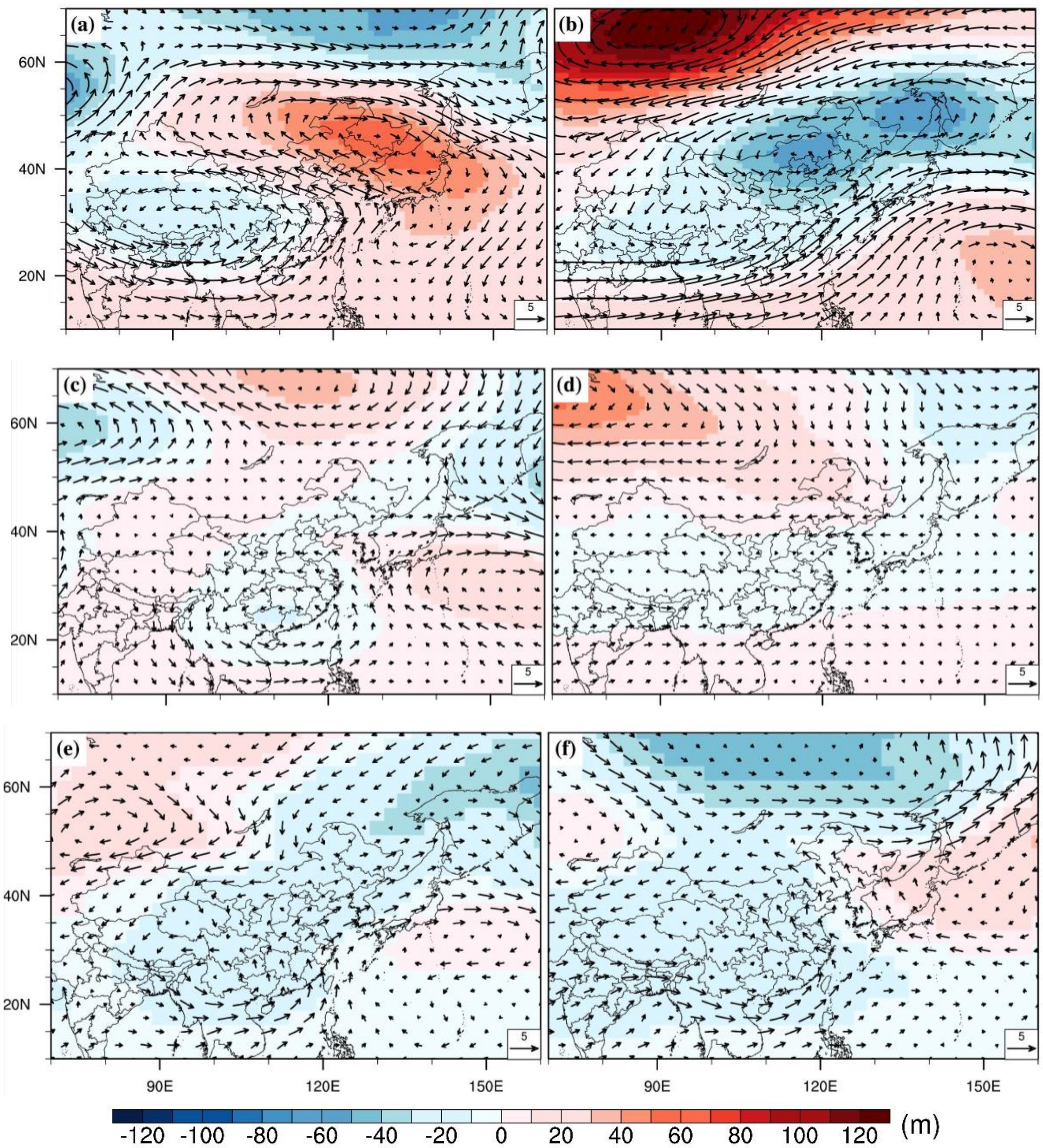

Fig. S5. Anomaly (relative to 1987-2016) of geopotential height and wind vector at 500 hPa for the ensemble mean of El Nino events, i.e., Fig. S5a (peak of super El Nino: 198301/199712/201512), Fig. S5b (the decay of super El Nino: 198302/199801/201601), Fig. S5c (peak of moderate El Nino events since 1980: 199201/199412/200211/200412/200612/200912), Fig. S5d (the decay of moderate El Nino events since 1980: 199202/199501/200212/200501/200701/201001), Fig. S5e (peak of El Nino events before 1980: 195801/196311/196511/197211/197711), Fig. S5f (decay of El Nino events before 1980: 195802/196312/196512/197212/197712)

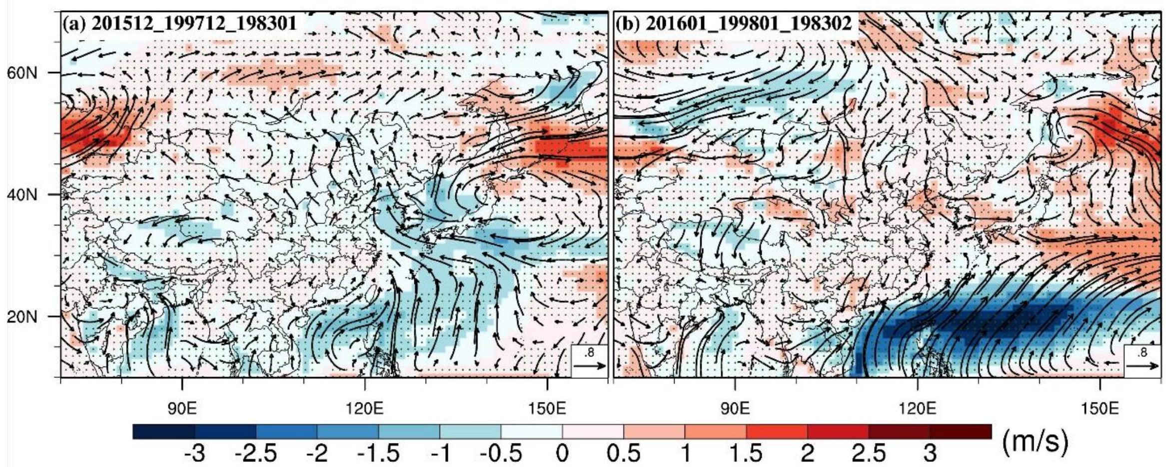

Fig. S6 Anomaly of 10-m wind vector (unit: m/s) with shading indicates the change in wind speed, the anomaly is the difference of mean value in December 2015, December 1997 and January 1983 relative to December 1987-2016 (Fig. S5a) and January 2016, January 1998 and February 1983 relative to January 1987-2016 (Fig. S5b). Stippled areas indicating exceedance of 90th confidence interval.

S2. A bug fix in the original Meteorology-Chemistry Interface Processor (MCIP) program

The Meteorology-Chemistry Interface Processor (MCIP) was used to post-process WRF results and prepare the input for CMAQ (Otte and Pleim, 2010), with the latest version of 4.3. During the process, we found a code bug in MCIP 4.3 when processing WRF output with MODIS land use 21. The bug was related to one type of land use named percentage of urban area (PURB). Starting from WRF/WPS version 3.8, land use was set up by default to the 21-class IGBP MODIS, which provides better and more detailed land use information compared to previously used data from United States Geological Survey (USGS). However, due to a bug in MCIP (getluse.f90; see the information below), PURB was set to missing value denoted using large positive or negative values shown in Fig. S7a. After fixing the problem (code fix in the information provided below), PURB looks reasonable (Fig. S7b). The incorrect PURB resulted in completely erroneous eddy diffusivity, leading to low $PM_{2.5}$ concentration such as in December 2015 (Fig. S8b) compared with observed concentration in Fig. S8a. After fixing the bug, the concentration of $PM_{2.5}$ was corrected and matched the observations much better (Fig.

S8c, the same as Fig. 5b in the manuscript). This error occurred when MCIP 4.3 was used to process WRF/WPS runs with version 3.8.1 or later, using the default 21 types of MODIS land use. Without the bug fix, the CMAQ simulations produced not only low concentrations of ozone, but also erroneous values for many other variables.

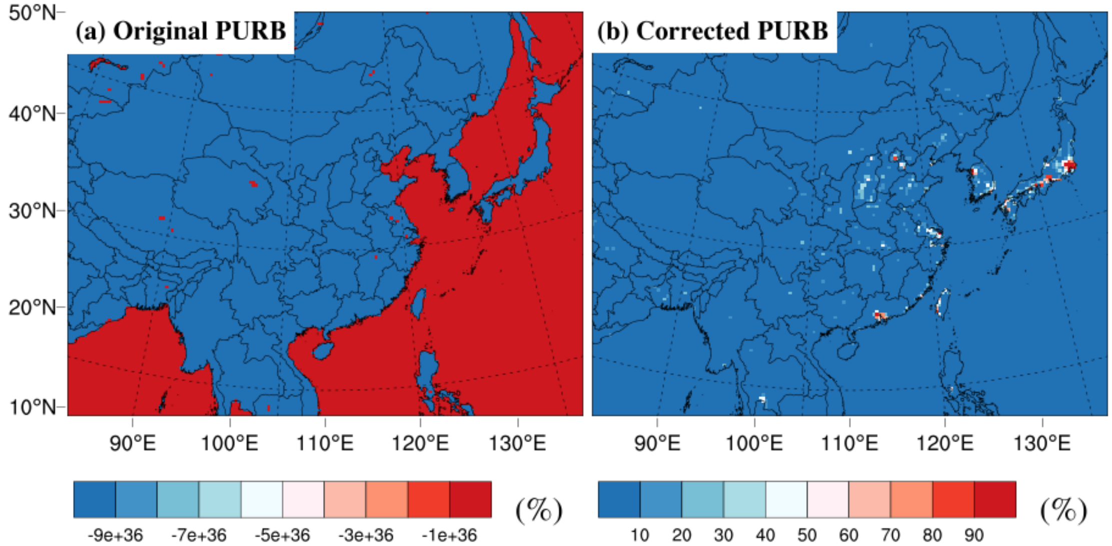

Fig. S7. Spatial distribution of PURB: pre-fix and after-fix of code bugs in MCIP

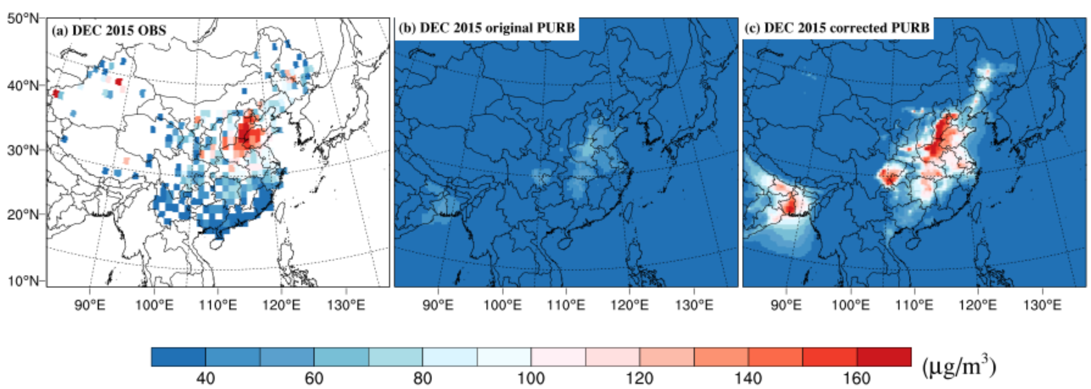

Fig. S8. Spatial distributions of monthly mean $PM_{2.5}$ concentration in December 2015 for observations (Fig. S7a), CMAQ results with the original PURB (Fig. S7b) and the corrected PURB (Fig. S7c)

Original code in MCIP 4.3 (getluse.f90) :

```
IF ( nummetlu == 33 ) THEN
    xpurb(col,row) = ( ( xluse(col,row,13) + xluse(col,row,31) +    &
                      xluse(col,row,32) + xluse(col,row,33) ) /  &
                    (1.0 - xluse(col,row,met_lu_water)) ) * 100.0
   ELSE IF ( nummetlu == 20 ) THEN
    xpurb(col,row) = ( xluse(col,row,13) /  &
                    (1.0 - xluse(col,row,met_lu_water)) ) * 100.0
   ENDIF
```

The original code should be revised to the code shown below:

```
IF ( nummetlu == 33 ) THEN
    xpurb(col,row) = ( ( xluse(col,row,13) + xluse(col,row,31) +    &
                      xluse(col,row,32) + xluse(col,row,33) ) /  &
                    (1.0 - xluse(col,row,met_lu_water)) ) * 100.0
   ELSE IF ( nummetlu == 20 ) THEN
    xpurb(col,row) = ( xluse(col,row,13) /  &
                    (1.0 - xluse(col,row,met_lu_water)) ) * 100.0
   ELSE IF ( nummetlu == 21 ) THEN
    xpurb(col,row) = ( xluse(col,row,13) /  &
                    (1.0 - xluse(col,row,met_lu_water)) ) * 100.0
   ENDIF
```

S3. Evaluation of monthly mean $PM_{2.5}$

Based on selected observational data from EANET (Acid Deposition Monitoring Network in East Asia, http://www.eanet.asia/product/index.html), 13 stations (shown in Table S1) in Japan, South Korea and Thailand were evaluated in terms of monthly mean $PM_{2.5}$ concentration. Please note over Cheju and Kanghwa in South Korea, only the data in January 2016 is available. From Fig. S9 shown below, we can tell that the model performs well (with low mean bias and error) among these stations.

Table S1. Station information of EANET sites

	Japan										South Korea		Thailand
Stations	Rishiri	Ochiishi	Tappi	Sado-seki	Happo	Ijira	Oki	Banryu	Yusuhara	Hedo	Cheju	Kanghwa	Bankok
Latitude	45.12	43.20	41.25	38.25	36.68	35.57	36.28	34.67	32.73	26.78	33.52	37.74	13.75
Longitude	141.23	145.52	141.35	138.40	137.80	136.70	133.18	131.70	132.98	128.23	126.52	126.49	100.50

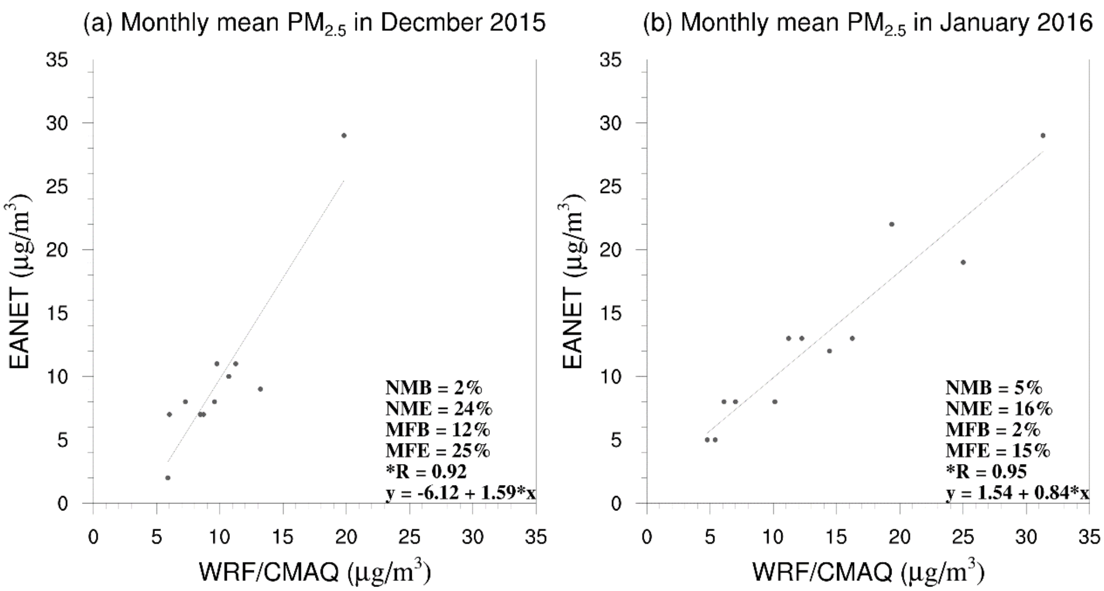

Figure S9 Evaluation of monthly $PM_{2.5}$ in CMAQ based on selected EANET observational data: (NMB: Normalized Mean Bias; NME: Normalized Mean Error; MFB: Mean Fractional Bias; MFE: Mean Fractional Error; R: correlation coefficient). The statistical significance of the linear correlation coefficient was performed and *R implies statistical significance at the 95% confidence level.