Emergency Response Measures to Alleviate a Severe Haze Pollution Event in Northern China during December 2015: Assessment of Effectiveness

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Text S1 Calculation of population-weighted $PM_{2.5}$ concentrations

The population-weighted $PM_{2.5}$ concentration ($PPM_{2.5}$) for a region of interest was calculated as follows:

$$PPM_{2.5} = \frac{\sum_{i=1}^{n} PM_{2.5,i} \cdot P_i}{\sum_{i=1}^{n} P_i} \qquad \text{(Eq. S1)}$$

$PM_{2.5,i}$ and P_i indicated the $PM_{2.5}$ concentration and the population in the i^{th} grid, respectively. n indicated the total number of model grids for the region of interest.

Table S1 Emergency response measures to reduce anthropogenic pollutant emissions in Beijing, Tianjin, Hebei, Henan, and Shandong during December 6 to 10, 2015

Emergency response measures	Beijing		Tianjin		Hebei		Henan		Shandong	
	Stage I (orange)	Stage II (red)	Stage I (yellow)	Stage II (orange)	Stage I (yellow)	Stage II (orange)	Stage I (orange)	Stage II (orange)	Stage I (yellow)	Stage II (yellow)
• More frequent road sprinkling	✓[a]	✓	✓	✓	✓	✓	✓	✓	✓	✓
• Termination of outdoor work at construction sites	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
• Termination or reduction of industrial production	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
• Prohibition of heavy-duty diesel vehicles on city roads	✓	✓		✓	✓	✓	✓	✓	✓	✓
• Reduction of number of vehicles on the road	✓	✓		✓	✓	✓	✓	✓		
• Ban on fireworks and outdoor barbecue	✓	✓					✓	✓		

[a] "✓" indicates that the emergency response measure was implemented at this stage.

Table S2 Effects of previous pre-planned emission controls before and during important international and national events on $PM_{2.5}$ reduction in Beijing

Events	Event dates	Start date of emission reduction (duration in days)	Area of emission reduction	Percentage of emissions reduction	Percentage of $PM_{2.5}$ reduction in Beijing
Sino-African Summit	November 4 to 5, 2006	November 1, 2006 (7)	Beijing	40% (Wang et al., 2007)	20% - 60% [c] (Cheng et al., 2008)
Beijing Olympic Games	August 8 to 24, 2008	July 1, 2008 (19) + July 20, 2008 (36) [b]	Beijing-Tianjin-Hebei (BTH), Shandong, Shanxi, Inner Mongolia	41% - 57% (S. Wang et al., 2010)	46% (S. Wang et al., 2010)
Asia-Pacific Economy Cooperation (APEC) Summit	November 5 to 11, 2014	October 20, 2014 (12) + November 1, 2014 (11)	BTH, Shandong, Shanxi, Inner Mongolia	30% - 68% (Liu et al., 2015) 6% - 33% (Zhang et al., 2016)	68% (Liu et al., 2015) 43% (Zhang et al., 2016)
Chinese Military Parade	September 3, 2015	August 16, 2015 (4) + August 20, 2015 (14)	BTH, Shandong, Shanxi, Inner Mongolia, Henan	17% - 67% (G. Wang et al., 2017)	34% - 48% (G. Wang et al., 2017)

[b] During this period, measures of emission reduction were strengthened.

[c] $PM_{2.5}$ number concentrations

Table S3 Parameters used to calculate the lifetime of $PM_{2.5}$ (τ) in the NCP boundary layer during the clean and polluted periods

	Clean period	Polluted period (Stages I and II)
$\bar{m}$ [d] (μg)	7.3×10^{16}	1.0×10^{17}
$\overline{\text{PBLH}}$ (m)	654	356
$\overline{L_{h-out}}$ (μg day^{-1})	7.5×10^{16}	1.5×10^{16}
$\overline{L_{v-out}}$ (μg day^{-1})	2.8×10^{15}	4.7×10^{15}
$\overline{L_{drydep}}$ (μg day^{-1})	3.0×10^{15}	1.2×10^{15}
τ (days)	0.90	4.8

[d] Average values during the clean period or the polluted period, respectively

Table S4 Simulated conversion ratios of anthropogenic precursors to secondary $PM_{2.5}$ components for individual cities and provinces in the NCP

Precursor conversion ratios [ppbv ppbv^{-1}]	Definition	Beijing	Tianjin	Hebei	Henan	Shandong
Sulfur oxidation ration (SOR)	$\frac{[SO_4^{2-}(a)]}{[SO_4^{2-}(a)]+[SO_2(g)]}$	0.36	0.31	0.30	0.53	0.23
Nitrogen oxidation ratio (NOR)	$\frac{[NO_3^{-}(a)]}{[NO_3^{-}(a)]+[NO_x(g)]}$	0.15	0.15	0.19	0.32	0.22
Ammonium conversion ratio (NHR)	$\frac{[NH_4^{+}(a)]}{[NH_4^{+}(a)]+[NH_3(g)]}$	0.83	0.80	0.69	0.56	0.57
Anthropogenic VOC oxidation ratio (VOR)[e]	$\frac{[SOA(a)]}{[SOA(a)]+[VOC(g)]}$	0.062	0.085	0.12	0.15	0.10

[e] Anthropogenic VOC precursors in our WRF-Chem simulation included ≥ C_4 alkanes, alkenes, and aromatics.

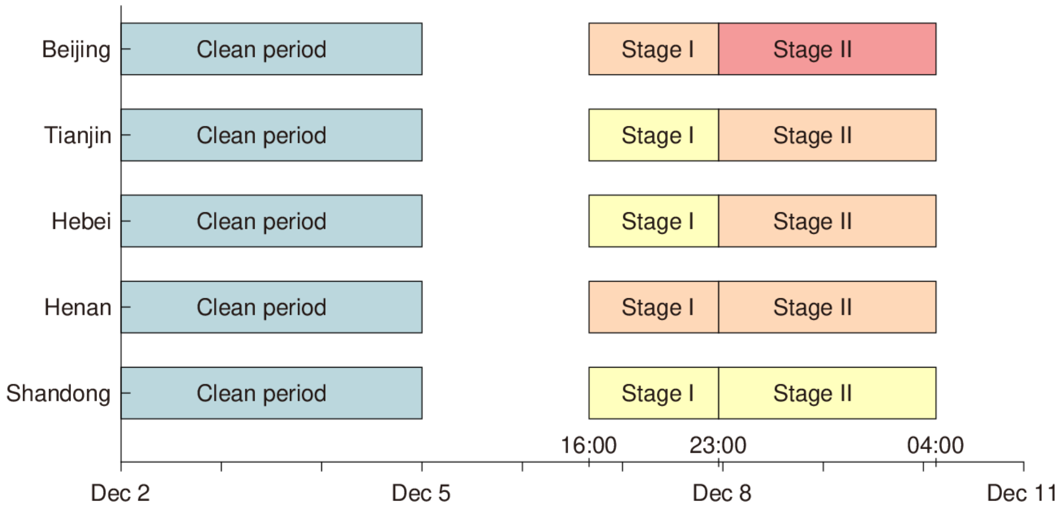

Fig S1. Timing of the clean period (blue) and the polluted period (Stages I and II) simulated in this study. The alert levels and their duration for each province and city in the NCP are shown in corresponding colors: yellow, orange, and red.

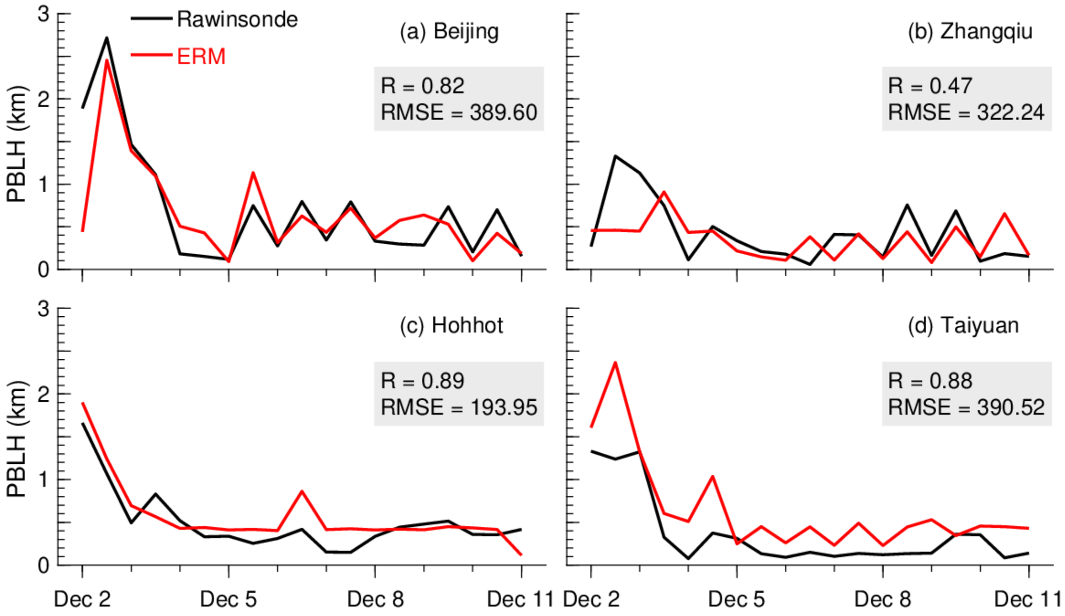

Fig S2. Comparisons of the simulated planetary boundary layer height (PBLH) against the rawinsonde measurements at four sites in Northern China during December 2 to 10: (a) Beijing (39.93° N, 116.28° E), (b) Zhangqiu (36.70° N, 117.55° E), Shandong Province, (c) Hohhot (40.81° N, 111.68° E), Inner Mongolia Autonomous Region, and (d) Taiyuan (37.78° N, 112.55° E), Shanxi Province.

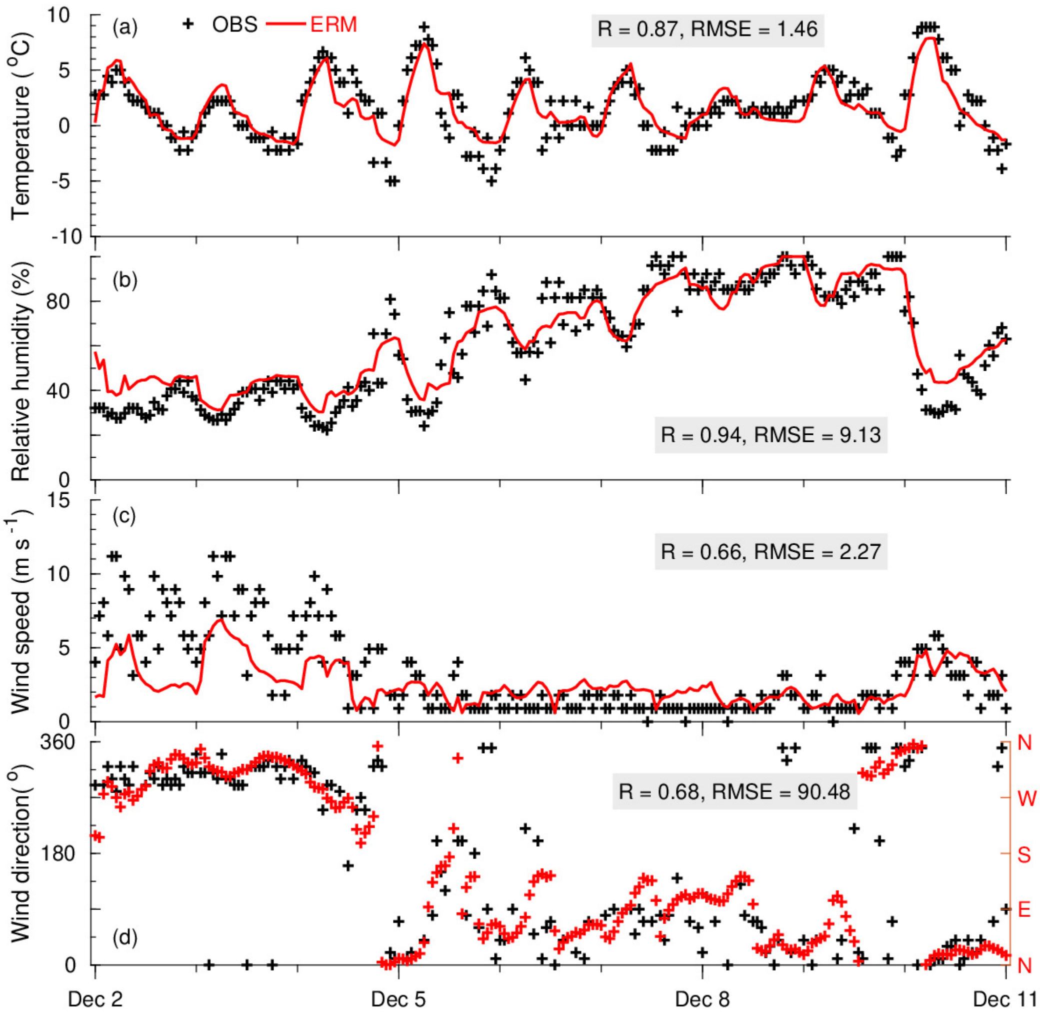

Fig S3. Comparisons of the observed (black) and simulated (red) surface meteorological variables at the Beijing Capital International Airport (40.08° N, 116.59° E) during December 2 to 10: (a) temperature, (b) relative humidity, (c) wind speed, and (d) wind direction. The correlations and the root mean square errors (RMSE) of the ERM simulation results relative to the observations are shown inset.

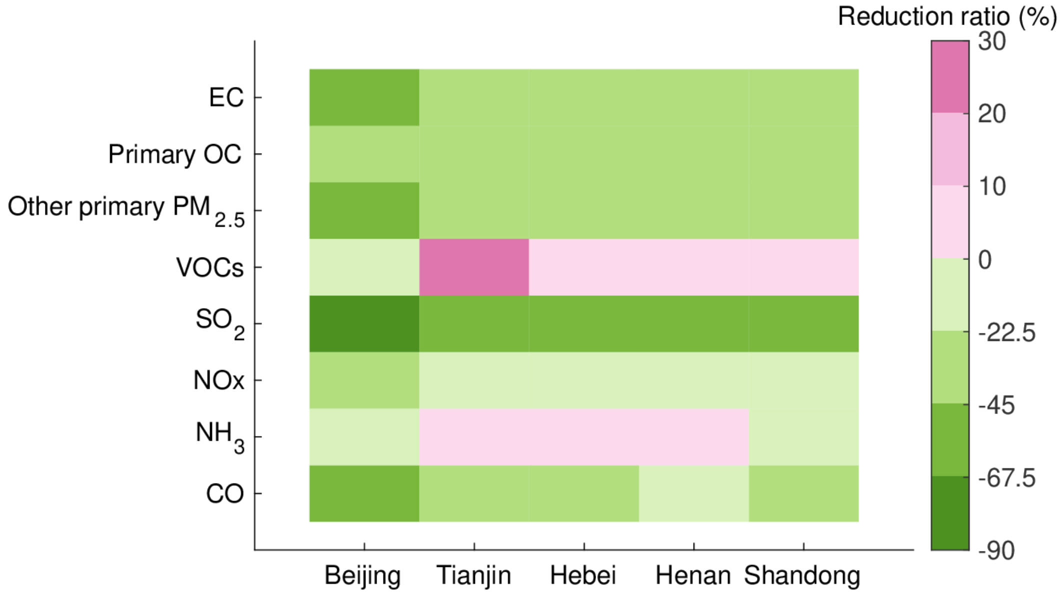

Fig S4. Percent difference in the annual anthropogenic emissions from the cities and provinces in the NCP estimated by Li et al. (2017) for the year 2016 relative to the estimation by Lu et al. (2011) for the year 2010.

References

Cheng, Y.F., Heintzenberg, J., Wehner, B., Wu, Z.J., Su, H., Hu, M., and Mao, J.T., 2008. Traffic restrictions in Beijing during the Sino-African Summit 2006: aerosol size distribution and visibility compared to long-term in situ observations. Atmos. Chem. Phys. 8, 7583-7594. DOI: 10.5194/acp-8-7583-2008.

Li, M., Zhang, Q., Kurokawa, J.-I., Woo, J.-H., He, K., Lu, Z., Ohara, T., Song, Y., Streets, D.G., Carmichael, G.R., Cheng, Y., Hong, C., Huo, H., Jiang, X., Kang, S., Liu, F., Su, H., and Zheng, B., 2017. MIX: a mosaic Asian anthropogenic emission inventory under the international collaboration framework of the MICS-Asia and HTAP. Atmos. Chem. Phys. 17, 935-963. DOI: 10.5194/acp-17-935-2017.

Liu, J., Xie, P., Wang, Y., Wang, Z., He, H., Liu, W., 2015. Haze observation and control measure evaluation in Jing-Jin-Ji (Beijing, Tianjin, Hebei) area during the period of the Asia-Pacific Economic Cooperation (APEC) meeting. Bulletin of the Chinese Academy of Sciences 30 (3), 368−377. DOI: 10.16418/j.issn.1000-3045.2015.03.011.

Lu, Z., Zhang, Q., and Streets, D. G., 2011. Sulfur dioxide and primary carbonaceous aerosol emissions in China and India, 1996–2010. Atmos. Chem. Phys. 11, 9839-9864. DOI: 10.5194/acp-11-9839-2011.

Wang, G., Cheng, S., Wei, W., Yang, X., Wang, X., Jia, J., Lang, J., and Lv, Z., 2017. Characteristics and emission-reduction measures evaluation of $PM_{2.5}$ during the two major events: APEC and Parade. Sci. Total Environ. 595, 81-92. DOI: 10.1016/j.scitotenv.2017.03.231.

Wang, S., Zhao, M., Wu, Y., Zhou, Y., Lei, Y., He, K., Fu, L., and Hao, J., 2010. Quantifying the air pollutants emission reduction during the 2008 Olympic Games in Beijing. Environ. Sci. Technol. 44 (7), 2490-2496. DOI: 10.1021/es9028167.

Wang, Y., McElroy, M. B., Boersma, K. F., Eskes, H.J., and Veefkind, J.P., 2007. Traffic restrictions associated with the Sino-African summit: Reductions of NO_x detected from space. Geophys. Res. Lett. 2007, 34 (8), 402-420. DOI: 10.1029/2007GL029326.

Zhang, L., Shao, J., Lu, X., Zhao, Y., Hu, Y., Henze, D.K., Liao, H., Gong, S., and Zhang, Q., 2016. Sources and processes affecting fine particulate matter pollution over North China: an adjoint analysis of the Beijing APEC period. Environ. Sci. Technol. 50 (16), 8731–8740. DOI: 10.1021/acs.est.6b03010.