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Atmospheric Chemistry and Physics
Discussions

Attributions of meteorological and emission factors to the 2015 winter severe haze pollution episodes in Northern China

Tingting Liu[1,2], Sunling Gong[2] Mengyu[3], Qichao Zhao[4], Huairui Li[4], Jianjun He[5], Jie Zhang[3], Lei Li[3], Xuguan Wang[3], Shuli Li[3], Yanli Lu[3], Haitao Du[6], Yaqiang Wang[2], Chunhong Zhou[2], Hongli Liu[2]

[1] School of Mechanical Engineering, Hangzhou Dianzi University, Hangzhou, 310018, China
[2] State Key Laboratory of Severe Weather & Key Laboratory of Atmospheric Chemistry of CMA, Chinese Academy of Meteorological Sciences, Beijing 100081, China
[3] Langfang Bureau of Environmental Protection, Langfang, Hebei, China
[4] Langfang Haihong Environmental Protection S&T Co., Langfang, Hebei, China
[5] The College of Environmental Science & Engineering, Nankai University, Tianjin 300071, China
[6] Langfang Bureau of Meteorology, Langfang, Hebei, China

Abstract

Northern China in the 2015 winter months of November and December has witnessed the most severe air pollution phenomena since the 2013 winter haze events occurred, which triggered the first ever Red Alert in the air pollution control history of Beijing, with an instantaneous $PM_{2.5}$ concentration over 1 mg m^{-3}. Analysis and modeling results show that the worsening meteorology conditions are the main reason behind this unusual increase of air pollutant concentrations and the emission control measures taken during this period of time have contributed to mitigate the air pollution in the region. This work provides a scientific insight of the emission control measures vs. meteorology impacts for the period.

1. Introduction

Severe air pollution has been observed in China for the last 15-20 years, with an elevated fine particular matter ($PM_{2.5}$) concentrations of annual mean ranging from 80 to 120 μg m^{-3} and over 1000 μg m^{-3} during some heavy haze episode. Haze phenomenon has become a major pollution problem in many China cities [*Han et al.*, 2013; *L Wang et al.*, 2015], which causes wide public concern and has a negative impact on human health and environment [*Gurjar et al.*, 2010; *Kan et al.*, 2012]. Therefore, it is necessary to comprehensively investigate the emission sources, meteorological factors, and other characteristics of the $PM_{2.5}$ pollution in China and provide more effective control measures [*L Wang et al.*, 2008; *S Zhang et al.*, 2014].

Since the strict control measures of air pollutants over the country were enforced in 2013 by the government, a steady decrease of air pollutant concentrations has been observed with an annual mean $PM_{2.5}$ concentration drop from about 85 μg m^{-3} in 2014 to 80 μg m^{-3} in 2015 for Beijing, from 86 to 70 for Tianjin, from 99 to 85 for Langfang, from 120 to 105 for Baoding, and from 118 to 88 for Shijiazhuang (http://www.mep.gov.cn/gkml/). However, due to the complex interactions between pollution sources and meteorology, the quantitative contributions for each factor remain to be separated. A number of papers have tried to analyze the meteorological contributions [*LIAO et al.*, 2015; *C WANG et al.*, 2013; *ZENG et al.*, 2014] for individual cases but hardly combined the emission changes for a comprehensive analysis. The most recent consensus is that these decreases partially can attribute to the difference in the meteorology conditions but largely should be attributed to the control measures taken.

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The year of 2015 was an unusual year in terms of air pollution situation in Northern China, which was in the middle of an El Niño event around the globe [*Varotsos et al.*, 2016]. Unusual climate and extreme weather happened everywhere. In the first half of the year, a steady decrease in major air pollutants was observed compared to those in 2014. However, in the last two months, a dramatic increase was found. The $PM_{2.5}$ concentration reached as high 1000 $\mu g\ m^{-3}$ in Beijing and triggered the first ever Red Alert of severer air pollution in the city. It has been reported that more (less) haze events occurred during El Niño (La Niña) winter with warmer (colder) Niño3.4-SST in association with ENSO [Zhao et al, 2016, personal communication]. Would this unusual increase of air pollution have anything to do with the El Niño event and what was the role of emission control being played in this?

This paper presents an analysis and modeling study of the last two months of 2015 air pollution conditions in Northern China and explores the major reasons behind these unusual increases from both the meteorological and emission points of views. To evaluate the contribution of meteorology factors toward the severe pollution in the last two months of 2015, wind speed convergence lines, static wind frequency data and other parameters for November and December in 2015 were specifically investigated and compared with data for the same period of 2014. An analysis of this heavy haze pollution episode was also simulated with the Chinese Unified Atmospheric Chemistry Environment (CUACE) model [*S. L. Gong and Zhang*, 2008] coupled with GRAPES_Meso meteorology forecast model [*Chen et al.*, 2016; *R Zhang and Shen*, 2008]. The aim of this study was to provide information on the impact degree and mechanism of meteorology variations and emission changes on the $PM_{2.5}$ haze pollution in this region.

2. Methodology

The research starts with the analysis of air pollution levels between 2014 and 2015, with a focus on the last two months of each year. The difference lays the foundation for the investigation, where the meteorology factors that mostly influence the air pollution levels such as the stable conditions, wind speed and directions as well as the relative humidity are probed, which will give a qualitative description of the reasons for pollution changes from 2014 to 2015. In order to quantify the meteorology impacts, a modeling study is carried with the same emission rates in the model for 2014 and 2015 where the pollution level changes are considered to be caused by meteorology only. The impact of emission changes on air pollution can then be inferred from the difference between the observed pollution level changes and the modelled level changes only due to the meteorology.

3. Air Quality Observations

The observational pollution data used in this study were from the near real time (NRT) monitoring stations of the Ministry of Environmental Protection across the Northern China (http://www.cnemc.cn/), with hourly concentrations of six major pollutants: $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO and O_3. Bases upon the entire year data for 2014 and 2015, the annual mean concentrations of $PM_{2.5}$ are overall in a decreasing trend (Fig. 1). For four typical Northern cities of Beijing, Langfang, Baoding and Shijiazhuang, the annual mean $PM_{2.5}$ concentrations in 2015 are 5.4%, 13.9%, 12.8% and 25.6% lower than those in 2014, respectively. The two year monthly mean $PM_{2.5}$ concentrations (Fig. 1) indicate that from January to October, the concentrations in 2015 are much lower than those at the same month in 2014. If the data for

November and December of 2015 were removed from the analysis, the drops in $PM_{2.5}$ concentrations from 2014 to 2015 would be 21%, 25.3%, 16.8% and 34.9% for Beijing, Langfang, Baoding and Shijiazhuang, respectively, indicating the impact of the unusual increases in December on the annual means for these cities.

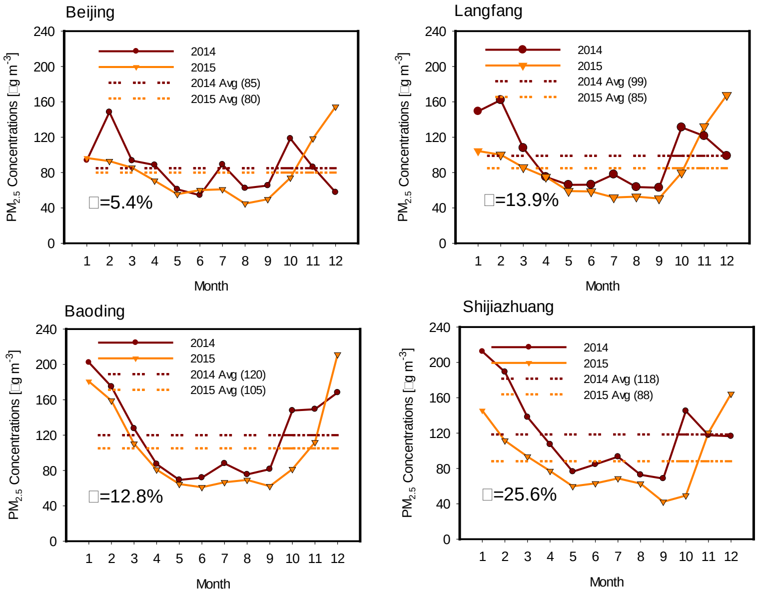

Figure 1: Comparison of monthly mean $PM_{2.5}$ concentrations of 2015 and 2014 in four cities of Northern China

Regionally, the monthly mean $PM_{2.5}$ concentrations in December 2015 saw a large increase compared to the same month in 2014, ranging from 163% to 18% (Table 1) in Northern China. Beijing had the largest increase of 163%, jumping from approximately 58 µg m^{-3} in 2014 to 151 µg m^{-3} in 2015 (Fig. 2). For the city of Langfang neighboring South Beijing, the December increase in $PM_{2.5}$ concentration was 70%, changing from approximately 97 µg m^{-3} in 2014 to 165 µg m^{-3} in 2015. Other Pollutants were seen the similar increases as well (Table 1), except for SO_2.

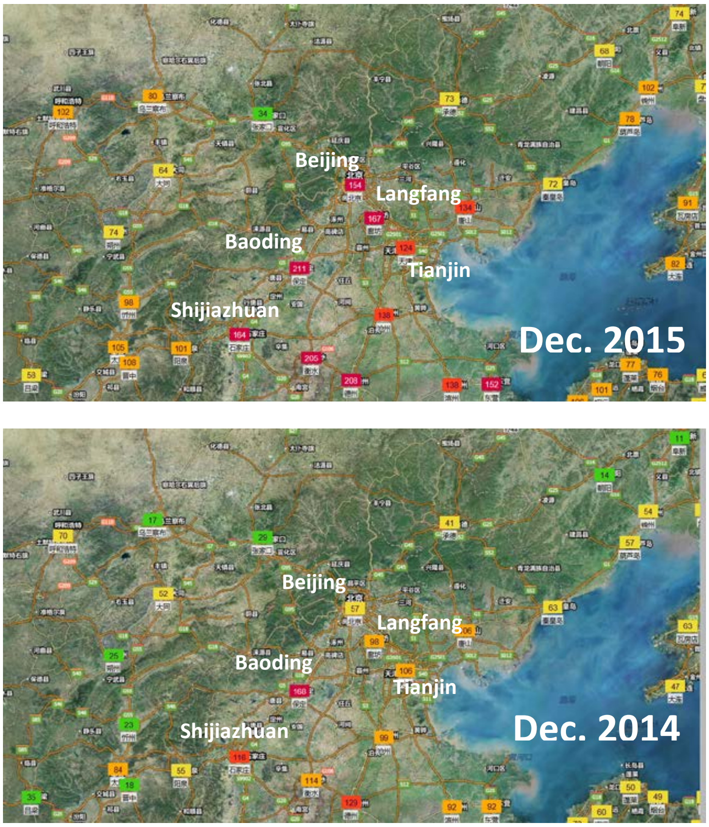

Figure 2: Comparison of monthly mean PM2.5 concentrations of December 2015 and 2014 in Northern China

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Table 1: Change of major pollutants in December 2015 compared to December 2014

City	$PM_{2.5}$ (μg m^{-3})			SO_2 (μg m^{-3})			CO (mg m^{-3})			NO_2 (μg m^{-3})		
	2014	2015	Diff(%)	2014	2015	Diff(%)	2014	2015	Diff(%)	2014	2015	Diff(%)
BJ	57	154	162.5	27	19	−30.4	1.54	2.86	85.5	53	76	44.5
LF	98	167	70.4	52	40	−22.4	1.92	3.06	59.2	53	76	42.8
SJZ	116	164	39.8	112	75	−33.3	2.23	3.27	46.4	64	76	19.6
BD	168	211	27.3	144	92	-36.3	4.14	4.64	12.2	75	99	31.8
TJ	106	124	17.7	75	45	-40.0	2.05	2.06	0.4	65	66	1.50

BJ: Beijing, LF: Langfang, SJZ: Shijiazhuang, BD: Baoding, TJ: Tianjin; Diff: 2015-2014

Certain factors must have had a dramatic change to cause this to happen. In view of the steady decreases of air pollutants across the Northern China in the first ten months of 2015, it can be inferred that the emission reduction measures implemented in the region was effective in bringing the averaged concentrations of major pollutants down from 2014 to 2015, except for the last two months. In next session, the meteorological conditions for the last two months of 2015 will be analyzed in details to elucidate the reasons for this dramatic increase in Northern China.

4. Meteorology Factor Analysis

Previous studies have shown that a major factor controlling the pollutant accumulation is the atmospheric stability in association with the convergence at lower levels, which leads to the gathering of the polluted air from the surrounding areas and prevents pollutants from diffusing away from the source regions [*LIAO et al.*, 2015; *C WANG et al.*, 2013; *ZENG et al.*, 2014]. Therefore, the location of the convergence zone is critical in identifying the meteorological conditions that are favorable or not for the formation of heavy pollution.

Using the surface meteorological data from the CMA (China Meteorological Administration, http://www.cma.gov.cn/en2014/) for 2014 and 2015, the wind speed convergence lines (WSCL) averaged for November and December of 2014 and 2015 are constructed (Fig. 3). The WSCL identifies the convergence line along which the pollutants are mostly accumulated due to stable conditions. It is clearly shown that the line has shifted northerly from southern Hebei Province in 2014 to the central to North Hebei in 2015, crossing the middle of the Beijing City.

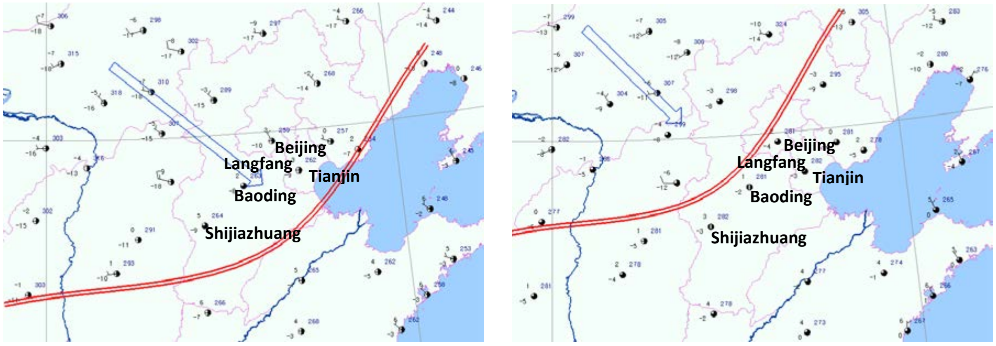
(a) 2014 (b) 2015

Figure 3: The wind speed convergence lines (WSCL) for November and December. (a) 2014 and (b) 2015. The blue arrows in each plot indicates the strength of the cold fronts.

Observational evidence has shown a teleconnection between the central Pacific and East Asia during the extreme phases of ENSO cycles. This Pacific–East Asian teleconnection is confined to the lower troposphere. The key system that bridges the warm (cold) events in the eastern Pacific and the weak (strong) East Asian winter monsoons (EAWM) is an anomalous lower-tropospheric anticyclone (cyclone) located in the western North Pacific [*B Wang et al.*, 2000]. Research [*Si et al.*, 2016] has found that during the 2015 El Niño period, the EAWM was

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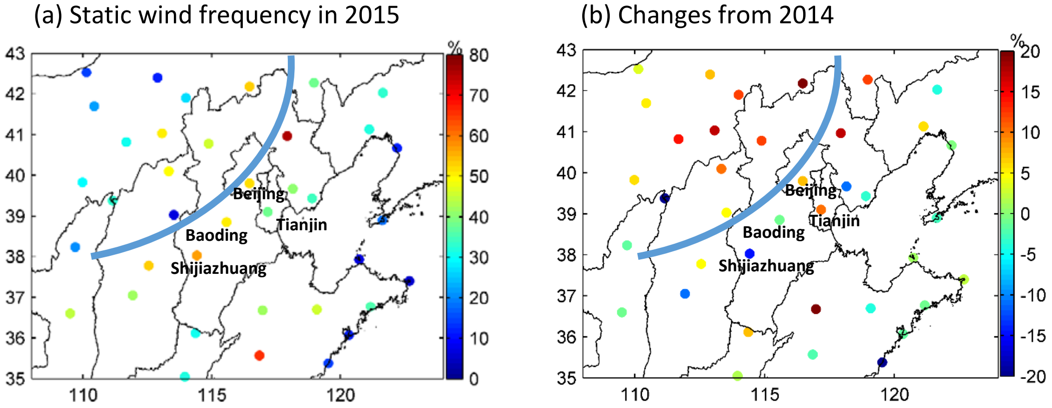
weaker than normal during the 2015 winter with a temperature anomaly of 1.1 °C. The subtropical high was stronger and had a large area than normal years [*Li et al.*, 2016]. As a consequence of the weaker EAWM, the cold front in 2015 could not extend to the degree as in 2014, leading to a northerly shifting of the WSCL.

There are two consequences of the WSCL shifting. First of all, accompanied with the northerly shift of the WSCL is the shifting of the stable atmosphere zone to the central Hebei and Beijing areas in 2015, allowing the pollutants to easily accumulate along the lines. The observed static wind frequency (SWF, wind speed less than 1 m s^{-1}) distribution clearly supports this observation. Figure 4a is the regional distribution of SWF for November and December in 2015, showing a high frequency along the convergence line, with the SWF changes from 2014 (Fig. 4b). It is also clear that the increase is high along or on the north side of the line (Fig. 4b) and the decreasing trend is on the south side of the line. Table 2 lists the SWF for four cities in Northern China. Except for Shijiazhuang which had an unusual high SWF in 2014 and a decreasing SWF in 2015, other cities were all experienced an increasing trend for stable weather. Impacted heavily by the shifting, Beijing and Langfang had a 6-7% increase of SWF compared to 2014. Even with a decreasing trend for SWF, Shijiazhuang had a similar SWF with other cities with more than half of the days (>50%) under static stable environment.

Table 2: Comparison of SWF (%) and RH (%) for November and December 2015 and 2014

City	Beijing		Tianjin		Shijiazhuang		Langfang	
	SWF	RH	SWF	RH	SWF	RH	SWF	RH
2014	44	43	27	48	71	42	47	43
2015	51	70	38	71	56	72	53	71


(a) Static wind frequency in 2015

(b) Changes from 2014

Figure 4: (a) The observed static wind frequency (SWF) distributions averaged for November and December in 2015; (b) Changes from 2014. The thick lines indicate the WSCL in 2015.

In Beijing, the WSCL shifting in 2105 not only increased the SWF but also changed the wind directions. It is shown from Figure 5 that the north-west winds that usually diffuse the air pollution away from Beijing were reduced by about 16% in November and December of 2015 compared to the same period in 2014, while the south-west and north-east wind frequencies were increased by 11% that brought air pollution to Beijing. Compared to Beijing, the city of Shijiazhuang was not seen such a large change (Fig. 5). The SWF in Shijiazhuang was reduced, indicating a slightly better diffusing conditions compared to 2014, and the northerly wind frequency was even increased from about 20% in 2014 to 23% in 2015.

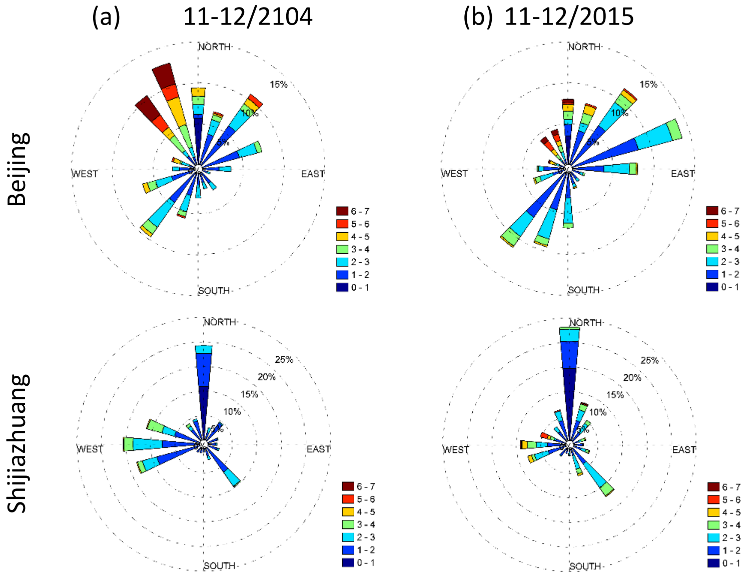

(a) 11-12/2104
(b) 11-12/2015

Figure 5: (a) The observed wind frequency and directions averaged for November and December in 2014; (b) for 2015, respectively for Beijing and Shijiazhuang

The second consequence of the WSCL shifting is the northerly movement of moisture from the South. Figure 6 shows the averaged relative humidity (RH) for November and December of 2015 (Fig. 6a) and changes from 2014 (Fig. 6b). It is obvious that as the shift of the WSCL to North, the RH increases are primarily on the north side of the WSCL with an increase of more than 27% in Beijing (other cities in Table 2). The impact of increasing RH has an adverse influence on the visibility under the same loading of particulate matters and also promotes the formation of secondary formation of particulate matters from gaseous species. Because of the WSCL shifting, the increase of RH in Shijiazhuang was even larger than that in Beijing, at about 30%. Researches [*Chang et al.*, 2009] have shown that the extent of SO_2 oxidation to sulfate and NO_2 oxidation to nitrate increased with the increase of relative humidity during both of the episode daytime and nighttime pollution in Taiwan. Gund et al. [1991] found that the oxidation rate of SO_2 to sulfate could increase by about 10 times if the RH increased from 40 to 80% in sea-salt aerosols. If NO_2 (SO_2:NO_2 = 1:1) was added to the gas phase, the rate for example at a RH of 40% - could be increased by 24 times, indicating the enhanced conversion tendency of SO_2 to $PM_{2.5}$ by both RH and NO_2 [*Gund et al.*, 1991]. Though the detailed mechanism of this enhanced oxidation in Northern China needs further study, the increased RH may partially be attributed to the decreases of SO_2 during the heavy pollution months in 2015 winter as compared to the same period of 2014 (Table 1).

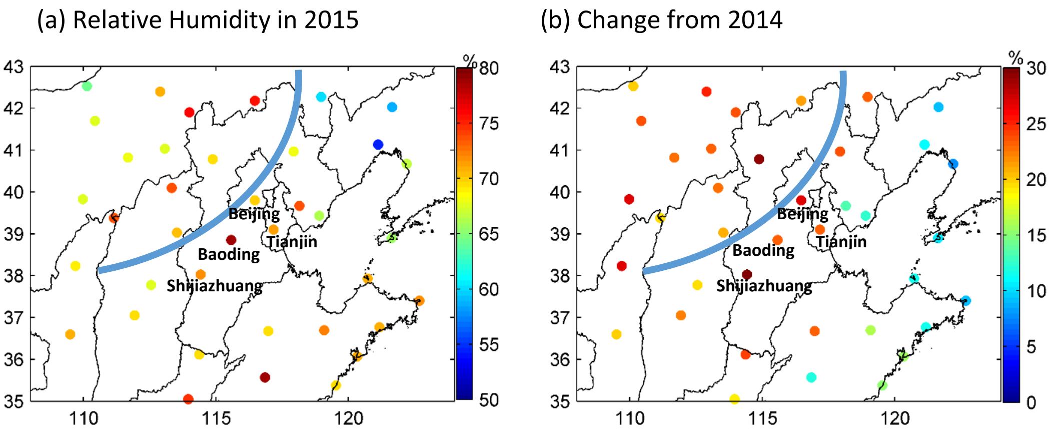

(a) Relative Humidity in 2015 (b) Change from 2014

Figure 6: (a) The observed relative humidity distributions averaged for November and December in 2015; (b) Changes from 2014. The thick lines indicate the WSCL in 2015.

5. Modeling Analysis

In order to further explore the meteorological impact on the changes of the air pollution situation between Decembers of 2014 and 2015, a comparison of two year's simulations with the same emission data was performed for November and December. The differences of the results in any air pollutants can be attributed to the difference in the meteorological conditions.

The integrated GRAPE-CUACE model has been used to provide haze simulation and forecasts in China and East Asia [*Hong Wang et al.*, 2010]. GRAPES_Meso is the real-time operational weather forecasting model used by the CMA, which includes 3-D meteorological field data assimilation, a fully compressible non-hydrostatical model core as well as a modularized physics package. The model's temporal discretion uses a semi-implicit and semi-Lagrangian temporal advection scheme [*R Zhang and Shen*, 2008]. The CUACE is an atmospheric chemistry module including an emission inventory system, gaseous/aerosol and chemistry processes, as well as related thermodynamic equilibrium modules for processing the transformation between gas and particle matter [*S.L. Gong et al.*, 2003; *H. Wang et al.*, 2009; *Zhou et al.*, 2012]. The Sparse Matrix Operator Kernel Emissions system (SMOKE) was used to transform the 2010 HTAP emission inventory data into the hourly-gridded data.

The mode was run with a horizontal resolution of 9 km centering at the Baoding city of Hebei Province. Two months (November and December) of simulations were done for 2014 and 2015, respectively, with the result differences presented for the analysis.

Figure 7a shows the December $PM_{2.5}$ concentration difference between 2015 and 2014. It is clear that the meteorological conditions alone have contributed to the worsening air quality ($PM_{2.5}$) in Northern China, with a high degradation of about 50-90 μg m^{-3} in the southern Beijing and southern Hebei regions in December 2015, corresponding well with WSCL from the surface meteorological data analysis (Fig. 3), which indicates the more stable zone moving to closer to southern Beijing.

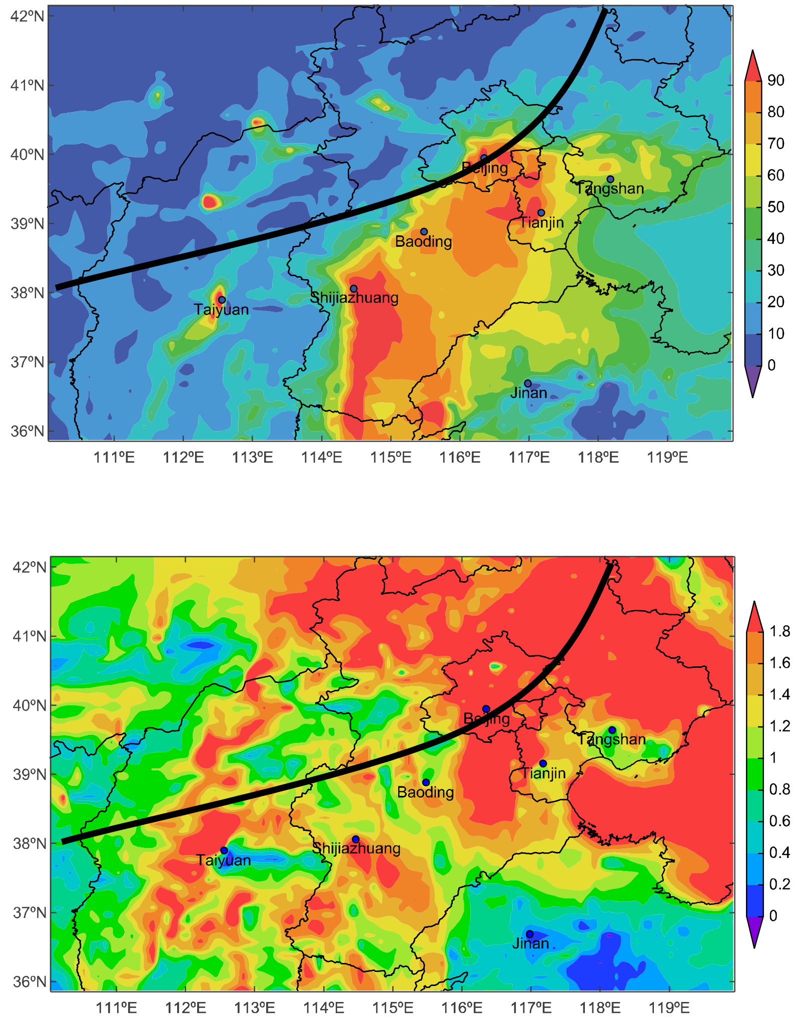


Figure 7: (a) Simulated $PM_{2.5}$ concentrations difference between December of 2015 and 2014. (b) $PM_{2.5}$ fractional difference. The thick black lines indicate the WSCL in 2015.

From the modeling results, it can also be found out that the $PM_{2.5}$ difference percentage due to meteorological difference between December 2014 and 2015 for the major cities in Northern China is in the range of 40-180% (Fig. 7b), a system-wide negative impacts on air quality in the region in 2015. This simulated difference is a comprehensive consequence of the meteorological impacts, including the circulation, dispersing ability, deposition, transports and chemical reactions.

It is well known that the $PM_{2.5}$ concentrations are determined by three major factors: emissions, meteorology and atmospheric processes. Given that the degree of meteorological impacts was simulated by the model as well as the observed differences between December 2014 and 2015 were known, the impact from emission changes can be inferred from the observed differences and the simulated meteorological impacts.

Table 3 is a summary of the difference for major cities in Northern China between December 2014 and 2015. The observed percentage changes are all smaller than those by simulations, indicating that if no emission controls measures were taken during this period, the observed difference would be much larger than the reality. Therefore, it can be deduced that despite of the un-favorite weather conditions that worsened the air quality in December 2015, the control measures have made a great contribution to reduce the ambient concentrations in the region.

For Beijing region, the simulation indicates that the difference between meteorological conditions in December 2014 and 2015 would contribute to more than 168% of $PM_{2.5}$ monthly mean concentration difference under the same emissions. Compared with observed difference

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(162%), it can be estimated that emission control would contribute about 8% in the mitigation of $PM_{2.5}$ in Beijing. The emission control effects varies from city to city, ranging from 8% in Tianjin to about 40-50% in Langfang and Baoding (Table 3).

Table 3: Comparison of observed and simulated $PM_{2.5}$ in December 2015 and 2014

City	Observed $PM_{2.5}$ (μg m^{-3})			Simulated $PM_{2.5}$ (μg m^{-3})		
	2014	2015	Diff (%)	2014	2015	Diff (%)
BJ	58	151	162.5	35	94	168.6
LF	97	165	70.4	44	93	111.4
BD	168	214	27.3	78	139	78.2
TJ	107	125	17.7	75	94	25.3

6. Conclusions

The meteorological data analysis and modeling study of 2015 winter heavy haze pollution episodes were carried out to explore the causes of the unusual increase of haze ($PM_{2.5}$) in November and December. It is found out that the monthly mean $PM_{2.5}$ concentrations in December 2015 saw a large increase compared to the same month in 2014, ranging from 163% to 17%. As unusual atmospheric circulation in winter 2015 (El Niño event), the warm and wet flow has been enhanced in North China and the WSCL has shifted northerly compared to that in 2014. The SWH and RH increase 7 and 27% in Beijing, respectively. These changes of meteorology brought more static stable weather, which was the primary responsibility for degradation of air pollution in winter 2015. Modeling analysis further confirmed that the

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meteorological conditions contributed to the worsening air quality in North China in winter 2015, with the $PM_{2.5}$ concentration for the major cities in December 2015 increased 25-168% compared to the same period of 2014. With the same emission data in the modeling study for 2014 and 2015, the relative changes of pollution level between two years were larger than the those from the observation, indicating the control measures have effectively brought the $PM_{2.5}$ down to compensate the negative meteorological impacts.

Acknowledgments

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