Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-204, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 4 April 2016

Atmospheric Chemistry and Physics Discussions
Open Access

Contributions of meteorology and emission to the 2015 winter severe haze pollution episodes in Northern China

Ting Ting Liu[1,2], Sunling Gong[2], Meng Yu[3], Qi Chao Zhao[4], Huai Rui Li[4], Jian Jun He[5], Jie Zhang[3], Lei Li[3], Xu Guan Wang[3], Shu Li Li[3], Yan Li Lu[3], Hai Tao Du[6], Ya Qiang Wang[2], Chun Hong Zhou[2], Hong Li 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.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-204, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 4 April 2016

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 Northern 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, a steady decrease of air pollutant concentrations has been observed with an annual mean $PM_{2.5}$ concentration drop from about 85 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 Shijianzhuang (http://www.mep.gov.cn/gkml/). These decreases partially can attribute to the difference in the meteorology conditions but largely should attribute to the control measures taken.

However, the year of 2015 was an unusual year in terms of air pollution situation in Northern China. In the first half of the year, a steady decrease in major air pollutants was observed compared to 2014. However, in the last two months, a dramatic increase was found. The $PM_{2.5}$ concentration reached as high 1000 μg m^{-3} in Beijing and triggered the first ever Red Alert of severer air pollution in the city.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-204, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 4 April 2016

Atmospheric Chemistry and Physics Discussions

It is well known that different seasons and geographic locations will influence haze pollution, which is closely related to local emission characteristics and meteorological conditions [*Huang et al.*, 2013; *W Li et al.*, 2011; *L Wang et al.*, 2012]. In order to effectively reduce the emissions, a detailed and accurate understanding of $PM_{2.5}$ sources, their temporal and spatial variations as well as their relationship with meteorology are needed to determine the exact composition of $PM_{2.5}$ in Northern China[*W Li et al.*, 2011; *X Li et al.*, 2015; *J Tao et al.*, 2014a] where the scientific control measures can be formulated. Source apportionment of $PM_{2.5}$ is usually based on analysis of its detailed chemical compositions, with source-related information indicated by different chemical compositions to analyze the contributions from different sources [*Du et al.*, 2011; *M Tao et al.*, 2014b]. However, the source contributions will be changed by the time-varying emissions and affected by a changing meteorology [*H Wang et al.*, 2014; *S Zhang et al.*, 2014], which makes it very difficult to separate the relative contributions of them. The year 2015 is in the middle of an El Nino event around the globe [*Varotsos et al.*, 2016]. Unusual climate and extreme weather happened everywhere. 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].

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 of

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 is also simulated with the Chinese Unified Atmospheric Chemistry Environment (CUACE) model [*Gong and Zhang*, 2008] coupled with GRAPES_Meso, which is a numerical weather prediction model and has been developed in accordance with strict software engineering requirements [*Chen et al.*, 2016; *R Zhang and Shen*, 2008]. The integrated GRAPE-CUACE model [*H Wang et al.*, 2010; *L Wang et al.*, 2015] provides haze simulation and forecasts in China and East Asia[*L Wang et al.*, 2012; *R Zhang and Shen*, 2008]. The aim of this study was to provide information on the impact degree and mechanism of meteorology variations on the $PM_{2.5}$ haze pollution in this region.

2. 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. Looking at 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 PM2.5 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 in 2015 compared to 2014 would be 21%, 25.3%, 16.8% and 34.9% for Beijing,

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-204, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 4 April 2016

Atmospheric Chemistry and Physics
Open Access
Discussions

Langfang, Baoding and Shijiazhuang, respectively, indicating the impact of the unusual increases in December on the annual means for these cities.

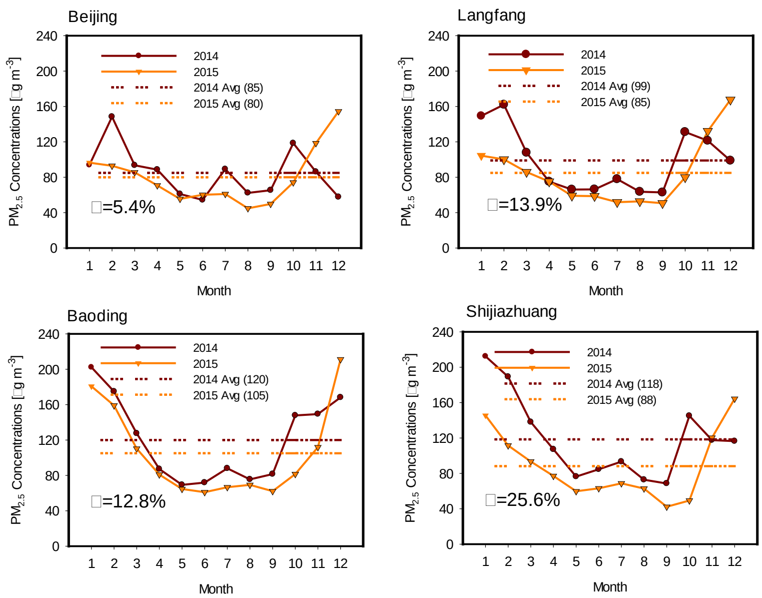

Figure 1: Comparison of monthly mean $PM_{2.5}$ concentrations of 2015 and 2014 in Northern China in four cities

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 17% (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.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-204, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 4 April 2016

Atmospheric Chemistry and Physics Discussions
Open Access

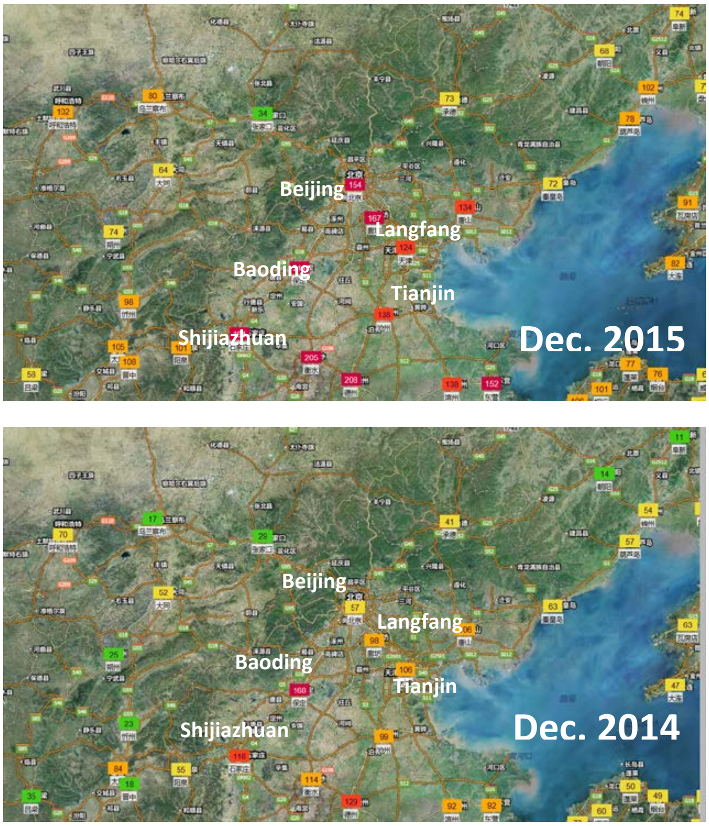

Figure 2: Comparison of monthly mean PM2.5 concentrations of December 2015 and 2014 in Northern China

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	58	151	162.5	27	19	-30.4	1.54	2.86	85.5	53	76	44.5
LF	97	165	70.4	52	40	-22.4	1.92	3.06	59.2	53	76	42.8
SJZ	116	162	39.8	112	75	-33.3	2.23	3.27	46.4	64	76	19.6
BD	168	214	27.3	144	92	-36.3	4.14	4.64	12.2	75	99	31.8
TJ	107	125	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

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-204, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 4 April 2016

Atmospheric Chemistry and Physics Discussions
Open Access

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 10 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.

3. Meteorology Factor Analysis

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). 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

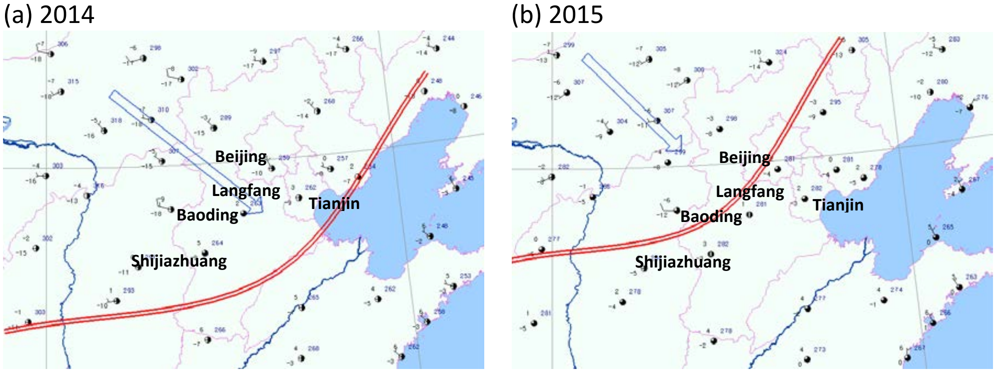

Figure 3: The wind speed convergence lines (WSCL) for November and December. (a) 2014 and (b) 2015

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-204, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 4 April 2016

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. As a coastal city, Tianjin was better than other cities (~38%).

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

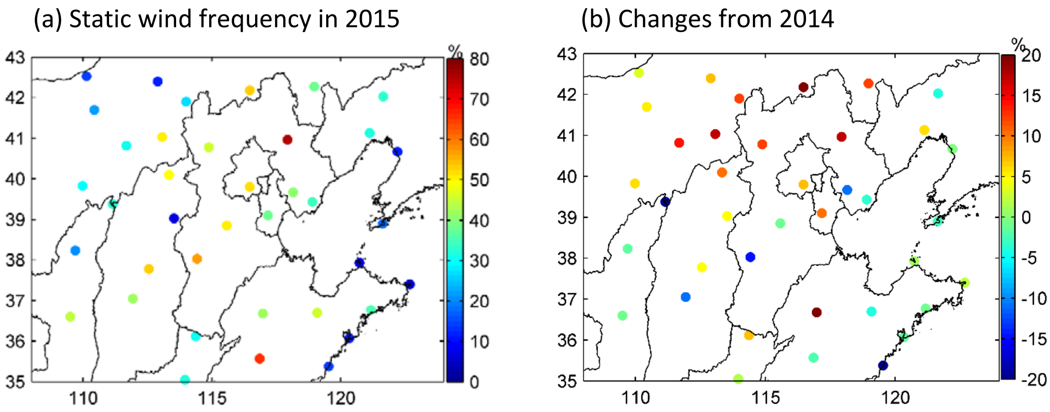

Figure 4: (a) The observed static wind frequency (SWF) distributions averaged for November and December in 2015; (b) Changes from 2014.

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.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-204, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 4 April 2016

Atmospheric Chemistry and Physics
Discussions
Open Access

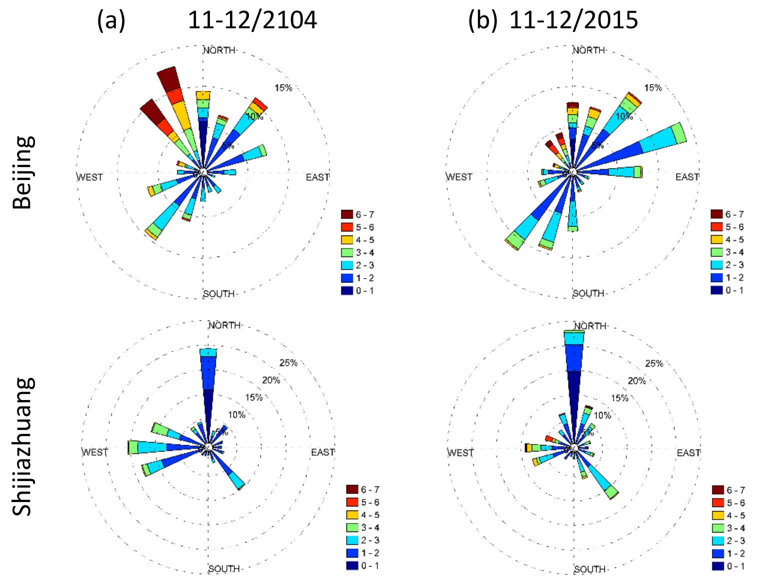

Figure 5: (a) The observed wind frequency and directions (SWF) averaged for November and December in 2014; (b) for 2015, respectively for Beijing and Shijiazhuang

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

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-204, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 4 April 2016

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).

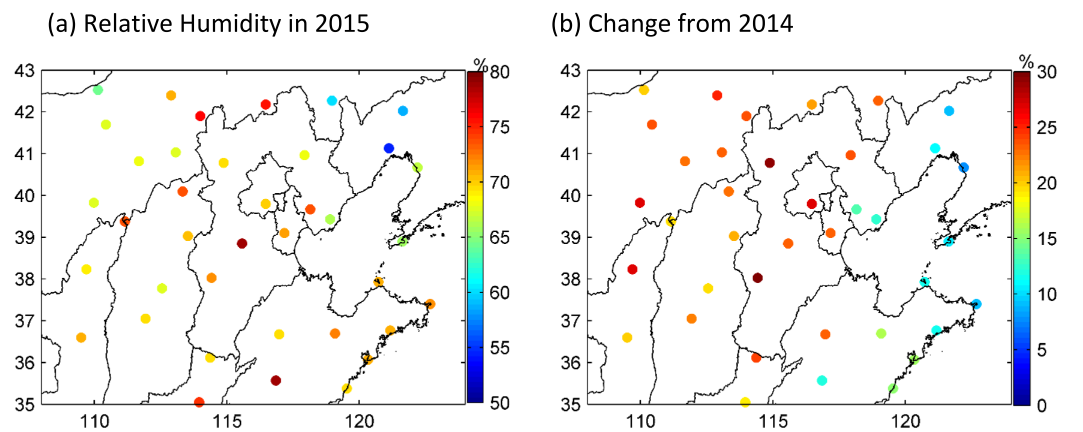

Figure 6: (a) The observed relative humidity distributions averaged for November and December in 2015; (b) Changes from 2014.

4. Modeling Results

In order to further explore the meteorological impact on the changes of the air pollution situation between 2014 and 2015, a comparison of two years simulations with the same emission data was performed for November and December. The differences of the results in

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-204, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 4 April 2016

any air pollutants can be attributed to the difference in the meteorological conditions. The CUACE model is run with a resolution of 9 km.

Figure 7 shows the December $PM_{2.5}$ concentration difference between 2015 and 2014. It is clear that the metrological 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.

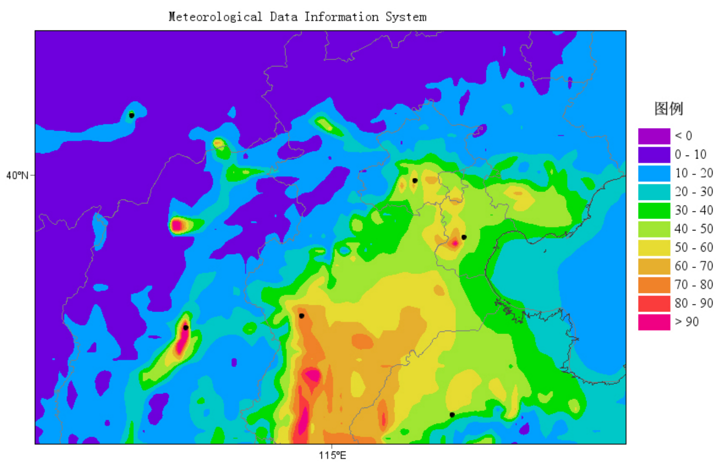

Figure 7: Simulated $PM_{2.5}$ difference between December of 2015 and 2014.

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. 8), a system-wide negative impacts on air quality in the region. This simulated difference is a comprehensive consequence of the

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-204, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 4 April 2016

meteorological impacts, including the circulation, dispersing ability, deposition, transports and chemical reactions.

Table 3 is a summary of the difference for major cities in Northern China. 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.

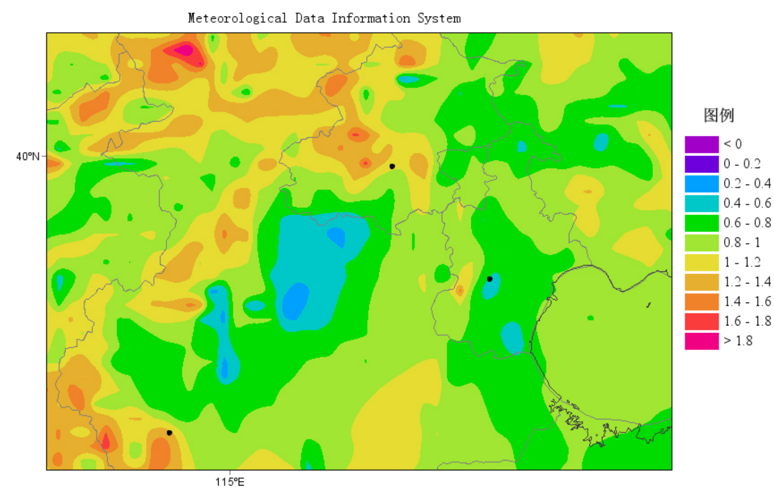

Figure 8: Simulated $PM_{2.5}$ percentage difference between December of 2015 and 2014.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-204, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 4 April 2016

Atmospheric Chemistry and Physics
Discussions
Open Access

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

City	Observed $PM_{2.5}$ ($\mu g\ m^{-3}$)			Simulated $PM_{2.5}$ ($\mu g\ m^{-3}$)		
	2014	2015	Diff (%)	2014	2015	Diff (%)
BJ	58	151	162.5	35	94	168.6
LF	97	165	70.4	44	93	111.4
SJZ	116	162	39.8	51	123	141.2
BD	168	214	27.3	78	139	78.2
TJ	107	125	17.7	75	94	25.3

5. 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 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 meteorological conditions contributed to the worsening air quality in North China in winter 2015. The $PM_{2.5}$ concentration for the major cities in North China in December 2015 increased 40-180% compared to the same period of 2014. With the same emission data in modeling for 2014 and

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-204, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 4 April 2016

Atmospheric Chemistry and Physics Discussions

2015, the relative changes of pollution level between two years from modeling were larger than observation, indicating the great contribution of the control measures.

Acknowledgments

This research was financially supported by the National Natural Science Foundation of China (No.51305112).

Reference:

Chang, L. P., Y. C. Yao, C. F. Liao, S. W. Chiang, and J. H. Tsai (2009), Influence of ozone and humidity on the formation of sulfate and nitrate in airborne fine particles, *Journal of Environmental Science and Health Part A*, *44*(8), 767-777.

Chen, L., J. Chen, J. Xue, and Y. Xia (2016), Development and testing of the GRAPES regional ensemble-3DVAR hybrid data assimilation system, *Journal of Meteorological Research*, *29*(6), 981-996, doi:10.1007/s13351-015-5021-y.

Du, H., L. Kong, T. Cheng, J. Chen, J. Du, L. Li, X. Xia, C. Leng, and G. Huang (2011), Insights into summertime haze pollution events over Shanghai based on online water-soluble ionic composition of aerosols, *Atmospheric Environment*, *45*(29), 5131-5137, doi:10.1016/j.atmosenv.2011.06.027.

Gong, S. L., and X. Y. Zhang (2008), CUACE/Dust - an integrated system of observation and modeling systems for operational dust forecasting in Asia, *ATMOSPHERIC CHEMISTRY AND PHYSICS*, *8*, 2333-2340, doi:10.5194/acp-8-2333-2008.

Gund, G., F. Wien, and W. Weisweiler (1991), Oxidation of S02 to sulfate in sea salt aerosols, *Fresenius J Anal Chem*, *340*, 616-620.

Gurjar, B. R., A. Jain, A. Sharma, A. Agarwal, P. Gupta, A. S. Nagpure, and J. Lelieveld (2010), Human health risks in megacities due to air pollution, *Atmospheric Environment*, *44*(36), 4606-4613, doi:10.1016/j.atmosenv.2010.08.011.

Han, X., M. Zhang, J. Tao, L. Wang, J. Gao, S. Wang, and F. Chai (2013), Modeling aerosol impacts on atmospheric visibility in Beijing with RAMS-CMAQ, *Atmospheric Environment*, *72*, 177-191, doi:10.1016/j.atmosenv.2013.02.030.

Huang, K., G. Zhuang, Y. Lin, Q. Wang, J. S. Fu, Q. Fu, T. Liu, and C. Deng (2013), How to improve the air quality over megacities in China: pollution characterization and source analysis in Shanghai before, during, and after the 2010 World Expo, *Atmospheric Chemistry and Physics*, *13*(12), 5927-5942, doi:10.5194/acp-13-5927-2013.

Kan, H., R. Chen, and S. Tong (2012), Ambient air pollution, climate change, and population health in China, *Environ Int*, *42*, 10-19, doi:10.1016/j.envint.2011.03.003.

Li, W., S. Zhou, X. Wang, Z. Xu, C. Yuan, Y. Yu, Q. Zhang, and W. Wang (2011), Integrated evaluation of aerosols from regional brown hazes over northern China in winter: Concentrations, sources, transformation, and mixing states, *Journal of Geophysical Research*, *116*(D9), doi:10.1029/2010jd015099.

Li, X., et al. (2015), Source contributions of urban PM2.5 in the Beijing–Tianjin–Hebei region: Changes between 2006 and 2013 and relative impacts of emissions and meteorology, *Atmospheric Environment*, *123*, 229-239, doi:10.1016/j.atmosenv.2015.10.048.

Tao, J., L. Chen, x. Xiong, M. Zhang, P. Ma, J. Tao, and Z. Wang (2014a), Formation process of the widespread extreme haze pollution over northern China in January 2013: Implications for regional air quality and climate, *Atmospheric Environment*, *98*, 417-425, doi:10.1016/j.atmosenv.2014.09.026.

Tao, M., L. Chen, Z. Wang, P. Ma, J. Tao, and S. Jia (2014b), A study of urban pollution and haze clouds over northern China during the dusty season based on satellite and surface observations, *Atmospheric Environment*, *82*, 183-192, doi:10.1016/j.atmosenv.2013.10.010.

Varotsos, C. A., C. G. Tzanis, and N. V. Sarlis (2016), On the progress of the 2015–2016 El Niño event, *Atmospheric Chemistry and Physics*, *16*(4), 2007-2011.

Wang, H., S. Gong, H. Zhang, Y. Chen, X. Shen, D. Chen, J. Xue, Y. Shen, X. Wu, and Z. Jin (2010), A new-generation sand and dust storm forecasting system GRAPES_CUACE/Dust: Model development, verification and numerical simulation, *Science Bulletin*, *55*(7), 635-649, doi:10.1007/s11434-009-0481-z.

Wang, H., J. Xu, M. Zhang, Y. Yang, X. Shen, Y. Wang, D. Chen, and J. Guo (2014), A study of the meteorological causes of a prolonged and severe haze episode in January 2013 over central-eastern China, *Atmospheric Environment*, *98*, 146-157, doi:10.1016/j.atmosenv.2014.08.053.

Wang, L., et al. (2008), A Modeling Study of Coarse Particulate Matter Pollution in Beijing: Regional Source Contributions and Control Implications for the 2008 Summer Olympics, *Journal of the Air & Waste Management Association*, *58*(8), 1057-1069, doi:10.3155/1047-3289.58.8.1057.

Wang, L., Z. Wei, W. Wei, J. S. Fu, C. Meng, and S. Ma (2015), Source apportionment of PM2.5 in top polluted cities in Hebei, China using the CMAQ model, *Atmospheric Environment*, *122*, 723-736, doi:10.1016/j.atmosenv.2015.10.041.

Wang, L., J. Xu, J. Yang, X. Zhao, W. Wei, D. Cheng, X. Pan, and J. Su (2012), Understanding haze pollution over the southern Hebei area of China using the CMAQ model, *Atmospheric Environment*, *56*, 69-79, doi:10.1016/j.atmosenv.2012.04.013.

Zhang, R., and X. Shen (2008), On the development of the GRAPES——A new generation of the national operational NWP system in China, *Science Bulletin*, *53*(22), 3429-3432, doi:10.1007/s11434-008-0462-7.

Zhang, S., et al. (2014), Historic and future trends of vehicle emissions in Beijing, 1998-2020:A policy assessment for the most stringent vehicle emission control program in China, *Atmospheric Environment*, *89*, 216-229, doi:10.1016/j.atmosenv.2013.12.002.