Gravity-Current Driven Transport of Haze from North China Plain to Northeast China in Winter 2010-Part I: Observations

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Abstract

Haze exerts a large effect on visibility reduction and has serious impacts on air quality and human health. Understanding the sources and transport of haze is of importance to improve the regional air quality and evaluate its health effects. In this study, we investigated a typical haze episode that occurred in northeast (NE) China during 4−6 November 2010 by analyzing the ground PM_{10} measurements from 11 monitoring sites, aerosol Lidar observations, synoptic charts, MODIS satellite imageries, and back trajectories. Our analyses suggest that the regional haze formed in the North China Plain (NCP) under stagnant conditions can be transported to NE China in ~1−3 days across Bohai Bay and Liaodong Bay − a typical transport pathway associated with the topography of northern China. The haze episode appeared to evolve progressively from southwest to northeast in the region of NE China, in agreement with the appearance of PM_{10} peak values, wind patterns, MODIS images and the back trajectories of air masses. Due to the haze impact, NE China showed significantly elevated particulate matter pollution by a factor of ~4−6 with the peak concentrations reaching ~410 μg m^{-3}. The results together indicate that the regional transport from the NCP has a significant contribution to the PM pollution in NE China, thus efforts to control the source emissions over the NCP would be effective to improve the air quality in NE China.

1. Introduction

Due to its rapidly expanding economic and industrial developments, China is currently considered to be the engine of world's economic growth. In the course of this expansion, medium-sized cities and small towns have sprung up around the larger cities, forming city clusters with similar or interdependent economies, e.g., the North China Plain (Beijing-Tianjin-Bohai: NCP) and the Northeast Plain (NE China) − two large city clusters in Northern China (Shao et al. 2006). The combination of rapid economic growth and urbanization has led to rapidly deteriorating air quality throughout China, which is the worst in city clusters. Urban haze, an atmospheric phenomenon that leads to low visibility, has increased in occurrence in city clusters over the last several years, due to the continuous economic growth and the increasing of consumption of fossil fuels. With the increasing number of regional haze episodes reported by media, much attention has been paid to reducing air pollutant emissions in region to improve air quality (Streets et al. 2007). Although the air pollution has a large impact on public health, the actual regional pollution control measures were mainly implemented within the city clusters due to the cost-effectiveness and feasibility of pollution control measures. The cooperation for simultaneous reduction of the source emissions among different city clusters is rather limited.

The formation of urban haze episode depends on meteorological conditions (e.g., stagnant air), emission intensity, e.g., the increasing of motor vehicles (Tan et al. 2009), distribution of emissions and certain episode-prone orography restricting the dispersion of pollutants, meanwhile, middle or long range transport of pollutants also play an important role (Ramanathan et al. 2001). Due to the diversity and large-scale of synoptic patterns, pollutants from one city cluster can affect its receptor in the downwind via regional transport, and the harmful effects to the receptor are of great concern.

NE China was the former national center for heavy industry. In recent years, some high-pollution enterprises have been closed down, ordered to cut down production, amalgamated with others, or required to switch to other products, due to the growing environmental pressures. The contributions of local emissions to the air pollution in the NE China thus have been much reduced. However, high particulate matter pollution episodes were frequently observed due to the regional transport. During 4−6 November 2010, the NE China city cluster suffered severe haze pollution. Our results suggest that the haze episode occurring in NE China was mainly due to the regional transport from the NCP city cluster. Given the current control measures pay less attention on cooperation with adjacent city clusters, results in this study have important implications for the air pollution control strategies on a regional scale.

In this paper, we investigate the sources and transport of the haze episode with multi-source observations. The results of air quality model and the contribution of regional transport to the haze formation are presented in a consecutive paper. A brief description of the dataset is presented in Section 2. The urban haze episode occurring in NE China city cluster is described in Section 3. Section 4 discusses the main results and interpretations.

2. Dataset

Hourly concentrations of PM_{10} were analyzed using the automatic sampling data from the intensive observations in the winter of 2010, which were measured by Liaoning, Jilin and Heilongjiang province Environmental Monitoring center under the support of commonweal project in Ministry of Environmental Protection. To estimate regional transport, four air quality monitoring sites (Fig. 1, red points) were carefully selected from the data set. The four sites are located in a southwest-northeast line, ~100−300 km between each other, and Yingkow (YK) is located near the Bohai bay, more sensible with the air pollution from NCP; TieLing (TL) and LiaoYang (LY) are the representative cities in the Liaoning central city cluster; Jilin (JL) is set up at a remote area. There are no large anthropogenic pollution sources like power plants and highway in the vicinity of these sites. Thus, they are representative for studying the regional transport.

A regional air quality observation network covering NCP was used to provide surface hourly PM_{10} observational data. It has been applied to assess the air quality of Beijing and its surrounding areas during the Beijing 2008 Olympic Games (Xin et al. 2010). The distribution of seven monitoring sites of this network is shown in Fig. 1 with blue points.

The Lidar was set up at the State Key Laboratory of Atmospheric Boundary Layer and Atmospheric Chemistry at the Institute of At-

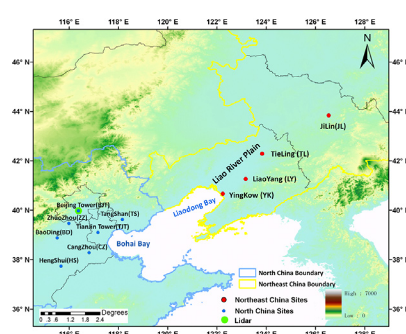

Fig. 1. Geographical locations of the PM_{10} monitoring in NCP and NE China. The Lidar measurements were conducted at IAP, CAS, Beijing (green solid circle).

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mospheric Physics (IAP) (39°58′N, 116°22′E), Chinese Academy of Sciences in Beijing, about 2 km away from the Olympic Stadium (the "Bird's Nest"). This is a highly polluted urban site (Fig. 1). Regular Lidar measurements were conducted in Nov. 2010. Details of the Lidar parameters and operations can be found in Yang et al. (2010) and Shimizu et al. (2011).

3. Impact of haze on ambient air quality in NE China

Figure 2 shows the time series of the hourly PM_{10} concentration from air quality monitoring stations YK, LY, TL and JL in NE China. The PM_{10} concentration peaked at 20:00 LST (Fig. 2a) on 4 Nov. 2010 at YK station at about 177 μg m^{-3}, rising from 112 μg m^{-3} in two hours. The average concentration at YK station was 108 μg m^{-3} during the episode, whereas the daily PM_{10} concentration remained at 40−50 μg m^{-3} without haze impact. It is apparent that the haze from the regional transport on average contributed to more than half of the PM pollution at YK during this case. The second station LY is located ~100 km northeast of YK (Fig. 1). The PM_{10} concentration firstly peaked at 07:00 LST on 5 Nov. at LY station at about 201 μg m^{-3}, approximately 11 hours later than the first station YK (Fig. 2b).The third station TL is located ~115 km northeast of LY (Fig. 1). The PM_{10} concentration firstly peaked at 00:00, 6 Nov. 2010 at TL station at about 304 μg m^{-3}, approximately 17 hours later than the second station LY (Fig. 2c). The last station JL located ~300 km northeast of the third station TL (Fig. 1), peaking at 18:00, 6 Nov. 2010, 18 hours later than the adjacent TL station (Fig. 2d). The four monitoring sites in NE china (YK, LY, TL and JL) are located in an approximate straight line from southwest to northeast with the distances ~100−300 km between each other. The appearances of peak values of PM_{10} followed the order of YK→LY→TL→JL, indicating a progressive transport of the haze from southwest to northeast. Also note that the haze can be transported hundreds of kilometers in ~1−2 days, and affects the air quality over a large scale.

4. Source identification and the regional transport

4.1 Synoptic meteorology patterns

Mainland China was dominated by a high-pressure system centered in Siberian, with small cold air persistently moving southward (figure not shown). The above synoptic pattern, occurring in NCP and NE China, was often responsible for air pollution episodes (Su et al. 2004a, b; Zhang et al. 2010). To give a clear picture about the wind vector in the study region, Weather Research and Forecasting (WRF) model was employed to conduct mesoscale meteorological simulations to help understand the regional transport during the episode. The model configuration and validation have been described in the Supplement 1. Surface winds (at height of 10 m) were used to investigate the synoptic patterns over East China. During the haze episode, consistently westerly-southwesterly winds at the average wind speeds of ~2−4 m s^{-1} were observed above the Bohai Sea and NE China (red rectangle, Fig. 3) The synoptic wind patterns and wind speeds together led to a transport of the haze from the southwest to the northeast at a speed of ~170−350 km day^{-1}, consistent with the appearance of peak values of PM_{10} at four sites in NE China.

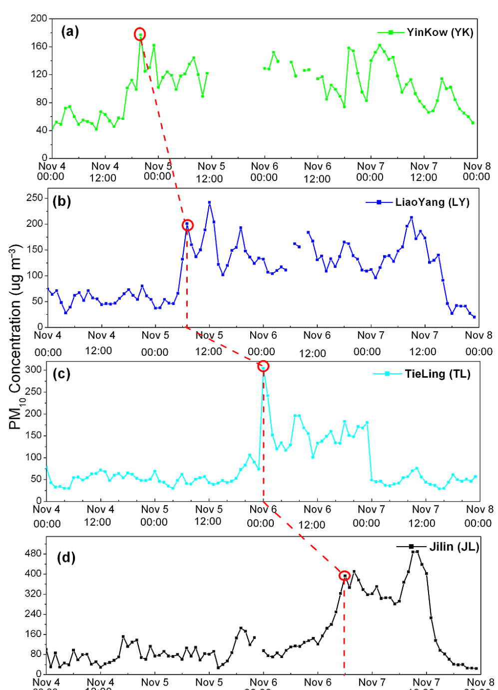

Fig. 2. The PM_{10} hourly concentration in the haze episode (4 Nov. to 6 Nov. 2010) at (a) Yinkow (YK), (b) LiaoYang (LY), (c) TieLing (TL) and (d) JiLin (JL) (Local Standard Time: LST)

4.2 Haze episode in NCP

a. Variations of PM_{10} concentration in NCP

The variations of hourly PM_{10} concentration variations at seven representative sites in NCP are shown in Fig. 4. A typical extended pollution episode associated with the stagnant conditions (e.g., low wind speed in Fig. 3a) occurred between late 3 Nov. and 6 Nov. when the hourly PM_{10} concentration exceeded the Chinese National Ambient Air Quality Standard− Grade II (CNAAQS, GB3095-1996) of 150 μg m^{-3} for at least 18 hours each day at all sites. The PM_{10} concentration reached its first peak 520 μg m^{-3} at 6:00 LST on 4 Nov., jumping from 168 μg m^{-3} in two hours, and presented a maximum of 771 μg m^{-3} at 10:00 LST on 5 Nov. at TS site. The particulate matter remained at a high concentration level from 4 to 6 Nov. with the three-day average ~340 μg m^{-3} at all sites, which is more than twice higher than CNAAQS Grade-II. The high PM_{10} concentrations make the NCP as a potential source region of haze for the high PM pollution observed in NE China.

b. Lidar observations in Beijing

Given that the aerosol properties may vary significantly as a function of height, knowledge of the vertical distribution of aerosols in the atmosphere is thus important to study regional transport (Ramanathan et al. 2001; Satheesh et al. 2006; Sugimoto et al. 2010). The vertical distribution of aerosols over at the urban location, Beijing in the central NCP, was examined using a Lidar system. The boundary-layer dynamics and its impact on regional transport are investigated. Figure 5 shows the Lidar-derived aerosol backscatter profile at 532 nm from 4 to 6 Nov. 2010 when the haze episode occurred. The time reported in Fig. 5 is Local Standard Time (LST). The haze episode was first observed during the late noon of 4 Nov., and the aerosol profile showed a strong turbulent mixing, lifting the aerosols upwards. Thus, the aerosol layer deepens significantly to reach as high as about 2.2 km (from ~1 km at early in the morning), a height which favors the long-range transport (Badarinath et al. 2010). A clean aerosol layer is observed in the morning of 5 Nov. in Beijing, due to the high pressure system in the northwest pushing the regional haze to the east and southeast. The haze appeared to circulate in the NCP for ~1 day on 4 Nov., and then quickly moved to NE China

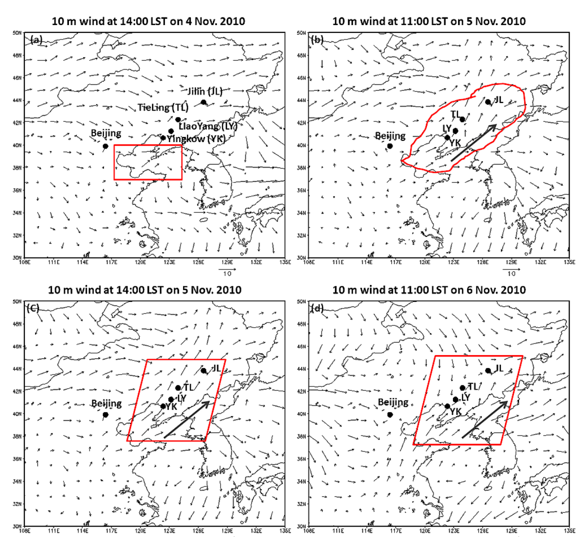

Fig. 3. Distribution of wind vector simulated by WRF model, corresponding with the MODIS True color composite images acquisition moment, during the haze episode (a) 14:00 LST on 4 Nov. 2010; (b) 11:00 LST on 5 Nov. 2010; (c) 14:00 LST on 5 Nov. 2010; (d) 11:00 LST on 6 Nov. 2010 (LST: Local Standard Time). Red rectangle represents research interest region.

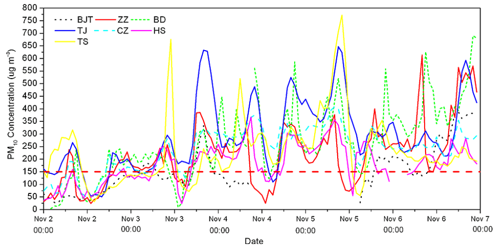

Fig. 4. The hourly PM_{10} concentration during the haze episode (2 Nov.− 6 Nov. 2010) in BJT (Institute of Atmospheric Physics (IAP), CAS), ZZ (Zhuozhou), BD (Baoding), TJ (Tianjin), CZ (Cangzhou), HS (HengShui) and TS (Tangshan) sites. Data missing is between 10:00 LST on 4 Nov. and 15:00 LST on 5 Nov. for PM_{10} at BJT station.

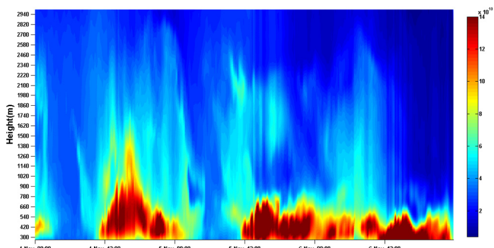

Fig. 5. Evolution of LIDAR range squared corrected signal (RSCS) at 532 nm between 4 Nov. and 6 Nov. 2010. The color scale denotes the intensity of the RSCS and warm colors stand for stronger light scattering and aerosol concentrations. LST (Local Standard Time)

across the Bohai Sea associated with the southwesterly winds. This is further supported by the satellite images and back trajectory analyses in the following sections.

4.3 Satellite observations of the haze episode

Satellite remote sensing has the advantage of being able to monitor the evolution of haze over a large spatial scale. The MODIS true color composite images from 4 to 6 Nov. (http://rapidfire.sci.gsfc.nasa.gov/) are shown in Fig. 6. The satellite image (Fig. 6a) shows a heavy haze over NCP-Bohai Bay while clear sky over Liaodong Bay and NE China on 4 Nov. 2010. Due to the topography of the NCP which is bowl-like and surrounded by the mountainous terrain to the west, north and northeast, the haze can remain near the surface until the meteorological condition changes (Lee et al. 2006). This accumulated haze can travel horizontally to the northeast and reach NE China under certain atmospheric circulation conditions (Lee et al. 2006). In ~1-day, the haze was transported to the Liaodong Bay−Liao River Plain; while the corner of northeast (e.g., North Korea) is still clear (Fig. 6b). The haze over the Liao River Plain appeared to be mixed with scattered cirrus clouds (Fig. 6b). Despite this, the haze quickly evolved to the northeast and impacted the whole NE region in 3 hours (Fig. 6c). The three images (Fig. 6a, 6b, 6c) on 4 and 5 Nov., clearly indicate a transport of regional haze from the NCP to NE China via the Bohai Bay−Liaodong Bay−Liao River Plain. As the regional haze moved further to the northeast, the NCP became clearer (Fig. 6d), consistent with the lower concentrations of PM_{10} in comparison to previous days. The impact of the regional haze on the NE regions ended on 7 Nov., and the PM_{10} concentrations at four sites in the Liao River Plain were all back to the previous concentration levels without haze impact.

The transport height is another important issue we are concerned about. As the NCP−Bohai Bay−Liaodong Bay−Liao River Plain was impacted by the haze episode successively from 4 to 6 Nov. 2010, the East−West the Yan Mountains, separating the NCP and NE China, remained clear over the whole time (Fig. 6). We also employ Froude number (Kaimal and Finnigan 1994) to investigate how the air parcels behave when they meet the barrier (e.g., the Yan Mountains).

Taking the characteristic length of the hill as h (average height of the Yan Mountains is ~400 m), the characteristic velocity in the boundary layer as U, and buoyancy frequency as N, the ratio we require is the Froude number Fr.

$$Fr = \frac{U}{N \times h}, \quad N = \left(\frac{g}{\bar{\theta}} \frac{\partial \bar{\theta}}{\partial z} \right)^{1/2},$$

where g is the gravitational acceleration; $\bar{\theta}$ is the average potential temperature, $\partial\bar{\theta}/\partial z$ is the gradient of average potential temperature. Kaimal and Finnigan (1994) pointed out that 1 is the critical value for Froude number. For $Fr < 1$, the flow will go around the Yan Mountains. For $Fr > 1$, the flow will climb over them. The Froude number between Nov. 1 and Nov. 7 was calculated by Radiosonde measurements (http://weather.uwyo.edu/upperair/sounding.html) at Beijing site. Figure 7 depicts the variation of Froude number in Beijing Site between Nov. 1 and 7. During the haze episode (3−6 Nov. 2010), the average Froude number was 0.5 (significantly lower than critical value: 1), whereas the Froude number was ~1.2−2.5 without haze episode (Fig. 7). Low Froude number illustrates that air masses went around the Yan Mountains and transported to NE China rather than passing over it, corresponding to the satellite observations (Fig. 6). Given that the average height of the Yan Mountains is approximately 400 m, such phenomenon for the haze transport might imply that regional transport mainly occurred in the planetary boundary layer.

4.4 Backward trajectory analysis

To better characterize the transport pathway of air parcels, The NOAA/ARL Hybrid Single-Particle Lagrangian Integrated Trajectory (Draxier and Hess 1998) model driven with hourly WRF output was used to calculate the backward trajectories of air parcels that reached YK, LY, TL and JL at 00 LST, 6 Nov. 2010 (LST = UTC + 8). The 72-hour backward trajectories of air parcels at height of 100 and 400 m are shown in Fig. 8. Hysplit 4 model calculation results showed that the

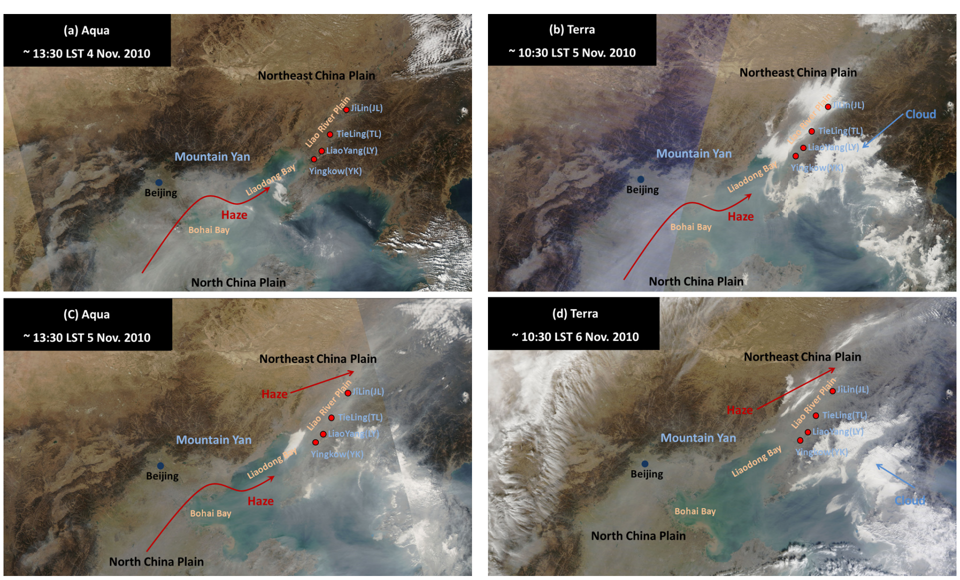

Fig. 6. MODIS True color composite images at around (a) 13:30 LST 4 Nov. 2010: Aqua (b) 10:30 LST 5 Nov. 2010: Terra (c) 13:30 LST 5 Nov. 2010: Aqua (d) 10:30 LST 6 Nov. 2010: Terra. Bright white pixels are clouds and bluish-white hue tint pixels are haze (Engel-Cox et al. 2004).

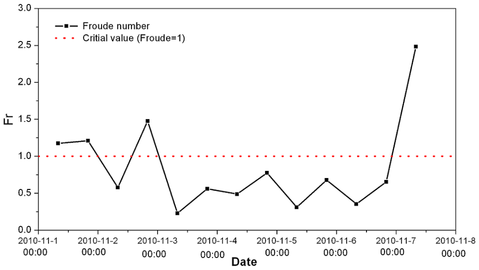

Fig. 7. The variation of Froude number in Beijing Site between Nov. 1 and 7.

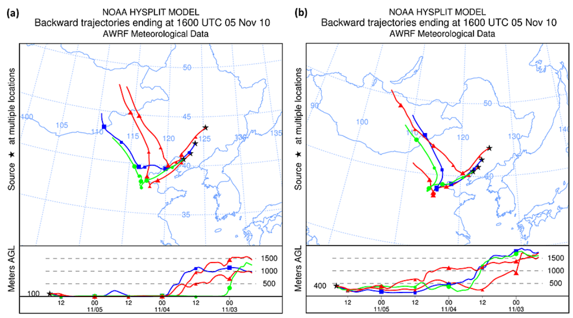

Fig. 8. 72-hour backward trajectory analysis by applying WRF-simulated wind field and NOAA HYSPLIT model, ending at 00:00 LST 06 Nov. 2010 (local standard time, LST = UTC + 8) at the height of (a) 100 m (b) 400 m, respectively. Color denotes the starting position of the trajectory lines and the internal is the locations of the air parcel every 12 h.

air masses originating from northwest of China moved to the NCP on 3 Nov., then circulated and mixed with the haze over the NCP on 4 Nov., and finally arrived at the Liao River Plain by passing through the Bohai Bay and Liaodong Bay. Results here suggest that the NCP is a significant source of regional haze pollution, which can be transported to the NE and our neighboring countries (e.g., Korea and Russia) in a few days and affects the air quality on a large scale. Our analyses also have important implication for PM control strategies that control the sources emissions in the NCP and would be effective to improve the air quality in both NCP and NE China.

5. Summary

Urban haze has become a major environment concern in China in recent years. In the present study, an early wintertime regional transport haze occurred in NE China was investigated during 4−6, Nov. Analyses combing PM_{10} measurements from 11 sites, synoptic meteorology, satellite observations, comprehensive mesoscale meteorological modeling, and backward trajectory were carried out to investigate the atmospheric dynamics and transport mechanism of this haze episode. The summaries are listed below.

1. In situ measurements show a regional haze episode in NE China from 4 to 6 Nov. 2010, with PM_{10} concentration up to 410 μg m^{-3}. The monitoring sites in NE China (YK, LY, TL and JL) which are located in a southwest-northeast line and ~100−300 km between each other, were successively impacted with the peak time intervals ~11−18 hours.
2. Synoptic-scale analysis with WRF output suggests that the prevailing westerly-southwesterly wind favored the regional transport of haze from the NCP to NE China. In situ measurements at 9 sites in NCP confirmed the formation of the haze episode on 4 Nov., with average daily PM_{10} concentration up to 340 μg m^{-3}. Lidar measurements over Beijing revealed aerosols were uplifted to ~2.2 km during the haze episode, which favored the regional transport. Satellite images and backward trajectories driven by WRF hourly output captured well the transport processes, and the results indicated that the haze in NE China was greatly influenced by regional transport from NCP along the NCP-Bohai Bay−Liaodong Bay−Liao River Plain. The transport appeared to mainly occur in the boundary layer.
3. The study highlights the important role of regional transport in exporting the NCP haze to NE China in winter. Our results have important implications for PM control strategies that cooperation among different city clusters to reduce the sources emissions is of importance to improve the air quality over a regional scale.

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Supplements

Supplement 1 the configuration and validation of WRF model.

References

Badarinath, K. V. S., S. K. Kharol, D. G. Kaskaoutis, A. R. Sharma, V. Ramaswamy, and H. D. Kambezidis, 2010: Long-range transport of dust aerosols over the Arabian Sea and 12 Indian region − A case study using satellite data and ground-based measurements. *Global and Planetary Change*, **72**, 164−181.

Draxier, R. R., and G. D. Hess, 1998: An overview of the HYSPLIT_4 modelling system for trajectories, dispersion and deposition. *Aust. Meteorol. Mag.*, **47**, 295−308.

Engel-Cox, J. A., C. H. Holloman, B. W. Coutant, and R. M. Hoff, 2004: Qualitative and quantitative evaluation of MODIS satellite sensor data for regional and urban scale air 1 quality. *Atmos. Environ.*, **38**, 2495−2509.

Kaimal, J. C., and J. J. Finnigan, 1994: *Atmospheric boundary layer flows: Their structure and measurement*. Oxford University Press, USA, 289 pp.

Lee, K. H., Y. J. Kim, and M. J. Kim, 2006: Characteristics of aerosol observed during two severe haze events over Korea in June and October 2004. *Atmos. Environ.*, **40**, 5146−5155.

Ramanathan, V., P. J. Crutzen, J. Lelieveld, A. P. Mitra, D. Althausen, J. Anderson, M. O. Andreae, W. Cantrell, G. R. Cass, C. E. Chung, A. D. Clarke, J. A. Coakley, W. D. Collins, W. C. Conant, F. Dulac, J. Heintzenberg, A. J. Heymsfield, B. Holben, S. Howell, J. Hudson, A. Jayaraman, J. T. Kiehl, T. N. Krishnamurti, D. Lubin, G. McFarquhar, T. Novakov, J. A. Ogren, I. A. Podgorny, K. Prather, K. Priestley, J. M. Prospero, P. K. Quinn, K. Rajeev, P. Rasch, S. Rupert, R. Sadourny, S. K. Satheesh, G. E. Shaw, P. Sheridan, and F. P. J. Valero, 2001: Indian Ocean experiment: An integrated analysis of the climate forcing and effects of the great Indo-Asian haze. *J. Geophys. Res. Atmos.*, **106**, 28371−28398.

Satheesh, S. K., M. K. Krishna, Y. J. Kaufman, and T. Takemura, 2006: Aerosol optical depth, physical properties and radiative forcing over the Arabian Sea. *Meteor. Atmos. Phys.*, **91**, 45−62.

Shao, M., X. Y. Tang, Y. H. Zhang, and W. J. Li, 2006: City clusters in China: air and surface water pollution. *Front Ecol Environ.*, **4**, 353−361.

Shimizu, A., N. Sugimoto, I. Matsui, I. Mori, M. Nishikawa, and M. Kido, 2011: Relationship between Lidar-derived dust extinction coefficients and mass concentrations 14 in Japan. *SOLA*, **7A**, 1−4.

Streets, D. G., J. S. Fu, C. J. Jang, J. M. Hao, K. B. He, X. Y. Tang, Y. H. Zhang, Z. F. Wang, Z. P. Li, Q. Zhang, L. T. Wang, B. Y. Wang, and C. Yu, 2007: Air quality during the 2008 16 Beijing Olympic Games. *Atmos. Environ.*, **41**, 480−492.

Su, F. Q., Z. H. Ren, Q. X. Gao, and Z. G. Zhang, 2004a: Convergence system of air contamination in boundary layer above Beijing and north China: Transportation 1815 convergence in boundary layer. *Res. Environ. Sci.*, **17**, 21−33 (in Chinese).

Su, F. Q., M. Z. Yang, J. H. Zhong, and Z. G. Zhang, 2004b: The effects of synoptic type on regional atmospheric contamination in north China. *Res. Environ. Sci.*, **17**, 16−20 (in Chinese).

Sugimoto, N., Y. Hara, K. Yumimoto, I. Uno, M. Nishikawa, and J. Dulam, 2010: Dust emission estimated with an assimilated dust transport model using Lidar network 4 data and vegetation growth in the Gobi Desert in Mongolia. *SOLA*, **6**, 125−128.

Tan, J. H., J. C. Duan, D. H. Chen, X. H. Wang, S. J. Guo, X. H. Bi, G. Y. Sheng, K. B. He, and J. M. Fu, 2009: Chemical characteristics of haze during summer and winter in Guangzhou. *Atmos. Res.*, **94**, 238−245.

Xin, J., Y. Wang, G. Tang, L. Wang, Y. Sun, Y. Wang, B. Hu, T. Song, D. Ji, W. Wang, L. Li, and G. Liu, 2010: Variability and reduction of atmospheric pollutants in Beijing and its surrounding area during the Beijing 2008 Olympic Games. *Chinese Science Bulletin*, **55**, 1937−1944.

Yang, T., Z. F. Wang, B. Zhang, X. Q. Wang, W. Wang, A. Gbauidi, and Y. B. Gong, 2010: Evaluation of the effect of air pollution control during the Beijing 2008 Olympic Games using Lidar data. *Chinese Science Bulletin*, **55**, 1311−1316.

Zhang, Y. H., Y. J. Ma, and Y. F. Wang, 2010: Synoptic, climatic and environmental characteristics of haze in center area of Liaoning province. *Ecology and Environmental Sciences*, **19**, 1114−1118 (in Chinese).

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