Response to comments by referee 1

We would like to thank Prof. McKendry for your comments and helpful suggestions. We revised our paper according to these comments and suggestions.

Specific comments:

Question 1. The title should be modified - I suggest something like: Impact of emission controls on air quality in Beijing during APEC 2014: lidar ceilometer observations.
Response 1: Thank you for your suggestion. We agree with you and revise the title to "Impact of emission controls on air quality in Beijing during APEC 2014: lidar ceilometer observations".

Question 2. The manuscript badly needs a map in which the regions in which emission controls were implemented are shown. Some discussion of the types of emission controls (where and what?).
Response 2: Thank you for your suggestion. We illustrate our measurement site and to describe the regions with emission controls.

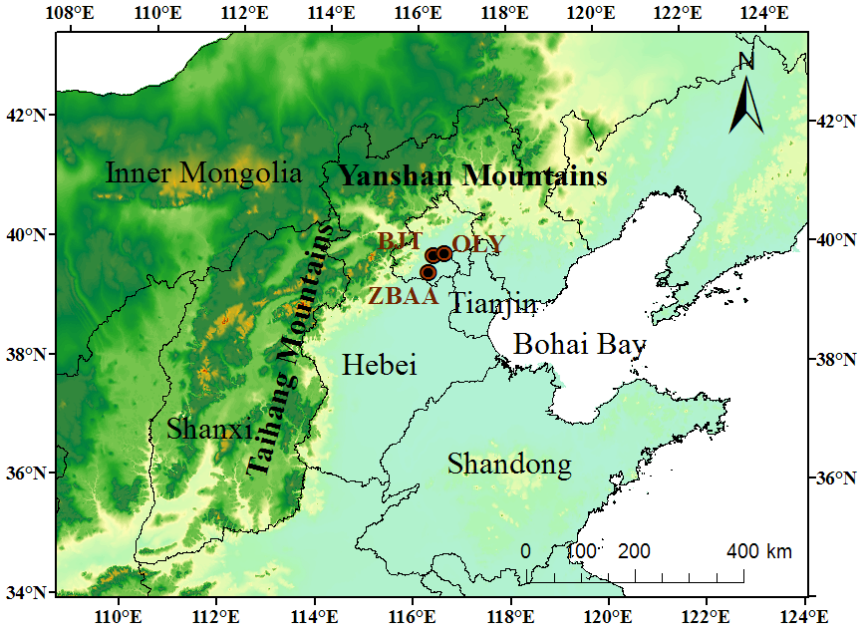


Figure 1 Observation sites and topography

Besides, we also added some description in the section of introduction to explain the emission controls. Please see the revision as follows.
Consequently, more than 460 businesses with high emissions in Beijing were required to stop or limit their production during 3–12 November, 2014. The number of private vehicles in operation during the same period was reduced by 50% through an odd/even number plate rule. Further, 9298 enterprises were suspended, 3900 enterprises were ordered to limit production, and more than 40,000 construction sites were shut down in all six provinces, cities and autonomous region.

Question 3. There is a terminology problem where "process" is used to describe "degraded air quality episodes". The various places where this occurs is highlighted in the marked up PDF.

Response 3: In section 3.2.3, visibility was used to indicate the degree of atmospheric pollution. With the decreasing of the visibility, the evolution of the air pollution was illustrated statistically. It was not the same with the actual episode. Therefore, we revised the manuscript thoroughly. For the actual air pollution, we used episode. For the statistical evolution of the air pollution using visibility, we used different air pollution degrees. Besides, to avoid the misunderstandings, the initial accumulation stage was revised to the transition period because of the significant changes of the air pollution and the peak pollution stage was revised to the polluted period.

Question 4. Similarly, the term "High Layer atmosphere" I think refers to upper boundary layer?

Response 4: Please see the responses of the technical comments.

Technical comments in the paper:

Question 1: Page 3, line 1. By comparing the PM2.5 concentrations before, during and after APEC (BAPEC, DAPEC and AAPEC, respectively), we found that the concentration of fine particles decreased by 60% and visibility improved by 60% during APEC.

Response 1: We are sorry for the misunderstanding. We compare the period of DAPEC to BAPEC and AAPEC, and the rates of change are not the same for BAPEC and AAPEC. To avoid the misunderstandings, we revised this sentence to "By comparing the $PM_{2.5}$ concentrations and visibility before, during and after APEC (BAPEC, DAPEC and AAPEC, respectively), we found that the concentration of fine particles decreased by 59.2 and 58.9% and visibility improved by 70.2 and 56.0% during APEC compared to DAPEC and AAPEC, respectively."

Question 2: Page 3, line 22.

Response 2: Thank you for your suggestion. We have fixed this mistake.

Question 3: Page 4, line 1.

Response 3: Thank you for your suggestion. We have fixed this mistake.

Question 4: Page 4, line 11. Not quite sure what is meant here. Do you mean that in the absence of measurements, model output must be used?

Response 4: We are sorry for the misunderstanding. Because the vertical variations of aerosols are lacking, we don't know how to do the coordinated regional prevention and control. Some people want to do this work using air quality model. However, lacking the validation of the observations, the results

from the air quality model are not reliable. To avoid the misunderstanding, we revised this paragraph into "Although coordinated regional prevention and control has been proposed for many years, it is difficult to obtain evidence and quantify the intensity of regional transport solely based on ground observations. Thus, reductions in regional emissions have not been implemented. Previous studies attempted to use air quality model to quantify the intensity and height of regional transport (Wu et al., 2011). However, the vertical gradient of air pollutants was not measured to test the model; therefore, the results are not reliable. Thus, it is of great importance to measure the vertical gradient of air pollutants to quantify the intensity and height of the regional transport."

Question 5: Page 4, line 21.
Response 5: Thank you for your suggestion. We have revised it to "sand storms".

Question 6: Page 4, line 27.
Response 6: Thank you for your suggestion. We have revised it to "sand storms".

Question 7: Page 5, line 6.
Response 7: Thank you for your suggestion. We have revised it to "aforementioned".

Question 8: Page 5, line 7.
Response 8: Thank you for your suggestion. We have deleted "a".

Question 9: Page 5, line 10.
Response 9: Thank you for your suggestion. We have deleted "the".

Question 10: Page 5, line 11.
Response 10: Thank you for your suggestion. We have deleted "the".

Question 11: Page 5, line 12.
Response 11: Thank you for your suggestion. We have deleted "the".

Question 12: Page 6, line 4.
Response 12: Thank you for your suggestion. We have revised it to "episodes".

Question 13: Page 9, line 1.
Response 13: Thank you for your suggestion. We have revised it to "different atmospheric pollution degrees".

Question 14: Page 9, line 12.

Response 14: Thank you for your suggestion. We have revised it to "nine poor air quality episodes were observed".

Question 15: Page 9, line 13-17.
Response 15: Thank you for your suggestion. We have revised them to "episode".

Question 16: Page 10, line 2.
Response 16: Thank you for your suggestion. We have revised it to "episode".

Question 17: Page 10, line 8.
Response 17: Thank you for your suggestion. We have added "(Fig. 2)" in the end of this sentence.

Question 18: Page 10, line 16.
Response 18: Thank you for your suggestion. We have revised it from "evaluation" to "evolution".

Question 19: Page 10, line 23.
Response 19: Thank you for your suggestion. We have revised it to "Therefore, the attenuated….".

Question 20: Page 11, line 5.
Response 20: Thank you for your suggestion. We have revised it to "The presented results showed….".

Question 21: Page 11, line 13-21.
Response 21: Thank you for your suggestion. We have revised it to "According to the average vertical gradient of the attenuated backscattering coefficients during the period of observation, we found clear differences between ….".

Question 22: Page 12, line 5-7.
Response 22: Thank you for your suggestion. We have revised from "fine particles may originate from different locations in the different degrees of air pollution of each pollution episode"

Question 23: Page 12, line 9.
Response 23: Thank you for your suggestion. We measured visibility using the Belfort Model 6000 Visibility Sensor in our institute. I have added some sentence to give some introduction about the measurement in section 2.4.

Question 24: Page 13, line 1.
Response 24: Thank you for your suggestion. We added "the" before atmosphere.

Question 25: Page 13, line 2.

Response 25: Thank you for your suggestion. We revised the sentence to "…results in decreased concentrations between the space from 300 to 900 m".

Question 26: Page 13, line 7.

Response 26: Thank you for your suggestion. We revised it to "pollution episode intensity".

Question 27: Page 14, line 3.

Response 27: Thank you for your suggestion. We revised this sentence to "…in $PM_{2.5}$ concentration because of the similar meteorological conditions during these three periods".

Question 28: Page 17, line 6.

Response 28: Thank you for your suggestion. We revised this sentence to "When cold, dry air masses go through Beijing, the attenuated ….".

Question 29: Page 17, line 9.

Response 29: Thank you for your suggestion. We revised this sentence to "Subsequently, the evolution of a pollutant episode was completed.".

Question 30: Page 17, line 13.

Response 30: Thank you for your suggestion. We revised it to "episode".

Question 31: Page 17, line 18.

Response 31: Thank you for your suggestion. We revised it to "in the space from 0 to 900m".

Question 32: Page 18, line 5.

Response 32: Thank you for your suggestion. We revised it to "upper boundary layer".

Question 33: Page 18, line 9.

Response 33: Thank you for your suggestion. We revised it to "by convective mixing".

Question 34: Page 18, line 10.

Response 34: Thank you for your suggestion. We revised it to "upper boundary layer".

Question 35: Page 18, line 13.

Response 35: Thank you for your suggestion. We revised it to "led".

Question 36: Page 18, line 15.
Response 36: Thank you for your suggestion. We revised it to "southerly flow was not significant, and it was replaced by near-surface static winds….".

Question 37: Page 18, line 18.
Response 37: Thank you for your suggestion. We revised it to "upper boundary layer".

Question 38: Page 18, line 20.
Response 38: Thank you for your suggestion. We revised it to "upper boundary layer".

Question 39: Page 19, line 1.
Response 39: Thank you for your suggestion. We have deleted "the".

Question 40: Page 19, line 3.
Response 40: Thank you for your suggestion. We have deleted "the".

Question 41: Page 19, line 7.
Response 41: Thank you for your suggestion. We revised it to "upper boundary layer".

Question 42: Page 19, line 9.
Response 42: Thank you for your suggestion. We revised it to "of different pollution degrees".

Question 43: Page 19, line 13.
Response 43: Thank you for your suggestion. We revised it to "upper boundary layer".

Question 44: Page 19, line 16-17.
Response 44: Thank you for your suggestion. We added ~ before the percent.

Question 45: Page 19, line 24.
Response 45: Thank you for your suggestion. We revised it to "coal burning for heating".

Question 46: Page 20, line 4.
Response 46: Thank you for your suggestion. We have deleted "the".

Question 47: Page 33.
Response 47: Thank you for your suggestion. We have deleted "the".

Question 48: Page 35.

Response 48: Thank you for your suggestion. We revised it to “episode”.

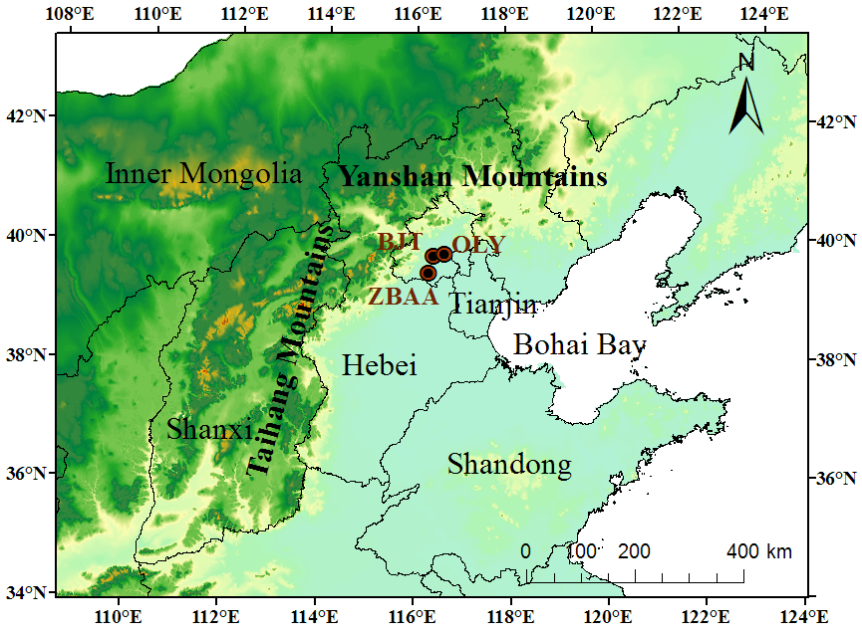
Response to comments by referee 2

We would like to thank you for your comments and helpful suggestions. We revised our manuscript according to these comments and suggestions.

Specific comments:

Question 1: Maps are needed to illustrate not only the locations of Beijing and surrounding provinces that involved in emission control, but also the location of the measurement site in the city of Beijing.

Response 1: Thank you for your suggestion. We illustrate our measurement site and to describe the regions with emission controls.



Observation sites and topography

Besides, we also added some description in the section of introduction to explain the emission controls. Please see the revision as follows.

Consequently, more than 460 businesses with high emissions in Beijing were required to stop or limit their production during 3–12 November, 2014. The number of private vehicles in operation during the same period was reduced by 50% through an odd/even number plate rule. Further, 9298 enterprises were suspended, 3900 enterprises were ordered to limit production, and more than 40,000 construction sites were shut down in all six provinces, cities and autonomous region.

Question 2: Improvement in wording is needed, polishing by a native English speaker is recommended.

Response 2: Thank you for your suggestion. We have polished our manuscript by a native English speaker.

Question 3: It is recommended to elaborate on winter heating policy in China since the central heating in Northern China all stick to the same schedule, which provide a unique opportunity to evaluate the impact of coal-fired heating. Otherwise the readers may be confused why the impact of the heating can be estimated.

Response 3: We really thank you for your suggestion. We have added some descriptions in the section of introduction as follows.

Besides, with the heating supply began to run extensively after 15 November, there was also a slight difference in emissions in the time period before vs. after APEC. Therefore, the implementation of these emission variability methods resulted in significant variations in regional transport and local pollutant contributions. In this study, a lidar ceilometer was used to determine the mixing layer height and the attenuated backscattering coefficient before and after APEC (15 October to 30 November 2014).

Response to comments by Prof. Wiegner

We would like to thank you for your comments and helpful suggestions. We revised our manuscript according to these comments and suggestions.

Question 1: For this reason the authors should not use terms as "aerosol attenuated backscattering coefficient profile" (e.g. 13174/9, 13178/24, 13182/19, 13190/27) or "vertical aerosol profile" (13177/23). Moreover, "aerosol concentration" (13177/28) is strongly misleading as only the particle backscatter coefficient (see Wiegner et al., 2014) as an optical property can be derived provided the signal has been calibrated.
Response 1: We really thank you for your suggestion. We have read your paper introduced in the comment. It is very important for us to improve the manuscript. As you said, the attenuated backscattering coefficient is not the same as aerosol concentrations, which is influenced by the water vapor absorption. Therefore, we have revised the in proper words in the manuscript according to your suggestions. The revisions mainly include removing the word "aerosol" and adding some descriptions about the observed deviations due to water vapor absorption.
The revision in the section 2.2 is as follows.
"Although aerosol concentration cannot be measured directly by a ceilometer (Wiegner et al., 2014), the attenuated backscattering coefficient is a good indicator of the aerosol stratification. However, uncertainties might occur in the attenuated backscattering coefficients measured by the lidar ceilometer, especially above the boundary layer where the aerosol concentration is low (Jin et al., 2015). In addition, the attenuated backscattering coefficients measured in the spectral region of 910nm are influenced by water vapor absorption, and the strength of the influence can be highly variable in time and space (Wiegner and Gasteiger, 2015). Therefore, the representativeness of the attenuated backscattering coefficient must be evaluated by comparison with other observations, and a good relationship indicates that the influence of water vapor absorption is negligible."
The revision in the section 3.2.1 is as follows.
"It is noteworthy that any comparison with other parameters (PM or AOD) cannot lead to full agreement as long as we cannot quantify the water vapor effect (Wiegner and Gasteiger, 2015). Even so, the significant correlations between the attenuated backscattering coefficients and concentrations of PM2:5 and the AOD showed that the vertical attenuated backscattering coefficient profile measured by the lidar ceilometer could accurately represent the vertical distribution of atmospheric aerosols in Beijing."

Question 2: Another issue is the "validation". As discussed in Wiegner et al. (2014) it is not possible to determine the particle extinction coefficient from data of a simple backscatter lidar or ceilometer. Thus, comparisons with independently determined AOD (here: microtops) suffer from the unknown lidar ratio. A good correlation between AOD and integrated backscatter (but see comments above!) can be

plausible but cannot serve as validation. By the way it is not clear what is meant by "AOD concentration" (13183/5).

Response 2: Thank you for your suggestion. Actually, validation is not proper in the manuscript. Therefore, we have revised it to “evaluation” because we want use it as an indicator of the aerosols. Otherwise, we revise “AOD concentration” to “AOD”.

Question 3: Finally, I want to mention that the abstract seems to be too long, and that in contrast to the text (13183/13) "variations" cannot be seen in Fig. 5. This figure should be explained in more details as it is surprising that such a smooth signal is obtained as an average of measurements: it resembles simulated idealized signals (see also Fig. 6a).

Response 3: Thank you for your suggestion. I have rewritten the abstract and delete the word “variations” in page 13183, line 13. Also, we have revised the word “decline” to “lapse rate” and the word “decreasing rate” to “lapse rate” for the title of Fig. 6 in the revised manuscript.

In addition, you are surprised that the signal of the backscattering coefficient is very smooth. Because the data are easily affected by noise and interference from the aerosol layering structure, time and space were smoothly averaged before the backscattering coefficients can be used to illustrate the vertical profiles. Therefore, we have added some descriptions in the section as follows. “To filter the noise of the observed data, 240m vertical, 1200 s time smoothly averaging was applied by BLVIEW software before analyses (Münkel et al., 2007).”

Manuscript prepared for Atmos. Chem. Phys. Discuss.
with version 2015/04/24 7.83 Copernicus papers of the LaTeX class copernicus.cls.
Date: 19 October 2015

~~Vertical variations~~ Impact of ~~aerosols and the effects responded to the~~ emission ~~control: application of lidar ceilometer~~ controls on air quality in Beijing during APEC ~~,~~ 2014: lidar ceilometer observations

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Abstract

During The implementation of emission reductions during the 2014 Asia-Pacific Economic Cooperation (APEC) summit , a reduction of air pollution sources was coordinated to ensure good air quality in Beijingand the surrounding provinces and cities. By investigating variations in air pollution during this period, the effects of local emissions and regional transport can be better understood and the information can be used to evaluate the effectiveness of emission reduction strategies and provide a theoretical basis to guide future emission reduction strategies. provides a valuable opportunity to study air pollution in Beijing. From 15 October to 30 November 2014, the height of the atmospheric mixing layer and the aerosol vertical attenuated backscattering coefficient profile profiles were observed online using a lidar ceilometer. By investigating the correlation between Compared with fine particulate matter ($PM_{2.5}$) data near the surface and attenuated backscattering coefficients measured by the lidar ceilometer as well as the correlation between and aerosol optical depth (AOD) and attenuated backscattering coefficients of the 0 to 4500column, we found that data, the attenuated backscattering coefficient coefficients measured by the lidar ceilometer is highly were strongly correlated with the $PM_{2.5}$ concentration and AOD (correlation coefficients of 0.89 and 0.86, respectively). This result demonstrates demonstrated the reliability of the vertical profile of aerosols distribution of particles measured by the lidar ceilometer. By analyzing the atmospheric backscattering profileclassifying different air pollution degrees based on visibility, we found that during the initial stage of pollution accumulation, which is transition period of air pollution, which was affected by transport of southerly jet flows at low altitudeflows in the mixing layer, the attenuated backscattering coefficient of atmospheric aerosols from 0 to 1500 m was greatly enhanced by approximately 1.4 $Mm^{-1}\,sr^{-1}$ (140 %). At the peak pollution stage, the height of the mixing layer gradually decreased, the ratio of CO/gradually increased and emissions were dominated by local emissions. The During the polluted period, the attenuated backscattering coefficient of aerosols from 0 to 300 m suddenly increased, and the aerosols near surface had the highest value coefficient near the surface peaked (approximately 14 $Mm^{-1}\,sr^{-1}$); how-

ever, the attenuated backscattering coefficient ~~of aerosols~~ from 300 to 900 m ~~gradually decreased~~ decreased gradually, and the average value from 0 to 1500 m decreased by 0.5 $Mm^{-1}\,sr^{-1}$ (20 %). ~~By comparing the concentrations before, during and after APEC (BAPEC, DAPECand AAPEC, respectively), we found that~~ The height of the mixing layer gradually decreased, and the ratio of CO/SO_2 gradually increased, which indicate that the polluted period was dominated by local contribution. Due to the emission reductions during APEC (DAPEC), the concentration of ~~fine particles decreased by 60~~$PM_{2.5}$ decreased by 59.2 and 58.9 % and visibility improved by ~~60during APEC. In addition, compared with the BAPEC~~70.2 and ~~AAPEC periods, the~~ 56.0 % compared to before (BAPEC) and after APEC (AAPEC), respectively. The contribution of regional transport in ~~the DAPEC period~~ DAPEC decreased by approximately 36 and 25 % ~~, respectively,~~ and the local contribution decreased by approximately 48 and 54 % compared to BAPEC and AAPEC, respectively. ~~Thus, the~~ The most effective method of controlling air pollution in the Beijing area is to reduce regional emissions during the ~~initial stage of air pollution~~ transition period and reduce local emissions during the ~~peak pollution stage~~polluted period.

1 Introduction

Aerosols are ~~a relatively stable suspension system~~ relatively stable suspensions formed by micro-liquid and solid particles that are uniformly distributed in the air (Seinfeld, and Pandis, 1998). Atmospheric aerosols can directly change the balance and distribution of global radiation by scattering or absorbing sunlight, and they can also affect the formation of clouds and fogs (as condensation nucleus) and indirectly affect the global climate (Shine and Forster, 1999; Myhre et al., 2001; IPCC, 2007). Furthermore, atmospheric aerosols are carriers of photochemical reactions and provide good reaction beds for chemical reactions; therefore, they promote the occurrence of atmospheric photochemical reactions (Seinfeld and Pandis, 1998). Because of ~~the~~ their small radii and high specific areas, atmospheric aerosols can ~~be easily accumulated~~ easily accumulate as hazardous material and can be

absorbed by human bodies, where they are deposited in the lungs and threaten human health (Englert, 2004; Campbell et al., 2005; Peters, 2005; Auger et al., 2006).

With the rapid economic development ~~in~~ of China, the amount of industrial products and the number of vehicles ~~continue to increase every year, which increases the~~ increase year-by-year, thus lead to an increase of energy consumption (National Bureau of Statistics of China, 2014). The North China Plain region has one of the highest global aerosol concentrations (Lu et al., 2010). Beijing~~is ,~~ the economic, political and cultural center of China, ~~and it~~ is adjacent to the ~~Yan~~ Yanshan Mountains to the north and Taihang Mountains to the west and is on the north boundary of the North China Plain ~~. Such a~~ (Fig. 1). This special horseshoe-shaped geographical ~~location results in~~ region provides efficient southerly transport of pollutants to Beijing, which affects ~~the~~ air quality (Ding et al., 2005; Xin et al., 2010). In 2012, China promulgated the ~~"~~Air Pollution Prevention and Control Action Plan ~~"~~ to prevent and control air pollution, and the details were disseminated in September 2012. The key ~~controlled~~ control region for air pollution is the North China Plain, which contains Beijing, Tianjin and Hebei~~, and the~~ . The coordinated prevention and control of pollution in this region ~~are~~ have been proposed (State council, 2013).

Although coordinated regional prevention and control ~~has~~ have been proposed for many years, it is difficult to obtain evidence and quantify the intensity of regional transport solely based on ground observations. Thus, reductions in regional emissions have not been implemented. ~~To~~ Previous studies attempted to use air quality model to quantify the intensity and height of regional transport ~~, the vertical gradient of atmospheric pollutants must be measured or the air quality model must be evaluated~~(Wu et al., 2011). However, ~~in previous studies of regional transport based on air quality models,~~ the vertical gradient of air pollutants was not measured to test the model; therefore, the results are not reliable~~(Wu et al., 2011).~~ . Thus, it is of great importance to measure the vertical gradient of air pollutants to quantify the intensity and height of the regional transport.

Studies of the vertical distribution characteristics of atmospheric aerosols include layered observations from meteorological observation towers, mooring boats, airplanes, ground remote sensing and satellites, and such data can be utilized for exploration and measure-

ments of different spatial regions from the near-surface to ~~high-level~~ the free atmosphere. Using these observation methods to study the vertical gradient, the effects of sand ~~dusts~~ storms (Zhang et al., 2006; McAuliffe and Ruth, 2013), volcanic ~~explosions~~ eruptions (Emeis et al., 2014), and anthropogenic sources (Tesche et al., 2007; ~~van der~~ Kamp et al., 2008; Zhang et al., 2009; Hänel et al., 2012; Sun et al., 2013) on the atmospheric environment have been evaluated in ~~various~~ several countries. However, such studies in ~~North~~ north China remain at the initial stages. Using the airplane observation method, Zhang et al. (2006) classified the origin of atmospheric aerosols in Beijing and showed that they are primarily affected by sand ~~dusts~~storms, southerly transport and local emissions. Their airplane data were used to determine the concentration of aerosol particles and vertical distribution characteristics of particle radii in the Beijing area during the periods when atmospheric aerosols are mainly affected by anthropogenic sources. Zhang et al. (2009) also analyzed the causes of vertical aerosol distribution under different meteorological conditions by considering meteorological factors. Guinot et al. (2006) and Sun et al. (2013) used the layered meteorological observation method to show variations in the vertical gradient of air pollutants during periods of heavy pollution. Although the ~~abovementioned~~ aforementioned studies analyzed the vertical variation of aerosols in the Beijing area, the results are not ideal because they have ~~a~~ low resolution, small sample size and low observational height; they are unrepresentative; and they lack evidence for regional transport. In recent years, satellite observations have become increasingly important in investigations of atmospheric aerosol profiles. In addition, ~~the~~ satellite observations provide reliable results compared with ~~the~~ ground remote sensing (Wu et al., 2014). However, ~~because of the short passing time and low data~~ the resolution of the satellite observation method is very low because of short passing time. Therefore, surface remote sensing is the best method ~~for determining the~~ to acquire the continuous vertical structure of atmospheric aerosols in high resolution.

The Asia-Pacific Economic Cooperation (APEC) summit was held from 3 to 11 November 2014 in Beijing, and it was important to ensure good air quality to provide for a successful summit. Thus, the governments of Hebei ~~Province, Tianjin City, Shanxi Province~~province, Tianjin city, Shanxi province, Inner Mongolia ~~Province~~autonomous region, and Shandong

~~Province~~ province cooperated with the government of Beijing to increase the intensity of emissions reductions for the entire region of ~~North~~ north China during the APEC summit, and a series of emission reduction methods were conducted. ~~The~~ Consequently, more than 460 businesses with high emissions in Beijing were required to stop or limit their production during 3–12 November, 2014. The number of private vehicles in operation during the same period was reduced by 50 % through an odd/even number plate rule. Further, 9298 enterprises were suspended, 3900 enterprises were ordered to limit production, and more than 40,000 construction sites were shut down in all six provinces, cities and autonomous region. Besides, with the heating supply began to run extensively after 15 November, there was also a slight difference in emissions in the time period before vs. after APEC. Therefore, the implementation of these emission ~~reduction~~ variability methods resulted in significant variations in regional transport and local pollutant contributions~~, and these data were utilized in the present study, which measured the vertical aerosol profiles and heights of the mixing layers using a lidar ceilometer~~. In this study, a lidar ceilometer was used to determine the mixing layer height and the attenuated backscattering coefficient before and after APEC (15 October to 30 November 2014). The values for fine particulate matter ($PM_{2.5}$) and aerosol optical depth (AOD) were combined, and the present study tested and ~~verified~~ compared the attenuated backscattering coefficient measured by the lidar ceilometer from 15 October to 30 November ~~2014 and analyzed the~~ 2014. By applying visibility as an index to classify the degrees of air pollution, the vertical gradients of ~~aerosol concentrations in multiple pollution processes during different pollution periods~~ the attenuated backscattering coefficient were analyzed during multiple pollution episodes to determine the origin of atmospheric ~~aerosols. Changes in the vertical aerosol~~ pollution for different degrees of air pollution. Afterwards, changes in the attenuated backscattering coefficient profiles before, during and after APEC (BAPEC, DAPEC and AAPEC, respectively) reflect the causes of variation during different pollution ~~periods~~ degrees and relative contribution of regional transport and local emissions in ~~the DAPECperiod~~DAPEC. Finally, three typical pollution ~~processes~~ episodes were analyzed in ~~the~~ BAPEC, DAPEC and AAPEC ~~periods~~ to show the origin of atmospheric ~~fine particles~~ pollution in different pol-

lution ~~periods~~ degrees in Beijing and the effects of the emission reduction methods in ~~the DAPECperiod~~DAPEC. The results strengthen our knowledge of pollution formation and development in the Beijing area and provide a scientific basis for the control of air pollution in Beijing.

2 Methods

2.1 Measurements of ~~aerosol~~ attenuated backscattering coefficients

An observational station (BJT) was built in the Tieta courtyard of the Institute of Atmospheric Physics of the Chinese Academy of Science (West of Jiandemen, Haidian District, Beijing) ~~. The station is~~ (Fig. 1). The station was between North Third Ring Road and North Fourth Ring Road, and route G6 ~~is~~ was on the east side. The geographic location of the station ~~is~~ was 39.97° N, 116.37° E, and the altitude ~~is~~ was 60 m.

The equipment used in this study included an enhanced single-lens lidar ceilometer (CL51, Vaisala). This equipment ~~adopts~~ adopted the strobe laser lidar (laser detection and distance measurement) technique (910 nm) to measure the atmospheric attenuated backscattering coefficient profiles~~of atmospheric particles~~. The detection distance of the CL51 ceilometer ~~is~~ was 15.4 km, and it ~~has~~ had a temporal resolution of 6–120 s and vertical resolution of 10 m. Because the height of the atmospheric mixing layer barely ~~exceeds~~ exceeded 4 km and the concentration of aerosols in the ~~high-level~~ free atmosphere above the mixing layer is low in the Beijing area, high detection distance ~~is~~ was not necessary to study the air pollution in this area. To strengthen the echo signals and reduce detection noise, the detection height of the ceilometer was reduced by half to 7.7 km. Additional data were obtained to smooth the noise of detection signals by setting the temporal resolution of detection to 16 s. To filter the noise of the observed data, 240 m vertical, 1200 s time smoothly averaging was applied by BLVIEW software before analyses (Münkel et al., 2007).

2.2 ~~Validation~~ Evaluation method of attenuated backscattering coefficients

~~Uncertainties~~ Although aerosol concentration cannot be measured directly by a ceilometer (Wiegner et al., 2014), the attenuated backscattering coefficient is a good indicator of the aerosol stratification. However, uncertainties might occur in the attenuated backscattering coefficients measured by the lidar ceilometer, especially above the boundary layer where the aerosol concentration is low (Jin et al., 2015). ~~To verify~~ In addition, the attenuated backscattering coefficients measured in the spectral region of 910 nm are influenced by water vapor absorption, and the strength of the influence can be highly variable in time and space (Wiegner and Gasteiger, 2015). Therefore, the representativeness of the attenuated backscattering coefficient must be evaluated by comparison with other observations, and a good relationship indicates that the influence of water vapor absorption is negligible.

To evaluate the atmospheric attenuated backscattering coefficients measured by the lidar ceilometer, two methods based on the near-surface $PM_{2.5}$ concentration and AOD column data were adopted in this study. The reliability of measured results based on calibration of the near-surface attenuated backscattering coefficients was ~~verified~~ evaluated by comparing the near-surface $PM_{2.5}$ concentrations and near-surface atmospheric attenuated backscattering coefficients. Observational $PM_{2.5}$ data were downloaded from the Chinese Environmental Protection Administration website (http://www.zhb.gov.cn/), and observational data at the Olympic center ~~, which is~~ (OLY), which was the closest landmark to the observational station, were chosen for comparison ~~.~~ (Fig. 1). The AOD data were measured using the MICROTOPS II heliograph at BJT station (Fig. 1), and the weather conditions were sunny and partly cloudy. Each measurement was repeated three to five times, and the average value was used as the mean value at each time step. Because the waveband of the heliograph is different from the observational range of the lidar ceilometer, the AOD at 910 nm, which is consistent with the wavelength of the lidar ceilometer, was derived from the measured AOD at 1020 nm using the heliograph and wavelength indices of four wave bands. The derivation method ~~is~~ was based on Eq. (1), where α is the wavelength

index between 340 and 675 nm, and τ is the AOD:

$$\ln \alpha = \frac{\ln \tau(1020\,\mathrm{nm}) - \ln \tau(910\,\mathrm{nm})}{\ln 1020 - \ln 910} \quad (1)$$

2.3 ~~Method to calculate~~ Calculation of mixing layer height

Because the particle lifetimes are long and range from several days to tens of days, the distribution of particle concentrations in the atmospheric mixing layer is more uniform than that of gas-phase pollutants (Seinfeld, and Pandis, 1998). In addition, huge differences ~~are observed~~ in the concentrations of particles ~~in~~ are observed between the mixing layer and free atmosphere. The profile of attenuated backscattering coefficients in the atmosphere can be analyzed to determine the location of sudden changes caused by variations in the attenuated backscattering coefficients, which is at the top of the atmospheric mixing layer. The lidar ceilometer is ~~low-cost~~ inexpensive and convenient and has been widely applied in observations of the mixing layer height (Michael et al., 2006; Münkel et al., 2007; McKendry et al., 2009; Emeis et al., 2012; Yang et al., 2013; Pandolfi et al., 2013; Schween et al., 2014; Scarino et al., 2014). In this study, the gradient method ~~is~~ was used to identify the mixing layer height, and maximum negative gradient value ($-\mathrm{d}\beta/\mathrm{d}x$) of the attenuated backscattering coefficient profile ~~of aerosols is~~ was at the top of the mixing layer (Michael et al., 2006; Emeis et al., 2012). Because the data are easily affected by noise and interference from the aerosol layering structure, time or space must be smoothly averaged before the ~~improved~~ gradient method can be used to calculate the mixing layer height from the ~~averaged~~ profile data (Münkel et al., 2007).

2.4 Other data

Because Beijing has a low concentration of industry and a large ~~quantity~~ amount of vehicle traffic, the emissions of SO_2 are low, while the emissions of CO are high. Thus, the ratio of CO to SO_2 may provide a partial indication of the origin of atmospheric pollutants. The CO and SO_2 data at ~~the Olympic Center~~ OLY station published by the Chinese Environment

Protection Administration were also used to help analyze the origin of atmospheric pollutants ~~.~~ (Fig. 1). The observational data were downloaded from the live-updated website published by the Chinese Environment Protection Administration (http://www.zhb.gov.cn/).

~~To~~ Visibility was measured at BJT station using a Belfort Model 6000 visibility sensor to characterize the degree of atmospheric pollution during this period. In addition, to understand the transport characteristics of different atmospheric pollution ~~stages,~~ degrees, wind speed and direction vertical profile data ~~of wind speeds and directions are required. Meteorological data~~ were obtained from the ~~website of the University of Wyoming, and meteorological sounding~~ international standard weather station (ID: ZBAA) (Fig. 1). The meteorological sounding profile data were measured twice a day at 08:00 and 20:00 LT ~~()~~at station ZBAA.

3 ~~Result~~ Results and discussion

3.1 ~~Characteristics~~ Overview of ~~variations in concentration~~air pollution

During the summit, a number of controls were adopted to guarantee good air quality in Beijing. To understand the pollution variation tendency during this period~~of time~~, the $PM_{2.5}$ concentration was plotted against time using the hourly $PM_{2.5}$ concentration data from 15 October to 30 November (Fig. ~~1~~2). The observation period lasted for 47 days, and ~~9 pollution processes~~ nine poor air quality episodes were observed, ~~each of~~ which lasted for 5.2 days on average. During each pollution ~~process~~episode, the $PM_{2.5}$ concentration was characterized as “slowly accumulating and rapidly disappearing”. At the ~~pollution accumulation~~ transition stage during each pollution ~~process~~episode, the pollutant concentration increased. After reaching the maximum value, the pollutant concentration plateaued for 1–2 days and then rapidly decreased, which usually lasted for four to six days from the beginning of the pollution ~~process~~ episode to the end. This result is consistent with ~~that of~~ previous studies (Jia et al., 2008).

A statistical analysis of the ground concentrations of $PM_{2.5}$ and heights of the mixing layers at the same time showed that with mixing layer heights rising from 0 to 1000 m, the average $PM_{2.5}$ concentration decreased from 158.9 to 67.9 $\mu g\,m^{-3}$. When mixing layer heights rose above 1200 m, the $PM_{2.5}$ concentration suddenly decreased (lower than 35 $\mu g\,m^{-3}$) and did not vary with increasing height of the mixing layer (Fig. ~~2~~3). Thus, when the mixing layer was lower than 1000 m, the $PM_{2.5}$ concentration was negatively correlated with the mixing-layer height, and when the mixing layer was above 1000 m, the air was of good quality and the negative correlation between the $PM_{2.5}$ concentration and mixing-layer height disappeared. Therefore, increased pollution during each pollution ~~process gradually leads~~ episode gradually led to the accumulation of $PM_{2.5}$ above 60 $\mu g\,m^{-3}$, and the corresponding mixing layer heights ~~are~~ were all below 1000 m. This result indicates that the vertical diffusion capability of the atmosphere is weak, and atmospheric pollution in Beijing ~~is possibly~~ may be enhanced by local emissions. Because the level of industry and coal pollution is low and the number of vehicles is high in Beijing, the ratio of CO/SO_2 can reflect the contribution of local emissions to air pollution, with higher ratios indicating higher local contributions. The ratios of CO/SO_2 ~~were calculated, and they~~ show that with decreasing mixing layer height, the ratio of CO/SO_2 gradually ~~increases.~~increased (Fig. 3). This result also suggests that with increasing pollution, the amount of pollutants transported from other regions gradually decreases while the local contribution gradually increases.

3.2 Characteristics of ~~the vertical structure variation of atmospheric aerosols~~attenuated backscattering coefficients

3.2.1 ~~Validation~~ Evaluation of ~~the~~ attenuated backscattering ~~coefficient profile~~coefficients

Because the vertical distribution of atmospheric pollutants in the convective layer can better represent the ~~evaluation~~ evolution characteristics of pollution, the $PM_{2.5}$ and AOD data observed during this time period were used to compare the near-surface atmospheric attenuated backscattering coefficient and 0 to 4500 m column attenuated backscattering co-

efficient, and the results could be used to ~~verify~~ evaluate the attenuated backscattering coefficient profile ~~of atmospheric aerosols~~ measured by the lidar ceilometer ~~and help~~ helping us to better understand the vertical structure of atmospheric ~~aerosols~~pollution.

~~Overlap~~ The overlap of the laser beam of the ceilometer and its receiver field-of-view is smaller than 1 in the near range. Therefore~~in this paper~~ , the attenuated backscattering coefficient values at a height of 100 m ~~height have been chosen for the comparison with~~ were chosen for comparison with the near-surface $PM_{2.5}$ concentration. The correlation showed that ~~in addition to~~ besides differences during several peak periods, the variations were generally consistent (Fig. ~~3a~~4a), which indicates that the attenuated backscattering coefficients ~~above~~ at 100 m and corresponding $PM_{2.5}$ concentrations ~~are~~ were significantly positively correlated ($R = 0.89$) (Fig. ~~3b~~4b). For the column concentration, 4500 m can generally cover the entire mixing layer; therefore, the interference of cloud layers from 0 to 4500 m was manually removed~~and~~ , the atmospheric attenuated backscattering coefficients ~~of atmosphere~~ were integrated in this region, and the values were compared with ~~the AODconcentration~~AOD. The results showed that ~~the AOD concentration~~ AOD varied directly with the integrated attenuated backscattering coefficient of the atmospheric column (Fig. ~~4a~~5a), and the positive correlation coefficient was as high as 0.86 (Fig. ~~4b). Thus,~~ 5b).

It is noteworthy that any comparison with other parameters (PM or AOD) cannot lead to full agreement as long as we cannot quantify the water vapor effect (Wiegner and Gasteiger, 2015). Even so, the significant correlations between the attenuated backscattering ~~coefficient of aerosols~~ coefficients and concentrations of ~~fine particles~~ $PM_{2.5}$ and the AOD ~~show~~ showed that the vertical attenuated backscattering coefficient profile measured by the lidar ceilometer could accurately represent the vertical ~~structure~~ distribution of atmospheric aerosols in Beijing.

3.2.2 Vertical ~~structure~~ distribution of ~~atmospheric aerosols~~attenuated backscattering coefficients

~~Figure 5 shows variations in~~ According to the average vertical gradient of ~~atmospheric aerosols~~ the attenuated backscattering coefficients during the period of observation~~. The figure shows clear differences among~~ , we found clear differences between the attenuated backscattering coefficients~~of the atmospheric aerosols~~, with the highest values ~~at~~ in the near-surface ~~atmosphere~~ and average values reaching 4.5 $Mm^{-1}\,sr^{-1}$ ~~. The vertical decline (Fig. 6). The vertical~~ lapse rate of the attenuated backscattering coefficients for layers from 0 to 200 m was small, and the attenuated backscattering coefficients showed limited variation; however, the vertical ~~decline~~ lapse rate above 200 m ~~increases~~ increased and the attenuated backscattering coefficients significantly ~~decrease~~decreased. After reaching the maximum value at the height of 400 to 800 m, the vertical ~~decline began to gradually decrease~~ lapse rate began to decrease gradually. Above 1000 m, the attenuated backscattering coefficient was ~~lower than~~ below 0.65 $Mm^{-1}\,sr^{-1}$, and at approximately 2000 m, the coefficient was lower than 0.1 $Mm^{-1}\,sr^{-1}$. A vertical gradient with high values below and low values above is consistent with the characteristics of vertical gradient ~~variations~~ in other cities and regions (Tesche et al., 2007; Zhang et al., 2009; Liu et al., 2012; Cao et al., 2013; McAuliffe and Ruth, 2013), although it is different from those ~~of~~ regions that are severely affected by regional transport (Yang et al., 2007). Thus, the gradual declining trend in the attenuated backscattering coefficient from the near-surface to ~~high-level atmospheric layers~~ the upper boundary layer also indicates that the main sources of atmospheric aerosols are from the near-surface layers in Beijing.

3.2.3 ~~Variation in the vertical gradient of atmospheric aerosols~~ Attenuated backscattering coefficients during different pollution ~~stages~~degrees

Although the main sources of atmospheric aerosols ~~are from~~ occur in the near-surface layers, fine particles may originate from different locations ~~in the pollution stages~~ for the different pollution degrees of each pollution ~~process. Visibility~~ episode. To analyze the origin of air pollution, visibility was used as an index to indicate the degree of air pollution and applied in the analysis of the vertical gradient profile of the attenuated backscattering coefficients under different visibility conditions (Fig. ~~6~~7). When the visibility was above 40 km,

small differences occurred in the vertical gradients of the ~~aerosol~~ attenuated backscattering coefficients from the ground to 1.5 km, and the corresponding attenuated backscattering coefficients were all below 2 $Mm^{-1}\,sr^{-1}$. With decreasing visibility, the attenuated backscattering coefficients increased to varying degrees from the ground to 1.0 km. The ~~near-ground~~ near-surface layer presented a 2.1-fold increase from 2.4 to 7.4 $Mm^{-1}\,sr^{-1}$ when the visibility decreased from 20 to 4 km, and the mean attenuated backscattering coefficient from 0 to 1500 m presented a 1.4-fold increase from 1 to 2.4 $Mm^{-1}\,sr^{-1}$. In addition, the highly polluted region shifted from 0 to 300 to 0 to 900 m, indicating that transport in ~~high-level atmospheric layers~~ the upper boundary layer played an important role from the ~~clean stage to the initial accumulation stage~~ clear period to the transition period with medium haze. When the visibility decreased from 4 to 1 km, the ~~backscatter coefficient of aerosols~~ attenuated backscatter coefficient near the surface varied from 7.4 to 14 $Mm^{-1}\,sr^{-1}$~~, which was almost double~~. However, the mean attenuated backscattering coefficient from 0 to 1500 m significantly decreased from 2.4 to 1.9 $Mm^{-1}\,sr^{-1}$ (approximately 20 %). The ~~significant decrease in the mean column concentration differed from the rapid increase of the near-surface concentration. The~~ attenuated backscattering coefficient from 300 to 900 m significantly decreased and the variation at approximately 450 m reached the maximum value (~~decreased by~~ decreasing approximately 4 $Mm^{-1}\,sr^{-1}$), resulting in a sudden shift of the near-surface high concentration region from 0 to 900 m to 0 to 300 m. The significant decrease in the mean column concentration differed from the rapid increase of the near-surface concentration. Such a phenomenon is primarily caused by the weakened transport capability of ~~atmosphere during the~~ the atmosphere during heavy haze, which results in decreased concentrations in the ~~high-level atmosphere~~space from 300 to 900 m, and the increased contributions of local pollutants ~~leads~~ lead to a sudden increase of pollutant concentrations. Thus, during the ~~initial increasing stage of~~ transition period of air pollution, regional transport plays an important role, and within 0 to 600 m, it is characterized by strong regional transport. During the ~~peak pollution stage~~polluted period, local emissions are the most important factor and determine the accumulation rate of pollutants and pollution episode intensity.

3.3 ~~Evaluation~~ Impact of emission ~~reduction~~ controls during APEC

To evaluate the effectiveness of the emission reduction strategies during APEC, the observation periods were divided into three parts: BAPEC (15 October to 2 November), DAPEC (3 to 12 November) and AAPEC (13 to 30 November). A statistical analysis of the $PM_{2.5}$ concentration during these three time periods (Table 1) showed that the $PM_{2.5}$ concentrations in ~~the~~ BAPEC, DAPEC and AAPEC ~~periods~~ were 126.8, 51.5 and 125.2 $\mu g\,m^{-3}$, respectively. Compared with ~~the concentrations of~~ BAPEC and AAPEC, the $PM_{2.5}$ concentration in ~~the DAPEC period~~ DAPEC was decreased by approximately 60 %. Correspondingly, the visibility was increased from 17.5 km in ~~the BAPEC period~~ BAPEC and 19.1 km in ~~the AAPEC period~~ AAPEC to 29.8 km in ~~the DAPECperiod~~DAPEC, which is an increase of approximately 60 %. To evaluate the diffusion capability of the atmosphere during these three periods of time, the corresponding wind speeds and mixing-layer heights were calculated. The wind speeds in ~~the~~ BAPEC, DAPEC, and AAPEC ~~periods~~ were 2.4, 3.1 and 2.6 $m\,s^{-1}$, respectively, and the mixing-layer heights were 502.3, 452.8 and 423.9 m, respectively. Because wind speeds and mixing layer heights can represent atmospheric diffusion capacity along the horizontal and vertical ~~direction~~directions, respectively, the ventilation coefficient (wind speed multiplied by the mixing layer height) was used as an index to evaluate the total diffusion capacity of the atmosphere. The ventilation coefficients in ~~the~~ BAPEC, DAPEC, and AAPEC ~~periods~~ were 1208.3, 1400.0 and 1085.9 $m^2\,s^{-1}$, respectively. Thus, the diffusion capability of the atmosphere ~~in the DAPEC period was the best~~ was best in DAPEC, but the variation magnitude was far below the decreased magnitude of the ~~fine particles~~$PM_{2.5}$, which indicates that coordinated regional emission reductions might have caused the significant decrease in ~~fine particle concentration in the atmosphere~~$PM_{2.5}$ concentration because of the similar meteorological conditions during these three periods.

The results in Sects. 3.1 and 3.2 show that ~~fine particles~~ $PM_{2.5}$ originate from different sources during different pollution ~~stages. In order to~~ degrees. To identify the vertical gradient variations during different pollution ~~stages in the~~ degrees in BAPEC, DAPEC and AAPEC~~periods~~, the $PM_{2.5}$ concentration was divided as follows: 50, 50 to 100 and

$> 100\,\mu g\,m^{-3}$, which represented the clean period, ~~accumulation period and peak~~ transition period and polluted period, respectively. The vertical gradient variations of the atmospheric attenuated backscattering coefficients under the three different pollution concentrations were statistically analyzed to obtain the attenuated backscattering coefficient profile plots for the three periods ~~of time~~ (Fig. ~~7~~8).

During the clean period, the attenuated backscattering coefficients for ~~the~~ BAPEC, DAPEC, and AAPEC ~~periods~~ from 0 to 2000 m were similar, and the coefficients for the ~~near surface~~ near-surface were all below $1.5\,Mm^{-1}\,sr^{-1}$. (Fig. 8a). The near-surface attenuated backscattering coefficients in ~~the AAPEC period was~~ AAPEC were $0.3\,Mm^{-1}\,sr^{-1}$ higher than those during other periods ~~by 0.3~~because of wide-spread heating after 15 November. The variation magnitude was approximately 20 %.

Because of the important effect of regional transport from 0 to 1000 m, the attenuated backscattering coefficients were all higher during the ~~initial pollution accumulation stage compared with that of the clean stage for all three periods of time,~~ transition period compared with the clean period for BAPEC, DAPEC, and AAPEC, with 1.2- to 3-fold changes at different heights . (Fig. 8b). Interestingly, compared with ~~other periods~~BAPEC and AAPEC, greater decreases in the coefficients occurred in ~~the DAPEC period~~ DAPEC with increasing height, and at 1000 m, the value was approximately 35 and 25 % ~~higher~~ lower compared with that of BAPEC and AAPEC, respectively. The smallest decrease of the attenuated backscattering coefficients occurred near the surface at only 10 %. The decreased pollutant concentration in the upper ~~air~~ boundary layer relative to the ~~near surface~~ near-surface showed that during the ~~initial pollutant accumulation stage~~transition period, regional transport was an important contributor to air pollution in Beijing. Considering the dominant effect of regional transport during this ~~stage and jet~~ period and southerly flow transport in the lower atmosphere within 300 to 900 m, the mean attenuated backscattering ~~coefficient of atmospheric aerosols in the~~ coefficients in DAPEC, BAPEC, and AAPEC ~~periods was~~ were calculated to eliminate the effect of local emission. The results showed that the attenuated backscattering coefficient for ~~the DAPEC period~~ DAPEC decreased by 36 and 25 % relative to ~~the~~ BAPEC and AAPEC, respectively~~; thus,~~ , which indicate that the

contribution of regional transport to atmospheric aerosols in Beijing decreased by approximately 36 and 25 %, respectively.

Compared with the ~~initial accumulation stage~~transition period, the near-surface attenuated backscattering coefficients for ~~the~~ DAPEC, AAPEC and BAPEC ~~periods~~ were all greatly enhanced during the heavy pollution stage and began to decrease at 600 to 1000 m. The near-surface attenuated backscattering coefficients in ~~the~~ BAPEC and AAPEC ~~periods~~ exceeded 8 $Mm^{-1}\,sr^{-1}$, which was approximately twice ~~of~~ the variation that occurred in the ~~initial accumulation stage~~transition period. The near-surface attenuated backscattering coefficient ~~at the DAPEC peak stage~~ during the DAPEC polluted period was only 4 $Mm^{-1}\,sr^{-1}$, and the increase compared to the ~~initial accumulation stage~~ transition period was 25 %. Compared with ~~that of the~~ BAPEC and AAPEC, the attenuated backscattering coefficients in ~~the DAPEC period~~ DAPEC in the space from 0 to 2000 m were decreased by 0 to 48 % and 0 to 54 %, respectively, and the near-surface attenuated backscattering coefficients showed the greatest decrease at 48 and 54 %, respectively. With ~~the increase of~~ increased height, the decreasing magnitude of the attenuated backscattering coefficients ~~gradually decreased~~ decreased gradually. The higher decreasing magnitude of the near-surface ~~level relative to higher atmospheric levels~~ relative to the upper boundary layer indicates that during the ~~peak pollution~~ polluted period, local emission contributed significantly to air pollution. Considering the dominant role of local emissions during ~~this period of time~~ the polluted period and using the near-surface attenuated backscattering coefficient as a baseline, the significant decreases in ~~the DAPEC period relative to the~~ DAPEC relative to BAPEC and AAPEC ~~periods~~ indicate that the contribution of local emissions decreased by 48 and 54 %, respectively.

Although a number of air pollution controls were implemented ~~during the DAPECperiod~~in DAPEC, the increased heat supply ~~is~~ was the only difference between BAPEC and AAPEC. To evaluate the effect of heat supply on air pollution during the heavy haze periods in Beijing, the near-surface ~~aerosol~~ attenuated backscattering coefficients in ~~the~~ BAPEC and AAPEC ~~periods~~ were compared, and the result showed that they were 1.1-fold higher in ~~the AAPEC period compared with that of the BAPECperiod~~AAPEC than BAPEC, which indicates that

the contribution from the heat supply to atmospheric aerosols in Beijing is approximately 10 % during the heavy haze periods.

Based on the above discussion, three conclusions can be drawn: (1) the regional transport in ~~the DAPEC period~~ DAPEC decreased by 25 and 36 % compared with BAPEC and AAPEC, respectively, (2) the contribution of local emissions in ~~the DAPEC period~~ DAPEC decreased by 48 and 54 % compared with ~~that of~~ BAPEC and AAPEC, respectively; and (3) the contribution of the local heat supply to atmospheric aerosols in Beijing was approximately 10 % during the heavy haze periods. Although the quantitative contributions of local and regional areas are given, ~~it is still a rough estimate for the different episode~~these are still rough estimates for different episodes. Detailed contributions of local and regional sources over ~~Northern~~ north China still need further investigation and additional observational and modeling studies (although beyond the scope of the present analysis) are suggested for further work.

3.4 ~~Pollution variation characteristics during~~ Characteristics of heavy pollution ~~processes~~episodes

To predict the occurrence and development of air pollution ~~at different stages~~ under different pollution degrees in Beijing more precisely, the atmospheric attenuated backscattering coefficients, mixing layer height, ratio of CO to SO_2 during ~~the~~ BAPEC, DAPEC, and AAPEC ~~periods~~ and backscattering profile ~~of atmospheric aerosols and~~ with wind vectors during typical periods (Figs. ~~8–13~~9–14) were evaluated in a time-series plot to investigate the characteristics ~~of variation and causes of~~ and the causes of the attenuated backscattering coefficients during different pollution ~~stages~~ degrees at different heights. The heavy pollution ~~processes in the~~ episodes in BAPEC and AAPEC ~~periods~~ (Figs. ~~8,~~ 9, ~~12 and~~ 10, 13 and 14) showed that during the ~~initial accumulation stage~~ transition period (21–23 October and 17–18 November), southerly ~~low-level jet~~ flow resulted in increased mixing-layer height and a gradual ~~increasing~~ increase of the atmospheric attenuated backscattering coefficient from the near-surface (100 m) to ~~high-level atmosphere~~ the upper boundary layer (300 to 900 m). From 300 to 800 m, the effect of the southerly ~~low-level jet~~ flow was significant, and the pol-

lutant concentration rapidly increased. However, during the ~~pollution maintenance stage~~ polluted period (23–25 October and 19–20 November), the southerly ~~low-level jet~~ flow disappeared. Thus, the mixing-layer height decreased because of the westerly and northerly ~~jet~~ flows and the attenuated backscattering coefficient of the ~~high-layer atmosphere~~ upper boundary layer began to decrease. The reduction in mixing-layer height and relatively low wind speed promoted an increase in near-surface pollutants, which quantitatively accumulated during the ~~peak pollution~~ polluted period. When ~~the pollution was dissipated,~~ cold, dry air masses go through Beijing, the attenuated backscattering coefficient and CO/SO_2 ratio in the lower and upper air both rapidly decreased with the rapidly increased mixing layer height, and the $PM_{2.5}$ in the atmosphere was significantly decreased. Subsequently, the ~~entire pollution process~~ evolution of a pollutant episode was completed. Although the mixing layer height gradually decreased, the "slow accumulation and rapid disappearance" characteristics of the ~~fine-particle~~ $PM_{2.5}$ concentration, which were obvious in ~~the~~ BAPEC and AAPEC~~periods~~, were not clear in the pollution ~~process in the DAPEC period~~ episode in DAPEC (6–11 October). In addition, variations in the $PM_{2.5}$ concentration and atmospheric attenuated backscattering coefficient appeared as zigzag shapes, and accumulation and disappearance alternated (Fig. ~~10). At the initial accumulation stage in the DAPEC period~~12). During the transition stage in DAPEC, the variations of air pollutants were similar to those of ~~the~~ BAPEC and AAPEC. Because of the effect of the southerly ~~low-level jet~~ flow, the simultaneous increase ~~from low- to high-layer atmosphere~~ in the space from 0 to 900 m that occurred in ~~the~~ BAPEC and AAPEC also occurred in ~~the DAPEC period~~ DAPEC (Figs. ~~10 and~~ 11 and 12). In addition, the ratio of CO to SO_2 was low, indicating that regional transport was dominant during this period~~of time. At the pollution maintenance stage~~. During the polluted period, the attenuated backscattering coefficient of the upper ~~air in the DAPEC period~~ boundary layer in DAPEC significantly decreases because of the disappearance of westerly jet flows, which is consistent with what occurred in ~~the~~ BAPEC and AAPEC~~periods~~. However, the near-surface attenuated backscattering coefficient did not show a sharp increase (up and down), and the CO/SO_2 ratio did not increase as expected. Instead, the near-surface attenuated backscattering coefficient decreased. Thus, ~~at~~

~~the peak pollution stage in the DAPEC~~ during the DAPEC polluted period, the decreased local contribution magnitude of pollutants was insufficient to maintain the increases of pollutant concentrations at the near surface, which resulted in a zigzag distribution of atmospheric attenuated backscattering coefficients ~~at the pollutant accumulation stage~~during the polluted period.

Based on the above discussion, southerly ~~low-level jet flow occurred in the initial accumulation stage~~ flow occurred during the transition period (21–22 October, 7–8 November, 17–18 November) in the ~~high-level atmosphere~~ upper boundary layer (300 to 900 m), and ~~they~~ it transported large quantities of pollutants from the south to Beijing. In turn, the attenuated backscattering coefficients ~~in the low- and high-layer atmosphere~~ from the near-surface to the upper boundary layer increased, and the abundance of pollutants in the mixing layer increased. Pollutants transported during the daytime are mixed with pollutants released locally ~~because of the turbulence~~by convective mixing, and pollutants transported at night remain above the mixing layer overnight and then move to the near surface through ~~high atmosphere~~ upper boundary layer convection after the development of the mixing layer. Because of the transportation effect, the variation rate of the entire profile was relatively small and resulted in increased column concentrations of pollutants throughout the mixing layer, which ~~lead~~ led to the air pollution. ~~At the peak pollution stage~~ During the polluted periods (24–26 October, 8–11 November, and 19–21 November), ~~low-level jet flow were~~ southerly flow was not significant, and ~~they were~~ it was replaced by near-surface static winds and westerly and northerly winds in the high layers. Because of this effect, the near-surface attenuated backscattering coefficient continued to increase, whereas that of the ~~high-layer atmosphere~~ upper boundary layer continued to decrease, resulting in increased variation rates of the entire profile with height. The contribution of local emissions to pollution ~~at the peak pollution stage~~ during the polluted period increased, and its contribution to the ~~high-layer atmosphere~~ upper boundary layer was reduced.

4 Conclusions

The APEC summit was held in Beijing from 3 to 11 November 2014. During this period, six provinces, cities and autonomous region near Beijing (Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, and Shandong) worked together to control the air pollution by emission reduction, ~~and this period provides~~ so this period provided the best experimental platform for studying regional pollution and transport. The following conclusions have been drawn based on the ~~backscattering profile of the atmospheric aerosols~~ attenuated backscattering coefficient and mixing layer height in the Beijing area as measured by ~~the~~ lidar ceilometer for the period 15 October to 30 November 2014.

1. A comparison of ~~the~~ $PM_{2.5}$ concentrations and AOD values showed that the near-surface and 0 to 4500 m attenuated backscattering coefficient measured by the lidar ceilometer were well correlated with the near-surface $PM_{2.5}$ and AOD values, respectively, indicating that the lidar ceilometer can be used to study air pollution and indicate regional transport characteristics of atmospheric aerosols in ~~high layers~~the boundary layer.

2. Air pollutants ~~at different stages in Beijing are~~ under different pollution degrees in Beijing were from different sources. The ~~initial stage is~~ transition period was primarily affected by southerly ~~low-level jet~~ flow, and pollutant transport in the space from 300 to 900 m ~~atmosphere is~~ was significant, which ~~results~~ resulted in the accumulation of pollutants and air pollution in Beijing. However, ~~at the peak pollution stage~~during the polluted period, the contribution of ~~high-layer~~ upper air transport is decreased and local contributions ~~play~~ played an important role.

3. $PM_{2.5}$ concentrations in ~~the DAPEC period~~ DAPEC in Beijing were affected by coordinated regional emission reductions and decreased by approximately 60 %, and the visibility was enhanced by approximately 60 %. ~~At the initial increasing stage~~During the transition period, the concentration was mainly affected by regional transport, and the contribution of regional transport to aerosols in the Beijing area was decreased

by 36 and 25 % compared to BAPEC and AAPEC, respectively. ~~At the peak pollution stage~~During the polluted period, the concentration was dominated by local contributions, and the local contribution in Beijing was significantly decreased by 48 and 54 % relative to ~~the~~ BAPEC and AAPEC~~periods~~. A comparison of the near-surface attenuated backscattering coefficients in ~~the~~ BAPEC and AAPEC ~~periods~~ showed that the contribution of ~~the heat supply~~ coal burning for heating to air pollution during the heavy haze period was approximately 10 %.

Therefore, local emissions are the key factors ~~for~~ determining the formation and development of air pollution in the Beijing area, and a reduction in local emissions can greatly decrease local pollution. However, regional transport can promote air pollution~~; therefore,~~ , so such processes cannot be ignored, particularly ~~at the initial pollution stage~~during the transition period, which results in enhanced intensity and increased accumulation of local pollution. Thus, ~~at the initial pollution stage, the~~ during the transition period, emissions in areas surrounding Beijing should be reduced to effectively control regional transport and reduce the load of regional pollution. ~~At the peak pollution stage~~During the polluted period, local emissions should be reduced to control pollution. Our results can provide a scientific basis for emission control and management and air pollution forecasting and prevention~~and~~ , and they have the potential for use in the design and implementation of coordinated regional reduction strategies.

Acknowledgements. This work was supported by ~~National Natural Science Foundation of China (nos. 41230642 and 41222033) and~~ the CAS Strategic Priority Research Program Grant (no. XDB05020000 and XDA05100100)~~.~~ , the Haze Observation Project Especially for Jing-Jin-Ji Area (HOPE-J3A) (No. KJZD-EW-TZ-G06-01-04) and National Natural Science Foundation of China (nos. 41230642 and 41222033).

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Table 1. Meteorological conditions and atmospheric particle concentrations during ~~different periods of APEC~~BAPEC, DAPEC and AAPEC.

	WS ($m\,s^{-1}$)	MLH (m)	Ventilation coefficient ($m^2\,s^{-1}$)	Visibility (km)	$PM_{2.5}$ ($\mu g\,m^{-3}$)
BAPEC	2.4	502.3	1208.3	17.5	126.8
DAPEC	3.1	452.8	1400.0	29.8	51.5
AAPEC	2.6	423.9	1085.9	19.1	125.2

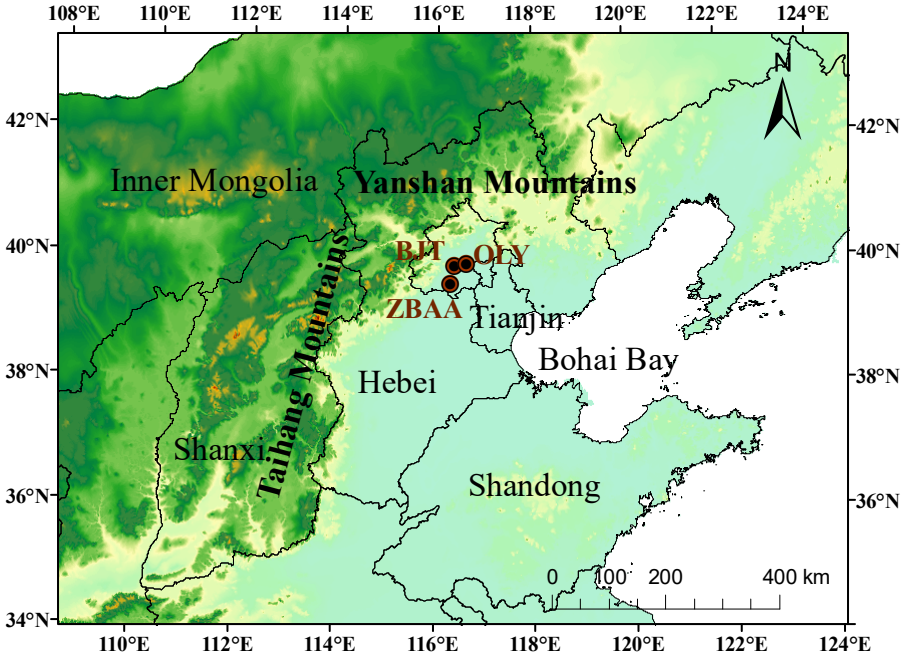

Figure 1. Observation sites and topography over Northern China.

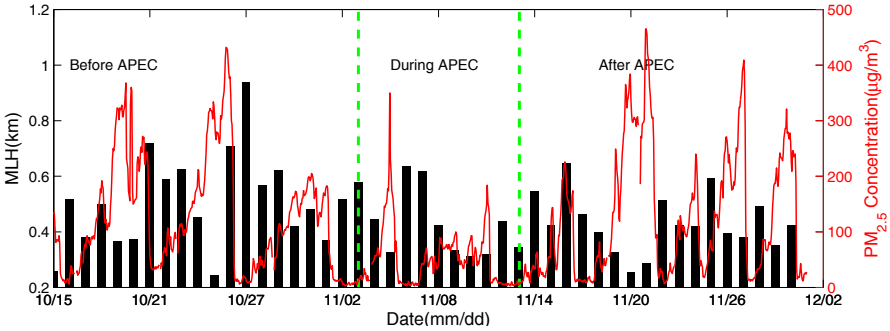

Figure 2. $PM_{2.5}$ concentrations and mixing-layer heights vs. time from 15 October to 30 November 2014.

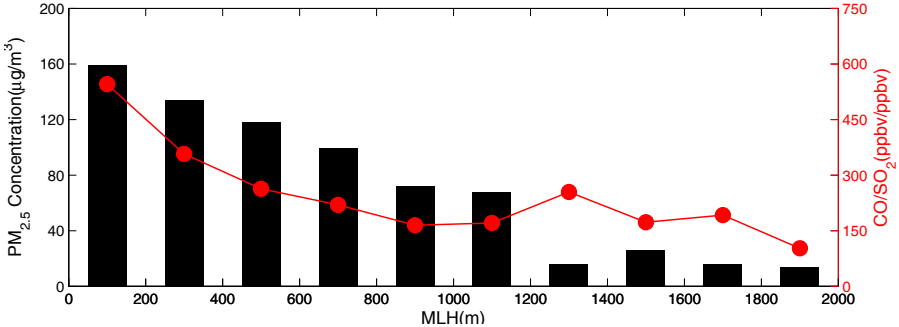

Figure 3. $PM_{2.5}$ concentrations and CO/SO_2 ratios of the mixing layer at different heights.

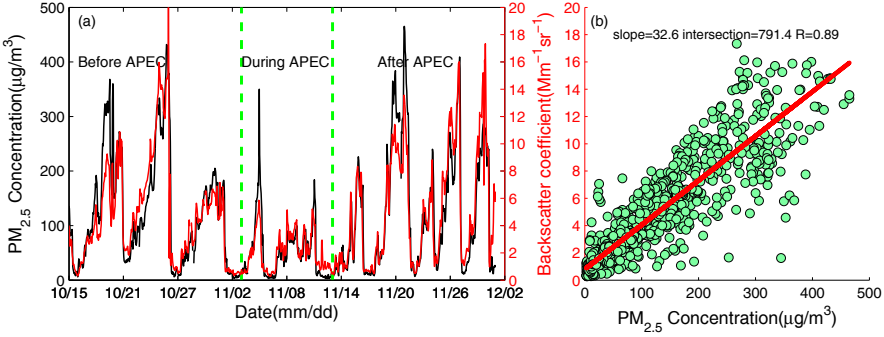

Figure 4. $PM_{2.5}$ concentrations and attenuated backscattering coefficients vs. time **(a)** and their correlations **(b)** from 15 October to 30 November 2014.

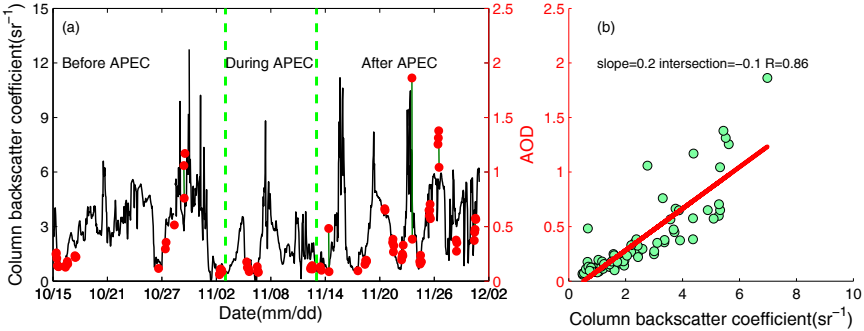

Figure 5. AOD values and 0 to 4500 m column attenuated backscattering coefficient vs. time **(a)** and their correlations **(b)**.

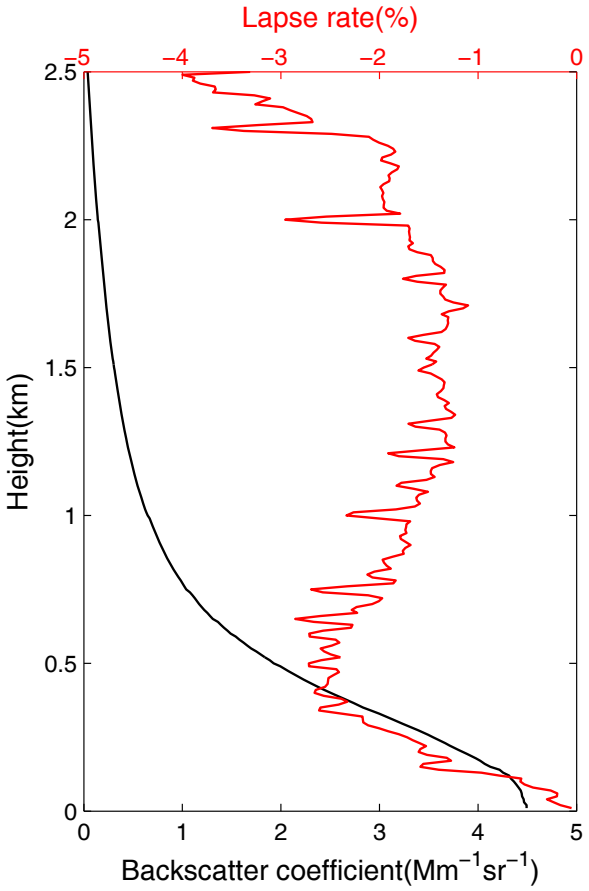

Figure 6. The vertical attenuated backscattering coefficient ~~vertical profiles of atmospheric aerosols~~ profile and the ~~decreasing~~ lapse rate.

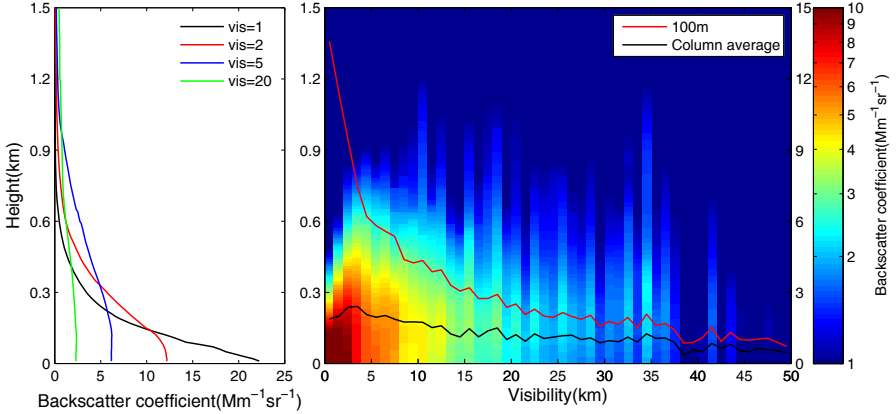

Figure 7. ~~Variations in the~~ The vertical gradient of attenuated backscattering coefficients under different visibility conditions.

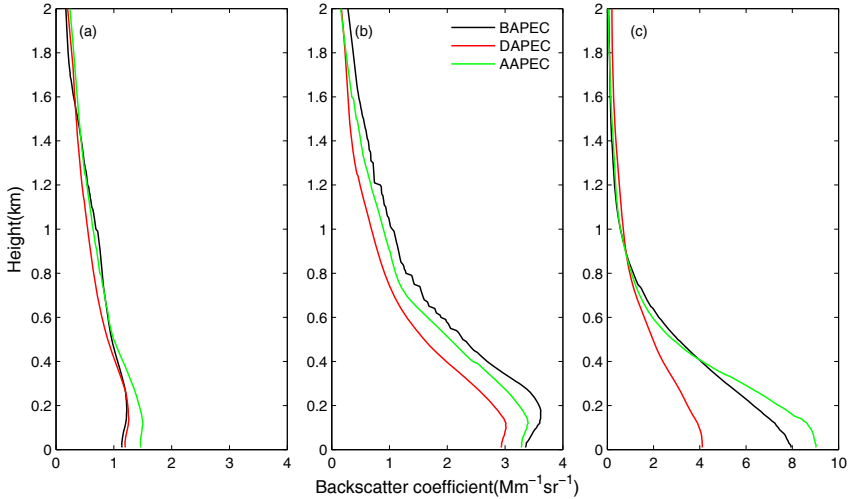

Figure 8. ~~Backscattering~~ Attenuated backscattering profiles under different air pollution ~~conditions~~ degrees during ~~the periods of~~ BAPEC, DAPEC and APPEC **(a)** PM $< 50\,\mu g\,m^{-3}$, **(b)** $50\,\mu g\,m^{-3} <$ PM $< 100\,\mu g\,m^{-3}$, **(c)** PM $> 100\,\mu g\,m^{-3}$.

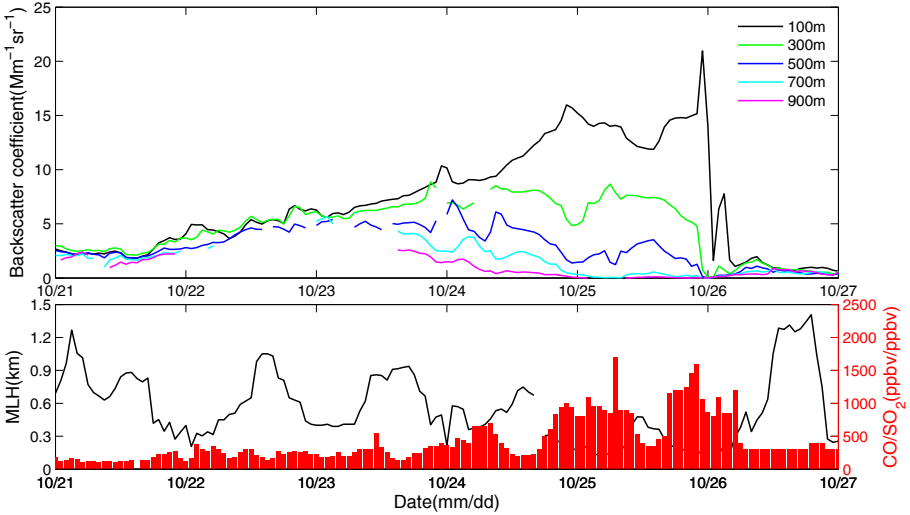

Figure 9. ~~Variations in the attenuated~~ Attenuated backscattering coefficients at different heights and near-surface CO/SO_2 ratios from 21–26 October.

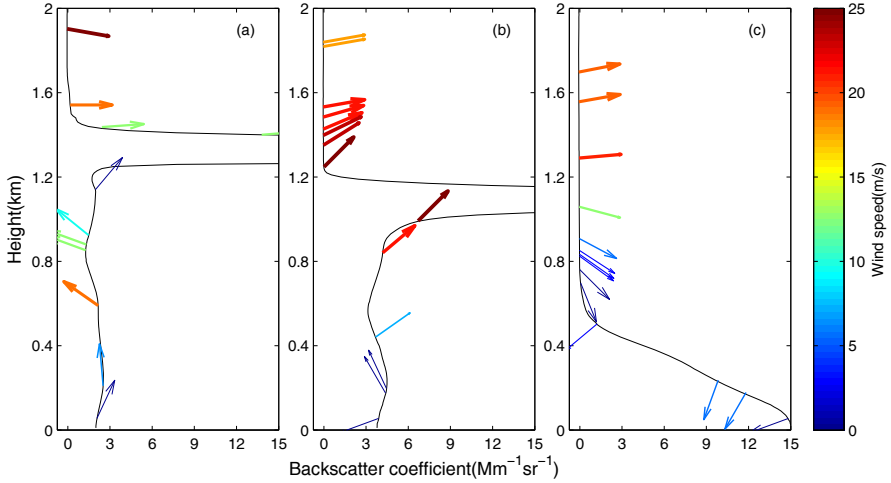

Figure 10. Attenuated backscattering ~~coefficient profiles~~ coefficients and wind ~~profiles during the heavy pollution~~ vectors for the periods 21–26 October at **(a)** 08:00 LT on 21 October, **(b)** 08:00 LT on 22 October, and **(c)** 08:00 LT on 25 October.

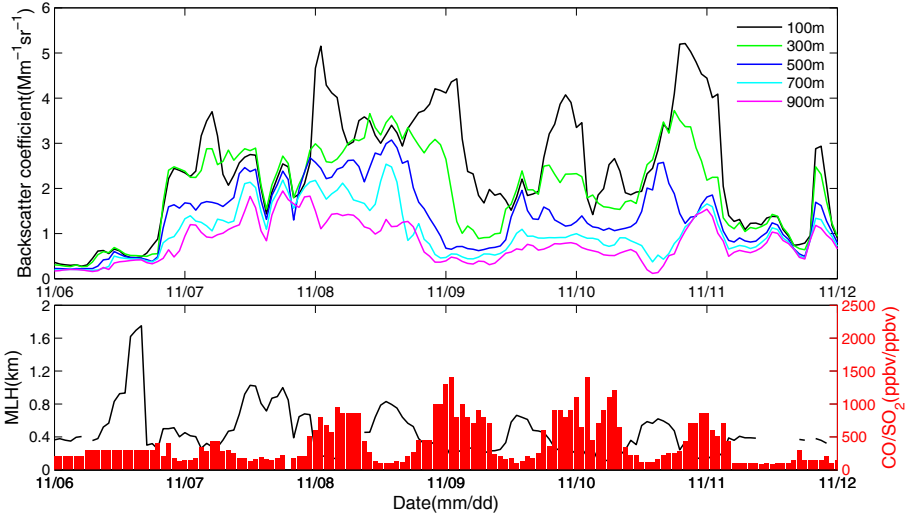

Figure 11. Attenuated backscattering coefficients at different heights and near-surface CO/SO_2 ratios ~~for~~ from 6–11 November.

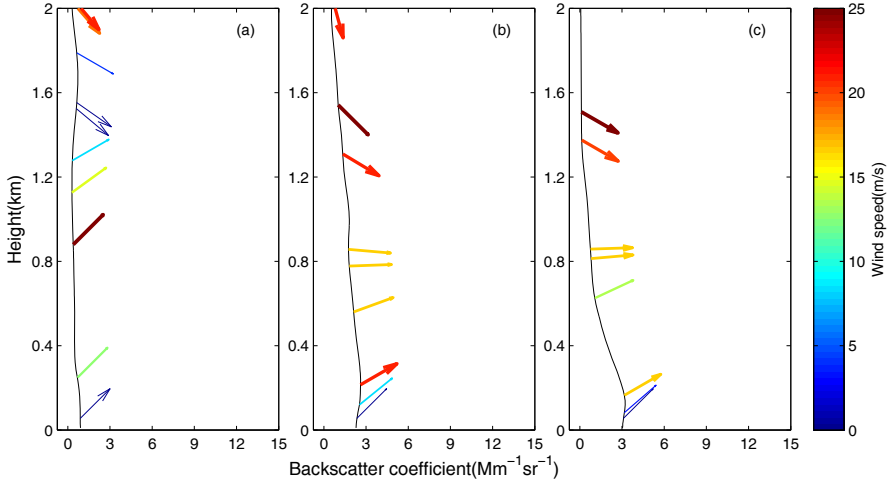

Figure 12. Attenuated backscattering ~~coefficient profile~~ coefficients and wind ~~profile during the heavy pollution process~~ vectors for 6–11 November at **(a)** 20:00 LT on 7 November, **(b)** 20:00 LT on 8 November, and **(c)** 20:00 LT on 10 November.

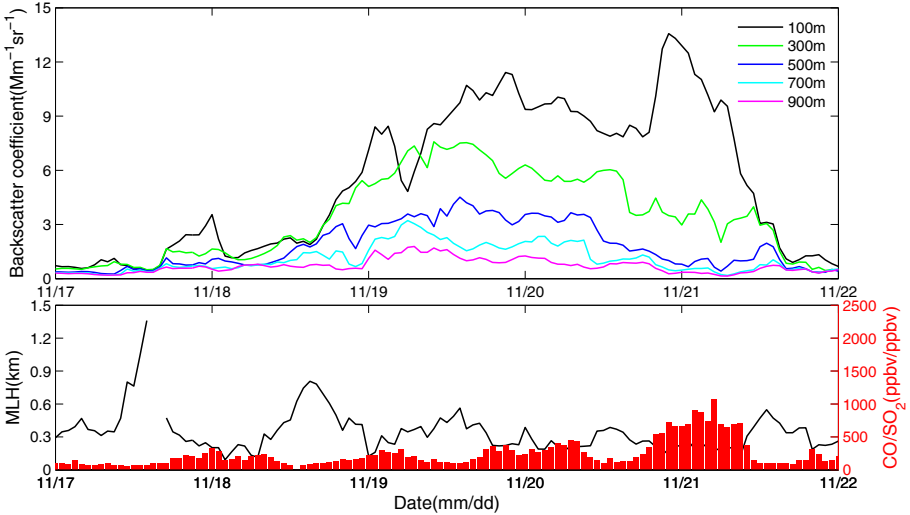

Figure 13. Attenuated backscattering coefficients at different heights and near-surface CO/SO_2 ratios ~~for~~ from 17–21 November.

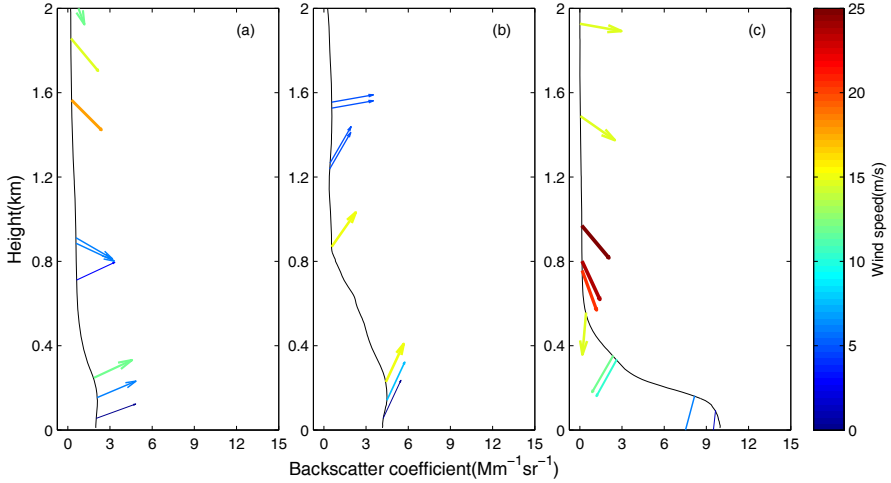

Figure 14. Attenuated backscattering ~~coefficient profile~~ coefficients and wind ~~profile during the heavy pollution process~~ vectors for 17–21 November at **(a)** 20:00 LT on 17 November, **(b)** 20:00 LT on 18 November, **(c)** 20:00 LT on 21 November.