

Vertical Observations and Analysis of PM_{2.5}, O₃, and NO_x at Beijing and Tianjin from Towers during Summer and Autumn 2006

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ABSTRACT

During the period between 18 August and 22 September 2006, an ultraviolet photometric O₃ analyzer, a NO-NO₂-NO_x chemiluminescence analyzer, and a quartz micro-oscillating-scale particle concentration analyzer were simultaneously used for monitoring at three different heights each at Beijing (325-m tower) and Tianjin (255-m tower). These towers belong to the Institute of Atmospheric Physics (IAP) of the Chinese Academy of Sciences (CAS) and to the Tianjin Municipal Meteorological Bureau, respectively. These measurements were used to continuously measure the atmospheric O₃ and NO_x volume-by-volume concentrations and the PM_{2.5} mass concentration within a vertical gradient. When combined with meteorological data and information on the variation of vertical characteristics of the various atmospheric pollutants in the two cities, analysis shows that these two cities were seriously polluted by both PM_{2.5} and O₃ during summer and autumn. The highest daily-average concentrations of PM_{2.5} near the ground in Beijing and Tianjin reached 183 $\mu\text{g m}^{-3}$ and 165 $\mu\text{g m}^{-3}$, respectively, while the O₃ concentrations reached 52 ppb and 77 ppb, and NO_x concentrations reached 48 ppb and 62 ppb for these two cities, respectively. The variations in the daily-average concentrations of PM_{2.5} between Beijing and Tianjin were demonstrated to be consistent over time. The concentrations of PM_{2.5} measured in Beijing were found to be higher than those in Tianjin. However, the overall O₃ concentrations near the ground in Tianjin were higher than in Beijing. NO_x concentrations in Tianjin were consistently lower than in Beijing. It was also found that PM_{2.5} pollution in Beijing's atmosphere may also be affected by the pollutants originating in and delivered from Tianjin, and that Tianjin was impacted by Beijing's pollutants at a significantly reduced level.

Key words: urbanization in Bohai, O₃, NO_x, PM_{2.5}, vertical distribution near the ground

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1. Introduction

Within multi-city agglomerations in certain developed regions, pollutants diffuse and mix, thereby forming a plume effect leading to regional large-scale contamination. Under specific conditions for atmospheric winds, temperature, and moisture, these pollutants are usually spread to the leeward side in the

form of a city plume. Such plumes can extend for hundreds of kilometers (Oke, 1982; Xu et al., 2004; Ancelet and Ravetta, 2005). China's urbanization ratio has increased from 10% in 1949 to 32%, while the urbanization rate within the eastern coastal regions has reached 40%–50%. It has been forecast that this latter rate will reach 70% in 2010. Currently, the most representative group of urban agglomeration are in the

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area around Bohai, including Beijing, Tianjin, and the surrounding areas, and in the Yangtze River Delta and the Pearl River Delta urban agglomerations. Data released by the State Statistics Bureau shows that there are currently more than 15 million residents within the city limits of Beijing and about 10.5 million more within Tianjin. These two cities are the closest of the four largest cities in China, where the population currently surpasses 10 million citizens. This study is focused on observations and research based within these two mega-cities that make up an urban agglomerations surrounding Bohai.

Atmospheric particulate matter (PM_{10}) is a main pollutant that influences human health, atmospheric visibility and the Earth's radiation balance, while also being an efficient contributor to atmospheric chemical reactions (Corsmeier et al., 2005). $PM_{2.5}$ (aerodynamic diameter $\leq 2.5 \mu m$) size range is also of considerable concern due to its relationship to secondary pollution and inter-regional transportation (Yang et al., 2002). Concentrations of $PM_{2.5}$ have been found to correlate significantly with the health status of the local population (Panyacosit, 2000) and has been shown to have great influence on the reduction of atmospheric visibility (Chan et al., 1997; Christoforou et al., 2000). The harm to human health associated with $PM_{2.5}$ has been confirmed by a large collection of epidemiological and toxicological research efforts, both internationally and domestically (Kenneth and Lowenthal, 1984; Dockery et al., 1993, Dockery and Pope, 1994; Yang et al., 1995; Jones, 1999).

The gases O_3 and NO_x , have been found to significantly jeopardize human health and that of animals and plants. It should be noted that NO_x is the standard symbol for the combination of both NO and NO_2 gases, and is the main prerequisite for acid deposition. The photochemical reactions that involve O_3 , NO_x , and VOCs (volatile organic compounds) are the predominant sources of the most serious photochemical pollutants (Wang et al., 2005). Meanwhile, the secondary particles formed by these photochemical reactions seriously affect human health, the environment and the climate. Furthermore, O_3 , NO_x , and particulate matter are all important factors that have been found to affect the air quality within the Beijing region (Sun et al., 2006a). During summer and autumn the O_3 and secondary particulate matter pollution are most significant.

The atmospheric layer within the first 100 meters above the ground is the most influential to human activity. The atmospheric pollutants from ground sources, mainly motorized transport, diffuse into this layer and are harmful to those living below. The lower atmosphere is characterized by weather factors such as

the wind, temperature, moisture, and pressure, especially those which influence various atmospheric chemical compositional changes. Such changes vary, both spatially and temporally, to a more considerable degree than they do in the upper atmosphere, and this is particularly true of changes occurring along the vertical direction. Therefore, it is important for both basic research and for practical applications in atmospheric chemistry, pollution meteorology, urban air-quality forecasting, and forecasting theory to obtain detailed information concerning the changes that occur in the weather and in the associated atmospheric chemical characteristics within this layer. To further study the diffusion of these atmospheric pollutants and the associated photochemical reaction mechanisms that occur within the urban boundary layer, and to start numerical simulations of these atmospheric pollutants within the micro-scale boundary layer, observations and research of the characteristics of the vertical profiles of these atmospheric pollutants and the rules governing their change within a typical urban boundary layer are required (Sun et al., 2006b). Currently, a large number of research institutions are working to obtain such experimental observations using the boundary layer tower data from both Beijing and Tianjin synchronously, in an effort to study the regional atmospheric pollution situation relevant to the Beijing Olympics. It is of great significance that both the mass concentrations of $PM_{2.5}$ and volume-by-volume concentrations of O_3 and NO_x be measured in real time.

2. Experimental method

2.1 Observational equipment

The experimental equipment required included six 49C UV photometric O_3 analyzers, six 42CTL NO_2 - NO_x precision chemiluminescence analyzers that were manufactured by Thermo Electron, Inc. of USA, and six $PM_{2.5}$ particulate matter monitors that were supplied by various American R&P companies. Three types of these machines were installed in groupings within cabinets which included air conditioning and were lifted onto the towers. These cabinets were fixed onto the tower observation platforms. The real-time data was collected and transferred via ground telephone switches through modems that were located within the aforementioned cabinets, and the tower network data were transmitted to a data acquisition computer.

According to the World Meteorological Organization (WMO)—Global Atmosphere Watch (GAW) QA regulations, ozone analyzers are calibrated at regular

time intervals with a transfer standard (TECO 49C PS). The NO_x instruments are routinely calibrated every ten days with a known flow of calibration gas (50 ppm NO in N_2 , State Center for Standard Matter, China) which is dynamically diluted to atmospheric concentration ranges. The conversion efficiencies of the converter for NO_2 are determined by measurements of NO_2 produced by gas phase titration of the NO standard with ozone. For quality control, several informal intercomparisons with other instruments under calibration and ambient air conditions were carried out before the experiment. Under ambient air conditions (ranges: lower than detection limit up to 1.5 ppb for NO, 1–4 ppb for NO_2 , 1–2 ppb for O_3) the deviations between the two systems (Beijing and Tianjin) were well below 6% in the case of NO, below 1.5% for NO_2 , and below 2% for O_3 at correlation coefficients of $r=0.95$, 0.96, and 0.97 respectively. Ozone analyzers (TECO 49C) have “zero noise” of 0.5 ppb, The detection limit is 1.0 ppb, The zero drift is less than 1 ppb (24 h^{-1}) and 2 ppb (7 d^{-1}), The span drift is less than 1% per month. $\text{NO-NO}_2\text{-NO}_x$ analyzers (TECO 42C) have zero noise of 0.20 ppb, Their detection limit is 0.40 ppb (60 second averaging time), and zero drift (24 hour) of less than 0.40 ppb. Their span drift (24 hour) is $\pm 1\%$ fullscale. The $\text{PM}_{2.5}$ analyzers (R&P Series 1400a Ambient Particulate Monitor) have a detection limit of $0.01 \mu\text{g m}^{-3}$. The instrument has a precision of $\pm 5.0 \mu\text{g m}^{-3}$ for 10-minute averaged data and $\pm 1.5 \mu\text{g m}^{-3}$ for 1-hour averages.

2.2 Sampling sites

The Beijing meteorological tower ($39^\circ 58' 27.6''\text{N}$, $116^\circ 22' 17.5''\text{E}$, 325 m) was set up in 1978 by the Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences (CAS), and is surrounded by buildings of 30 to 60 m in height, located at around 50 m away from the IAP tower. Surrounded by residential areas, the tower lies between the 3rd and 4th ring roads of the city and is approximately 1 km away from a highway. No direct industrial sources of atmospheric pollutants are located near the site. The cabinets are equipped with O_3 , $\text{NO-NO}_2\text{-NO}_x$, and $\text{PM}_{2.5}$ monitoring instruments at three different heights (8 m, 120 m, and 280 m) along the tower to continuously monitor the O_3 and NO_x volume-by-volume concentrations and $\text{PM}_{2.5}$ mass concentrations. The meteorological tower ($39^\circ 04' 29.4''\text{N}$, $117^\circ 12' 20.1''\text{E}$, 255 m) of the Meteorological Bureau of Tianjin lies in the center of a crossroads, surrounded by large residential areas. The buildings within a radius of 300 m average 20 m in height. Cabinets equipped with O_3 , $\text{NO-NO}_2\text{-NO}_x$, and $\text{PM}_{2.5}$ monitoring instruments were set up at heights of 40 m, 120 m, and 220 m along the height



Fig. 1. Map of Beijing and Tianjin observation towers.

of the tower. The two towers are separated by 120 km, with the Tianjin tower being located to the southeast of the Beijing tower (see Fig. 1).

There are a number of topological and surface changes that influence the winds that govern the transport of these various pollutants throughout the area. For instance, the elevation is higher in the northwest and lower in the southwest within the Beijing and Tianjin regions. The mountains and plains are significantly staggered and the surface elevation varies greatly. Downhill winds often appear during the night within Beijing, while Tianjin is closed to Bohai to the north and because of the uneven air temperature above both the land and sea, Tianjin is easily affected by daytime land/sea breezes. The wind fields caused by these pressure differences at the earth's surface greatly influence the atmospheric transportation of pollutants in the urban agglomeration region (Peng et al., 1988).

3. Results and discussion

3.1 Daily-average data analysis

The urban agglomeration that surrounds Bohai is located within the middle latitudes and the eastern bank of Eurasia and includes a strong monsoon circulation. This region belongs to temperate continental-monsoon climate and has distinct seasons that include a long winter and summer, coupled with a short spring and autumn. Summer is greatly affected by the Pacific subtropical high pressure, and most of the time it is controlled by a maritime airstream, with southerly winds, higher temperatures, higher humidity, and heavy rains. In autumn it is controlled by the subtropical high, the atmosphere is stable, the temperature moderate, and it is typically has considerable sun and lighter winds (Peng et al., 1988). It is easy to produce high concentrations of O_3 and secondary particle pollution when there are abundant

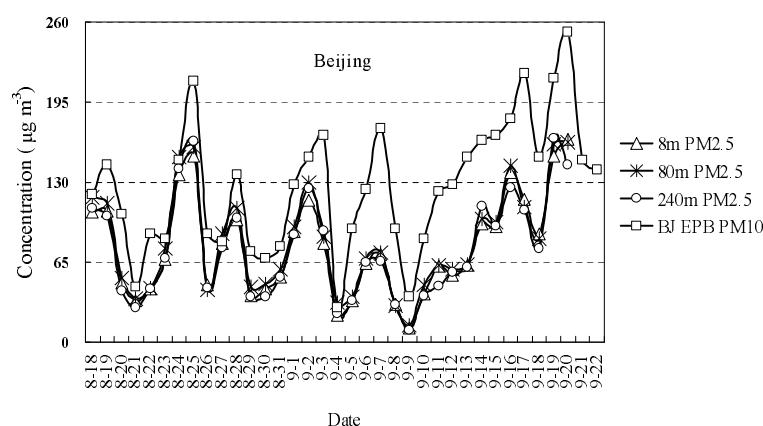


Fig. 2. The daily average data of $PM_{2.5}$ at Beijing's 325 m tower and PM_{10} from EPB.

concentrations of the corresponding precursors under the weather conditions observed during both summer and autumn. The experimental observation period for this work extended from 18 August to 22 September 2006, which encompasses the period of seasonal change between summer and autumn.

To certify the representativeness of our experimental observations, Beijing and Tianjin's daily air quality data that was collected over the same observation period were downloaded from <http://www.zhb.gov.cn>, which was published by the State Environmental Protection Administration of China (EPA). The data is the Air Pollution Index (API), which is calculated by the subsection function from the daily-average concentration data. Through backcalculation from the subsection function the daily-average mass concentration values of the PM_{10} concentration within Beijing and Tianjin during the observation period was obtained. This hourly-averaged observation data was processed into a daily-average observation dataset. As the $PM_{2.5}$ and PM_{10} mass concentrations were highly correlated,

the daily-averaged concentrations of PM_{10} in Beijing and Tianjin were compared with the $PM_{2.5}$ data for every layer (see Fig. 2 and Fig. 3). We can see that in both Beijing and Tianjin, the trends in the daily-average concentrations of the $PM_{2.5}$ in our observations and the PM_{10} from the EPA observational network were consistent. A strong correlation was observed (the correlation coefficient of Beijing's PM_{10} and $PM_{2.5}$ data was 0.86, and for Tianjin's was 0.89), thereby explaining that these experimental observations were appropriate for providing a regional representation. There was also a strong correlation between the daily-average concentration of $PM_{2.5}$ and the PM_{10} in both Beijing and Tianjin, and the apparent correlation coefficients were 0.68 and 0.70, respectively, showing that these two cities have similar pollution situations and indicating there may be pollution transmission between the two cities.

The EPA's publication, "Atmospheric Environment Quality Standards" (GB3095-1996), regulates the daily-average concentration of inhaled particulate

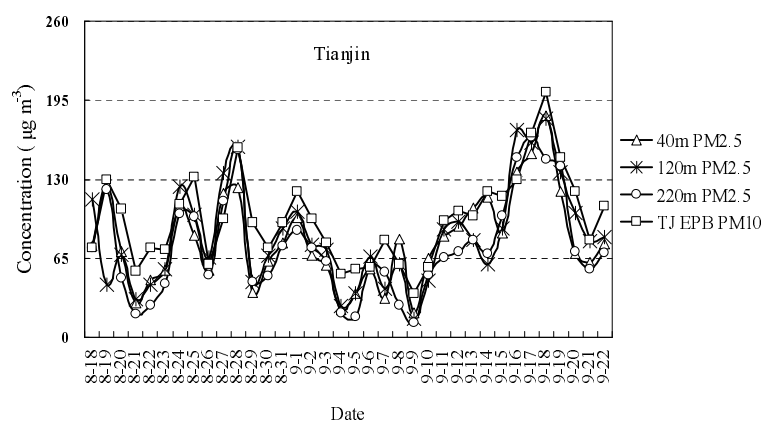


Fig. 3. The daily average data of $PM_{2.5}$ at Tianjin's 255 m tower and PM_{10} from EPA.

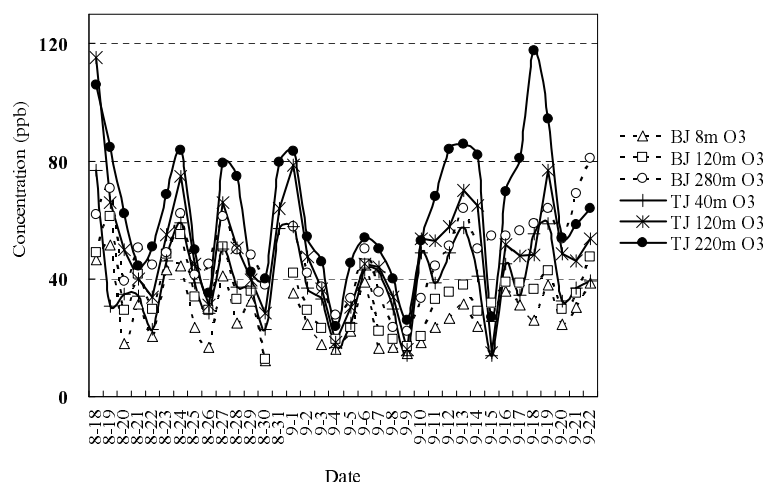


Fig. 4. The daily average concentration of O_3 in Beijing and Tianjin in gradient observations (BJ=Beijing Tower; TJ=Tianjin Tower).

matter (PM_{10}) in II standards to be less than 0.15 mg m^{-3} , while urban environments with higher PM_{10} concentrations than these values are typically considered mildly contaminated. There currently is no standard regulating the fine particle concentrations ($PM_{2.5}$) in China. The II standards concentration of the United States Environmental Protection Administration (U.S. EPA) is limited to $65 \text{ } \mu\text{g m}^{-3}$ for a 24-hour average (on 21 September 2006 that organization issued new particle standards for the 24-hour $PM_{2.5}$ standard, with the maximum reduced from $65 \text{ } \mu\text{g m}^{-3}$ to $35 \text{ } \mu\text{g m}^{-3}$). An environment with concentrations exceeding these standards will do harm to the human populace.

During the observation period, there were 12 days that exhibited PM_{10} concentrations exceeding the national standards in Beijing, with the highest daily-average concentration observed being $250 \text{ } \mu\text{g m}^{-3}$. There were 3 such days in Tianjin, with a maximum daily-average concentration of $200 \text{ } \mu\text{g m}^{-3}$. In the case of the $PM_{2.5}$ concentration within the initial 8 m layer of the Beijing tower, there were 18 days where the concentrations exceeded the former United States Environmental Protection Agency (U.S.EPA) standards and the highest daily average concentrations reached $165 \text{ } \mu\text{g m}^{-3}$. Within the initial 40 m layer of the Tianjin tower, there were 22 such days, with the highest observed daily-average concentration being $183 \text{ } \mu\text{g m}^{-3}$.

In these two locations, the daily-average volume-by-volume concentrations of O_3 within the three layers increased with increasing height (Fig. 4), but at Tianjin the O_3 concentration was generally higher than it was in Beijing at each corresponding level. Due to the low altitude of its emissions sources in general, the NO_x concentration increased with decreasing height. During the entire observation period, in the lowest 280 m of the Beijing tower the average concentrations of

O_3 and NO_x were 49 ppb and 18 ppb, respectively, with the highest daily average concentrations being 81 ppb and 27 ppb, respectively. In Tianjin, within the lowest 220 m layer of the tower, the average concentrations of O_3 and NO_x were 64 ppb and 11 ppb, respectively, with the corresponding maximum observed daily concentrations being 118 ppb and 34 ppb, respectively.

3.2 Analysis of daily variations

The $PM_{2.5}$ data within the three layers during the observation period were analyzed to determine the daily variations (Fig. 5). The daily variations in the $PM_{2.5}$ in Beijing and Tianjin had drastically different characteristics. In Beijing, changes occurred more slowly. In the lowest 240 m, the concentration was found to fall at the higher levels over the entire night. During the day, the concentrations were found to be lower than they were during the night, presumably because they were equally mixed. However, Tianjin had an obvious peak in the concentration within the diurnal cycle, and at night it was found to be lower than during the day. From 0500 LST, the concentration levels were observed to begin to increase within every layer. The peak concentrations appeared occurred at 0700, 0800, and 0900 LST, after which time the concentrations started to decline. At 1400 LST, the concentrations were found to reach a minimum, after which the concentrations maintained a slightly higher concentration until the evening.

A NO_x and O_3 variation gradient map is presented in Fig. 6 and shows that the overall changes characteristic of the O_3 concentration within Beijing and Tianjin were basically similar for the two pollutants. The concentrations were both were at their lowest at night and their highest during the daytime, with the

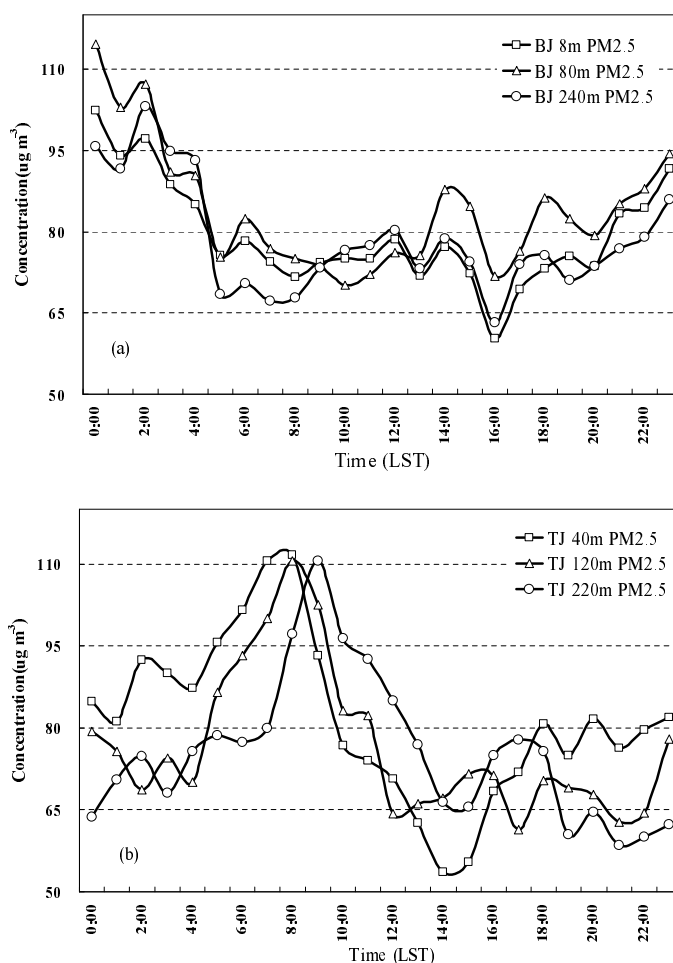


Fig. 5. The statistical daily variation of PM_{2.5} in (a) Beijing and (b) Tianjin (BJ=Beijing Tower; TJ=Tianjin Tower).

daytime peaks timed essentially the same. At night, the concentrations varied greatly in both cities, while during the afternoon in Beijing, the O₃ concentrations were distributed in a similar fashion with atmospheric height from high to low, while at the same time, within the initial 280-m layer, the O₃ concentration was still high. But within the lowest 120 m, O₃ concentration were very low at night. At night, the relative stratification of O₃ concentrations at Tianjin was higher than in Beijing. This is also the reason why the average concentrations observed in Tianjin were higher than they were in Beijing. Within the three layers during the morning between 0700 LST and 0800 LST, the concentration was obviously low. At this time, the NO_x and PM_{2.5} concentrations were at a maximum. The reason was perhaps because there was a sudden rise in emissions due to increased traffic, an increase in the titration reaction between NO to O₃, and because the heterogeneous reaction that occurs on the surface of

particles is not conducive to the formation of O₃. The NO_x daily variation was found to exhibit a unimodal distribution. At 0600 LST, 0800 LST, and 1000 LST, within every level the concentration gradually reached its peak. At the same time, Tianjin had the same distribution, but with added complexity. At 1400 LST, a second peak appeared and at 120 m there were also higher concentrations when compared with other layers. However, the O₃ concentrations were found to be significantly lower than they were at 40 m and 220 m during the afternoon. This is likely affected by the aforementioned emissions plume.

Because of the differences in characteristics of O₃, NO_x, and CO pollution sources and sinks and in meteorological conditions, the vertical distribution of concentrations in the city boundary layer were not homogeneous, and have different regulation. The difference is not obvious within 300 m according to average daily concentration of PM_{2.5} from the two tow-

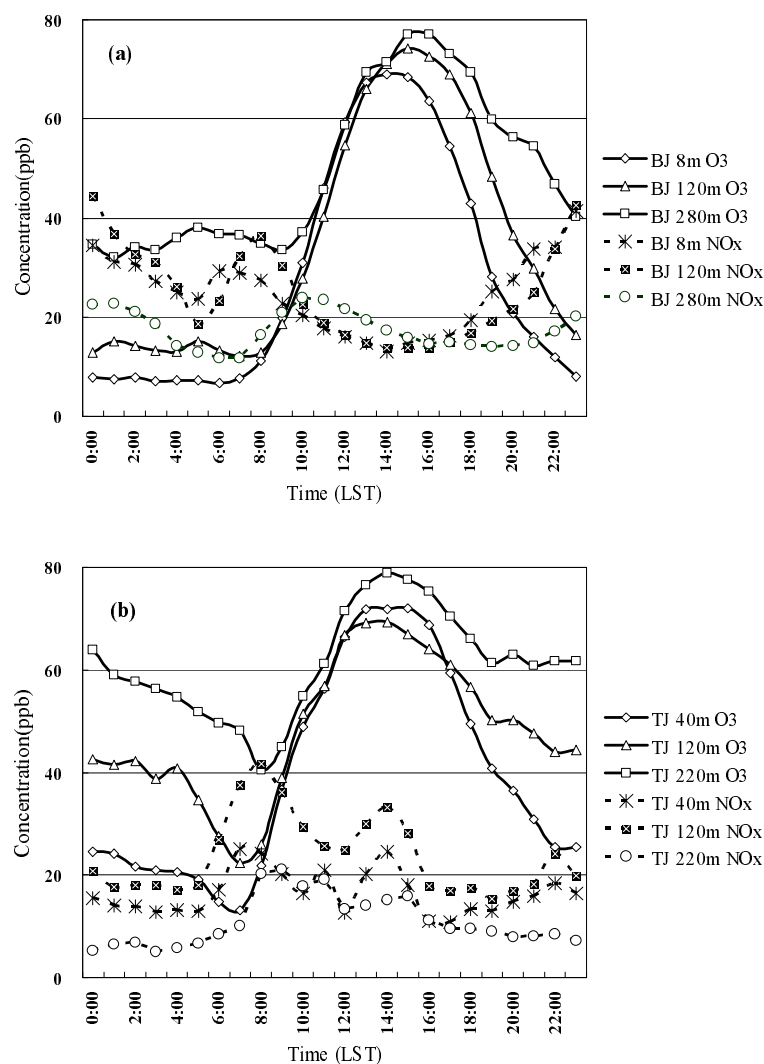


Fig. 6. The daily variation data of O₃ and NO_x in (a) Beijing and (b) Tianjin in gradient observations (BJ=Beijing Tower; TJ=Tianjin Tower).

ers, but there are more remarkable differences in daily statistical hourly averages. The PM_{2.5} data at 80 m of the Beijing tower is higher than for the other two layers from 1300 to 0200 LST, perhaps because air of this layer is well-mixed and representative of successful photochemical reaction conditions, including production and accumulation of secondary particles. The 8 m platform is close to the ground and surrounded by buildings, so there is a slow response time to pollution sources and the PM_{2.5} density is relatively low; there are strong wind speeds, higher atmospheric diffusion, and larger spatial representativeness, for the lower density of PM_{2.5} found at the 240-m platform. The PM_{2.5} concentration of different layers shows large change and does not have an obvious vertical distribution, perhaps due to some contributions from local

sources at the Tianjin tower. The O₃ and NO_x data show the same daily variation regularity between the tower of Beijing and Tianjin tower. The NO_x concentration decreased with height, showing that sources mainly come from the lower level, but O₃ concentration increased with height because of weak NO titration reactions and sufficient photochemical reactions at this height.

3.3 Analysis of meteorological factors

The concentration of the pollutants varied with the changes in the emissions from the various sources and with weather conditions. This experiment could not determine the exact sources of the changes, but considering that there were no heat events or other major events to result in changes in the concentrations of

emissions, it was assumed that the emissions changed very little. Therefore, the weather conditions were considered to be the most direct and important factors in creating the observed changes in the concentrations of the various pollutants most of the time. Weather conditions determine the spread, polymerization, and transport of these pollutants, as well as the reaction rate changes of the secondary pollutants. It is necessary to consider the pressure, temperature, humidity, wind direction, wind speed, and other factors in an effort to analyze the formation processes responsible for the current air quality situation. Experimental observations of the concentration of the pollutants and the meteorological factors associated with their collection were used to analyze and classify factors in an effort to reveal some of the regional causes for the creation of these pollutants in Beijing and Tianjin.

Related studies have shown that in the part of urban boundary layer, which is located above the constant flux layer, increases in the layer height leads to an increase in the retardation of the atmospheric response to the surface source information, and to a greater increase in the response time-scale (Bi et al., 2003), along with being more broadly representative of the atmospheric chemistry data. The observations at Beijing's 325 m tower showed that the standing flux layer extended up to above 100 m (Liu and Zhong, 2002). Data collected at Tianjin's 255 m tower showed that the layer with the highest frequency of stable stratification was at 140 m, while the layer with the highest frequency of strong winds was observed at 160 m and 220 m (Xie and Liu, 2003). Therefore, it is better and more broadly representative to compare the relationship between the observational data and meteorological factors at Beijing's 240 m platform and Tianjin's 220 m platform.

The weather data from Beijing and Tianjin from the CMA (China Meteorological Administration) during the experimental period includes the three-hour average sea-level pressure (SLP), temperature, dew point, wind speed, wind direction, precipitation, and level visibility from the two cities. Analysis showed that in early August, the regional meteorological conditions were conducive to the spread of pollutants and that there were a few rains which played a significant role in the settlement of these pollutants. The cold air activities were more frequent. During this time, there were some stable weather conditions later on, which therefore caused minor increases in pollution. In early September, which was affected by cold air regularly, good atmospheric pollutant dispersion was observed. During mid-September, the temperature was observed to be high in the upper air and the temperature differences between the day and night increased. At night,

there were often inversions in the temperature gradients. In the lower layer, there was typically either no wind or significantly weaker wind, and the weather was found to be relatively stable. Under these conditions, it was easy for the atmospheric pollutants to accumulate and hard for them to diffuse. Therefore, from the 14th to the 20th of September within the region, the pollutants were observed to rise consistently.

The weather situation at the ground-level was a combined reflection of diffusion and stability of the components of the upper and lower-level atmospheres. Analyzing the temperature, moisture, wind, and pressure on the ground was also helpful in understanding the external conditions governing the formation of the air pollution. In the past, other scholars have shown that the weather situation on the ground, including cold high-pressure conditions, high-pressure fronts, circumfluence, etc., in the Beijing region were conducive to the further spread of these pollutants, while either a weakly higher, equal, or lower pressure were not conducive to the further spread of pollutants and often led to increases in air pollution (Meng and Cheng, 2002). Firstly, through the combined analysis of the daily average sea-level-pressure, temperature, and daily averages of the $PM_{2.5}$ and O_3 concentrations, we found that because of the short distances between Beijing and Tianjin, generally similar weather conditions were observed. During the experimental observation period, the $PM_{2.5}$ and O_3 concentrations changed rapidly, with increasingly unstable weather situations. Generally, when the pressure increased, and the temperature inversion was negative over a 24 hour period, the concentration of the pollutants was greatly reduced. The reason for this was that this weather situations were conducive for the pollutants to spread, such as on 21 August, 29 August, 4 September, and 9 September, as shown in Fig. 7. During a period where the local surface pressure was weakening, there was a positive temperature inversion over a 24 hour period, with the atmosphere being observed to be stable, and the air trapped to the ground, so pollutants diffused only with difficulty and the concentration of the pollutants was found to increase correspondingly, such as occurred on 27 August, 28 August, and 6 September. In addition, the rainfall played a significant role in the cleaning of these atmospheric pollutants, such as occurred on 26 August, as at this time the air pressure reduced, the temperature inversion was negative, and so the daily mean $PM_{2.5}$ concentrations were substantially reduced.

The dew point reflects the total amount of atmospheric water vapor, where the higher the dew point, the higher the moisture content. Furthermore, with a higher dew point, atmospheric particles are more eas-

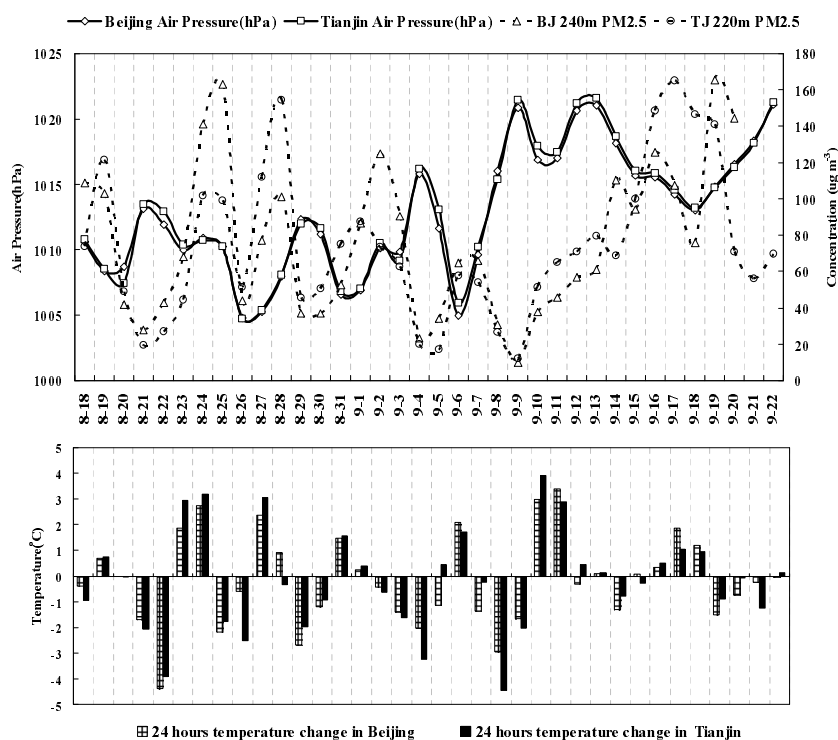


Fig. 7. Daily average sea level pressure, 24-hour temperature inversion, and daily PM_{2.5} (BJ=Beijing Tower; TJ=Tianjin Tower).

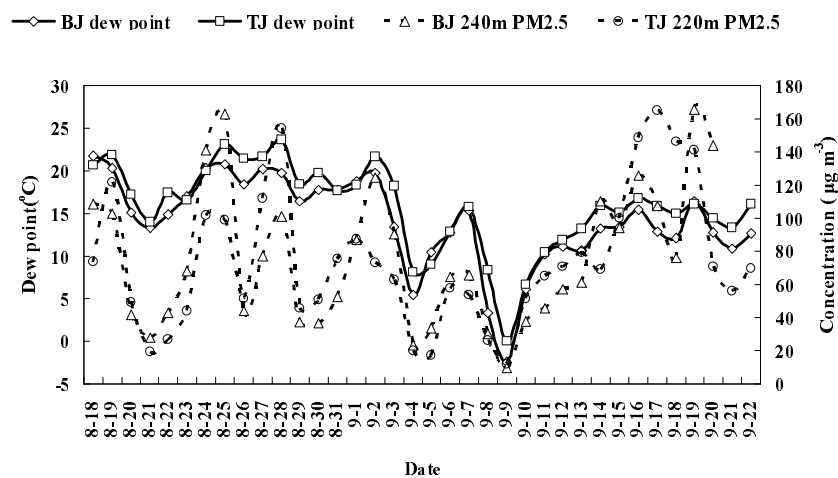


Fig. 8. The daily variation of dew point and the concentration of PM_{2.5} day by day (BJ=Beijing Tower; TJ=Tianjin Tower).

ily formed and the concentration is higher. Therefore, the dew point and the fine particle concentration are positively correlated. During the observation period, the dew point varied significantly, and in a staggered fashion, with changes in the PM_{2.5} concentration, As illustrated in Fig. 8, during the first time stage, which extended from 18 August to 2 September, the dew point was observed to be higher in value, with the exceptions of 21, 26, and 29 August. On these days, there

was sufficient precipitation and the PM_{2.5} concentrations were typically high and the dew point reached the highest values observed during this period, with a maximum value of 21.8°C in Beijing and 23.6°C in Tianjin. In the second stage, which extended from 3 to 9 September, due to the continued strong northern winds and the associated cooling, the dew point and PM_{2.5} concentrations were both reduced to the lowest levels measured. The minimum dew point was -2.5°C

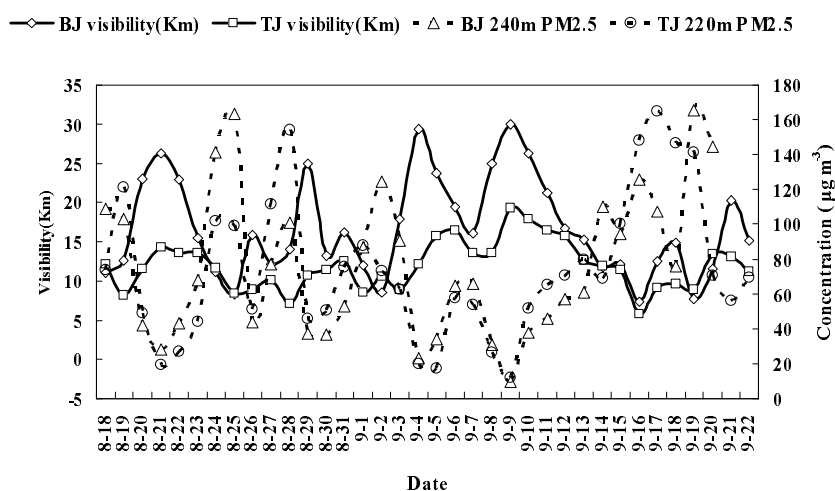


Fig. 9. The daily variation of the visibility level and $PM_{2.5}$ concentrations (BJ=Beijing Tower; TJ=Tianjin Tower).

in Beijing and $0.0^{\circ}C$ in Tianjin. At the same time, the lowest $PM_{2.5}$ concentration was $110 \mu g m^{-3}$, while in Tianjin it was only $12 \mu g m^{-3}$. During the third stage, from 10 to 22 September, the weather situation became stable and the $PM_{2.5}$ concentrations and dew points were found to gradually increase. Though the average dew point was slightly lower than it was during the first stage, the $PM_{2.5}$ concentrations at Tianjin on 17 September and at Beijing on 19 September still reached a maximum value of $165 \mu g m^{-3}$ for this observation period. In this experiment, the correlation coefficients between the dew point and fine particle concentration in Beijing and Tianjin were 0.56 and 0.50, respectively. During the observation period, the average dew point in Beijing was $14^{\circ}C$, was slightly lower than it in Tianjin, where it was $16^{\circ}C$; however, the average concentration of PM_{10} in Beijing was measured to be $113 \mu g m^{-3}$, which was higher than the average value in Tianjin, which was $98 \mu g m^{-3}$. Finally, the average concentration of $PM_{2.5}$ in Beijing was $76 \mu g m^{-3}$, which was slightly higher than in Tianjin, where the value was $74 \mu g m^{-3}$. It is quite likely that in these two cities the formation mechanism between PM_{10} and $PM_{2.5}$ is slightly different. While Beijing provides coarser particle emission sources, Tianjin is mostly affected by sea salt particles; therefore the ratio of small particles is larger.

Many studies have shown that the typically poor urban visibility is further reduced due to increases in the PM_{10} and $PM_{2.5}$ aerosol concentrations (Appel et al., 1985) along with increases in NO_2 gas (Hodkinson, 1966). In this experiment the correlation coefficients between the visibility and the PM_{10} , $PM_{2.5}$, and NO_x concentrations were -0.72 , -0.86 , and -0.21 in Beijing and -0.65 , -0.70 , and 0.03 in Tianjin, respec-

tively. As Fig. 9 shows, the visibility has a strong inverse relationship with the $PM_{2.5}$ concentration. The average concentrations of NO_x and PM_{10} in Tianjin were both lower than they were in Beijing. The correlation coefficient also showed that the $PM_{2.5}$ concentration played a major role in reducing the overall visibility. During the time when the $PM_{2.5}$ concentrations in the two cities were similarly low, the level of visibility in Tianjin was significantly lower than it was in Beijing, such as observed on 21 and 29 August, and 4 and 9 September. During the time when the $PM_{2.5}$ concentrations in the two cities were high and differed significantly, the visibility was low with minimal differences between the observed values, such as on 25 August and 2, 16, and 19 September. Possible reasons for this are as follows: first, the role that these particles play in leading to the extinction of the incident solar radiation was found to be quite dependent upon the different chemical constituents (Dzubay et al., 1982). The components of the $PM_{2.5}$ were also significantly different between Tianjin and Beijing and there was a much higher ratio of ammonium sulfate and ammonium nitrate observed when the higher extinction coefficients were observed in Tianjin (Barthelmie and Pryor, 1998), and the extinction coefficient of $PM_{2.5}$ was higher. Secondly, when the $PM_{2.5}$ concentration was low, the variations in the visibility range were larger and the variance in the extinction coefficient was fully manifested. On the other hand, when the $PM_{2.5}$ concentrations were high, the visibility dropped to the minimum, but this difference was not easily correlated. Finally, besides $PM_{2.5}$, there were other factors that may have affected the visibility in Tianjin much more significantly than they did in Beijing.

The wind speed and direction played an important

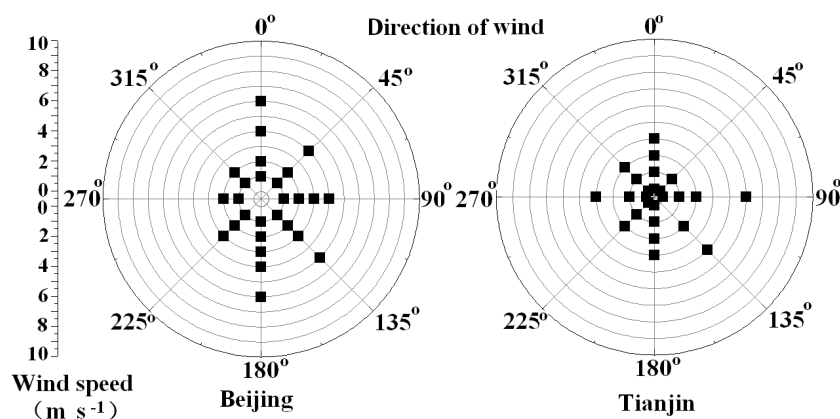


Fig. 10. Wind speed, wind direction frequency rose map.

role in distributing pollutants throughout the atmosphere. A comprehensive analysis of the mean wind speed, wind direction, and daily average $\text{PM}_{2.5}$ concentrations can show the transmission characteristics of the pollutants and the way in which the two cities impact each other. The local three-hour averaged wind speed and wind direction during the day, when the daily average of $\text{PM}_{2.5}$ concentrations were above $65 \mu\text{g m}^{-3}$ in the lowest 240 m at the Beijing tower and the lowest 220 m at the Tianjin tower, are presented in Fig. 10. When Beijing was seriously polluted, the southern and southeastern wind frequencies and wind speeds were high, while the western and northwestern wind frequencies were minimized. Beijing is located to the southeast of Tianjin, and therefore the air quality will typically be affected by events in Tianjin. When there was heavier pollution in Tianjin, the eastern and southeastern wind frequencies and the wind speeds were high, while the southwestern wind frequency and wind speed were low. For these reasons, Tianjin's $\text{PM}_{2.5}$ pollution was typically not delivered from sources in and around Beijing.

3.4 Analysis of an episode

During 18–29 September 2006, serious air pollution appeared both in Beijing and Tianjin, and these pollutant loads have been accumulated constantly since 10 September, reaching pollutant maximum values by the 18 and 19 September. The meteorological factors of this episode have been diagnosed as follows: The subtropical high pressure center began move to the south gradually in mid-September, and sometimes shifted to the north. The temperature of the northern area was generally higher, with average temperature reaching the second highest values for the same dates since 1951 in Beijing and Tianjin, with little rain. During this period, upper platform level temperatures were higher, the vertical gradient of temperature was large

with temperature inversions frequent at night, and the low level winds were calm. These conditions were relatively steady. The pollutants easily accumulated under these circumstances in Beijing and Tianjin. $\text{PM}_{2.5}$ and PM_{10} accumulated constantly from the 10 September (Fig. 2 and Fig. 3). The maximum concentration of pollutants occurred during the 18 September in Tianjin and the 19 September in Beijing. The O_3 peak value was 171.6 ppb and appeared at 2000 LST at the 220 m platform on 18 September in Tianjin (Fig. 11). That day, the routine observations show that O_3 exceeded 2nd grade standards of national environmental quality at lower levels for the daytime, and extreme O_3 concentrations appeared at higher level caused by transport and accumulation at night. $\text{PM}_{2.5}$ pollution was also serious with an maximum hourly average concentration of $279 \mu\text{g m}^{-3}$ on this day in Tianjin (Fig. 12). The concentrations of O_3 and $\text{PM}_{2.5}$ both were lower than for Tianjin in Beijing on the same day, but on the next day O_3 and $\text{PM}_{2.5}$ both became higher because of transport and accumulation. The O_3 concentration at higher levels surpassed that at ground level because the NO from ground sources cannot reach that high to react, and the reacting air mass transported from long range in the nocturnal stable boundary layer is aged. The variations of $\text{PM}_{2.5}$ are similar in each layer, but there was greatly variable amplitude above the nocturnal stable boundary layer (>200 m) because of stronger wind speeds and pollution transport.

In this air pollution process, the two locations were within the same weather system, and the meteorological conditions were basically consistent, with the maximum daily averages of $\text{PM}_{2.5}$ being $165.5 \mu\text{g m}^{-3}$ and $181 \mu\text{g m}^{-3}$, respectively, in Beijing and Tianjin. The $\text{PM}_{2.5}$ is made up of primary particles and secondary particles. With consideration of the reactions and the life cycle, the $\text{PM}_{2.5}$ source intensity may be assessed briefly: the $\text{PM}_{2.5}$ source intensity of Tianjin is higher

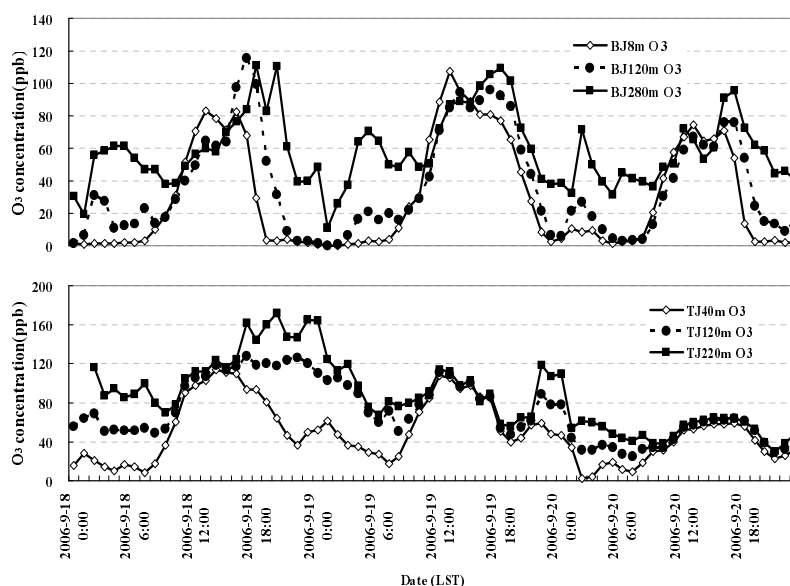


Fig. 11. Comparison of O_3 data between Beijing and Tianjin from 18 September to 20 September.

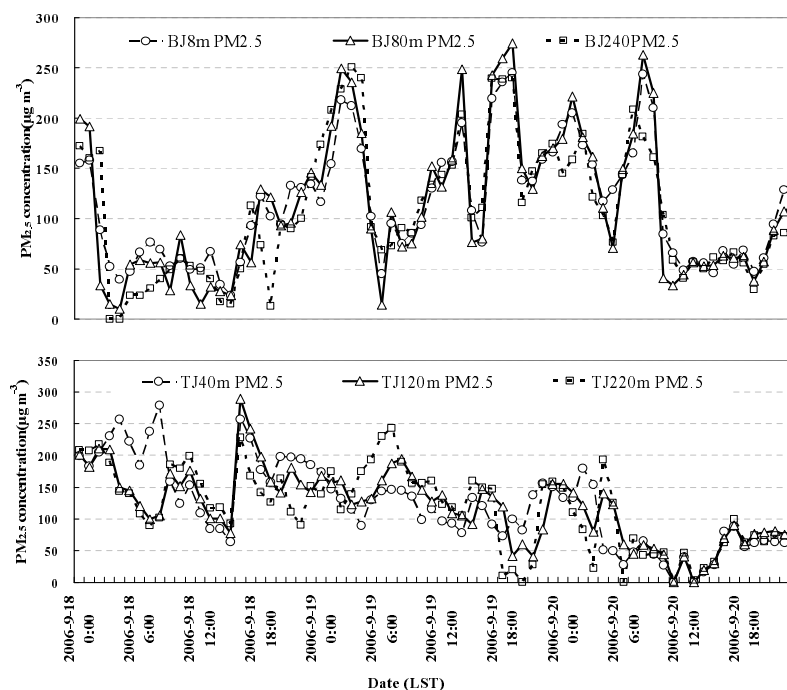


Fig. 12. Comparison of $PM_{2.5}$ data between Beijing and Tianjin from 18 September to 20 September.

than in Beijing.

4. Conclusion

The lower atmosphere at Beijing and Tianjin is polluted seriously by $PM_{2.5}$ and O_3 during the summer and autumn. The variance in the daily average concentrations of PM_{10} and $PM_{2.5}$ in Beijing and Tianjin were shown to be consistent with one another

and the levels of $PM_{2.5}$ pollution was similar between the two cities. The daily average concentrations of PM_{10} and $PM_{2.5}$ in Beijing and Tianjin were found to repeatedly exceed the U.S. EPA standards. Between these two cities, the features of the changes in the daily average concentrations of $PM_{2.5}$ showed a large amplitude cycle, with high values during the daytime and low values in the nighttime in Beijing; while in Tianjin there were high daytime and low nighttime lower

atmosphere concentrations of PM_{2.5} observed, with a peak in the morning.

The overall O₃ concentrations near the ground in Tianjin were larger than those observed in Beijing. The diurnal variations in the O₃ concentration were low at night and high during the daytime in both cities, and the peak values in the daytime were relatively consistent, but the nighttime values varied greatly. At a height of 220 m, there was a larger concentration of O₃ in Tianjin, but the atmospheric concentrations of NO_x in Beijing were higher than those in Tianjin, while at a height of 120 m there was a significantly higher concentration of NO_x in Tianjin.

Higher rainfall and cooler air were favorable for the removal of pollutants in these two cities. The atmospheric dew point in Tianjin was higher than it was in Beijing and the visibility level in Tianjin was lower than it was in Beijing, but the average concentrations of PM₁₀ and PM_{2.5} were lower than they were in Beijing. Maybe this is due to the differences in the formation mechanisms of the PM₁₀ and PM_{2.5} particles or due to the fact that their extinction coefficient was higher in Tianjin than it was in Beijing.

When the atmospheric concentrations of PM_{2.5} in Beijing were higher, the speed and frequency of the southeastern and southern winds were higher. During the time of the Olympics, the air quality in Beijing may be expected to be influenced by delivery of these atmospheric pollutants from Tianjin. While the atmospheric concentrations of PM_{2.5} in Tianjin were higher, eastern and southeastern winds increased in both speed and frequency, but this was not the case for northwestern winds. Therefore, the probability that Tianjin's PM_{2.5} pollution will be affected by occurrences in Beijing is very low.

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