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Diurnal Variations of Air Pollution and Atmospheric Boundary Layer Structure in Beijing During Winter 2000/2001

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ABSTRACT

The diurnal variations of gaseous pollutants and the dynamical and thermodynamic structures of the atmospheric boundary layer (ABL) in the Beijing area from January to March 2001 are analyzed in this study using data from the Beijing City Air Pollution Observation Field Experiment (BECAPEX). A heavy pollution day (22 February) and a good air quality day (24 February) are selected and individually analyzed and compared to reveal the relationships between gaseous pollutants and the diurnal variations of the ABL. The results show that gaseous pollutant concentrations exhibit a double-peak-double-valley-type diurnal variation and have similar trends but with different magnitudes at different sites in Beijing. The diurnal variation of the gaseous pollutant concentrations is closely related to (with a 1–2 hour delay of) changes in the atmospheric stability and the mean kinetic energy in the ABL.

Key words: Beijing, air pollutant, diurnal variation, atmospheric boundary layer

1. Introduction

Air pollution is always a public concern, in particular, in the metropolitan areas, such as in Beijing. Air pollution is mainly caused by the existence of emission sources of gaseous pollutants and by the weather conditions, such as the atmospheric boundary layer (ABL) stability, wind speed and direction, turbulence, and topography etc. (Li et al., 2003). Study of the variations of gaseous pollutants and their relationships with both dynamical and thermodynamic structures of the ABL is of importance not only to the environmental protection but also to the public.

It is well know that gaseous pollutants are harmful to human health in different ways, such as sulfur oxides, nitrogen oxides, hydrocarbons, and carbon oxides, etc. The carbon oxides mainly include carbon monoxide and carbon dioxide from burning. The carbon monoxide is an asphyxiating gas. Although carbon dioxide is not poisonous, it may cause the greenhouse effect and bring about grave consequences, such as rising sea levels (Wang, 1999; Li et al., 2003).

Variations of the ABL and gaseous pollutant concentrations are issues of public concern and also draw much attention from environmental scientists. One of the important areas in China, which has been studied to some extent, is the metropolitan area of Beijing (Min et al., 2002; Zhang et al., 2001; Bian et al., 2002; Wang, 2001; Xu et al., 2003a). Xu et al. (2003a) have investigated the spatial and temporal variations of air pollution in Beijing and found that the pollutants NO_x, SO_2 and CO possess an in-phase variation in a large area, and the O_3 concentration has the same variation trend, but in an opposite phase. The vertical distribution of pollution gases and aerosols in the Beijing area is significantly correlated with the vertical structure of the large-scale inversion layer within the urban ABL. Bian et al. (2002) analyzed the structure of the urban ABL in Beijing and showed that the urban heat island effect is remarkable in the urban area.

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The vertical distributions of wind speed and direction display an inflection point below 100–200 m and a general consistency above 300 m, indicating that the wind profiles both in the urban and suburban areas are affected by the urban ABL. Wang et al. (2001) analyzed major air pollutant concentrations in the urban area of Beijing in the winter of 1999/2000, and pointed out that the diurnal variations of pollutant concentrations at different heights in the urban area display a distinct double-peak pattern with the two peaks occurring between 0700 and 0800 LST and between 1900 and 2300 LST, respectively.

The objective of this study is to document the diurnal variation of air pollution in the Beijing area during the Beijing City Air Pollution Observation Field Experiment (BECAPEX) from January to March of 2001. We will focus on the diurnal variations of different gaseous pollutants, and their relationships with the dynamical and thermodynamic structures of the ABL. After a brief description of the data used in this study in section 2, we will analyze the mean diurnal variation of gaseous pollutant concentrations at three sites in Beijing in section 3. The diurnal variations of the ABL kinetic energy and stability for a polluted day and a good air quality day will be analyzed and compared in section 4. Our major results will be summarized in the last section.

2. Data and analysis method

The BECAPEX data are used to analyze the winter diurnal variation of air pollutants in Beijing. The surface observations during the BECAPEX included the three air pollutants sites at Chedaogou, Shuangyushu and Lianhuaxiaoqu, and a meteorological observing site, the ABL meteorological tower of the Institute of Atmospheric Physics of the Chinese Academy of Sciences (IAP–CAS) (Xu et al., 2003b; Xu and Tang, 2003). The dynamical and thermodynamic 3-D structures of the ABL, and the vertical distribution of air pollutants were continuously observed in the two periods of 5–13 January and 21 February–28 March 2001. The pollutant concentrations of SO_2, NO_x, CO, and O_3 were continuously and automatically observed on average over time intervals of one hour at the top of the high buildings of Shuangyushu, Lianhuaxiaoqu, and Chedaogou observation sites. The three observing sites of Shuangyushu (86 m height), Lianhuaxiaoqu (83 m height) and Chedaogou (50 m height) are located in the northwest part of the Beijing urban area and between the Third Ring Road and Fourth Ring Road, which are the main traffic roads in the Beijing urban area (Xu and Tang, 2003). The meteorological observing site of IAP is also located in the northwest part of the Beijing urban area. The wind and temperature profiles were observed using kite balloon sounders and the 325-m meteorological tower. The gradient observations of wind and temperature were performed at the IAP-CAS site at 15 heights of 8, 15, 32, 47, 65, 80, 100, 140, 160, 180, 200, 240 m, including 47, 120, and 280 m heights, where the ultrasonic wind/temperature sounder of rapid response was used (Lu et al., 2002; Su and Hong, 1994). The geographic locations of the three air pollution observation sites (Shuangyushu, Chedaogou, Lianhuaxiaoqu) and the meteorological observation site (IAP-CAS) are given in Fig. 1.

The ABL stability is a critical parameter affecting the diffusion of air pollutants. Wang et al. (2001) analyzed the gaseous pollutant concentrations and meteorological conditions in the winter of 1999/2000 in Beijing and found that different atmospheric stabilities have different effects on the pollutant concentration. There are several measures of atmospheric stability. One commonly used is the Passquill method (P_L method; Passquill, 1961) in which the atmospheric stability is reckoned according to surface wind speed, solar radiation, and cloud cover, etc. The second is the temperature difference method ($\Delta T/\Delta Z$; Carpenter, 1971) in which the stability is calculated from the temperature difference at two heights. The third one is based on the dynamical and thermodynamic structures of the ABL, namely, the gradient Richardson number (Ri), bulk Richardson number (Ri_{b}), and the Monin-Obuhov length (L) (Xu and Zu, 1983).

With the use of the Lanzhou urban ABL data, Liu et al. (2001) examined various computational methods of atmospheric stability and found that the temperature difference method is the best one, and the Richar-

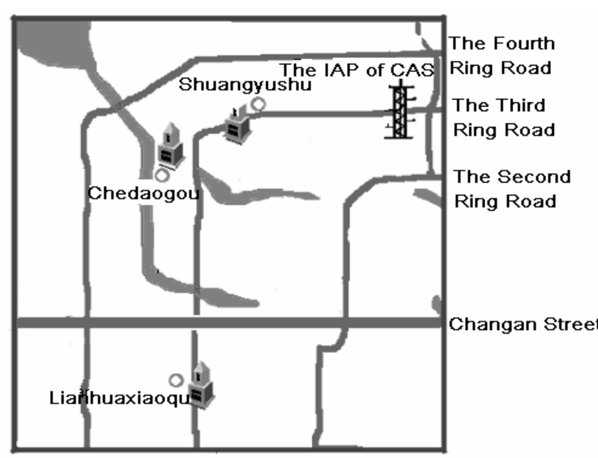

Fig. 1. Geographic locations of the three air pollution observation sites and the meteorological observation site in the Beijing urban area.

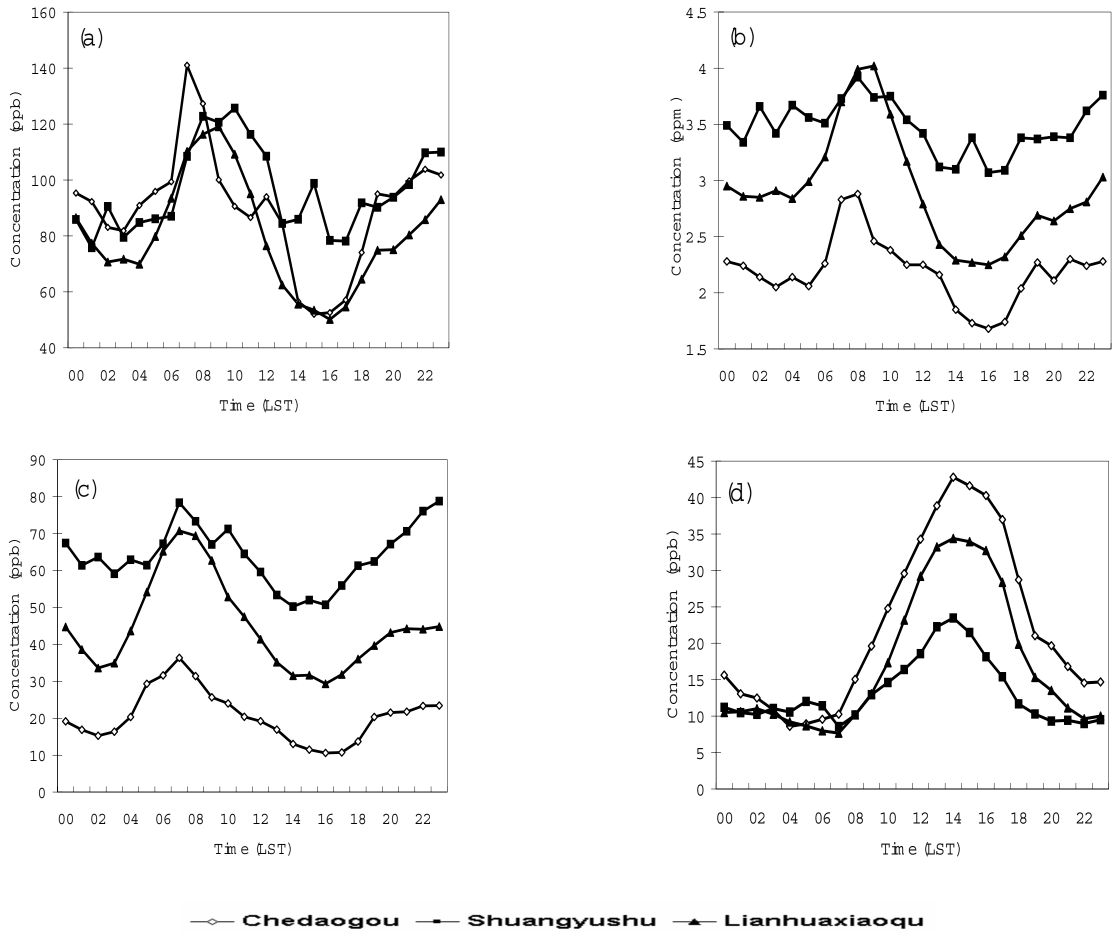

Fig. 2. Composite mean diurnal variations of gaseous pollutant concentrations at three different sites in January–March 2001. (a) NO_x; (b) CO; (c) SO_2; (d) O_3.

dson number method has a bias towards a stable state. Therefore, in this study, we will use the temperature difference method and calculate $\Delta T/\Delta Z$ to determine the ABL stability with IAP temperature data at 15 different heights. Stability at different heights is calculated by temperature at the current level and the next level below.

The horizontal wind is another important parameter that determines the diffusion and dilution of pollutants. The wind directly determines the rate of the transport and dilution of pollutants in the air. The pollution areas are always in the downwind side of pollutant sources. Winds also diffuse and dilute pollutant plumes directly. The larger the wind speed, the faster the clean air is entrained into the plume in unit time. Therefore, pollutant concentrations are inversely proportional to the wind speed. The variation of wind with height in the surface layer is also related to the intensity and property of turbulence, which indirectly affects the pollutant concentration (Zhou and Shu, 1994). In our analysis, the strength of wind is measured by the mean kinetic energy (MKE) which is calculated according to Stull (1988):

$$E_{\rm MK} = \frac{1}{2}(\overline{U}^2 + \overline{V}^2 + \overline{W}^2) \tag{1}$$

where $\overline{U}, \overline{V}, \overline{W}$ are the mean zonal, meridional, and vertical wind components averaged in 30-min intervals. The turbulence kinetic energy (TKE) is defined as (Stull, 1991):

$$E_{\rm TK} = \frac{1}{2}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) \tag{2}$$

where u', v', w' are the departure of the instantaneous three wind components from the corresponding 30-minute mean. The amount of TKE reflects the extent of turbulent motion and it is the key physical parameter that determines the transport and exchange between the ABL and the free atmosphere above.

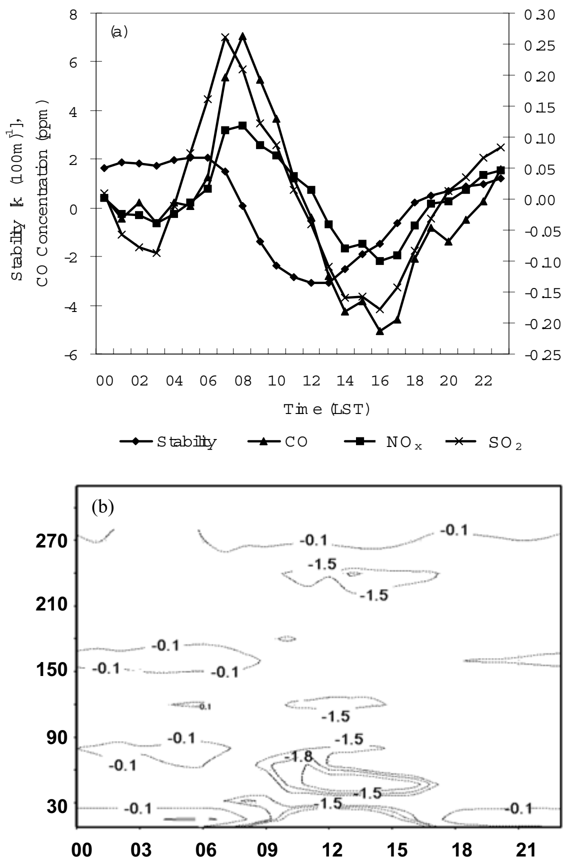

Fig. 3. Low level atmospheric stability distribution in January–March 2001. (a) Stability averaged over 8–320 m at the IAP site and the standardized variables of NO_x, SO_2, and CO concentrations averaged at the three sites shown in Fig. 2; (b) Vertical distribution of the mean diurnal evolution of the ABL stability at the IAP site.

Bian et al. (2002) analyzed the urban ABL structure in Beijing and found that the vertical distributions of wind speed and direction display an inflection point below 100–200m and a general consistency above 300 m, indicating that the wind profiles both in the urban and suburban areas are affected by the city overlay. Therefore, we will use the wind and temperature data of the 325-m meteorological tower in this paper to analyze the diurnal evolutions of atmospheric stability and mean and turbulent kinetic energies.

3. Mean diurnal variation

After analyzing the BECAPEX observations, Ding et al. (2002) pointed out that the temporal trends of air pollutants at different sites and heights in the ABL possess a general consistency. Therefore, their mean diurnal variations are expected to be comparable among different sites in the urban area as well. We thus first examine the composite mean diurnal variations of pollutant concentrations during the BECAPEX period.

Figure 2 shows the mean diurnal variations of SO_2, NO_x, and CO concentrations at the three observation sites in January and February 2001. Overall, the diurnal variations exhibit a similar double-peak-double–valley pattern at all three sites. The pollutant concentrations of SO_2, NO_x and CO first peak at 0000 LST, decrease afterwards with a valley at 0300 LST, and then gradually increase and reach the second maximum at about the time of sunrise (0700 to 0900 LST). They decrease gradually after the sunrise and experience another valley at 1600 LST, and then increase and reach another peak at about midnight. In contrast to the other three gaseous pollutants, the diurnal variation of O_3 concentration shows a one-peak-one-valley pattern, with the minimum between 0700 to 0900 LST and the maximum between 1500 to 1600 LST.

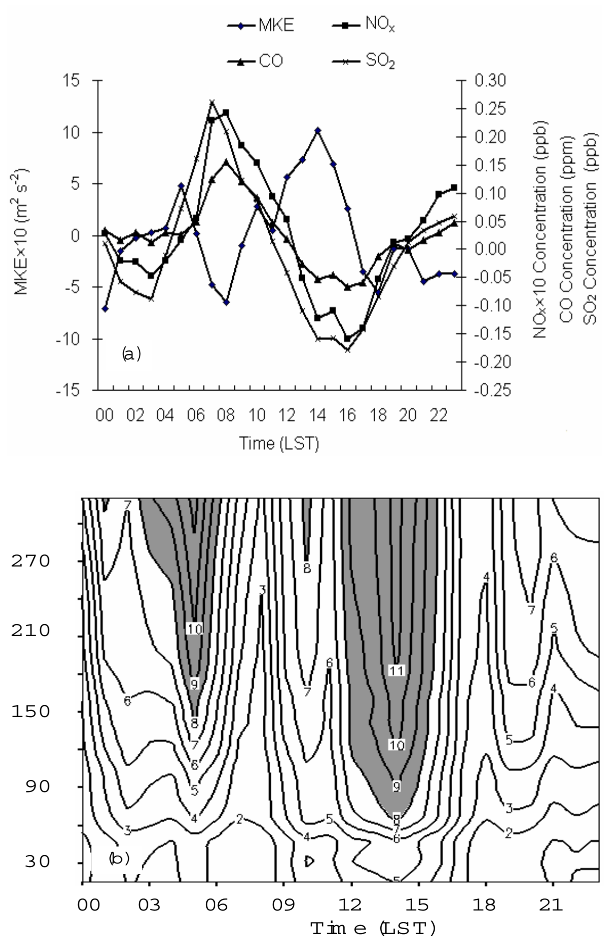

Fig. 4. Diurnal evolution of $E_{\rm MK}$ at the IAP site for January–March 2001 in Beijing. (a) Standardized variables of the mean kinetic energy and pollutant concentrations averaged over 8–320 m; (b) Vertical distribution (8–320 m) of the diurnal variation of mean kinetic energy.

The diurnal variation trends of the four gaseous pollutant concentrations at three different sites (Fig. 2) are basically similar, but the absolute pollutant concentrations differ greatly at different sites due to the different geographic locations. The diurnal variation ranges of NO_x and O_3 concentrations at the Chedaogou site are the largest among the three sites while it shows the minimum in SO_2 concentration. The SO_2 and CO concentrations at Shuangyushu are the maximum with the SO_2 concentration about 3 times of that at Chedaogou, and the diurnal variation ranges of CO and SO_2 concentrations at Lianhuaxiaoqu are the largest. These differences seem to be related to the relative locations to the pollutant sources, local prevailing winds, and traffic road conditions.

Figure 3a compares the mean ABL stability averaged over 8–320 m at the IAP site with the pollutant concentrations averaged at the three sites in January–March 2001. The atmospheric stability reaches its daily maximum at 0600 LST when the radiative inversion reaches its maximum height (Fig. 3b). After sunrise, the surface absorbs the solar radiation increasingly, and the surface air is warmed first. As a result, the unstable layer develops upward and gradually thickens. In the unstable conditions, the strong vertical mixing makes the physical properties vertically uniform. The air pollutants diffuse upwards with the surface pollutant concentrations decreasing. By noon, the inversion layer weakens and vanishes, and pollutant concentrations reach the minimum of the day between 1500 and 1600 LST. From 1200 to 2300 LST, the atmospheric stability gradually increases, the diffusion of air pollutants weakens and the pollutant concentrations increase. In particular, after sunrise, a distinct peak of pollutant concentration appears due to the increased emission of gaseous pollutants from industries and automobile exhausts, together with the effect of strong temperature inversion in the ABL.

Viewed from the vertical distribution of stability (Fig. 3b), the range of the diurnal variation is largest in the surface layer below 100 m, wherein the stratification is unstable around 1200 LST. Therefore, a convective ABL fully develops, and air pollutants rapidly diffuse upwards. The diurnal variation of pollutant concentrations usually lags that of stability by 1–2 hours.

The mean $E_{\rm MK}$ diurnally varies in an opposite phase against the pollutant concentrations (Fig. 4a). The wind speeds are greater than 6 m s^{-1} during 0700–0900 LST and 1000–1600 LST, the pollutants are easily dispersing and hence the pollutant concentrations are low. It can be seen from the vertical cross section of the diurnal variation of the $E_{\rm MK}$ (Fig. 4b) that the large diurnal variation lies in the upper ABL, 100 m above the surface. At about 0800 LST, the $E_{\rm MK}$ reaches the minimum of the day, and the pollutant concentration attains its maximum; while around 1400 LST, the $E_{\rm MK}$ reaches its maximum, and the pollutant concentration attains its minimum.

4. Contrast of diurnal variations between a heavy pollutant day and a good air quality day

The dates of 22 and 24 February are selected for the purpose of a comparison of a heavy pollution day with a good air quality day. On 22 February, the gaseous pollutant concentrations exceeded the standard criteria at all three sites. Generally, the surface wind speed, ABL temperature inversion, and precipitation are the major meteorological parameters that influence the pollutant concentrations of aerosols (Zhou et al., 1994). In the two cases selected, the rainfall on the 22 is 2 mm, and null on the 24. Except for the washout effect of precipitation, major factors influencing the pollutant concentration in Beijing are the surface wind speed and temperature inversion in the ABL.

Figure 5 gives the diurnal evolution of pollutant concentrations averaged from three sites on a heavy pollution day and a good air quality day. Consistent with the mean diurnal variation shown in Fig. 2, the diurnal variation of pollutant concentrations on a good air quality day also exhibits a double-peak-double-valley pattern.

Figure 6 displays the corresponding MKE. It can be seen that although the $E_{\rm MK}$ is smaller at 8 m than at 160 m and 320 m, it corresponds to the pollutant concentration quite well. On the heavy pollution day, the $E_{\rm MK}$ decreases between 0300 and 0700 LST, during which the gaseous concentration of pollutants increases; and the $E_{\rm MK}$ increases between 0700 and 1000 LST, while the pollutant concentration gradually decreases. Later on, as the $E_{\rm MK}$ increases, the pollutant concentration also decreases consistently (Fig. 6a). On the good air quality day, the $E_{\rm MK}$ corresponds to the pollutant concentration even better. For example, the $E_{\rm MK}$ decreases while the pollutant concentration increases between 1200 and 2300 LST (Fig. 6b).

The difference in pollutant concentrations during the period of 1700–2300 LST between the two cases may be explained by TKE. As can be seen from Fig. 7, on the good air quality day, the TKE falls rapidly from 1400 to 2400 LST. The ABL generally becomes unstable during the mid-day, favoring the development of turbulence and the enhancement of vertical mixing. In the period after midnight, however, radiative cooling cools the surface and the ABL becomes stable, suppressing the turbulence, and thus the TKE decrea-

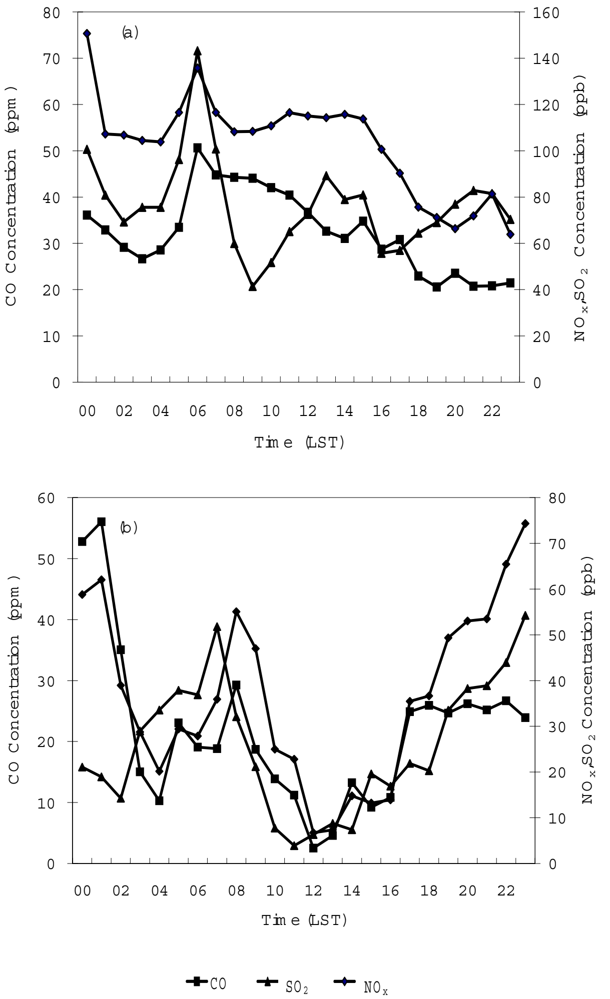

Fig. 5. Diurnal evolution of CO, SO_2, and NO_x concentrations averaged from three sites on (a) 22 February 2001 (heavy pollution day) and (b) 24 February 2001 (good air quality day).

ses while the pollutant concentration increases. In contrast, on the heavy pollution day, the relative change of TKE during 1400–2400 LST is smaller. The TKE increases from 1400 to 1800 LST, and the pollutant concentration decreases correspondingly. From 1800 to 2400 LST the TKE decreases, the SO_2 and NO_x concentrations slightly increase, but the CO concentration continues to decrease, showing the different trends of the different gaseous pollutants.

5. Conclusions

In this study, we have analyzed the mean diurnal variation of gaseous pollutants and the associated dynamical and thermodynamic structures of the atmospheric boundary layer in the Beijing area from January to March 2001 using the data from BECAPEX. A heavy pollution day (22 February) and a good air quality day (24 February) are selected and individually analyzed to reveal the relationships between gaseous

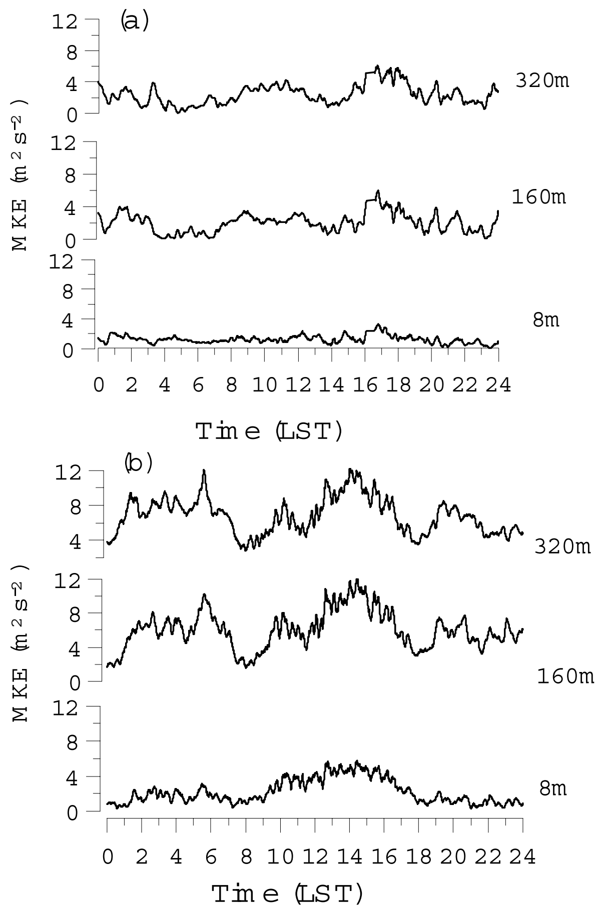

Fig. 6. Diurnal evolution of the E_{MK} at three heights of IAP site on (a) 22 February 2001 (heavy pollution day) and (b) 24 February 2001 (good air quality day).

pollutants and the diurnal variations of the atmospheric boundary layer structure. Our main results are summarized below.

(1) Viewed from the averaged features in the winter of 2000/2001, concentrations of the gaseous pollutants NO_x, SO_2, and CO in the Beijing area exhibit a double-peak-double-valley diurnal variation pattern. The maximum concentrations of NO_x, and CO occur at 0900 LST, and the maximum of SO_2 at 0700 LST. However, diurnal variation of the O_3 concentration is out of phase with the other gaseous pollutants and reaches the minimum at 0700 LST and the maximum at 1400 LST.

(2) It is found from comparing the gaseous pollutant concentrations at three different sites in Beijing urban area that the concentrations of SO_2, and CO at the Shuangyushu site are the largest, followed by those at the Lianhuaxiaoqu and Chedaogou sites. Among

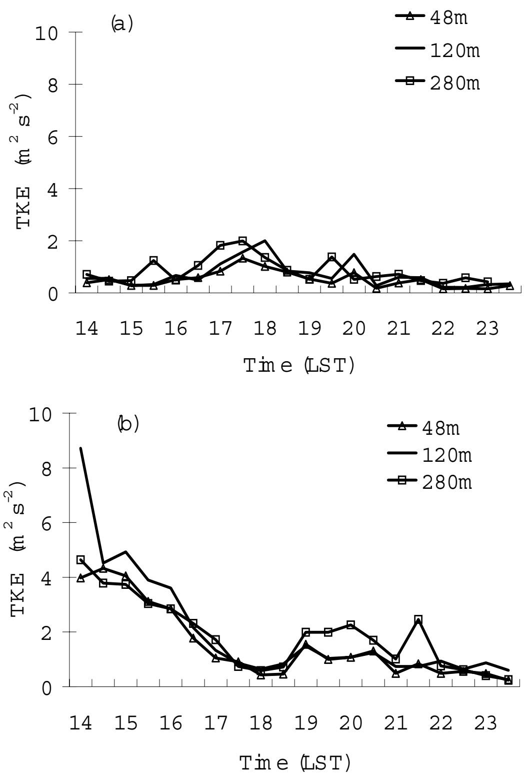

Fig. 7. Comparison of the TKE at the IAP site at three different heights on (a) the heavy pollution day and (b) the good air quality day.

them the concentration of SO_2 at Shuangyushu is about three times that at Chedaogou. The concentration of O_3 at Chedaogou is the largest. The diurnal variation range of the gaseous pollutant concentrations at the Lianhuaxiaoqu site is the largest.

(3) The diurnal variations of stability and kinetic energy are closely related to that of the pollutant concentration, and the peak concentration of pollutants occurs 1–2 hours after the peak in stability and the minimum in kinetic energy.

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