Regional Meteorological Patterns for Heavy Pollution Events in Beijing

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ABSTRACT

The present study investigates meteorological conditions for the day-to-day changes of particulate matter (PM) concentration in Beijing city during the period 2008–2015. The local relationship of PM concentration to surface air temperature, pressure, wind speed, and relative humidity displays seasonal changes and year-to-year variations. The average correlation coefficient with PM_{10} in spring, summer, fall, and winter is 0.45, 0.40, 0.38, and 0.30 for air temperature; –0.45, –0.05, –0.40, and –0.45 for pressure; 0.13, 0.04, 0.53, and 0.50 for relative humidity; and –0.18, –0.11, –0.45, and –0.33 for wind speed. A higher correlation with wind speed is obtained when wind speed leads by half a day. The heavily polluted and clean days, which are defined as the top and bottom 10% of the PM values, show obvious differences in the regional distribution of air temperature, pressure, and wind. Polluted days correspond to higher air temperature in all the four seasons, lower sea level pressure and anomalous southerly winds to the south and east of Beijing in spring, fall, and winter, and a northwest–southeast contrast in the pressure anomaly and anomalous southerly winds in summer. Higher relative humidity is observed on polluted days in fall and winter. The polluted days are preceded by an anomalous cyclone moving from the northwest, accompanied by lower pressure and higher air temperature, in all four seasons. This feature indicates the impacts of moving weather systems on local meteorological conditions for day-to-day air quality changes in Beijing.

Key words: PM_{10}, Beijing, local meteorology, seasonal dependence, weather system

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1. Introduction

With the rapid development of the economy in China over the past few decades, air pollution has become a serious issue because of its significant impacts on the environment and human health. Rohde and Muller (2015) reported that particulate pollution is an extensive problem affecting nearly all of China's population. Particulate matter (PM) has adverse effects on human health (Cheng et al., 2013); it can increase the risk of lung cancer and respiratory diseases (Pope et al., 2009; Fann et al., 2012) and reduce life expectancy (Chen et al., 2013). Thus, understanding the factors controlling the variations of air quality—particularly in big cities—is a topic of great significance.

Located at the northwest flank of the North China Plain, Beijing is a political, cultural, and economic center of China, with mountains to the west and north (Fig. 1a). Air quality in Beijing has become a serious concern of the government and the public. Studies have unraveled the characteristics of PM variations in the region. Clear seasonal variations are observed in $PM_{2.5}$ and PM_{10}

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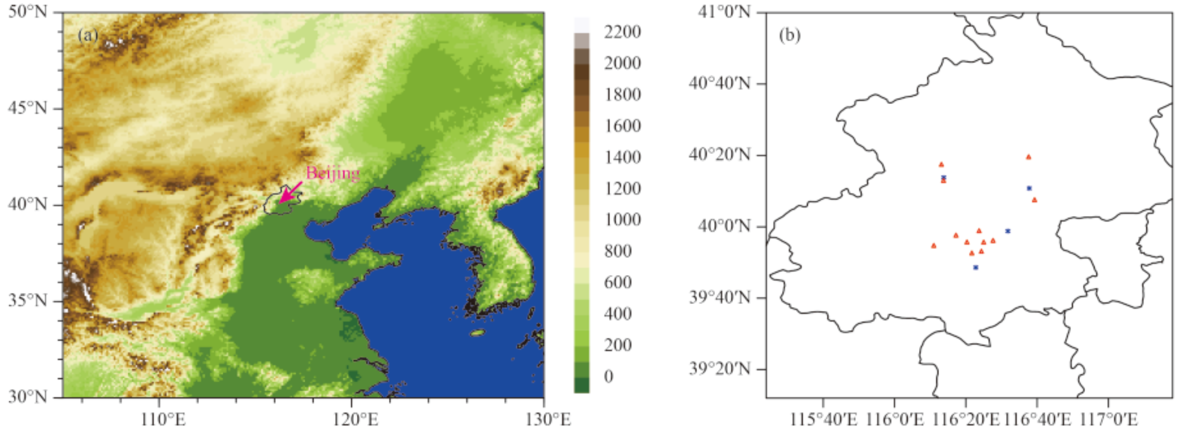

Fig. 1. (a) Terrain of the region surrounding Beijing. (b) Location of 12 particulate matter sampling stations (red triangles) and 4 meteorological stations (blue squares) in Beijing.

concentrations, with the maximum in winter and the minimum in summer (Zhang et al., 2015). Tian et al. (2014) showed that air quality has improved significantly over the last decade in Beijing metropolitan region, with a distinct reduction in the number of atmospheric pollution days. Lv et al. (2016) found that annual average concentrations of $PM_{2.5}$ exhibit a declining trend for the last decade. The mass concentration of $PM_{2.5}$ tends to increase during the night and decrease during the day (Wang et al., 2004; Zhao et al., 2009; Liu et al., 2015; Lv et al., 2016). Short-term, day-to-day variations in aerosol concentrations have been observed in the North China Plain (Chen et al., 2008; Wei et al., 2011; Zhang et al., 2012).

The variation in air quality is significantly influenced by meteorological conditions (e.g., Choi et al., 2008; Jacob and Winner, 2009), in addition to changes in emissions. The conditions that favor poor air quality include high relative humidity (Wise and Comrie, 2005; Quan et al., 2011; Chen et al., 2012; Liu et al., 2013), temperature inversion (Ji et al., 2012), weak winds (Rigby and Toumi, 2008; Ye et al., 2016), low planetary boundary layer height (Han et al., 2009; Ji et al., 2012; Quan et al., 2013), and subsidence (Liu et al., 2013). Generally, atmospheric pressure is the most important meteorological feature influencing PM_{10}, followed by relative humidity and wind speed (Tian et al., 2014). Wind speed is inversely correlated with air pollutant concentrations (Zhang et al., 2010b, 2015). Moreover, high relative humidity contributes to high pollutant concentrations (Zhang et al., 2015).

Synoptic weather patterns and wind direction have been a concern of recent studies (Chen et al., 2008; Wei et al., 2011; Zhang et al., 2012, 2016; Zhao et al., 2016a), as these determine the atmospheric diffusion conditions. High levels of air pollution tend to occur in stagnant weather conditions (Xu et al., 2011; Tao et al., 2012; Zhu et al., 2012; Yang et al., 2014; Zhang et al., 2016). The peak of the mass concentration of PM in winter is most likely due to increased emissions from heating sources and the meteorological conditions that limit the dispersion of pollutants (Zhao et al., 2016b). Research indicates that the air pollution in the North China Plain tends to be more severe when southerly winds prevail (Chen et al., 2008; Wang et al., 2010, 2013). Zhang et al. (2015) showed that easterly winds lead to the highest $PM_{2.5}$ concentration in Beijing, while northerly winds are related to lower concentrations. Ye et al. (2016) identified several flow types for high occurrence frequencies of low visibility events. These flow patterns contribute to low visibility by inducing weak wind and high relative humidity. Cold fronts associated with midlatitude cyclones are major agents for the ventilation of pollutants (Cooper et al., 2001; Ordóñez et al., 2005).

Studies indicate that the East Asian monsoon plays a role in the seasonal and interannual variations of air quality in the North China Plain (Niu et al., 2010; Zhang et al., 2010a, 2016; Mu and Liao, 2014). In summer, the monsoon rainfall is a factor contributing to better air quality (Duan et al., 2006; Qu et al., 2010). A significant connection exists between the interannual variations of air pollution and the East Asian summer monsoon (Zhang et al., 2010a; Yan et al., 2011; Zhu et al., 2012; Mu and Liao, 2014). Zhu et al. (2012) indicated that the decadal weakening of the East Asian summer monsoon has contributed to the increases in aerosols in China.

There is evidence that the relationship between local meteorological variables and air quality changes vary with season, and the main factors for air quality changes differ among different seasons (Fung and Wu, 2014; Tian et al., 2014). In addition, as the atmospheric conditions are subject to interannual variations, the relationship may change from year to year. In this context, the present study examines the relationship between air quality changes and meteorological variables in different seasons and in different years, to understand the seasonal dependence and year-to-year change in the relationship. Relatively few studies have been conducted on the regional meteorological patterns associated with air quality changes in Beijing (Ye et al., 2016; Zhang et al., 2016). Thus, this study contrasts the regional distribution of relevant meteorological variables for a better understanding of the occurrence of pollution days. Additionally, we investigate the temporal evolution of the meteorological patterns for pollution days, to identify the precursory signals of air quality changes, which may provide important information for the prediction of air pollution conditions.

Air quality variations operate on different timescales (Tian et al., 2014). In particular, large seasonal and day-to-day variations are present in observed changes of PM concentrations. The seasonal variations are related to climatological features of changes in the atmospheric state. The atmospheric state shows large day-to-day variations as well, which may lead to drastic variations in air quality. It is likely that the relationship between air quality and meteorological variables may differ among the variations on different timescales. Most previous studies have not distinguished the timescale when analyzing the relationship. It is unknown whether the relationship identified based on total variations applies to variations on individual timescales. It is therefore necessary to investigate the relationship between air quality variations and meteorological variables on different timescales for a better understanding of the main factors affecting variations of air quality at various timescales.

The occurrence of air pollution in a specific city is related to several factors, including the terrain around the city, local emissions, the location of the city relative to the surrounding sources of emissions, and the meteorological conditions. Given fixed terrain and regular emission changes, the occurrence of air pollution is mainly determined by the changes in meteorological conditions, which is the topic of the present study. This study focuses on the relationship between high frequency (day-to-day) variations of PM concentrations and local meteorological variables and regional meteorological patterns in Beijing. Following this introduction, Section 2 describes the data and methods used in the study. Section 3 documents the local relationship between PM concentrations and variations in meteorological variables. Section 4 contrasts the regional meteorological patterns corresponding to polluted and clean days in Beijing. Section 5 examines the temporal evolution of meteorological fields before pollution days, the purpose being to understand the movement of weather systems. A summary and discussion are provided in Section 6.

2. Data and methods

Daily mean PM_{10} concentration data were collected at 12 national air quality monitoring sites in Beijing operated by the Beijing Municipal Environment Protection Bureau. The PM concentration was measured with Tapered Element Oscillating Microbalance (TEOM) RP1400 instruments from Thermo Scientific Company. The TEOM RP1400 instruments had a resolution of 0.1 $\mu g\ m^{-3}$, with precisions of $\pm 1.5\ \mu g\ m^{-3}$ (1-h average) and 0.5 $\mu g\ m^{-3}$ (24-h average). The time period is from 1 January 2008 to 25 September 2015. The surface meteorological data at four stations used in this study include hourly air temperature, pressure, relative humidity, and wind speed, during 1 January 2007 through 30 March 2015, from the China Meteorological Administration. Daily mean values of station meteorological variables are constructed from hourly values. The locations of the 12 air quality monitoring sites and 4 meteorological stations are shown in Fig. 1b. The averages of PM values at the 12 sites are used to represent the mean PM value for Beijing. Similarly, the averages of meteorological variables at the four stations represent mean meteorological state at Beijing.

We use four times (0000, 0600, 1200, and 1800 UTC) daily gridded air temperature at 2 m, sea level pressure, relative humidity at 1000 hPa, and winds at 10 m from the National Centers for Environmental Prediction–Department of Energy (NCEP–DOE) Reanalysis-2 data (Kanamitsu et al., 2002). The air temperature and winds are on T62 Gaussian grids and the sea level pressure and relative humidity are on 2.5° × 2.5° grids. For consistency, daily means of these reanalysis variables are constructed by averaging values at the four times that fall within a day of local time as daily mean PM concentrations.

The present study focuses on variations with periods shorter than 90 days. A harmonic analysis is applied to original daily data and variations with periods shorter than 90 days are extracted by using a reconstruction after the harmonics with periods longer than 90 days are excluded. This is distinct from most previous studies, which have tended not to separate variations on different timescales. It is likely that the relationship of air quality variations to meteorological variables may depend upon the timescale. Separation of the variations on different timescales allows detection of a clear signal on high frequency day-to-day variations, as will be shown.

In this study, we focus on the PM_{10} variations from 1 March 2008 to 28 February 2015. The meteorological data in the corresponding time period are analyzed to examine the relationship. Following tradition, spring refers to the three months of March–April–May, summer is June–July–August, fall is September–October–November, and winter is December–January–February. As the harmonic analysis is conducted for a time period of available data that is longer than the time span of analysis of the relationship, the possible edge effect is avoided when obtaining the high frequency day-to-day variations.

We use Pearson correlation to characterize the relationship between two variables. The Student's *t* test is applied to examine the significance of the correlation coefficient. Composite analysis is employed to obtain the common features on polluted and clean days, as will be elaborated upon later. The two-tailed Student's *t* test is employed to examine the significance of differences in meteorological variables between polluted and clean days.

3. Relationship with local meteorological variables

Changes in the PM concentration in the air depend on emissions of local and surrounding sources and meteorological conditions that determine the dispersion and transport of air pollutants. Given regular changes in emissions, the day-to-day changes in PM concentrations are mainly associated with the meteorological conditions. In this section, we document the relationship of PM concentrations with local meteorological variables. The local meteorological variables to be examined include air temperature, surface pressure, relative humidity, and wind speed. Previous studies have indicated that the variations of air pollution are related to these variables (e.g., Tian et al., 2014; Zhang et al., 2015). As the relationship may depend upon the season (Fung and Wu, 2014; Tian et al., 2014), we analyze the correlation between day-to-day variations of meteorological variables and PM_{10} concentrations in the four seasons, separately. We also analyze the correlation in individual years to examine the robustness of the relationship.

The seasonal change in the relationship to the PM_{10} concentration depends on the variable. For air temperature, a significant positive correlation is observed in all four seasons, though the correlation coefficient is somewhat smaller in winter compared to the other three seasons (Figs. 2a–d). For surface pressure, negative correlation is significant in spring, fall, and winter, but weak in summer (Figs. 2e–h). For relative humidity, a significant positive correlation appears in fall and winter (Figs. 2k, l). The correlation, however, is weak in spring and summer (Figs. 2i, j). For wind speed, the correlation is large in fall and winter, but relatively weak in summer (Figs. 2m–p).

Obvious year-to-year change can be observed in the relationship to PM_{10} concentration in different seasons. For air temperature in spring, a low correlation occurs in 2012, though the correlation is high in the other years (Fig. 2a). A similar feature is observed for surface pressure in spring (Fig. 2e). For relative humidity in winter, relatively low correlation appears in 2008 and 2009 (Fig. 2l). For wind speed, positive correlation is observed in spring 2011 (Fig. 2m), summer 2014 (Fig. 2n), and winter 2009 (Fig. 2p)—opposite to the other years.

In comparison, the correlation of PM_{10} concentration with air temperature appears relatively more robust, with a 7-yr average correlation coefficient of 0.45, 0.40, 0.38, and 0.30 in spring, summer, fall, and winter, respectively. This is followed by the correlation with surface pressure, which has an average correlation coefficient of –0.45, –0.40, and –0.45 in spring, fall, and winter, respectively. The correlation with relative humidity appears robust in fall and winter, with an average correlation coefficient of 0.53 and 0.50, respectively. The average correlation coefficient with wind speed is –0.45 and –0.33 in fall and winter, respectively.

The results of the above correlation analysis are generally consistent with previous studies (e.g., Tian et al., 2014; Zhang et al., 2015). The positive correlation of air temperature is related to the impact of temperature on the inversion layer (Ji et al., 2012) and the ozone formation (Jacob and Winner, 2009). The negative correlation of sea level pressure is associated with the formation of lower-level wind convergence affecting the accumulation and dispersion of aerosol particles. The positive correlation of relative humidity is due to the effect of higher relative humidity being favorable for the hygroscopic growth of aerosols (Chen et al., 2012). The negative correlation of wind speed reflects the influence of wind on the dispersion and transportation of aerosols (Ye et al., 2016).

The above results indicate that the dominant factors for air quality changes in Beijing are different among the four seasons. The results also suggest that the impacts of different meteorological variables on the air quality changes may vary largely from year to year. Thus, caution is required when interpreting the day-to-day air qua-

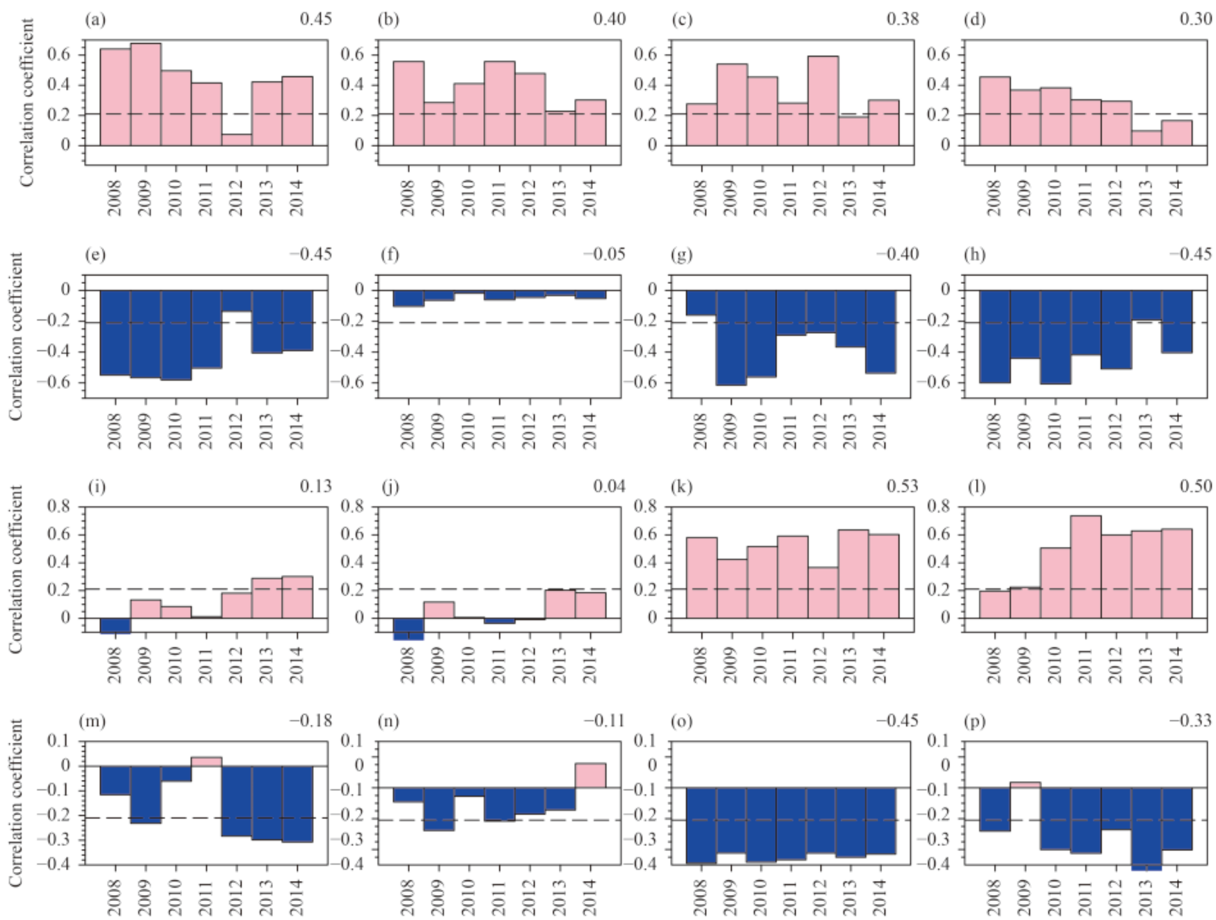

Fig. 2. Correlation coefficient between PM_{10} concentration and (a–d) air temperature, (e–h) pressure, (i–l) relative humidity, and (m–p) wind speed, in (a, e, i, m) spring, (b, f, j, n) summer, (c, g, k, o) fall, and (d, h, l, p) winter, in different years. The horizontal dashed line denotes the 95% confidence level of the correlation coefficient. The numbers on the top right denote the mean value of correlation coefficient over 2008–2014.

lity changes based on analysis of limited-length data. The reason for year-to-year change in the relationship may be related to interannual variations of large-scale meteorological conditions that may modulate the main factor for day-to-day changes in air pollution.

4. Regional patterns of meteorological fields

In this section, we examine the regional patterns of different meteorological variables. These patterns set up the local conditions for the occurrence of air pollution. A few studies have examined the flow patterns and their impacts on the occurrence of pollution in Beijing (Ye et al., 2016; Zhang et al., 2015). Here, we contrast the regional patterns of four meteorological variables (air temperature, sea level pressure, relative humidity, and wind speed) corresponding to polluted and clean days in Beijing.

The polluted and clean days are defined as the top and bottom 10% of the PM_{10} values in Beijing, respectively. There are 63 days for each category in individual seasons. Table 1 shows the mean PM_{10} values for the polluted and clean days in the four seasons. The standard deviations of PM_{10} values in each category are also included to provide information about the differences among the selected cases. For the polluted days, the highest mean PM_{10} value (307.9 μg m^{-3}) is in spring and the lowest mean PM_{10} value (188.5 μg m^{-3}) is in summer. Note that the selected cases have mean PM_{10} values well above the national standard of 150 μg m^{-3} (He et al., 2014) for polluted days by more than one standard deviation in all the four seasons. Thus, the majority of the se-

Table 1. The mean and standard deviation (in parenthesis) of PM_{10} concentration (μg m^{-3}) during polluted and clean days in the four seasons. The polluted and clean days refer to the top and bottom 10% of the PM_{10} values

	Polluted days	Clean days
Spring	307.93 (103.61)	40.30 (17.48)
Summer	188.45 (36.18)	35.85 (18.21)
Fall	268.36 (57.88)	27.85 (12.65)
Winter	294.99 (90.15)	26.04 (12.53)

lected cases correspond to heavy pollution events. For the clean days, the lowest PM_{10} value (26.0 μg m^{-3}) is in winter and the highest mean PM_{10} value (40.3 μg m^{-3}) is in spring. Composite maps for the polluted and clean days are constructed for the 4 reanalysis variables in different seasons by averaging reconstructed variations with periods shorter than 90 days (called anomalies, to distinguish them from original values) at each grid point. In the following, we examine surface air temperature, sea level pressure, lower-level relative humidity, and surface wind anomalies, separately.

4.1 *Air temperature*

The surface air temperature anomaly shows a pronounced difference between polluted and clean days. On polluted days, air temperature is higher in most of eastern China (Fig. 3, left-hand panels). Positive temperature anomalies appear in northern China in all four seasons as well, as in southern China in spring, fall, and winter. In comparison, the temperature anomalies are smaller in summer compared to the other three seasons. Opposite temperature anomalies with similar features are observed on clean days (Fig. 3, right-hand panels). The differences in temperature anomalies between polluted and clean days are significant over most regions of eastern China. Locally, polluted days correspond to higher air temperature and clean days correspond to lower temperature. This is consistent with the correlation highlighted in the previous section between PM concentration and air temperature. This consistency indicates that local temperature change occurs under a regional pattern of temperature anomalies.

4.2 *Sea level pressure and surface winds*

The sea level pressure and surface wind anomalies also display a prominent contrast between polluted and clean days. On polluted days, lower sea level pressure covers eastern China in spring, fall, and winter (Figs. 4a, e, g). Consistently, southerly or southeasterly wind anomalies blow from the tropical western North Pacific to Northeast China and southerly wind anomalies cover southern China (Figs. 4a, e, g). The wind anomalies are weak over northern China. This indicates lower-level anomalous wind convergence around Beijing, which is favorable for accumulation of aerosol particles. In summer, the sea level pressure anomaly displays a distribution featuring higher pressure to the southeast and lower pressure to the northwest of Beijing (Fig. 4c), consistent with Zhao et al. (2016a). Anomalous southerly winds cover northern China (Fig. 4c). Such southerly winds may bring more air from regions south of Beijing where more emissions are located (Wang et al., 2010; Tian et al., 2014).

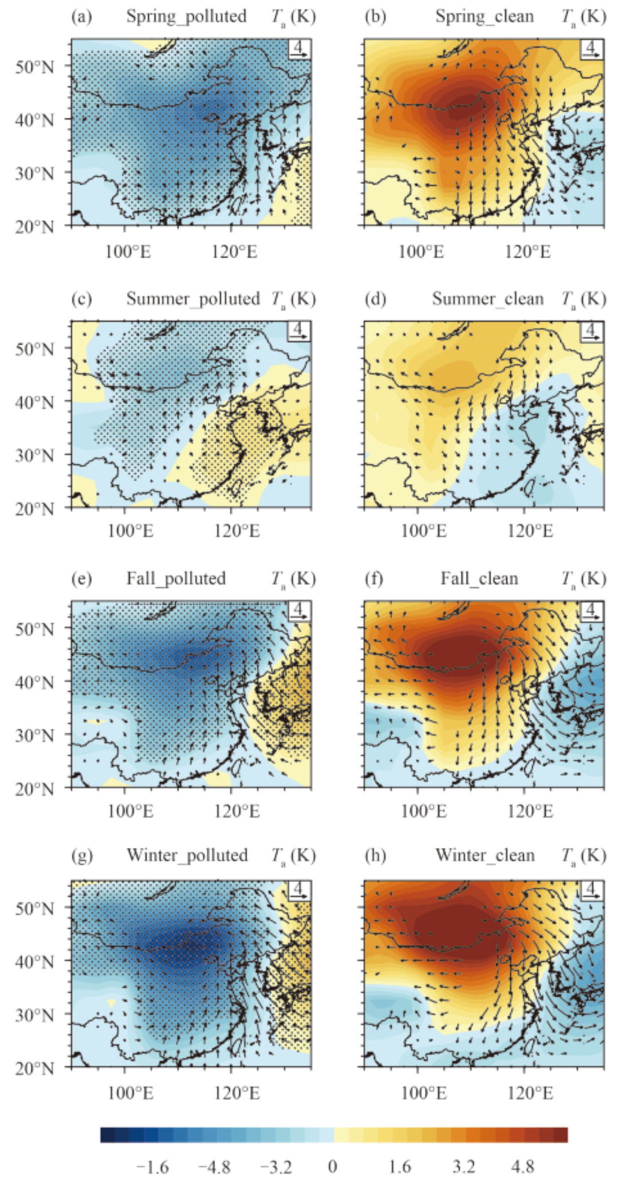

Fig. 3. Composite anomalies of 2-m air temperature T_a (K) on (a, c, e, g) polluted and (b, d, f, h) clean days in (a, b) spring, (c, d) summer, (e, f) fall, and (g, h) winter, based on PM_{10} concentration. Dotted regions denote that the difference between the polluted and clean days is significant at the 95% confidence level. The location of Beijing is indicated in Fig. 1a.

On clean days, opposite pressure and wind anomalies are observed, with similar distributions (Fig. 4, right-hand panels). The pressure anomaly difference between polluted and clean days is significant over many regions. During spring, fall, and winter, northerly/northwesterly wind anomalies increase from northern China to the subtropical western North Pacific (Figs. 4b, f, h), indicating lower-level anomalous wind divergence around Beijing, favorable for dispersion of aerosol particles. During summer, anomalous northerly winds (Fig. 4d) may reduce the transport of aerosol particles from the south.

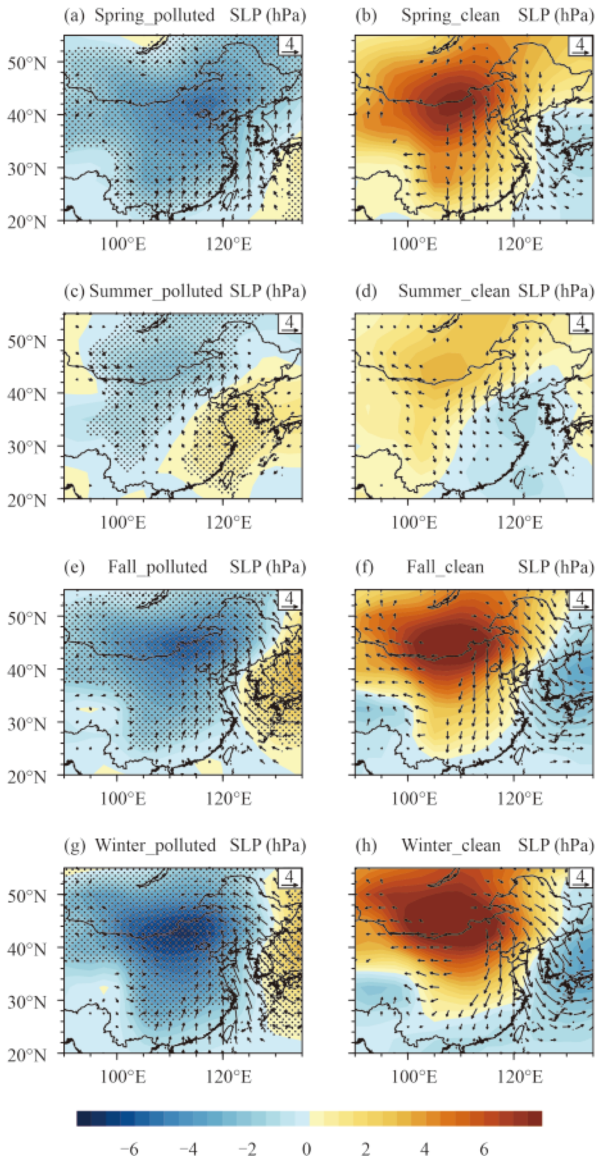

Fig. 4. As in Fig. 3, but for sea level pressure (SLP; hPa) and wind at 10 m (m s^{-1}). Only wind vectors with zonal and/or meridional wind difference significant at the 95% confidence level are plotted.

The contrast in local surface pressure and wind anomalies between polluted and clean days is consistent with the correlation analysis. For example, in summer, the small local pressure difference between polluted and clean days around Beijing agrees with the weak correlation between PM concentration and surface pressure. In spring, fall, and winter, southerly (northerly) wind anomalies on polluted (clean) days around Beijing indicate a weakening of surface winds, as climatological mean winds are northerly, which agrees with the local negative correlation of surface wind speed. The consistency suggests that local meteorological conditions for air pollution changes are controlled by the regional meteorological pattern.

4.3 *Relative humidity*

Relative humidity displays opposite anomalies in fall and winter between polluted and clean days. Relative humidity in northern China is higher on polluted days (Figs. 5e, g), but lower on clean days (Figs. 5f, h). In spring and summer, the relative humidity anomalies around Beijing are negative on polluted days (Figs. 5a, c), but positive on clean days (Figs. 5b, d). The anomalies in spring and summer are opposite to those in fall and winter, indicative of a strong seasonal dependence of the relative humidity anomalies. The results are mostly consistent with the correlation analysis in fall and winter, but not so in spring and summer. Previous studies have indicated that air pollution tends to occur on high relative humidity days (Tian et al., 2014; Zhang et al., 2015; Ye et al.,

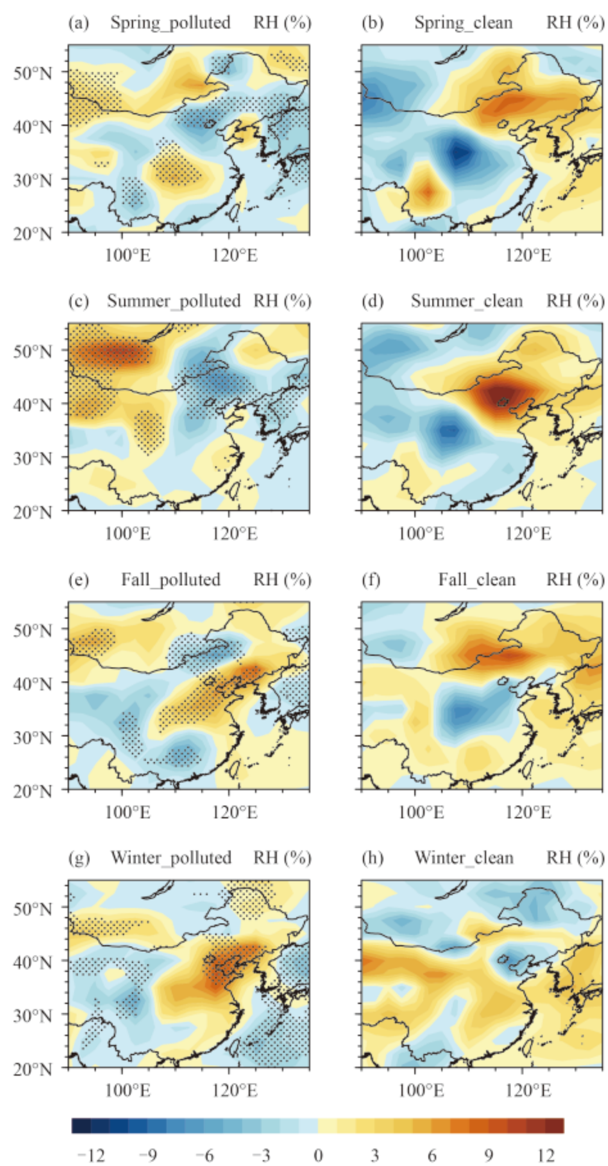

Fig. 5. As in Fig. 3, but for relative humidity (%) at 1000 hPa.

2016). Our results indicate that this may not be applicable to high frequency day-to-day variations in spring and summer.

5. Temporal evolution of meteorological patterns

In this section, we examine the temporal evolution of meteorological patterns. This can help to understand where the origins are of the systems that lead to air pollution in Beijing. Such information can serve as a precursory signal for the occurrence of pollution states and may be used in the prediction of air pollution changes. A similar method is used to construct the composite maps from three days before the polluted days in the four seasons. As some of the polluted states may continue for several days, we only select those days that are the first days to construct the composite. We identified 39 cases in spring and 35 cases in summer, fall, and winter. The mean PM value is 293 μg m^{-3} in spring, 187 μg m^{-3} in summer, 253 μg m^{-3} in fall, and 306 μg m^{-3} in winter. In the following, we examine the temporal evolution of composite variables in the four seasons, separately.

5.1 *Spring*

Obvious movement of the spatial patterns is observed for surface air temperature, sea level pressure, and surface wind anomalies. The higher air temperature on the polluted days can be traced to the region west of Lake Baikal (around 52°–55°N, 105°–110°E) three days before (Fig. 6, left-hand panels). The higher temperature region moves southeastwards with time, reaching northern China one day before the polluted days. The higher air temperature is observed in the southeastern part of an anomalous cyclone and a lower pressure where there are anomalous southwesterly winds (Fig. 6, middle panels). The anomalous cyclone is located southwest of Lake Baikal three days before and moves southeastwards with time. Thus, it appears that advection by anomalous winds is an important reason for the temperature anomaly. Anomalous southwesterly winds bring warmer air from lower latitudes, leading to higher air temperature.

Before the polluted days, there are two regions of lower relative humidity—one located south of Lake Baikal and the other over central China (Fig. 6, right-hand panels). The northerly one moves southeastwards and reaches Beijing starting two days before the polluted days. The southerly one moves eastwards to the Yellow Sea one day before the polluted days. A positive anomaly region appears over central China one day before. The positive anomaly increases and moves eastwards. The occurrence of higher relative humidity may be related to the anomalous southerly winds that transport wetter air from lower latitudes. This indicates the importance of the circulation system in the change of air quality.

5.2 *Summer*

A systematic movement in surface air temperature, sea level pressure, and surface wind anomalies is also observed in summer. Three days before, a high air temperature region covers Northwest China through Mongolia to Northeast China, and eastern China south of 40°N is within a region of lower air temperature (Fig. 7, left-hand panels). The higher temperature region moves southeastwards with time, reaching northern China one day before. This is associated with anomalous southwesterly winds that display a similar southeastward movement along with the lower pressure (Fig. 7, middle panels). Again, it indicates the effect of anomalous wind advection in the formation of higher temperature. The signal in relative humidity is not so clear. In general, the relative humidity anomalies are small around Beijing (Fig. 7, right-hand panels).

5.3 *Fall and winter*

A systematic temporal evolution is observed in surface air temperature, sea level pressure, and surface wind anomalies in fall and winter. Here, we only show the composite anomalies in fall. Apparent large and positive air temperature anomalies can be traced to higher latitude regions west of Lake Baikal (Fig. 8, left-hand panels). With the southeastward movement of the higher temperature region, Beijing experiences a large change in temperature anomalies from negative to large and positive. As in spring, the higher temperature is associated with southwesterly wind anomalies located to the southeast of lower pressure (Fig. 8, middle panels), indicating the impact of anomalous wind advection.

Notable temporal change is observed in relative humidity anomalies as well. Three days before, northern China has lower relative humidity (Fig. 8, right-hand panels). A positive relative humidity anomaly region is present in southwestern China and it moves eastwards and then northeastwards to northern China. At the same time, the positive anomalies experience an increase. Thus, the signal in relative humidity appears clearer in fall and winter than in spring and summer.

5.4 *Station mean evolution*

To further understand the temporal evolution of local meteorological conditions, we construct area-mean air temperature, pressure, relative humidity, and wind speed

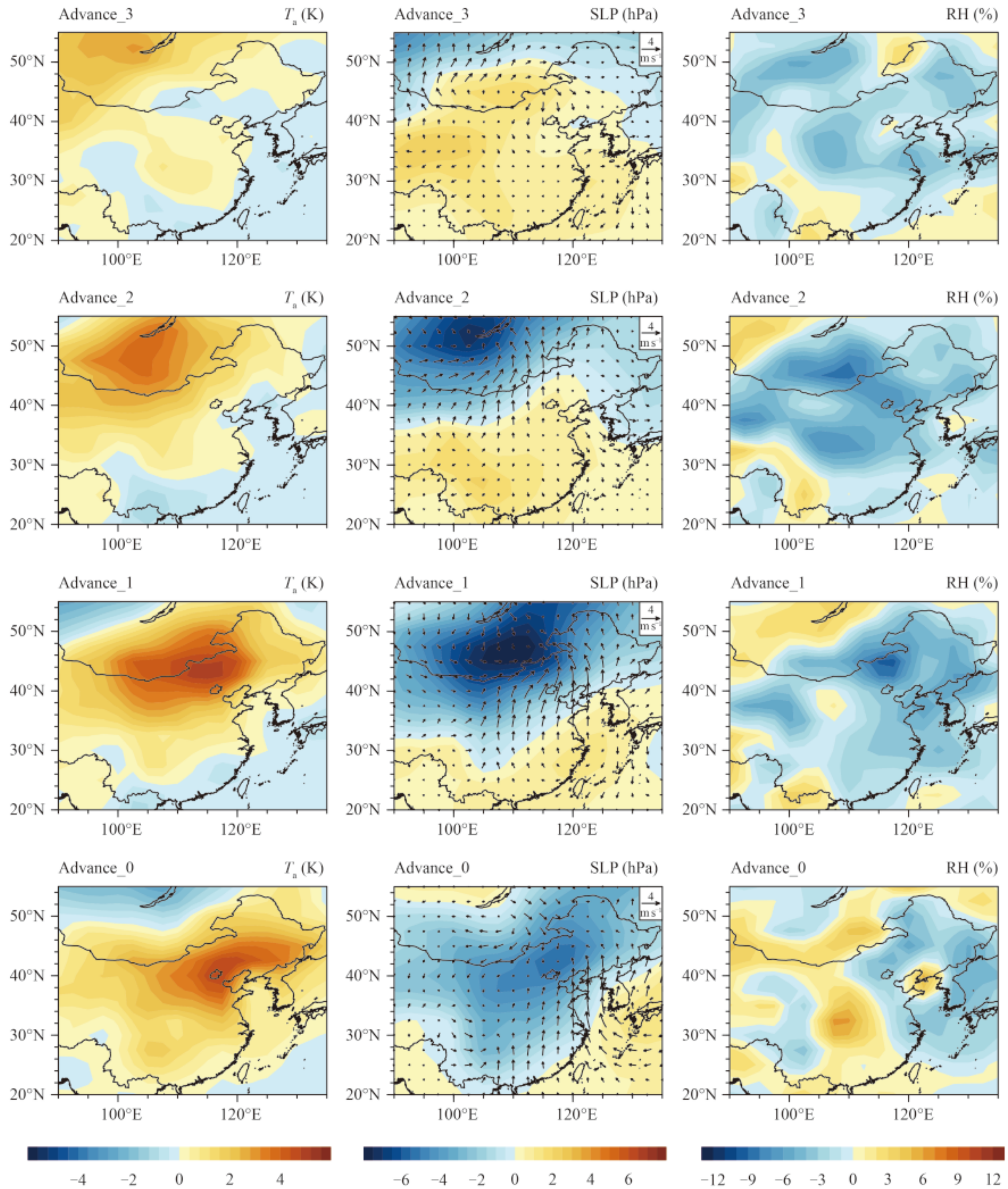

Fig. 6. Composite anomalies of 2-m air temperature (K; left-hand panels), sea level pressure (hPa) and 10-m wind (m s^{-1}) (middle panels), and relative humidity at 1000 hPa (%; right-hand panels), from three days before polluted days in spring, based on PM_{10} concentration.

anomalies based on the average of the four meteorological station observations. The results are shown in Fig. 9, from five days before to five days after the polluted days, separately for the four seasons.

An obvious upward change in air temperature is observed in all four seasons (Fig. 9a). This feature is associated with the southeastward movement of the higher temperature region (Figs. 6–8, left-hand panels). Positive temperature anomalies appear earlier in spring than in the other three seasons. On the first polluted days, the temperature anomalies are the largest in spring. The largest temperature anomalies are observed one day after the first polluted days in fall and winter. After that, the temperature anomalies decrease. This decrease in temperature anomalies may be partly due to the effects of aerosol particles that reduce the solar radiation reaching the surface.

A large decrease in surface pressure is observed one

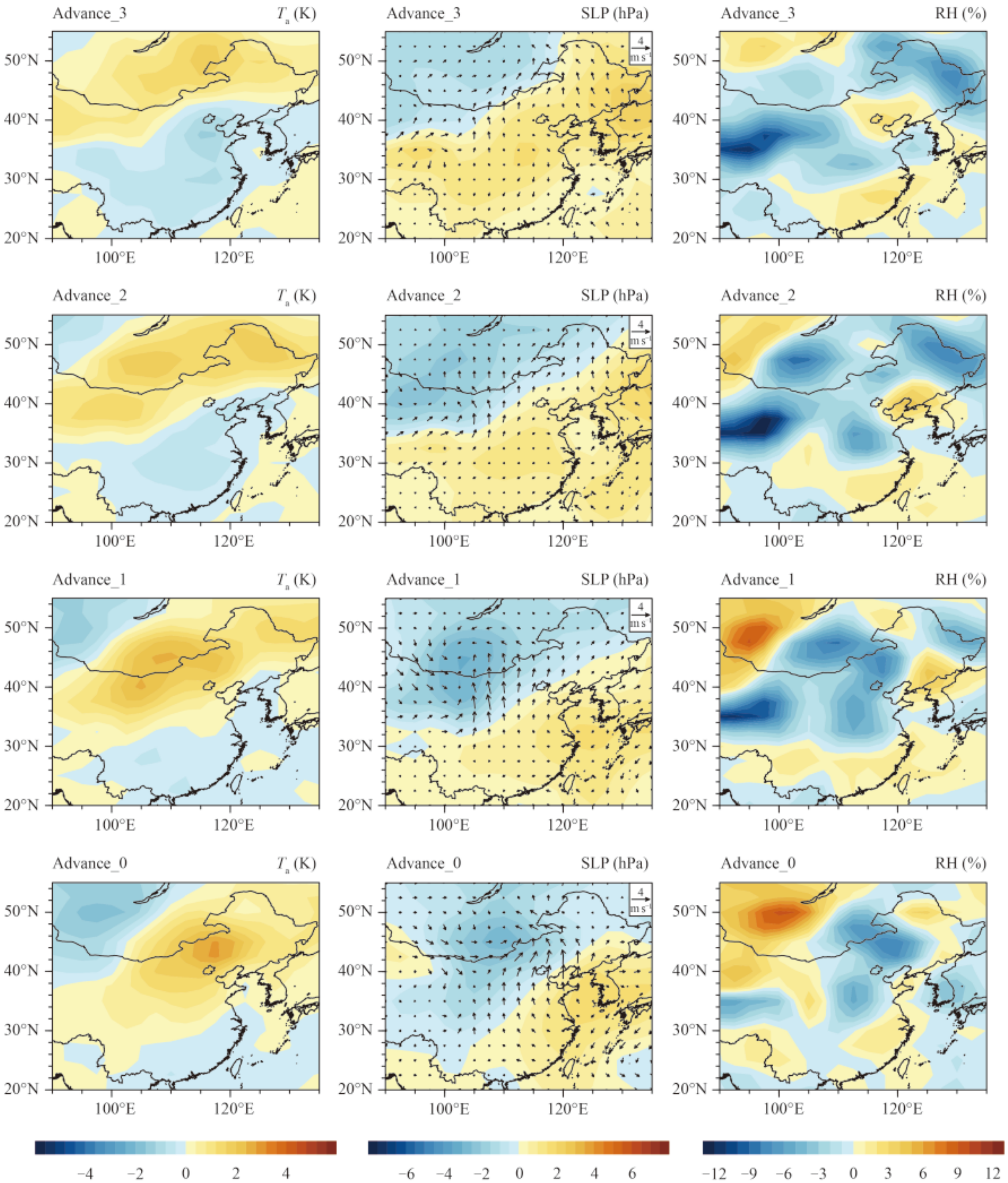

Fig. 7. As in Fig. 6, but for summer.

day before the polluted days and the pressure turns to rise after the first polluted days in spring, fall, and winter (Fig. 9b). The pressure change is much less in summer. Distinct from the other seasons, the lowest pressure in summer occurs after the polluted days. This feature is consistent with the pressure anomaly pattern on the polluted days in summer (Fig. 4c) and its southeastward movement (Fig. 7, middle panels).

An obvious upward change at 1–2 days before the first polluted days is observed in relative humidity in spring, fall, and winter (Fig. 9c). The relative humidity increase in summer occurs on the first polluted days. The increase is much larger in fall and winter than in spring and summer. Correspondingly, the relative humidity anomalies on the first polluted days are large and positive in fall and winter, but relatively small in spring and summer. The relative humidity turns to decrease quickly after the polluted days in spring, fall, and winter.

A large decrease in wind speed is observed in fall and winter, followed by that in spring (Fig. 9d). The wind

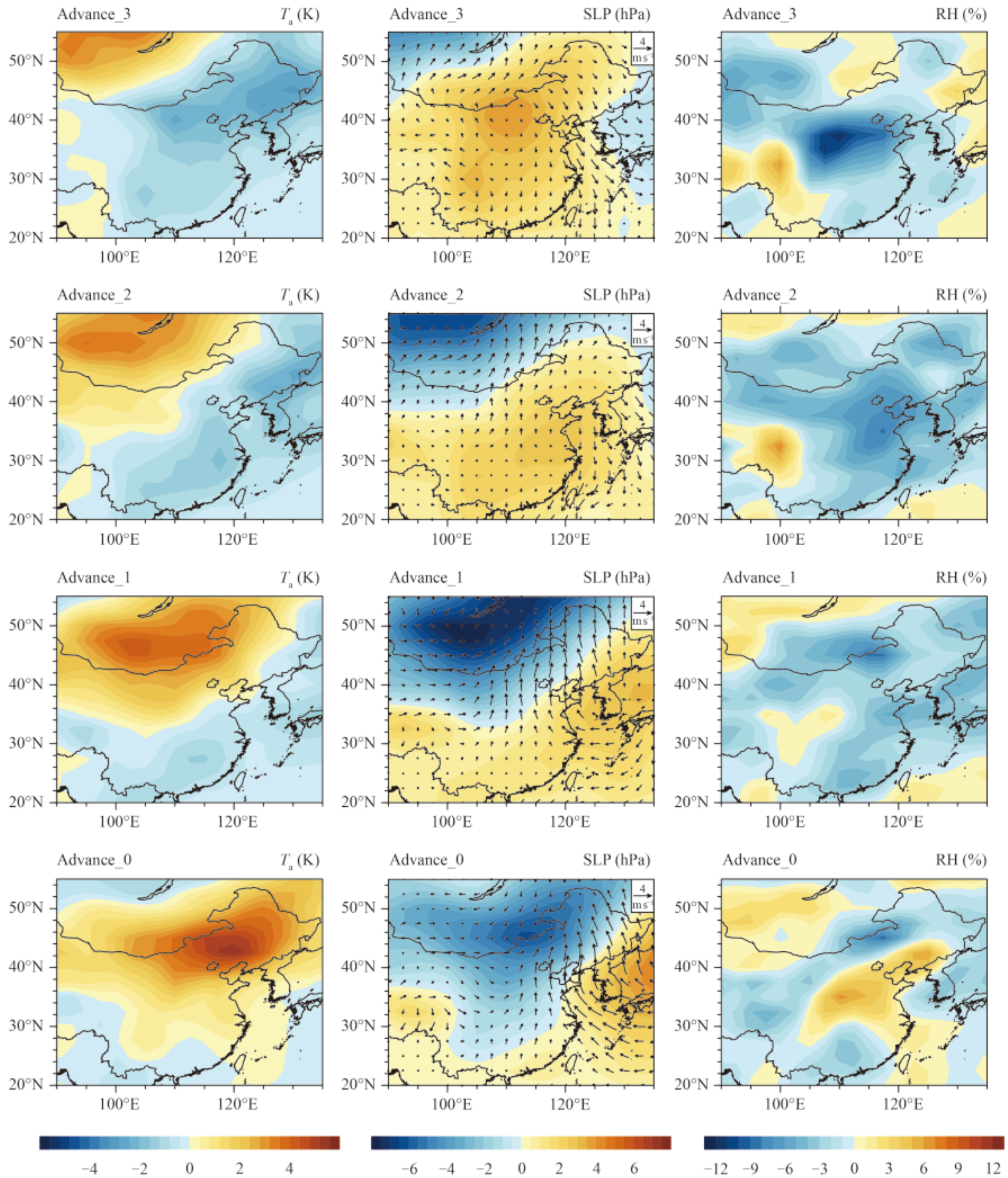

Fig. 8. As in Fig. 6, but for fall.

speed anomalies are smaller in summer than in the other seasons. Common to spring, fall, and winter, the decrease in wind speed appears before the first polluted days (Fig. 9d). This result indicates that polluted days tend to occur after weak winds. We calculate the correlation with the wind speed leading PM_{10} by 12 h. Indeed, the PM_{10} concentration displays a larger and more robust correlation with wind speed half a day before (Fig. 10).

Compared to temperature and pressure, the wind speed signal appears earlier. This feature is consistent with the impacts of the moving weather system. Climatological mean winds in North China are northerly in spring, fall, and winter. When the low pressure system moves southeastwards, anomalous southwesterly winds that are located in the southeast sector of the low pressure approach Beijing first. These anomalous winds are against mean winds, reducing the wind speed. The low pressure center arrives in Beijing about half a day later. Anomalous southwesterly winds reduce cold advection, contributing

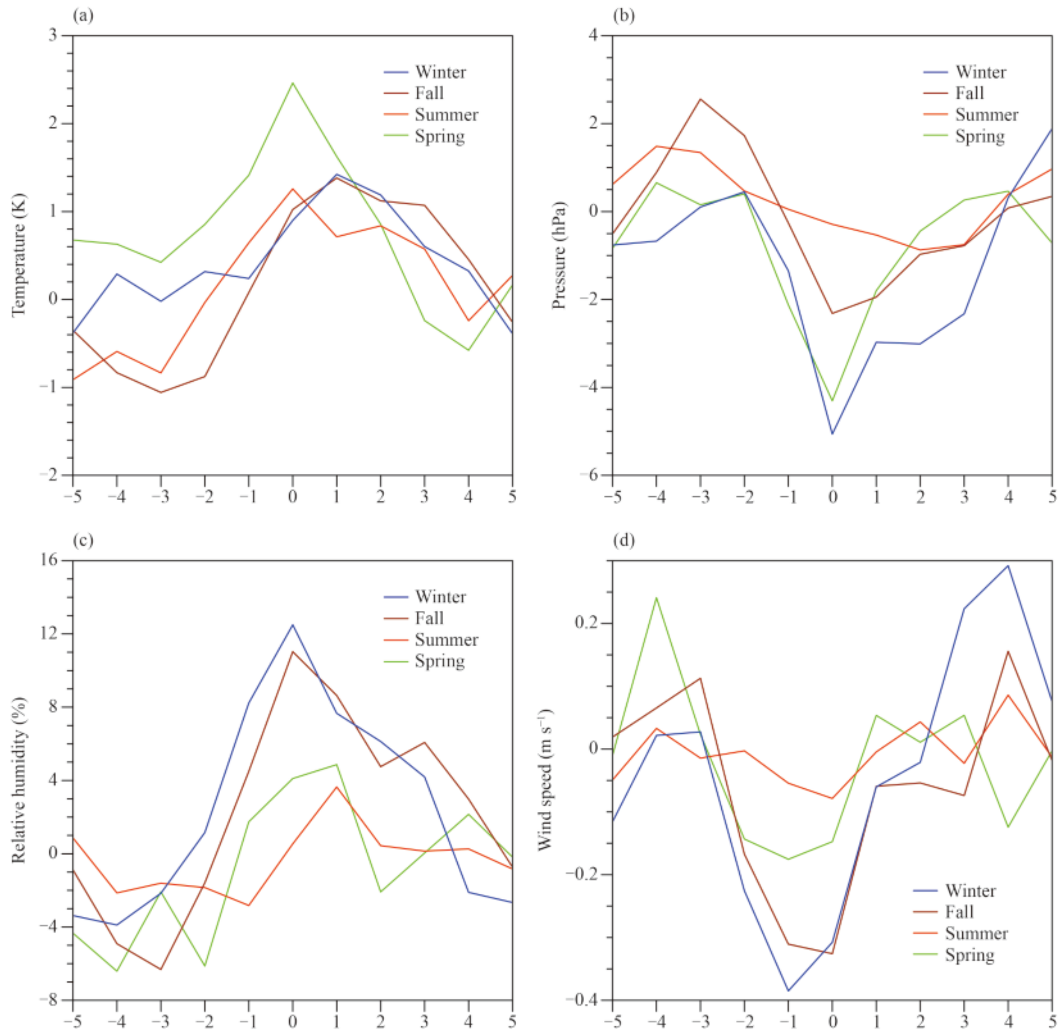

Fig. 9. Temporal evolution of the anomalies of station mean (a) air temperature T_a, (b) pressure, (c) relative humidity, and (d) wind speed during the polluted days (based on PM_{10} concentration) in the four seasons.

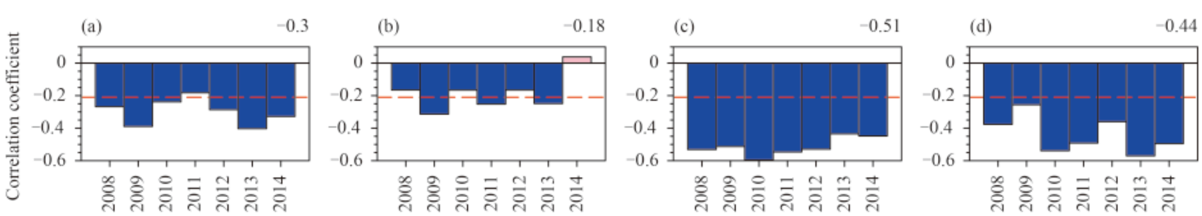

Fig. 10. Correlation coefficients between PM_{10} concentration and wind speed, with wind speed leading by 12 h, in (a) spring, (b) summer, (c) fall, and (d) winter, in different years. The horizontal dashed line denotes the 95% confidence level of the correlation coefficient. The numbers in the top right denote the mean value of correlation coefficient over 2008–2014.

to an upward temperature change. The highest temperature lags the anomalous winds by about half a day. According to the above sequence, a fundamental factor for air pollution change is wind speed. The temperature and relative humidity changes appear to be byproducts of the wind changes.

The temporal variation in local meteorological variables appears to be consistent with the spatiotemporal evolution of regional meteorological patterns. For example, the increase in local temperature before the polluted days follows the movement of a high temperature region from the west. The local pressure drops when a low pressure system moves in before the polluted days in spring, fall, and winter. The surface wind speed in Beijing is reduced before the polluted days, accompanying the invasion of southerly wind anomalies that are against climatological mean winds in spring, fall, and winter. The consistency suggests that the variations in local meteorological conditions are controlled by the movement of weather systems.

6. Summary and discussion

Based on daily mean PM_{10} concentration data, station hourly surface air temperature, pressure, wind speed, and relative humidity data, and daily gridded NCEP–DOE reanalysis surface air temperature, sea level pressure, surface wind, and 1000-hPa relative humidity data during 2008–2014, the present study documents the local relationship of day-to-day PM concentration variations to meteorological variables in Beijing city and compares regional meteorological patterns between polluted and clean days in Beijing.

The local relationship of PM concentration to surface meteorological variables in Beijing displays seasonal change and year-to-year variation. Overall, the relationship of PM_{10} concentration to air temperature is good in all four seasons; the relationship to pressure is generally good in spring, fall, and winter, but not summer; and the relationship to relative humidity and wind speed is better in fall and winter than in spring and summer. In addition, the PM_{10} concentration variation has a larger and more robust relationship to wind speed half a day before than to concurrent wind speed.

The regional meteorological patterns show pronounced differences between the heavily polluted and clean days in Beijing. Polluted days tend to occur when air temperature is higher in all four seasons, sea level pressure is lower, and anomalous southerly winds blow to the south and east of Beijing in spring, fall, and winter. In summer, polluted days tend to occur when the pressure anomaly shows a northwest–southeast contrast, and anomalous southerly winds blow around Beijing. In fall and winter, higher relative humidity is observed on polluted days.

Analysis of the spatiotemporal evolution displays obvious precursory signals in temperature, pressure, and wind changes for the polluted days in Beijing. The polluted days are preceded by an anomalous cyclone moving from the northwest, accompanied by lower pressure and higher temperature in all four seasons. The spatiotemporal relation of these variables suggests that the most basic factor for the air quality change is the wind. The spatiotemporal evolution in regional meteorological patterns largely determines the variations in local meteorological conditions for the PM concentration changes. These results indicate an important impact of moving synoptic weather systems on the day-to-day air quality change in Beijing.

The seasonal change and the year-to-year variations in the local relationship indicate that the main factors for air quality change may vary. This calls for caution when applying previously obtained results in interpreting the occurrence of pollution events in individual seasons of different years. The present analysis focuses on the meteorological conditions for the air quality change in Beijing city. The applicability of the obtained results to other regions needs to be investigated in the future. Detailed analysis shows some persistent pollution days. What type of weather systems may favor such events is another issue worthy of investigation.

The occurrence of pollution events depends upon both emissions variations and meteorological conditions. The present study is concerned with the influence of meteorological conditions and does not consider the impact of emissions variations. On the one hand, the emissions variations are not likely to alter the cases selected in the composite analysis of the present study that have very high PM values. On the other hand, the magnitude of change in the PM concentration resulting from the meteorological conditions is related to emissions in both local and surrounding sources. For example, there are differences in emissions between summer and winter in Beijing. That points to the necessity to separate different seasons when addressing air pollution changes. Further work is needed to address the respective contributions of emissions variations and meteorological conditions to air pollution changes.

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