doi:10.1029/2007JD008888 In press

Weekly cycle of aerosol-meteorology interaction over China

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Abstract. Weekly cycles of the concentration of anthropogenic aerosols have been observed in many regions around the world. The phase and the magnitude of these cycles, however, vary greatly depending on region and season. In the present study the authors investigated important features of the weekly cycles of aerosol concentration and the co-variations in meteorological conditions in major urban regions over east China, one of the most polluted areas in the world, in summertime during the period 2001-2005/2006. The PM10 (aerosol particulate matters of diameter $< 10\mu m$) concentrations at 29 monitoring stations show significant weekly cycles with the largest values around midweek and smallest values in weekend. Accompanying the PM10 cycle, the meteorological variables also show notable and consistent weekly cycles. The wind speed in lower troposphere is relatively small in the early part of the week, and increases after about Wednesday. At the same time, the air temperature anomalies in low levels are positive, and then become negative in the later part of the week. The authors hypothesized that the changes in the atmospheric circulation may be triggered by the accumulation of PM10 through diabatic heating of lower troposphere. During the early part of a week the anthropogenic aerosols are gradually accumulated in the lower troposphere. Around midweek, the accumulated aerosols could induce radiative heating, likely destabilizing the mid- to lower troposphere and generating anomalously vertical air motion, and thus resulting in stronger winds. The resulting circulation could promote ventilation to reduce aerosol concentrations in the boundary layer during the later part of the week. Corresponding to this cycle in anthropogenic aerosols the frequency of precipitation, particularly the light rain events, tends to be suppressed around mid-weekdays through indirect aerosol effects. This is consistent with the observed anthropogenic weather cycles, i.e., more (less) solar radiation near surface, higher (lower) maximum temperature, larger (smaller) diurnal temperature range, less (more) precipitation events in mid-weekday (weekend).

1. Introduction

During recent decades, China has become one of the heaviest sources of air pollutants in the world [*Qian et al.*, 2003; 2006; *Richter et al.*, 2005], and the climatic impact of anthropogenic aerosols emitted in this region has become a topic of intense study [*Qian and Giorgi*, 1999; *Menon et al.*, 2002; *Giorgi et al.*, 2002; 2003; *Cheng et al.*, 2005; *Qian et al.*, 2006; *Zhao et al.*, 2006; *Lau et al.*, 2006; *Rosenfeld et al.*, 2007; *Zhang et al.*, 2007; *Huang et al.*, 2007]. Most of previous studies attempted to relate the observed long-term trends in regional climate variables during the past decades to a concurrent increase in the anthropogenic aerosols in the region. Although these diverse studies provided valuable insights into the effects of increased concentrations of aerosols on the regional climate, large uncertainties regarding the underlying aerosol-meteorology feedback still exist. Analysis of day-to-day aerosol-meteorology interactions can help to improve our understanding of how weather and long-term climate respond to aerosol forcing. However, the effects of short-time variations in aerosol concentration and its interaction with the regional meteorology over heavily polluted China have not been investigated.

On the short-term time scale, a recently highlighted phenomenon is the significant differences in atmospheric physical conditions between weekend and mid-week days. Weekly cycles of the concentration of anthropogenic pollutants have been observed in many regions around the world [*Lebron*, 1975; *Brönnimann and Neu*, 1997; *Marr and Harley*, 2002;*Beirle et al.*, 2003; *Jin et al.*, 2005]. The phase and the magnitude of these observed weekly aerosol cycles and the associated changes in meteorological variables vary significantly, depending on geographical location [*Forster and Solomon*, 2003] and season [*Gong et al.*, 2006]. However, the details of the mechanisms associated with the weekly cycle remain to be understood. Anthropogenic emissions and the complex feedbacks between the aerosols and atmospheric processes (including temperature variation, cloud formation, precipitation, and radiation) play important roles in modulating the temporal features of the pollutant concentration [*Cerveny and Balling*, 1998; *Forster and Solomon*, 2003; *Jin et al.*, 2005; *Gong et al.*, 2006; *Bäumer and Vogel*, 2007]. In the present study the analysis of the surface and upper-air sounding data, revealed for the first time a weekly cycle of PM10 (aerosol particulate matters having diameters $< 10\mu m$) concentrations in the major urban areas in China. Accompanying the PM10 cycles, there are significant co-changes in a number of atmospheric variables including horizontal wind, vertical motion,and thermal structure.

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0148-0227/07/$9.00

doi:10.1029/2007JD008888 In press

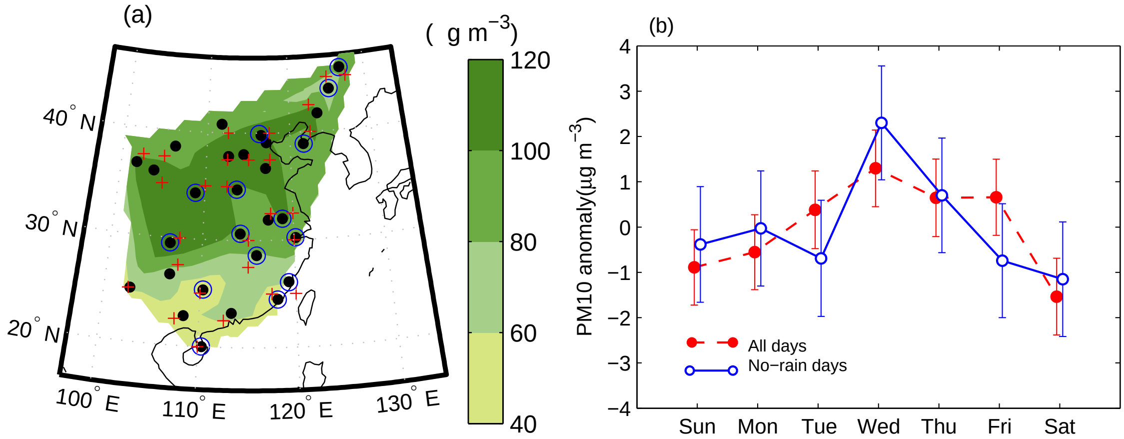

Figure 1. (a) Distribution of the mean PM10 concentration during June–August averaged over 2001–2006. The locations of the 29 pollution stations used are represented by '●' and R2 grids closest to the 29 stations are represented by '+'. The 15 stations with radio-sounding temperature observations used during 2001–2005 are represented by '○'. (b) Weekly changes in the PM10 anomalies are shown as the average values of the 29 stations. In order to remove the difference in the PM10 means among the stations, the anomaly is calculated for each station separately. The error bars correspond to a standard error of ±1 about the 29-sample mean.

Presumably, these indicate a self-modulation mechanism in aerosol-meteorology interaction corresponding to the PM10 cycles.

2. PM10 Data

The daily mean concentrations of PM10, a leading pollutant, in the major cities of China have been measured in the form of the ambient air pollution index (API). The daily API and the corresponding pollutants (PM10, SO_2, or NO_2) have been archived at the State Center of Environment Monitoring of China. The details of the API and PM10 are presented in Appendix. In this study, we selected 29 stations located to the east of 100°E (Figure 1a) where the records of daily API, maximum and minimum temperatures, and precipitation are available from June 1, 2001 to July 18, 2006. The original API data for 29 stations used in the study can be found in online auxiliary material. Only the months of summer (June–August) are considered in this study because PM10-polluted days and relatively clean days (characterized by daily PM10 $< 50\mu$g m^{-3}, $SO_2 < 50\mu$g m^{-3}, and $NO_2 < 80\mu$g m^{-3}) account for 96% of the total days in these months. A polluted day means that the daily API is above 50 (see Appendix for detail). During the other three seasons, the influence of PM10 on short-term meteorology is less dominant since the number of days that are either heavily influenced by the PM10 or relatively clean is well below 90% of the total number of days. Furthermore, dust storms, which produce anomalously high PM10 concentrations of natural origin (largely mineral dusts), are less frequent in summer. A majority of PM10 in summer is in the form of fine particulates of diameters less than 2.5μ m (PM2.5) and the ratio of PM2.5 to PM10 is approximately 0.7 in most regions in China [*Shi et al.*, 2003; *Cao et al.*, 2004; *Wang et al.*, 2006; *Yu et al.*, 2006]. The aerosol size distribution over China is much more homogeneous during summer than during the rest of the year. Aerosol size distribution, particularly that of fine aerosols, plays a significant role in the nucleation of cloud particles which is one of the primary mechanisms of indirect aerosol effects [*Dusek et al.*, 2006]. The most important constituents of the fine fraction of PM are carbonaceous particles (black carbon and organic carbon), which account for 20–45% of the PM2.5 mass concentration in most regions in eastern China [*Ye et al.*, 2003; *Cao et al.*, 2004; *Wang et al.*, 2006; *Yu et al.*, 2006]. Black carbon originating from fuel combustion is particularly important due to its strong ability to absorb solar radiation, resulting in local radiative heating of the atmosphere.

3. Significant weekly cycle of PM10

To delineate the characteristics of the day-to-day changes in PM10 concentration during a week, the average values of the observed PM10 concentrations at individual stations were calculated for each day of the week over all the summer days during the period 2001–2006. Subsequently, anomalies of the PM10 concentration on each day of the week were calculated by subtracting the daily mean values from the mean values over the total summer days at each station. Finally, the anomalies at individual stations were averaged over all the 29 stations to obtain the mean anomalies of PM10 concentration on each day of the week (Figure 1b). The resulting daily PM10 anomalies show a well-defined weekly cycle-they increase from Sunday through Wednesday and decrease during the later part of the week.

We tested the PM10 difference between the weekly maximum and minimum (i.e., Wednesday minus Saturday) at the 29 stations by using an ordinary two-tailed t-test; this difference was used as an indicator of the weekly cycle. The null hypothesis of the test is that the mean of the differences at the 29 stations is zero, i.e., the weekly cycle signals are randomly arranged among the stations. The results of the test show that the null hypothesis is rejected at the 1% confidence level.

Usually, the significance of the weekly cycle and the means for each day of the week can also be estimated from their error bars. It should be noted that the calculation of the error bars using all the stations as independent data points may overestimate the significance if these stations are inter-correlated. Since some of the stations used here are closely located, and some weather variables such as temperature, pressure are of large spatial scale, the estimated significance of their weekly changes is most likely biased. In the present study, we employed a Monte Carlo approach to yield a better estimation. We randomly changed the order of the day of the week. To simulate the possible inter-correlations of PM10 and meteorological variables among stations, we applied the same order to all of the 29 stations each once.

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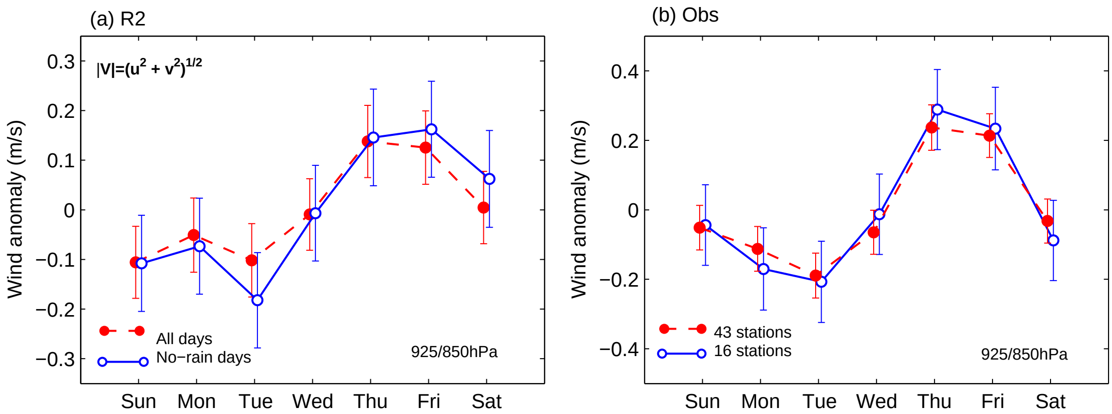

Figure 2. Anomaly of the horizontal wind velocity in the lower troposphere between 925 and 850 hPa levels shown as: (a) The average from 29 R2 grids, (b) Means from 16 and 43 radio-sounding stations for June–August from 2001–2005. The error bars correspond to a ±1 standard error about the sample means. For the locations of 16 and 43 radio-sounding wind stations, refer to Figure 3.

Then we got a simulated mean for each day of the week and the corresponding standard errors of the means. This process was repeated 1000 times, yielding 1000 standard errors. The 95th percentiles of the simulated standard errors are used as the significance criteria in our analysis and plotted together with the observed means. Error bars for other variables analyzed in the following sections are all estimated using the same method. These error bars all are moderately larger than the standard errors estimated from 29 observations, thus they are somewhat stricter standards. These tests confirm that the weekly cycle of the PM10 concentration is statistically significant.

Precipitation can wash out tropospheric aerosols effectively. To examine the impact of wet scavenging on the PM10 weekly cycle, we repeated the above analysis by using the data from only the days when there was no rain. The weekly cycle of the PM10 concentration observed for these days is very similar to that for all days (Figure 1b). Thus, the weekly cycles of aerosol concentrations observed in this study are most likely robust signals.

4. Associated wind changes

Wind is a critical variable for near-surface ventilation condition, which greatly impacts the pollutant concentration. At first, it is reasonable to detect possible changes in wind speed in lower troposphere in the context of weekly cycle. Here we investigated the weekly cycles of wind speed constructed in the same manner as the PM10. We found that there are detectable wind changes even though the daily winds are highly variable and noisy. Surface wind speed measured at 29 stations shows a tendency to increase after Wednesday with higher values in Thursday to Friday (see also Discussion and Conclusion). It is worthy to note that in regular observations at meteorological stations in China, the surface wind records are observed four times every day (0200 h, 0800 h, 1400 h, and 2000 h, Beijing local time). The wind speed is the average value of each observing time for a 2-minute period. The surface wind in such a short time period could be heavily impacted or contaminated by the transient turbulence relating to the diverse microenvironments and atmospheric chaos. As height rises, the noise would drops. Therefore, the daily mean low-level wind fields were examined using the relatively less noisy Reanalysis 2 (R2) data of 925 hPa and 850 hPa pressure levels, which are obtained from the National Centers for Environmental Prediction/Department of Energy (NCEP/DOE) with a resolution of 2.5 [*Kanamitsu et al.*, 2002]. Compared to surface wind observations, the R2 wind used in the present study is on a much larger spatial scale and the influence of noisy turbulence should be suppressed or reduced. We selected R2 grid points that are closest to the 29 pollution stations (Figure 1a). The resulting low-level wind anomalies show that the horizontal wind speed below the 2-km level, in which high aerosol concentration occurs, is relatively weak during the period from Saturday to Wednesday (Figure 2a). This is consistent with the continuous accumulation of PM10 during the same period because poor ventilation favors the occurrence of higher pollutant concentrations in urban areas (Figures 1b and 2a). The wind speed anomalies during the later part of the week are positive with a maximum of about +0.2 m s^{-1} on Thursday-Friday.

It should be pointed that some of the R2 grid points, selected in this study, are located approximately 100–150 km away from the corresponding pollution stations. For a typical horizontal wind speed of 4–6 m s^{-1} in the boundary layer, the time scales for the advection of PM10 over the distance between the stations and the R2 grid points are less

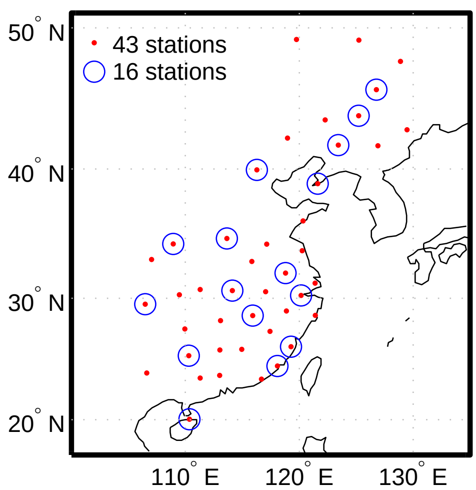

Figure 3. Locations for the radio-sounding wind stations used in Figure 2b.