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Key Points:
- Thunderstorms of central and southeast China have distinctly different weekly cycles
- In both regions, pollution levels have similar weekly cycles: lower on weekdays than on weekends
- The phase difference in thunderstorms is associated with aerosol type

Supporting Information:
- Supporting Information S1

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Distinct weekly cycles of thunderstorms and a potential connection with aerosol type in China

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Abstract This study identified distinct weekly cycles in thunderstorm activities and convection-associated variables in two regions of China dominated by different types of aerosol during the summers of 1983–2005. In both regions, visibility has similar weekly cycle: lower on weekdays than on weekends. Barring any possible "natural" weekly cycles, the findings of the poorest and best visibility on Friday and Monday, respectively, point to the weekly variations in anthropogenic emissions. However, the phases of the thunderstorm cycles between the two regions were different. In central China, thunderstorms occurred more frequently from Saturday to Monday than on other days. The cycles were out of phase in southeast China. It is hypothesized that the phase difference is associated with aerosol type. In central China aerosol absorption is strong, which suppresses convection more on weekdays. In southeast China aerosols are less absorbing but more hygroscopic, which helps invigorate thunderstorms more on weekdays.

1. Introduction

The amount of air pollution varies regularly during the week according to the level of industrial production and daily urban life activities. As a consequence, some meteorological parameters affected by anthropogenic aerosols are expected to show weekly variations. Weekly variations in aerosol properties have been observed in many regions [*Cerveny and Balling*, 1998; *Murphy et al.*, 2008; *Xia et al.*, 2008; *Satheesh et al.*, 2011; *Wang et al.*, 2012]. Weekly variations in meteorological variables such as lightning, cloud amount, and the diurnal temperature range were also reported. Some of these changes have been linked to weekly cycles in aerosols and their interaction with atmospheric dynamics [*Gong et al.*, 2006; *Baumer and Vogel*, 2007; *Bell et al.*, 2009].

Pollution aerosols can affect clouds and precipitation through two primary mechanisms depending on meteorological conditions and aerosol properties. On the one hand, the aerosol microphysical effect leads to an invigorative effect on convective clouds and thunderstorm activities [*Andreae et al.*, 2004; *Rosenfeld et al.*, 2008; *Kar et al.*, 2009; *Wang et al.*, 2011; *Yuan et al.*, 2011; *Yang and Li*, 2014]. On the other hand, aerosol radiative effects suppress convection and thunderstorm activities as shown from observation analyses [*Yang et al.*, 2013b] and model simulations [*Fan et al.*, 2008; *Wang et al.*, 2013]. Our analysis of long-term meteorological trends indicates a steady decrease in the frequency of thunderstorms in central China [*Yang et al.*, 2013b] and an increase in the frequency of thunderstorms in southeast China [*Yang and Li*, 2014]. While both regions have experienced significant decreases in visibility, the distinct effects associated with different types of aerosol may also be echoed in the weekly cycles.

This study examines the weekly cycles of visibility and thunderstorm activities over central and southeast China dominated by different types of aerosol. To date, a few studies on weekly cycles in China have been conducted [*Gong et al.*, 2006, 2007], but no attempt has yet been made to differentiate the weekly cycles in terms of different aerosol-cloud-interaction mechanisms due to different types of aerosol and meteorology. The paper is structured as follows. Section 2 describes the data sets used and the methodology. Weekly cycles of air pollution levels, thunderstorms, and their associated meteorological variables are presented in section 3. Conclusions are given in section 4.

2. Data Sets and Methodology

The study makes use of meteorological observations collected in central (Guanzhong Plain and Mount Hua in Shaanxi province) and southeast (east of 110°E and south of 31°N) China. Figure 1 shows the topography of the two regions and the locations of the sites considered in this study. Meteorological data sets used

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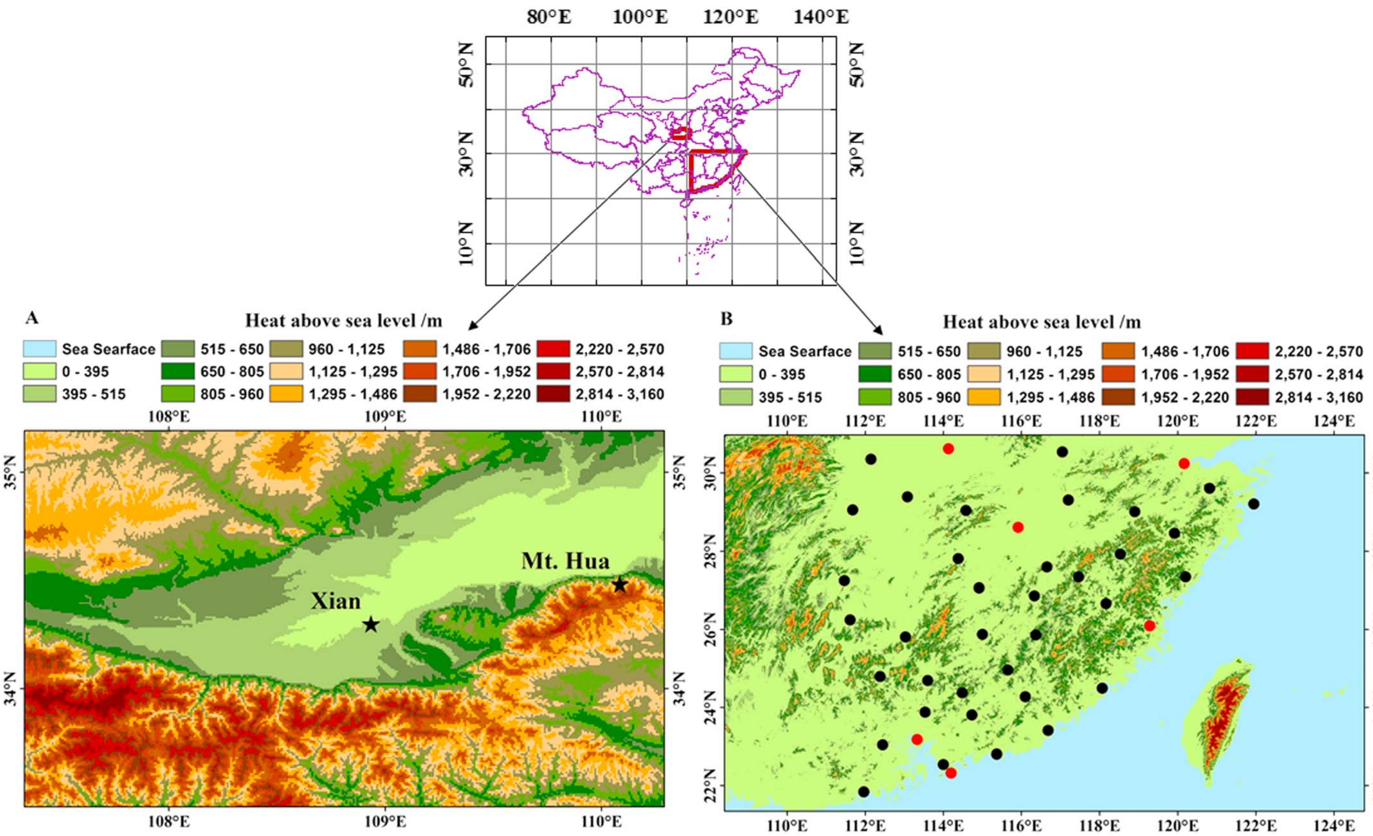

Figure 1. (top) Locations of the two study areas in China (outlined in red). (lower left) A topographic map of the Guanzhong Plain and locations of the meteorological stations in the megacity Xi'an and on Mount Hua. The altitude of the Mount Hua station is 2064.5 m. (lower right) A topographic map of southeast China and locations of the meteorological stations. The black dots denote megacity stations, and the red dots represent other stations in southeast China.

include visibility, precipitation, wind, thunderstorm, total cloud fraction, and surface solar radiation data. General meteorological data are measured 4 times a day at 02:00, 08:00, 14:00, and 20:00 local time (LT). Thunderstorm data for the Guanzhong Plain are obtained from the Meteorological Information Center of Shaanxi Province. These data are the digital version of the original weather reports recorded on paper. Other meteorological data used in this study are provided by the China Meteorological Administration such as radiosonde data. A thunder or lightning event is reported with the start and end times of its occurrence. A thunderstorm day is defined as a day when there is at least one record of thunder or lightning on that day [*Yang et al.*, 2013b]. Meteorological data from stations in southeast China are from the National Meteorological Information Center of China [http://data.cma.cn]. Also employed is the Tropical Rainfall Measuring Mission (TRMM) lightning product from the Lightning Imaging Sensor (LIS) and Level 2A rain characteristics data from the precipitation radar (PR) (TRMM Product 2A23). The latter provides the storm height or the maximum height at which a radar echo is detected denoting cloud vertical development [*Bell et al.*, 2008; *Yang and Li*, 2014]. Lightning density data, i.e., the number of strikes per square kilometer, from the TRMM LIS are used to investigate the weekly variation in intense convective activity over southeast China. Total Ozone Mapping Spectrometer (TOMS) aerosol index data are also employed that are particularly sensitive to transported dust and smoke aerosols.

Horizontal visibility in kilometer is used as a proxy for pollution level. We used the daily average visibility, which was calculated by using measurements at 02:00, 08:00, 14:00, and 20:00 LT. If the relative humidity was greater than 98% or if the total cloud fraction of low clouds was 100% at any of the four time points in the day, the corresponding visibility record was not included in the calculation of daily average visibility. This threshold of relative humidity is slightly higher than that used in the study by *Wu et al.* [2007]. Using a higher threshold may result in the inclusion of severe hazy day cases. This consequently increases the chances of treating some foggy conditions as severely polluted cases. However, this would not have much influence on the weekly variations in thunderstorm activities and convection-associated variables because natural variations in fog and humidity likely do not have a weekly cycle [*Murphy et al.*, 2008]. Weekly variations in general meteorological variables have been observed in China after the beginning of the 1980s when China's economy started to accelerate, giving rise to a rapid increase in anthropogenic pollution emissions. Therefore, many studies about weekly cycles associated with aerosols have focused on the period after the 1980s [*Gong et al.*, 2006, 2007; *Wang et al.*, 2012]. There are no gaps in data through 2005 when the Xi'an station on the Guanzhong Plain was relocated. Given the data availability and the level and change in anthropogenic aerosol loading, the period of 1983–2005 is chosen for this study. Note that the weekly cycles in thunderstorms in the two subperiods are similar but not the same, as shown in Figure S1 in the supporting information. The discrepancies result from small data sample size when they are divided into two periods. Poor visibility occurred on Wed-Fri, while best visibility on weekend–Monday. This weekly variation of pollution aerosol strongly modulates the weekly cycle of thunderstorms, whereas the selection of time period is not the leading cause for the weekly phase of thunderstorm activities.

Anomaly values were obtained by averaging the estimated weekly cycles during the study period. The bootstrap method (resampling) was used to establish the strength of weekly variations in thunderstorms and other meteorological quantities. This method has been widely used in previous studies [*Collier and Bowman*, 2004; *Bell et al.*, 2008] to test the significance level of weekly cycles of rainstorms.

Resampling begins by first dividing the original time series of observations into smaller time series of 4, 5, or 6 days (randomly chosen for each subset of observations). Each subset is then replaced randomly by another subset of the same length and position in the week. This resampling process was carried out 10,000 times and generated a new time series. The parts of this synthetic time series with amplitudes greater than those of the original time series were then chosen. This time series was used to estimate the significance level of the weekly cycle of a particular meteorological parameter under study by fitting the observations with the function

$$r(t) = r_0 + c\cos\omega t + s\sin\omega t, \quad (1)$$

where r_0 is the weekly mean value of the meteorological parameter under study, $\omega = 2\pi/7$ days, and t is the day number in the week. The coefficients c and s can be estimated from week to week. The variances of c and s can represent the overall uncertainty in the amplitude, assuming that the correlation of the coefficients among all available weeks is negligible. Following *Bell and Reid* [1993] and *Bell et al.* [2008], the statistical significance value, p, of the sinusoidal amplitudes for each meteorological parameter under study is calculated as

$$p = \exp\left(-r^2 \Big/ \sigma^2\right), \quad (2)$$

where r is the amplitude, $\sigma^2 = [\mathrm{var}(c) + \mathrm{var}(s)] \Big/ n$, and n is the number of weeks in each time series.

3. Results and Discussion

3.1. The Weekly Cycle of Local Air Pollution Levels

Ground-based aerosol measurements were not made over most of China until the recent decade. As a result, horizontal visibility has been used as a proxy for aerosol concentration, especially in long-term trend studies [*Rosenfeld et al.*, 2007; *Wang et al.*, 2009]. Visibility measurements made in cities often suffer from visual obstructions due to urban development and the relocation of weather stations. The occurrence of dust storm events and fog could also affect visibility, but these natural factors are unlikely to have 7 day cycles [*Murphy et al.*, 2008]. This is consistent with the finding by *Ginoux et al.* [2012], which points out that both central and southeast China (our study areas) have little dust emissions and dust blown there has a natural origin. The dust occurrence reported at Xi'an also shows no weekly cycle, as shown in Figure S2a. Closely related to dust activities, the aerosol index derived from the TOMS measurements over the Guanzhong Plain region (108.5°E–109.5°E, 34°N–35°N) also did not show a clear weekly cycle, as shown in Figure S2b. Neither of the weekly variations in Figures S2a and S2b is statistically significant. Despite the limitations that aerosol index data from TOMS are not available every day and that the dust events have no information on their sources (natural or anthropogenic), there is no compelling reason to attribute the weekly variations in visibility to

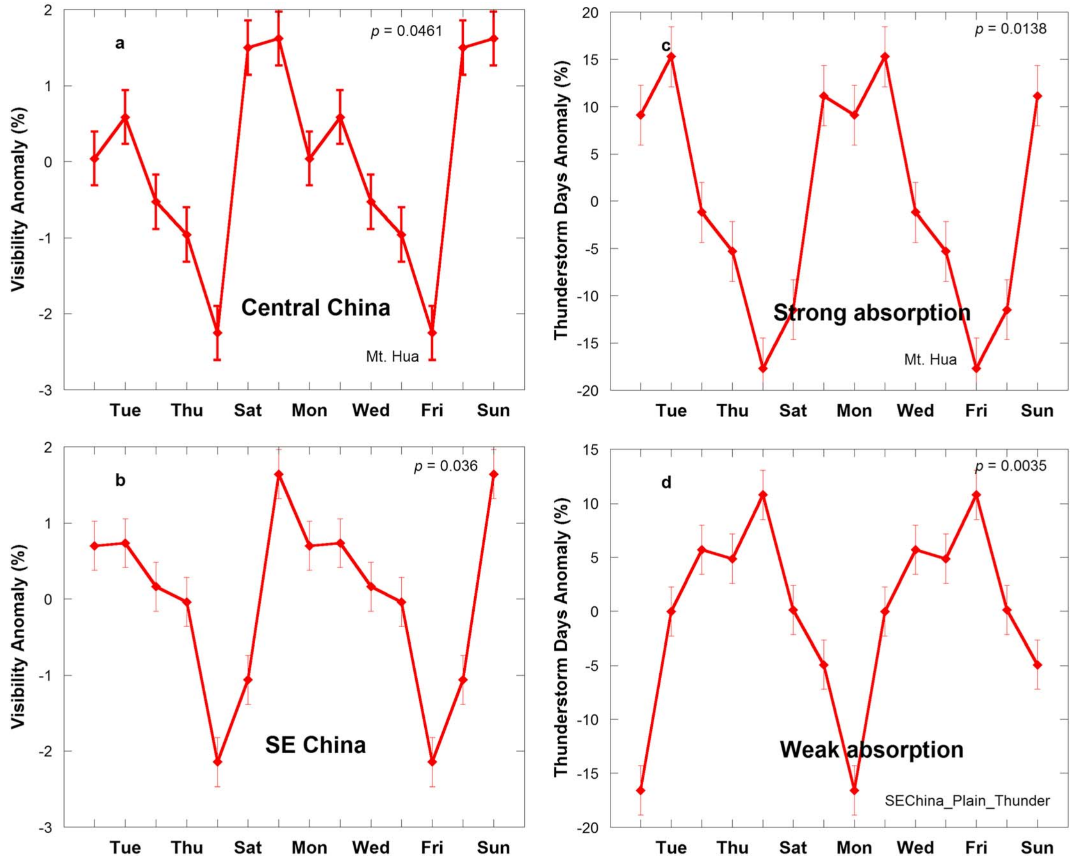

Figure 2. Mean visibility anomalies (a) at Mount Hua and (b) over southeast China as a function of the day of the week. Thunderstorm day anomalies (c) at Mount Hua and (d) for SE China region as a function of the day of the week. The vertical bars in all panels represent the standard deviation ($\pm\sigma$). Significance levels, p, are given.

something naturally driven. Moreover, dust storms have exhibited a decreasing trend in recent decades [*Wang et al.*, 2004; *Zhao et al.*, 2004; *Zhu et al.*, 2008]. As in previous studies [*Rosenfeld et al.*, 2007; *Yang et al.*, 2013a], visibility data from weather stations are analyzed to represent the gross features of variations in the pollution level.

Figure 2 shows the weekly variations in visibility and in thunderstorms during the summer seasons of 1983–2005 for the Guanzhong Plain and southeast China. A strong periodicity with a similar phase is found for both regions, as shown in Figures 2a and 2b. The amplitude of the weekly cycle in the Guanzhong Plain is about 6% of the total visibility value at a statistical significance level of $p = 0.0461$. For southeast China, the weekly cycle, its amplitude, and statistical significance level ($p = 0.0360$) are similar to those in the Guanzhong Plain. The daily average visibility for these two regions is at a maximum on Sunday and steadily drops from Tuesday to Friday after which the visibility starts to increase again. This pattern suggests that pollution emissions accumulate during the weekdays and dissipate over the weekend. Likewise, particulate matter up to 10 μm in size, another measure of surface pollution, is also low during the weekend and high on weekdays [*Gong et al.*, 2007]. The reduction in pollution levels is also seen during the traditional Chinese spring festival when most people do not work [*Gong et al.*, 2014]. This observational finding suggests that aerosol concentrations are sensitive to human activities to such a degree that it could have a footprint in nature. To further test if such statistical relationships are physically sound, we have examined the relationships in regions dominated by different types of aerosols whose interactions with meteorological variables may differ considerably, especially with regard to aerosol-radiation interactions (ARI) and aerosol-cloud interactions (ACI) [*Intergovernmental Panel on Climate Change*, 2013], as shown in many previous studies [*Koren et al.*, 2008; *Rosenfeld et al.*, 2008; *Li et al.*, 2011; *Jacobson*, 2014; *Yang and Li*, 2014].

Note that visibility represents only one aspect of aerosol properties, namely, the total light extinction of aerosols at the ground level. However, the aerosol effects of concern to this study depend on aerosol-absorbing properties which cannot be inferred from visibility data. Rather, it was inferred from the aerosol single scattering albedo as retrieved by *Lee et al.* [2007]. A unique aspect of this study, relative to previous ones, is that an attempt is made to attribute the observed natural weekly cycles in thunderstorm activities to the distinct differences in aerosol absorption between the two study regions, noting that aerosol loading is heavy in both regions.

Lee et al. [2007] have combined Moderate Resolution Imaging Spectroradiometer reflected radiance and surface transmittance data to retrieve aerosol single scattering albedos and found low values in central China (0.75–0.8) and high values in southeast China (0.95–1), implying that absorbing (e.g., soot) and nonabsorbing or weakly absorbing (e.g., sulfate) aerosols dominate these regions, respectively. Previous studies have also indicated that the concentration of strongly absorbing organic and elemental carbon is much higher in Xi'an than in southeast China in both winter and summer [*Cao et al.*, 2007; *Zhang et al.*, 2012]. A recent study has reported that sulfate and ammonium components of nonabsorbing or weakly absorbing aerosols are more prevalent in southeast China than in central China and that aerosols composed of dust are more common at Xi'an than in southeast China [*Huang et al.*, 2014].

3.2. The Weekly Cycle of Thunderstorms: Invigoration Versus Inhibition of Thunderstorms Over Southeast and Central China

Figure 2c shows the weekly variations in the number of thunderstorm days at Mount Hua. The maximum is reached on Tuesday and then steadily decreases until Friday when it reaches a minimum. From Friday to Tuesday, the number of thunderstorm days begins to rise again. The statistical significance level for this weekly cycle of thunderstorm days at Mount Hua is $p = 0.0138$. The weekly variation in thunderstorms at Xi'an is similar to that of Mount Hua, as shown in Figure S3a. These weekly patterns in thunderstorm days generally follow the weekly variation in visibility (Figure 2a); i.e., more aerosol emissions are accompanied by less thunderstorm activities. *Yang et al.* [2013b] have argued that absorbing aerosols suppress intense convection over the Guanzhong Plain and Mount Hua through their radiative effect, namely, atmospheric heating and surface cooling. The former is due exclusively to aerosol absorption, while the latter is due to both aerosol absorption and scattering (more dominant). Together, they increase atmospheric stability, especially in the boundary layer, and thus inhibit the development of convection [*Wang et al.*, 2013]. As emissions accumulate throughout the week, thunderstorm activities diminish until reaching a minimum on Friday, after which visibility begins to recover and thunderstorm activities begin to rise once again.

In southeast China, thunderstorm activities also show a significant weekly variation but with an opposite phase to that in central China, as shown in Figure 2d (plain stations) and Figure S3b (megacities). From Monday to Friday, thunderstorms in southeast China increase gradually and then decrease sharply until Monday. The statistical significance level is $p = 0.0035$ and $p < 0.001$ for the 42 plain stations and six megacities, respectively. The weekly variation in thunderstorms is opposite to the visibility changes shown in Figure 2b in southeast China; i.e., more thunderstorm activities occur when the pollution level is higher.

Southeast China is much more humid, and the aerosol single scattering albedo is considerably higher there than in central China [*Lee et al.*, 2010]. As a result, aerosol absorption in the atmosphere is insignificant [*Li et al.*, 2010]. The changes in atmospheric stability resulting from the radiative effect should then be much less in southeast China. The aerosol microphysical effect becomes more important there, fueled by the presence of more moist air [*Fan et al.*, 2008]. The aerosol invigoration effect [*Rosenfeld et al.*, 2008] could thus be more responsible for the observed increase in thunderstorms. This contrast is also mirrored in the long-term trends in thunderstorms between the two regions [*Yang and Li*, 2014].

Figure 3a shows the weekly cycle of storm heights over southeast China observed by the TRMM PR. The rate of lightning strikes over southeast China derived from the TRMM LIS is shown in Figure 3d. Both the storm height and the lightning strike rate show significant weekly variations: maxima on weekdays and minima on the weekend. The periodical variations in both the storm height and the lightning strike rate are similar to that in the number of thunderstorm days derived from weather reports. The lightning strike rate and storm height indicate the occurrence frequency and the vertical development of convective activities, respectively.

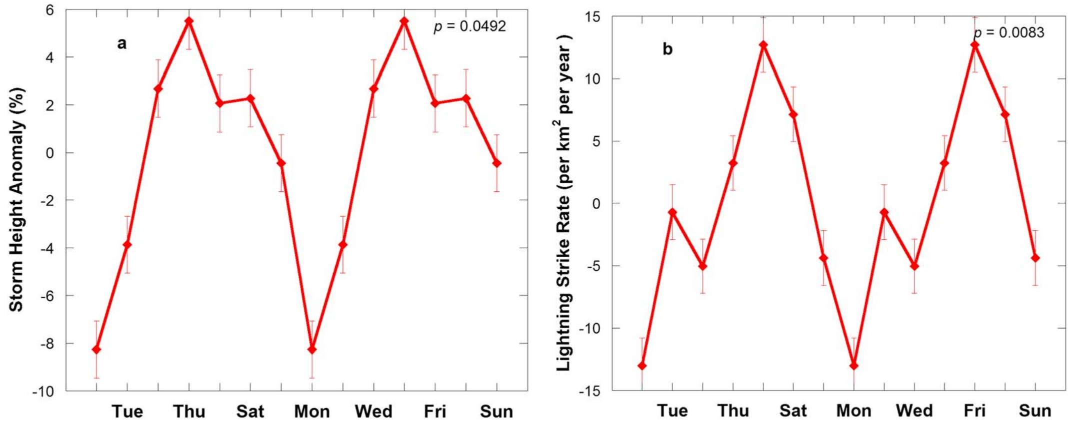

Figure 3. (a) Storm height anomalies over southeast China as a function of the day of week. Data are from the TRMM Product 2A23 and cover the period of 1998–2009. Only data recorded from 10:00 to 13:00 LT of each day are considered. (b) Lightning strike rate over southeast China as a function of the day of the week. Data are from the TRMM LIS product and cover the period of 1998–2009. The vertical bars in all panels represent the standard deviation ($\pm\sigma$). Significance levels, *p*, are given.

Note that thunderstorms with a large vertical extent do not necessarily have large lightning strike rates [*Zipser*, 1994; *Ushio et al.*, 2001]. The two analyses thus do not involve two correlated meteorological variables [*Daniel et al.*, 2012]. Although they are not totally independent, these similar weekly variations in convection-related variables extracted from different data sets suggest that the periodic changes in both the frequency and intensity of thunderstorms may be linked to ACI as previous studies have suggested [*Rosenfeld et al.*, 2008; *Koren et al.*, 2008; *Li et al.*, 2011; *Yang and Li*, 2014].

Due to the different aerosol types present at the Guanzhong Plain and in southeast China, the dominant mechanism driving ACI is also different between these two regions. In the Guanzhong Plain, the reduction in the number of midweek thunderstorms is likely associated with aerosol radiative effects. This can be further tested by examining the weekly cycle of wind speed based on the influence of the vertical distribution of wind speed from aerosol radiative effects [*Jacobson and Kaufman*, 2006]. Increasing aerosol loading leads to less solar radiation reaching the surface. This cooling effect weakens surface-heated convection and results in the reduction of vertical turbulence and the exchange of horizontal momentum between regions of low and high aerosol loading. Since surface wind (horizontal momentum) is generally weaker than that at upper levels, aerosols decrease the downward transport of wind energy aloft to the surface. The decrease in the vertical transport of wind energy would result in a reduction in surface wind speed and an increase in winds aloft. This theory concerning changes in wind speed due to aerosol radiative effects has been supported by both model simulations [*Jacobson and Kaufman*, 2006] and observations [*Yang et al.*, 2013b]. Figure 4a shows the weekly variation in wind speed at Mount Hua (with an elevation of 2064.5 m): maximum in the middle of the week and minimum on Sunday, presumably because of strong radiative heating. Figure 4b shows the vertical distributions of weekday and weekend wind speeds, which appears to support the aerosol-wind relationship. The workday-weekend difference in wind speed is statistically significant at the $p = 0.05$ level. From the dirtier weekdays to the cleaner weekend, surface winds become stronger while winds at the 800–850 hPa level diminish. The decrease is likely because of the recovery of the vertical turbulence transfer of slow winds from the near surface to upper levels, in line with what is expected of the ARI. In southeast China, the midweek increase in thunderstorm activity is more likely linked to aerosol microphysical effects [*Wang et al.*, 2011; *Yang and Li*, 2014].

In addition to the strongly absorbing aerosol type present, the suppression of thunderstorm activity in the Guanzhong Plain is also associated with the high aerosol concentration in this region. Under high aerosol loading conditions (aerosol optical depth > 0.3), the aerosol invigoration effect of clouds is saturated while the ARI effect is further strengthened [*Koren et al.*, 2014]. In the Guanzhong Plain, aerosol loading is more than twice the threshold value of 0.3 [*Yang et al.*, 2013a; *Wu et al.*, 2014]. Therefore, local convection and thunderstorm activity are significantly reduced through aerosol radiative effects. In rainy southeast China, the aerosol concentration is relatively lower in the summer season [*Huang et al.*, 2014] and clouds are more readily invigorated by nonabsorbing aerosols. This pattern in southeast China agrees with that in

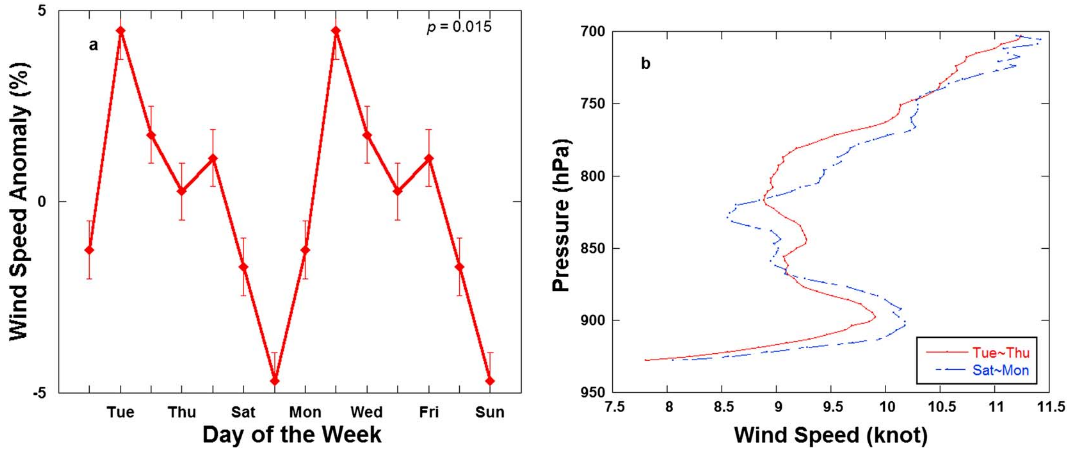

Figure 4. (a) Mean wind speed anomalies at Mount Hua (measured at 14:00 LT) as a function of the day of the week. The vertical bars represent the standard deviation ($\pm\sigma$). The statistical significance level of the weekly cycle of wind speed at Mount Hua is $p = 0.015$. (b) The distribution of vertical afternoon wind speeds at Xi'an, derived from sounding data collected over the period of 1983–2005. The red and blue lines show the distribution of "midweek" and "weekend" wind speeds at 20:00 LT, respectively. The midweek-weekend difference in wind speed between pressure levels 925 and 750 hPa is statistically significant at the 0.05 level based upon a Student's *t* test.

the southeast U.S. where nonabsorbing sulfate aerosols also dominate [*Attwood et al.*, 2014]. Relatively speaking, few studies on the weekly cycle have been conducted in regions dominated by absorbing aerosols. The opposite weekly cycles between these two regions thus give us more confidence on the influence of aerosols, unless one can relate the weekly cycles of meteorological variables such as thunderstorm activity to other physical causes.

The longitudinal variation in thunderstorm activities is also investigated to explore other possible reasons. Figure S4 shows the lightning strike rate anomaly as a function of the day of the week for four 10° × 10° regions from west to east in the 30°N–40°N latitudinal zone. No gradual change in the weekly phase of lightning strike rate is seen. Therefore, the difference in the weekly phase between the Guanzhong Plain and southeast China does not result from the movement of weather systems from west to east.

4. Conclusions

Analyses of various meteorological data sets have revealed distinct weekly variations in local convection-related parameters in central and southeast China during the summertime periods of 1983–2005. These cyclic variations corresponded generally well with the weekly cycle of visibility, a proxy for air pollution. The weekly patterns of the number of thunderstorm days, storm height, lightning strike rate, and wind speed clearly follow the cycle of visibility whether the phase is the same or is opposite. The relationships between visibility and various convection-related variables are consistent at each of the two regions in China but are opposite to each other. The distinct aerosol types present in the two regions may explain this difference. In central China, aerosol absorption is strong and aerosol particles are less hygroscopic, whereas in southeast China, aerosols are much less absorbing and are highly hygroscopic. We attempt to attribute the observed natural phenomena of the weekly cycles to the distinct differences in aerosol properties of the two study regions.

Previous studies have linked the weekly cycles of meteorological variables to that of anthropogenic activities but have not investigated whether there is any connection between the phase of weekly cycles and aerosol type/properties. Convection is weaker during weekdays than on the weekend in central China, whereas the opposite is true in southeast China. Since the two regions have heavy aerosol loading in common, but distinctly different aerosol single scattering albedos (low in central China and high in southeast China), we argue that the distinct phases of the weekly cycles may present plausible evidences of a causal relationship between aerosol radiative and microphysical processes, and the aerosol invigoration effect, although the causality is still subject to large uncertainties. Coherent weekly cycles were found for the number of thunderstorm days, storm height, lightning strike rate, and visibility, which helps reinforce our argument/hypothesis.

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