Why do tornados and hail storms rest on weekends?

Daniel Rosenfeld and Thomas L. Bell
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ABSTRACT:
When anthropogenic aerosols over the eastern USA during summertime are at their weekly mid-week peak, tornado and hail storm activity there is also near its weekly maximum. The weekly cycle in storm activity is statistically significant and unlikely to be due to natural variability. The pattern of variability supports the hypothesis that air pollution aerosols invigorate deep convective clouds in a moist, unstable atmosphere, to the extent of inducing production of large hailstones and tornados. This is caused by the effect of aerosols on cloud-drop nucleation, making cloud drops smaller, delaying precipitation-forming processes and their evaporation, and hence affecting cloud dynamics.

POPULAR SUMMARY:
Human production of atmospheric pollution changes with the day of the week. In particular, production of particulate pollution (aerosols) in the U.S. is largest during the middle of the workweek and at a minimum on Sundays. Previous research on weather over the southeast U.S. during the summer months has shown that storms, on average, grow larger during the middle of the week, produce more clouds and rain, and are accompanied by more lightning activity. This behavior can be explained by the effect aerosols have on cloud formation: more aerosols provide more nuclei around which cloud droplets form, resulting in smaller cloud water droplets. Smaller droplets are lighter and, instead of falling from the cloud as rain, rise to greater heights where they freeze, releasing more heat that drives the cloud to even higher altitudes than they would normally reach. This has been verified by the Tropical Rainfall Measuring Mission (TRMM) satellite.

This theory predicts that storms formed in polluted air have stronger updrafts and generate more ice aloft. Such conditions favor formation of large hail stones. The invigorated storms generate tornados more readily. This paper examines data collected by the Storm Prediction Center of the National Weather Service to see if there are indeed more reported tornados and more hail storms in the middle of the week. Just as the theory of aerosol effects on storms predicts, we find that there are more summertime tornados and hail storms over the southeast U.S. during the middle of the week than on weekends. The theory also predicts that there should be less of an aerosol effect on storm behavior in the western half of the U.S. and during non-summer months, and our analysis of the data confirms this, too. The average aerosol concentrations in the atmosphere vary with the day of the week by only about 10%, and tornado and hail-storm frequencies vary only by about 10%. But what is the background level of aerosol pollution doing to our weather? The amounts and kinds of aerosol pollution have steadily changed over the past century. This research raises the possibility that we may be experiencing different levels of severe storm activity in recent decades compared with pre-industrial times because of aerosol pollution.

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Why do tornados and hail storms rest on weekends?

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ABSTRACT

This study shows for the first time statistical evidence that when anthropogenic aerosols over the eastern USA during summertime are at their weekly mid-week peak, tornado and hail storm activity there is also near its weekly maximum. The weekly cycle in summertime storm activity for 1995–2009 was found to be statistically significant and unlikely to be due to natural variability. It correlates well with the weekly cycle of other previously observed measures of storm activity. The pattern of variability supports the hypothesis that air pollution aerosols invigorate deep convective clouds in a moist, unstable atmosphere, to the extent of inducing production of large hailstones and tornados. This is caused by the effect of aerosols on cloud-drop nucleation, making cloud drops smaller and hydrometeors larger. According to simulations the larger ice hydrometeors contribute to more hail. The reduced evaporation from the larger hydrometeors produces weaker cold pools. Simulations showed that too cold and fast expanding pools inhibit the formation of tornados. The statistical observations suggest that this might be the mechanism by which the weekly modulation in pollution aerosols is causing the weekly cycle in severe convective storms during summer over the eastern USA.

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1. Introduction

This study puts to a statistical test the hypothesis that air pollution increases the chance of severe convective storms. The motivation for posing this question is based on physical considerations that are described in Section 1.2 of the Introduction. These considerations have already been partially supported by the observations of a weekly cycle in rainfall, storm heights, and large-scale vertical winds, made by *Bell et al.* [2008]. We believe this hypothesis does two things: 1) it provides a framework for understanding the observations originally reported by *Bell et al.* [2008]; and 2) it has been a very successful tool for predicting weekly cycles in other meteorological quantities, some of which have been reported elsewhere [e.g., lightning activity [*Bell et al.*, 2009a], and fractional cloud cover and cloud-top temperatures [mentioned in *Bell et al.*, 2009b)], and some of which (weekly cycles in hailstorm and tornado activity) are reported here.

We believe that a strong observational case is made in this paper for the existence of a weekly cycle in hailstorm and tornado activity over the eastern U.S. during the summer. We would not have looked for such evidence had we not had the physical theory we present below to guide us. Nevertheless, we should emphasize that the observations we report here only show a correlation in hailstorm and tornado activity with the well-established weekly cycle in pollution over the same area, and correlations do not prove causality. These observations provide the impetus for more detailed observational studies and advances in modeling of the effects of aerosols on storm development that will be capable of establishing the causal connection, a connection we can only present as a hypothesis here.

1.1 The weekly cycle in rain intensity and lightning activity

The weekly cycle of working weekdays and resting weekends is associated with weekly-varying levels of particulate air pollution [e.g., *Bell et al.*, 2008]. This cycle has been shown to be associated with weekly cycles of midweek rainfall amounts, storm heights [*Bell et al.*, 2008; *Bell et al.* 2009b], and lightning activity [*Bell et al.*, 2009a] in the warm and moist climate of summer months in the southeast USA. It was hypothesized that this is caused by mid-week enhanced particulate air pollution invigorating convective storms, as will be described in Section 1.2. Theoretical considerations and cloud simulations, described in Section 1.3, support this hypothesis.

1.2 The physical basis for aerosols invigorating convective clouds

Particulate air pollution can invigorate convective storms whose cloud bases are warm enough that the cloudy air has to rise several km before reaching the freezing level. In clouds forming in pollution-free air, rain can develop and precipitate from the lower parts of the cloud without freezing. This early rain can be inhibited by the pollution aerosol particles that act as cloud drop condensation nuclei (CCN) and nucleate greater concentrations of smaller cloud drops that are slower to coalesce into rain drops [*Gunn and Phillips*, 1957]. In clouds with warm cloud-base temperatures the freezing level is several km above cloud base, so that rain can develop and fall from the rising air in the cloud. Because the effect of aerosols is to suppress coalescence, rain is delayed and a larger fraction of the cloud water ascends above the 0°C isotherm level, where it is accreted on ice precipitation particles that fall and melt at lower levels [*Molinié and Pontikis*, 1995; *Andreae et al.*, 2004]. The additional release of latent heat of freezing

aloft and reabsorbed heat at lower levels by the melting ice implies greater upward heat transport for the same amount of surface precipitation in the more polluted atmosphere. In addition, greater evaporative cooling of the cloud water in the downdrafts transfers even more heat downward [*Lee et al.*, 2010]. This means that more instability is consumed for the same amount of rainfall. The inevitable outcome is invigoration of the convective clouds [*Rosenfeld et al.*, 2008]. Cloud simulations have supported this hypothesis by showing that updrafts increase in warm-base clouds (~ 20°C) with added aerosols that suppress the warm-rain processes [*Khain et al.*, 2004, 2005, 2008; *Khain and Lynn*, 2009; *Wang*, 2005; *Tao et al.*, 2007; *Lee et al.*, 2008a; *van den Heever et al.* 2006; *van den Heever and Cotton* 2007; *Ntelekos et al.* 2009]. According to these simulations, invigoration was not necessarily associated with added rainfall amounts. Enhanced rainfall was simulated only in warm, moist, unstable and low shear environments [*Khain et al.*, 2008; *Lee et al.*, 2008b; *Fan et al.*, 2007 and 2009]. The stronger updrafts and downdrafts resulted in more coherent organization of the simulated convection that feeds back into the intensity of the storms [*Ntelekos et al.* 2009; *Lee et al.*, 2010]. The invigoration was supported also by observations of more polluted convective clouds growing taller [*Koren et al.*, 2005, 2008 and 2010].

1.2 The physical basis for aerosols enhancing lightning, hail and tornadoes

The invigorated updrafts with added supercooled water and ice hydrometeors provide the conditions for enhanced cloud electrification [*Molinié and Pontikis*, 1995; *Williams et al.*, 2002; *Andreae et al.*, 2004]. However, the observational evidence was questioned due to the difficulty in separating the roles of meteorology and aerosols [*Lyons et al.*, 1998; *Williams and Stanfill*, 2002; *Williams et al.*, 2002; *Williams*, 2005].

Critical supporting observational evidence for the validity of the invigoration hypothesis was obtained very recently, where volcanic aerosols, whose variability was completely independent of meteorology, were observed to invigorate deep convective clouds over the northwest subtropical Pacific Ocean and more than double the lightning activity [*Yuan et al.*, 2011; *Langenberg*, 2011].

The greater amount of supercooled cloud water in polluted situations means greater growth rate of ice hydrometeors. The stronger updrafts mean that larger hail stones can be suspended in the cloud before falling to the ground. Therefore, it is reasonable to expect that clouds in more polluted air would produce larger hail stones. This is supported by some observations [*Andreae et al.*, 2004; *Wang et al.*, 2009] and simulations [*Storer et al.*, 2010; *Khain et al.*, 2011].

The dynamics of convective storms respond to the initial changes in precipitation by changes in the downdrafts and their evaporative cooling, which feed the cold pools and their gust fronts. Early simulations [*Gilmore et al.*, 2004; *van den Heever and Cotton,* 2004] showed that storm dynamics was very sensitive to changes in hydrometeor size, such that smaller hydrometeors created larger cold pools and stronger gust fronts that fed back to the storm dynamics. Colder downdrafts would produce a faster moving gust front that would tend to cause faster propagation of the squall line. A supercell can be regarded as quasi steady state convective storm, where the gust front is not outrunning and undercutting the updraft in the feeder clouds. Therefore, less evaporative cooling into the downdraft would reduce the cooling and extent of the cold pool. A slower moving gust

front with respect to its originating cell would drive the convective system closer to a state of a supercell, which is the typical cloud type that produces large hail and tornadoes.

Ludlam [1963] proposed that air parcels within the downdraft tended to be less negatively buoyant (warmer) in tornadic vs. nontornadic supercells. Tornadic vortices increased in intensity and longevity as downdraft parcel buoyancy increased, because colder parcels were more resistant to lifting. This was supported by observational and numerical modeling studies [*Markowski et al.*, 2002 and 2003]. Simulations of the sensitivity of tornadogenesis to the hydrometeor size distribution, done at the high resolution of 100 m [*Snook and Xue*, 2008], showed that by merely increasing the hydrometeor size an EF2 intensity tornado was produced by the model. When the cold pool is strengthened by decreasing the hydrometeor sizes, the updraft is tilted rearward by the strong, surging gust front, causing a disconnection between low-level circulation centers near the gust front and the mid-level mesocyclone.

Clouds with smaller drops were observed to produce larger rain drops for the same rain intensity [*Rosenfeld and Ulbrich*, 2003]. This was confirmed by simulations of warm rain [*Altaratz et al.*, 2008] and mixed phase clouds [*Khain et al.*, 2011]. Incorporating this effect in simulations of an idealized supercell thunderstorm [*Lerach et al.*, 2008] showed that the added aerosols suppressed the precipitation and produced larger and fewer hailstones and raindrops. This produced an EF-1 tornado. The unpolluted simulation produced more evaporative cooling, and thus a stronger surface cold pool that surged and destroyed the rear flank downdraft structure. This resulted in a single gust front that propagated more rapidly away from the storm system, separating the low-level vorticity source from the parent storm and thus hindering the tornadogenesis process.

In this brief review we have shown that there is a physical basis for the hypothesis that added aerosols can contribute to the occurrence of large hail and tornadoes. In the next sections the hypothesis that the weekly cycle in pollution aerosols is associated with a similar cycle in the hail and tornadoes will be tested using observational data for hail and tornado activity.

2. The data

Based on the physical considerations above, we expect that the occurrences of severe convective storms would be enhanced in a more polluted atmosphere during the summer months in the eastern USA, where the convective storms occur in a warm and moist atmosphere and are least forced by synoptic weather systems such as cold fronts. In order to test whether there is a weekly cycle, daily counts of tornados or hail, categorized by intensity, were analyzed.

Data for tornado and hail observations were obtained from the web site of the Storm Prediction Center [*SPC*] of the National Oceanic and Atmospheric Administration [*Carbin*, 2010]. The observational data maintained by the SPC are based on reports collected by local National Weather Service Forecast Offices from a wide variety of sources (trained spotters, emergency personnel, the media, the general public, etc.). The assignment of tornado strength on the enhanced Fujita scale [*EF*] for a tornado probably reflects both estimates of the intrinsic strength of the tornado and valuations of the level of property damage found along the path of the tornado. A characteristic hailstone size is assigned to hail storm events. The NOAA Warning Coordination Meteorologist attempts to identify duplicate observations and storms that span several jurisdictions. The data we used were current as of 16 March 2010.

Schaeffer and Edwards [1999] suggest a number of possible biases in these data: tornados generally go unreported where no one lives; both population and population awareness has increased over the years; and the adoption of warning systems has made people more alert to tornados. More tornados are observed near populated areas than away from them. Storms that are particularly severe are probably missed less often, however. The total numbers of tornados and of hail storms have generally trended upwards with the years (Figure 1), but the conventions for attributing a given Fujita scale to a storm have also evolved. Rapid increases in the numbers reported may be due to the introduction of new technology: implementation of the WSR-88D radars with Doppler capability in about 1991, for example, may have led to increased reporting of tornados after that date. An analysis by *Ray et al.* [2003] suggests that tornados are reported more often near population centers and that tornado occurrences prior to 1992 may have been underestimated by about 40%. Contrariwise, *Aguirre et al.* [1993, 1994] conclude that some of these "biases" may in fact be caused by environmental changes imposed by human habitation.

The observational biases that may be present in the data can easily be imagined to change with the day of the week. Weekly changes in media coverage are possible, for instance. We argue later in the paper that both the lack of a weekly cycle in the less populated western half of the U.S. and during the spring season in the eastern half, and the agreement of the weekly cycle in tornado and hail activity seen in the eastern half with the weekly cycle seen in other indicators of severe storm activity (indicators that are not subject to the same concerns about weekly biases in the observational system)

suggest that the weekly variations in tornado and hail activity are mostly real and not the result of weekly shifts in coverage by the observational network.

In preparing the data for analysis, we edited a small fraction of the data entries based on the recommendations accompanying the data provided by the SPC and on the need to resolve various ambiguities. Entries with missing state identifications were ignored. Entries with either zero latitude or longitude locations were ignored. Entries with negative Fujita scales or hail diameters were ignored. Apparently misidentified time zones were corrected. Multiple entries associated with a single tornado event were consolidated into one entry (not an issue in the hail dataset). Tornados that crossed state boundaries were treated as two separate events, however. Fifteen entries of hail sizes of 0.25 and 0.5 inches in 2007 were pooled with the entries for 0.75 inches. In total, fewer than 2% of the tornado dataset entries required editing. A far smaller percentage of hail data entries required editing. The number of tornado events for 1980–2009 in our edited dataset was approximately 33,000, while the number of hail events was approximately 235,000.

3. The data analysis

In the following subsections we provide details about the assumptions and methods used in the statistical analysis of the tornado and hailstorm data.

3.1. Statistical model of data under the null hypothesis

Testing the data for the presence of a weekly cycle requires a description of the statistics of the data under the null hypothesis, which is that the frequency of tornados or hailstorms does not vary cyclically with the day of the week. In modeling the statistics of hailstorms and tornado occurrences under the null hypothesis, we try to accommodate the known variations in statistics with the season and year. Our goal is not to determine the "true" seasonal cycle or decadal trend but simply to produce something likely to be closer to the truth than ignoring the seasonal cycle or year-by-year trend altogether.

We used the average seasonal cycle over the years 1980–2009 to represent the modulation of the expected count with the seasons (i.e., with the day of the year). Though we used 15 years of data (1980–1994) prior to the period we are concentrating on (1995–2009), they were used only to help establish the background seasonal cycles and decadal-scale trends, and for the bootstrap statistical analysis described later. The seasonal cycle estimated from 30 years of data is smoother than the cycle estimated using 15 years (1995–2009), as would be expected, but is not substantially different. We believe that using data prior to 1995–2009 to increase the stability of our estimate of the seasonal cycle increases the overall robustness of our statistics, but that if we had confined our averaging to the years 1995–2009 our conclusions would not be changed in any substantial way.

We show in Figure 2 the average number of reported tornados for each day of the year. The averages for each day of the year in Figure 2 exhibit quite a lot of variability from day to day, almost certainly due to the sample size (30 samples, one for each year) in the daily averages. Rather than trying to build a smoother, parameterized model for the seasonal cycle, we applied a kind of running average to the 365 daily averages (leap

years treated as having 365 days). The filter devised by *Lee* [1986] produced a satisfactory curve when we applied the filter twice with a window size of 11 days (on either side of the central value), as shown in Figure 2. The Lee filter produces a smooth fit to the data but tries also to capture sudden jumps in the local mean.

The annual counts for each year from 1980 to 2009 vary quite a bit from year to year (e.g., see Figure 1), possibly attributable to large-scale influences such as ENSO or to sample sizes, but there appears to be a decadal trend in the counts as well. Some of these trends can be explained by changes in the methods of collecting the data, as mentioned above.

The seasonal cycles of the different tornado strengths are very similar, we found, as are the seasonal cycles for different hail sizes, except for overall normalization.

In order to test whether the tornado/hailstorm statistics differ significantly from what would be expected under the null hypothesis that there is no weekly cycle, we need a statistical model for the expected number of storms under the null hypothesis. Since we only test data from particular seasons rather than from a full year, we take this into account in constructing the model. We assume that the expected number of tornado/hail events for a given day and season/year is proportional to the total number of storms for that season (thus capturing the interannual variability in Figure 1) and to the average number of storms for the given day of the year (as represented by the smooth curve in Figure 2). If there is a weekly cycle, we assume that the cycle is described by a sinusoidal oscillation multiplying the expected number (Equation 3 below).

To represent the expected number of tornados $n_0(y,j)$ in year y and day j for summertime tornados (June 1 – August 31, i.e., $152 \le j \le 243$) under the null hypothesis, then, we assume that the number is proportional to the number of tornados that summer $n(y)$ and to the seasonal cycle $f(j)$ represented by the smooth curve in Figure 2. Thus,

$$n_0(y,j) = n(y)\frac{f(j)}{\sum_{j'=152}^{243} f(j')}. \quad (1)$$

If $n(y,j)$ is the actual number of observed storm occurrences in year y for day j, $j = 1,\ldots,$ 365 (or 366 in a leap year), we define the ratio variable

$$r(y,j) = n(y,j)/n_0(y,j), \quad (2)$$

which has an average very near 1 when averaged over all years of data, or when averaged over all j, by construction.

A plot (not shown) of the variance of the ratio variable (2) over the 92 days of each summer vs. the number of tornados for that summer indicates that the variance is fairly uniform over the years and doesn't seem to vary in a consistent way with the number of tornados that summer. This suggests that it is reasonable to treat the statistics of the ratio variable (2) as stationary from year to year.

3.2. Statistical model of weekly cycle

We determine whether there is a weekly cycle in the ratio variable $r(y,j)$ by fitting the time-dependent data $r(t)$ to a 7-day sinusoid

$$r(t) = r_0 + r_7 \cos[\omega_7(t - \varphi_7)] + \varepsilon(t) \quad (3)$$

with $\omega_7 = 2\pi/(7 \text{ days})$, where r_0 is the mean of the ratio variable, r_7 is the amplitude of the cycle, and φ_7 is the time during the week when the weekly cycle peaks. The error in the

fit is denoted by $\varepsilon(t)$. The time t is measured in days starting from an arbitrary date (Tuesday, 1 January 1980, for instance).

It is perhaps worth reminding the reader here that by fitting the data to a pure sinusoid (Equation 3) we are not assuming that this is in fact an exact description of the weekly cycle in the data. A periodic signal with period 7 days can always be expressed as a sum of sinusoids with periods of 7 days and their higher harmonics. The higher harmonics tend to be noisier and harder to estimate from small amounts of data, and we have chosen not to examine them. Moreover, because the sinusoid is fit using data from all days of the week, the sinusoid makes much better use of the data (with more robust statistics) than a search for a weekly cycle that uses only averages of data from single days of the week, a practice that is fairly common in searches for weekly cycles in data.

3.3 Statistical tests for weekly cycle

By writing $r_7 \cos[\omega_7(t - \varphi_7)] = c_7 \cos(\omega_7 t) + s_7 \sin(\omega_7 t)$ and using linear-least-squares fits to this expanded version of Eq. (3) for each week of data, we can use the variance of the coefficients c_7 and s_7 from week to week to estimate the overall uncertainty σ_7 in the amplitude r_7, assuming that the correlation of the coefficients from week to week is negligible and the number of samples (weeks) for variance estimates is large enough that the coefficients are approximately normally distributed. (Time correlations of the fitted amplitudes from week to week were found to be consistent with the assumed correlation 0.) The ratio $(r_7/\sigma_7)^2$ then has a Fisher-Snedecor F distribution with two degrees of freedom in the numerator and the number of weeks in the data series in the denominator. Details of this approach can be found in *Bell et al.* (2008). The quantity r_7/σ_7 is used as a measure of the signal strength (signal-to-noise ratio). The significance level p of the

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amplitude r_7, under the null hypothesis that there is no weekly cycle, can be calculated from this ratio as

$$p = \exp[-(r_7 / \sigma_7)^2] \quad (4)$$

as explained in *Bell et al.* (2008). For example, this means that the probability p that r_7 is larger than 1.73 σ_7 is $p = 0.05$.

Because of the normalization of the observed number $n(y,j)$ by the expected number $n_0(y,j)$ in Eq. (2), the value of r_0 in (3) obtained by the fitting procedure is typically very close to 1. [It is not exactly 1 because the seasonal cycle $f(j)$ is based on an average over all years (1980–2009).]

The statistical significance of the amplitude r_7 is estimated both by the method described above and by a second method. The second method of estimating the statistical significance of the fitted amplitude r_7 uses a bootstrap approach in which the original data are re-sampled in chunks 11-days long in a way that destroys any 7-day periodicity in the original data. Chunk sizes of 11 days are used based on the belief that the correlation of weekly-cycle fits to the chunks from one chunk to the next is small. Where we have checked, it is indeed small. To randomize with respect to the day of the week, chunks are selected that are displaced from the original chunk anywhere from 7 days before to 6 days after the original chunk (i.e., whose starting point is chosen from within a 14-day window). We choose chunks from prior or future seasons up to 5 years away, instead of confining ourselves to data from the same year, to increase the number of replacement choices. Thus, for example, if the chunk we are replacing starts on 10 August 2001, we may randomly select a chunk from the original dataset beginning anywhere from August

3 to August 16 and from any year from 1996 to 2006. This tends to generate simulated datasets with statistics that change with the day of the year in the same way as the original dataset, as far as preserving the seasonality of the statistics and decadal trends, but having no real weekly cycles. Note that because we have access to years prior to 1995, we may select random chunks from years as early as 1990 when a chunk from year 1995 is being replaced. Note that because the statistics of the ratio variable $r(y,j)$ seem to be fairly constant from year to year, we create simulated datasets starting with the original dataset for $r(y,j)$ rather than of $n(y,j)$ itself, thereby minimizing the impact of seasonal and interannual variability on the statistics of the simulated datasets.

Synthesized datasets assembled from the 11-day chunks are used to estimate values of r_7 for each dataset, and the statistical significance of the value of r_7 obtained from the original dataset is set at the fraction of synthesized datasets with r_7 larger than that of the original value. We found that the two methods produced comparable significance levels p (the probability that the value of r_7 could equal or exceed its value under the null hypothesis $r_7 = 0$).

4. Analysis Results

4.1. Results for tornados east of 100W

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In accordance with the hypothesis that the impact of air pollution on invigorating severe storms would be greatest in a moist and warm atmosphere, we follow our previous geographic partitioning [*Bell et al.*, 2008 and 2009a], and examine data for the summer months, June–August, and areas east of 100W for all latitudes within the USA (our earlier studies were constrained by the latitudinal coverage of the satellite data we used). The longitude of 100W separates the moist air mass to the east, where invigoration can be

expected, from the dry air masses to the west, where cloud bases are too high and cold to be substantially invigorated by added aerosols. This is evident in the map of climatic mean dew point temperature for July, shown in Figure 3a.

Hail and tornado data are available from 1950, but their quality has evolved over time. The completeness of the coverage has been improving, especially for the weaker and thus less noticeable events. Observational coverage of tornados seems to have stabilized since the mid 1990's, whereas coverage of hail appears to have grown continuously (see Figure 1). We have therefore focused our search on the period 1995-2009.

A weekly cycle in the aerosol impacts on clouds depends on the existence of a weekly cycle in anthropogenic aerosols. Such a cycle is observed clearly in Figure 4, in both PM10 and PM2.5 (particulate matter concentrations for particle diameters greater than 10μm and 2.5μm respectively). The data are collected by the Environmental Protection Agency (EPA) and are discussed in *Bell et al.* [2008]. The weekly cycle of hail and tornadic storms for the years 1995-2009, also shown in Figures 4 and 5, behaves very similarly to the cycle in the aerosols, with a distinct minimum on weekends.

The temporal and spatial distribution of the weekly cycle matches the distribution of the warm, moist and unstable conditions in which aerosols have the strongest tendency to invigorate deep convective clouds [*Rosenfeld et al.*, 2008]. During summer, the longitude of 100W coincides with the transition from the moist climate to the east of it to the hot and dry climate to the west, as shown in Figure 3a.

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The moisture peaks in the months of June, July and August and reaches the northeast USA, but starts to retreat southward during late August and September. The aerosol invigoration effect can become apparent in moist atmospheres when synoptic forcing is less dominant. In cool base clouds (i.e, temperature of about 10°C or less) the effect might even reverse [*Rosenfeld et al.*, 2008]. This is in agreement with the spatial and temporal distribution of the weekly cycle, as depicted in Figure 6. The figure shows the state of the weekly cycle over three latitudinal bands east of 100W as a function of the time of year. Each arrow represents the statistics for a bimonthly period and the years 1995–2009. The length of the arrow shows the amplitude of the weekly cycle r_7 as a fraction of the mean r_0. The direction indicates the day of the week when the sinusoidal fit peaks. The color indicates the significance level p of the fit, reflecting the signal-to-noise ratio of the fit. The figure shows that the transition from the synoptically forced storms in the spring, when moisture levels are also much lower (Figure 3b), to the more locally unstable storms that form in a moist unstable air mass in the summer is accompanied by an increase in the weekly cycle modulation tending to have a mid-week maximum. The return of the synoptic forcing and not as moist air in the early fall to the north part of the domain is similarly associated with a decrease of the weekly cycle there. Note that the weekly cycle of tornados only becomes established sometime in June, even though tornadic activity is reaching its peak well before then (See Figure 2). The consistency of these patterns of occurrence of the weekly cycle in time and space and the predictions of the hypothesis that the pollution aerosols are the cause of the observed weekly cycle in severe convective storms lend additional credence to the hypothesis.

The overall statistical significance of the weekly cycles of tornado and hail activity for the 15-year period 1995–2009 is quite high (see caption to Figure 4). We can also examine the weekly cycle for individual summers based on sinusoidal fits to the data for each summer alone, though the results are noisy given that there are only 13 weeks in a summer. The results of such an analysis were displayed in earlier papers as ``clock plots" for rainfall [*Bell et al.*, 2008] and for lightning [*Bell et al.*, 2009a]: the phase and amplitude of sinusoidal fits were used to plot a point on a clock dial running from Saturday to Friday and with the distance of the plot point from the center of the plot proportional to the ``signal-to-noise ratio" of the amplitude. The ``noise" σ_7 is determined from the variance of weekly fits to the data. The signal to noise ratio r_7/σ_7 is given (See Eq. 4) by $[-\log(p)]^{1/2}$, where p is the significance level of the amplitude r_7, i.e., the probability that an amplitude this large could have occurred by chance, due to small-sample effects, when there is in fact no weekly cycle present.

Despite the small number of samples in each summer of data, it was found [*Bell et al.*, 2009a] that the phases of the weekly cycles in lightning activity for summers between 1998 and 2009 fell year after year in the non-weekend sectors of the clock plot. This strongly suggests that the weekly cycle in the data has a period of *exactly* 7 days and is not an atmospheric wave with a period "in the neighborhood" of 7 days. Because tornado and hail events are not nearly as numerous as lightning events, and the tornado/hail observational coverage not nearly as dense, we would expect the year-by-year clock plots of hail and tornado weekly cycles to be noisier than for lightning. The clock plots for hail and tornados are shown in Figure 7. They cover the years 1995–2009. In order to maximize the weekly cycle signal, only data from the afternoons (1200–2400 local solar

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time), when convective instability is highest, are used in these plots. Though the phases do not avoid the weekend sectors as completely as the lightning weekly-cycle phases did, there is still a clear tendency for the weekly cycles of hail storms and tornados to peak in the middle of the week. When the phase falls on weekends, the signal-to-noise ratio is quite low, implying that the statistical uncertainty in the determination of the phase is large. Note that the hail data contain about 7 times as many events as the tornado data and therefore have more stable statistics, and the phases are more consistent in avoiding the weekend sectors (Figure 7a).

4.2. Results for tornados west of 100W

The average July dew point temperatures are smaller than 10°C at most of the area to the west of 100W (see Figure 3a). Therefore we do not expect to find there evidence of weekly storm invigoration. Even though there is a pronounced weekly cycle in aerosols measured by ground-based EPA stations west of 100W (Figure 8), no significant weekly cycle is apparent to the west of 100W (Figure 9).

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5. Discussion

The results are in agreement with our previous reports of similar weekly cycles in the rainfall [*Bell et al.*, 2008] and lightning [*Bell et al.*, 2009a] over the USA. The cycle was ascribed there to aerosols invigorating deep convective clouds in a warm, moist atmosphere. It is therefore not too surprising to find that the invigorated clouds also produce more hail and tornados.

We show in Figure 7 that the hail and tornado data are consistent with earlier results for rain and lightning at the SE U.S. in another respect: when the phase ϕ_7 and signal

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strength r_7 for each summer of data for the years 1995–2009 are displayed on a "clock plot", there is a clear tendency for the phases to avoid the weekend period, despite the fact that there are only 13 weeks of data in a single summer and estimates of the weekly cycle are quite noisy. It is not surprising that the avoidance is not as clear as it was for the lightning data [*Bell et al.*, 2009a], since lightning occurs far more frequently than hail storms and tornados and the effective sample size for lightning is far larger.

It is conceivable that the storm data could be affected by a weekly bias in the observations of storms. However, it is shown in Figures 9a and 9b that no sign of a statistically significant weekly cycle in tornado or hail occurrence is visible in the data west of 100W. If there is a weekly-varying bias in storm reports it would have to be present in the eastern half of the U.S. and absent in the western half to explain our results. Furthermore, the weekly cycle from March to May over the eastern USA (see Figure 6), is not statistically significant, and no longer points to a mid-week maximum. If anything, it is pointing more towards the weekend, but without any statistical significance. The signal is too weak to support the possibility of reversal in the convective invigoration effect in cool base clouds, as hypothesized by *Rosenfeld et al.* [2008]. The lack of a clear weekly cycle in the spring along with its existence in the summer, plus the clear correspondence of the weekly cycle we see in the summer storm data with the cycles observed in other variables with no possible weekly-varying observational bias, suggests that the weekly cycle in storms is a real one and not an artifact of the data collection methods.

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The weekly cycle we see is firmly pegged to the work week. It is not plausible that it is a reflection of a quasi-periodic 7-day cycle in atmospheric dynamics, whose phase

would surely wander from year to year — something we do not see in any of the clock plots. *Kim et al.* [2010] recently raised the possibility that the weekly cycle can occur due to natural random variability [*Kim et al.*, 2010]. This might be the case for a weekly cycle that is found in general upper tropospheric synoptic features that have no clear hypothesis to the way that they might be linked to anthropogenic effects [*Stinov*, 2010]. However, this is not likely to be the case here, based on the lack of evidence of a weekly cycle in the synoptic properties that correlate with lightning activity that was presented in the supporting online materials of *Bell et al.* [2009a]. Previous reports of a weekly cycle of hail in Southern France [*Dessens et al.*, 2001] did not show a change in hail frequency, but showed a larger kinetic energy of the hailstones on weekends. It was postulated that ice forming nuclei (IFN) emitted during the weekend from the local industry was creating larger number of ice hydrometeors and therefore decreasing the hailstone sizes due to greater competition on the available supercooled water. There is no information whether IFN have a weekly cycle in the eastern USA.

This study has shown a clear relation between the weekly cycle of anthropogenic aerosols and the occurrences of severe convective storms, which is very unlikely to be a result of natural variability. The observed associations cannot serve as proof for causality. However, the results are consistent with the hypothesis that air pollution aerosols invigorate deep convective clouds in moist and unstable atmosphere, and the possibility that they can even induce the storms to produce large hail and tornados. Therefore, these results support this hypothesis. It is worth pointing out that if a roughly 10% weekly variation in pollution levels is resulting in a similar change in severe storm activity, then the "background" aerosol level, which is elevated with respect to the pre-industrial level

even during weekends, is also likely to be changing the storm frequency we experience today.

Acknowledgements

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FIGURES

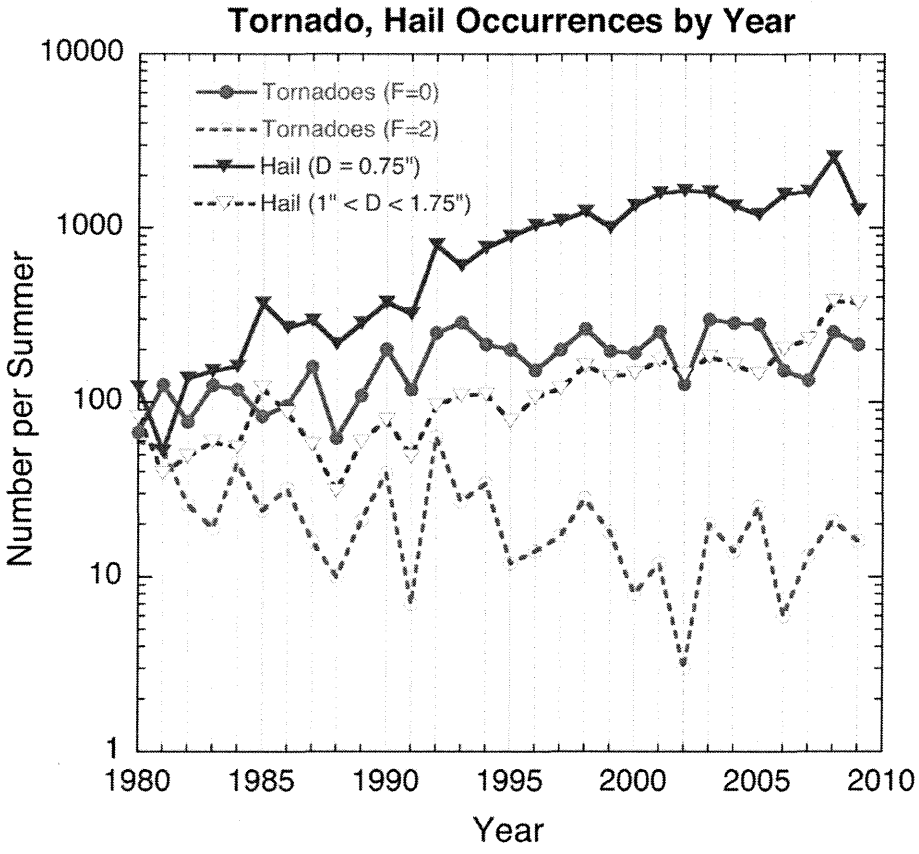

Figure 1. Number of tornado and hailstorm events each summer (Jun–Aug) for 1980–2009. Graphs are shown for tornados classified as F0 and as F2 in strength, and for hailstorms with reported hail diameters of 0.75 inches, and between 1 and 1.75 inches (exclusive). Because hail diameters are generally given in 0.25-inch increments, this bin includes mostly hail diameters of 1.25 and 1.5 inches.

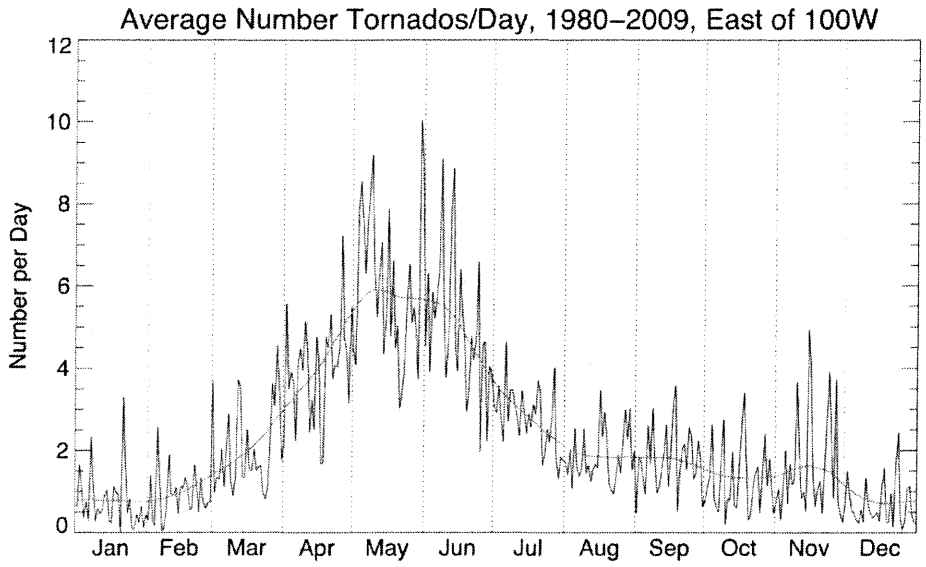

Figure 2: Average number of tornados per day (solid circles), all strengths, for years 1980–2009. Smooth red curve shows fit to data using Lee filter, as described in the text, and was used by us as the expected tornado count for days of the year. It is denoted by *f(j)* in the text.

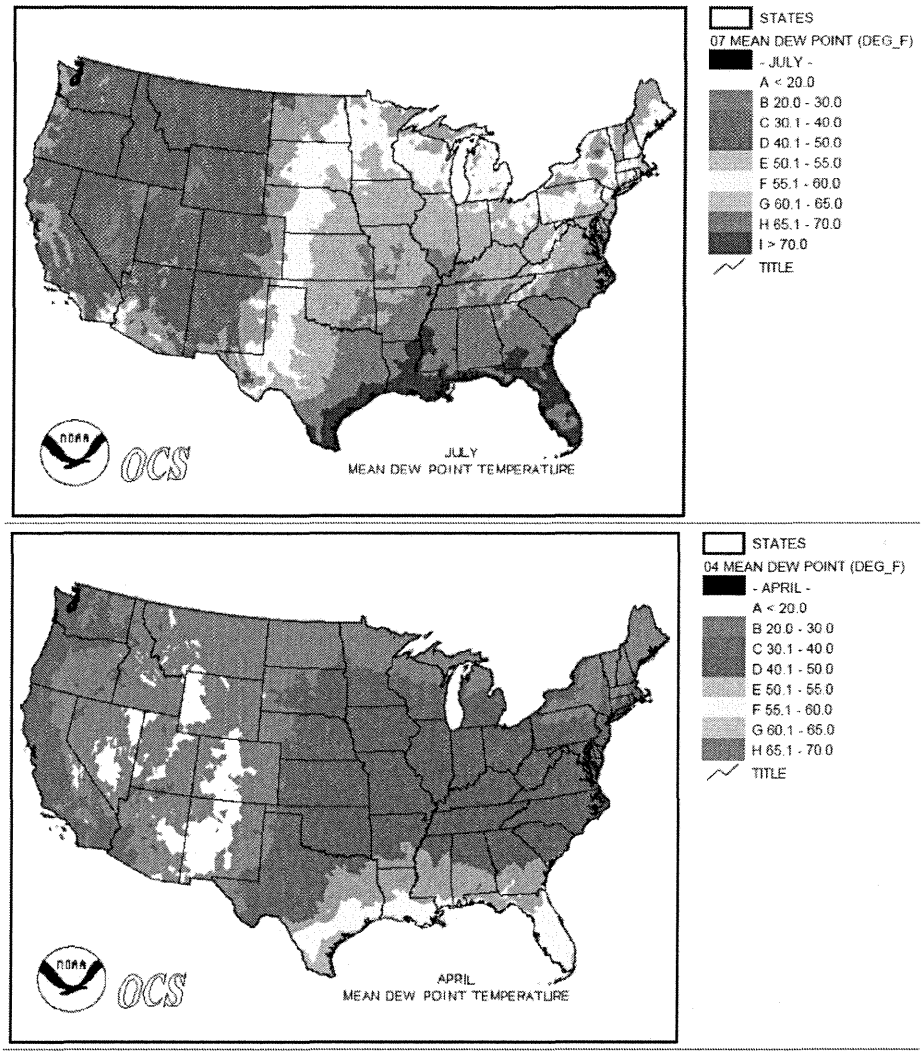

Figure 3: Mean dew point temperature for July (top) and April (bottom). From NOAA Climatic Data Center.

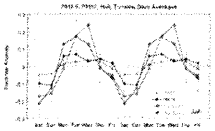

Figure 4: A weekly cycle of the aerosols (PM2.5 and PM10), as measured by the EPA over the USA during JJA of 1998-2005 to the east of 100W, along with the associated weekly cycle of the SPC-reported hail storms and tornados over the same area averaged over JJA for 1995–2009. The significance level p for the weekly cycle of tornados is $p =$ 0.011 (F-test) and $p = 0.033$ (bootstrap test). The significance level for the hail data is $p = 0.00013$ (F-test) and $p = 0.0008$ (bootstrap test with 10^4 simulated datasets).

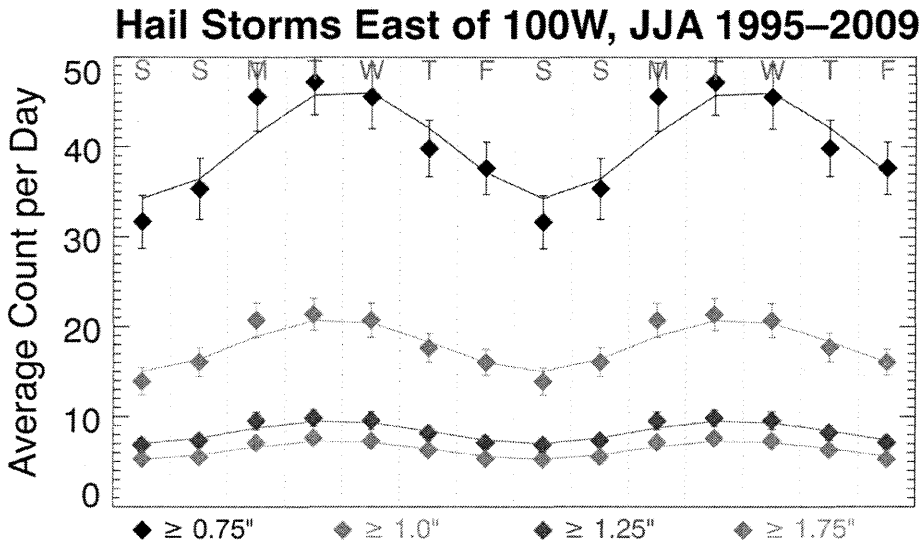

Figure 5a. Daily averages for hail occurrences of various strengths (hail diameters) are shown, using data for hail storms east of 100W for June–August, 1995–2009.

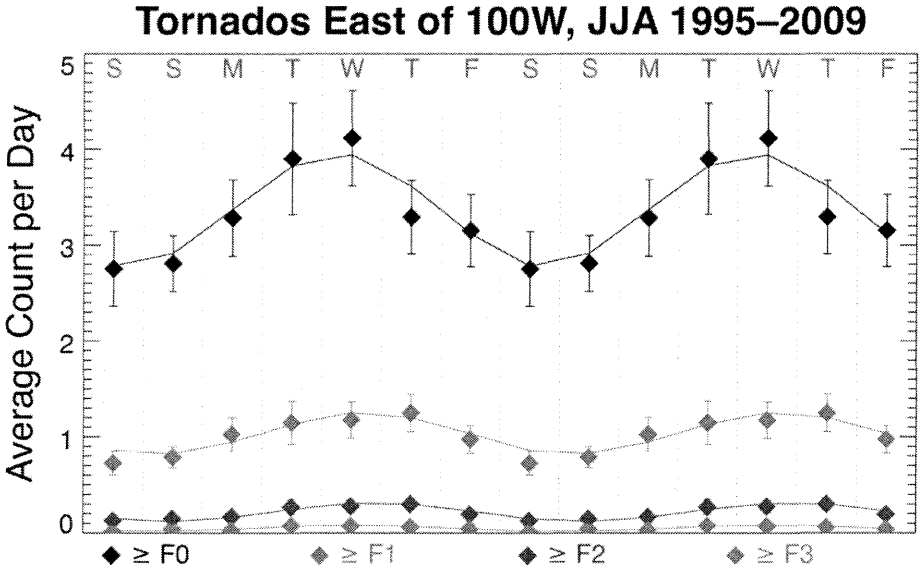

Figure. 5b. Daily averages for tornado occurrences of various strengths (F values) are shown, using data for tornados east of 100W for June–August, 1995–2009.

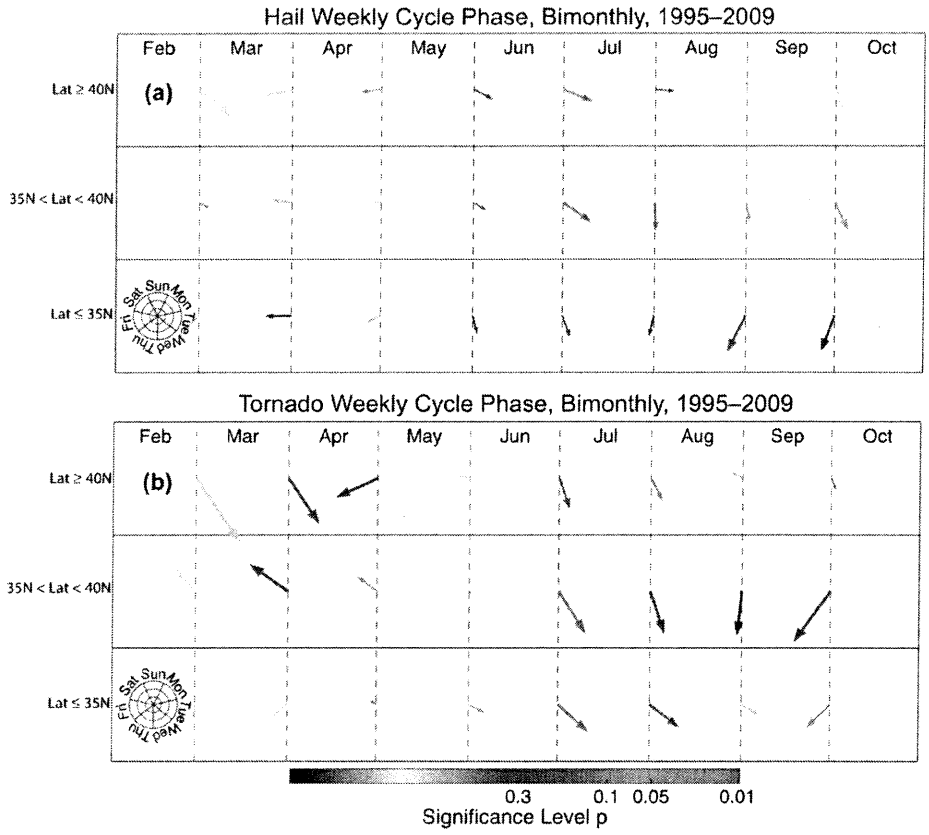

Figure 6: The dependence of the phase of the weekly cycle in hail (a) and tornadic (b) storms on the time of year and geographical latitude to the east of 100W. Each arrow represents averages of the two months to either side of its location. The latitudes contributing to each row of statistics are shown to the left of the figure. The direction of the arrow points to the day of the week when the sinusoidal fit is a maximum, and the length indicates the weekly amplitude as a fraction of the bimonthly mean, according to

the key at the bottom left of the figures. The radius of the outermost circle in the key represents a fractional anomaly of 0.15. The arrows are colored according to their significance level, with the color bar below indicating the significance level assigned to each color.

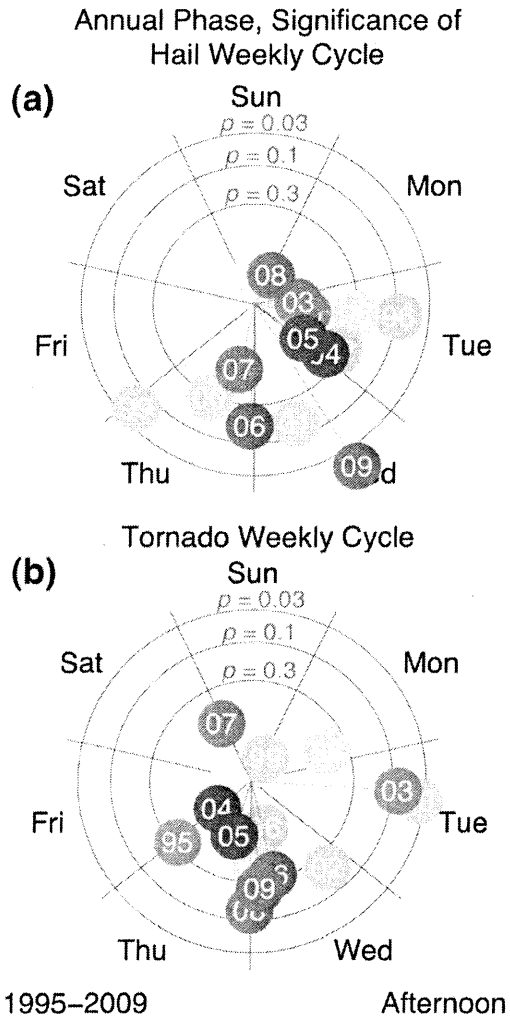

Figure 7: The phase (day of the week) and amplitude of the weekly cycle (Eq. 1) of data for each summer for the years 1995–2009. The amplitude is represented by the distance from the origin and is proportional to the signal-to-noise ratio of the amplitude, r_7/σ_7. The last two digits of the year are shown in the colored balloons. The probability p that the amplitude of the weekly cycle could exceed a given radius, under the null hypothesis $r_7 = 0$, is shown by the circles labeled by the corresponding value of p. (a) Hail data. (b) Tornado data.

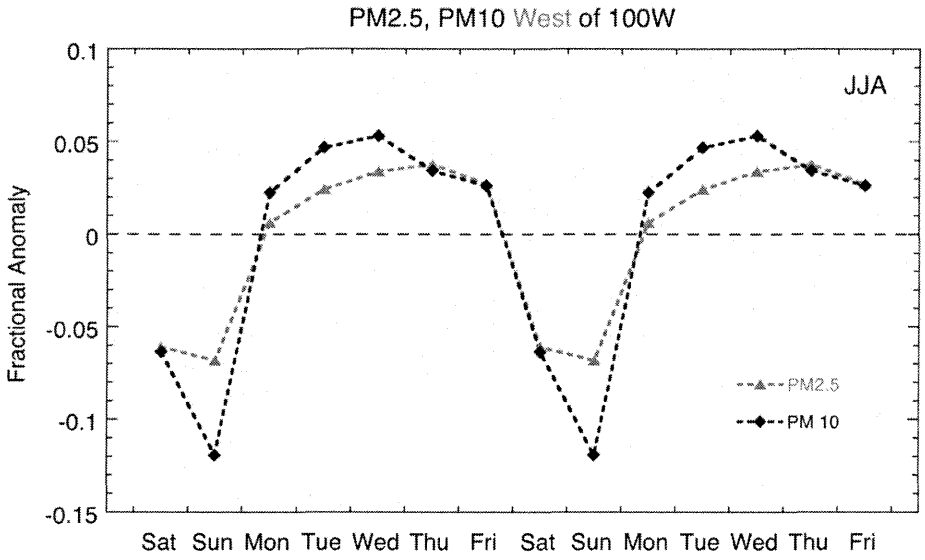

Figure 8. Weekly cycle of the aerosol concentrations (PM2.5 and PM10), as measured by the EPA over the USA during JJA of 1998–2005 to the west of 100W. Daily averages are expressed as fractional anomalies relative to the overall means.

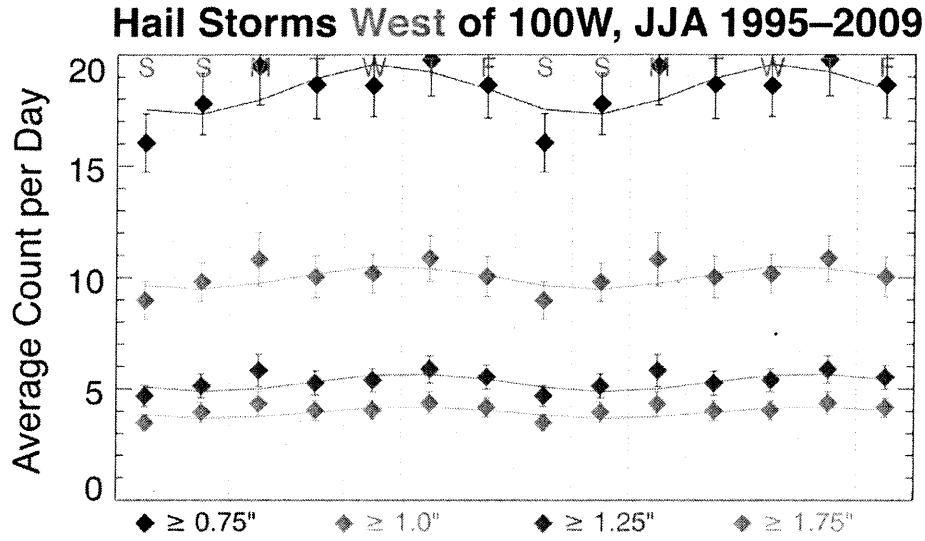

Figure 9a. Daily averages for hailstorm occurrences of various strengths (hail diameters) are shown, using data for hail storms west of 100W in JJA and for 1995–2009. The weekly cycles are not statistically significant.

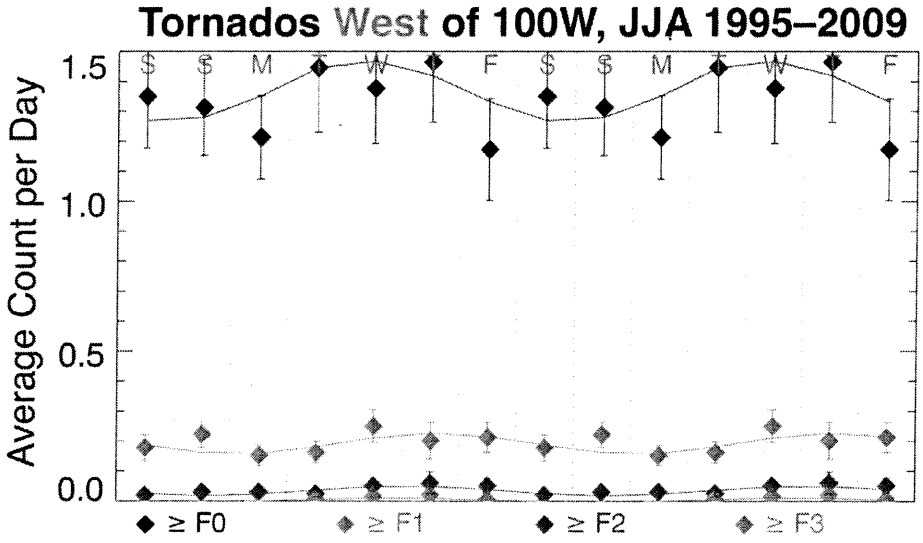

Figure 9b. Daily averages for tornado occurrences of various strengths (EF values) are shown, using data for tornados west of 100W in JJA and for 1995–2009. The weekly cycles are not statistically significant.