Commentary on "Why do tornados and hailstorms rest on weekends?" by D. Rosenfeld and T. Bell

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1. Introduction

[1] The paper "Why do tornados and hailstorms rest on weekends?" [*Rosenfeld and Bell*, 2011] (hereinafter RB2011) contains key misunderstandings of US spring and summer tornadoes, supercell storms, and their environments. In this comment, we show that (1) there is not a robust weekly cycle or midweek maximum in tornado occurrence or tornado days, (2) RB2011's physical explanation for how increased aerosol concentrations would cause increased frequency and severity of tornadoes and hail in supercells is inconsistent with actual supercell storm structures and their environments, and (3) RB2011's method of averaging aerosol and tornado data from 100°W eastward conflates an aerosol weekly cycle in one geographic location with tornado occurrence in another.

2. The Weekly Cycle in Tornadoes is a Mirage

[2] What are the characteristics of a robust weekly anthropogenic effect? As *Vermeesch* [2009] points out, the null hypothesis for a weekly cycle in phenomenon X is mathematically equivalent to saying phenomenon X occurs with exactly equal frequency on each day of the week. For data sets of intermittent phenomena, such as tornadoes or earthquakes, such perfect uniformity is highly unlikely. Furthermore, tornados do not occur independently of each other. The synoptic-scale atmospheric environment can favor the formation of groups of storms each producing multiple tornados over their lifetimes [*Verbout et al.*, 2006]. Counts of tornadoes by day of the week over a multiyear period are prone to becoming nonuniform due to a few individual, highly prolific tornado events. *Vermeesch* [2009] found a statistically significant weekly cycle for earthquake occurrence that peaks on Sundays illustrating that statistical significance in itself is not sufficient to warrant the pronouncement of a weekly anthropogenic effect. Additional necessary conditions for a robust weekly anthropogenic effect include reproducibility with independent data sets, examination of potential sensitivities and biases, and a solid physical basis for causation between correlated weekly cycles [*Daniel et al.*, 2012].

2.1. April and May Tornadic Supercell Storms Also Have Warm Cloud Bases but Do Not Have a Weekly Cycle

[3] As part of making their case for the causation of a weekly cycle in tornadoes by aerosols, RB2011 have to explain why they found no weekly cycle in tornadoes during April and May. According to RB2011, dew points ≥15°C are necessary in order to have sufficiently warm cloud bases for aerosol effects to occur (RB2011, para. 12). RB2011 explain the lack of a weekly tornado cycle during April and May (their Figure 7b, their paragraph 48) as being "consistent with the diminution of the convective invigoration effect in cool base clouds." RB2011 mischaracterize storm environments by using *monthly mean* dew points ≥15°C as the criterion to exclude April and May storms east of 100°W from their analysis. Instead, an examination of tornado environments *on a case-by-case basis* is needed in order to justify the exclusion of April and May tornadoes from their study.

[4] We examine the validity of RB2011's exclusion of the April and May tornadoes using the severe weather data set developed by *Smith et al.* [2012] for the CONUS region over the years 2003–2011. Smith et al.'s data set contains the strongest tornado that is reported each hour within each 40 km × 40 km analysis grid box of the Rapid Update Cycle (RUC) model [*Benjamin et al.*, 2004]. Meteorological variables from the corresponding time and RUC 40 km × 40 km grid box are used to describe the environmental characteristics of each tornado. We filter the data set to retain only tornadoes produced by supercells that occurred during April–August and in locations east of 100°W. These filters yield a sample of 4490 tornadoes—2791 in March and April and 1699 in June, July, and August—that we will call the "tornado cases."

[5] Ninety percent of the tornado cases in April and May have dew points ≥15°C that fit the RB2011 criterion for warm-based clouds, and 27% have dew points ≥20°C (Figures 1 and 2). In each year examined, there are more tornado cases with dew points ≥15°C in the two months of April and May than in the three months of June through August combined. *Following the logic of RB2011, exclusion of the*

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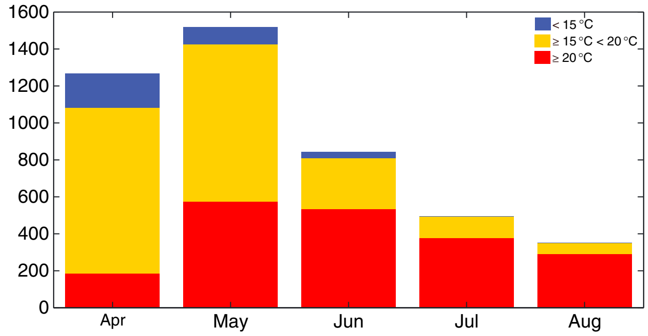

Figure 1. Bar plot of surface dewpoints associated with supercell tornadoes east of 100°W longitude by month. Data are from *Smith et al*. [2012] for 2003–2011.

vast majority of April and May tornado cases which have surface dew points ≥15°C would be unwarranted.

2.2. Varying Day of Week for Tornado Maximum for Different Intensities and Time Periods

[6] In this section, we use the same Storm Prediction Center (SPC) tornado report database (http://www.spc.noaa.gov/wcm#data) as RB2011 for the region east of 100°W, except that we look at a longer stretch of years and treat tornadoes that cross state boundaries as one tornado rather than as separate tornadoes as RB2011 did. From 2000 to 2011, there are 15,701 tornadoes in the database. Of those tornadoes, 169 of them cross state lines, and three of those traverse three states. So, ≈1% of the tornadoes in the database cross state lines. We also distinguish between all tornadoes of intensity F0 and greater (F0+) and F1 and greater (F1+). This distinction is made since F1+ tornadoes are more consistently reported than F0s [*Doswell et al*., 2009]. RB 2011 use the period 1980–2009 to determine the average number of tornadoes per day of year and use the post-WSR-88D period from 1995–2009 for their weekly cycle analysis. They do not discuss either reproducibility for independent data sets nor the sensitivity of their results to tornado intensity.

[7] Table 1 shows the tornado counts and tornado days east of 100°W by day of the week for 1995–2009, 1980–1994, and 1965–1979 for different sets of months and ranges of tornado intensity. There are many more F0s than F1s—typically 30–70% depending on the period examined—since frequency of tornadoes falls off as the intensity increases [*Brooks and Doswell*, 2001]. We reproduce RB2011's Wednesday peak for JJA and F0+ from 1995 to 2009. We do not reproduce their minimum of Saturday and instead have minimum on Sunday. This minor discrepancy is not significant and likely a result of a combination of our use of an updated version of the SPC database (RB2011's access was prior to August 2011 while we downloaded the data in July 2012) and RB2011's use of 3 day running average to smooth the data. Once one looks outside of RB2011's selected temporal subset of SPC data, the lack of a robust weekly cycle in tornado counts is clear (Table 1 and Figure 3).

[8] The days of the week for which the maximum and minimum in tornado counts occur are sensitive to tornado intensity (Table 1 and Figure 3). Use of the more consistently reported F1+ tornadoes during JJA for 1995–2009, i.e., just the removal of the F0 tornadoes, shifts the weekday tornado count maximum to Thursday. For 1980–1994 F0+ in JJA, the tornado maximum is Tuesday, and the minimum is Friday, while for F1+, it is Monday and Friday, respectively. Including tornadoes that occurred during May more than doubles the sample size with very little contamination from tornadoes not fitting RB2011's 15 °C warm cloud base criterion (Figures 1 and 2). For these data, the maximum in tornado counts for 1995–2009 jumps from Sunday for F0+ to Thursday for F1+. Additionally, tornadoes for MJJA in 1995–2009 with intensity of F0+ have maximum and minimum tornado counts on consecutive days (Sunday and Monday). Going further back into the record for the period 1965–1979, the maximum and minimum for F0+ during MJJA are on consecutive days (Thursday and Friday) as well. The occurrence of maximum and minimum tornado counts on consecutive days is incompatible with the sinusoidal weekly pattern to which RB2011 fit their data (their section 3.2).

[9] The use of raw tornado counts can also be problematic because a few days have large outbreaks of tornadoes whereas many days have no tornadoes. Examination of the number of days on which any tornado occurred east of 100°W (Table 2) shows a lower amplitude cycle regardless

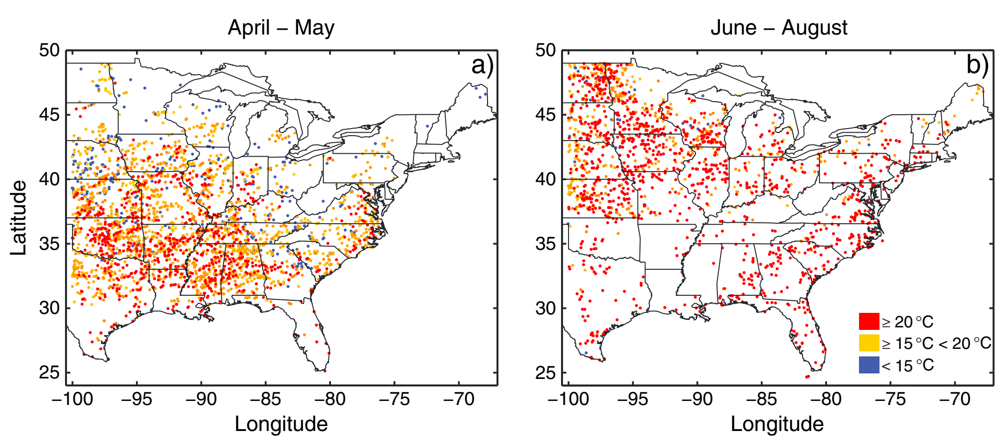

Figure 2. Maps of surface dewpoints associated with supercell tornadoes east of 100°W for the months of (a) April and May and (b) June, July, and August. Data are from *Smith et al*. [2012] for 2003–2011.

Table 1. Tornado Counts East of 100°W by Day of Week (No Smoothing Is Applied)[a]

Period and Intensity	Sun.	Mon.	Tue.	Wed.	Thu	Fri.	Sat.
			JJA				
1995–2009 F0+	*530*	583	745	**787**	640	613	534
1995–2009 F1+	154	202	224	229	**247**	192	*142*
1980–1994 F0+	624	652	**673**	560	567	*510*	590
1980–1994 F1+	314	**343**	335	254	273	*250*	315
1965–1979 F0+	**556**	511	536	500	551	*459*	504
1965–1979 F1+	**358**	317	315	310	322	*293*	326
			MJJA				
1995–2009 F0+	**1207**	*946*	1163	1186	1156	1153	1091
1995–2009 F1+	448	*331*	374	366	**474**	439	364
1980–1994 F0+	925	941	876	*840*	**957**	929	884
1980–1994 F1+	486	**522**	444	*425*	491	480	459
1965–1979 F0+	839	843	798	789	**864**	*664*	756
1965–1979 F1+	**559**	557	469	525	530	*429*	503

[a]For each row, maximum value is in bold, and minimum value is italicized. Data from SPC tornado report database.

of the time period examined. The data in Tables 1 and 2 are incongruous with a robust weekly cycle whether one uses tornado reports prior to the 1995 implementation of the WSR-88D radar network or not.

3. Hypothesized Aerosol Influences Do Not Make Sense for Supercell Thunderstorms

[10] Most tornadoes are produced by supercell thunderstorms (Figure 4), including almost all EF2 and greater tornadoes [*Smith et al.*, 2012]. RB2011's hypothesized aerosol influences upon tornadoes rely upon an overly simplified view of supercell formation, structure, and storm-scale processes.

[11] Large vertical wind shear is fundamental to supercell formation because supercell updrafts derive their midlevel vertical vorticity via tilting of environmental horizontal vorticity, and because they derive their longevity from both the separation of precipitation from the parent updraft and from the dynamical enhancement of upward accelerations attributable to the presence of vertical wind shear (see the reviews by *Klemp* [1987], *Rotunno* [1993], and *Davies-Jones et al.* [2001]). These effects of vertical wind shear in turn contribute to the 3D character of supercells' precipitation, wind, and temperature fields, which are distinctly different from those of ordinary thunderstorms. Although RB2011 do not appear to consider the 3D complexity of supercells, they do acknowledge the importance of vertical wind shear (their paragraph 9), and for this reason, they discount "aerosol-induced invigoration of the updraft" as a valid effect in supercells, citing the modeling study of *Fan et al.* [2009]. Instead, RB2011 propose that "aerosol-induced changes in the precipitation particle size distribution reduce the evaporative cooling in the precipitation shaft" (their paragraph 9) and then connect this to previous observations that significantly tornadic supercells tend to have less negative buoyancy in their rear-flank outflows [*Markowski et al.*, 2002; *Grzych et al.*, 2007; *Hirth et al.*, 2008].

[12] The connection of aerosols to outflow temperature, as envisioned by RB2011, proceeds as follows. "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…" (their paragraph 5), which in turn would be expected to enhance riming aloft (their paragraphs 5 and 7). RB2011 explain that the net effects of this change would then increase the total latent heat release aloft (their paragraph 5), which could invigorate the updraft (although RB2011 discount the importance of this effect for supercells, as noted above). RB2011 also surmise that larger hailstones should result; presumably, they believe this is due to the enhanced amount of supercooled liquid water aloft, since RB2011 stipulate that the updraft invigoration effect is thought to be negligible for supercells. The end result envisioned by RB2011 is that the aerosol-enhanced clouds have fewer and larger raindrops (their paragraph 11), which would lessen the potential for evaporative cooling and thus yield weaker (warmer) outflow from the storm.

[13] We question whether RB2011's chain of aerosol influences is applicable to supercells on the basis that there is little time for droplet growth below the 0°C level within supercell updrafts as-is, and that the distribution of precipitation particles and formation pathways varies markedly from sector to sector within supercell storms, making the aerosol linkage to outflow temperature near the tornado indirect at best. Most rain in supercells is a result of melting and shedding [e.g., *Rasmussen and Heymsfield*, 1987], with or without an overabundance of aerosols, and the presence of rain is highly dependent on the variable trajectories that larger ice hydrometeors take in these storms [*Knight and Knight*, 2001]. Tornadogenesis simulations conducted by *Lerach et al.*

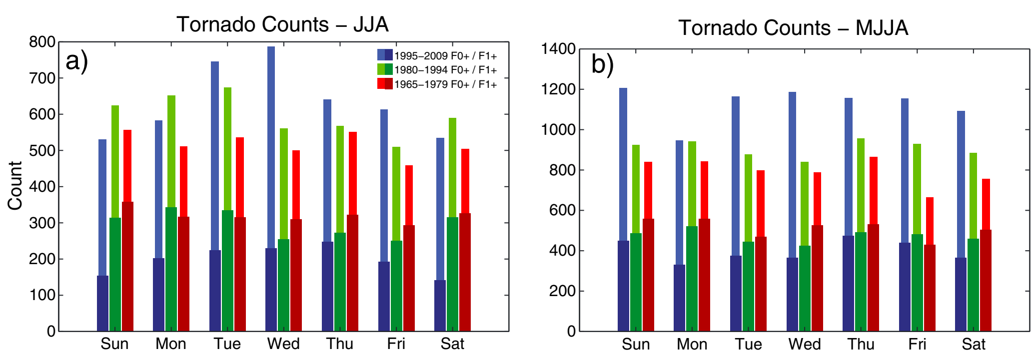

Figure 3. Bar plots of tornado counts by day of week, with and without magnitude F0 tornadoes, for different 14 year periods. Data from SPC tornado report database.

Table 2. Days With Tornadoes East of 100°W by Day of Week (No Smoothing Is Applied)[a]

Period and Intensity	Sun.	Mon.	Tue.	Wed.	Thu	Fri.	Sat.
			JJA				
1995–2009 F0+	129	132	**134**	129	132	128	*126*
1995–2009 F1+	70	66	*63*	**78**	68	70	*63*
1980–1994 F0+	**144**	141	143	140	136	*125*	126
1980–1994 F1+	**108**	101	97	*85*	94	88	93
1965–1979 F0+	144	138	**156**	146	142	147	*135*
1965–1979 F1+	112	116	**123**	**123**	*101*	116	*101*
			MJJA				
1995–2009 F0+	178	*170*	179	182	**186**	180	177
1995–2009 F1+	**111**	*90*	92	**111**	102	110	93
1980–1994 F0+	**194**	193	191	185	182	*173*	*173*
1980–1994 F1+	**141**	138	127	*119*	129	126	127
1965–1979 F0+	191	193	**204**	196	190	193	*183*
1965–1979 F1+	151	**165**	**165**	164	143	154	*142*

[a]For each row, maximum value is in bold, and minimum value is italicized. Data from SPC tornado report database.

[2008] and *Lerach and Cotton* [2012] suggest that while aerosols can have a small impact on tornadogenesis where everything else is equal, other factors, such as cold pool dynamics, have a much greater influence.

3.1. Supercell Updrafts Have Little Time for Droplet Growth

[14] A recurring radar signature of supercells, most prominent at midlevels, is a relative minimum in reflectivity colocated with the updraft, surrounded by an annulus of higher reflectivity. This so-called *bounded weak echo region* (BWER) is where updraft velocities are sufficiently strong to inhibit both precipitation formation and precipitation fallout (Figures 4b and 4c). Significantly, BWERs usually extend well above the 0°C level (note the location of the freezing level in Figure 4c). The fact that supercell updrafts usually have BWERs is an important point, because BWERs illustrate that droplets do not have much time to grow via collision-coalescence below the 0°C level in most supercell updrafts. The conditions needed to obtain large supercooled liquid water content and enhanced riming aloft are actually routinely present in supercells, without the need to invoke any aerosol influences.

3.2. The Microphysical Pathways and Resultant Outflows in Supercells are Complex

[15] We have already noted in section 3.1 that the aerosol impacts on warm rain that RB2011 describe should be muted within supercell updrafts. In addition, their argument

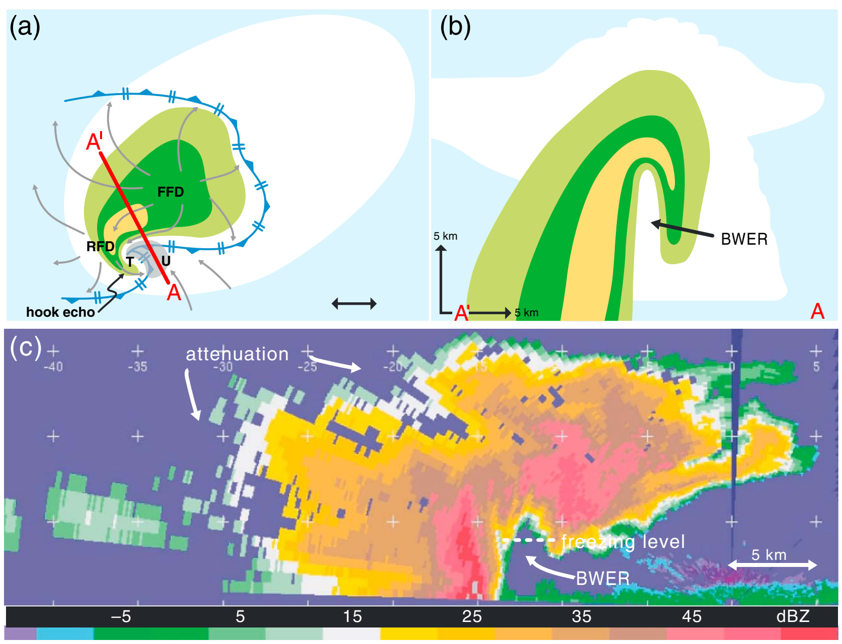

Figure 4. (a) Schematic representation of a supercell thunderstorm, adapted from the conceptual model presented by *Lemon and Doswell* [1979] and reviewed by *Markowski and Richardson* [2010]. The light green, dark green, and yellow shading indicates low, moderate, and high radar reflectivity. The locations of the forward-flank downdraft (FFD), rear-flank downdraft (RFD), hook echo, and main updraft region (U; gray shading) are indicated, as is the typical location of a tornado (T), if one occurs. The outflow boundary is indicated by the barbed contour. A few storm-relative streamlines also are drawn (gray arrows). The white region represents the extent of the anvil cloud. (b) Schematic vertical cross section from A' to A (refer to the red line in Figure 4a), showing the location of the BWER, which resides within the updraft. (c) Actual quasi-vertical cross section of radar reflectivity in a supercell thunderstorm obtained from a helically scanning radar mounted in the tail of an aircraft at 2306 UTC 16 May 1995 during the Verification of the Origin of Rotation in Tornadoes Experiment. The BWER is indicated, as is the freezing level within the updraft, which is at approximately 4.2 km AGL, per the sounding shown in Figure 1 of *Wakimoto et al.* [1998], who analyzed the same storm.

regarding hailstone size employs an overly simplified understanding of bulk hail population, as they ignore the wide variety of hailstone trajectories in supercells, the diversity of which is primarily due to differential size sorting [*Knight and Knight*, 2001]. Model simulations of hailstorms have suggested that the impacts on hail from aerosols are complex and hard to predict. Simulations by *Khain et al*. [2011] demonstrated an increase in hail mass and hail diameter when cloud condensation nuclei (CCN) concentration changed from 100 to 3000 cm^{-3}. Simulations by *Noppel et al*. [2010] covaried both CCN concentration (from 100 to 2100 cm^{-3}) and cloud droplet size distributions. They found differing relationships among increasing CCN concentration, hail mass, and the number concentration of large hail stones depending on the shape of the cloud drop size distribution (their Tables 3 and 4). They concluded that "the complexity of a hailstorm – the manifold microphysical processes that interact with each other as well as the dynamics of the storm – make it difficult, if not impossible, to predict what will happen if one microphysical parameter like CCN is changed."

[16] RB2011 hypothesizes that the increase in supercooled water due to aerosol-laden updrafts leads to the growth of larger hail. Only hailstones that follow favorable trajectories through sufficient supercooled liquid water will become large, and then only if the hail particle has a high collection efficiency for the supercooled droplets. The first aerosol indirect effect is that increased aerosol concentrations lead to increased cloud droplet numbers and result in smaller cloud droplets for a given vapor mass flux through a cloud [*Twomey*, 1974]. Theory and experimental data for hailstone embryo growth [*Cober and List*, 1993] and hailstone growth [*Greenan and List*, 1995] show that smaller cloud droplets result in significantly smaller collection efficiencies, making it *more difficult* for hailstones to grow. These collection efficiencies approach zero for cloud droplets that are too small (Stokes parameter <1, see Cober and List's Figure 10 and Greenan and List's Figure 14, which show collection efficiencies for hail embryos and hailstones, respectively). The end result is that smaller (not larger) hailstones could result from increased aerosol number concentrations, which would short-circuit RB2011's mechanism.

[17] In addition, we are skeptical that RB2011's purported aerosol influence on precipitation and the resulting outflow temperature, even if it were sound, could be uniformly applied across the 3D structure of a supercell thunderstorm. The classic *Lemon and Doswell* [1979] conceptual model of a supercell (Figure 4a) simplifies a more complex structure. The forward-flank outflow may often be quite weak [e.g., *Shabbott and Markowski*, 2006; *Frame et al*., 2009], and the rear-flank outflow is apparently quite variable in both temperature and winds [e.g., *Beck et al*., 2006; *Grzych et al*., 2007; *Marquis et al*., 2008, 2012; *Lee et al*., 2012]. In addition, regardless of the aerosol concentration of the environment, the precipitation in a supercell already contains different populations of drops and ice particles in different parts of the storm [e.g., *Romine et al*., 2008; *Kumjian and Ryzhkov*, 2008, 2012; *Van Den Broeke et al*., 2008; *Kumjian*, 2011]: dual-polarization radar data suggest that at low altitudes, the forward flank largely comprises sparse large drops, the main downdraft largely comprises hail and meltwater shed from hail, and the hook echo is complicated with different mean drop sizes in different parts of the hook area *Frame et al*. [2009].

[18] Tornadogenesis (or tornadogenesis failure) appears to be closely related to outflow temperatures in the vicinity of the hook echo and within the near-surface mesocyclone [e.g., *Markowski et al*., 2002, 2003]. The precipitation size distribution in that part of the storm is temporally unsteady and results from a number of competing processes including horizontal advection by the storm's 3D wind field (as reviewed by *Markowski* [2002]), size sorting [e.g., *Kumjian and Ryzhkov*, 2008, 2012; *Van Den Broeke et al*., 2008; *Kumjian*, 2011], and small-scale episodic descent of pockets of precipitation particles from aloft (i.e., "descending reflectivity cores") [*Rasmussen et al*., 2006; *Byko et al*., 2009]. Indeed, *Kumjian* [2011] called the drop size distributions in hook echoes "exotic and atypical of rainfall from other precipitating systems." RB2011's one-size-fits-all approach attempts to relate aerosol content to a storm's mean precipitation diameter, a quantity that likely has little relevance for outflow temperatures in supercells' rear flanks.

4. Regional Variations in Tornado Reports and Aerosol Weekly Cycles Are Ignored

[19] RB2011 find a Tuesday peak in the concentration of PM_{10} and a Wednesday peak in $PM_{2.5}$ using Environmental Protection Agency monitoring site data. They neglect regional variations in the aerosol cycle by averaging data over all the monitoring sites east of 100°W during JJA of 1998–2005 (RB2011, caption for their Figure 4), when in fact the aerosol cycle is much weaker where tornadoes are most frequent.

[20] Previous work indicates that weekly variations in aerosol concentrations across the US are different region to region. The largest magnitude variations between work week highs and weekend lows in the US are associated with urban areas [e.g., *Motallebi et al*., 2003; *DeGaetano and Doherty*, 2004; *Shutters and Balling*, 2006]. *Xia et al*. [2008] used 1° × 1° satellite observations of aerosol optical depth (MODIS 550 nm AOD) to examine the weekly cycle of AOD worldwide. AOD can be a reasonable proxy for CCN [*Andreae*, 2009]. For the US region east of 100°W, they found the "work week" (Tues. – Fri.) AOD peaks (often $>20\%$ departure from the weekly average) primarily east of the Appalachian Mountains. Weekly cycles in AOD with large amplitudes up to 30% deviation from weekly average were found along the Washington D.C. to Boston corridor and in the Carolinas [*Xia et al*., 2008, Figure 7]. In contrast, the amplitudes of the weekly cycles of AOD west of the Appalachian Mountains, where most of the JJA tornadoes east of 100°W occur (Figure 3b), are typically $\leq 10\%$ deviation from weekly average with many observation locations failing to meet a 90% significance threshold. Furthermore, some locations in Wisconsin, Iowa, and Minnesota had a low-amplitude "weekend" (Sat.–Mon.) peak in AOD observations (typically $\leq 10\%$ deviation from weekly average), opposite that described in RB2011. *Bell et al*. [2008, Figure 2] showed only cycles in PM2.5 with an amplitude of $\leq 10\%$ deviation from weekly average for the US region from 90° W to 100° W spanning Minnesota south to the Gulf Coast. By averaging aerosol station data from 100°W eastward, RB2011 have conflated phenomena in different geographic regions: an aerosol cycle that is stronger in the eastern US and tornadoes that occur more frequently in the central US.

5. Discussion

[21] RB2011's hypothesis that there is causation between a weekly cycle of aerosols and a weekly cycle in tornadoes for the region east of 100°W does not withstand close scrutiny. The SPC tornado report data show that there is no robust weekly cycle in tornado occurrence or in tornado days whether one considers JJA or MJJA. Based on their own analysis, there is no significant weekly cycle in tornadoes east of 100°W during April and May, yet 85% of the April storms and 94% of the May storms have dew points fitting the $>\approx 15\,^{\circ}$C criteria for warm-based clouds supposedly susceptible to aerosol effects. Last, the weekly cycles of aerosols are usually weak to insignificant in the regions east of 100°W with a high frequency of tornadoes [*Bell et al.*, 2008; *Xia et al.*, 2008].

[22] It is probably not surprising that the purported signals are not robust, because the dynamical and microphysical structures of supercells are inconsistent with RB2011's hypothesized physical basis. Supercell updrafts already have limited growth of drops below the 0°C level (muting any of the purported aerosol influences), and supercell precipitation cascades are heterogeneous. Perhaps, this explains why meteorological parameters such as boundary layer relative humidity and lifting condensation level height have proven to be skillful at discriminating tornadic supercells from nontornadic supercells [*Rasmussen and Blanchard*, 1998; *Markowski et al*., 2002; *Thompson et al*., 2003; *Craven and Brooks*, 2004] without taking into account the aerosol content or the size distribution of hydrometeors. Such humidity variables have a significant correlation with outflow temperature in supercells [*Markowski et al*., 2002; *Shabbott and Markowski*, 2006], as well as a much more direct physical linkage through decreased evaporation in environments with increased relative humidity.

[23] Empirical evidence for a cause and effect relationship between higher aerosol concentrations and an increased incidence of tornadoes has yet to be shown. Modeling studies that examine the sensitivity of storms to *only* perturbations in CCN concentration cannot address the *relative* role of CCN compared to other plausible sources of storm variability. For example, plausible causal factors for weekly, annual, and decadal trends in summer severe storm frequency over the US include: air temperature and humidity variations associated with large-scale weather systems and persistent sea surface temperature anomalies in the Gulf of Mexico, aerosol direct effects, land surface changes, and changes in large-scale circulations associated with interannual and interseasonal oscillations, to name a few. Until such causal factors can be simultaneously examined in sensitivity studies with techniques like factor separation [*Stein and Alpert*, 1993], the attribution of any purported effect to one particular cause is premature.

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