Tornadoes in the Central United States and the "Clash of Air Masses"

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An Article for the *Bulletin of the American Meteorological Society*
Submitted 26 November 2013
Revised 20 January 2014
Revised 9 March 2014

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ABSTRACT

After tornado outbreaks or individual violent tornadoes occur in the central United States, media stories often attribute the location, number, or intensity of tornadoes to the "clash of air masses" between warm tropical air and cold polar air. This article argues that such a characterization of tornadogenesis is oversimplified, outdated, and incorrect. Airmass boundaries and associated temperature gradients can be important in tornadogenesis, but not in the ways envisioned on the synoptic scale with the clash-of-air-masses conceptual model. In fact, excessively strong horizontal temperature gradients (either on the synoptic scale or associated with a storm's own cool outflow) may be *detrimental* to tornadogenesis. Where adjacent air masses *are* relevant is through their vertical distribution that produces the requisite instability for the convective storm, but that instability is not directly related to the formation of tornadoes. Therefore, this article recommends that a greater effort be made to communicate accurately to the public the current scientific understanding of the conditions under which tornadoes are formed.

CAPSULE

Media reports that clashing air masses produce tornadoes mischaracterize the abundant new observational and modeling research on how tornadoes form.

The central United States is home to the most frequent violent tornadoes on Earth (Fig. 1). When major outbreaks of such tornadoes occur, the media often explains their occurrence as the result of the "clash of air masses." Consider the following example:

> Oklahoma provides a fertile breeding ground for tornadoes because of the clash between the warm, moist air from the Gulf and cold air from the Rockies and Canada: One of the main keys to tornado formation … is "a large temperature spread over a short distance." "Water holds its heat more than land or air.... So Oklahoma's proximity to the Gulf of Mexico means there is a source of very warm, moist air. As cold air comes from Canada, you can get temperatures of 80 degrees [F] in the body of the state while it is in the 20s in the Panhandle." [The interviewee says this provides] the power to fuel severe thunderstorms.
>
> http://www.usatoday.com/story/news/nation/2013/06/08/oklahoma-tornadoes-ef5-moore/2401885/

Other examples of media reporting that the clash of the air masses is responsible for tornadoes may be found at http://www.independent.co.uk/news/tornado-disaster-clash-of-air-masses-in-tornado-alley-1091490.html, http://www.myfoxaustin.com/story/21871999/weather-facts-tornado-rotation, in the November 2013 issue of *National Geographic* (http://ngm.nationalgeographic.com/2013/11/biggest-storm/tornado-formation), and in Fig. 2. There is no intention to single out any particular person or media source with this list, but rather to exemplify the type of storyline that appears in the media. Therefore, the consistent message in the media is that tornadoes form along the boundaries between air masses, such as cold fronts or drylines, with tornado formation being directly linked to the intensity of the "clashing" between adjacent air masses. Such clashing could perhaps be thought to provide the lift in the three ingredients of deep, moist convection: lift, instability, and moisture (Johns and Doswell 1992).

The reality is that air masses "clash" all the time, but frontal zones only produce tornadoes on relatively few occasions. Further, as we will discuss, many tornadoes occur outside of regions where air masses are "clashing." Therefore, using this canard as an explanation for the occurrence of tornadoes is at best a gross oversimplification.

Why and when the specific phrase "clash of the air masses" was introduced to explain tornadoes in the central United States is not clear. One possible origin may be this 1942 quote from Sylvester E. Decker, the climatologist for the Weather Bureau Office in Des Moines, Iowa, describing tornadoes in Iowa over the past 15 months (House 1963, p. 141):

> Usually more than two air masses are present. There is first of all the original cold air mass to the north of the front, a warm [air] mass to the south of the front with a stable air mass that is drier and warmer aloft over the warm air mass.

Reference in the above quote is made to a front. The concept of fronts as airmass boundaries originates from the Norwegian cyclone model (Bjerknes 1919; Bjerknes and Solberg 1921, 1922), which describes the formation of low-pressure systems along the polar front, a region where cold polar air is adjacent to warm tropical air. That World War I had recently ended at the time of the introduction of this frontal terminology (think *All Quiet on the Western Front*) is no coincidence (Friedman 1989, pp. 187–188).

In the relatively flat central United States, continental polar, continental tropical, and maritime tropical air masses meet easily, a factor in creating the baroclinic environments that favor extratropical cyclones. The extratropical cyclones that bring together the ingredients for severe convective storms (moisture from the Gulf of Mexico, steep lapse rates coming off the high and dry terrain of the Rocky Mountains, and vertical wind shear) are closely tied to the pole-to-equator thermal gradients, but the mere presence of those gradients on the synoptic scale is no guarantee that these ingredients will be brought together to produce tornadoes in any specific extratropical cyclone.

Horizontal temperature gradients also exist on the storm scale. Temperature gradients associated with downdrafts and outflow are likely important in tornadogenesis in supercells (the most violent tornadoes are almost always associated with rotating convective storms called supercells, Fig. 3), but, as we will discuss, "airmass clashing" is not the best way to describe the role of such storm-scale temperature gradients in tornadogenesis. In fact, excessively strong storm-scale temperature gradients are associated with *nontornadic* supercells (e.g., Markowski and Richardson 2009).

MOVING BEYOND THE "CLASH OF THE AIR MASSES" ON THE SYNOPTIC SCALE. If the clash of the air masses has any validity as an explanation for tornadoes, there are two ways that synoptic-scale horizontal temperature contrasts can be thought to have some relevance in tornado development. One is through their link to vertical wind shear (essential to supercell storms), and the other through their link, at times, to storm initiation.

With regard to vertical shear, the vertical derivative of the geostrophic wind is directly related to the horizontal temperature gradient, which is why it is called the *thermal wind shear*. Thus, for example, a north–south temperature contrast implies an increasing westerly wind component with height. Another part of the wind shear is that associated with the *ageostrophic wind*, which is *not* directly related to the horizontal temperature gradient. Moreover, whatever the source of the shear, it must be located where there is buoyant instability to feed a storm. Tornadic storms are not necessarily collocated with the maximum vertical shear; rather, they are located where there is sufficient shear and that shear overlaps with buoyant instability. So, although there is a loose connection between temperature gradients and vertical wind shear, the connection is even looser between temperature gradients and tornadic storms. Indeed, Diffenbaugh et al. (2013) showed that under expected climate change, while vertical shear at midlatitudes decreases in general as a result of weakening meridional thermal gradients, the number of days with conditions favorable for severe weather increases, owing to the greater overlap of regions of favorable shear and instability.

With regard to the initiation of storms, *all convective storms* are initiated when air parcels with convective available potential energy (CAPE) reach their level of free convection

(LFC), with one of the most common mechanisms for storm initiation being ascent associated with airmass boundaries (e.g., fronts, drylines) or other subsynoptic-scale boundaries (e.g., outflow boundaries, sea-breeze fronts). Thus, the frequent proximity of low-level temperature gradients to developing convective storms is not unique to supercells. Only a small percentage of convective storms initiated along airmass boundaries become tornadic.

In addition, the strength of the temperature gradient along a synoptic-scale airmass boundary has no precise relationship to the potential for storms initiated along the boundary to spawn tornadoes (often supercells have moved a significant distance *away from* a synoptic-scale initiating boundary by the time they reach maturity and pose a tornado threat).[1] If anything, there is some indication that *squall lines*, not supercells, are more likely when the temperature gradient associated with an airmass boundary is intense (e.g., Roebber et al. 2002; Arnott et al. 2006; Stonitsch and Markowski 2007; Dial et al. 2010; Duda and Gallus 2010; Schumann and Roebber 2010). In other words, strong horizontal temperature gradients may actually pose a *decreased* risk of significant tornadoes (EF2 or greater tornadoes; Hales 1988), given that squall lines are less likely to produce significant tornadoes than are discrete supercells (Trapp et al. 2005a; Thompson et al 2012; Smith et al. 2012).

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[1] In contrast, nonsupercell tornadoes are favored in storms that have a slow forward motion relative to the initiating airmass boundary. Nonsupercell tornadoes (e.g., Wakimoto and Wilson 1989) also seem to require that the initiating boundary be associated with misocyclones at the surface (i.e., cyclonic vorticity at the surface that precedes the tornadoes) (e.g., Lee and Wilhelmson 1997).

One instance in which an airmass boundary can influence tornadogenesis may be the interaction of an ongoing supercell with a pre-existing airmass boundary. Some supercell storms move along or across airmass boundaries such as warm fronts, stationary fronts, or outflow boundaries produced by other storms, where the likelihood of tornado formation may be locally increased owing to enhanced wind shear and moisture near the boundary (e.g., Maddox et al. 1980; Markowski et al. 1998; Rasmussen et al. 2000; Wurman et al. 2007). So, in some cases, the temperature gradient along a front may be a component of a favorable environment for tornadic supercells, although certainly not in all cases. Supercells produce tornadoes in the absence of such storm–boundary interactions, and many storm–boundary interactions result in *weakening* of the supercell and decreased tornado potential (Markowski et al. 1998; Doswell et al. 2002). These interactions are not well understood and, moreover, are not essential for tornado formation. If anything, storm-boundary interactions seem *least likely* to trigger tornadogenesis when the boundary is accompanied by a large temperature gradient, which usually implies a rapid increase in the convective inhibition (as well as decreasing surface-based CAPE) encountered by a storm moving across the boundary (Doswell et al., 2002).

Not only is the strength of the temperature gradient associated with clashing air masses of questionable relevance to tornadic supercell initiation, many tornadic supercells are not even initiated along fronts. Three examples follow. First, tornadic storms commonly form along or near a dryline, a zone of strong moisture contrast but only a modest temperature gradient, depending on the time of day (e.g., Rhea 1966; Schaefer 1974;

Ziegler and Rasmussen 1998). Second, tornadic supercells commonly develop as a result of moist, unstable air flowing gently upslope (i.e., toward the west) on the High Plains, especially in regions where such orographic lifting is enhanced (e.g., Palmer Divide of eastern Colorado, Cheyenne Ridge of southeastern Wyoming). Such upslope severe weather regimes typically are found on the cool side of (not along) a synoptic-scale front or outflow boundary produced by an antecedent mesoscale convective system (e.g., Doswell 1980). Third, supercells may even form along rainbands in hurricanes (e.g., McCaul 1987; Baker et al. 2009; Molinari and Vollaro 2010; Green et al. 2011; Edwards et al. 2012). Thus, there are diverse situations in which strong tornadoes could form with no strong temperature gradient present.

If there is any clashing of air masses associated with supercell tornadoes, perhaps it is in the *vertical*, rather than the horizontal. But, media explanations typically do not refer to this vertical distribution of air masses. Specifically, deep moist convective storms, including supercells, form as a result of the release of buoyant instability, and this instability in the central United States frequently comes from the vertical collocation of maritime tropical air *underneath* continental tropical air at midlevels from the southwest, the so-called elevated mixed layer (e.g., Carlson et al. 1983). Critically, this vertical distribution of air masses must also be associated with deep-layer shear over several kilometers in depth to allow storm-scale rotation to occur within supercells. As described above, although a part of this wind shear is associated with horizontal temperature gradients due to thermal wind balance, the area of greatest "clashing between two air masses" is not necessarily the area of greatest tornado development. Moreover, this vertical distribution of air masses occurs much more frequently in this region than the occurrence of tornadoes, so the concept has limited predictive ability for tornadogenesis (as discussed in the next section).

To summarize, the clash of air masses on the synoptic scale may be associated with strong horizontal temperature gradients, but these situations tend not to be particularly favorable for supercells and tornadoes. Instead, the clash of the air masses most relevant for supercells may be in the vertical as warm moist air from the Gulf of Mexico underlies the steep lapse rates within the elevated mixed layer, producing buoyant instability and vertical wind shear, environmental conditions favorable for supercellular convection, but not specifically tornadogenesis.

MOVING BEYOND “CLASH OF THE AIR MASSES” ON THE STORM SCALE.

Existing understanding of tornadogenesis on the scale of a convective storm is far from complete. Only around 25% of supercells with radar-detected mesocyclones (rotation of a broader scale than a tornado) become tornadic (Trapp et al. 2005b), so the key issue is what conditions permit tornado formation in only a minority of supercells.

Observations with airborne and mobile radars have suggested that strong rotation, down as low as several hundred meters above the ground, can be present in a supercell without the potentially damaging rotation of a tornado ever developing at the surface (e.g., Trapp 1999; Markowski et al. 2011). Unlike the rotation at midlevels, rotation at the surface cannot develop with only an updraft and environmental shear (horizontal vorticity) because parcels will be moving away from the ground as the vorticity is tilted into the vertical (e.g., Davies-Jones and Brooks 1993). Thus, the downdrafts in a supercell are essential to tornadogenesis.

Leading hypotheses for tornadogenesis suggest that vertical vorticity develops as air descends within a storm-scale temperature gradient within the outflow (e.g., Davies-Jones et al. 2001; Markowski and Richardson 2009; Wurman et al. 2013). If the near-surface circulation produced in this manner within the outflow moves into a region of strong ascent, the circulation can be accelerated upward and contracted to tornadic strength via conservation of angular momentum. Although the degree of storm-scale baroclinity available to produce the tornadic circulation increases as the outflow temperature decreases, the low-level temperature decrease makes it difficult to carry out the final contraction because the low-level vertical accelerations required to contract the circulation are inhibited by negatively buoyant air. Therefore, there is a “sweet spot” in the temperature contrast that allows the development of significant circulation while still allowing the final contraction to take place. This situation is in contrast to the hypothesis that tornado likelihood increases with the intensity of the temperature contrast. In addition, there is some indication that colder outflow in nontornadic supercells may be shunted away from the location of maximum updraft, such that the final contraction does not occur (Snook and Xue 2008; Markowski and Richardson 2014).

Two empirical factors seem to be helpful in discriminating between tornadic and nontornadic supercells: the lifting condensation level (LCL) and the vertical wind shear in the lowest kilometer (e.g., Rasmussen and Blanchard 1998; Brooks et al. 2003; Thompson et al. 2003; Grams et al. 2012; Thompson et al. 2012). A low LCL is related to high low-level relative humidity and, presumably, warmer downdrafts (Markowski et al. 2002; Shabbott and Markowski 2006). Strong low-level shear enhances and lowers the base of the midlevel mesocyclone (formed through tilting of environmental horizontal vorticity as described above), which is then associated with greater ability to lift (and contract) the outflow air due to vertical pressure gradients associated with changes in rotation with height (Markowski and Richardson 2014). Therefore, the two empirical factors favored for tornado environments refute the concept that a colder downdraft (i.e., "greater clashing") is better on the storm scale. Thus, there appears to be little support for clashing air masses on the storm scale being responsible for tornadogenesis.

CONCLUSION. Based on our arguments above, we conclude that the notion of tornadogenesis being directly related to the "clash of air masses" has limited utility as an explanation on both the synoptic scale and storm scale. Therefore, repeating this myth in the media does the public a disservice and does not reflect the science of severe storms as it has developed in recent decades. If there is any value in retaining the airmass concept, it is in the vertical collocation of air masses that produce the instability requisite for intense convective storms, but this explanation does not pertain to tornadoes specifically, just to the environment of convective storms in the central United States.

Therefore, we recommend that the weather enterprise work with the media to adopt a new explanation for tornadic storms. Instead of "Yesterday's storms were the result of a clashing of air masses," we believe that an explanation along these lines would be more appropriate for a lay audience in the vast majority of cases [with parenthetical information included if applicable to the specific case].

> "Yesterday's storms occurred when warm humid air near the surface lay under drier air aloft with temperature decreasing rapidly with height [originating from higher terrain to the west or southwest], providing energy for the storms through the production of instability. Large changes in wind with height ("wind shear") over both shallow (lowest 1 km) and deep (lowest 6 km) layers—combined with the instability and high humidity near the surface—created a situation favorable for tornadoes to form."

This explanation, albeit longer than the clashing explanation, is pithy and accurate, describing both the ingredients that make the synoptic environment favorable for convective storms and the known factors that favor tornado formation.

Given the large investment in tornado research by the National Science Foundation (e.g., over $10 million on VORTEX2 alone; Wurman et al. 2013) and the rapid progress in understanding of tornadoes that has resulted, we hope that future information provided to the public can better reflect that growth in scientific understanding.

Acknowledgments. We thank Editor Jeff Waldstreicher, Greg Forbes, and three anonymous reviewers for their comments that have improved this manuscript. Partial funding for Schultz was provided by the U.K. Natural Environment Research Council to the University of Manchester for the Diabatic Influences on Mesoscale Structures in

Extratropical Storms (DIAMET) project (grant NE/I005234/1) and the Tropopause Folding, Stratospheric Intrusions and Deep Convection (TROSIAD) project (grant NE/H008225/1). Funding for Richardson and Markowski was provided by the U.S. National Science Foundation (AGS-1157646).

REFERENCES

Arnott, N. R., Y. P. Richardson, E. M. Rasmussen, and J. M. Wurman, 2006: Relationship between a weakening cold front, misocyclones, and cloud development on 10 June 2002 during IHOP. *Mon. Wea. Rev.,* **134**, 311–335.

Baker, A. K., M. D. Parker, and M. D. Eastin, 2009: Environmental ingredients for supercells and tornadoes within Hurricane Ivan. *Wea. Forecasting*, **24**, 223–244.

Bjerknes, J., 1919: On the structure of moving cyclones. *Geofys. Publ.,* **1** (2), 1–8.

_____, and H. Solberg, 1921: Meteorological conditions for the formation of rain. *Geofys. Publ.,* **2** (3), 3–61.

_____, and H. Solberg, 1922: Life cycle of cyclones and the polar front theory of atmospheric circulation. *Geofys. Publ.,* **3** (1), 3–18.

Brooks, H., J. W. Lee, and J. P. Craven, 2003: The spatial distribution of severe thunderstorm and tornado environments from global reanalysis data. *Atmos. Res.*, **67–68**, 73–94.

Carlson, T. N., S. G. Benjamin, G. S. Forbes, and Y-F. Li, 1983: Elevated mixed layers in the regional severe storm environment: Conceptual model and case studies. *Mon. Wea. Rev.*, **111**, 1453–1474.

Davies-Jones, R., and H. Brooks, 1993: Mesocyclogenesis from a theoretical perspective. *The Tornado: Its Structure, Dynamics, Prediction, and Hazards.* Geophys. Monogr., No. 79, Amer. Geophys. Union, 105–114.

_____, R. J. Trapp, and H. B. Bluestein, 2001: Tornadoes and tornadic storms. *Severe Convective Storms*, *Meteor. Monogr.*,No. 28, Amer. Meteor. Soc., 126–221.

Dial, G. L., J. P. Racy, and R. L. Thompson, 2010: Short-term convective mode evolution along synoptic boundaries. *Wea. Forecasting,* **25,** 1430–1446.

Diffenbaugh, N. S., M. Scherer, and R. J. Trapp, 2013: Robust increases in severe thunderstorm environments in response to greenhouse forcing. *Proceedings of the National Academy of Sciences.* **110,** 16361–16366.

Doswell, C.A. III, 1980: Synoptic-scale environments associated with High Plains severe thunderstorms. *Bull. Amer. Meteor. Soc.*, **61**, 1388–1400.

_____, D. V. Baker, and C. A. Liles, 2002: Recognition of negative mesoscale factors for severe-weather potential: A case study. *Wea. Forecasting*, **17**, 937–954.

_____, G. W. Carbin, and H. E. Brooks, 2012: The tornadoes of spring 2011 in the USA: An historical perspective. *Weather*, **67**, 88–94.

Duda, J. D., and W. A. Gallus Jr., 2010: Spring and summer Midwestern severe weather reports in supercells compared to other morphologies. *Wea. Forecasting,* **25,** 190–206.

Edwards, R., A. R. Dean, R. L. Thompson, and B. T. Smith, 2012: Convective modes for significant severe thunderstorms in the contiguous United States. Part III: Tropical cyclone tornadoes. *Wea. Forecasting,* **27**, 1507–1519.

Friedman, R. M., 1989: *Appropriating the Weather: Vilhelm Bjerknes and the Construction* *of a Modern Meteorology.* Cornell Univ. Press, 251 pp.

Grams, J. S., R. L. Thompson, D. V. Snively, J. A. Prentice, G. M. Hodges, and L. J. Reames, 2012: A climatology and comparison of parameters for significant tornado events in the United States. *Wea. Forecasting,* **27**, 106–123.

Green, B. W., F. Zhang, and P. Markowski, 2011: Multiscale processes leading to supercells in the landfalling outer rainbands of Hurricane Katrina (2005). *Wea. Forecasting*, **26**, 828–847.

Hales, J. E., Jr., 1988: Improving the watch/warning program through use of significant event data. Preprints, 15th Conf. on Severe Local Storms, Baltimore, MD, Amer. Meteor. Soc., 165–168.

House, D. C., 1963: Forecasting tornadoes and severe thunderstorms. *Severe Local Storms, Meteor. Monogr. 27,* Amer. Meteor. Soc., 141–155.

Johns, R. H., and C. A. Doswell III, 1992: Severe local storms forecasting. *Wea. Forecasting,* **7,** 588–612.

Lee, B. D., and R. B. Wilhelmson, 1997: The numerical simulation of non-supercell tornadogenesis. Part I: Initiation and evolution of pretornadic misocyclone circulations along a dry outflow boundary. *J. Atmos. Sci.*, **54**, 32–60.

Maddox, R. A., L. R. Hoxit, and C. F. Chappell, 1980: A study of tornadic thunderstorm interactions with thermal boundaries. *Mon. Wea. Rev.*, **108**, 322–336.

Markowski, P. M., and Y. P. Richardson, 2009: Tornadogenesis: Our current understanding, forecasting considerations, and questions to guide future research. *Atmos. Res.*, **93**, 3–10.

_____, and _____, 2013: How to make a tornado. *Weatherwise*, **66** (4), 12–19.

_____, and _____, 2014: The influence of environmental low-level shear and cold pools on tornadogenesis: Insights from idealized simulations. *J. Atmos. Sci.*, **70**, 243–275.

_____, E. N. Rasmussen, and J. M. Straka, 1998: The occurrence of tornadoes in supercells interacting with boundaries during VORTEX-95. *Wea. Forecasting*, **13**, 852–859.

_____, J. M. Straka, and E. N. Rasmussen, 2002: Direct surface thermodynamic observations within the rear-flank downdrafts of nontornadic and tornadic supercells. *Mon. Wea. Rev.*, **130**, 1692–1721.

_____, M. Majcen, Y. Richardson, J. Marquis, and J. Wurman, 2011: Characteristics of the wind field in three nontornadic low-level mesocyclones observed by the Doppler on Wheels radars. *Electronic J. Severe Storms Meteor.*, **6**, 1–48.

McCaul, E. W., 1987: Observations of the Hurricane "Danny" tornado outbreak of 16 August 1985. *Mon. Wea. Rev.*, **115**, 1206–1223.

Molinari, J., and D. Vollaro, 2010: Distribution of helicity, CAPE, and shear in tropical cyclones. *J. Atmos. Sci.*, **67**, 274–284.

Rasmussen, E. N., and D. O. Blanchard, 1998: A baseline climatology of sounding-derived supercell and tornado forecast parameters. *Wea. Forecasting*, **13**, 1148–1164.

_____, S. J. Richardson, J. M. Straka, P. M. Markowski, and D. O. Blanchard, 2000: The association of significant tornadoes with a baroclinic boundary on 2 June 1995. *Mon. Wea. Rev.*, **128**, 174–191.

Rhea, J. O, 1966: A study of thunderstorm formation along dry lines. *J. Appl. Meteor.*, **5**, 58–63.

Roebber, P. J., D. M. Schultz, and R. Romero, 2002: Synoptic regulation of the 3 May 1999 tornado outbreak. *Wea. Forecasting,* **17,** 399–429.

Schaefer, J. T., 1974: The life cycle of the dryline. *J. Appl. Meteor.*, **13**, 444–449.

Schumann, M. R., and P. J. Roebber, 2010: The influence of upper-trospospheric potential vorticity on convective morphology. *Mon. Wea. Rev.,* **138,** 463–474.

Shabbott, C. J., and P. M. Markowski, 2006: Surface in situ observations within the outflow of forward-flank downdrafts of supercell thunderstorms. *Mon. Wea. Rev.*, **134**, 1422–1441.

Smith, B. T., R. L. Thompson, J. S. Grams, C. Broyles, and H. E. Brooks, 2012: Convective modes for significant severe thunderstorms in the contiguous United States. Part I: Storm classification and climatology. *Wea. Forecasting*, **27**, 1114–1135.

Snook, N., and M. Xue, 2008: Effects of microphysical drop size distribution on tornadogenesis in supercell thunderstorms. *Geophy. Res. Letters*, **35**, L24803, doi:10.1029/2008GL035866.

Stonitsch, J. and P. Markowski, 2007: Unusually long duration, multiple-Doppler radar observations of a front in a convective boundary layer. *Mon. Wea. Rev.,* **135,** 93–117.

Thompson, R. L., R. Edwards, J. A. Hart, K. L. Elmore, and P. M. Markowski, 2003: Close proximity soundings within supercell environments obtained from the Rapid Update Cycle. *Wea. Forecasting*, **18**, 1243–1261.

_____, B. Smith, J. S. Grams, A. R. Dean, and C. Broyles, 2012: Convective modes for significant severe thunderstorms in the contiguous United States. Part II: Supercell and QLCS tornado environments, *Wea. Forecasting*, **27**, 1136–1154.

Trapp, R. J., 1999: Observations of nontornadic low-level mesocyclones and attendant tornadogenesis failure during VORTEX. *Mon. Wea. Rev.*, **127**, 1693–1705.

_____, S. A. Tessendorf, E. S. Godfrey, and H. E. Brooks, 2005a: Tornadoes from squall lines and bow echoes: Part I: Climatological distribution. *Wea. Forecasting*, **20**, 23–34.

_____, G. J. Stumpf, and K. L. Manross, 2005b: A reassessment of the percentage of tornadic mesocyclones. *Wea. Forecasting*, **20**, 680–687.

Wakimoto, R. M., and J. W. Wilson, 1989: Non-supercell tornadoes. *Mon. Wea. Rev.,* **117,** 1113–1139.

Wurman, J. W., Y. Richardson, C. Alexander, S. Weygandt, and P. F. Zhang, 2007: Dual-Doppler and single-Doppler analysis of a tornadic storm undergoing mergers and repeated tornadogenesis. *Mon. Wea. Rev.*, **135**, 736–758.

_____, D. Dowell, Y. Richardson, P. Markowski, E. Rasmussen, D. Burgess, L. Wicker, and H. B. Bluestein, 2013: The Second Verification of the Origins of Rotation in Tornadoes Experiment: VORTEX2. *Bull. Amer. Meteor. Soc.*, **93**, 1147–1170.

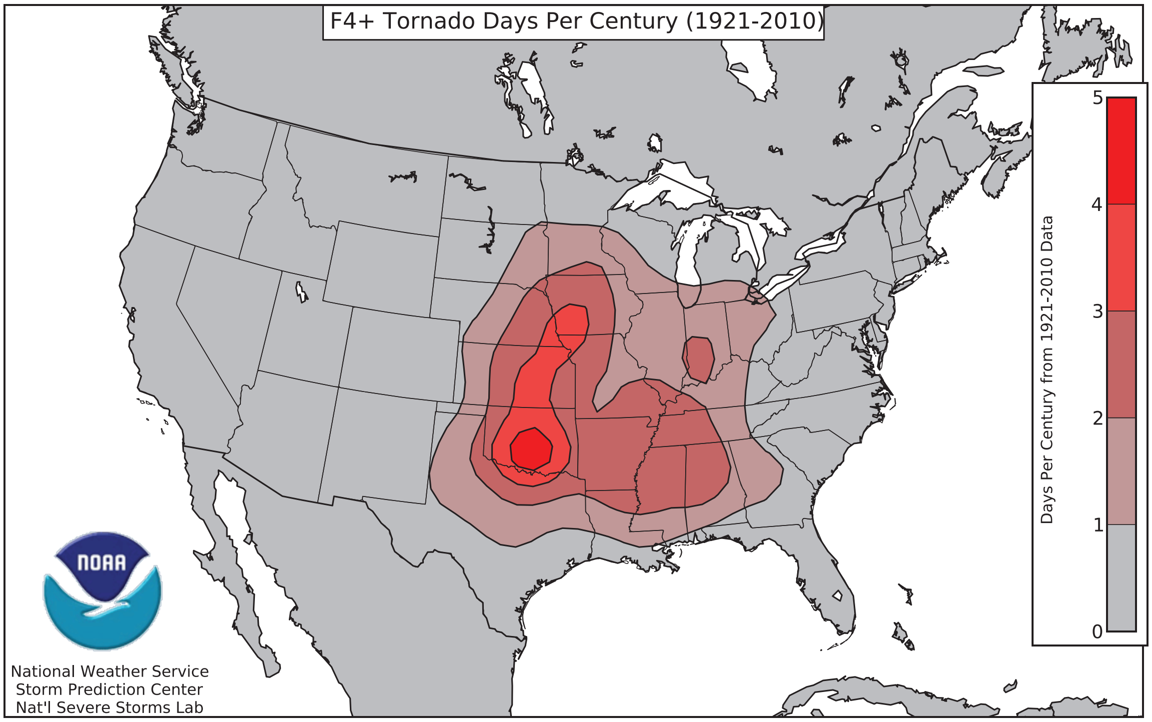
Ziegler, C. L., and E. N. Rasmussen, 1998: The initiation of moist convection at the dryline: Forecasting issues from a case study perspective. *Wea. Forecasting*, **13**, 1106–1131.

FIGURE CAPTIONS

Figure 1. Shaded contours (see the key) showing the number of days per century a violent tornado (EF4 to EF5) touched down within 25 miles (40 km) of a point during the period 1921–2010 (inclusive) (Fig. 1 in Doswell et al. 2012).

Figure 2: British Broadcasting Corporation (BBC) Science Editor David Shukman's tweet the day after the 20 May 2013 Moore, Oklahoma, tornado. The link points to http://www.bbc.co.uk/weather/feeds/22608236.

Figure 3. Photo of a previously tornadic supercell storm on 10 June 2010 near Last Chance, Colorado (copyright C. A. Doswell III).



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Clash of air masses led to Oklahoma #tornado - excellent explainer by @bbcweather: bbc.co.uk/weather/feeds/…

RETWEETS 5
FAVORITE 1

4:01 AM - 21 May 2013

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