The Occurrence of Tornadoes in Supercells Interacting with Boundaries during VORTEX-95

PAUL M. MARKOWSKI

School of Meteorology, University of Oklahoma, Norman, Oklahoma

ERIK N. RASMUSSEN

Cooperative Institute for Mesoscale Meteorological Studies, National Severe Storms Laboratory, Boulder, Colorado

JERRY M. STRAKA

School of Meteorology, University of Oklahoma, Norman, Oklahoma

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ABSTRACT

During the Verifications of the Origins of Rotation in Tornadoes Experiment, nearly 70% of the significant tornadoes occurred near low-level boundaries not associated with the forward or rear flank downdrafts of supercells. In general, these were preexisting boundaries readily identified using conventional data sources. Most of the tornadoes occurred on the cool side of these low-level boundaries and generally within 30 km of the boundaries. It is likely that the low-level boundaries augmented the ‘‘ambient’’ horizontal vorticity, which, upon further generation in the forward-flank region, became sufficient to be associated with tornadic low-level mesocyclones. Some implications for forecasting and further research are discussed.

1. Background and relevance

A number of past studies have presented evidence that strongly implied, in the cases studied, that low-level boundaries were associated with tornadic storms (e.g., Maddox et al. 1980; Purdom 1976; Weaver and Nelson 1982; Weaver and Purdom 1995; Weaver et al. 1994, 1996). During the Verifications of the Origins of Rotation in Tornadoes Experiment (VORTEX; Rasmussen et al. 1994), it was found that many of the tornadoes also occurred in the vicinity of boundaries. For example, Richardson et al. (1998, manuscript submitted to *Mon. Wea. Rev.*, hereafter RRSMB) recently have completed an analysis of the 2 June 1995 tornadoes (a VORTEX intercept). Over a dozen supercells were observed by Weather Surveillance Radar-1988 Doppler (WSR-88D) in western Texas and eastern New Mexico during the late afternoon and evening, but the only tornadoes occurred within 50 km of a preexisting outflow boundary, on the cool side (and all but two were within 30 km of the outflow boundary, on the cool side). The outflow was produced by a convective system roughly 6 h prior to the first tornado report.

Our purpose is to attempt to establish an association between boundaries and significant tornadoes in VORTEX-95.[1] This sample is too small to allow for general inferences about boundary importance. However, because the majority of tornadoes in this experiment was associated with identifiable, preexisting boundaries, the findings do imply that further climatological studies are warranted in other regions. Meteorologists responsible for tornado forecasts and warnings should be cognizant of this association.

We speculate that the horizontal vorticity generated at boundaries is an important vorticity source for low-level mesocyclones via tilting and stretching. Preexisting vertical vorticity associated with boundaries, as diagnosed by Maddox et al. (1980), could also be important; however, horizontal vorticity is typically an order of magnitude larger than the magnitude of the vertical vorticity at a boundary ($\sim 10^{-2}$–10^{-3} s^{-1} vs $\sim 10^{-3}$–10^{-4} s^{-1}, as evidenced by VORTEX observations[2]). This

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Corresponding author address: Dr. Paul M. Markowski, School of Meteorology, University of Oklahoma, 100 E. Boyd Street, Room 1310, Norman, OK 73019.
E-mail: marko@rossby.ou.edu

[1] In this manuscript we sometimes refer to ‘‘boundary interactions.’’ We have used this terminology not only when referring to storm interactions with the narrow zone of strong gradients at the leading edge of a boundary, but also to include interactions with a distinct ‘‘ambient’’ air mass found behind the boundary by as much as a few tens of kilometers.

implies that horizontal vorticity typically could lead to low-level [which we define as ~1–3 km above ground level (AGL)] mesocyclones upon tilting without requiring as much stretching as low-level preexisting vertical vorticity requires.

The low-level horizontal vorticity associated with boundaries is generated through solenoidal effects owing to buoyancy gradients. From a theoretical perspective, it is easily shown (e.g., Klemp and Rotunno 1983; Rotunno et al. 1988; Rasmussen and Rutledge 1993) that strong (e.g., ~10^{-2} s^{-1}) horizontal vorticity can be produced along baroclinic boundaries (e.g., old outflow boundaries, warm fronts, etc.) with parcel residence times of as little as 10 min, given typical (5–10 K) temperature differences across the boundary. Because of large accelerations in storm inflow, the baroclinically generated horizontal vorticity can be amplified by horizontal stretching (Brooks et al. 1993) even prior to reaching the updraft itself.[3] A vigorous updraft, such as those that occur in environments with strong deep shear and sufficient convective available potential energy, can readily tilt and stretch the low-level horizontal vorticity present with the boundary (Weisman and Klemp 1982; Klemp and Rotunno 1983) if the updraft draws air from beneath the boundary interface. Possible added effects may be that the updraft itself may be intensified by the local convergence associated with a boundary, or enhanced moisture depth at a boundary (J. Weaver 1997, personal communication).

In this analysis, we consider only boundaries that are not directly associated with the supercell updraft region or the precipitation from the storm. For example, we exclude from consideration the forward flank and rear flank boundaries shown in the conceptual model of Lemon and Doswell (1979). This exclusion leaves us to consider preexisting mesoscale boundaries and fronts, boundaries generated by net radiation differences near the anvil shadow edge on storms with extensive anvils (Markowski et al. 1998a), and outflow boundaries from storms other than the tornadic supercell being analyzed. Most of the boundaries being considered could be detected operationally using visible satellite imagery (e.g., the 31 May and 2 June cases), surface airways observations (SAO) and automated surface observing systems (ASOS) data (e.g., the 19 April, 12 May, and 17 May cases), radar fine lines (e.g., the 16 May and 2 June cases), and sufficiently dense mesonetwork data (e.g., the Oklahoma Mesonet; the 7 May, 17 May, and 8 June cases).

With regard to the forward flank boundary in the Lemon and Doswell (1979) conceptual model, we have found that it sometimes existed in the VORTEX tornadic storms, but not always. In fact, if the tornadic storm is found on the cool side of a boundary, in low-level air that has large relative humidity, the forward flank boundary can be absent. The lack of a forward flank storm-generated boundary was observed in at least two well-sampled cases (Friona and Dimmitt tornadic storms of 2 June 1995). This observation is consistent with the notion that the forward flank boundary is generated by evaporative cooling in the forward flank precipitation region. In other words, if the inflow air is nearly saturated, little cooling can occur.

In section 2, we discuss our methodology, including the data sources and analysis techniques. Section 3 is a summary of the VORTEX-95 findings with comments regarding the implications for forecasting. A few closing remarks are provided in section 4.

2. Methodology

Boundaries were identified through the examination of surface, radar, and satellite observations. Surface data included hourly SAOs, 5-min ASOS archives, Oklahoma Mesonet (Brock et al. 1995) data, and VORTEX mobile mesonet (Straka et al. 1996) data. WSR-88D data (level II archive) were used to identify radar fine lines associated with many boundaries. *Geostationary Operational Environmental Satellite-8* (*GOES-8*) visible imagery was especially useful to identify boundaries associated with preexisting convection. All relevant data were combined to produce detailed analyses of the locations of boundaries near the tornadic supercells for each case day. (These are available from the authors upon request, but are too numerous to include herein.)

Many uncertainties naturally arose when analyzing boundary locations with respect to tornado occurrences. A high level of precision (±3 km uncertainty) could be obtained when boundaries were manifested as radar fine lines, or where the VORTEX mobile mesonet had collected high-resolution surface data. For the other cases, in which boundary locations were determined using satellite data and more conventional surface observations, boundaries were located to within ±10 km. Uncertainties in reported tornado times led to additional boundary location uncertainties (with respect to the reported tornadoes) on the order of 1 km. These errors were estimated using the angle between the tornado motion and boundary orientation, and by assuming the tornado motion was equal to the radar-derived storm motion and that tornado time reporting errors were confined to within 5 min or less. For example, a storm crossing a boundary at a 10° angle at 12.5 m s^{-1} would be estimated to have a 0.65-km uncertainty in tornado location with respect to the boundary. Errors involving the reporting of the exact tornado locations may have also been present, but cannot be accounted for reasonably.

In this study, all of the VORTEX operations days are considered in 1995 (Table 1) in which tornadoes were

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[2] RRSMB present such evidence in the 2 June 1995 VORTEX case. Findings were similar in other VORTEX cases not yet formally documented.

[3] In VORTEX intercepts on 2 June and 8 June 1995, order of magnitude increases in low-level horizontal vorticity were observed, probably attributable largely to horizontal stretching (Markowski et al. 1998b).

TABLE 1. A summary of tornado occurrences on VORTEX operations days during 1995. See sections 1 and 2 for a description of which boundaries and tornadoes were included in the sample. In the rightmost three columns are tornado locations with respect to the boundaries (as defined in section 1) in km.

Date	Location	Data used to detect boundary	Tornadoes in absence of boundaries[d]	Boundary presence unknown	10 km on warm side to 10 km on cold side	10–30 km on cold side	30–50 km on cold side
17 Apr 95	Southwest OK	N/A[a]	3				
19 Apr 95	North TX	SAO			2		
7 May 95	North TX/southern OK	*GOES-8*, OK Mesonet		2	4		
12 May 95	Northwest KS	*GOES-8*, SAO			2		
16 May 95	Southwest KS	Mobile mesonet, SAO, WSR-88D, *GOES-8*			3		
17 May 95	Northwest OK	OK Mesonet				1	
22 May 95	Eastern TX panhandle	N/A[c]		2			
31 May 95	North-central TX	*GOES-8*, SAO, WSR-88D			2		
2 Jun 95	West Texas	*GOES-8*, SAO, mobile mesonet, WSR-88D				8	2
3 Jun 95	Eastern TX panhandle/ southwest OK	N/A[c]		2			
8 Jun 95[b]	Eastern TX panhandle	OK Mesonet, mobile mesonet	7			7	

[a] N/A is shown to indicate that no boundaries were detected that were not directly associated with the supercell updraft region or the precipitation from the storm (as defined in section 1), although forward and rear flank boundaries may have been detected.

[b] This boundary was generated by differential heating attributed to an anvil shadow. A formal publication is upcoming on this case.

[c] N/A is shown for the 22 May and 3 June cases because no interacting boundaries were detected with *GOES-8* or WSR-88D, and the VORTEX mobile mesonet did not sample the storm vicinities; thus the presence of boundaries cannot be ruled out.

[d] Again, this only applies to boundaries as defined in section 1. Forward and rear flank boundaries may have been present.

reported in the VORTEX domain (Rasmussen et al. 1994). The sample comprises 11 tornado days and over 70 reported tornadoes. However, to reduce the uncertainties in our analysis, we have considered only the 47 tornadoes reported as strong (F2 intensity and greater) in *Storm Data* (NOAA 1995a–c) and those of lesser intensity reported by VORTEX scientists and eyewitnesses the authors know to be reliable. This was done to mitigate the usual vagaries of tornado reporting (Doswell and Burgess 1988; Rasmussen and Crosbie 1996). (Many of the reports of ‘‘brief, weak, and non-damaging’’ F0 and F1 tornadoes in *Storm Data* have been found, in our experiences, to be unreliable; therefore, we did not include these if no experienced observers could corroborate the reports. However, we have made the assumption that tornadoes rated as F2 intensity or greater in *Storm Data* are unlikely to be false reports; therefore, these were included even if not witnessed by a reliable observer. We concede that this may not have been the most ideal way to construct our sample; however, we believe that our findings from this sample remain scientifically valuable.) To maintain the objectivity of this analysis, we included tornadoes in the sample even if the storms were not intercepted by VORTEX, or for some other reason we could not determine the presence or type of a boundary.

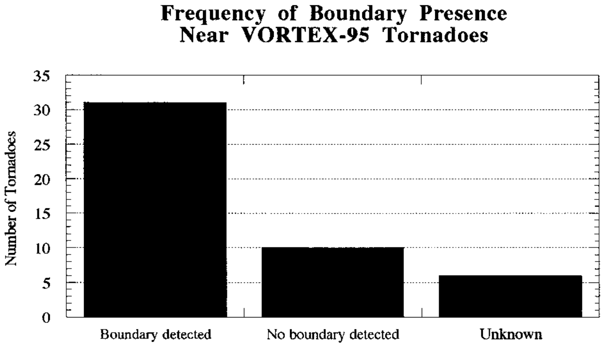


FIG. 1. Frequency distribution of tornado occurrences in the close proximity of boundaries (as defined in section 1) during VORTEX-95. Included in the sample are all tornadoes reported on VORTEX operations days as strong (F2 damage and greater) in *Storm Data* and those reported by eyewitnesses the authors know to be reliable.

3. VORTEX-95 findings and implications

The frequency distribution of tornado occurrences relative to boundaries is shown in Fig. 1. Nearly 70% of the tornadoes observed in VORTEX were associated with boundaries as defined in the introduction. The generality of this finding must be verified through much larger climatologies including regions other than the southern Great Plains. In a small fraction of the cases (6 of the 47 tornadoes in the sample), data were insufficient to determine the presence or absence of a boundary. Note that the boundaries were usually identified through *conventional* data sources; identification

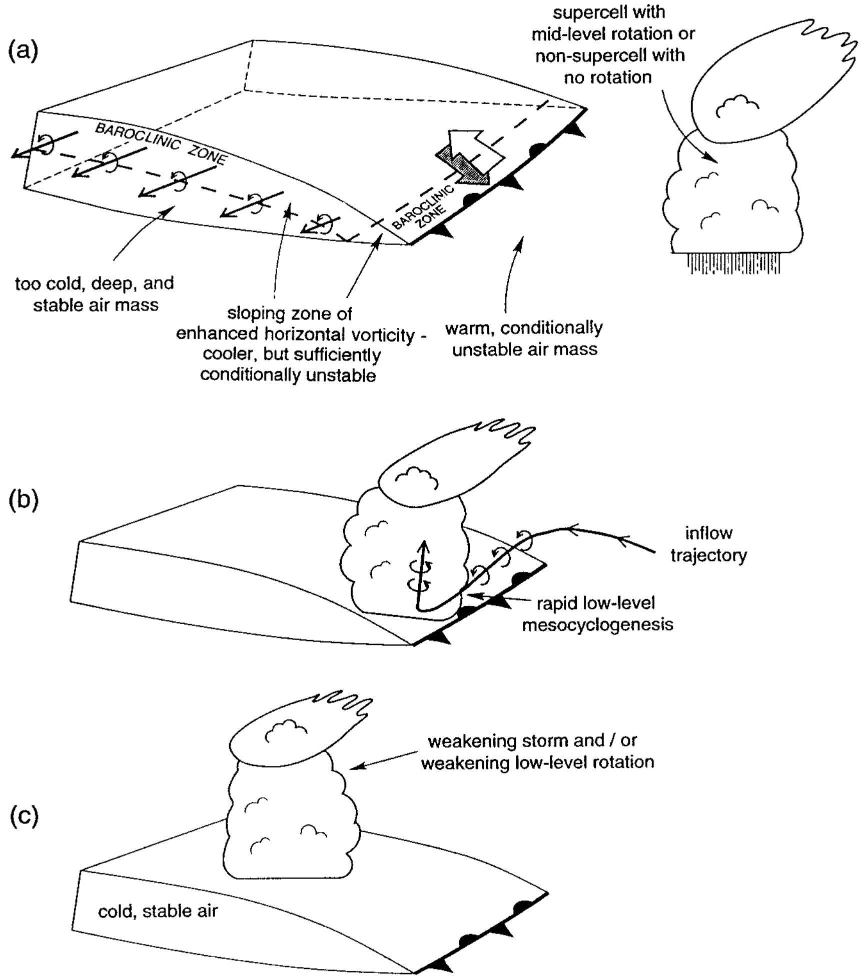


FIG. 2. A conceptual model for how an updraft-boundary interaction may lead to low-level mesocyclogenesis.

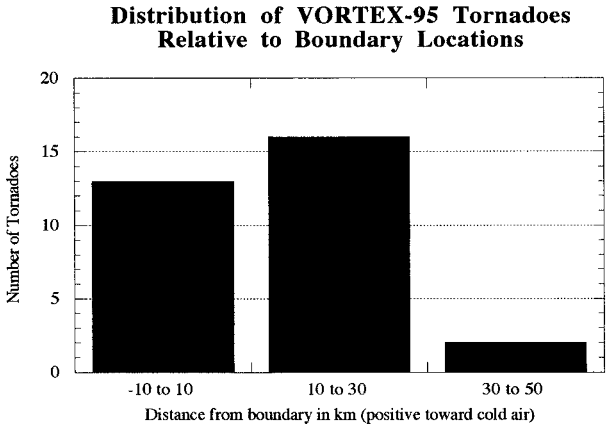
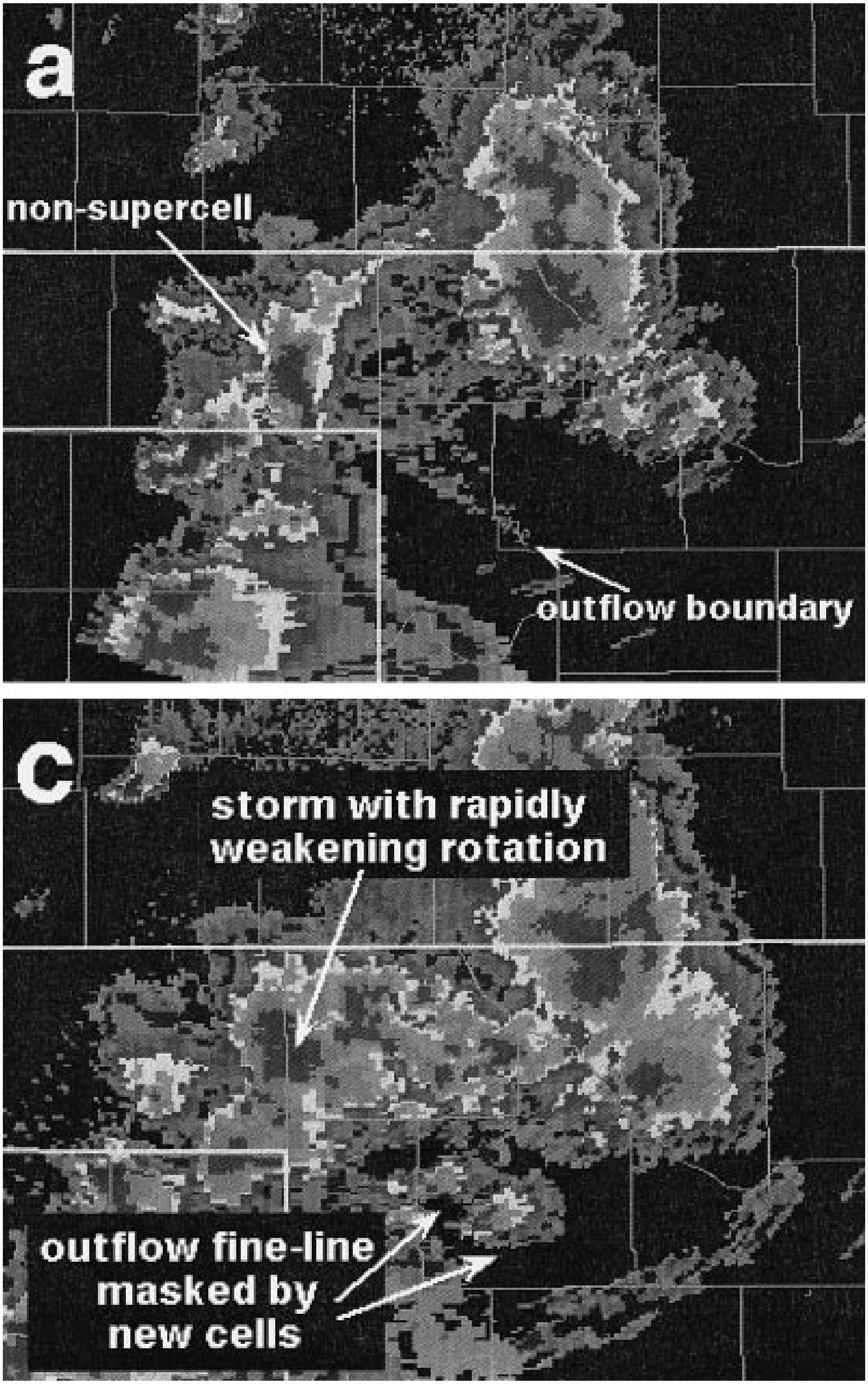


FIG. 3. Frequency distribution of tornado occurrences relative to boundary locations (distances from boundaries were known to within ±10 km) in cases where tornadoes occurred near detected boundaries.

did not rely heavily on the special VORTEX platforms. If it is found that the occurrences of significant tornadoes are generally associated with the presence of boundaries, then boundary identification will become a very useful tool for forecasting the tornadic potential of supercells.

Supercells can generate a certain amount of horizontal vorticity on their forward flanks (Klemp and Rotunno 1983; Rotunno and Klemp 1985), depending on the extent of the forward flank precipitation, storm-relative low-level flow, temperature and humidity contrasts, etc. This vorticity augments that already present in the inflow, which itself may have been augmented by the baroclinic effects of a nearby thermal boundary not associated with the supercell (e.g., a preexisting outflow boundary). The relative frequency of tornado occurrences in VORTEX suggests that the combination of ''ambient'' horizontal vorticity and storm-generated horizontal vorticity is usually not sufficient to be associated with tornado occurrence,


a
non-supercell
outflow boundary
c
storm with rapidly weakening rotation
outflow fine-line masked by new cells

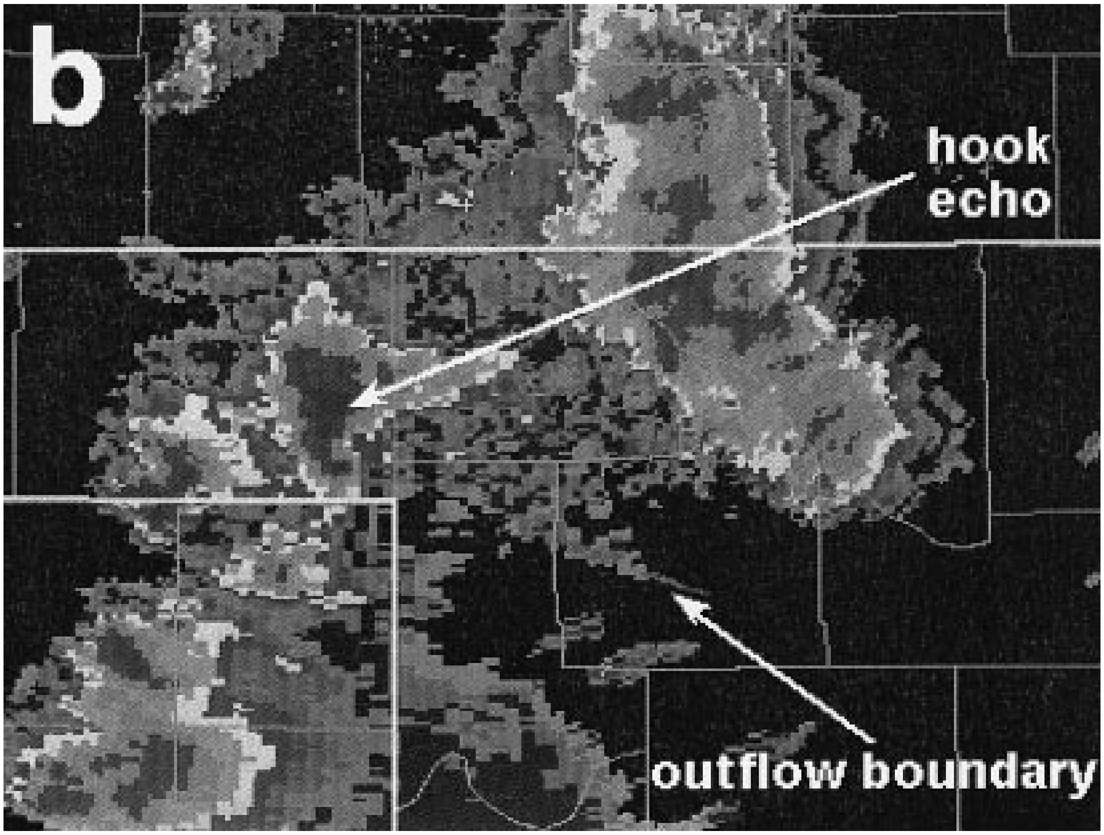


FIG. 4. Lowest elevation scan reflectivity from Dodge City, KS, is shown at (a) 2255, (b) 2310, and (c) 2325 UTC 8 June 1995. The sequence of radar images illustrates the conceptual model presented in Fig. 2. Note the development of a hook echo associated with the storm that passed over an outflow boundary in northwestern Oklahoma. The nonsupercell storm took on a supercell appearance after encountering the boundary. The same storm quickly weakened after encountering air too stable north of the boundary (surface temperatures 20 km north of the boundary were ~18°C). The storm did not produce a tornado, but it did contain a low-level mesocyclone at the time of (b). In (c), the outflow boundary is no longer visible as a radar fine line due to the initiation of new cells on the boundary.

and that horizontal vorticity augmentation[4] via boundaries (Markowski et al. 1998b) is often required for tornadogenesis (Fig. 2). For horizontal vorticity enhancement to be relevant for a storm, its updraft must draw inflow from the colder side of the boundary (where the vorticity augmentation via baroclinic generation occurs). The air parcels possessing the enhanced horizontal vorticity must also remain sufficiently buoyant in order to be processed by the updraft, which can ingest and tilt the enhanced vorticity into the vertical (Fig. 2). If a storm moves over an air mass that is too cold, deep, and stable to support continued surface-based convection, then low-level mesocyclogenesis, which owes to tilting and stretching of the enhanced horizontal vorticity, will not occur. Furthermore, storms that move along a boundary rather than directly across may have a better chance of processing sufficiently unstable air and being maintained for a prolonged period, all the while ingesting enhanced horizontal vorticity (Fig. 2). This hypothesis merits much more observational and modeling attention.

It is noteworthy that on 8 June 1995, the largest tornado outbreak of VORTEX, 7 of the 14 significant tornadoes were not associated with boundaries; thus, conditions can be sufficiently favorable to produce tornadoes without boundaries (i.e., large-scale horizontal vorticity combined with storm-generated horizontal vorticity via a forward flank baroclinic zone may be sufficient in some cases). There may be evidence, however, that even in some widespread outbreaks, boundaries and their horizontal vorticity augmentation may still be important in tornadogenesis [e.g., the Hesston, Kansas, tornado on 13 March 1990 (Weaver and Purdom 1995)].

The locations of the tornadoes with respect to the boundaries also have been examined and are summarized in Fig. 3. Tornado occurrences were most common

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[4] Horizontal vorticity augmentation may be manifested as enhancement of storm-relative helicity if the vorticity that is baroclinically generated has a streamwise component (Davies-Jones 1984; Davies-Jones et al. 1990).

on the cold side of boundaries. We believe that this is because, by definition, boundaries are ‘‘located’’ on the warm sides of temperature gradients. Thus, baroclinic horizontal vorticity generation occurs on the cold side of a boundary. If vertical vorticity alone were the reason for the observed tornadogenesis frequency near boundaries (Maddox et al. 1980; Wakimoto and Wilson 1989), then no bias toward the cold side of boundaries would be expected. Again, we do not claim that horizontal vorticity enhancements are always the most important effect at boundaries; in some instances other aforementioned effects could be of primary importance.

One of the most difficult questions related to this study that remains to be addressed is the distance into the cold air that a supercell can travel and still produce a tornado (Figs. 2–4). This distance likely is a function of the stability on the cold side, the depth of the cold air, and the vertical pressure gradient generated by an updraft in low-level shear. For unstable air on the cold side of a relatively shallow (say, <750 m) boundary, and a strong vertical pressure gradient (Rotunno and Klemp 1985; Klemp 1987), this distance would be maximized. To complicate the issue further, even if a supercell can survive given the above three conditions, it may no longer pose a tornado threat if its rear flank downdraft (RFD) is unable to penetrate the cold air mass at the surface [the RFD is hypothesized to be important in tornadogenesis (Lemon and Doswell 1979; Brandes 1984a,b; Rotunno and Klemp 1985; Klemp 1987; Davies-Jones and Brooks 1993)]. Based on the VORTEX findings, the greatest tornado potential probably is located between no more than 10 km into the warm air to roughly 30 km into the cold air (Fig. 3).

4. Closing remarks

Significant tornadoes that occurred within the VORTEX domain in 1995 were examined to determine the frequency of their associations with boundaries. Our definition of boundaries included all identifiable boundaries except the forward flank boundary and rear flank gust fronts of the conceptual model of Lemon and Doswell (1979). In general, the boundaries in our study were detected through conventional data sources, such as *GOES-8,* WSR-88D, and surface observations (SAO, ASOS, and mesonet). We found that nearly 70% of the tornadoes were associated with boundaries as defined, and tornadoes associated with boundaries usually occurred in a zone from up to 10 km on the warm side to 30 km on the cold side of these boundaries.

Although the VORTEX-95 sample is relatively small, if it is found to apply generally, our observations would imply that there is a strong physical relationship between tornado occurrences and boundaries. Based on these findings, we will spend the next few years testing the following *hypotheses* using observational and modeling datasets:

- Horizontal vorticity enhancements are necessary for low-level mesocyclogenesis, which appears to precede tornadogenesis if additional key supercell structures develop (e.g., the RFD). If low-level horizontal vorticity is locally enhanced, then significant vertical vorticity (e.g., $\sim 10^{-2}$ s^{-1}) would be obtained through tilting and stretching at a lower height than if no enhancement occurred.
- Horizontal vorticity enhancements can be achieved via baroclinic vorticity generation in forward flank baroclinic zones or within boundaries not associated with the precipitation or updraft region of a supercell (as defined in section 1). However, augmentation of the horizontal vorticity associated with the mean shear by a forward flank baroclinic zone alone is typically insufficient for tornadogenesis (only about 30% of VORTEX-95 tornadoes occurred in the absence of detectable boundaries, as defined in section 1). Tornadogenesis requires augmentation of the horizontal vorticity associated with the mean shear by the baroclinic vorticity generated by preexisting boundaries, or the combined baroclinic vorticity associated with a forward flank baroclinic zone and a preexisting boundary.
- Only in cases where large-scale low-level horizontal vorticity is already very high (e.g., 0–3-km mean horizontal vorticity of $\sim 1 \times 10^{-2}$ s^{-1} or greater or storm-relative helicity of ~ 500 m^2 s^{-2} or greater) or deep-layer shear is very strong (e.g., 50 m s^{-1} in the lowest 10 km AGL), can forward flank baroclinity alone provide sufficient augmentation of the horizontal vorticity associated with the large-scale mean shear for tornadogenesis to occur. When deep-layer shear is strong, forward flank baroclinic zones would tend to be longer, allowing for longer parcel residence times, which would allow for greater horizontal vorticity augmentation—augmentation comparable to that amount achieved by preexisting boundaries, in which parcel residence times (>1 h) are typically longer than the residence times in forward flank baroclinic zones.

If it is true that many significant tornadoes are associated with boundaries, then identifying these boundaries in an operational setting, through all available tools and inferences, is essential to improving the tornado warning capabilities of the modernized National Weather Service. The necessary first step is to improve our physical understanding of these boundaries, and the fundamental details of the physics of the interactions between the storms and boundaries. This is necessary so that we can distinguish operationally ‘‘important’’ boundaries from those with less significant potential for mesocyclone generation, and so that we can possibly infer the presence of boundaries indirectly when there is no direct evidence of their presence (e.g., if the WSR-88D accumulated precipitation algorithm indicates that earlier cells laid down a swath of precipitation and wetted the soil).

Future work will include better quantification of the amount of horizontal vorticity generated by boundaries through observations and numerical simulations. It is also imperative that supercell simulations begin to investigate the impacts of horizontal inhomogenities on storm morphology and evolution. Thus far, efforts at numerically simulating storms generally have assumed that the storms form in homogeneous environments. Finally, we intend to commence work on a national database to evaluate the general importance of storm-boundary interactions in tornado production. As our understanding of the effects of boundaries on convective storms improves, new tornado warning guidance likely will emerge.

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