Proposed Conceptual Taxonomy for Proper Identification and Classification of Tornado Events

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ABSTRACT

A practical approach is recommended for identifying and archiving tornado events, based on the use of definitions that label all vortices as either Type I, Type II or Type III tornadoes. This methodology will provide a more meaningful tornado climatology in *Storm Data*, which separates and classifies all vortices associated in any manner with cumuliform clouds.

Tornadoes produced within the mesocyclone of discrete supercell storms, with strong local updrafts (SLU), will be classified as Type I tornadoes. Frequently, these Type I tornadoes result from the interaction of the SLU with strong rear flank downdrafts (RFD), or with shear vortices in the PBL. Tornadoes produced in association with Quasi-Linear Convective Systems (QLCS) will be classified as Type II tornadoes (including cold pool, rear-inflow jets, bookend and mesovortex events along the line). All other vortex types (including landspouts, waterspouts, gustnadoes, cold air vortices and tornadoes not associated with mesocyclones or QLCS) will be labeled as Type III tornadoes. A general discussion is provided that further clarifies the differences and categorization of these three classifications (which encompass 15 tornado species), along with a recommendation that NOAA adopt this taxonomy in operational and data archiving practices. Radar analysis and field observations, combined with storm-scale meteorological expertise, should allow for the official "typing" of tornado reports by NOAA personnel. Establishment of such a climatological database in *Storm Data* may be of value in assessing the effects (if any) of 21st century global warming on USA tornado trends.
1. Introduction

Recent decades of scientific advancement have resulted in a much greater understanding of tornado formation, although challenges still remain. Along with this increased knowledge has come the realization that tornadoes can actually form in several different ways. This is illustrated in part by the evolution of the definition of a tornado. In 1959, the *Glossary of Meteorology* defined a tornado as "a violently rotating column of air, pendant from a cumulonimbus cloud." In 2000, the *Glossary of Meteorology* defines a tornado as "a violently rotating column of air, in contact with the ground, either pendant from a cumuliform cloud or underneath a cumuliform cloud." This new definition illustrates the acceptance of a broader range of vortex events such as landspouts, waterspouts and gustnadoes.

Whether or not tornadoes are defined according to their causative mechanisms or according to their physical appearance can/should make a difference in their potential identification and classification in *Storm Data*. For instance, if any cumuliform cloud occurring over water creates a columnar vortex, this vortex is defined as a waterspout and can only be labeled a tornado if it travels onto land. Consequently, waterspouts can occur with either thunderstorms (even supercells) or with weaker non-glaciated convective clouds. However, the landspout (see Bluestein 1985) is always called a tornado and is more typically produced by non-glaciated convective clouds (although such clouds can grow to the glaciated stage). These landspouts are typically produced by slow-moving cumulus congestus clouds or by seemingly non-severe thunderstorms, with vorticity spin-up in the boundary layer (which is not in association with a mesocyclone). These landspouts receive their name due to their one-cell laminar vortex structure (referred to in fluid mechanics terminology as a "soda-straw vortex"), and additionally because they have a similar physical appearance to the well known waterspout.
Additional confusion in tornado recognition comes with the *gustnado* phenomenon, an inertial instability that forms along a vortex sheet that is produced locally along the gust front of any thunderstorm (although typically more prevalent in the outflow of stronger thunderstorm events). Forbes and Wakimoto (1983) go far in documenting the occurrence of such vortex events in a severe weather outbreak near Springfield, Illinois on 6 August 1977.

It is also noted that the strongest tornadoes (F5/EF5) are most likely produced by mesocyclonic supercell storms (see Trapp et al. 2005), such as Moore, Oklahoma, 3 May 1999; Greensburg, Kansas, 4 May 2007 and Parkersburg, Iowa, 25 May 2008. These tornadoes (defined as Type I) are produced by a strongly rotating updraft *interacting* with a rear-flank downdraft, although most supercell tornadoes are weaker and some may not require the RFD for tornadogenesis. Other types of tornadoes of significant strength (F2/EF2 – F4/EF4) can be produced by a number of mechanisms including the tilting of solenoidal horizontal vorticity by a cold pool, and by rear inflow jets (RIJs) in quasi-linear convective systems (QLCS), (Taylor et al. 2002; Trapp and Weisman 2003; Weisman and Trapp 2003; Trapp et al. 2005) as well as by bookend vortices (BEVs) in bow echoes (also see Fujita 1978). Even non-supercell tornadoes of the landspout variety can achieve intensities as high as F2 (see Wakimoto and Wilson 1989).

Most meteorologists would likely say that every vortex event associated in any manner with any type of thunderstorm or convective cloud is a tornado (i.e., the 2000 *Glossary* definition). However, this approach could be viewed as counterproductive in establishing an appropriate system for the classification and archiving of tornado events. Florida, for example, has an elevated tornado count due to the frequency of land-falling waterspouts. Further, in this era of global warming with the anticipated increase in CAPE and convective storms in the 21st century (see IPCC 4th Assessment Report 2007; also Trapp et al. 2007) it might be useful to
separate the more locally-produced weaker vortex events from those more directly associated with supercells (Type I) and QLCS (Type II). The predicted increase in the number of severe thunderstorms in the USA in future decades offers the opportunity to see potential changes in the occurrence and distribution of the different tornado types, if an appropriate database can be established.

The objective of this paper is to introduce definitions for three types of tornado classifications, including 15 tornado species, thus offering a more detailed identification methodology with improved labeling of events in *Storm Data* archives. Such an improvement would also provide additional meteorological value to *Storm Data* reports, in addition to the engineering estimates of wind speeds based on damage assessment. This classification taxonomy is somewhat consistent with the views provided by Davies-Jones et al. (2001). Individual states in the USA would then have the total count for all tornado types, and better representation could be made in assessing any future climatological trends of tornadoes, including national and regional differences. It is further proposed that NOAA adopt this taxonomy for their reporting practices (which is clarified in more detail in the following sections).

2. The Type I vortex event

The nomenclature introduced for the discrete supercell tornado event is the Type I vortex, which represents the fundamental (and most complicated) series of meteorological events that lead to tornado formation. In this case the supercell thunderstorm possesses the key ingredient of a strong local updraft (SLU) extending vertically through a horizontal wind field that is rich in horizontal vorticity, resulting in the development of a well-defined *mesocyclone*. An example of this precursive condition to Type I tornado formation is shown in Fig. 1. Doppler radar does
well in the identification of these mesocyclones (see NWS definitions) and these can often be
detected without the subsequent formation of a tornado since the strongest rotation is usually
above the planetary boundary layer. Another key development in the series of events for Type I
tornado formation is the rear flank downdraft (RFD) that strategically produces vertical vorticity
in the PBL, in close proximity to and interacting with the SLU. The combined interaction of the
SLU and the RFD, resulting in the tilting of horizontal vorticity and the stretching of vertical
vorticity, creates the perfect environment for tornadogenesis. Subsequently, this tornado cyclone
(see Agee et al. 1976; and the Glossary of Meteorology 2000) can become increasingly stronger
(even of TVS strength) and Type I tornado formation is completed. It is noted, however, that
Type I tornadoes range over the full spectrum of tornado intensity from F0 to F5 (now EF0 to
EF5) and RFD involvement is not always required for tornadogenesis. If one examines the
Beltrami Vorticity Equation, it is evident that several processes can affect the local reservoir of
horizontal and vertical vorticity. These include the convergence and stretching of existing
vertical vorticity, the tilting and stretching of horizontal vorticity, the role played by baroclinicity
and preexisting boundaries – which are also favorable sources for eventual concentration of
vorticity into the developing tornado (see Houston and Wilhelmson 2007), and the effects of
frictionally-induced convergence. The intent here is to not explain the variety of intricate details
in the evolution of a Type I tornado, but to present the infrastructure or boilerplate format for
identification (and thus classification). In summary, the Type I Tornado is produced by a
discrete mesocyclonic supercell storm with a SLU that interacts favorably with the
environmental wind field. This process moves sequentially through the strong mesocyclone
formation (often observed with Doppler radar) and can subsequently result in spin-up in the PBL
(either through the RFD or other boundary layer processes), thus completing the formation of the
tornado vortex column (typically in the right-rear quadrant of the parent thunderstorm). The presence of the parent storm cell in a field of strong helicity \( \vec{V} \cdot \nabla \times \vec{V} \) adds to the rotational properties of the SLU and the intensification of the mesocyclone and the likelihood of tornadogenesis. It is further noted that the movement of the parent storm cell with respect to the environmental wind field can maximize the intake of stream-wise vorticity (i.e., storm-relative helicity) particularly in the lowest 500-1000 m (see Thompson et al. 2003). The combined properties of CAPE and storm-relative helicity (see Johns and Doswell 1992) are critical to the formation of severe rotating thunderstorms that are capable of producing the Type I tornado (as well as the Type II tornado discussed below). Such events can also occur in low tropopause conditions with high helicity and minimal CAPE, resulting in "low-top" strongly rotating mini-super cells (see Kennedy et al. 1993). It is further noted that hurricane environments can produce tornadoes from shallow supercells (see McCaul 1987; McCaul and Weisman 1996).

3. Type II vortex events

The Type II Vortex will represent those tornadoes that are produced by quasi-linear convective systems (QLCS), which is typically an MCS that has taken the form of a squall line or bow echo. The concept of a meteorological event known as the QLCS was first introduced by Weisman and Davis (1998) and the tornado climatology associated with QLCS was established by Trapp et al. (2005). Interestingly, the definition of the QLCS was not listed in the latest edition of the *AMS Glossary of Meteorology* (2000). The QLCS concept will include all "lines" of convective storms with features such as LEWPs, bows, BEVs, RIJs or any type of mesovortex event. The terminology used in this paper should not be confused with that presented by Gallus et al. (2008), as all nine categories of their storm morphologies basically equate to lines or cells. One in fact could argue that a "perfectly linear" system would not produce a Type II tornado,
since each of the above features/events result in some kind of irregularity in the line. The "cold pool process" is typically fundamental in producing the tilting of horizontal vorticity, thus aiding in tornado formation. An example of a bow structure that developed within a line is shown in Fig. 2a. Also, the bow feature can often produce a BEV as illustrated in Fig. 2b. Further the mesoscale development of RIJs can add to the production of shear-induced mesovortices that form along the QLCS. As stated earlier, the Type II tornadoes can be as strong as most of the Type I tornadoes (but generally not beyond F4/EF4 intensity). Finally, another example of a QLCS with Type II tornadoes is shown in Fig. 2c, which contains a number of mesovortices that developed in association with tornadogenesis (a phenomenon that has been numerically simulated by Trapp and Weisman 2003).

4. Type III vortex events

As stated earlier, both the Type I vortex (supercells) and the Type II vortex (QLCS) events will be labeled as tornadoes with a capability of producing significant damage (≥F2/EF2). Definitions and conceptual discussion of Type I and Type II events have been presented (and along with Type III events are summarized in a formal taxonomy presented in the next section). Interestingly, in the Type III tornado the act of vortex formation is somewhat uniquely controlled by the updraft (e.g., in non-glaciated cumuliform clouds) or by the downdraft (e.g., in association with the gust-front boundary) typically resulting in weaker tornado events. Thus the waterspouts, landspouts and gustnadoes would fall into a third category of tornado events (Type III). Stretching of shear vortices in the PBL by the updraft of non-supercells have in extreme cases produced F3 tornadoes (see Wakimoto and Atkins 1996). The best example of a locally produced, shear-driven vortex is the gustnado (see Fig. 3). This Type III vortex event can produce tornado damage, but typically is rather benign and only observed in dusty conditions
along thunderstorm gust front boundaries. The gustnado, however, can experience a metamorphic process, where it is advected into the core of a strong mesocyclone and subsequently evolves into a Type I tornado (see Bluestein et al. 2002). The concept of a gustnado was presented some years ago (e.g., see Doswell and Burgess 1993). One of the authors can personally recall a talk by Don Burgess at the 11th Severe Storms Conference with a slide presentation showing gustnadoes along a dusty gust front in an Oklahoma thunderstorm. A technical note by Douglas Crowley at the NWS office in Amarillo, Texas (http://www.srh.noaa.gov/topics/attach/html/ssd96-39.htm) is an excellent illustration of our need to properly identify tornado events and separate out the gustnadoes. The proposed Type I, II and III nomenclature presented here will address this issue. Further, tornado statistics will be more accurately presented for each state when totals are given for each tornado type. Another technical note by Richard Smith at the NWS office in Memphis, Tennessee (http://www.srh.noaa.gov/topics/attach/html/ssd96-8.htm) also shows the dilemma of vortex types and the need for appropriate classification.

The landspout (see Bluestein 1985) is another Type III vortex that is typically associated with a weak cumuliform cloud that has often not even achieved the glaciated stage. Radar observations show no indication of any suspect severe weather or tornado development (as seen in the URL reports noted above by Crowley and by Smith). Figure 4 shows a typical landspout, photographed by a local citizen near West Lafayette, Indiana on 25 June 2006, which was produced by a slow-moving cumuliform cloud. This landspout was observed by one of the authors (as the "parent" cloud drifted from the southeast to the northwest in light wind conditions) and certainly was viewed as similar to the waterspout events in the Florida Keys. Local Doppler radar gave no indication of any significant convection, let alone a tornado
circulation. Such an event is not attributable to strong low-level vertical shear in the horizontal wind. Thus it is different from the gustnado and any inertially-driven instability vortices that form in the boundary layer (but all such events would be classified as Type III tornadoes, and thus distinctly different from the Type I and Type II vortex events).

Finally, some brief comments are offered about hurricane-induced tornadoes (HITs). The occurrence of Type I and Type II HITs are noted, and these are the more common types of hurricane-induced tornadoes. However, if vortices develop in the eye wall region they would be viewed as a shear-induced inertial instability and thus represent Type III tornadoes (see Fujita 1993; Montgomery et al. 2002).

5. Taxonomy

Based on the above introductions and descriptions of Types I, II, and III tornadoes, it is now appropriate to present an organized taxonomy for classifying tornadoes. Figure 5 shows the organization of the three proposed types of tornadoes, which encompass 15 identifiable tornado species.

a. Type I

The Type I tornado is produced by the discrete supercell mesocyclone, as well as the low-top mini-supercell (previously discussed). It is also noted that the supercell is typically severe right-moving (SR), but in rare instances, it can be severe left-moving (SL) depending on the characteristics of the wind hodograph. Supercells that split into SR and SL storms have the potential to develop cyclonic and anticyclonic Type I tornadoes, respectively. Thirdly, another Type I tornado is produced by the low-top mini-supercell associated with landfalling hurricanes. These tornadoes are typically associated with convective cells located in the right-front quadrant of the hurricane (and are somewhat rare). Important to the development of discrete supercells is
the presence of low-level directional shear (as well as magnitude shear), a distinguishing feature in cells ‘vs.’ lines.

b. Type II

The Type II tornado is produced by a variety of physical processes that are associated with quasi-linear convective systems (QLCS). These tornadoes occur in association with mesocyclones and other mesovortices that arise in conjunction with cold pool dynamics, embedded convective cells, bow echoes and bookend vortices, rear inflow jets and line echo wave patterns (previously discussed). In addition, spiral bands in the right-front quadrant of a landfalling hurricane can produce tornadoes of the QLCS type. There is a total of six tornado species proposed as Type II events, as illustrated in Figure 5.

c. Type III

The Type III tornadoes are all of those events not classified as Type I (supercells) or Type II (QLCS). More specifically, these are localized convective and shear vortices. The Type III convective events include landspouts, waterspouts and cold air funnels. The Type III shear events are gustnadoes, anticyclonic secondary vortices and shear vortices associated with inertial instabilities in the eyewall of hurricanes. In addition, it is noted that Type III tornadoes can occur in association with supercells and QLCS (namely gustnadoes), even when no Type I or Type II tornadoes occur. Further, it is noted that Type I and Type II tornadoes can occur over water, and thus according to the 2000 Glossary would be labeled as waterspouts, but in this classification system these events (with landfall) would not be labeled as Type III tornadoes.
d. Guidelines for classification

Finally, Table 1 is provided as a description for each of the 15 tornado species, which is intended to provide guidance for the classification of tornadoes. As noted above, there are three species in Type I, six species in Type II, and six species in Type III.

6. Summary and conclusions

The concepts and descriptions of Type I, Type II and Type III tornado events have been presented, which are consistent with the definition of tornadoes provided in the *Glossary of Meteorology* (2000), as well as the views presented by Davies-Jones et al. (2001). The Type I tornado is produced by the discrete supercell thunderstorm, where a mesocyclone has formed due to a SLU interacting with a horizontal wind field with large values of horizontal vorticity. The resulting tilting and stretching processes create favorable conditions for interaction with RFD development or any other processes that help with vortex spin-up in the PBL. If supercells merge into a line, and thereafter a tornado is produced, the event would be classified as a Type II tornado (since there would be a QLCS structure at the time of tornadogenesis).

The Type II tornado events are defined as those associated with QLCS, and such events are often associated with cold pool and shear-induced mesovortex events that form along the line. Some of these Type II tornadoes can also be associated with bow echoes and BEVs that often develop in the comma-head. Rear-inflow jets (RIJs) along the line (e.g., see Taylor et al. 2002) can also add to shear-induced vertical vorticity and tornadogenesis. The Type III tornado is produced by locally concentrated updrafts in weaker cumuliform clouds, as well as by local wind shear effects in the planetary boundary layer associated with the gust fronts of stronger thunderstorm events. Therefore, the occurrence of waterspouts, landspouts, cold air funnels and gustnadoes would typically be classified as Type III tornadoes. In general, the class of Type I
tornadoes (supercells) and Type II tornadoes (QLCS) would be stronger than those classified as Type III tornadoes. It is also noted that an individual supercell could "parent" both Type I and Type III tornadoes, and similarly for QLCS events.

Further, it is recommended that NOAA adopt this taxonomy when archiving tornado events in Storm Data, drawing on the expertise of NWS personnel in the interpretation of radar data, field observations and visual evidence. Undoubtedly, some tornado events would be difficult to classify due to a lack of appropriate supporting information. This "typing" could also allow the NWS to issue more informative tornado warnings and severe weather advisories. Further, a more meaningful tornado climatology can potentially be established that better represents the different types of tornadoes both nationally and regionally, as well as for individual states (e.g., Florida versus Oklahoma). This tornado climatology could also be useful in assessing the effects (if any) of the climatic warming trend expected to continue through the 21st century and the hypothesized associated increase in severe thunderstorm activity (see Trapp et al. 2007). Decades of tornado "typing" could allow for detection of changes in tornado patterns that could potentially be linked to climate change or other cyclical weather patterns.

7. Acknowledgments

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three *WAF* reviewers who provided constructive criticism and made several suggestions for improving the revised manuscript.
References


Crowley, D. J., 1996: Is it a tornado? Technical attachment,


Figure Captions

Figure 1. A Doppler radar image of a supercell thunderstorm near Oklahoma City on 3 May 1999. The image on the left shows a nice example of a hook echo radar feature that often accompanies the mesocyclone. The image on the right shows the doppler velocity field and the color velocity couplet that locates a tornado vortex signature (TVS).

Figure 2. Examples of different QLCS structures that are viewed as capable of Type II tornadogenesis; a) An example of a bow echo near San Angelo, Texas on 7 April 2002; b) A bow echo and associated comma head over central Illinois on 4 June 2002. A weak tornado (F0) was reported by the Illinois State Police; c) QLCS in southwest Illinois during BAMEX on 6 June 2003 at 2300 UTC. Several tornadoes were produced by this event.

Figure 3. Gustnado in Australia, 7 April 2007, which formed along a dusty thunderstorm gust front.

Figure 4. Dusty landspout near West Lafayette, Indiana on 25 June 2006. No precipitation occurred near this vortex, and radar gave no indication of any possibility of severe weather (also, see Storm Data, June 2006).

Figure 5. Schematic of tornado types and associated species.
Table 1. Criteria for applying tornado taxonomy.

<table>
<thead>
<tr>
<th>Tornado Type</th>
<th>Characteristics for Classification Label</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ia</td>
<td>Discrete supercell with mesocyclone (typically a hook echo) with supportive values of CAPE and Storm Relative Helicity with low-level directional shear</td>
</tr>
<tr>
<td>Ib</td>
<td>Discrete mini-supercell with low top in low-tropopopause environment; typically minimal CAPE with large SRH; more common in early spring and late fall</td>
</tr>
<tr>
<td>Ic</td>
<td>Typically in the right-front quadrant (RFQ) of landfalling hurricanes; supportive values of CAPE, low-level shear and large ambient vertical vorticity</td>
</tr>
<tr>
<td>IIa</td>
<td>Line Echo Wave Pattern – A mesoscale wave pattern that adds to local vorticity field and mesocyclone formation</td>
</tr>
<tr>
<td>IIb</td>
<td>Bow echo produced by cold pool with enhancement of solenoidal field and tilting with increased shear</td>
</tr>
<tr>
<td>IIc</td>
<td>Bookend vortex typically at the top or cyclonic end of the bow echo with associated mesocyclone</td>
</tr>
<tr>
<td>IId</td>
<td>Rear Inflow Jets along sections of the QLCS that add to local shear and vorticity field and formation of mesovortices</td>
</tr>
<tr>
<td>IIe</td>
<td>Mesovortices that develop along a QLCS that are not associated with LEWPs, bows or RIJs</td>
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<tr>
<td>---</td>
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</tr>
<tr>
<td>IIIf</td>
<td>QLCS are typical in the outer spiral bands of a hurricane and may produce tornadoes in RFQ at landfall; supportive values of CAPE and ambient vertical vorticity</td>
</tr>
<tr>
<td>IIIa</td>
<td>Cumuliform cloud (sometimes not glaciated) with intense local updraft that converges and stretches vertical vorticity into misocyclone in the PBL</td>
</tr>
<tr>
<td>IIIb</td>
<td>Similar to IIIa (but over water) and typically not glaciated; not to be confused with Type I and Type II tornadoes over water</td>
</tr>
<tr>
<td>IIIc</td>
<td>Convective instability due to cold air aloft and favorable shear for vortex development in a cooler environment (typically does not reach the ground)</td>
</tr>
<tr>
<td>IIId</td>
<td>An inertial instability along a vortex sheet created by thunderstorm gust front in the PBL; typically weak and confined to shallow depths</td>
</tr>
<tr>
<td>IIIe</td>
<td>An inertial instability along the high shear zone of a hurricane eyewall resulting in intense misovortices</td>
</tr>
<tr>
<td>IIIIf</td>
<td>Anticyclonic vortices that form in close proximity to much stronger cyclonic tornadoes and within the clockwise shear zone and region of anticyclonic downdraft tilting</td>
</tr>
</tbody>
</table>
Figure 1. A Doppler radar image of a supercell thunderstorm near Oklahoma City on 3 May 1999. The image on the left shows a nice example of a hook echo radar feature that often accompanies the mesocyclone. The image on the right shows the doppler velocity field and the color velocity couplet that locates a tornado vortex signature (TVS).
Figure 2a-c. Examples of different QLCS structures that are viewed as capable of Type II tornadogenesis; a) An example of a bow echo near San Angelo, Texas on 7 April 2002; b) A bow echo and associated comma head over central Illinois on 4 June 2002. A weak tornado (F0) was reported by the Illinois State Police; c) QLCS in southwest Illinois during BAMEX on 6 June 2003 at 2300 UTC. Several tornadoes were produced by this event.
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Tornado Classification System

Type I
- Supercells* (with Mesocyclone)
  - Ia- Classic Supercells (SR, SL)
  - Ib- Low-Top Mini-Supercells
  - Ic- Tropical Storm/Hurricane Related Mini-Supercells

Type II
- QLCS* (Cold Pool, Shear, Mesocyclone)
  - Ila- LEWPs
  - IIb- Bows
  - IIc- BEVs
  - IIId- RIJs
  - IIe- Other Mesovortices
  - IIIf- Tropical Storm/Hurricane Spiral Bands

Type III
- Localized Convective and Shear Vortices
  - IIIa- Landspouts
  - IIIb- Waterspouts
  - IIIc- Cold Air Funnels
  - IIIId- Gustnadoes
  - IIIe- Hurricane Eyewall
  - IIIIf- Anticyclonic Secondary Vortices

*Type I and Type II "waterspouts" are possible

Figure 5. Schematic of tornado types and associated species.