MULTIPLE VORTEX PHENOMENA IN THUNDERSTORMS AND TORNADOES:
THREE SCALES FOR MULTIPLE VORTICES

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1. INTRODUCTION

It is recognized in the fluid mechanics of swirling flows that distinctly different vortex structures can occur beneath a single rotating updraft. Such structures have long been observed in tornadic thunderstorm events (Agee et al. 1976, Fujita 1976, Agee et al. 1977) as well as in laboratory simulations of tornado-like vortex flows (Ward 1972, Church et al. 1977). In the past two decades, the general availability of video cameras has led to a plethora of video recordings of rotating thunderstorms, wall clouds, singular and multiple vortex formations on a variety of spatial and temporal scales accompanied with documentation of unusual and interesting cycloidal debris patterns. Although multiple vortex (MV) structures have been simulated in the laboratory with great success, such laboratory experiments did not simulate different MV scales simultaneously, as is sometimes observed in thunderstorm and tornado systems.

It is well recognized that a number of different physical processes can contribute to vortex formation, maintenance, and structural evolution. On the thunderstorm cloud scale, a strong updraft in the presence of jet stream wind shear is a key to mid-level mesocyclone formation (through the vertical tilting of streamwise vorticity, or storm relative helicity). The source of low-level rotation is potentially more complicated however, because of the increasing importance of the various physical processes that can be considered (as seen in the Beltrami Vorticity Equation). Either the mid-level vortex intensifies and extends into the boundary layer or the low-level rotation can develop and subsequently connect with the mid-level mesocyclone. Many different scenarios of mesocyclone, tornado vortex signatures, and tornado formations have been documented in the literature (see Dowell and Bluestein 1997).
As introduced above, and as seen in the classical laboratory work at the University of Oklahoma and at Purdue University, it is a natural process for a vortex (under conditions of increasing swirl) to undergo vortex breakdown (VB), and even subsequently develop a pattern of subsidiary vortices. A downdraft in the vortex core is critical to the establishment of an annulus region of strong radial shear in the tangential velocity field that can lead to an inertial instability and MV formation (see Snow 1978). As discussed later, such multiple vortex events may occur in thunderstorms and tornadoes on three different scales.

It is also noted in the literature that mesocyclogenesis (as introduced in numerical simulations by Adlerman and Droegemeier (1999)) can account for multiple sequential formations of mesocyclones and accompanying tornadoes. Their mesocyclogenesis proceeeds through the evolution of an occlusion downdraft (OD) and the formation of a new, strengthening mesocyclone that can become tornadic. Although the authors like the results of their study, allowances must continue to be made for the occurrence of mini-tornado cyclones through vortex breakdown. In essence, there may be a “VB” versus “OD” controversy, yet from a kinematic viewpoint there are similarities (e.g. a downdraft in the central core region) while the dynamics are entirely different. The field investigation of the Garden City, Kansas storm (see Wakimoto and Liu 1998) and the subsequent follow-up paper on this event by Trapp (2000) illustrate the why and how of the “VB” versus “OD” controversy. The authors further note that “OD” tornado families tend to follow the series mode production of tornadoes, while the “VB” tornado families follow the parallel mode (curtate cycloidal) tracks, with even three or more vortex centers (a feature not simulated in the Adlerman and Droegemeier study).

2. THE THREE MV SCALES

This study proposes that multiple vortex structures can occur on three different spatial and temporal scales, separately and/or sequentially and/or simultaneously. In order to define these three scales of multiple vortices, the mesocyclone (M) is first introduced as the parent event for such formations.

The first and largest scale of multiple vortex phenomena (MV I) is the mini-tornado cyclone (first proposed by Agee et al. 1976). This scale is defined as two or more vortices (embedded within the mesocyclone) that rotate about a common central axis. Each of these centers can produce a visible wall cloud, and each can potentially be detected in doppler radar velocity fields. It is even possible that one or more of these vortex centers can produce a tornado on the ground, resulting in the familiar curtate cycloidal tornado track (first defined by Fujita et al. (1970), as the parallel mode tornado family).

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The second (and intermediate) scale of multiple vortex phenomena (MV II) is defined as multiple vortex columns extending beneath a single wall cloud. These vortex columns extend up through the boundary layer and well into the cloud layer. These vortices also surround a downdraft core and are most likely due to VB and the subsequent inertial instability. In fact, this scale of multiple vortex phenomena best corresponds to the MV patterns created in the University of Oklahoma and Purdue University laboratories. Such a multiple column tornado vortex event is denoted as a T_m tornado, whereas a single column tornado event is denoted as a T_s tornado.

The third (and smallest) scale of multiple vortex phenomena (MV III) is defined as suction vortices. These vortices are contained within the surface boundary layer and are seen to rotate rapidly around the base of a tornado vortex column (either T_s or T_m columns). MV III vortices produce the all familiar prolate cycloidal debris patterns in fields of corn stubble and other similar surface tracer material. The authors note that suction vortices live up to their name by accumulating and piling up debris in their path (a vortex that is responding to the strong effect of surface friction, as seen in the teacup vortex). It is further noted that tall individual tornado vortex columns evacuate material along the path of the center point of the vortex (as seen in the Moore, OK tornado on 3 May 1999).

3. A Vortex Classification System

The three scales of MV phenomena, as proposed, are now placed within a general system for the classification of all possible thunderstorm and tornado related events. A list of the ten possible combinations is given below, where the three MV scales are noted as I, II, and III (from the largest to the smallest scale).

1. M
2. M – T_s
3. M – I
4. M – I – T_s
5. M – T_m – II
6. M – T_s – III
7. M – T_m – II – III
8. M – I – T_m – III
9. M – I – T_s – III
10. M – I – T_m – II – III

Figure 1 is presented as a classification tree for these ten possibilities, all of which have been observed in nature. This classification tree is intended to show the different scenarios for the mesocyclone (M), the mini-tornado cyclone (scale I), singe (T_s) and multiple column (T_m) tornadoes – scale II, and suction vortices (scale III). Also, this tree structure illustrates the different path line for all possible events, e.g. a mesocyclone with a single-column tornado, surrounded by suction vortices (as seen in the West Lafayette, IN tornado on 20 March 1976). In this case the only MV phenomena was

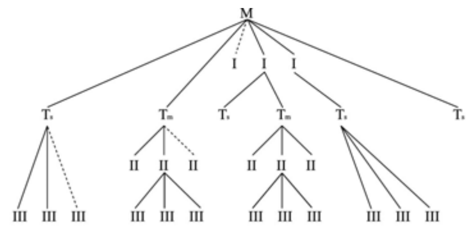

Fig. 1 A tree classification system for MV phenomena in thunderstorm-tornado events.

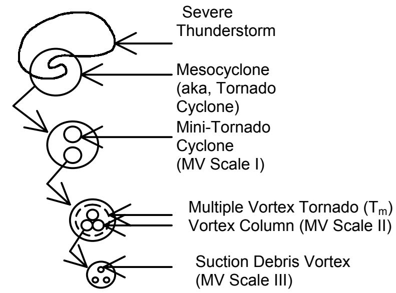

Fig. 2 A progressive example of all three scales of multiple vortex phenomena.

scale III. Figure 2 shows a different path line where all three scales of MV phenomena occur (as in Friendship, OK 11 May 1982 and Oakfield, WI 18 July 1996).

4. Selected Case Studies

Although numerous observational case studies have been assembled in this research effort that represent each of the ten possible events, six MV cases are presented in this paper.

4.1 Canadian, TX, 7 May 1986 (M – I – T_s)

Figure 3 shows the two wall clouds at 1636 CST, which represents MV I. In fact, each wall cloud contains a tornado, and two tornado tracks (parallel mode) are shown in Figure 4. It is further proposed that this MV I scale is due to VB and not OD, especially since the two tornadoes are

Fig. 3 Two mini-tornado cyclones each producing a T_s tornado near Canadian, TX (see Bluestein 1999).

occurring simultaneously. Also, there is no evidence of a rain-wrapped occlusion. The start

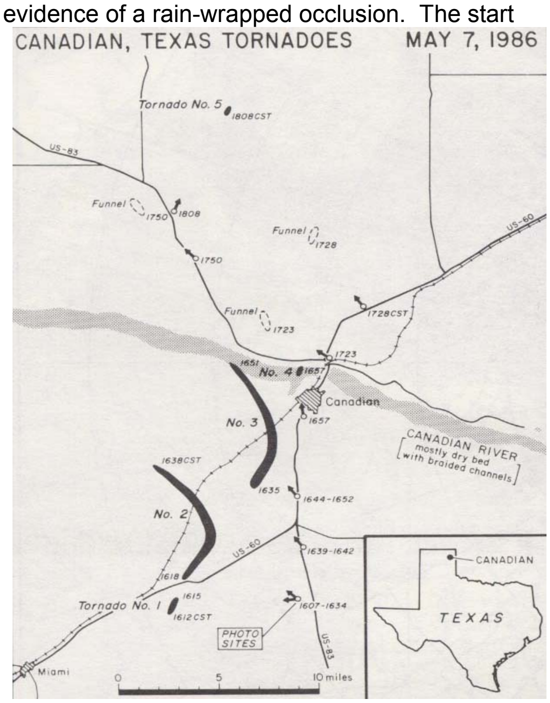

Fig. 4 Canadian, TX parallel mode tornado family exhibiting curtate cycloidal damage patterns.

time for each tornado is separated by 17 minutes, much less than the two hour (to one hour) intervals in the Adlerman et al. (1999) mesocyclogenesis study, and the twenty minute to two hour intervals reported by Darkow and Roos (1970).

4.2 Wichita Falls, TX, 10 April 1979 (M – I – T_m – II)

This thunderstorm-tornado event is an excellent example of MV scales I and II. Figure 5 shows a radar depiction of two mesocyclones (i.e. two mini-tornado cyclones) along with an insert of a visible photograph showing the two corresponding wall clouds (i.e. MV I). The southwest mesolow vortex later produced the F4 Wichita Falls tornado,

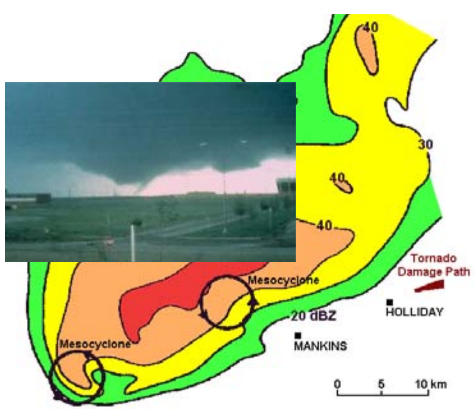

Fig. 5 Two mesocyclones depicted on radar imagery at 1730 CST, with superimposed photograph of two visible wall clouds taken at about 1750 CST.

Fig. 6 Multiple vortex columns (MV II) comprising the Wichita Falls, TX tornado of 10 April 1979.

which can be seen in Figure 6 as a distinct multiple column tornado (i.e. MV II).

4.3 West Lafayette, IN, 20 March 1976 (M – T_s – III)

This supercell storm produced a series mode tornado family across Illinois and Indiana (Fujita et al. 1976). The tornado track near West Lafayette was examined in a study by Agee et al. (1977), which showed a distinctive pattern of prolate cycloidal debris tracks caused by suction vortices. A number of photographs in the Agee et al. study show these patterns as well as still photographs of the suction vortices, located within the surface boundary layer around the bottom of a single conical vortex column.

4.4 Orienta, OK, 2 May 1979 (M – T_m – II – III)

This is one of the more famous tornadoes in movie/video camera archives, which was photographed by an NSSL storm chase team. This movie became instantly famous because it clearly displayed two scales of multiple vortex formation simultaneously (which are identified as MV scales II and III in this study). The authors did determine that the Orienta storm produced a series mode tornado family, and thus there was no evidence of MV scale I.

4.5 Garden City, KS, 16 May 1995 (M – I – T_s – III)

This storm event has been well studied and reported on in the literature. Wakimoto and Liu (1998) reported airborne doppler radar measurements of the mesocyclone that showed three vortex centers (MV scale I). Only one of these vortex centers produced a tornado, which did follow a curtate cycloidal path. Along this singular path there were distinct patterns of suction debris (prolate cycloidal) vortex tracks indicative of MV III, see Figure 7 (taken from Wakimoto and Liu). This case has garnered considerable attention due to the study by Trapp (2000), and the prospects for

Fig. 7 Cycloidal debris patterns embedded within the main track of the Garden City, KS tornado track, indicating MV scale III.

the misinterpretation of VB rather than OD formation of MV scale I.

4.6 Friendship, OK, 11 May 1982 (M – I – T_m – II – III)

This storm event is offered up as a case study that depicts all three scales of MVs. Although no doppler data are available, there is circumstantial evidence of MV scale I due to the parallel mode tornado family. Figure 8 clearly shows MV scale II, as several vortex columns are seen extending beneath a single wall cloud. Also, prolate cycloidal debris patterns (not shown) produced by suction vortices are evidence of MV III. Not discussed in this paper is another case of all three MV scales, namely the Oakfield, WI storm of 18 June 1996.

Fig. 8 Multiple vortex columns, MV II, comprising the Friendship, OK tornado of 11 May 1982 (see Bluestein 1999).

5. Summary and Conclusions

Three different scales of MV phenomena have been proposed and shown to occur in thunderstorm-tornado events. Also, a general classification system (with ten categories) has been presented, which encompasses all possible outcomes of mesocyclone and accompanying subsidiary vortex formation. The emerging "VB" versus "OD" controversy has been emphasized, and it is proposed that series mode tornado families correspond well with mesocyclogenesis, whereas parallel mode tornado families best correspond with VB and subsequent inertial instabilities. The time and space scales (smaller for VB, and larger for OD) has also been emphasized. Finally, the observational findings (VORTEX) by Dowell and Bluestein (2000) tend to be more supportive of the ideas presented in this paper than for "OD" mesocyclogenesis. Clearly, more research is needed, both field observations and numerical simulation.

Acknowledgements: This study was partially funded by NSF Grant ATM-9813687 awarded to Purdue University.

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