A Reassessment of the Percentage of Tornadic Mesocyclones

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ABSTRACT

A large set of data collected by numerous Weather Surveillance Radar-1988 Doppler (WSR-88D) units around the United States was analyzed to reassess the percentage of tornadic mesocyclones. Out of the 5322 individual mesocyclone detections that satisfied the relatively stringent WSR-88D Mesocyclone Detection Algorithm objective criteria, only 26% were associated with tornadoes. In terms of height or altitude of mesocyclone base, 15% of midaltitude mesocyclone detections were tornadic, and more than 40% of low-altitude mesocyclone detections (e.g., those with bases ≤ 1000 m above radar level) were tornadic. These results confirm that a *low-altitude* mesocyclone is much more likely to be associated with a tornado than is a *midaltitude* mesocyclone, and more generally, that the percentage of tornadic mesocyclones is indeed lower than previously thought.

1. Introduction

An unresolved issue both in research and operational forecasting endeavors concerns the percentage of mesocyclonic thunderstorms that spawn tornadoes. Underscoring the importance of the issue to forecasting, for example, is the following: "Mesocyclone signatures are the most often used Doppler radar inputs to tornado warnings. . ." (Burgess et al. 1993). Often cited in the literature is the statistic that ~50% of all mesocyclones are tornadic (e.g., Burgess et al. 1979). This percentage was based on research Doppler radar scans primarily of supercells in central Oklahoma; it is now generally believed to be lower, perhaps ~30% (e.g., Burgess and Lemon 1991; Burgess et al. 1993). Expressed in terms of height or altitude of mesocyclone base, the percentages of midaltitude (nominally, base altitudes ~3–7 km AGL) and low-altitude (nominally, base altitudes ≤ 1 km AGL) mesocyclones have yet to be formally estimated. The presumption that most low-altitude mesocyclones are tornadic has been called into question (Trapp 1999; see also Wakimoto and Cai 2000).

Herein, we exploit a large set of data, collected using the network of Weather Surveillance Radars-1988 Doppler (WSR-88D) units, to estimate the percentage of tornadic mesocyclones, including those qualified as mid altitude and low altitude. Our data, and the method by which they are processed, are described in section 2. The results from our study then are presented in section 3. Conclusions are given in section 4.

2. Method

Our dataset comprises WSR-88D data collected during 83 "events." Each event had a duration of about

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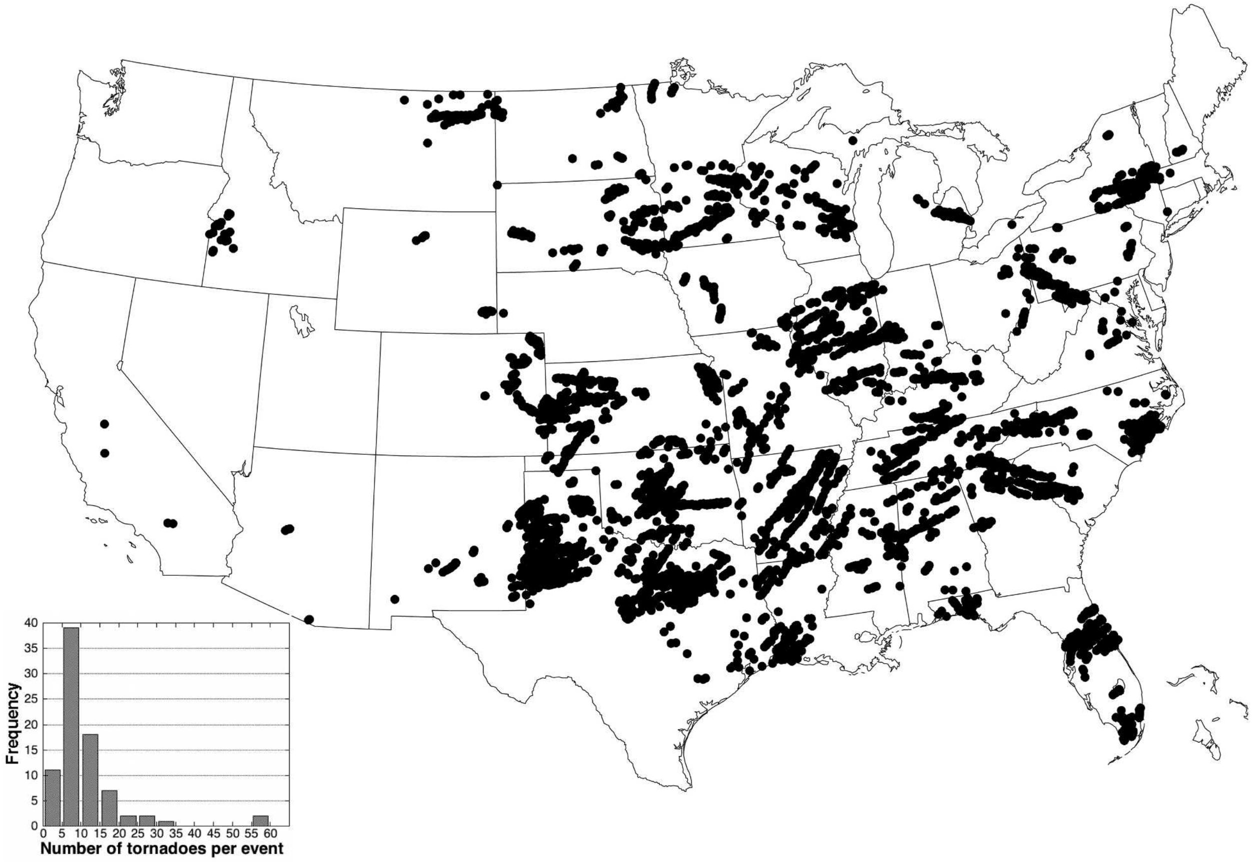

FIG. 1. Geographical location of mesocyclone detections in the dataset. Inset shows the distribution of number of tornadoes per tornadic event.

4–10 h (6.75 h on average), during which time one or more (tornadic and/or nontornadic) mesocyclonic thunderstorms occurred. A total of 546 tornadoes were spawned by mesocyclonic storms in 73 of the events, referred hereafter as tornadic events. Two of these events (21 January 1999 and 3 May 1999) included ≥ 50 tornadoes each and hence can be regarded as significant tornado outbreaks; two others had ≥ 25 tornadoes. More than half of the events, however, had 5 or fewer tornadoes (see Fig. 1). The tornadoes had a range of damage-based intensities, and originated from a variety of manually classified thunderstorm types (classic supercell, heavy-precipitation supercell, bow echo, etc.). Nontornadic mesocyclonic thunderstorms occurred during the remaining 10 events, hereafter referred to as null events. It is important to note that nontornadic mesocyclones also occurred during the tornadic events, since not all storms observed during these events produced tornadoes; nevertheless, as in studies of other intermittent phenomena, the possibility remains that we did not adequately sample the true populations of tornadic and nontornadic mesocyclones. Figure 1 demonstrates that the dataset, compiled from data during 1992–99 and drawn from 54 different WSR-88Ds, is geographically diverse.

We postprocessed WSR-88D data in Archive Level II format (Crum et al. 1993) using the National Severe Storms Laboratory (NSSL) Severe Storm Analysis Package (SSAP). The component of SSAP most relevant to this study is the WSR-88D Mesocyclone Detection Algorithm[1] (MDA; Stumpf et al. 1998). In our application of MDA, vortices were classified as mesocyclone detections if, in any given radar volume scan,

[1] Formerly known as the "NSSL MDA," this is now the operational mesocyclone detection algorithm in the WSR-88D, as part of the Open Radar Products Generator (ORPG). It was fully implemented in the Advanced Weather Interactive Processing System (AWIPS) in the spring 2005. In contrast to the algorithm available for this study, the operational version uses the 3-km depth criterion as well as a "25% relative-depth" criterion, computes the 3D strength rank for both, and chooses the greater of the two to describe the mesocyclone. The implication is that the relative-depth criterion enables the operational algorithm to better detect mesocyclones in low-topped supercells.

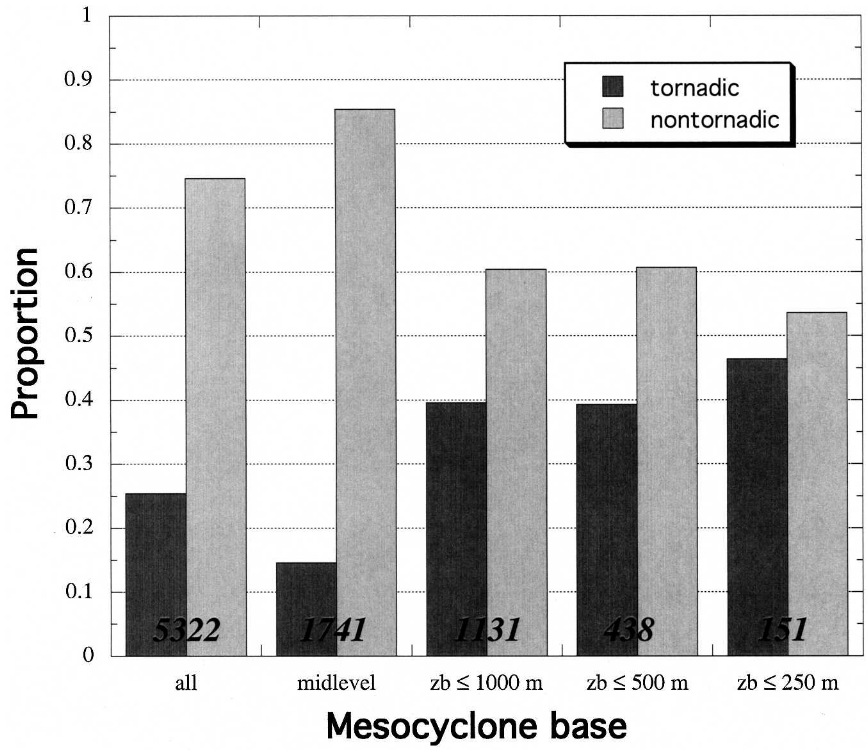

FIG. 2. Proportion of tornadic vs nontornadic mesocyclones, as a function of altitude of mesocyclone base (z_b). Here, "all" refers to all mesocyclone detections from the dataset that satisfied the NSSL Mesocyclone Detection Algorithm objective criteria (see text); "midlevel" denotes mesocyclone detections with bases at altitudes $3 \leq z_b \leq 7$ km ARL; and $z_b \leq 1000$, $z_b \leq 500$, and $z_b \leq 250$ m denote mesocyclone detections with bases at or below 1000, 500, and 250 m ARL, respectively. Bold numbers at bottom of columns are the number of mesocyclone detections in each altitude range.

the diagnosed radial velocity difference (ΔV) and radial velocity shear (S) across the perceived vortex had values

$$\Delta V \geq 30 \text{ m s}^{-1} \quad \text{and} \quad S \geq 6 \text{ m s}^{-1} \text{ km}^{-1} \quad \text{for ranges} \leq 100 \text{ km},$$

$$\Delta V > 22 \text{ m s}^{-1} \quad \text{and} \quad S > 3 \text{ m s}^{-1} \text{ km}^{-1} \quad \text{for ranges} > 200 \text{ km},$$

or exceeding the ΔV and S derived from a linear decrease in these thresholds for ranges between 100 and 200 km (see Stumpf et al. 1998); these thresholds define the mesocyclone strength rank-5 criteria used in the MDA. We additionally required that the rank-5 criteria be met at or below an altitude of 5 km above radar level (ARL), and over a vertical depth $\geq$ 3 km. Finally, we required that the depth and altitude criteria be met over a period longer than 5 to 6 min (i.e., more than one radar volume scan).

Strictly speaking, there is no dynamical significance to these specific mesocyclone criteria: one could use other sets of observations and define rotating updrafts/downdrafts in supercells in many different ways. The MDA criteria originated in part from those used by Burgess et al. (1979) during the Joint Doppler Operational Project (JDOP; see the appendix), and have been proven to identify mesocyclones with a high probability of detection and a corresponding low probability of failure (Stumpf et al. 1998). It should be emphasized that although the MDA is capable of identifying all storm-scale vortices, we have limited our study to vortices characterized strictly as mesocyclones, as defined using subjective and objective analyses of hundreds of convective storms observed in the United States. This consideration of what can be regarded as the most operationally significant storm-scale vortices is somewhat a philosophical choice, different from that of Jones et al. (2004), who included all but the very weakest (strength-rank 0) vortices in their statistical study. We acknowledge that weak and/or shallow vortices can on occasion be associated with tornadoes and severe winds, and that their exclusion here may introduce a bias to our statistics. On the other hand, our dataset does include mesocyclones from squall lines and bow echoes, for example, which may be perceived as generally weak and shallow but indeed can be detectable (see Manross et al. 2004 for a discussion of squall line and bow echo mesocyclone characteristics).

Tornado damage information such as from *Storm Data* or from poststorm surveys by NSSL personnel and during special field programs (see Stumpf et al. 1998) was used to determine an association (or lack thereof) between each mesocyclone detection and a tornado; the latter survey information is likely more reliable than *Storm Data* reports, which have possible errors and deficiencies as described by Witt et al. (1998). Following the procedure justified by Stumpf et al. (1998) and discussed further by Witt et al. (1998), a mesocyclone detection was considered tornadic if it was associated with a tornado report at some time during the interval

$$(T_B - 20\ \text{min}) \leq T_B \leq T_E \leq (T_E + 6\ \text{min}),$$

where T_B and T_E are the beginning and ending times, respectively, of the reported tornado. Particularly in instances of weak tornadoes, a mesocyclone detection would be incorrectly labeled nontornadic if an associated tornado was not reported and did no damage. A detection would be incorrectly labeled tornadic if associated straight-line wind damage was mistakenly deemed tornado damage.[2] Unfortunately, given the state of reports in *Storm Data*, we have no evidence to suggest a higher likelihood of either of these possible errors.

To emphasize and distinguish mesocyclone detections by altitude, we applied a simple scheme involving the mesocyclone base (z_b). Here, z_b is the lowest altitude of the 3D vortex. Thus, mesocyclone detections were defined as midaltitude when $3 \leq z_b \leq 5$ km ARL, or defined as low altitude when $z_b \leq 1000$ m; low-altitude thresholds of $z_b \leq 500$ m and $z_b \leq 250$ m ARL were also used. It is important to note that the MDA permits the lower end of the 3D vortex to weaken to strength rank 1 ($\Delta V \geq 10$ m s^{-1} and radial velocity shear ≥ 3 m s^{-1} km^{-1}) provided that the 3D vortex still has at least a 3-km vertical core in which the strength rank is ≥ 5.

[2] We attempted to account for this by omitting any tornado reports from *Storm Data* in which damage was not reported and the tornado path was described as "short and narrow," except in cases when a significant storm-scale vortex was visually observed in the radar data (Stumpf et al. 1998, p. 317).

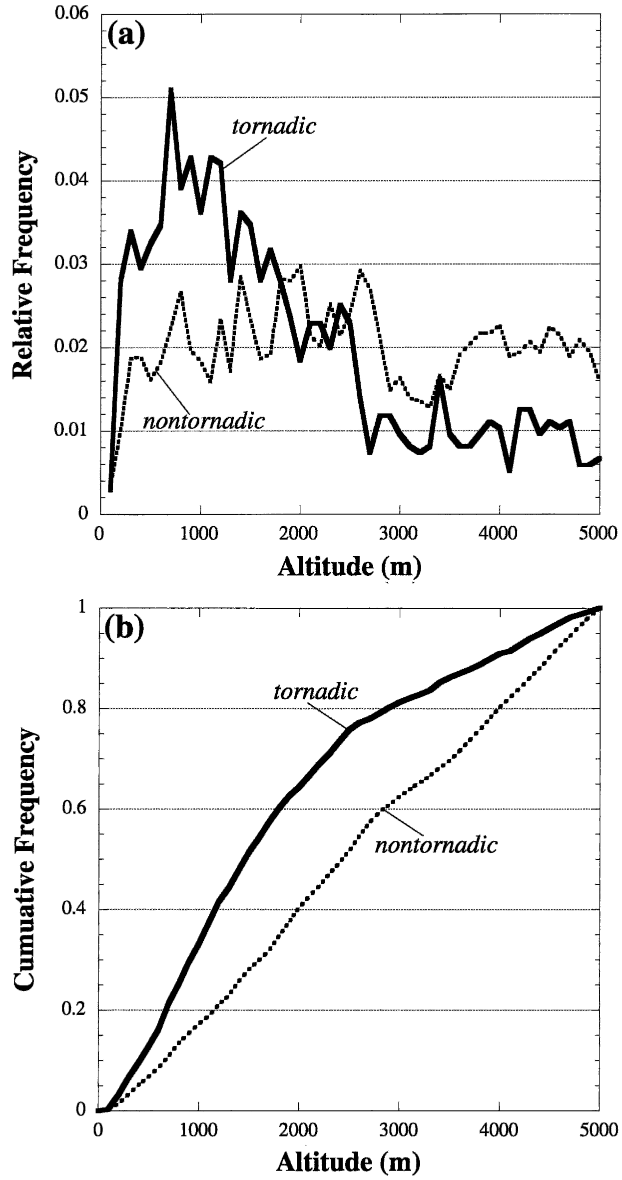

FIG. 3. (a) Relative and (b) cumulative frequency distributions of the base altitudes of tornadic and nontornadic mesocyclones.

3. Results

A total of 5322 mesocyclone detections within individual volume scans were identified by the MDA. Of these, 26% were associated with a tornado (Fig. 2). As a function of base altitude, 15% of the 1741 midaltitude mesocyclones were tornadic, as were 40%, 39%, and 46% of the 1131, 438, and 151 mesocyclones with $z_b \leq 1000$, $z_b \leq 500$, and $z_b \leq 250$ m ARL, respectively (Fig. 2). Hence, roughly 40% of the sampled low-altitude mesocyclone detections were tornadic, depending on the definition of "low altitude."

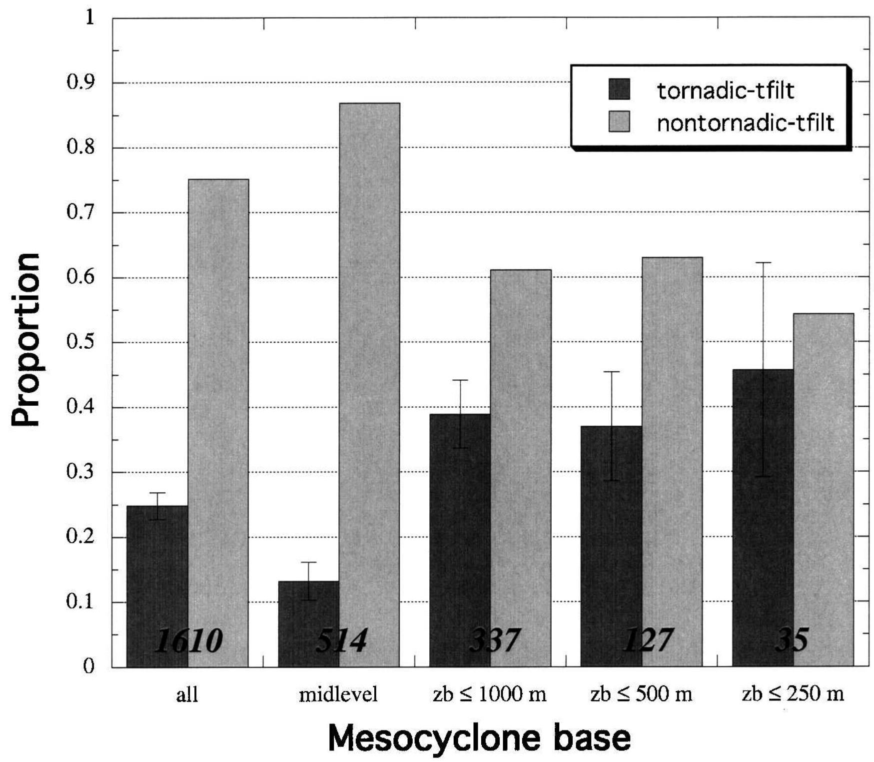

FIG. 4. As in Fig. 2, except for a subset of the dataset, in which consecutive mesocyclone detections during the same event are separated temporally by at least 45 min ("tfilt"). Error bars represent a 95% confidence interval and have lengths that are inversely proportional to $N^{1/2}$, where N is the number of detections in each altitude range (see text).

The actual number of low-altitude mesocyclones would be underestimated when deep mesocyclonic storms are not scanned at low altitudes owing to their occurrence at distant ranges. We investigated the effect of such situations on our statistics by considering only those midaltitude mesocyclone detections that occurred within a range of 100 km (and hence could have been sampled at low levels); 317 midaltitude detections met this criterion, and 13% of these were tornadic. Since this percentage of tornadic midaltitude mesocyclones is only slightly different than that for the entire sample, it appears as if our statistics are not adversely affected by this range issue.

We also evaluated separately the distributions of tornadic and nontornadic mesocyclone base altitudes. Relative frequency as well as cumulative frequency distributions of tornadic and nontornadic mesocyclone base altitudes show more clearly that tornadic mesocyclones have a higher probability of occurrence at low altitudes than do nontornadic mesocyclones (Fig. 3). For example, the cumulative probability of a tornadic mesocyclone base at or below 1000 m is 33%, compared to a 17% cumulative probability of a nontornadic mesocyclone base within these altitudes.

When interpreting the results thus far, one must keep in mind that the individual mesocyclone detections may in reality be volume-scan snapshots of one actual or complete mesocyclone having a multiple volume-scan lifetime. In other words, some mesocyclone detections from a given event can be mutually dependent.

To help filter such dependent observations, we reprocessed the MDA data with the additional requirement that the time separation between any two mesocyclone detections in a given event be greater than 45 min. Based on results presented by Burgess et al. (1982), this should be equivalent to requiring the lapse of a mature mesocyclone stage (or of an entire "multiple mesocyclone core" life cycle) between mesocyclone detections. One result of our time filtering procedure is a reduction of the total sample size to 1610. However, Fig. 4 shows that the resultant percentages of all, midaltitude, and low-altitude ($z_b \leq 1000$, ≤ 500, ≤ 250 m) tornadic mesocyclones still do not differ significantly from those presented in Fig. 2. Error bars that represent a 95% confidence interval are less than $\pm 10\%$, except in the low-altitude bin of $z_b \leq 250$ m; the error bar lengths are inversely proportional to $N^{1/2}$,

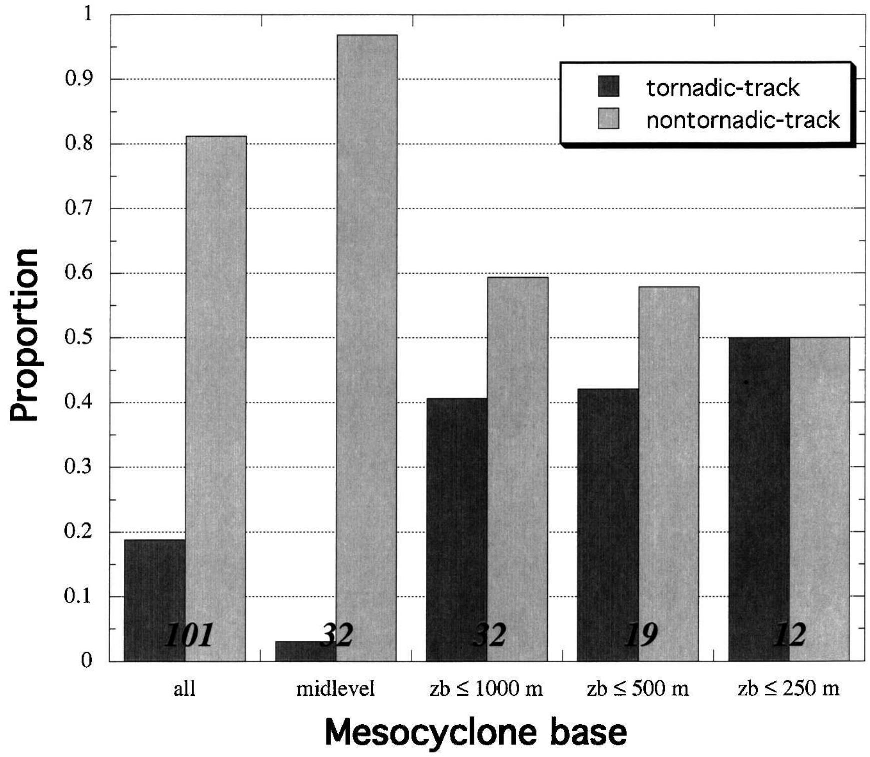

FIG. 5. As in Fig. 2, except based on data of the 101 complete mesocyclones ("track").

where N is the number of observations per bin (Wilks 1995, 119–121).

Implicit in the objective of the current study is a direct comparison of our WSR-88D mesocyclone data with research Doppler radar data originally analyzed by Burgess et al. (1979). The Burgess et al. statistics were based on the complete evolution of 62 manually tracked mesocyclones. A fair comparison requires from us a similar set of complete mesocyclones, which we constructed from individual detections as follows.

All detections with a strength rank 5 or greater in the dataset were sorted by time, date, and mesocyclone identification number (assigned to all individual detections believed by the algorithm to comprise a single mesocyclone). This automated sorting procedure led to the initial construction, from the individual detections, of 4133 complete mesocyclones. Specifically, a "complete mesocyclone" here is a list of consecutive detections that track a mesocyclone from its earliest detectable stages to its demise, when it is no longer meets mesocyclone criteria. After randomly shuffling the complete mesocyclone data, 101 were manually verified and enhanced, if necessary. This entailed viewing radar images to further assemble the entire life cycle of each of the 101 mesocyclones (i.e., if the mesocyclone identification number had changed). Thus, it is possible that during part of its life cycle, a mesocyclone's strength rank was less than 5. The mesocyclone was deemed tornadic if it was associated with a tornado at some time during its life.

In this sample of 101 complete mesocyclones, 19% were tornadic (Fig. 5). Upon determining the minimum altitude of the base of each mesocyclone during its life cycle, we found that only 3% of the midaltitude mesocyclones were tornadic. Otherwise, the percentages of tornadic mesocyclones considered low-altitude during their life cycle were in line with those shown in Figs. 2–3: 41%, 42%, and 50% of the 32, 19, and 12 mesocyclones with minimum $z_b \leq 1000$, ≤ 500, and ≤ 250 m ARL, respectively, were tornadic.

4. Conclusions

A large set of data collected by numerous WSR-88Ds was analyzed using the WSR-88D Mesocyclone Detection Algorithm to estimate the percentage of tornadic mesocyclones. A total of 5322 mesocyclone detections satisfied relatively stringent (i.e., strength rank of 5, depth of 3 km) criteria: (i) a height-unqualified 26% of these mesocyclone detections were tornadic; (ii) 15% of 1741 midaltitude mesocyclone detections were tornadic; and (iii) 40%, 39%, and 46% of the 1131, 438, and 151 low-level mesocyclone detections (respective bases z_b at altitudes $\leq$ 1000, $\leq$ 500, and $\leq$ 250 m ARL) were tornadic.

A time-filtered subset of this sample of mesocyclone detections, as well as a sample of 101 complete mesocyclones, also were analyzed. Consistently, about 40% of the mesocyclones/detections that had bases at or below 1000 m ARL were tornadic. Without reference to base altitude, less than 25% of all the mesocyclones/detections were tornadic.

Note that to meet our stated objective we evaluated no other mesocyclone attributes besides z_b and its classification as tornadic or nontornadic. Efforts are currently underway to evaluate a large number of additional attributes to find mesocyclone characteristics that best "predict" tornado occurrence (e.g., Marzban and Stumpf 1996; Marzban et al. 1999). These and related efforts would be especially fruitful if applied to a much expanded dataset—particularly on storms observed at close-to-moderate ranges—now obtainable owing to the increased accessibility to real-time and archived WSR-88D level II data and the use of advanced data mining techniques.

Our study confirms that the percentage of all tornadic mesocyclones is indeed much lower than initially reported, and now provides estimates of the percentages of tornadic mesocyclones as a function of altitude of mesocyclone base; clearly, a low-altitude mesocyclone is much more likely to be associated with a tornado than is a midaltitude mesocyclone. Additionally, our study quantifies Trapp's (1999) conclusion that existence of a low-altitude mesocyclone is an insufficient condition for tornadogenesis, and thereby aids those researchers forming tornadogenesis theories. Last, it provides guidance to forecasters who issue radar-based tornado warnings. Such forecasters likely have already reached conclusions similar to ours through their personal observations, and hence, are fully aware of other mesocyclone attributes as well as of the storm-spotter reports; radar, satellite, and lightning data; surface and upper-air observations; and numerical weather prediction model output that must be considered during the warning decision process.

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APPENDIX

JDOP Mesocyclone Criteria

As described by Burgess et al. (1979), an objectively defined mesocyclone during the Joint Doppler Operational Project was based first on the existence of azimuthal shear $\geq 5 \times 10^{-3}$ s^{-1} (at radar ranges less than 230 km), between closed contours of storm-relative radial velocity (isodops). It was necessary that this shear requirement also be met (i) throughout a vertical layer whose depth could be no less than 3 km or 50% of the nominal horizontal diameter of shear signature, and (ii) over a time interval defined by half the period of vortex revolution, deemed a "persistence scale":

$$\frac{\pi R \Delta\beta}{V_2 - V_1},$$

where $\Delta\beta$ is the angular distance (radians) between the radial velocity maxima in the two closed isodops, R is radar range (m), and $V_2 - V_1$ is the difference (m s^{-1}) between the two radial velocity maxima.

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