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TROCHOIDAL PATHS TRACED OUT BY A SUBVORTEX REVOLVING AROUND A PARENT VORTEX: A SIMULATION STUDY

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INTRODUCTION

- Trochoidal tracks traced out by tornadoes revolving around parent mesocyclones have been documented by numerous investigators.

OBJECTIVE OF THE STUDY

- To develop novel parametric equations for investigating and elucidating the transient behaviors of a tornado track traced out by a hypothetical tornado orbiting around a hypothetical parent mesocyclone (Fig. 1).

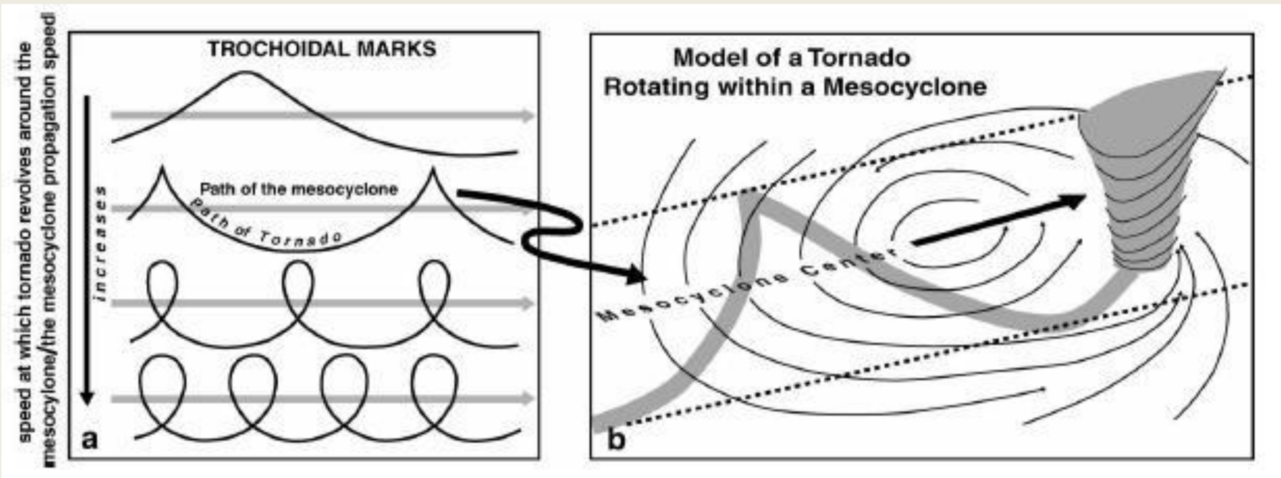


FIG. 1. Idealized illustration of (a) basic trochoidal marks (black curves) as a function of a hypothetical tornado center's rotational speed around a hypothetical mesocyclone center (gray arrows) and the motion of the mesocyclone and (b) a tornado track (gray shaded curve) if the ratio of the tornado's rotational speed to the mesocyclone's vortex movement speed is equal to one. (Figure from Wakimoto et al. 2003).

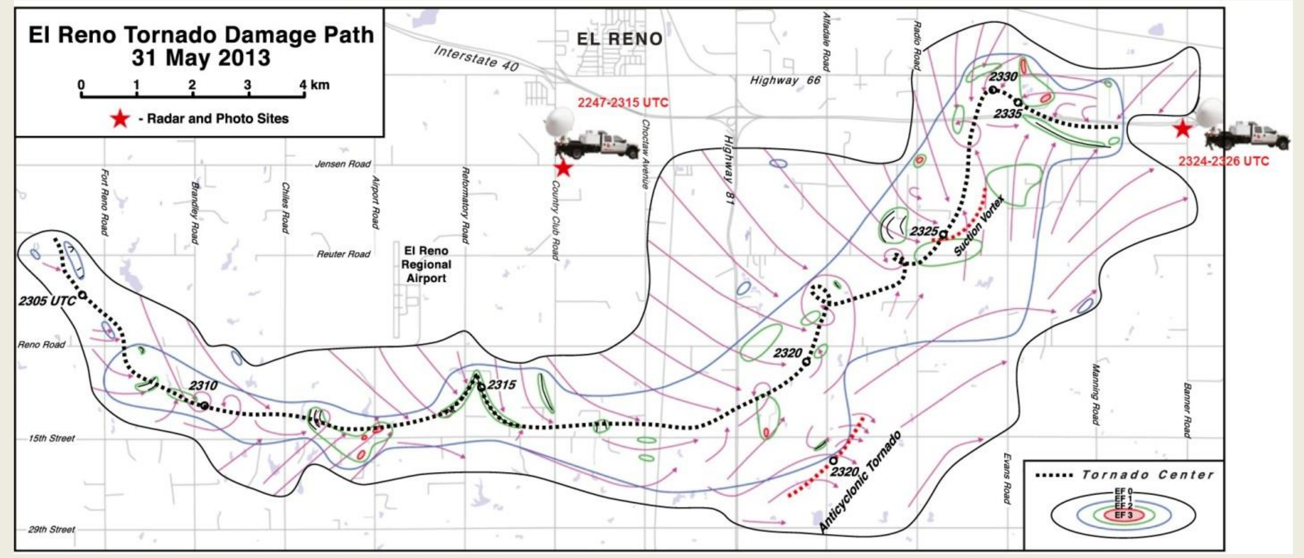


FIG. 2. Damage map of the El Reno, OK tornado of 31 May 2013. Black, blue, green, and red contours, respectively, denote the EF0, -1, -2, and -3 damage intensity isopleths. The tornado's damage track, including loops and cusps, is indicated by a black, dotted curve; Black, thick circles denote the time (UTC) of the radar-indicated location of the tornado. Two red, dotted curves denote the location of an anticyclonic tornado and cyclonic suction vortex. Magenta arrows represent the approximate flow depicted in the damage based on fallen trees, building debris, and streaks in the vegetation based on a detailed aerial survey. Red stars denote two deployment locations and times of the RaXPol mobile Doppler radar (shown by an icon of the truck). Photographs and high-definition video of the tornado were taken at both sides. (Figure from Wakimoto et al. 2015, 2016).

KINEMATICS OF A TROCHOIDAL MOTION

- Due to limited space in this poster, parametric equations for simulating a model trochoidal path traced out by a subvortex revolving around a parent vortex are kinematically described in Figs. 3 and 4 and also in the conference paper.

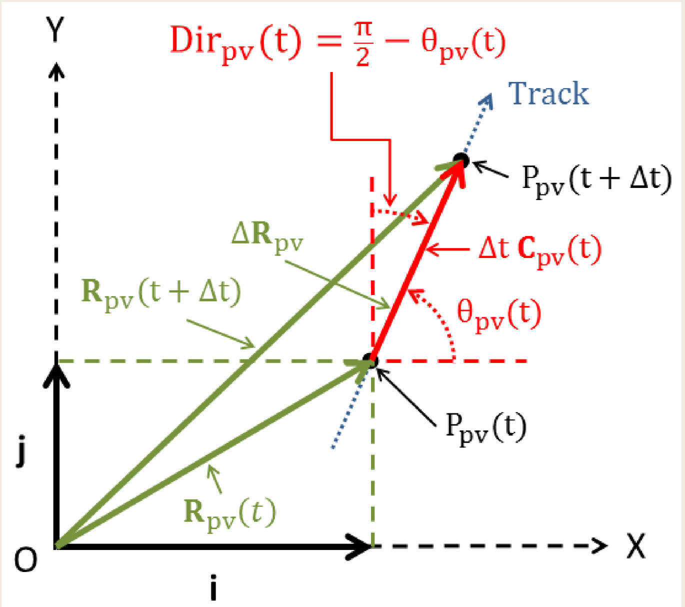


FIG. 3. Positions of a parent vortex axis P_{pv} at two different times t and t + Δt, relative to a given reference frame with origin O, are given by the parent vortex position vectors $\mathbf{R}_{pv}$ (green arrows) from point O to point P_{pv} (heavy black dots). Subscript (pv) stands for parent vortex. A blue circle with two arrows within which P_{pv} is centered represents a cyclonically rotating parent vortex. Δt is a small increment of time. The parent vortex's path angle θ_{pv} is indicated. The parent vortex moving at its (red) vector velocity $\mathbf{C}_{pv}$ along a curvilinear path (track) is indicated by a blue dotted line.

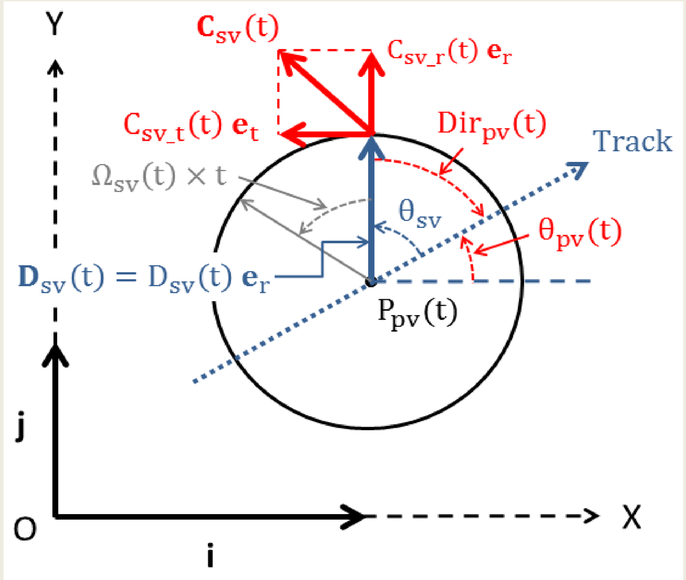


FIG. 4. Idealized illustration of the motion of a subvortex in a circular trajectory having Ω_{sv}. Subscripts (sv) and (pv), respectively, refer to subvortex and parent vortex. The radial and tangential components of the subvortex motion (speed and orbital direction) on the circumference of a circle (black) having its radius $D_{sv}(t)$ (blue thick line) are, respectively, indicated by the stretching (or shrinking) position vector $C_{sv\_r}(t)\mathbf{e}_{sv\_t}$ and the rotational velocity vector $C_{sv\_t}(t)\mathbf{e}_{sv\_t}$ relative to the position of the parent vortex point $P_{pv}(t)$. A blue, dotted line represents the parent vortex's track.

SIMULATION RESULTS

- We use the trochoidal motion model to provide what each input parameter in six experiments (Table 1) may be able to deduce about the transient behaviors of trochoidal marks traced out by a hypothetical tornado revolving around a hypothetical parent mesocyclone.

TABLE 1. Initial parameters that generate trochoidal tracks traced out by a model tornado axis revolving around a model parent mesocyclone axis as a function of time (t) up to 30 min are presented for six experiments (EXP) A-F. An arrow (→) located between two values represents a transient change from one value at $t=t_o$ to another value at $t=t_o+\Delta t$, where $\Delta t=$ 10 s. Units are: $C_{pv}(t)$ in m s^{-1}; $Dir_{pv}(t)$ in deg; $\theta_{pv}(t)$ in deg; $D_{sv}(t)$ in km; $\Omega_{sv}(t)$ in s^{-1}; $C_{sv\_t}(t)$ in m s^{-1}; & θ_{sv} in deg. See trochoidal motion animation in the conference paper.

TABLE 1

	Mesocyclone Axis			Tornado Axis			
EXP	$C_{pv}(t)$	$Dir_{pv}(t)$	$\theta_{pv}(t)$	$D_{sv}(t)$	$\Omega_{sv}(t)$	$C_{sv\_t}(t)$	θ_{sv}
A	25	90º	0º	1.5	10^{-2}	15	270º
B	15	90º	0º	1.5	10^{-2}	15	270º
C	5	90º	0º	1.5	10^{-2}	15	270º
D	1→40	90º	0º	1.5	10^{-2}	15	270º
E	40→1	90º	0º	1.5	10^{-2}	15	315º
F	25	90º	0º	1.5	0.0033→0.02	5→55	0º

EXPERIMENT A

- Evolutionary characteristics of $C_{tro}(t)$, $Dir_{tro}(t)$, $Dir_{sv}(t)$, PL_{tro}, $C_{pv}(t)$, $Dir_{pv}(t)$, and PL_{pv} are shown in Fig. 5.
- Distance between two red dots along the red dotted curve represents displacement during Δt = 10 s.
- The closer (farther apart) two red dots, the slower (faster) the tornado axis travels in its curvilinear motion.
- Two blue (black) dots along the red dotted curve represent a 1-min (5-min) update of the Phased Array Radar (WSR-88D).
- $R = C_{sv}(t)/C_{pv}(t) < 1.0$, indicated by blue circled curve.

EXPERIMENT B

- A cycloid with a zero-angle cusp (vertical slope) occurs only with R = 1.0. This R value produces three cycloidal marks in Fig. 6.
- $C_{tro}(t)$ is locally zero (maximum) to the left (right) of the mesocyclone track, indicating that the tornado is stationary (reaches its maximum trochoidal speed at 30 m s^{-1}).

EXPERIMENT C

- $R > 1.0$ produces three loops in Fig. 7. $C_{sv}(t) > C_{pv}(t)$.

EXPERIMENT D

- $C_{pv}(t)$ linearly increases from 1 m s^{-1} to 40 m s^{-1} (Table 1 and Fig. 8). Comparing to the upright loop (red, vertical line passing through the center of the loop in Fig. 7), the loop is tilted backward at earlier time, owing to the increased-propagating mesocyclone. R decreases with increasing $C_{pv}(t)$, while $C_{sv}(t)$ is kept constant.

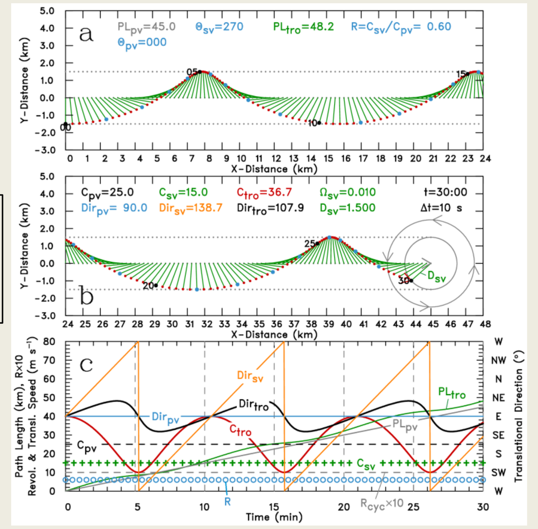
EXPERIMENT E

- Reverse Experiment D by stating that $C_{pv}(t)$ is now 40 m s^{-1} at initial time and $C_{pv}(t)$ is now 1 m s^{-1} at final time (Table 1 and Fig. 9).
- Fig. 9 is very similar to Fig. 8, except that the former figure is a mirror image of the latter figure.

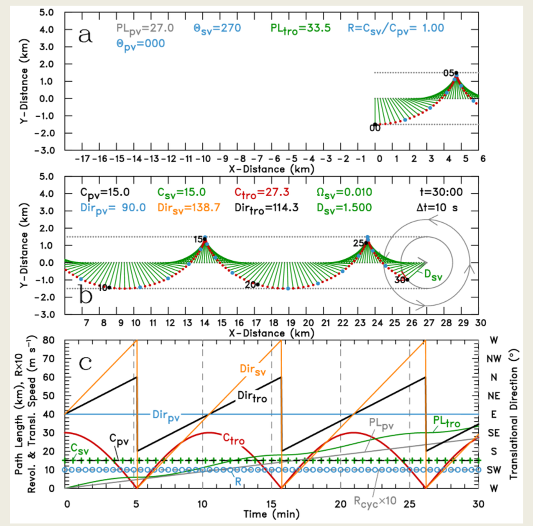
EXPERIMENT F

- The tornado's rotational speed $C_{sv}(t)$ linearly increases from 5 m s^{-1} at the start of track to 55 m s^{-1} at the end of track, indicating that the tornado axis rotates progressively and rapidly around the parent mesocyclone (Table 1 and Fig. 10).
- The varying $C_{sv}(t)$ causes to (a) change trochoidal marks and motions, (b) increase the distance between 2 successive red dots along the red dotted path, and (c) increase the loop size.

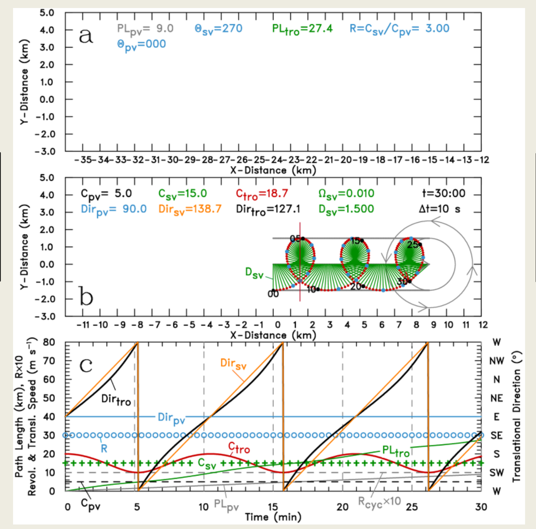
EXP A
FIG. 5



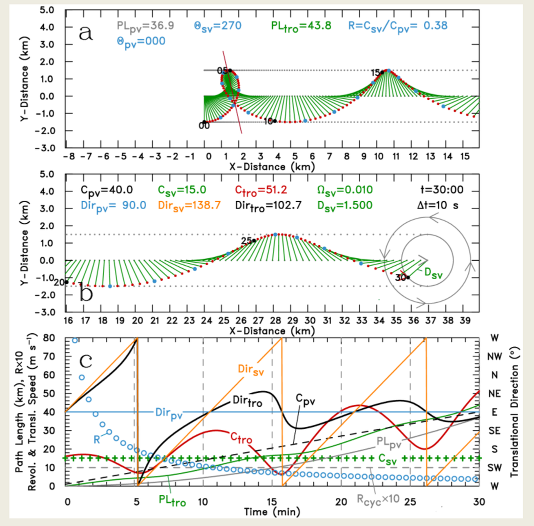
EXP B
FIG. 6



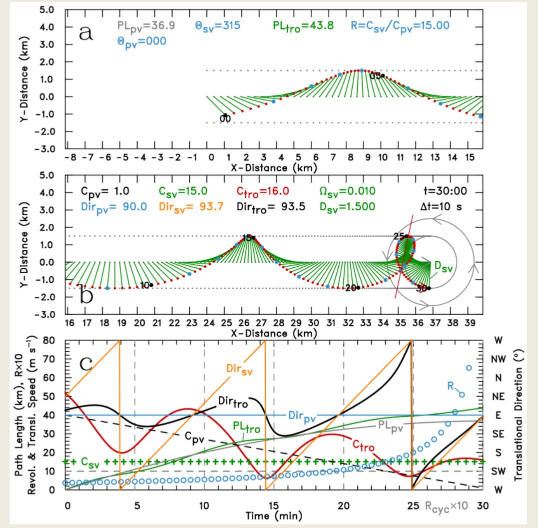
EXP C
FIG. 7



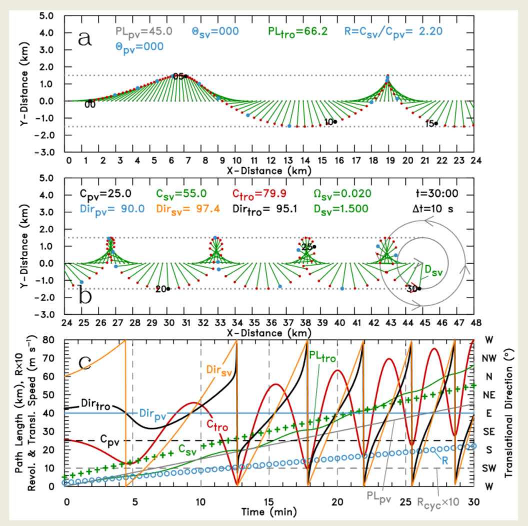
EXP D
FIG. 8



EXP E
FIG. 9



EXP F
FIG. 10



ON-GOING AND FUTURE WORKS

- Although trochoidal marks are the most interesting and useful of the marks left by tornadoes crossing open fields and towns (e.g., Fig. 2), we believe that the model developed in this study highlights the gap in our current understanding and interpretation of the relationship between the trochoidal motion simulations and the observed tornado damage tracks.
- In our on-going work, we plan to demonstrate that a model multiple-vortex tornado orbiting around a model parent mesocyclone will produce trochoidal marks traced out by the model multiple-vortex axes revolving cyclonically around the model parent tornado axis.
- We plan to map out near-surface tornadic wind fields produced by an analytical or numerical tornado orbiting around an analytical or numerical parent mesocyclone in an attempt to determine the duration of ground-relative windspeeds along a rectilinear/curvilinear tornado damage track.
- The trochoidal motion model will be applied to our future phased-array radar simulation studies. Zrnić and Istok (1980) provided single-Doppler data suggesting that the Del City, Oklahoma tornado of 20 May 1977 was orbiting cyclonically about a parent mesocyclonic circulation located at 35-40 km from the National Severe Storms Laboratory (NSSL) Doppler radar.

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