Tornadogenesis

TORNADOGENESIS

Davies-Jones recently (2006) stated that there are 3 stages in tornadogenesis:
1) rotating updraft aloft (well known mechanism)
2) development of rotation near the ground (questionable causes)
3) formation of tornado due to stretching of vorticity (well-known)

Burgess et al (1977) and Lemon and Doswell (1979) some of the best original discussions of tornadogenesis - stated the 3 stages a little differently:

1) organizing - supercell achieves dominance over nearby cells and turns right
   - it develops a mesocyclone
   - echo overhang forms (radar)
2) mature - mesocyclone builds down to lower levels
   - downdrafts intensify at low-mid levels
   - hook appendage forms on radar
   - weak tornado forms, pool of cold air forms at surface
3) collapse - BWER fills and downdrafts intensify
   - gust front surges outward
   - tornado forms at full strength at interface between updraft & downdraft
   - updraft weakens as perturbation low pressure forms in low levels as low rotates faster here than aloft, so PGF is directed downward

*Davies Jones has stated that long-lived tornadoes need a "buoyant cork" aloft to prevent filling of the low pressure due to rotation

SOME DETAILS ABOUT TORNADOES
- horizontal and vertical velocities have similar magnitudes, with maximums within 100 m of ground (modeling studies suggest peaks may be as low as 5-10 m)
- no good measurements of near ground tornado winds
- estimates of speed are very crude and based on damage - Fujita scale used for this but it is being modified. F5 may now indicate 200 mph winds instead of 300 mp

DIFFERING VIEWS OF THE ROLE OF MIDLEVEL ROTATION

1) it just helps bring potentially cold air to the forward left flank to create the forward flank downdraft and baroclinically-generated horizontal vorticity that can be tilted into vertical
2) passive role - rotation begins there and builds downward and upward (dynamic pipe), with stretching and tilting concentrating vertical vorticity into tornado

EQUATIONS:

$$\frac{\partial \zeta_z}{\partial t} = -V \cdot \nabla \zeta_z - w\frac{\partial \zeta_z}{\partial z} - \text{Div}(\zeta + f) - \left(\frac{\partial w}{\partial x}\frac{\partial v}{\partial z} - \frac{\partial w}{\partial y}\frac{\partial u}{\partial z}\right) - v\frac{\partial f}{\partial y} + \frac{1}{\rho^2}\left(\frac{\partial \rho}{\partial x}\frac{\partial p}{\partial y} - \frac{\partial \rho}{\partial y}\frac{\partial p}{\partial x}\right)$$

$$\frac{\partial \zeta_n}{\partial t} = -V \cdot \nabla \zeta_n - w\frac{\partial \zeta_n}{\partial z} - \frac{\partial u}{\partial n}\zeta_n + \frac{1}{\rho^2}\left(\frac{\partial \rho}{\partial n}\frac{\partial p}{\partial z} - \frac{\partial \rho}{\partial z}\frac{\partial p}{\partial n}\right)$$

SHOW PICTURES

QUESTIONS INCLUDE....
1) how can tilting of baroclinically-generated vorticity be important near the surface when w is small there?
2) how can tornado have vertical vortex lines close to the ground turning horizontal in the friction layer (how much tilting can occur near sfc?)

COMMON FEATURES IN TORNADIC SUPERCELLS:
1) mesocyclone -- 10 m/s over a km gives vertical vorticity of about 10^-2 s-1
   — large correlation between upward vertical velocity and vorticity

-- may have separate midlevel and lowlevel mesocyclones
-- rotation of supercell updraft is result of tilting and stretching of horiz vorticity in inflow (ideally it should be oriented streamwise)
-- this horiz vorticity in inflow may be due to:
a) large-scale vertical wind shear
b) mesoscale baroclinic boundaries
c) supercell's own forward-flank boundary
d) baroclinicity due to anvil shadow
-- streamwise horiz vorticity can also be intensified by stretching horizontally as inflow accelerates towrad updraft
-- downdrafts can also produce near-ground rotation
-- can have downdraft transport horiz vorticity and change it to some vertical vort and then be brought into updraft and changed again

2) Hook echo -- what causes it is unclear?
a) lateral extension of precipitation from main precpitation region
b) downward progressive development of precipitation to rear of WER

3) Rear-flank Downdraft -- gives updraft horseshoe shape
-- may be evidenced by clear slot that can be seen wrapping 2/3 or more of way around developing tornado cyclone, usually 5-10 minutes before tornado touchdown
-- causes are a bit of a mystery
A) loading, melting, evaporation? -- but RFD is often not too cold
B) vertical pressure gradients due to stagnation aloft -- but these should always be present and don't explain sudden RFD formation
C) low-level pressure deficits due to rotation create PGF -- but doesn't match location where clear slot is observed. This may more accurately be the occlusion downdraft mentioned by Wakimoto

4) Presence of Negative Vertical Vorticity in vortex
-- might be seen as anticyclonic flare in hook echo at far end

5) Tornado cyclone -- may be a smaller (1-5 km) area of more intense rotation within mesocyclone before tornado touchdown. Could be what gives the TVS on radar. However, might just be radar smearing out the tornado?

6) Tornado at interface of updraft and downdraft

EXISTING TORNADO HYPOTHESES:

1) Baroclinic generation of streamwise vorticity is essential - gets tilted into vertical
PROBLEM - tilting weak at ground and model study showed a tornado forming without this

2) Baroclinic generation and tilting in downdraft gives anticyclonic vertical vorticity which slides feet first due to strongest winds along ground, and then it becomes cyclonically oriented this way.
GOOD - gets around problem of small w at ground
PROBLEM - many observations show strongest flow might be 100-300 m above ground and sliding feet first wouldn't work well.

3) Streamwise vorticty erupts from ground due to very strong tilting as it slams into boundary like RFD
PROBLEM - again w still might not be strong enough

4) "landspout mechanism" -- already pre-esxisting vertically-oriented circulations are stretched

5) horizontal shearing instability causes a vertical sheet of vorticity to roll up into vortices which are stretched by updrafts

6) Occlusion downdraft might break down into smaller tornado vorticies

7) downdraft tilts horiz vort and advects vertical vort to ground, this vertical vort is stretched by the updraft as air spreads away from downdraft and under the updraft, then enhancement of low-level updraft occurs due to convergence along downdraft outflow

8) dynamic pipe effect

FAILS if there is insufficient low level rotation
SUCCESS if there is and rotation/conv intensifies progressively downward

NEW IDEAS FROM VORTEX:

IDEA 1
SHOW PICTURE AS DISCUSS BELOW:

1) helical updraft storm
2) RFD tilts vortex lines
3) enhanced cyclonic vort forms on one side with less or anticyclonic on other
4) cyclonic is stronger vortex and it wraps anticyclonic one around it
5) RFD hits the ground and at that point a tornado cyclone is in middle
6) RFD rotates around this, with some spreading outward, but others inward creati
ng
very strong convergence/stretching and tornado

NOTE: RFD would have to wrap much of way around to get strong enough convergence and must not be too negatively buoyant

QUESTION - Does RFD create increased low-level rotation or does the rotation create the RFD?

FAILURE MODES - too cold of an RFD would cause strong outward divergence of it also, if it doesn't come down in favored location along edge of helical updraft.

IDEA 2
"The Blob" - potentially barotropic mechanism (rain drag) in the right spot can tilt the vortex lines to bring strong vertical rotation toward ground. This can get moved under main updraft further stretching i
t.

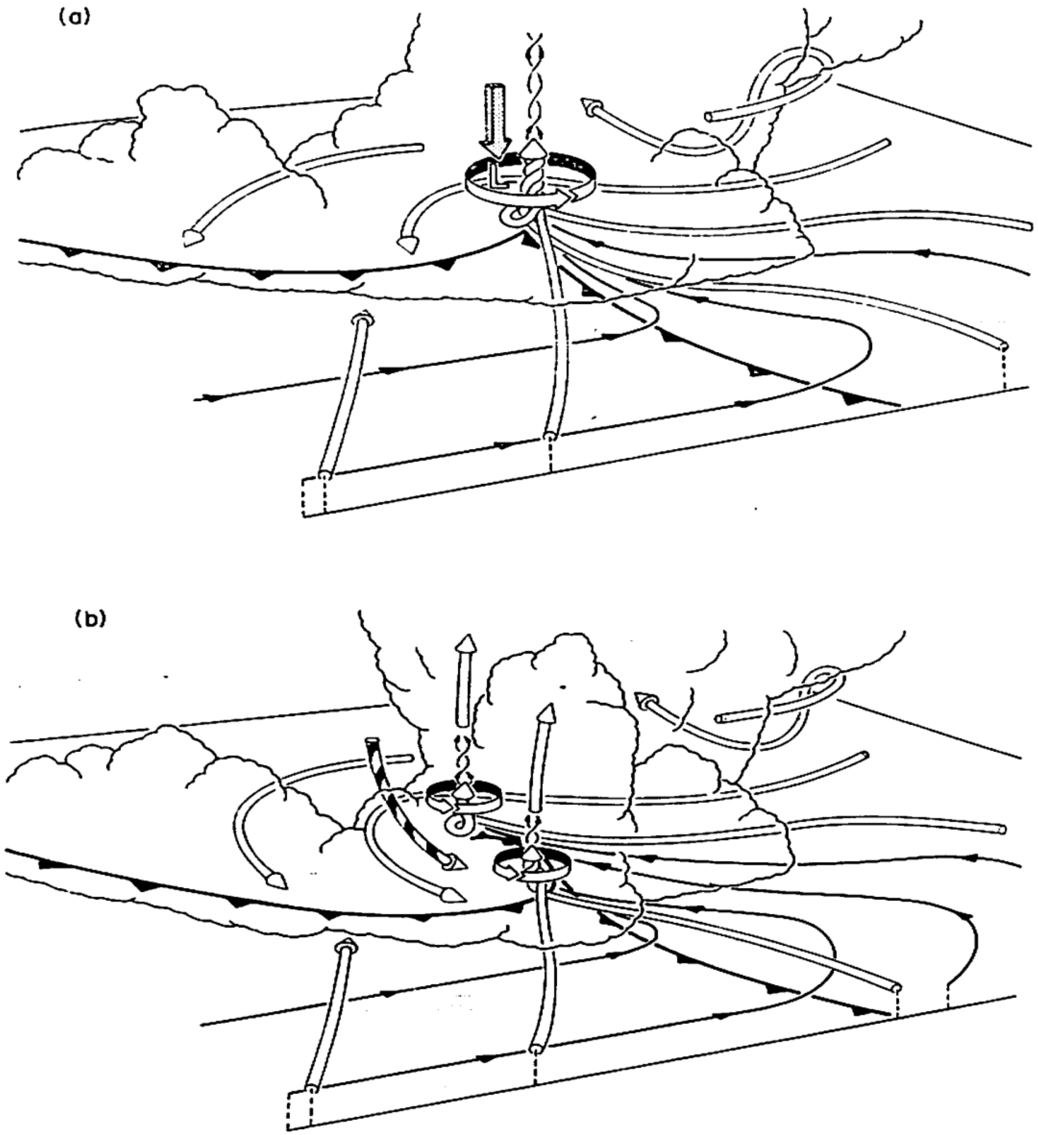


Fig. 9.38. Expanded three-dimensional perspective, viewed from the southeast, of the low-level flow (a) and (b) about 10 min later after the rear-flanking downdraft has intensified. The cylindrical arrows depict the flow in and around the storm. The vector direction of vortex lines are indicated by arrows along the lines. The sense of rotation is indicated by the circular ribbon arrows. The heavy barbed line works the boundary of the cold air beneath the storm. The shaded arrow in (a) represents the rotationally induced vertical pressure gradient, and the striped arrow in (b) denotes the rear-flanking downdraft. [From Klemp (1987). Copyright © 1987 by Annual Reviews, Inc. Reproduced with permission.]

Looking NW

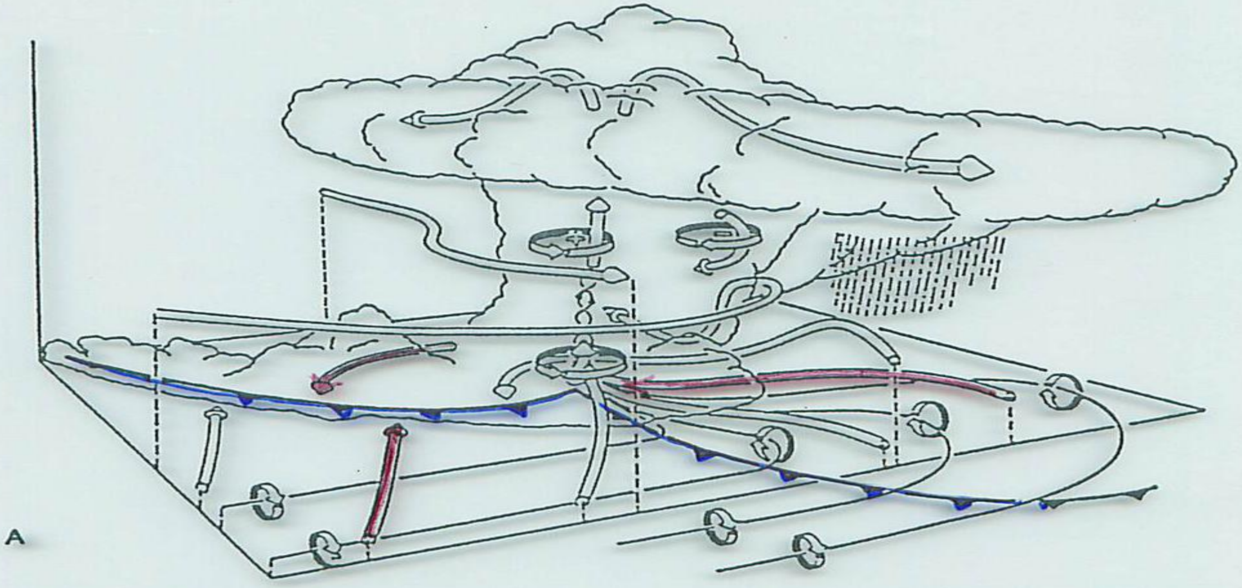


Figure 35A. Three-dimensional schematic view of a numerically simulated supercell thunderstorm at a stage when the low-level rotation is intensifying. The storm is evolving in westerly environmental wind shear and is viewed from the southeast. The cylindrical arrows depict the flow in and around the storm. The thick lines show the low-level vortex lines, with the sense of rotation indicated by the circular-ribbon arrows. The heavy barbed line marks the boundary of the cold air beneath the storm.

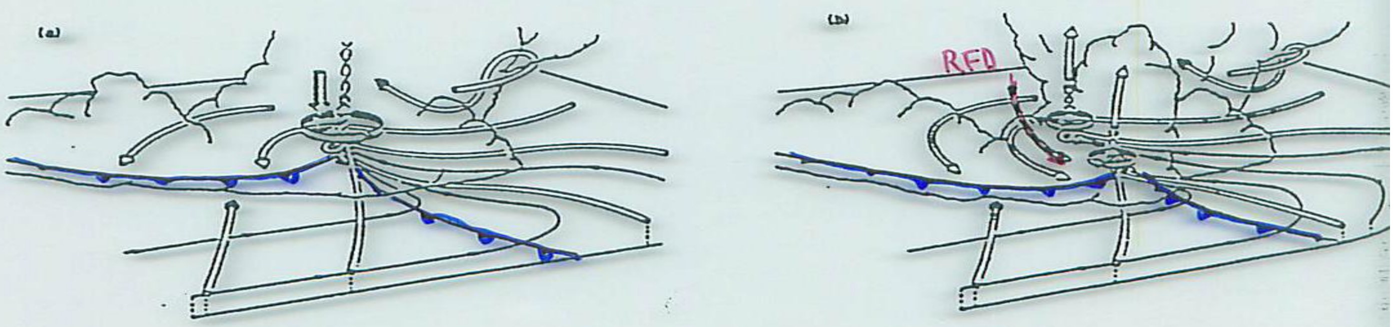


Figure 35B. Expanded three-dimensional perspective, viewed from the southeast, of the low-level flow (*a*) at the time depicted in Figure A , and (*b*) about 10 min later after the rear-flank downdraft has intensified. Features are drawn as described in Figure A , except that the vector direction of vortex lines are indicated by arrows along the lines. The shaded arrow in (*a*) represents the rotationally induced vertical pressure gradient, and the striped arrow in (*b*) denotes the rear-flank downdraft. KLEMP, 1987

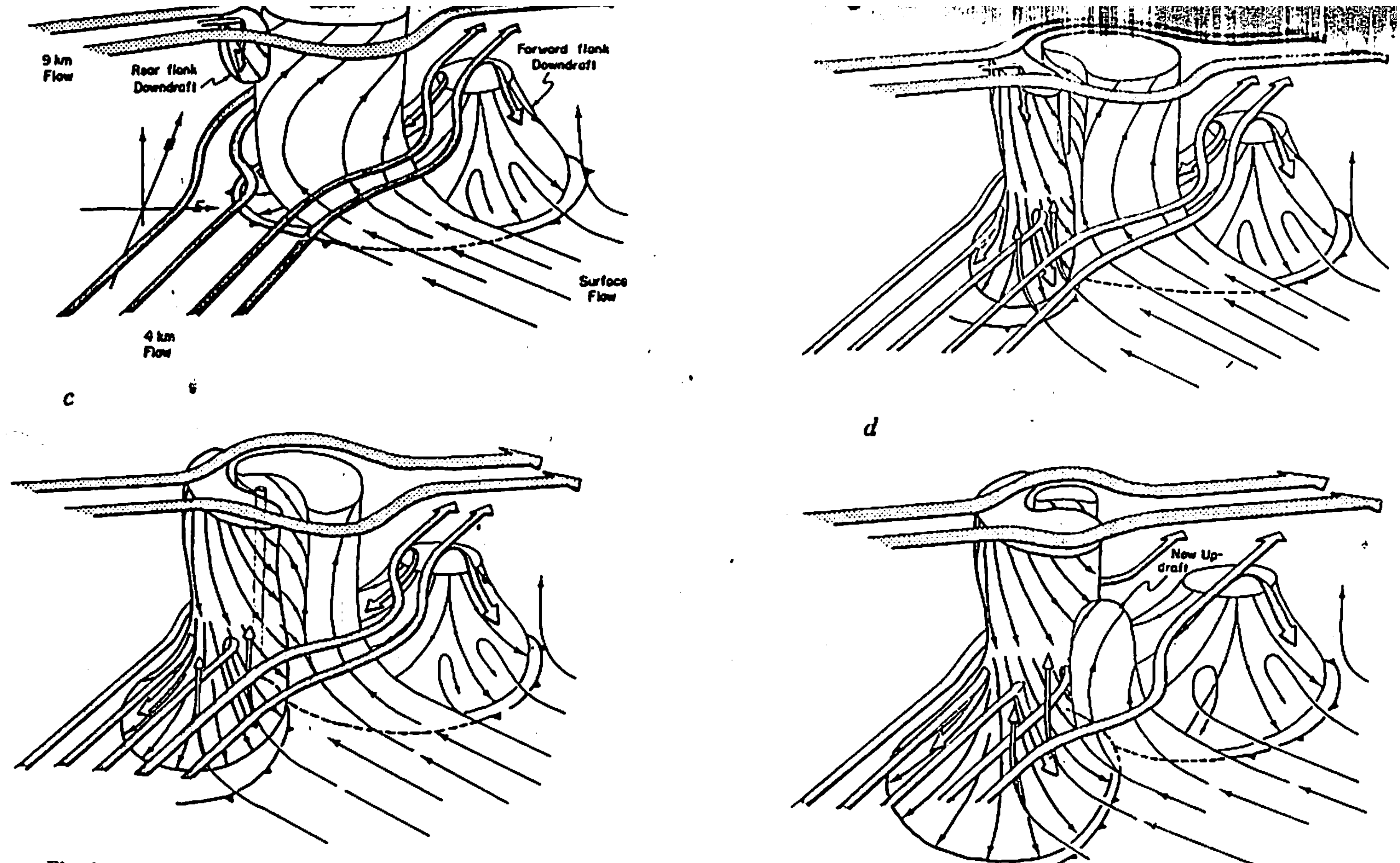


Fig. 9.36. Schematic three-dimensional depiction of evolution of the drafts, tornado, and mesocyclone in an evolving supercell storm. The stippled flow line suggesting descent of air from the 9-km stagnation point has been omitted from (c) and (d), for simplicity. Fine stippling denotes the TVS. Flow lines throughout the figure are storm relative and conceptual only, and are not intended to represent flux, streamlines, or trajectories. Conventional frontal symbols are used to denote outflow boundaries at the surface, as in Fig. 9.23. Salient features are labeled on the figure. [From Lemon and Doswell (1979).]

(b)

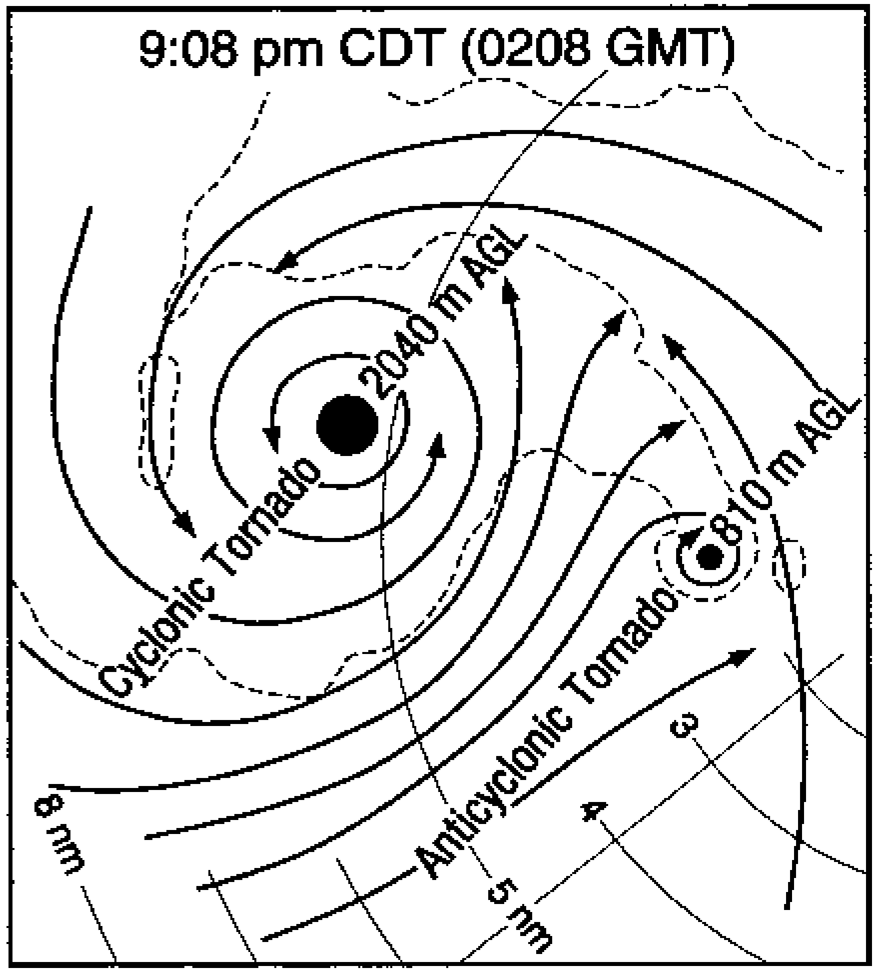


FIG. 5.16. (a) A cyclonic hook (from Garrett and Rockney 1962). (b) Surface flow (arrows) and radar echo (dashed) associated with simultaneous cyclonic and anticyclonic tornadoes at Grand Island, Nebraska, 3 June 1980. (From Fujita and Wakimoto 1982.) Note the wrapped-up cyclonic hook with a central eye and the anticyclonic hook to its ESE.

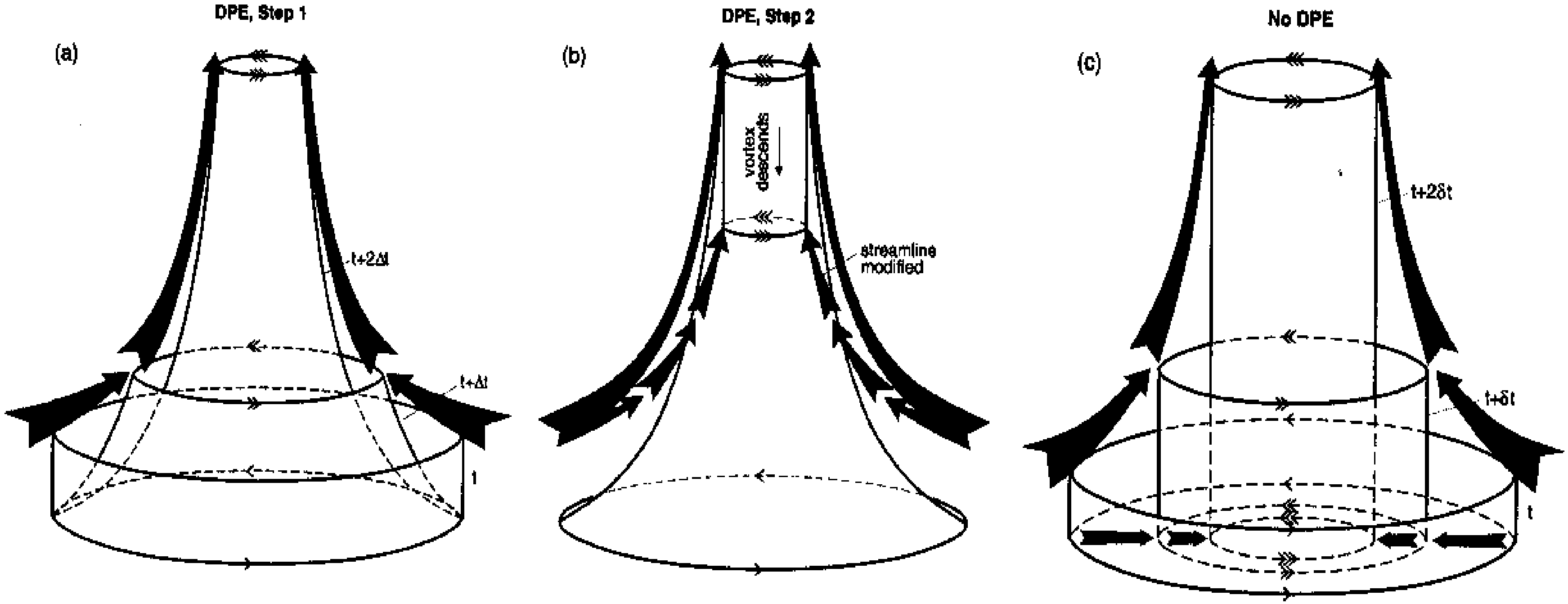


FIG. 5.18. Idealization of two modes of vortex formation within a rotating updraft (Trapp and Davies-Jones 1997). (a) and (b) illustrate the dynamic pipe effect. In (a) the radial inflow increases with height so an initial cylindrical vortex tube is stretched into a cone and a funnel cloud forms aloft first. In (b) the vortex pipe builds downward by increasing the radial inflow into its lower end through a suction effect as described in the text. The vortex descends to the ground relatively slowly. In (c) the radial inflow is constant with height so the DPE is absent. The initial cylindrical vortex tube remains cylindrical as it is stretched vertically so that the vortex spins up simultaneously at all heights, resulting in rapid tornado formation.

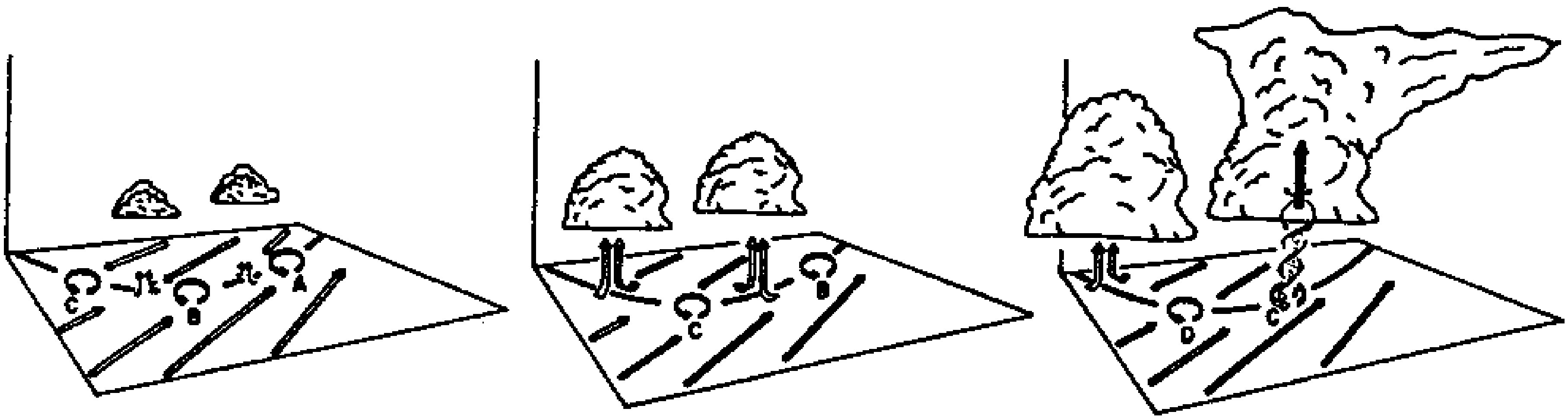


FIG. 5.21. Diagram showing genesis of a nonmesocyclone tornado (Wakimoto and Wilson 1989). Misoscale vortices (identified by letters) form along a windshift line (black line) as a result of shearing instability. A tornado results from one of these vortices (C) being stretched by overhead convection.

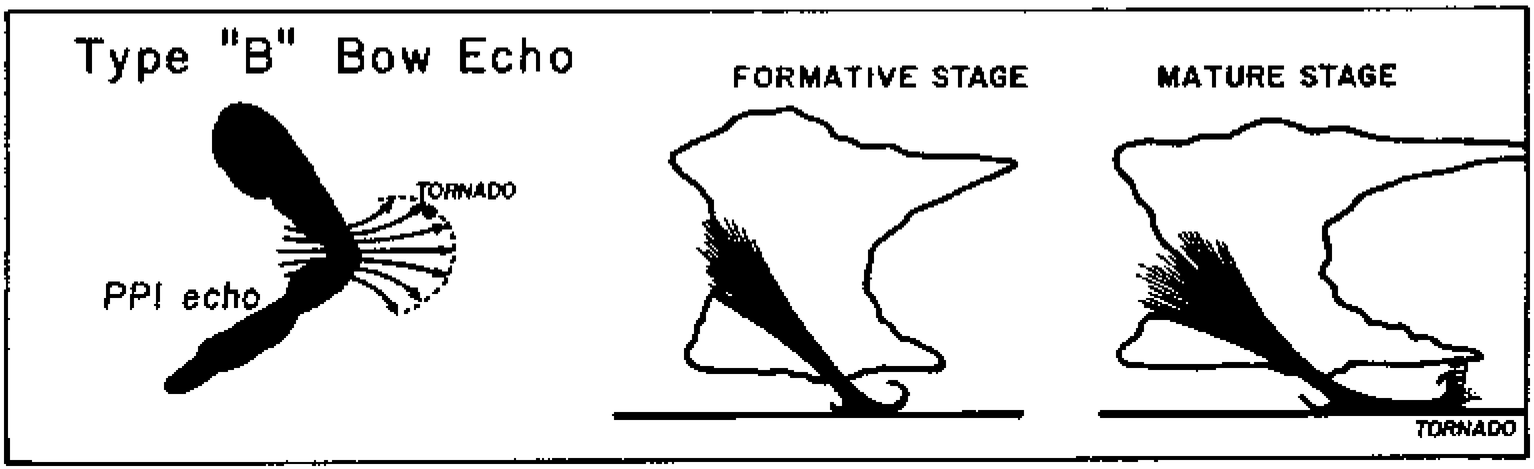
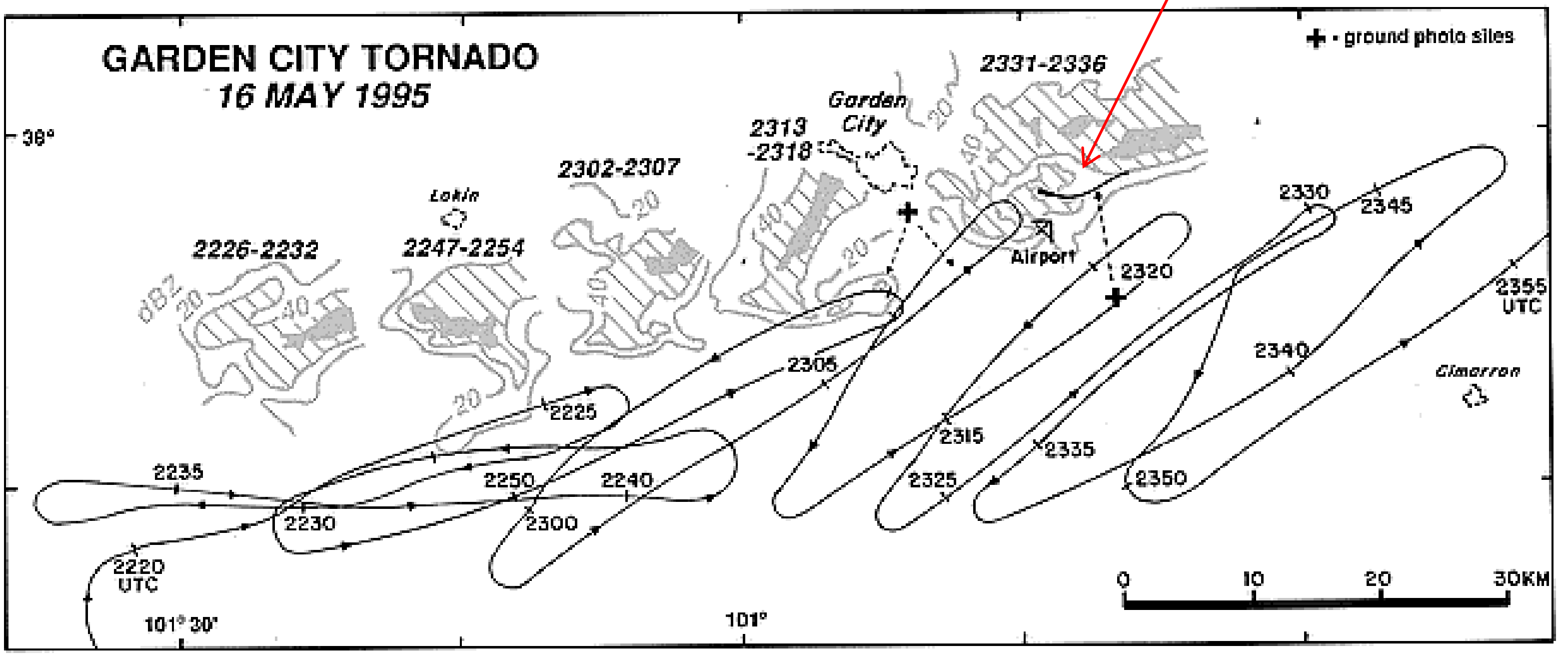


FIG. 5.22. Tornado formation within a bow echo according to Fujita (1985). Note the location of the tornado on the left side of the strong outflow.

Tornado damage track



Eldora aircraft track: Aircraft flying 300 m above surface

Remainder of material contained in Wakimoto powerpoint

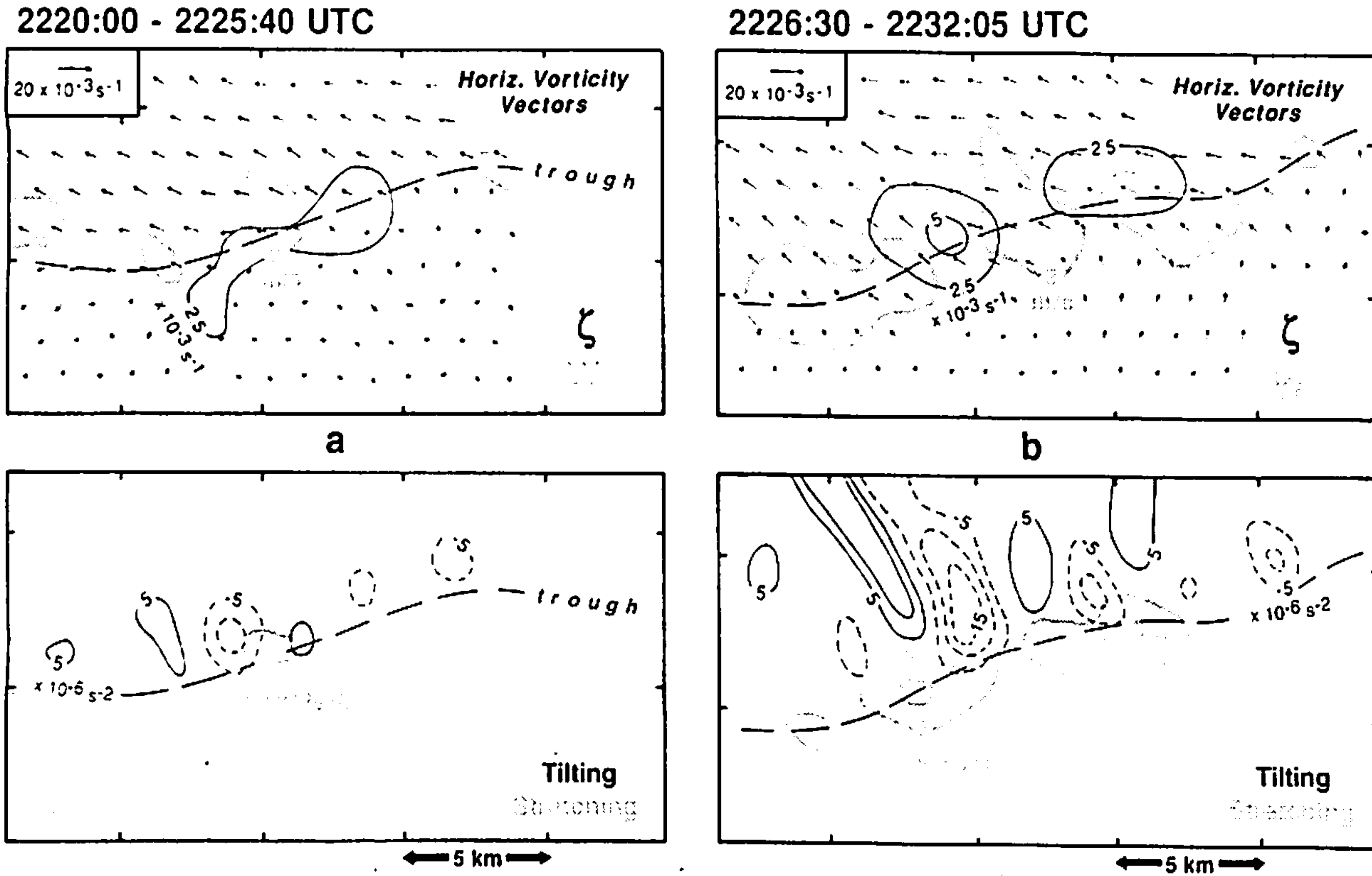


FIG. 7. Enlargement of the boxed-in areas shown in Figs. 6a and 6b. Vertical velocity, vertical vorticity, horizontal vorticity vectors (top figure), and the components of tilting and stretching from the vorticity equation (bottom figure) are shown at (a) 2220:00–2225:40 and (b) 2226:30–2232:05 UTC. Positive and negative vertical velocities are shown as solid and dashed gray lines, respectively. Positive and negative vertical vorticity values are shown as solid and dashed black lines, respectively. Positive and negative values of stretching are shown as solid and dashed gray lines, respectively. Positive and negative values of tilting are shown as solid and dashed black lines, respectively. The location of the synoptic-scale trough is shown by the long dashed black line.

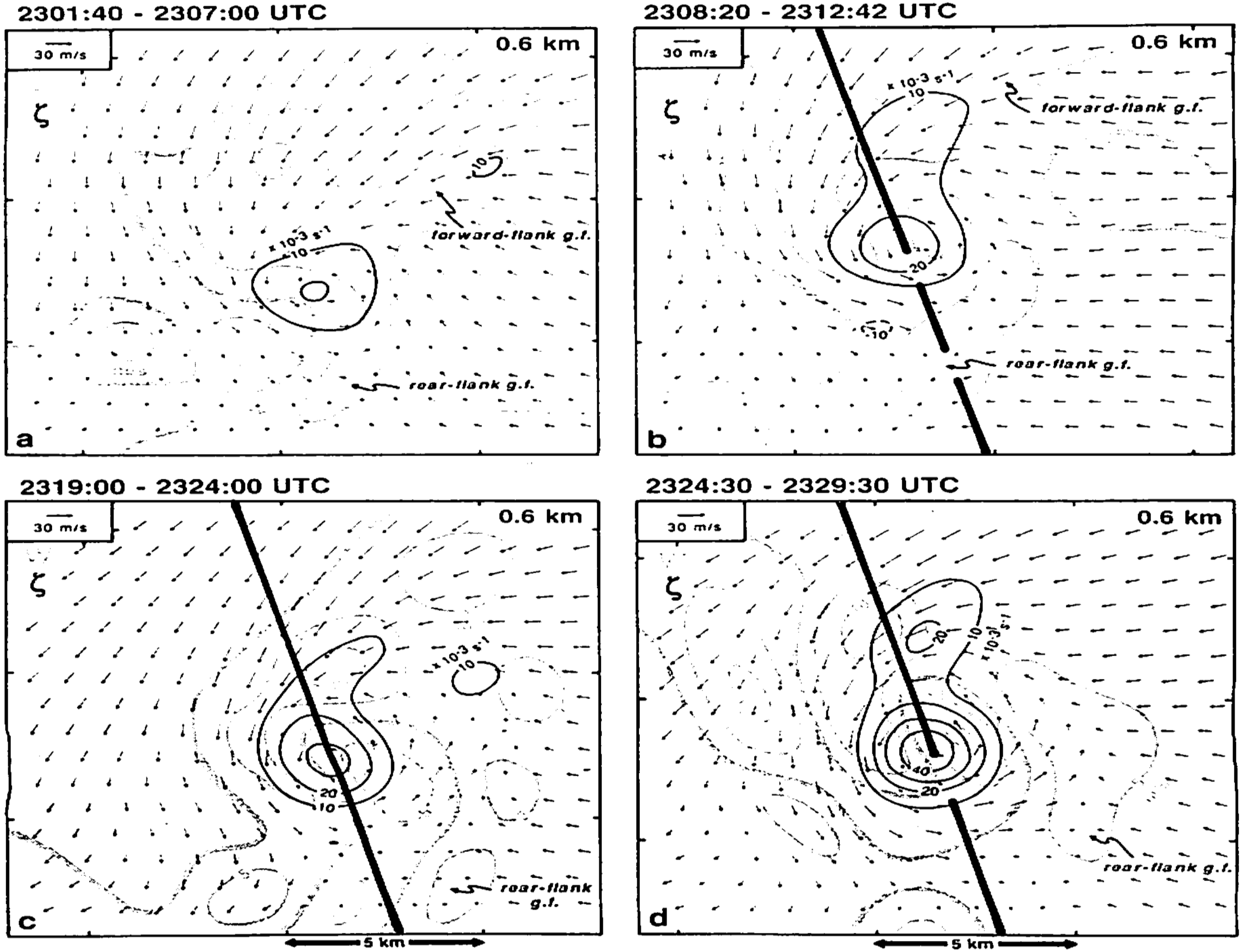


FIG. 8. Enlargement of the area centered around the low-level mesocyclone at (a) 2301:40–2307:00, (b) 2308:20–2312:42, (c) 2319:00–2324:00, and (d) 2324:30–2329:30 UTC. Storm-relative vectors are plotted. Vorticity values are drawn as black lines. Positive and negative vertical velocities are drawn as solid and dashed gray lines with the zero isopleth drawn as a thick gray line. The location of analysis shown in (b) and (d) are shown in Figs. 5e and 5f. Thick black lines indicate the location of vertical cross sections shown in Fig. 10.