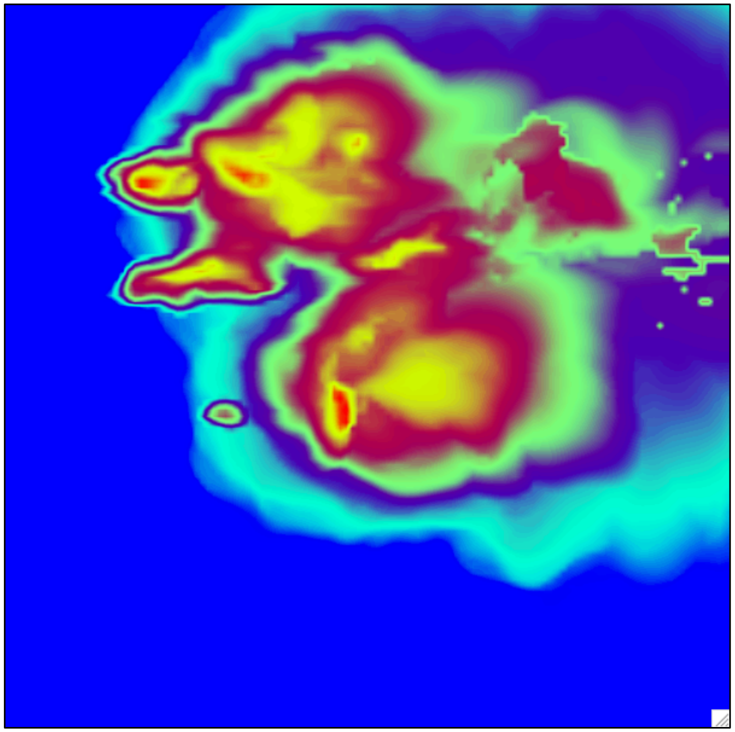
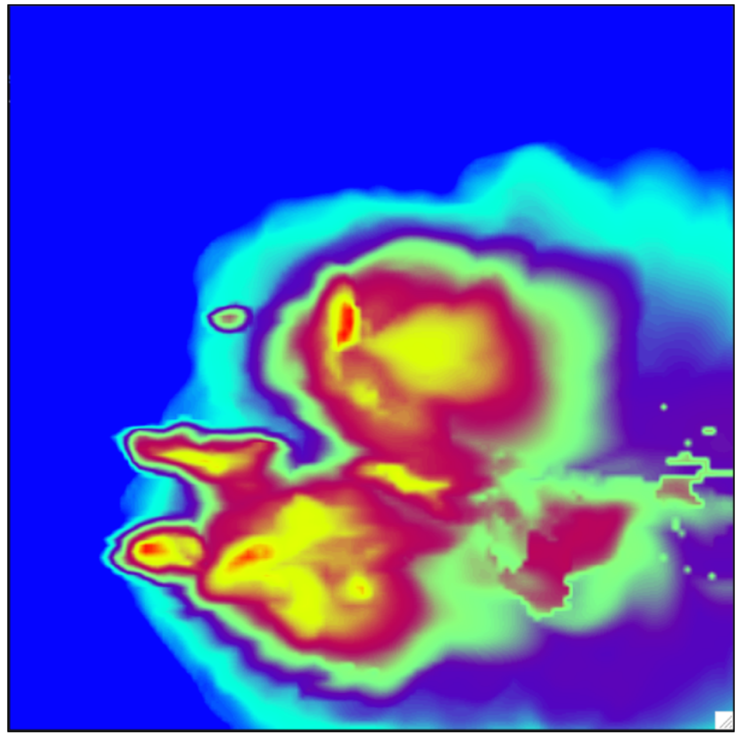
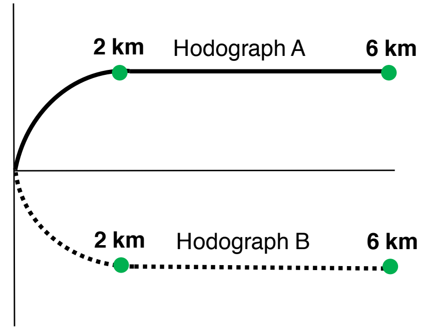
HW3: Composite reflectivity @ 2 hrs



Hodograph A



Hodograph B



Weisman and Rotunno (2000):
"*The Use of Vertical Wind Shear versus Helicity in Interpreting Supercell Dynamics*"

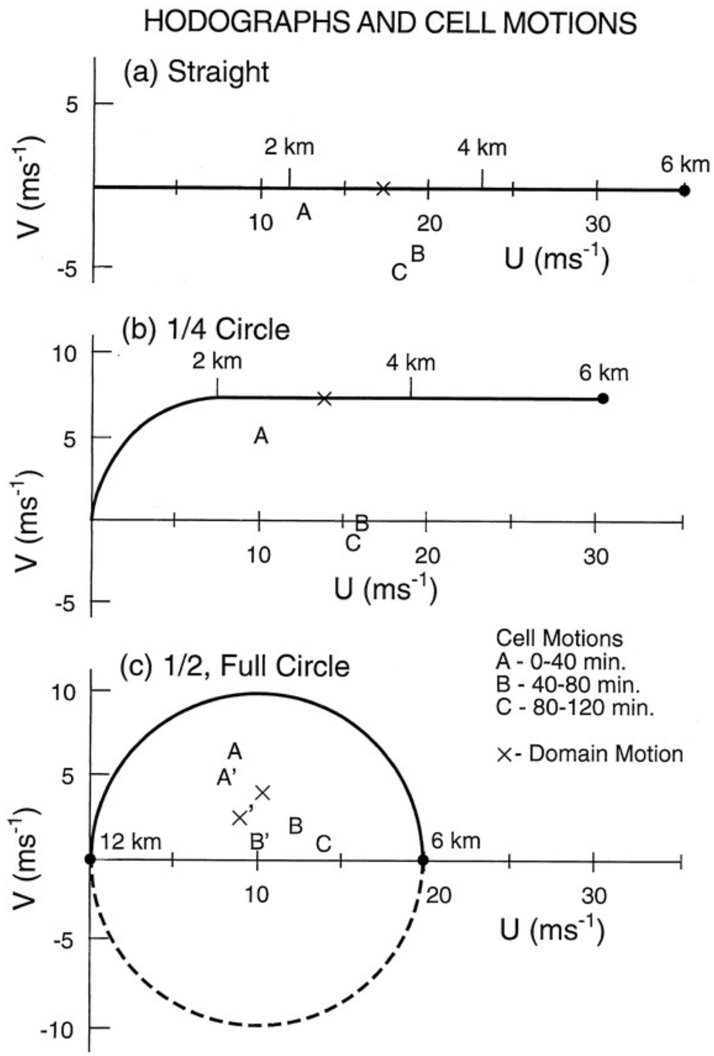
Clarify differences between:

1) **Non-linear** forcing – updraft/wind shear theory – tilting of horizontal vorticity into vertical

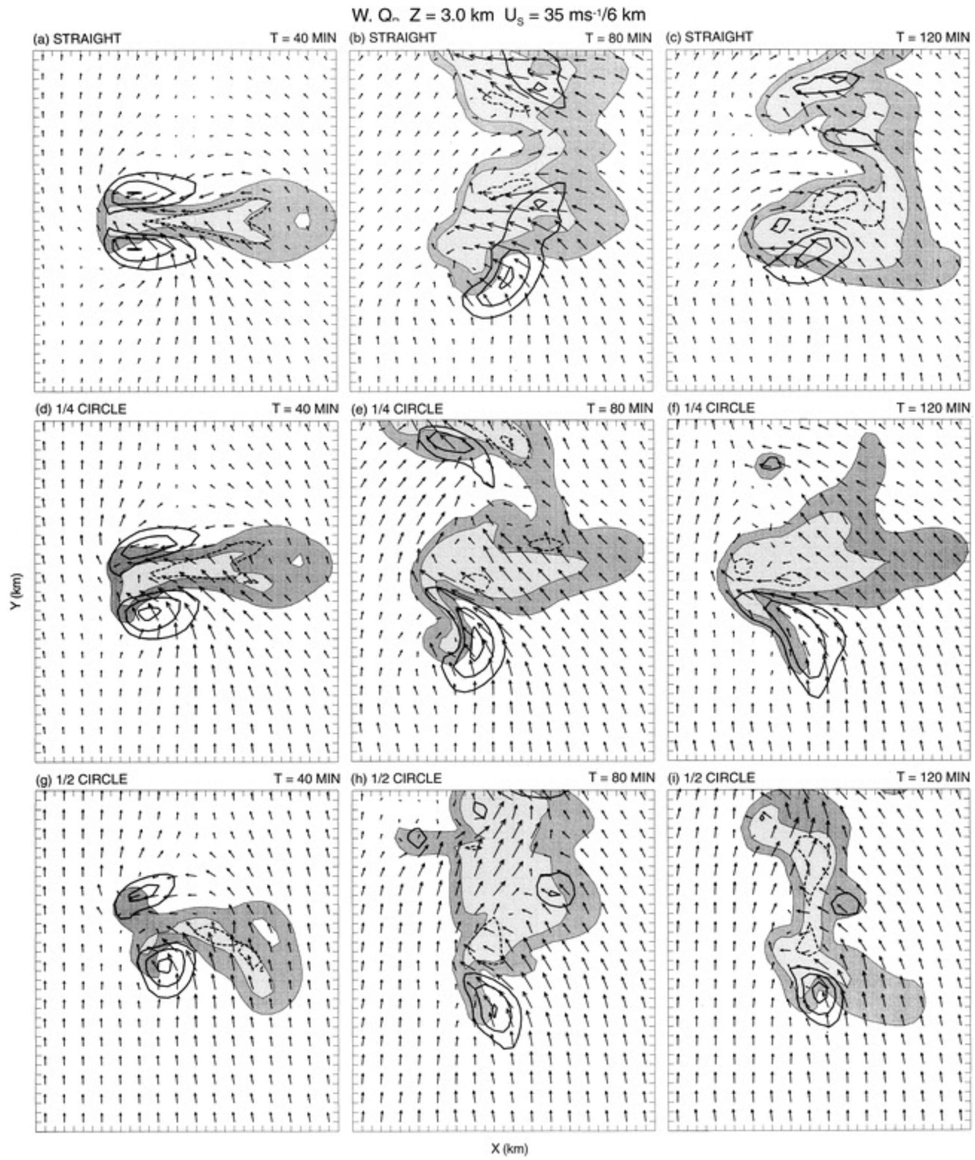
2) **Linear** forcing – streamwise vorticity theory – rotating shear vector

Which dominates?
What is most important to understanding supercell dynamics?
Are dynamics different from straight vs. curved hodographs?

The essence of this debate can be summarized in terms of whether a storm generates rotation by virtue of propagation, which is the helicity–streamwise vorticity viewpoint, or whether the propagation is a result of the development of a dynamically forced, rotating updraft, which is the vertical wind shear perspective. We believe that the present results reconfirm the latter interpretation.


HODOGRAPHS AND CELL MOTIONS
(a) Straight
(b) 1/4 Circle
(c) 1/2, Full Circle
V (ms-1)
U (ms-1)
2 km
4 km
6 km
12 km
Cell Motions
A - 0-40 min.
B - 40-80 min.
C - 80-120 min.
×- Domain Motion

Our results reconfirm that the basic processes by which a storm develops supercell characteristics (i.e., updraft forcing, updraft rotation, storm propagation, etc.) are similar, independent of hodograph curvature. The addition of hodograph curvature, however, does enhance updraft–rotational correlations somewhat and enhances updraft strength by about 10%, especially at early times. It also enhances the development of the cyclonic right-flank storm over the anticyclonic left-flank storm, as described in previous studies. An analysis of the dynamic vertical pressure gradient term in the vertical momentum equation also reconfirms that the processes contributing to updraft maintenance and propagation are significantly nonlinear, independent of hodograph curvature. However, the linear forcing terms do provide an increasing forcing bias as hodograph curvature is added, as also previously described.


W. Qr, Z = 3.0 km U$_S$ = 35 ms^{-1}/6 km
(a) STRAIGHT
T = 40 MIN
(b) STRAIGHT
T = 80 MIN
(c) STRAIGHT
T = 120 MIN
(d) 1/4 CIRCLE
T = 40 MIN
(e) 1/4 CIRCLE
T = 80 MIN
(f) 1/4 CIRCLE
T = 120 MIN
(g) 1/2 CIRCLE
T = 40 MIN
(h) 1/2 CIRCLE
T = 80 MIN
(i) 1/2 CIRCLE
T = 120 MIN
Y (km)
X (km)

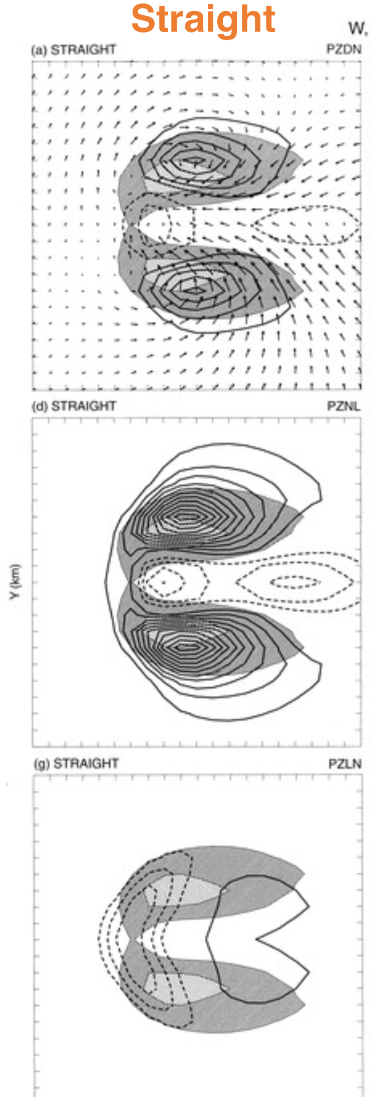
Early phase
(t = 40 min)

Straight

Total dynamic forcing

Non-linear dynamic forcing

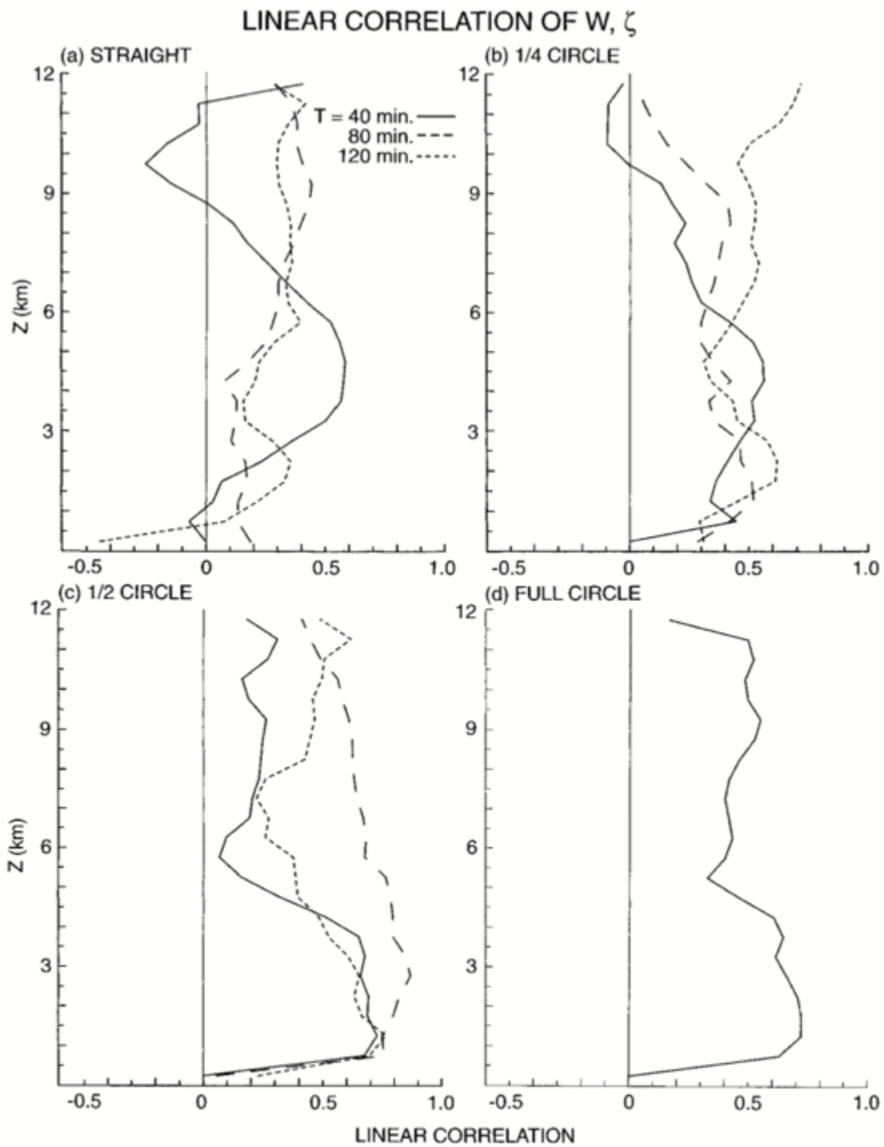
Linear dynamic forcing



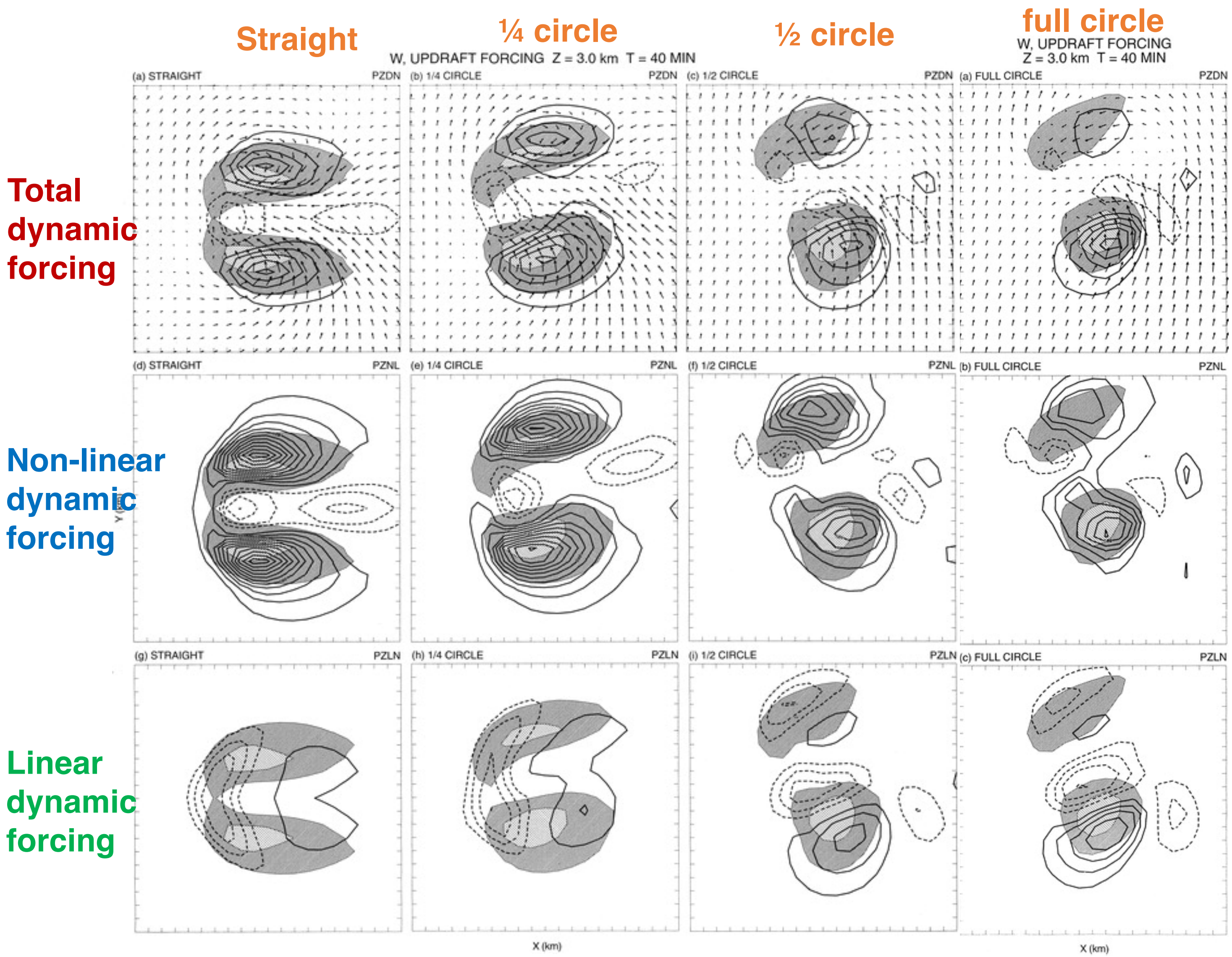
Symmetric areas of dynamic positive forcing for straight hodograph – cyclonic right-flank, anti-cyclonic left-flank

Splitting process *dominated by non-linear forcing.*

Weak linear forcing along flanks of updraft



"While there is a tendency for storms to develop larger updraft-vorticity correlations for increasing hodograph curvature, the larger curvature cases do not necessarily produce the most consistent correlations, due largely to the more unsteady nature of these storms"



Early phase (t = 40 min)

As curvature is added, linear forcing increases and is biased toward right-flank of storm, but non-linear forcing still is majority of dynamic forcing for ascent.

Non-linear forcing still dominates after t = 80 min.

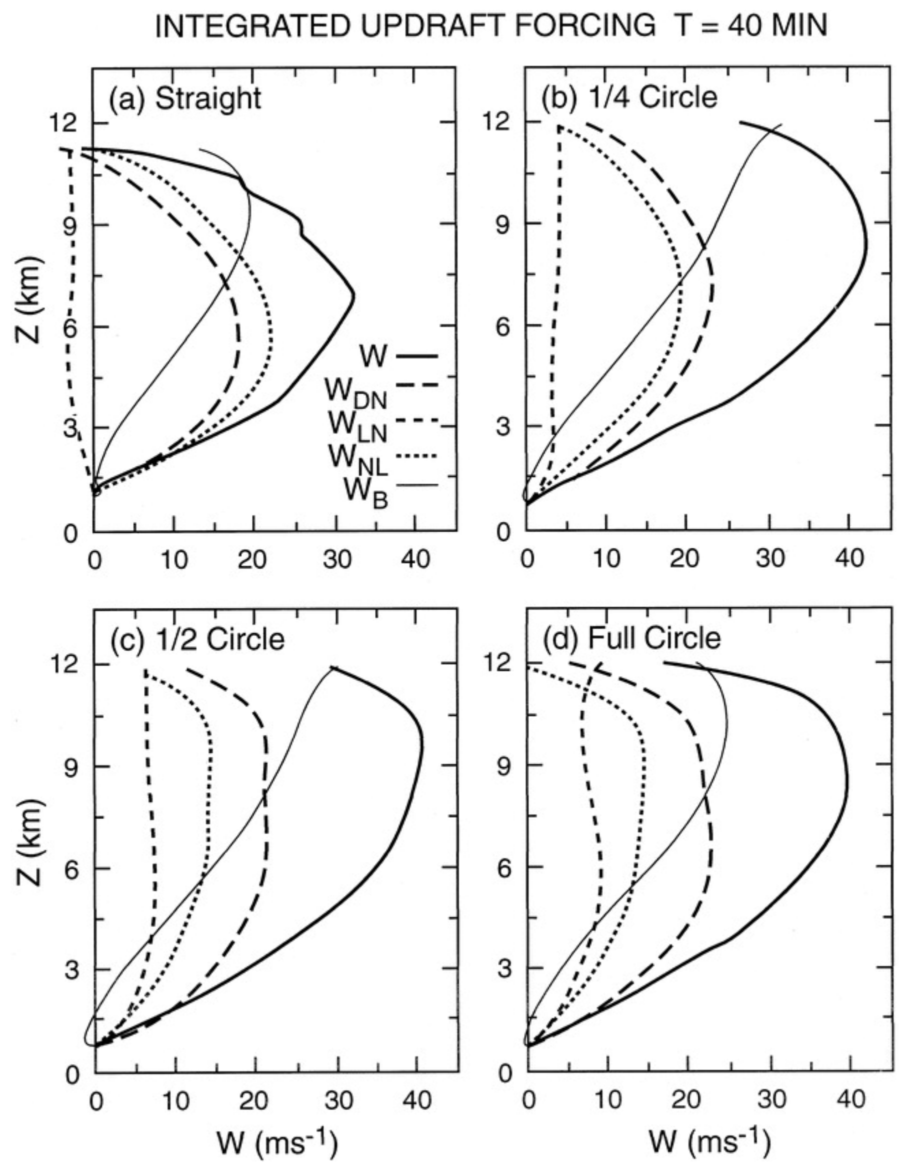
RW2000 computed **updraft trajectories** to analyze forcing along parcel path.

$$\frac{dw}{dt} = -C_p\overline{\theta}_v\frac{\partial \pi_{\mathrm{dn}}}{\partial z} + \left[-C_p\overline{\theta}_v\frac{\partial \pi_B}{\partial z} + B\right].$$

Dynamic forcing　　　Buoyancy forcing

$$w(x, y, z, t) = w_0 + \int_T -C_p\overline{\theta}_v\frac{\partial \pi_{\mathrm{dn}}}{\partial z}\,dt + \int_T\left[-C_p\overline{\theta}_v\frac{\partial \pi_b}{\partial z} + B\right]dt.$$

Forcing terms integrated in time along parcel trajectory ending up in maximum updraft at 3 km AGL. **W** due to forcing should match model **w** to have confidence in this approach (RW2000 notes that they match within 10% up to the level of maximum vertical velocity).

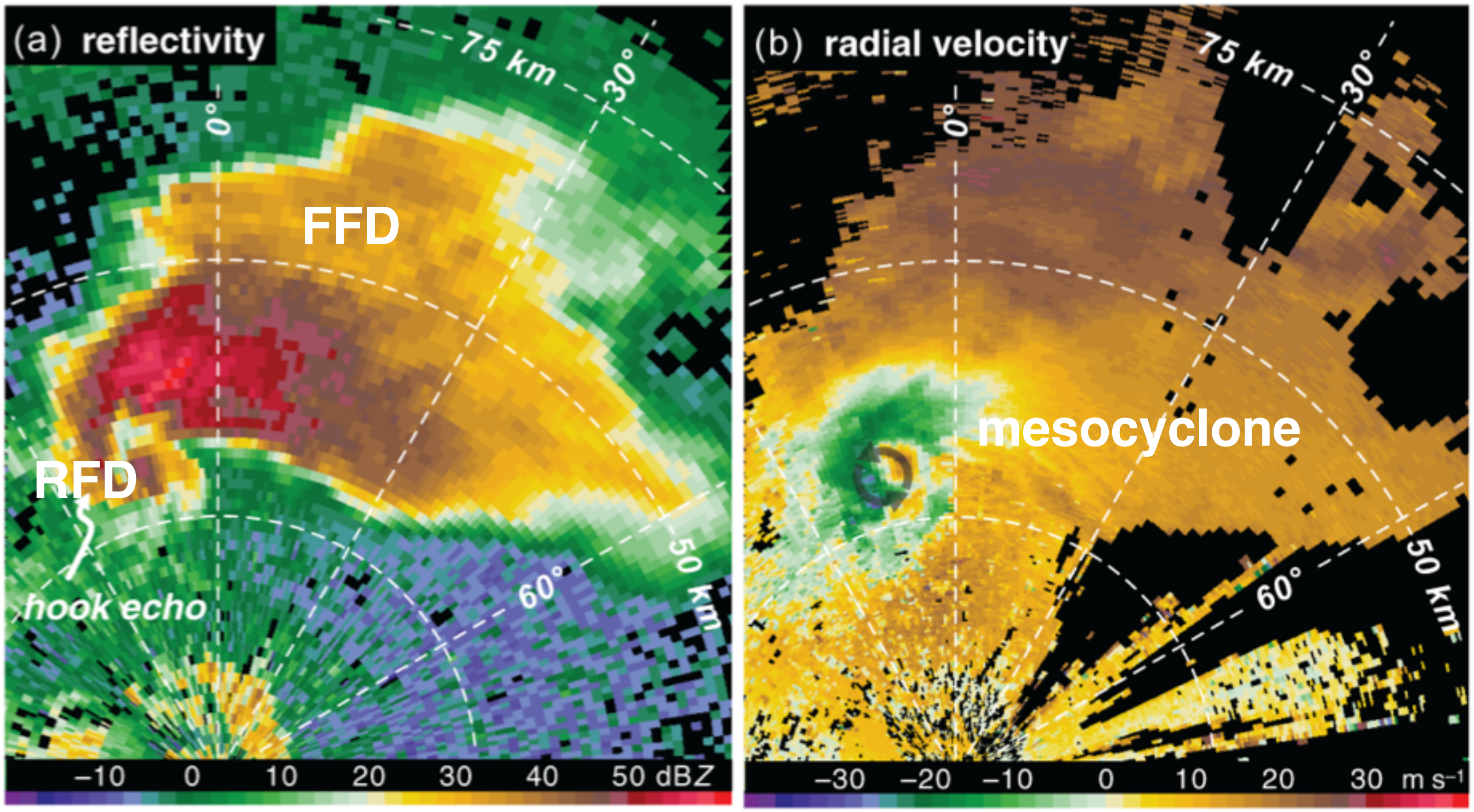


40-60% of updraft forcing comes from dynamic forcing!

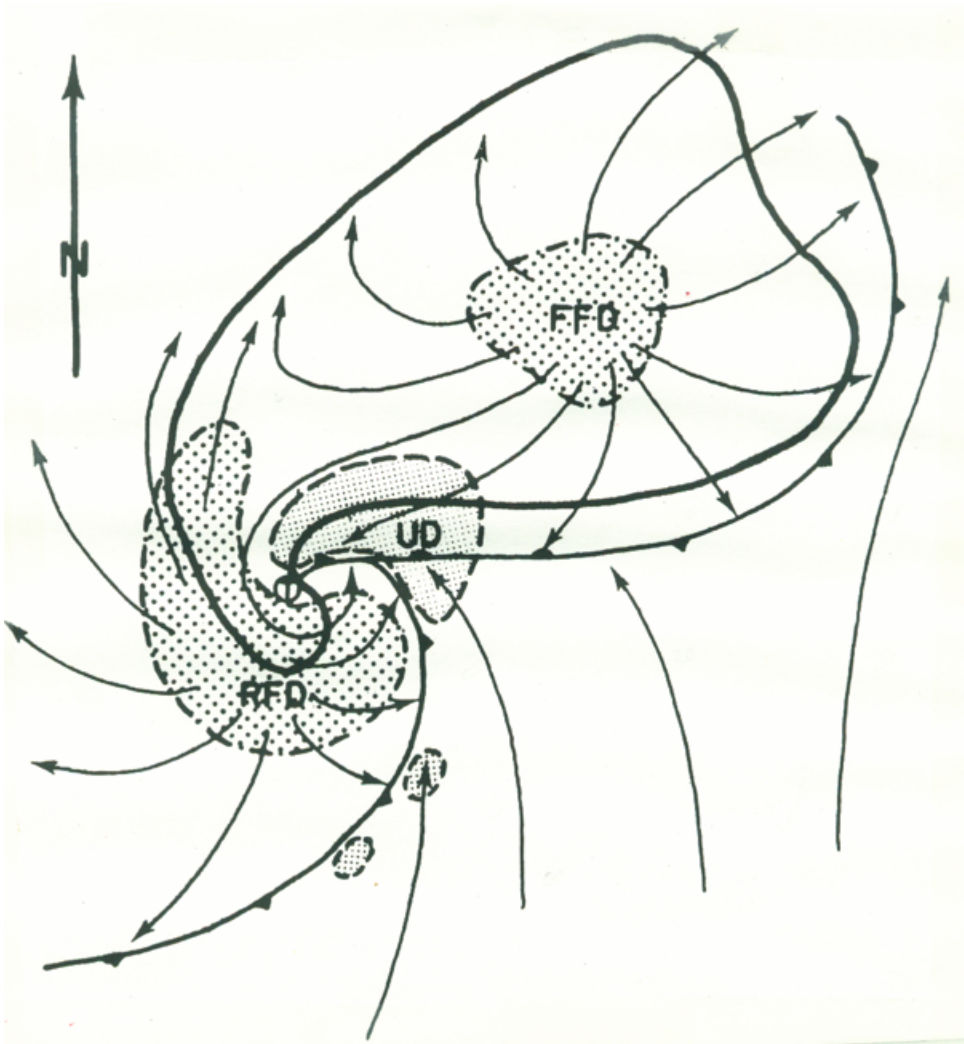
At lower altitudes, dynamic forcing is considerably larger than buoyancy forcing.

Linear forcing is negligible for straight and ¼ circle cases, but contribute 20-30% of forcing for ½ circle and full circle hodographs.

Nonlinear contributions dominate in both straight and curved hodograph cases.



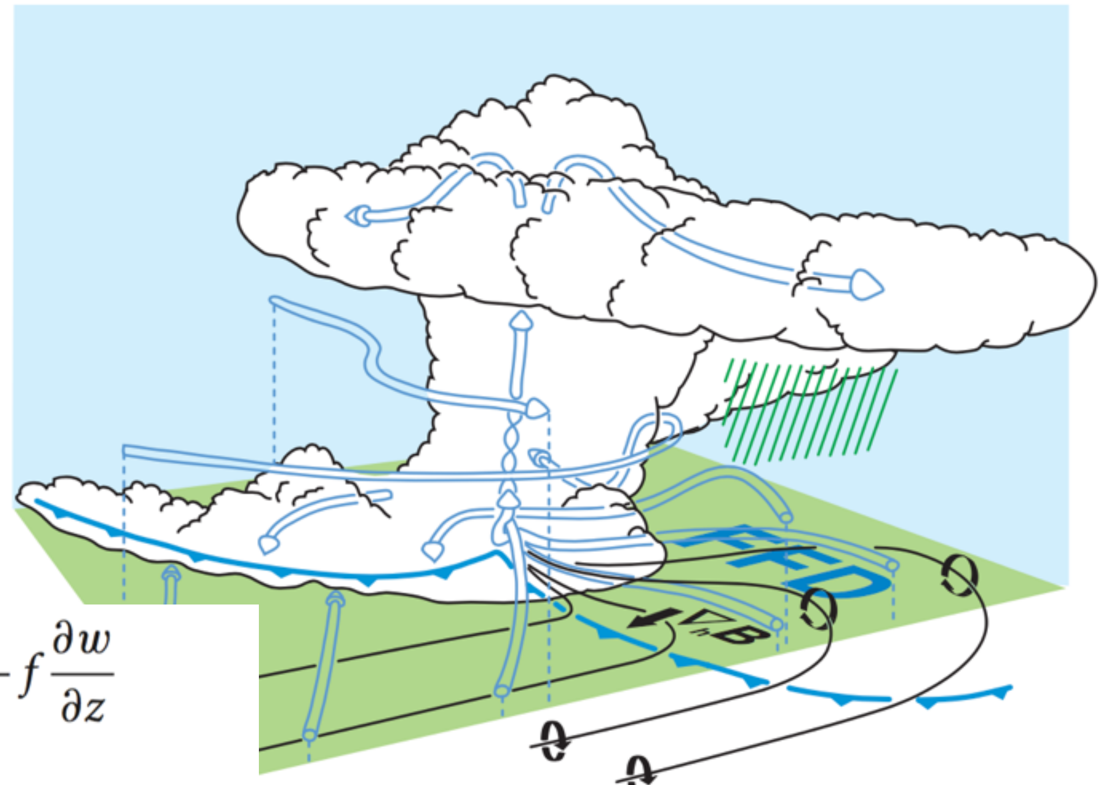
(a) reflectivity
75 km
30°
0°
FFD
RFD
hook echo
60°
50 km
−10 0 10 20 30 40 50 dBZ
(b) radial velocity
75 km
30°
0°
mesocyclone
60°
50 km
−30 −20 −10 0 10 20 30 m s−1



Low-level updraft typically comprised of air parcels that previously traversed areas within downdraft regions (both **FFD** and **RFD**).

Vertical vorticity generation by buoyancy within supercells

Horizontal buoyancy gradients in downdrafts can **increase** horizontal vorticity available for tilting into updraft.



$$\mathbf{k}\cdot\frac{\partial \boldsymbol{\omega}}{\partial t}=\frac{\partial \zeta}{\partial t}=-\mathbf{v}\cdot\nabla(\zeta+f)+\boldsymbol{\omega}\cdot\nabla w+f\frac{\partial w}{\partial z}+\frac{1}{\rho^2}\left(\frac{\partial \rho}{\partial x}\frac{\partial p}{\partial y}-\frac{\partial \rho}{\partial y}\frac{\partial p}{\partial x}\right)+\mathbf{k}\cdot\nabla\times\mathbf{F}. \quad (2.91)$$

Vertical vorticity generation by buoyancy within supercells

Parcels that pass through **FFD**, when lifted, can produce significant low-level rotation (low-level mesocyclones).

These parcels are responsible for producing the “**wall-cloud**” below a thunderstorm updraft.

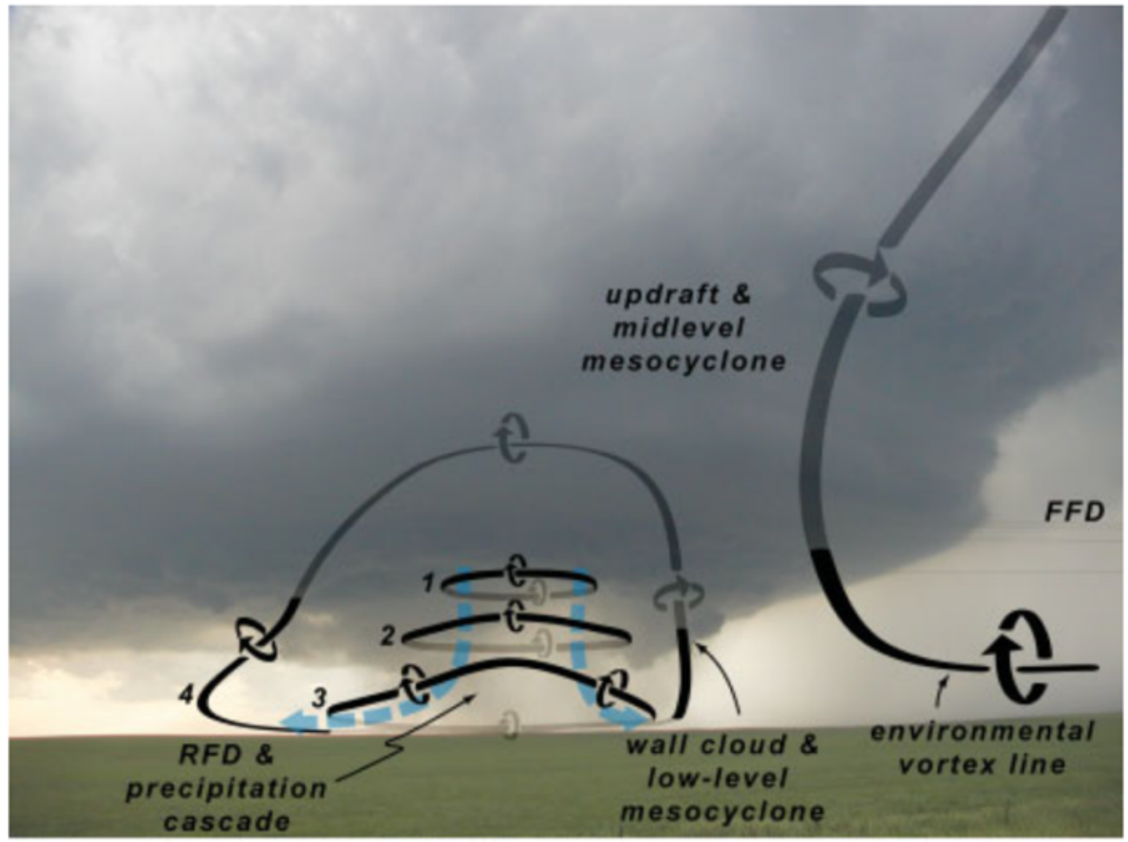
If parcel buoyancy too negative within **FFD**, sustained parcel lifting is more difficult.

Vertical vorticity generation by buoyancy within supercells

Baroclinic vorticity can also be produced within the **RFD** in a similar manner.

Rings of baroclinically generated vorticity within the **RFD** can be ingested into updraft and serve as an additional source of vorticity.

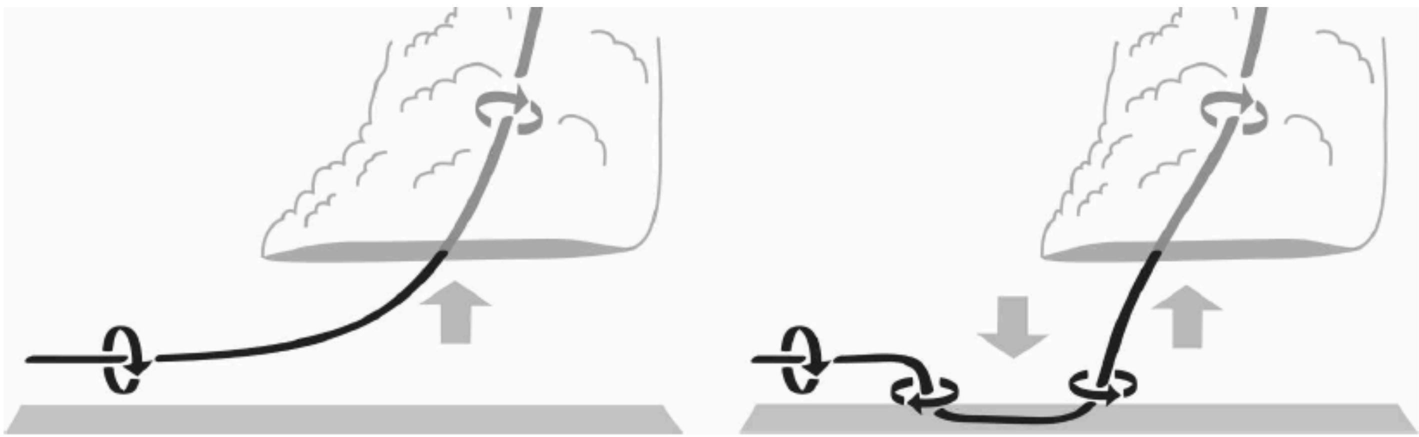
This **baroclinic** source of vorticity is distinct from **barotropic** “rearrangement” of environmental vorticity.



Markowski et al. 2008

Vertical vorticity generation by buoyancy within supercells

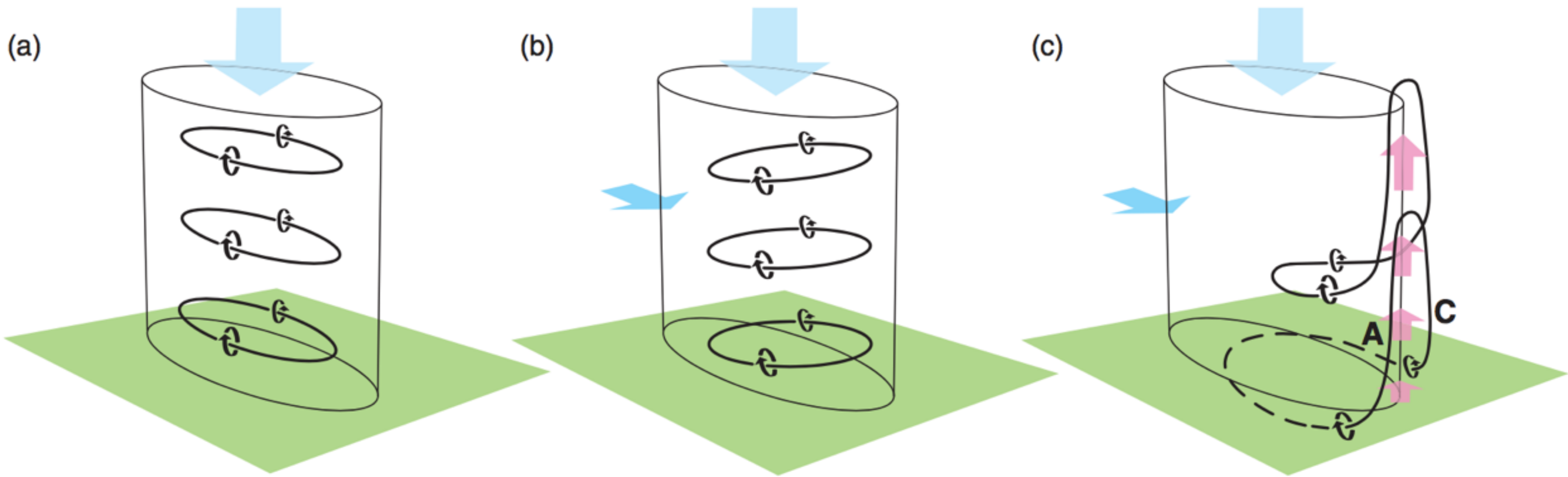
Barotropic vorticity redistribution by updraft/downdraft



Markowski et al. 2008

Vertical vorticity generation by buoyancy within supercells

Baroclinic vorticity generation by downdraft; subsequent redistribution by updraft



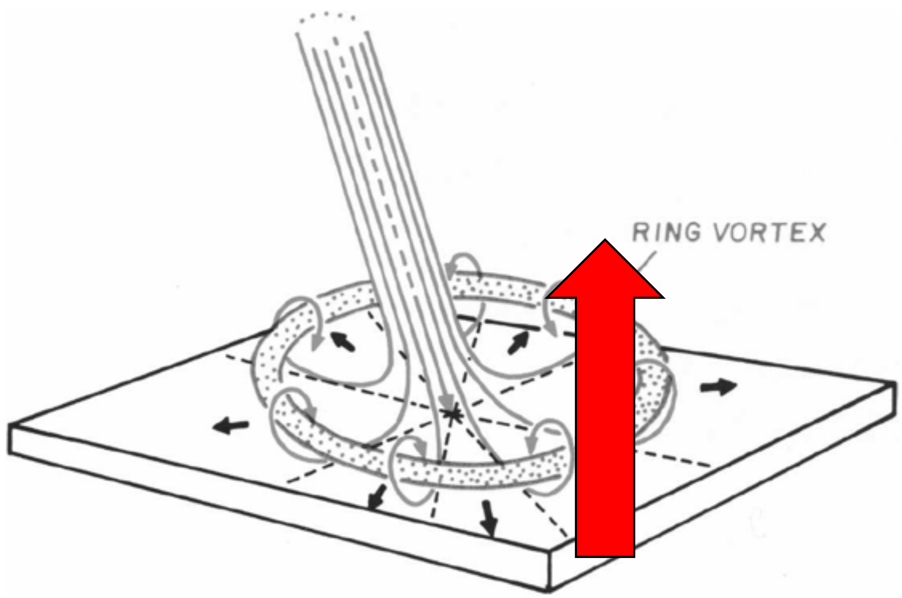
Vortex rings in vertical column associated with downdraft

Rings swept forward toward updraft and become tilted upward

Updraft further tilts rings upward and also results in stretching, leading to vortex “arches” and A/C couplets **near ground**.

Vertical vorticity generation by buoyancy within supercells

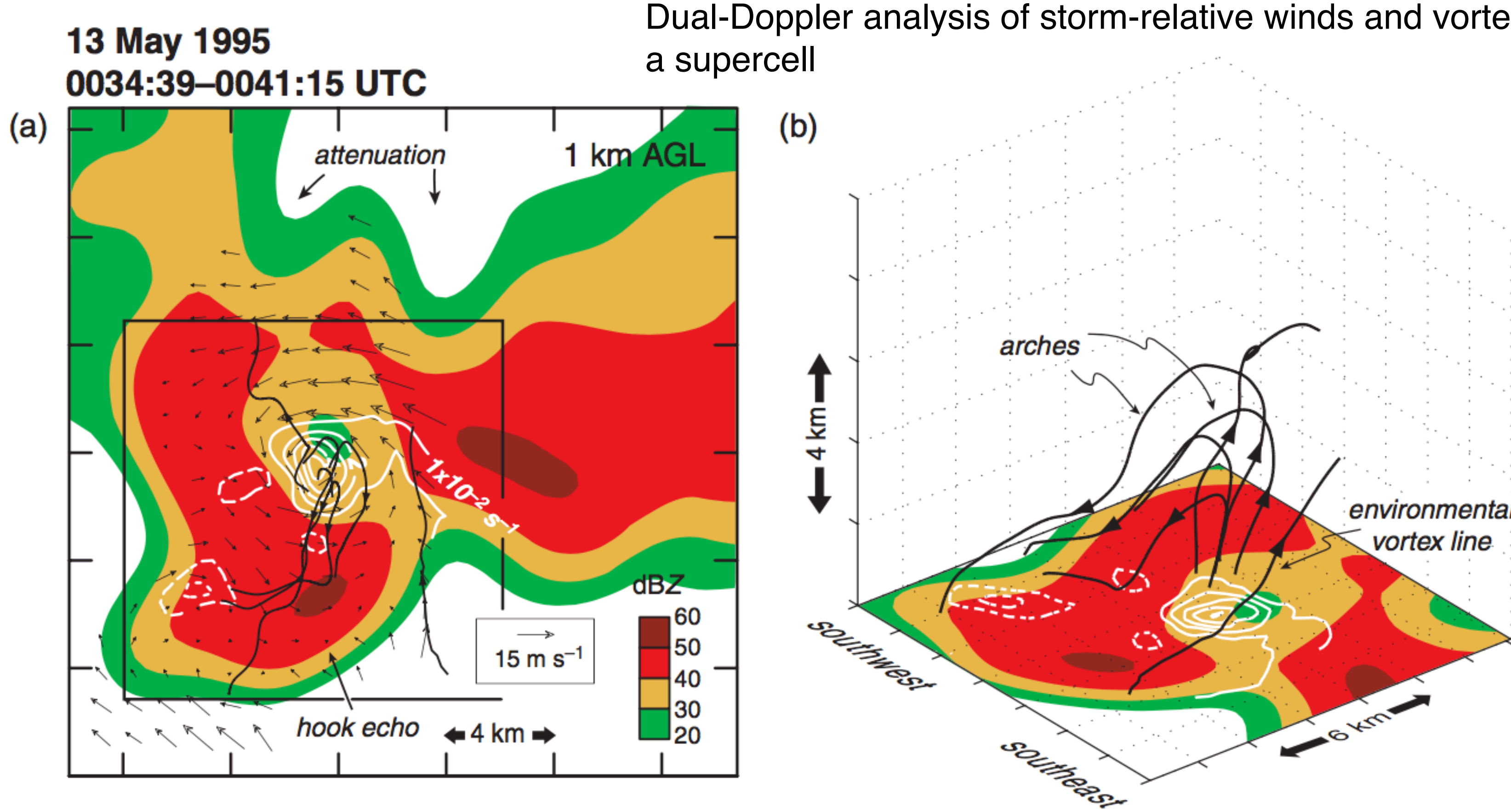
Can envision this as the development of a ring vortex within RFD that is subsequently tilted by adjacent updraft:



This doesn't require the presence of a closed loop, vortex lines could stretch into the adjacent FFD region.

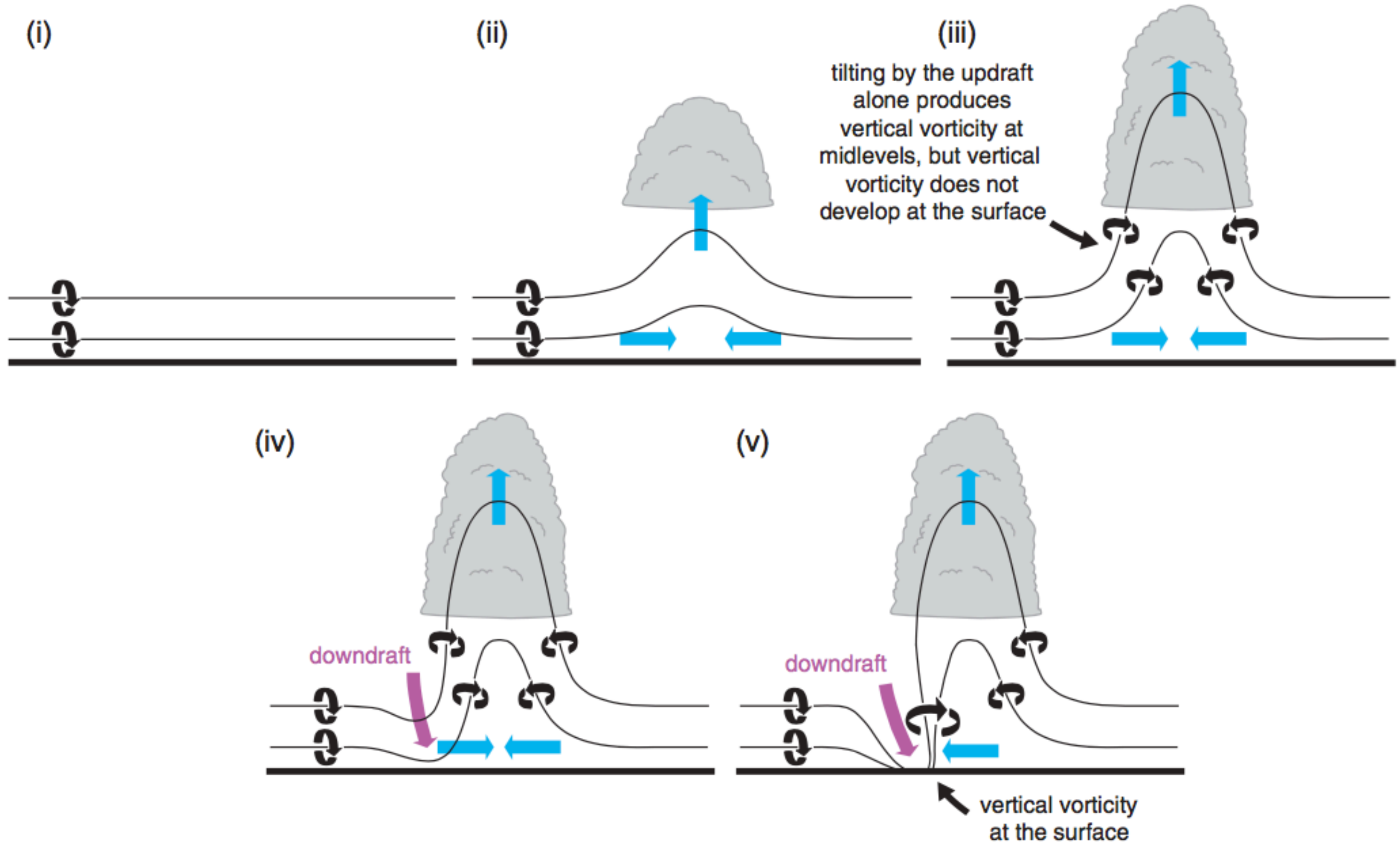
Vertical vorticity generation by buoyancy within supercells

Dual-Doppler analysis of storm-relative winds and vortex lines in a supercell

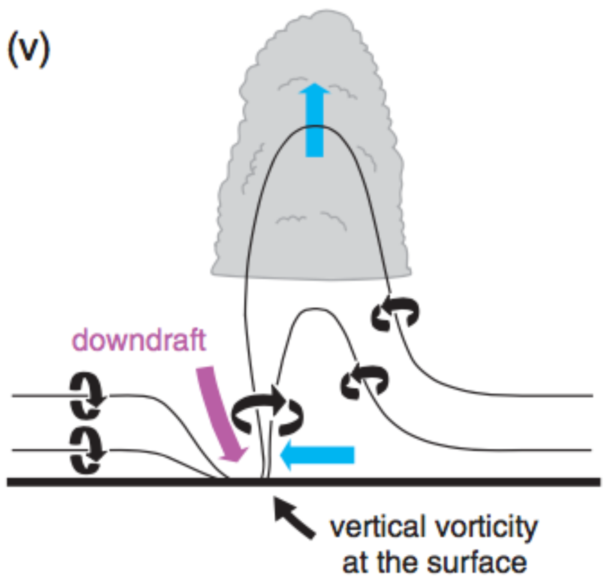


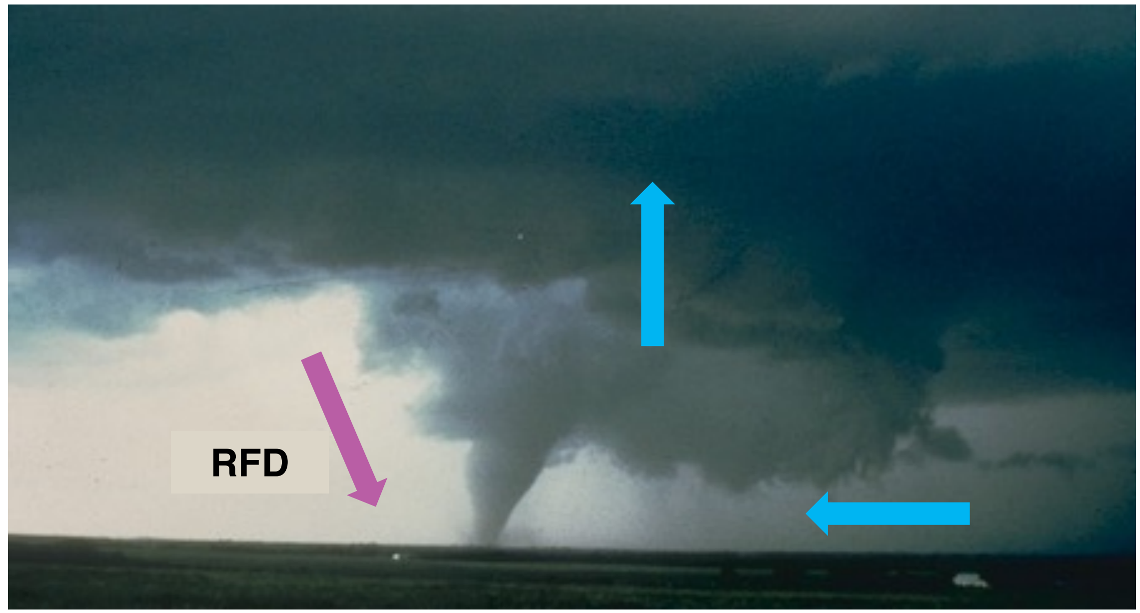
Developing vertical vorticity at the surface

(a) **vertical vorticity is initially negligible at the surface**



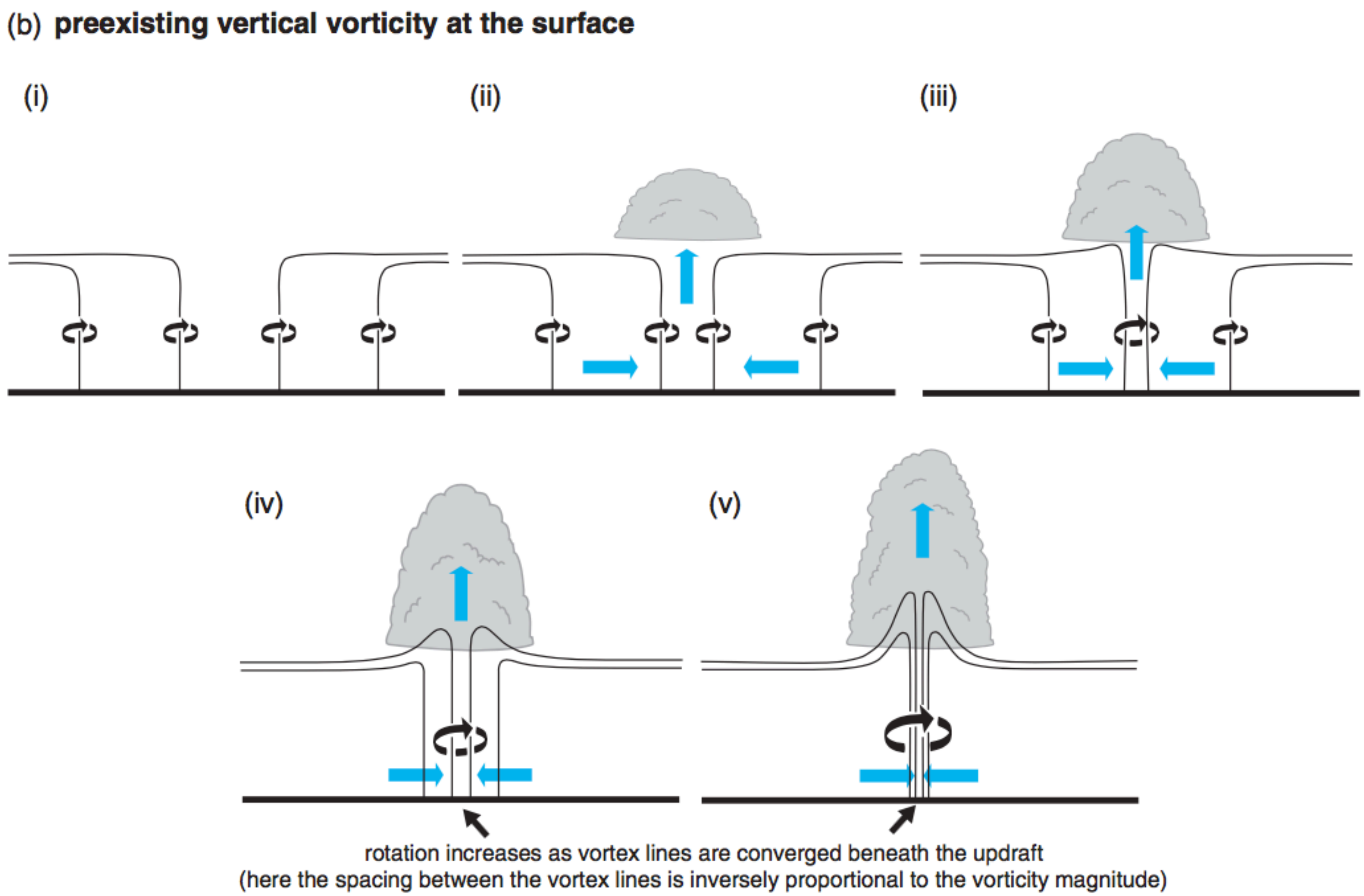
Developing vertical vorticity at the surface





Observations indicate that vortex lines associated with downdraft and not arched ***downward***, but ***upward***, indicating that the **baroclinic** vorticity generation in RFD plays a significant role in the formation of near-ground rotation.

Developing vertical vorticity at the surface – preexisting vertical vorticity



Vertical vorticity generation by buoyancy within supercells

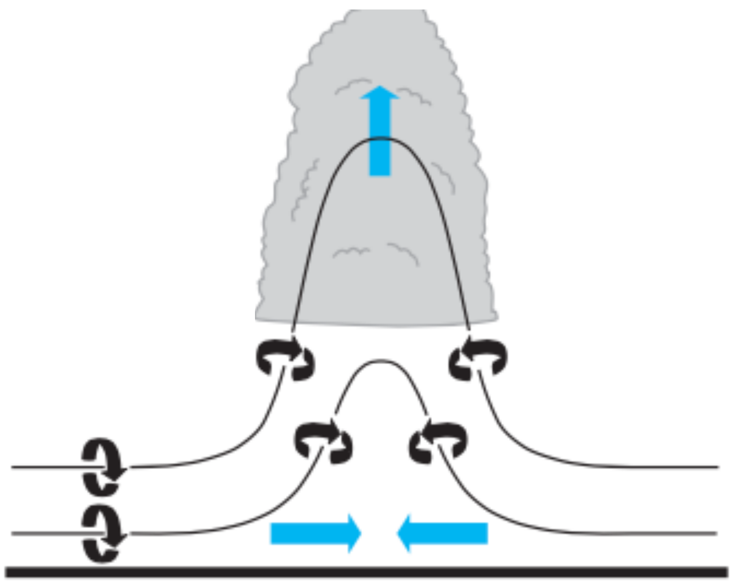
Summary:

In early stages of supercell development, mid-level mesocyclone produced from tilting of environmental vorticity.

Once baroclinic effects mature (i.e., cold pools develop), this vorticity can be augmented and produce a more significant low-level mesocyclone.

Additionally, a mature supercell can contain downdrafts that provide vortex rings that can intensity near-surface rotation.

Vertical vorticity generation by buoyancy within supercells



If considering only tilting, greater horizontal vorticity will result in greater vertical vorticity.

Thus, increasing horizontal vorticity (e.g., supplementing with baroclinic generation), will lead to a stronger mesocyclone.

This implies that rotation will be stronger near the surface (e.g., for a fixed threshold of rotation, that threshold will be met at a lower altitude).

Assuming similar surface rotation in both cases, this will **increase dp'/dz**.

This affects w, which can then increase stretching, further producing large low-level vertical vorticity.

Influence of low-level shear on updraft rotation

To optimize the development of near-ground rotation, need to maximize lifting (actually, dw/dz) to enhance stretching of air that is sufficiently rich with vertical vorticity.

How to do this?

For next week:

Read Markowski and Richardson (2014): "*The Influence of Environmental Low-Level Shear and Cold Pools on Tornadogenesis: Insights from Idealized Simulations*"