The influence of environmental low-level shear and cold pools on tornadogenesis: Insights from toy simulations

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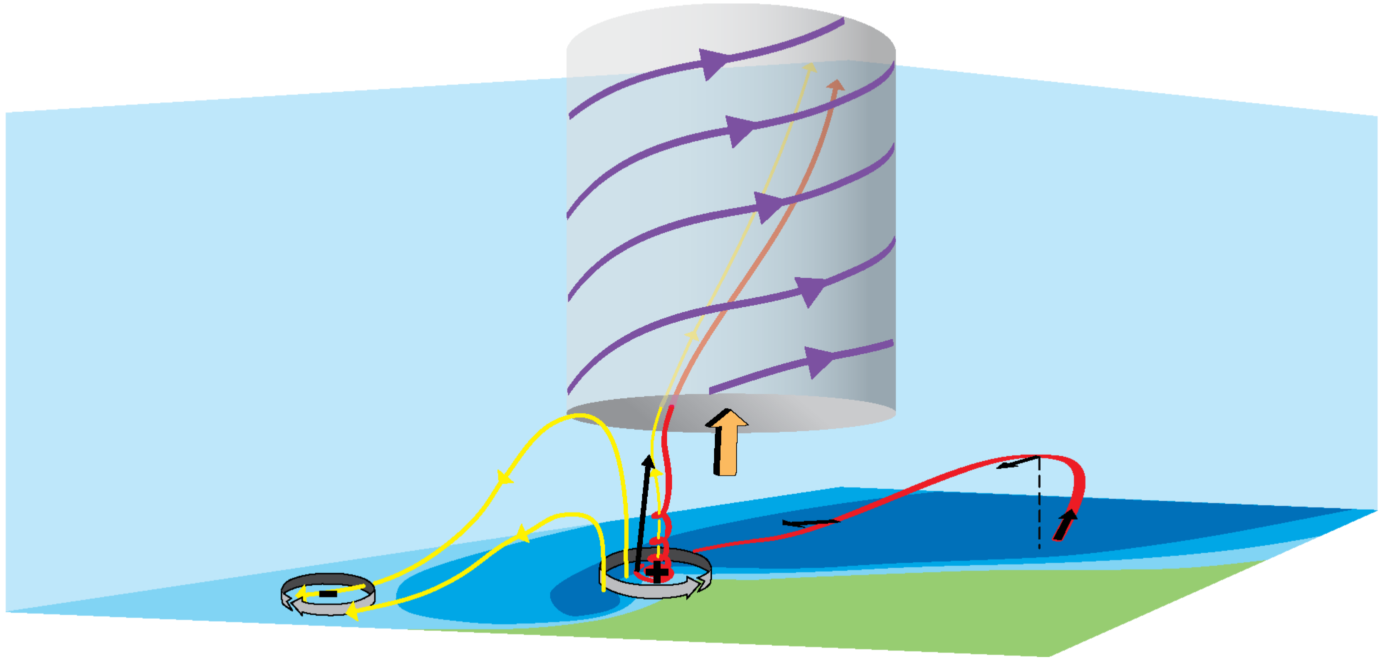


Motivating Questions

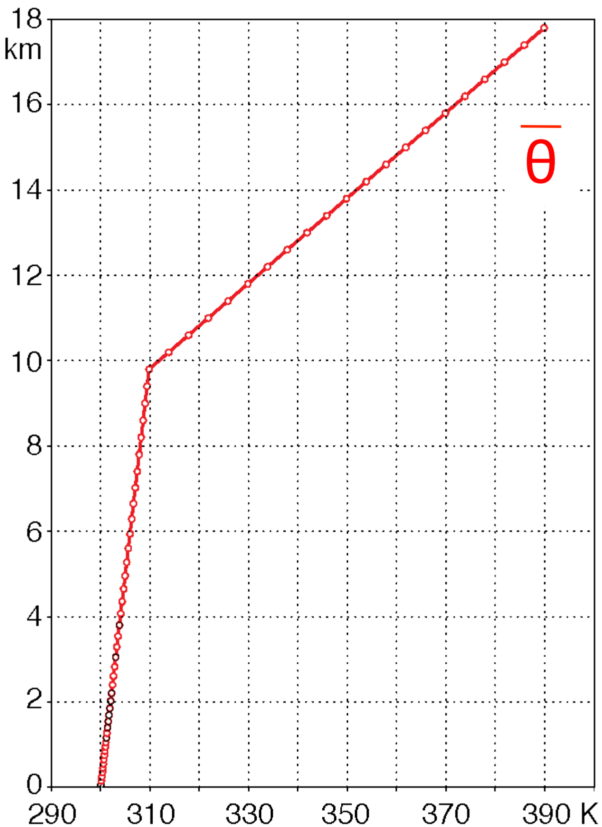
- What is the role of environmental horizontal vorticity in tornadogenesis?
  - Large environmental horizontal vorticity at low levels favors tornadic supercells
  - However, there's a mountain of evidence from both observations and simulations that the *baroclinic mechanism* is the dominant way by which near-surface cyclonic vorticity develops
    - e.g., material circuit analyses, vortex line analyses, and barotropic vs baroclinic vorticity decompositions

- Why is the combination of strong vertical shear and high boundary-layer RH so favorable for tornadoes?

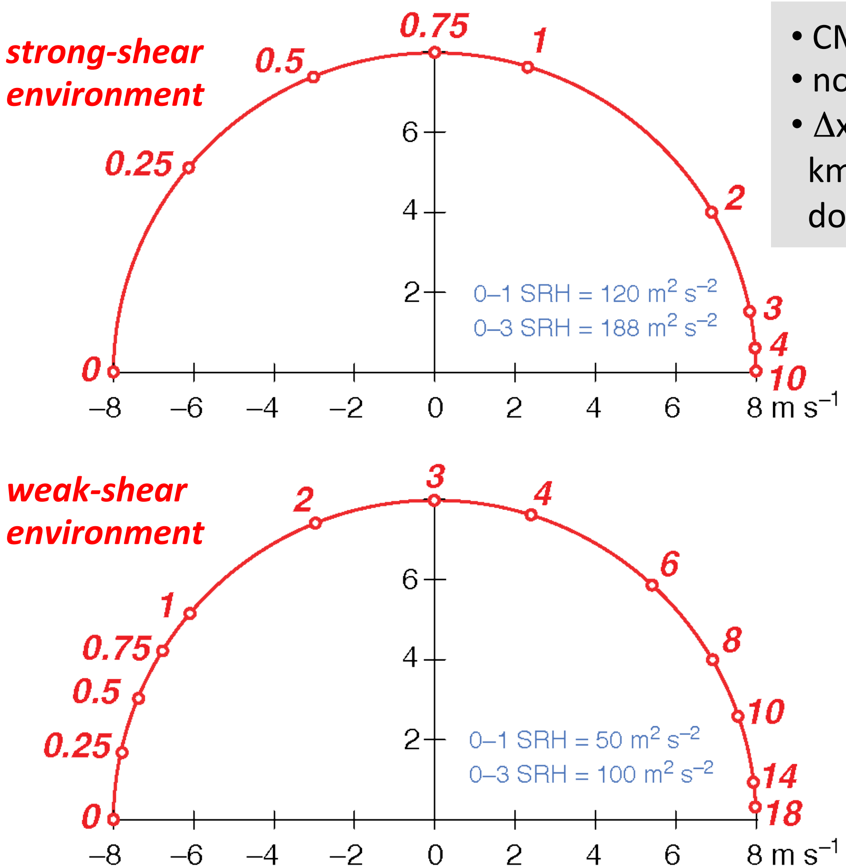
The Approach: "A Toy Model"

- Drive an updraft with a stationary, cylindrical heat source
  - The environmental wind profile is a semicircle (purely streamwise environmental vorticity); the updraft rotates cyclonically, rotation is a maximum at midlevels, rotation vanishes at the surface.

- CM1
- no water vapor
- Δx, Δy = 100 m in 25 x 25 km inner domain (entire domain is 100 x 100 km)



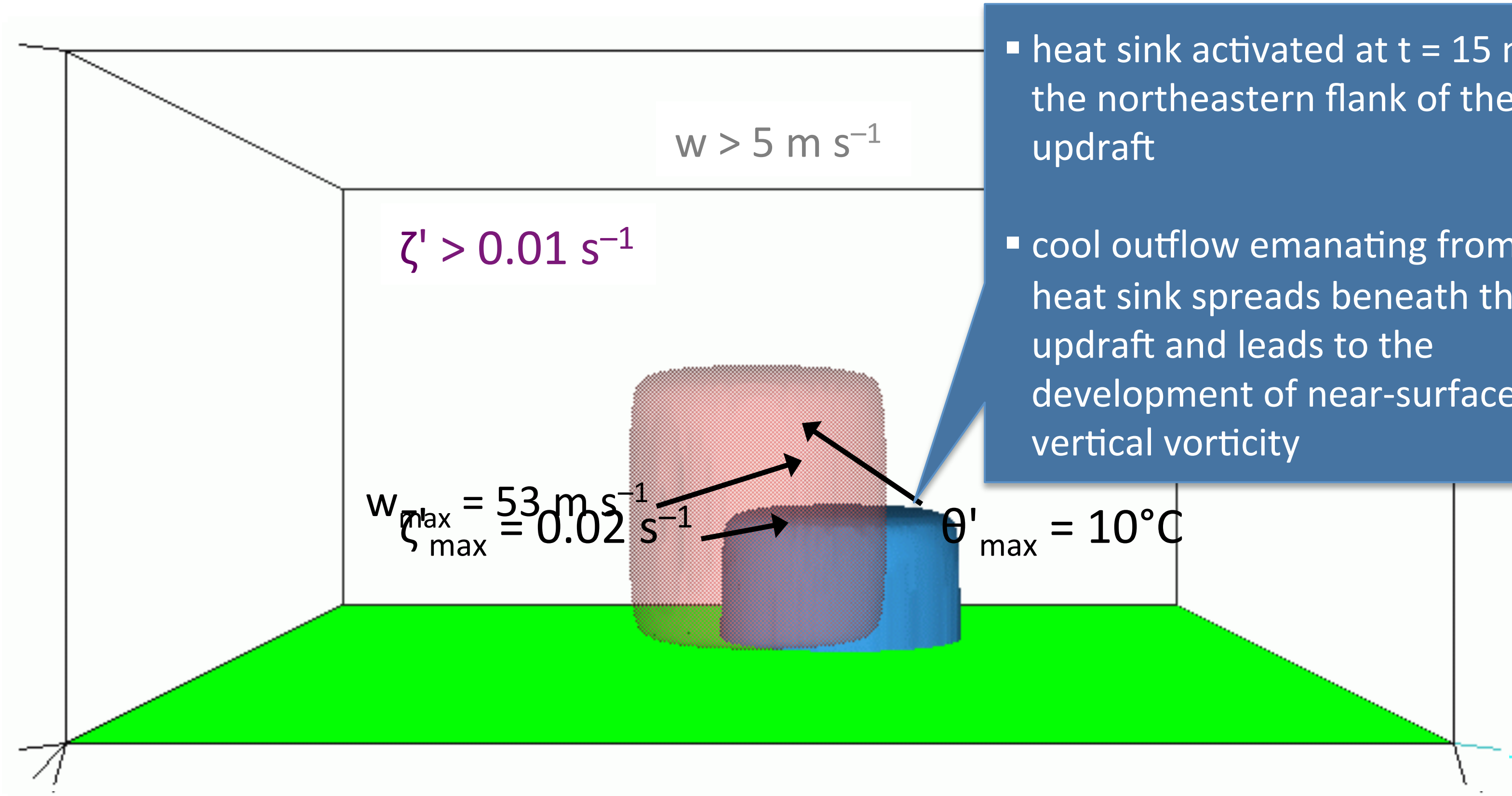
Walko (1993)



McCaul & Weisman (2001)

The Approach: “A Toy Model”

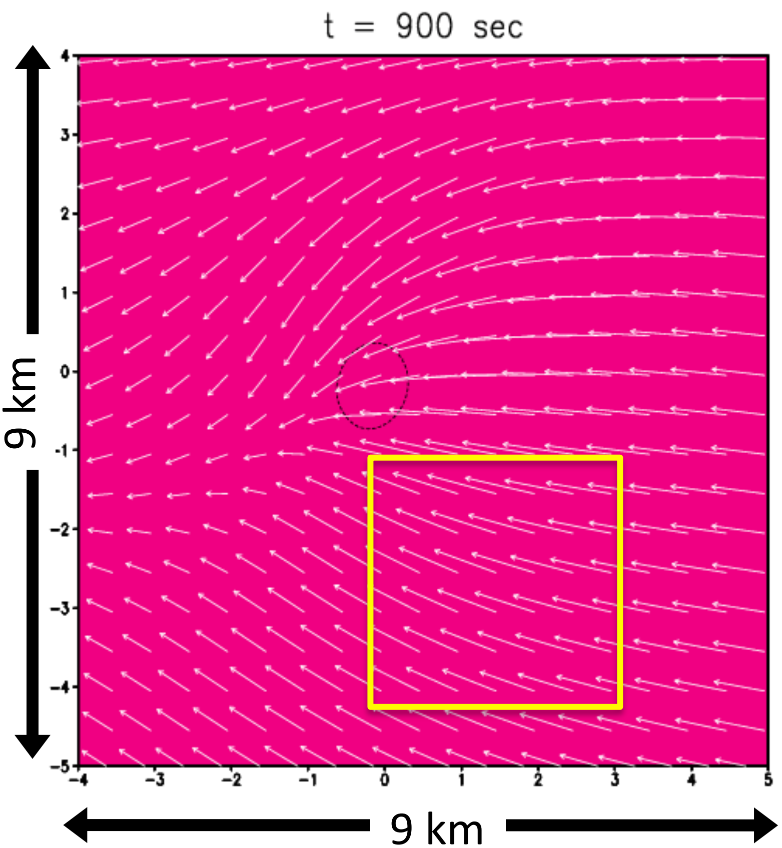
The simulations are not as realistic as those that incorporate more physical processes (e.g., latent heating, microphysics, etc.), but we believe the simplicity of such “toy models” can be advantageous in that it may be easier to isolate key dynamical processes and assign cause and effect.

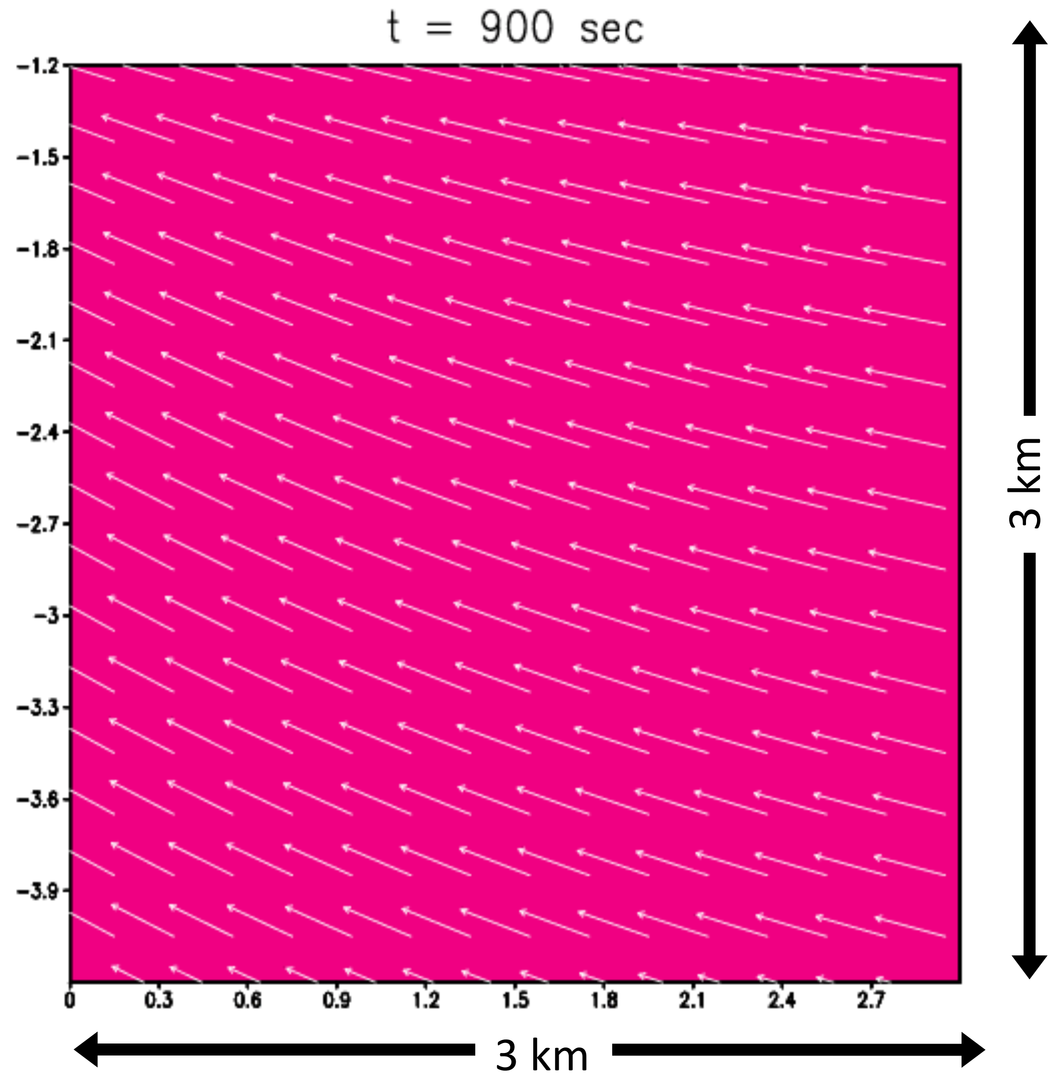


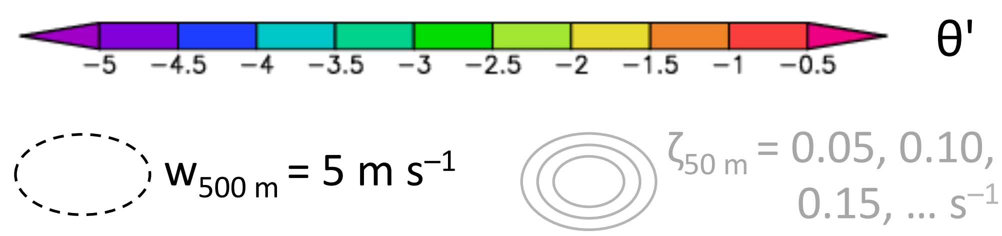
- heat sink activated at t = 15 min on the northeastern flank of the updraft
- cool outflow emanating from the heat sink spreads beneath the updraft and leads to the development of near-surface vertical vorticity

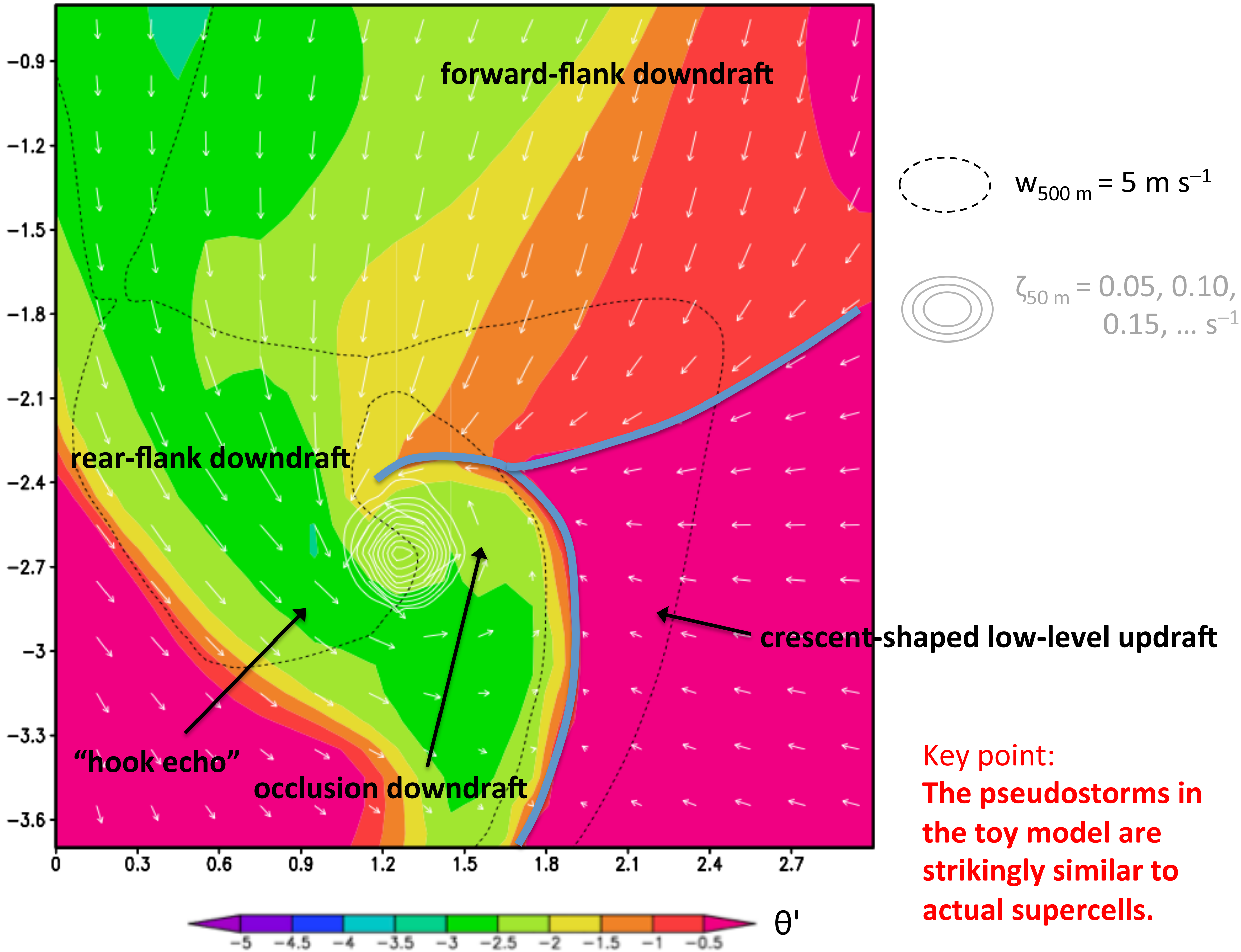
strong low-level shear, intermediate heat sink

ζ_{max} = 0.83 s^{-1}
v_{max} = 31 m s^{-1}
duration = 9.4 min



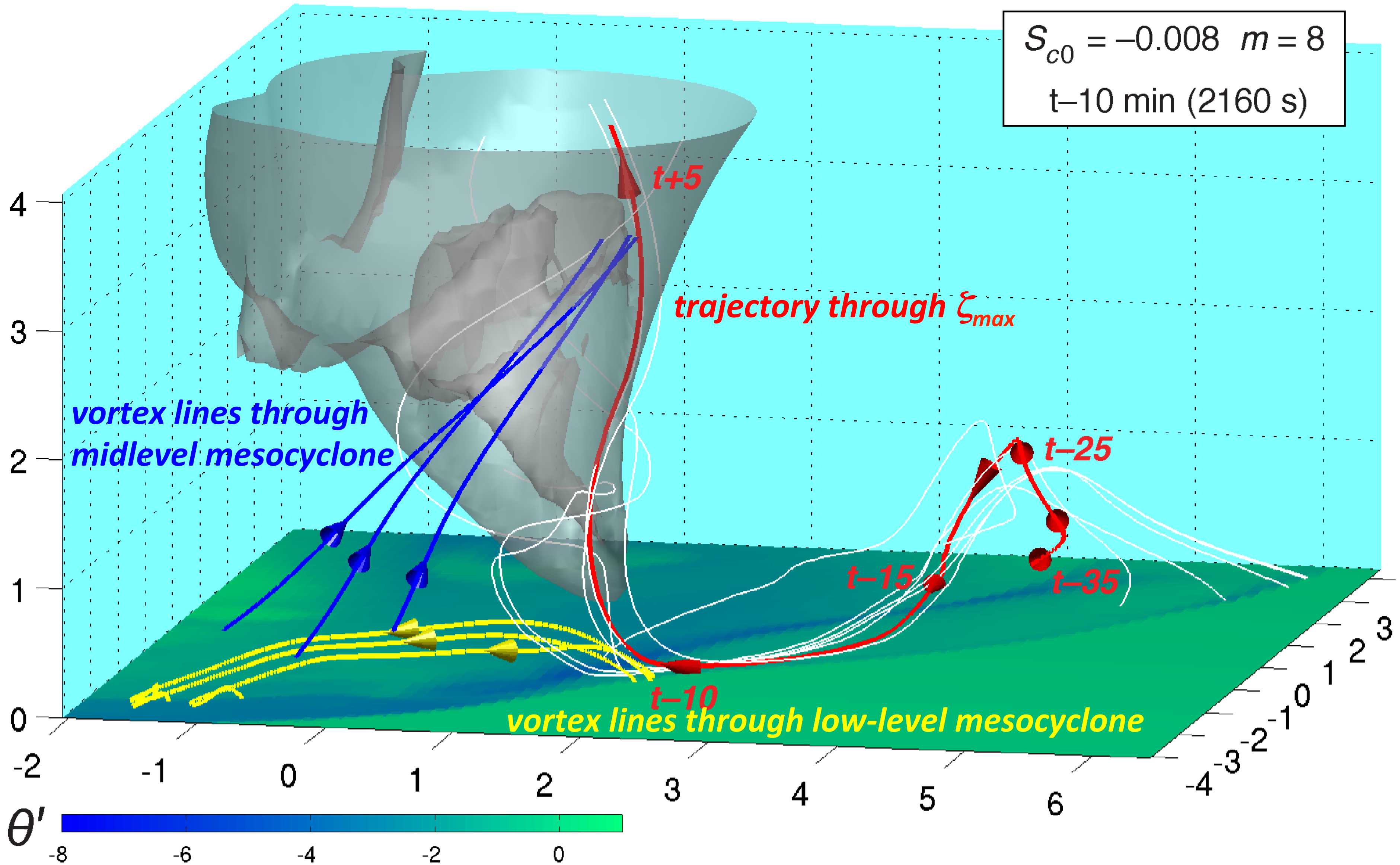






Key point:

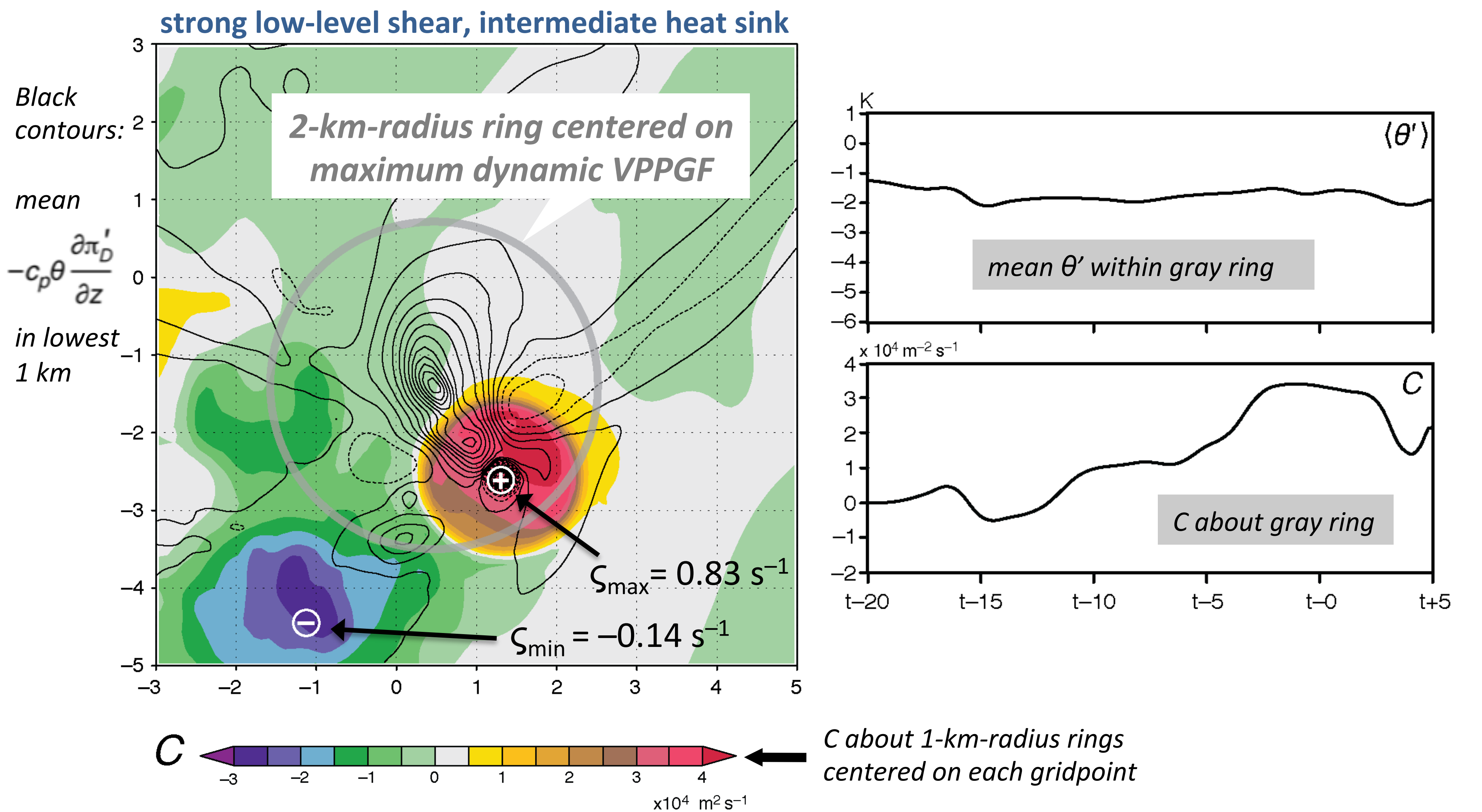
The pseudostorms in the toy model are strikingly similar to actual supercells.

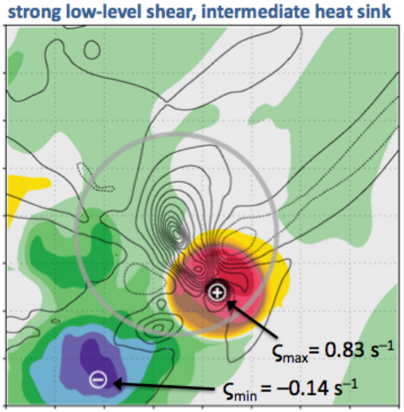


Key point:

There's "higher-order" similarity of the pseudostorms to actual supercells as well (e.g., vortex lines, trajectories, and the dynamical processes leading to the development of near-surface rotation compare well with actual supercells despite the simplicity of the toy model).

The development of an intense cyclonic vortex is the result of circulation-rich, near-surface air being associated with weak negative buoyancy and also experiencing a large upward-directed VPPGF owing to its proximity to the midlevel mesocyclone.





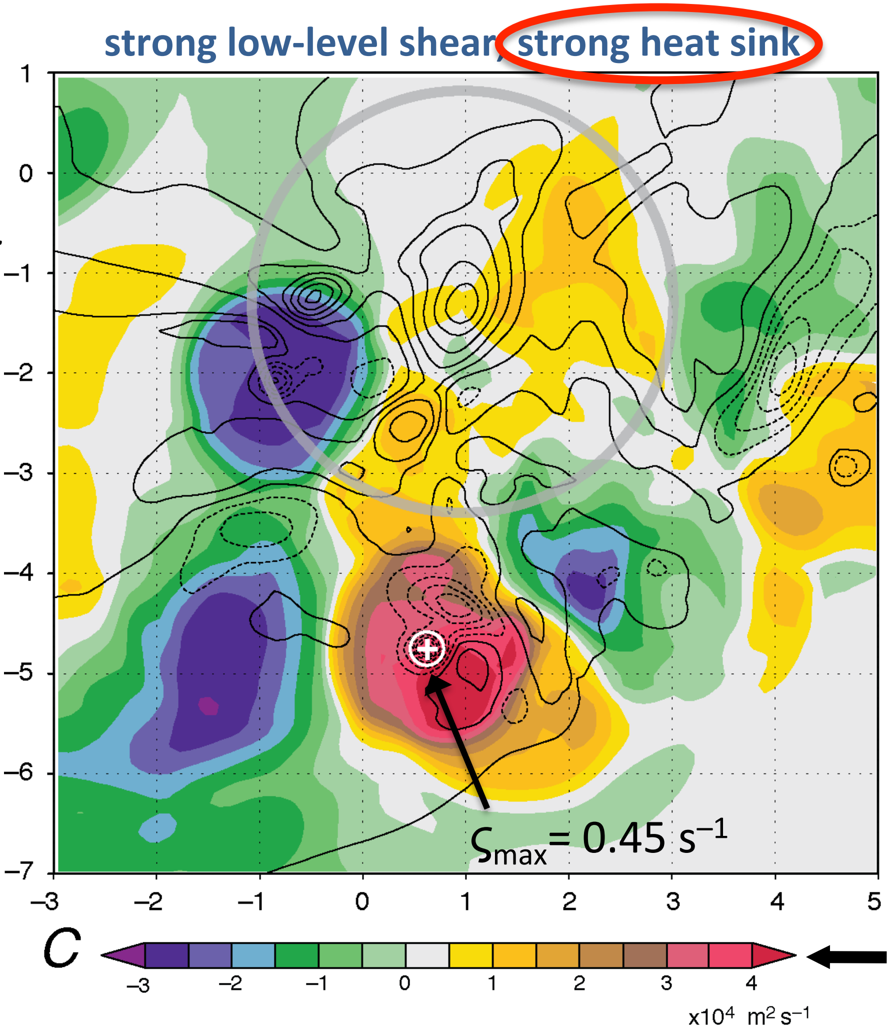
When the heat sink is strong, the maximum near-surface circulation is (slightly) stronger, but it is displaced farther from the region of dynamic lifting and is associated with larger negative buoyancy.

Black contours:

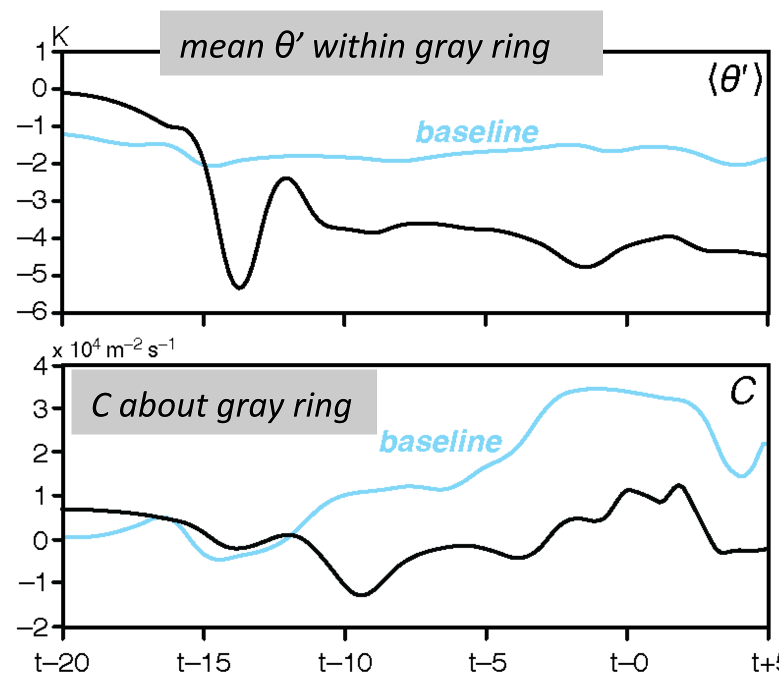
mean

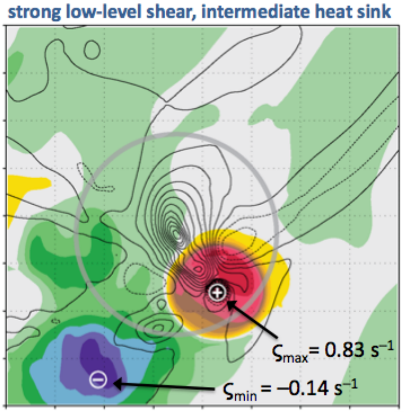
$$-c_p\theta\frac{\partial\pi_D'}{\partial z}$$

in lowest 1 km



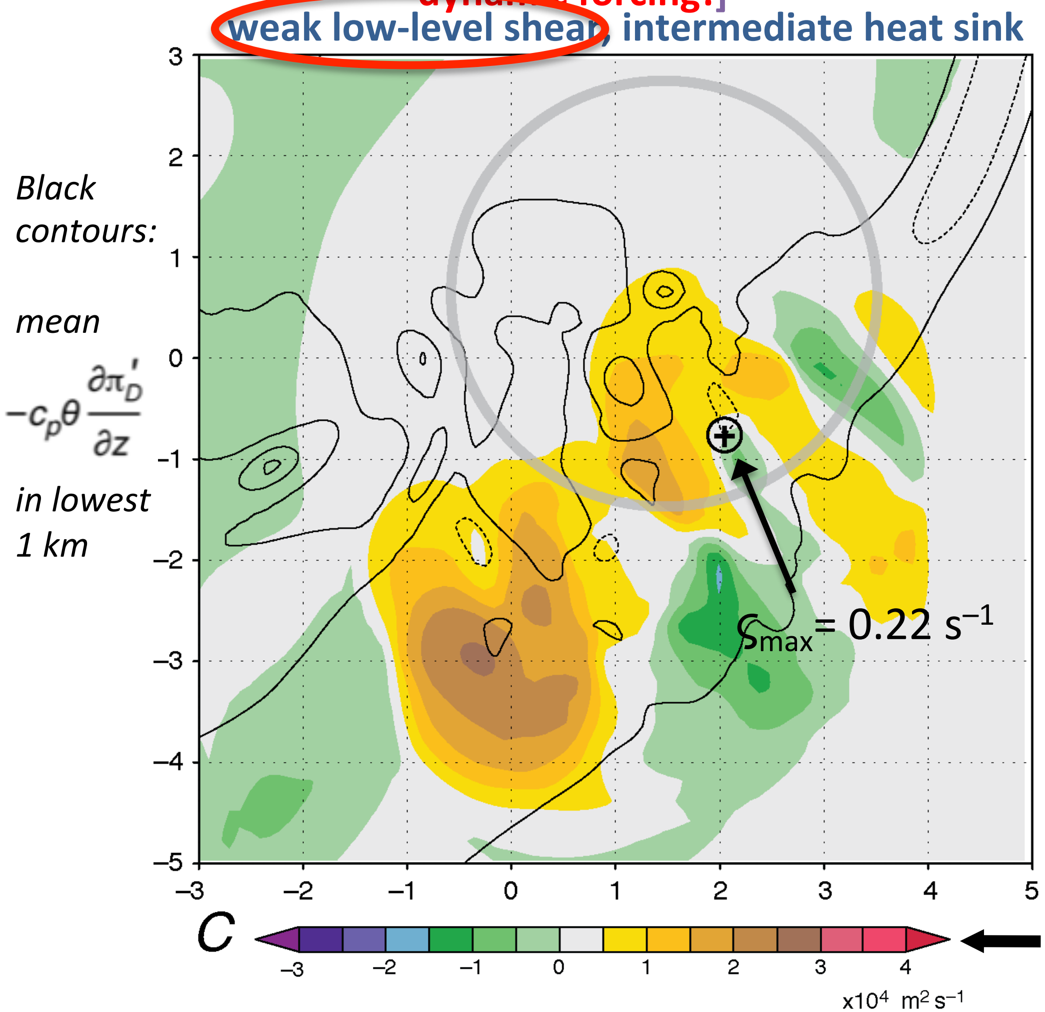
C about 1-km-radius rings centered on each gridpoint

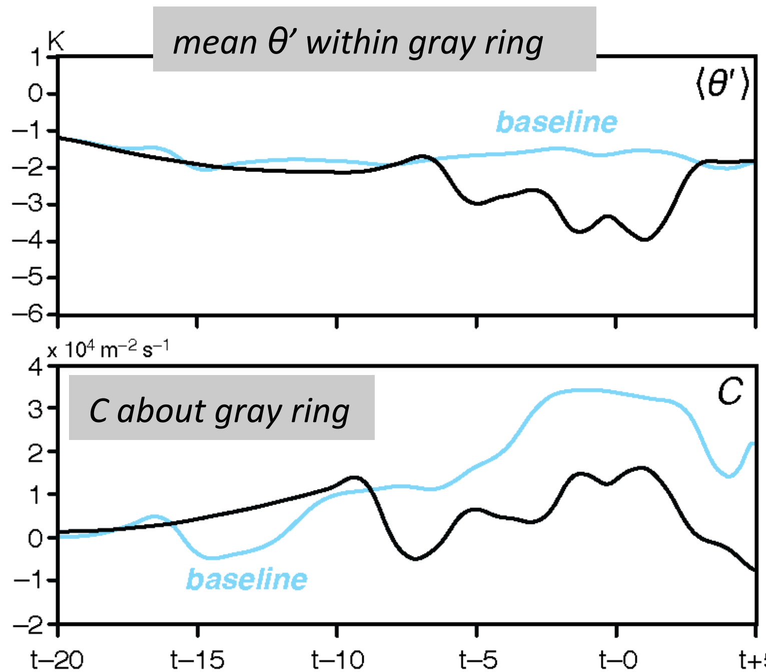




When the low-level shear is weak, the dynamic lifting is much weaker.

[The near-surface circulation also is less than in the baseline (intense vortex) simulation, displaced far from the dynamic lifting, and is associated with greater negative buoyancy. This illustrates the complex relationship between parcel residence times in the heat sink, exposure to baroclinity, and the location where large circulation develops relative to the dynamic forcing!]





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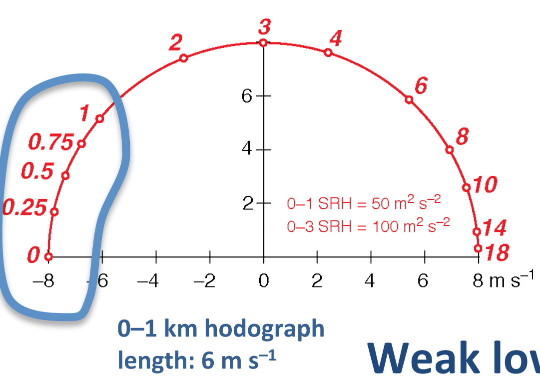
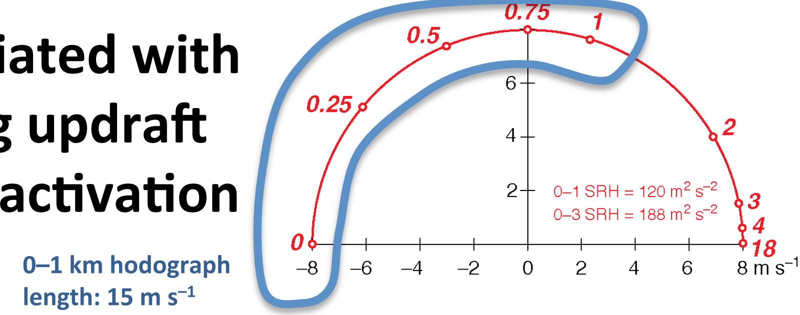
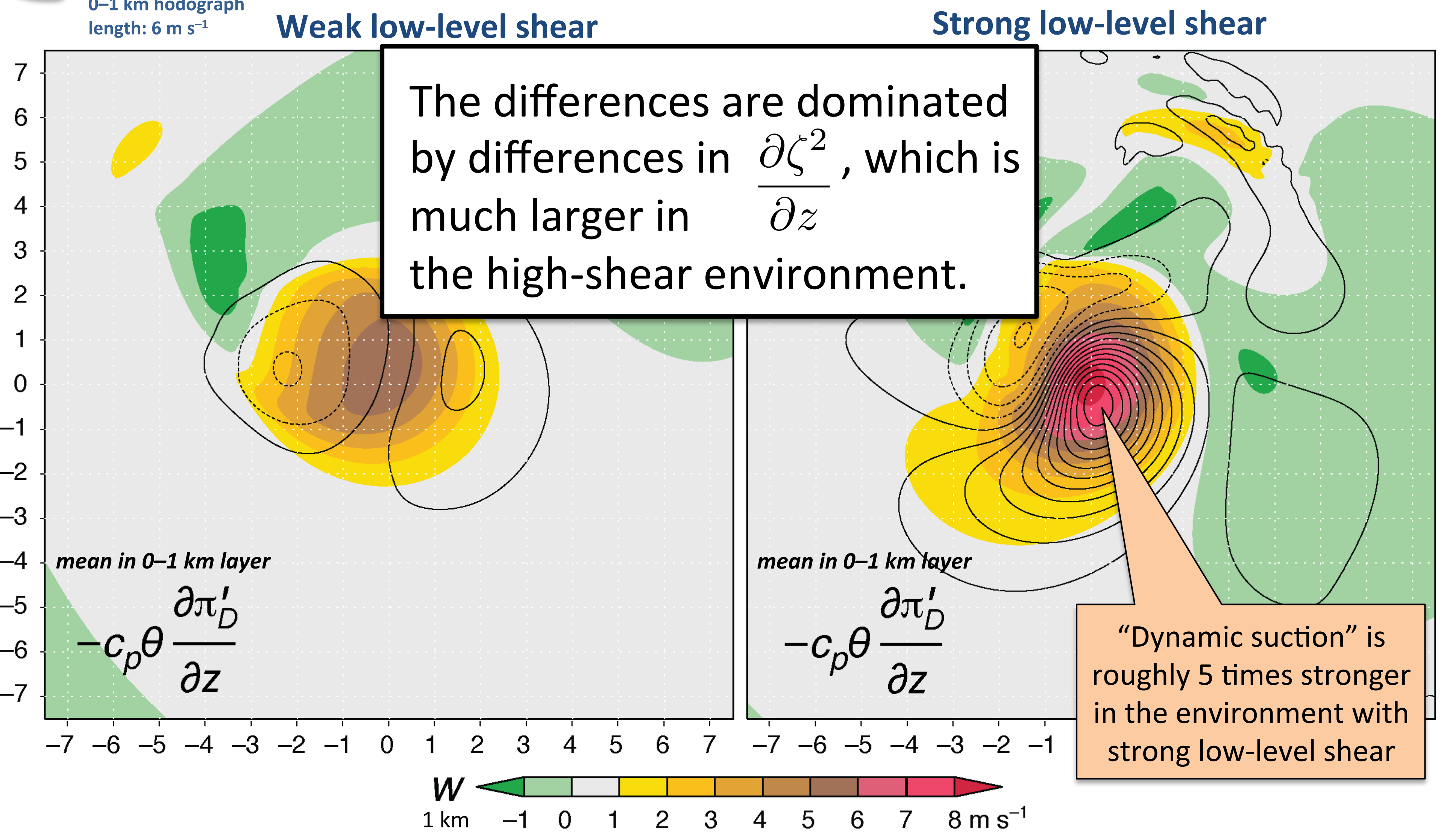
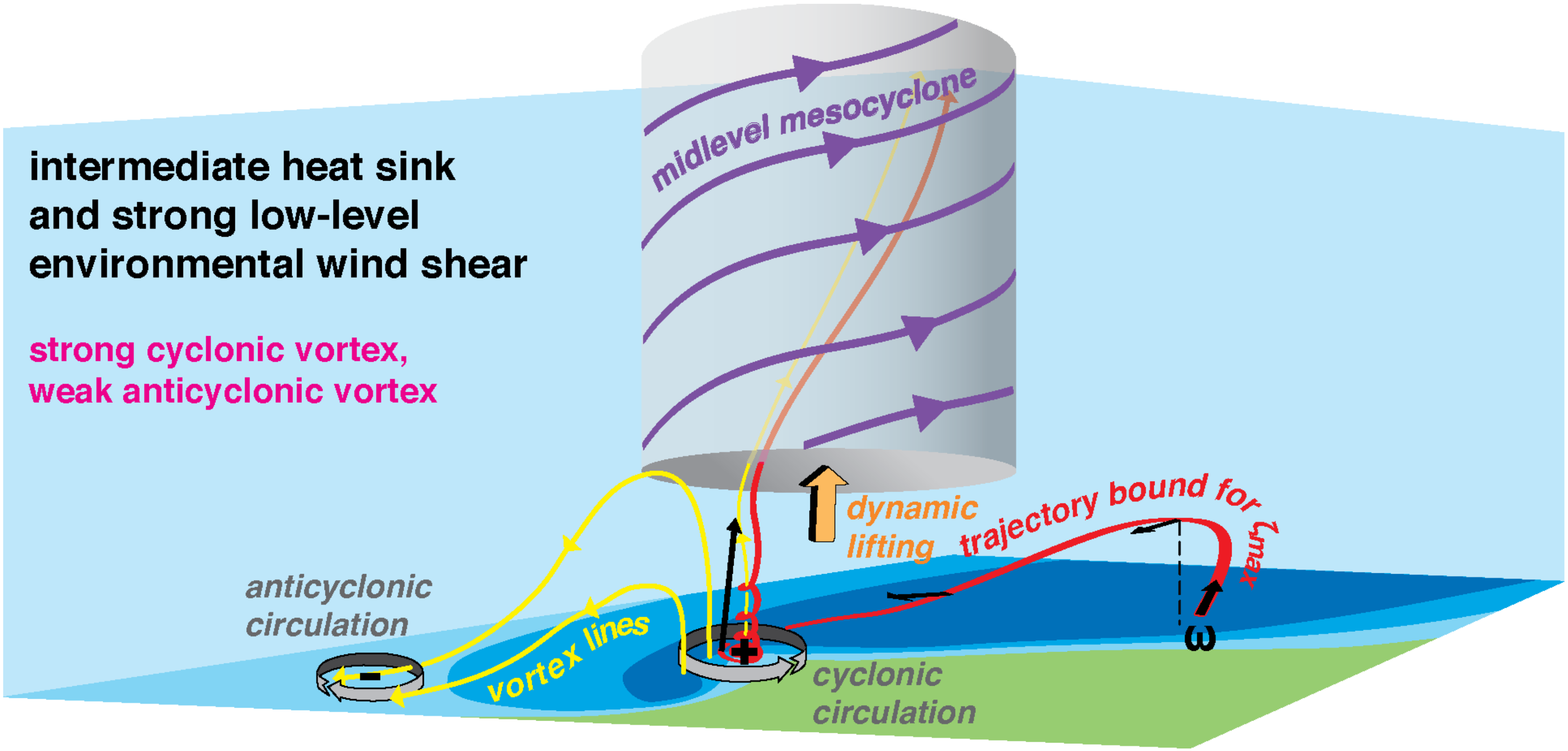
Dynamic VPPGF associated with quasi-steady rotating updraft just prior to heat sink activation



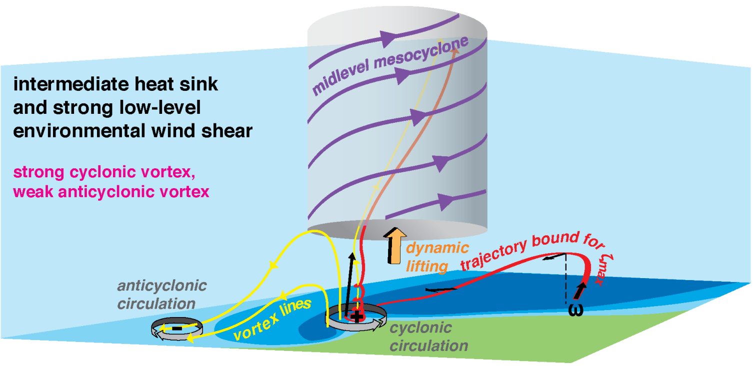


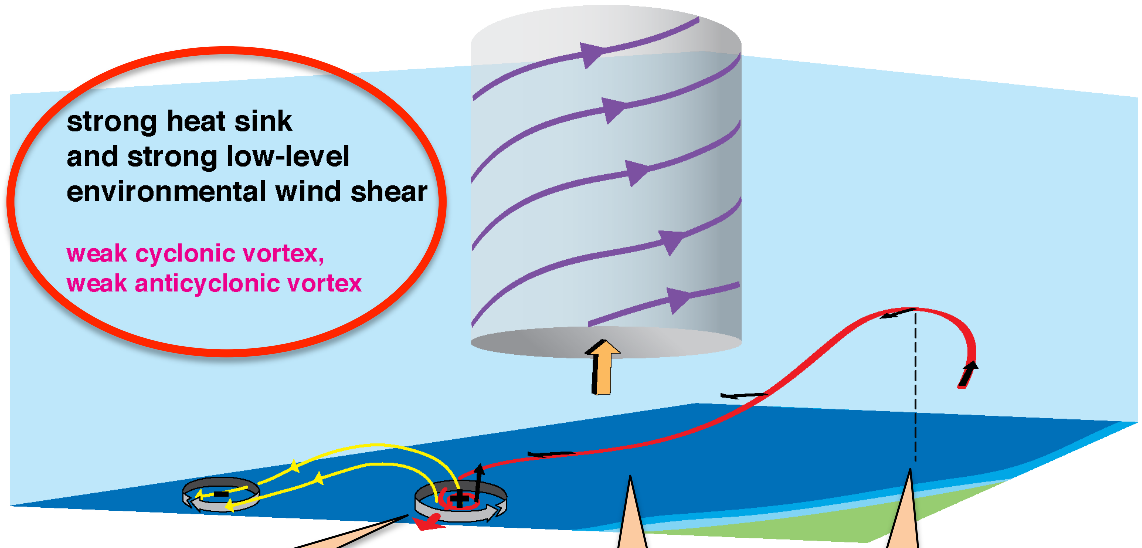


Summary



Take-home message: The development of an intense cyclonic vortex is the result of circulation-rich, near-surface air being associated with weak negative buoyancy and also experiencing a large upward-directed VPPGF owing to its proximity to the midlevel mesocyclone.



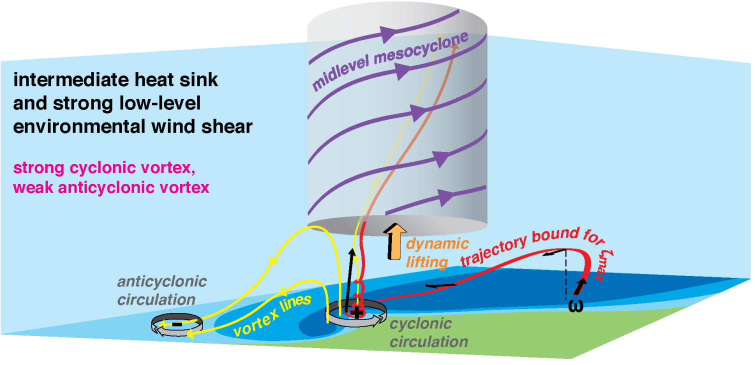


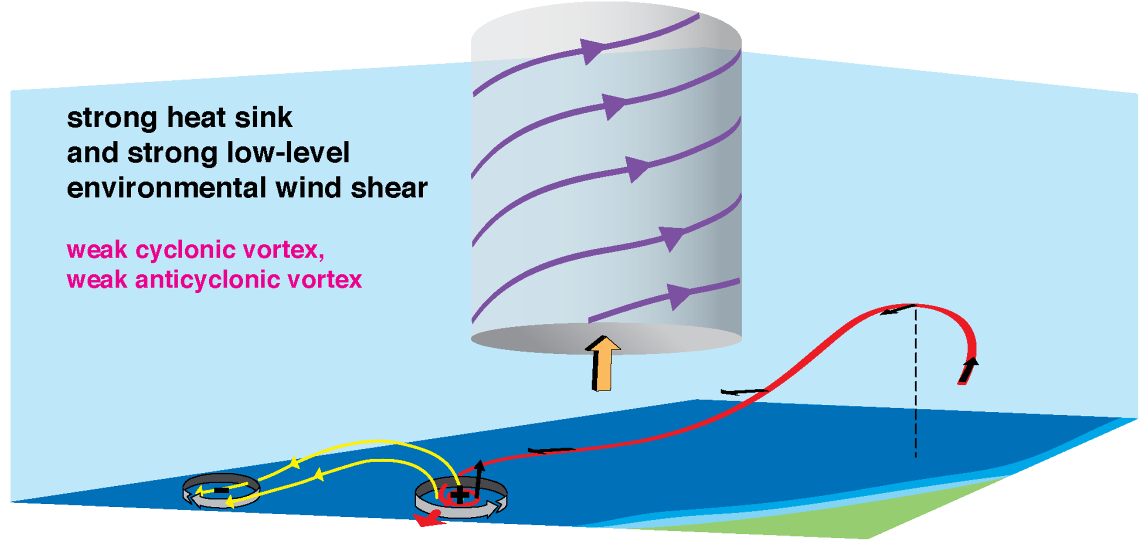
Strong near-surface cyclonic circulation develops, but it is **characterized by large negative buoyancy** and does not experience significant dynamic suction owing to the **large horizontal displacement of the circulation-rich air from the midlevel forcing**.

Colder outflow

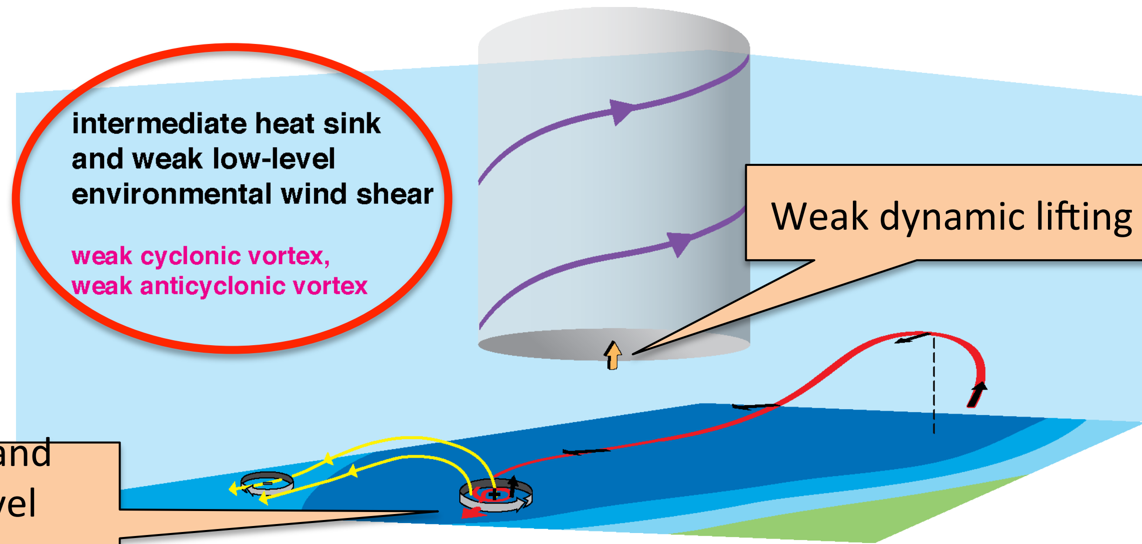
Downdraft parcels that develop vertical vorticity originate from higher altitude

Take-home message: **The development of an intense cyclonic vortex is the result of circulation-rich, near-surface air being associated with weak negative buoyancy and also experiencing a large upward-directed VPPGF owing to its proximity to the midlevel mesocyclone.**





Outcome is similar to simulation with strong heat sink and strong low-level shear



Weak dynamic lifting

Circulation-rich air is cold and displaced from the midlevel forcing

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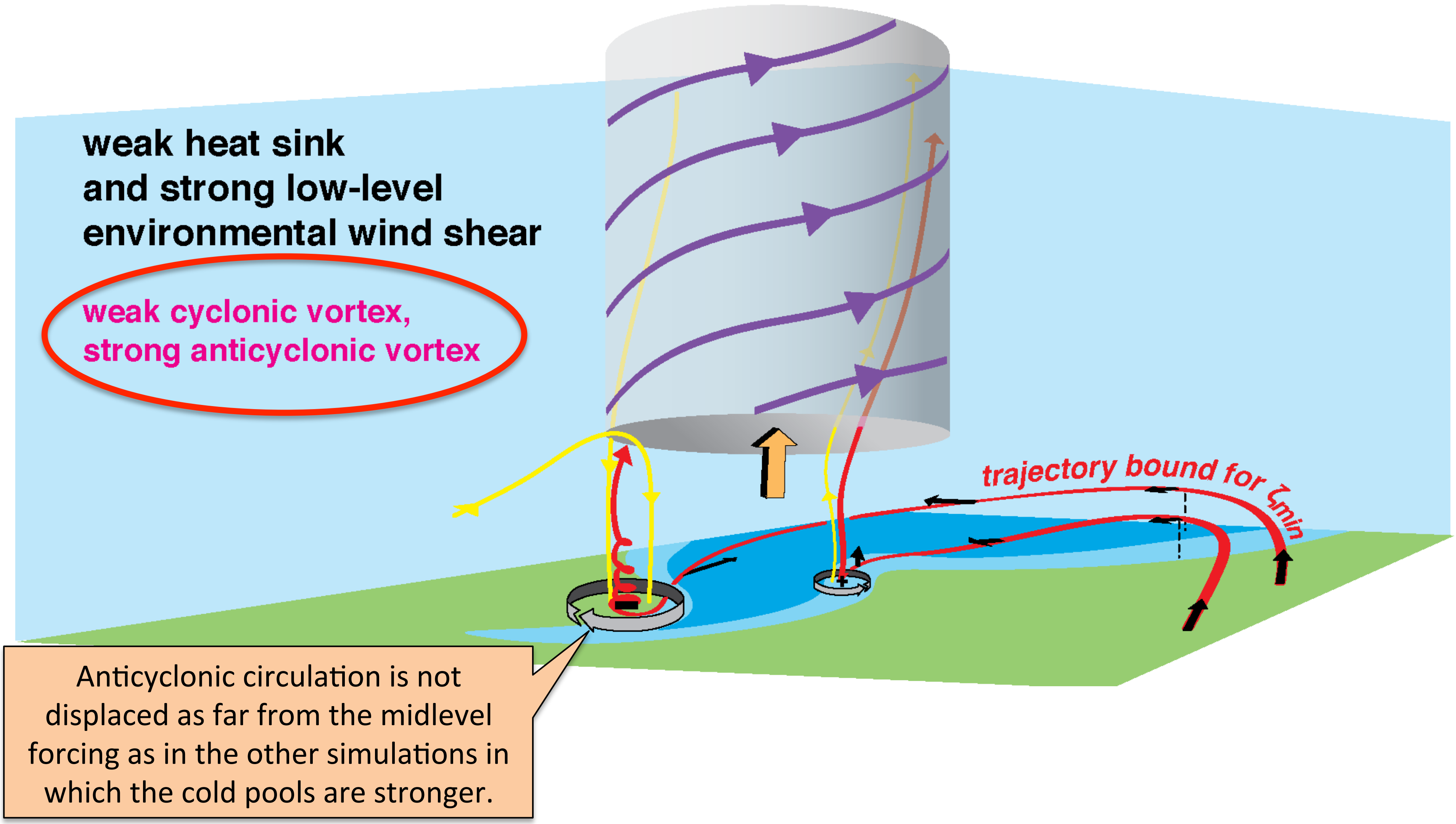

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Motivating Questions

- What is the role of environmental horizontal vorticity in tornadogenesis?

We are unable to refute the hypothesis that the environmental low-level horizontal vorticity's role is to promote dynamic lifting and convergence of circulation-rich, near-surface air, which is typically negatively buoyant.

- Why is the combination of strong vertical shear and high boundary-layer RH so favorable for tornadoes?

As the environmental low-level shear increases, dynamic lifting is enhanced. As boundary-layer RH increases, cold pools tend to become less negatively buoyant. The combination of a strong upward-directed VPPGF and weak negative buoyancy favors large upward accelerations and vertical vorticity stretching.

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http://www.meteo.psu.edu/~pmm116/toysims.pdf

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