On the Development of Large Surface Vorticity in High-Resolution Supercell Simulations

Johannes Dahl[1], Matthew Parker[1], and Louis Wicker[2]

[1]North Carolina State University, Raleigh, NC

[2]National Severe Storms Laboratory, Norman, OK

Thanks to …
George Bryan, Paul Markowski, Bob Davies-Jones, Casey Letkewicz, Adam French

Motivation

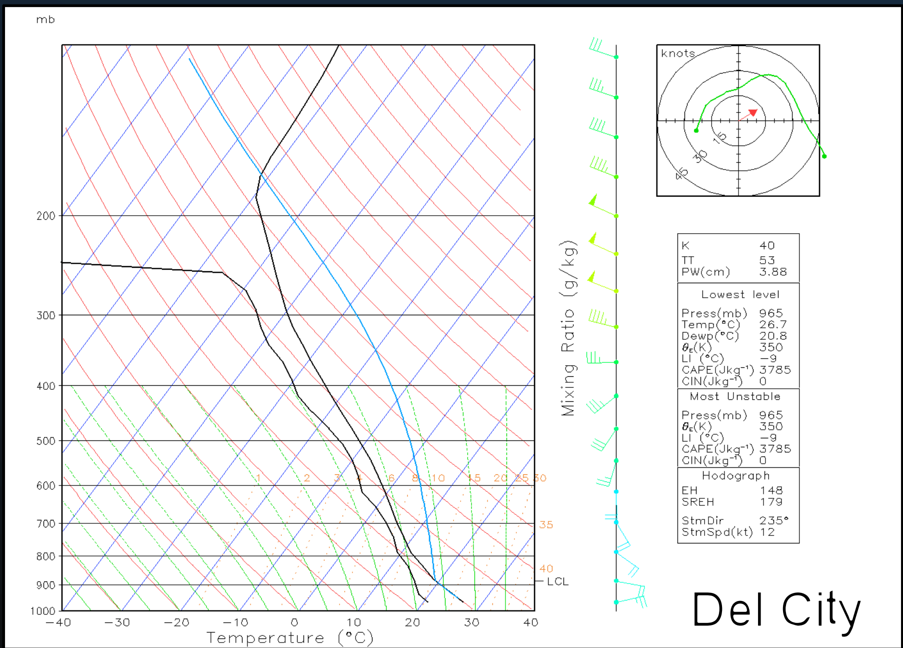
- Tornadogenesis thought of as three-stage process
    1. Midlevel mesocyclogenesis
    2. Development of vorticity at the surface
    3. Concentration of this vorticity into tornadic strength
- 2nd stage perhaps least understood fundamentally
- Some open questions:
    - Role of low-level shear in tornadogenesis
    - Role of baroclinic and barotropic processes

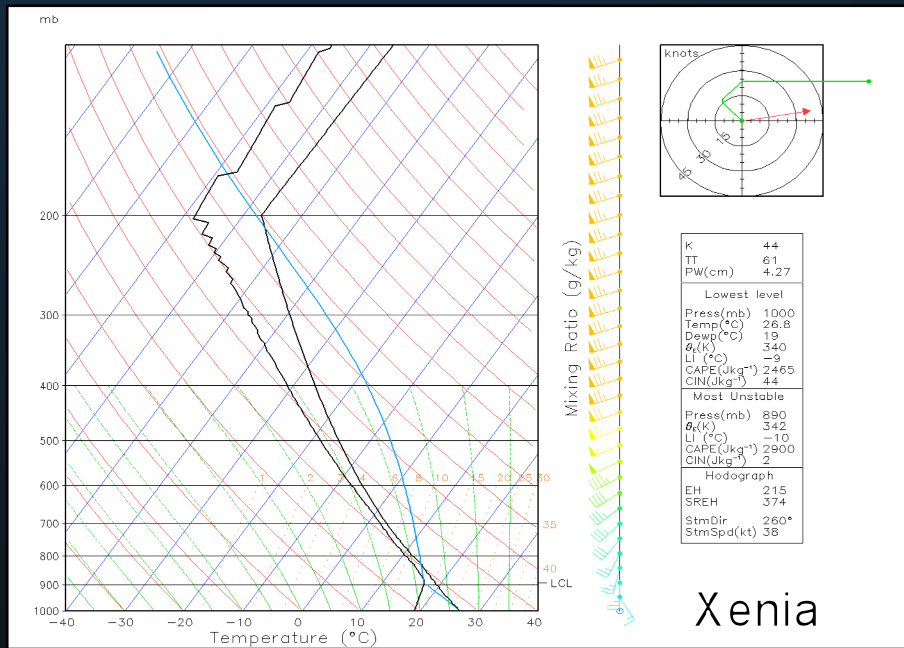
Simulations: overview

Two full-physics simulations using homogeneous base-state environments

- Del City, OK (20 May 1977): “benchmark” case

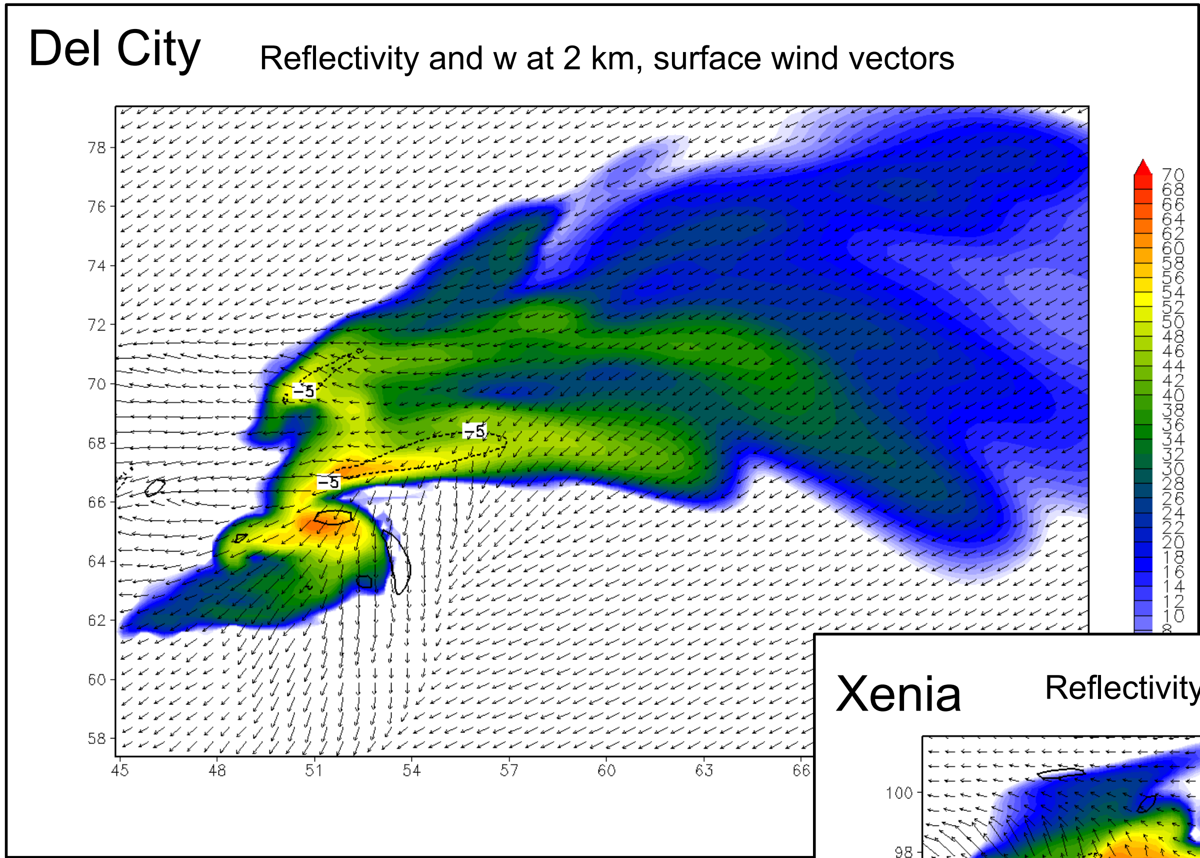
- “Frankenstein sounding”: wind profile based on Xenia, OH (3 April 1974), idealized thermodynamic profile; referred to as “Xenia case”

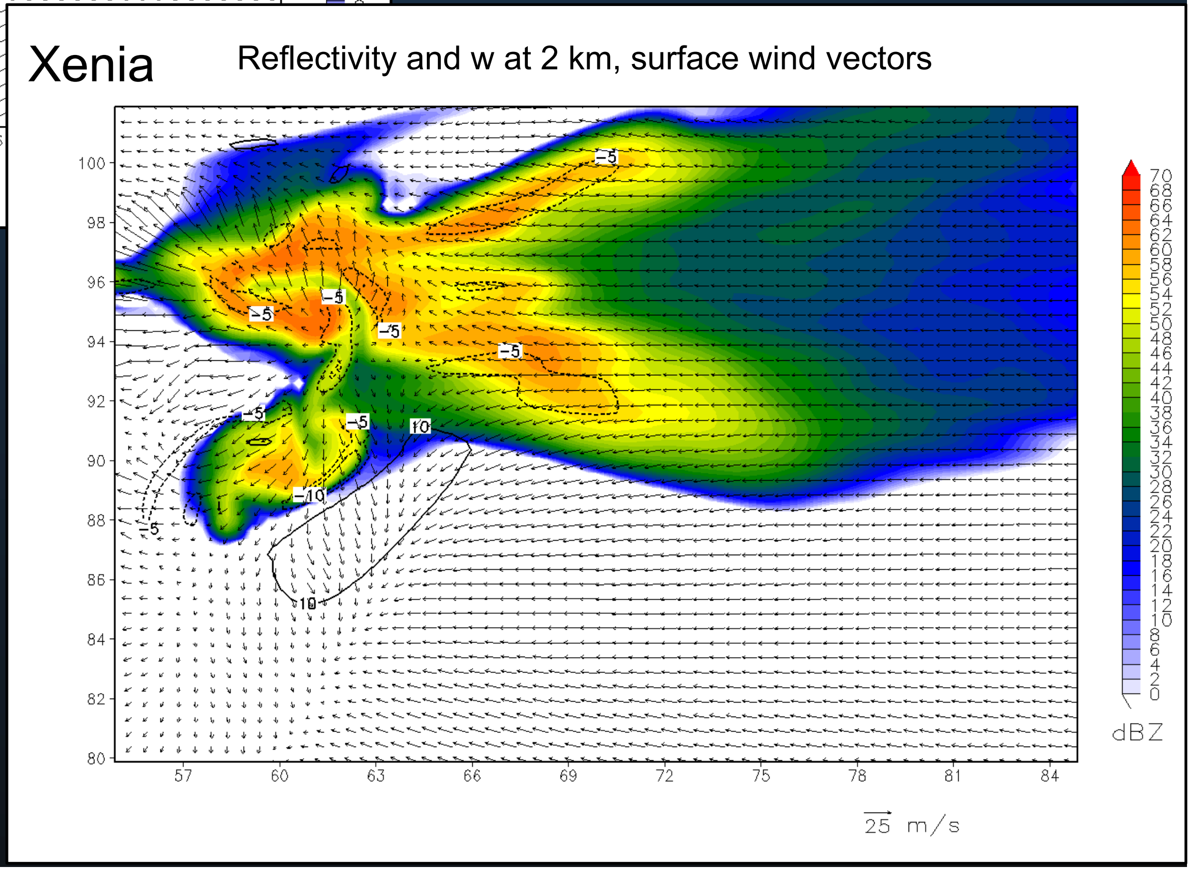


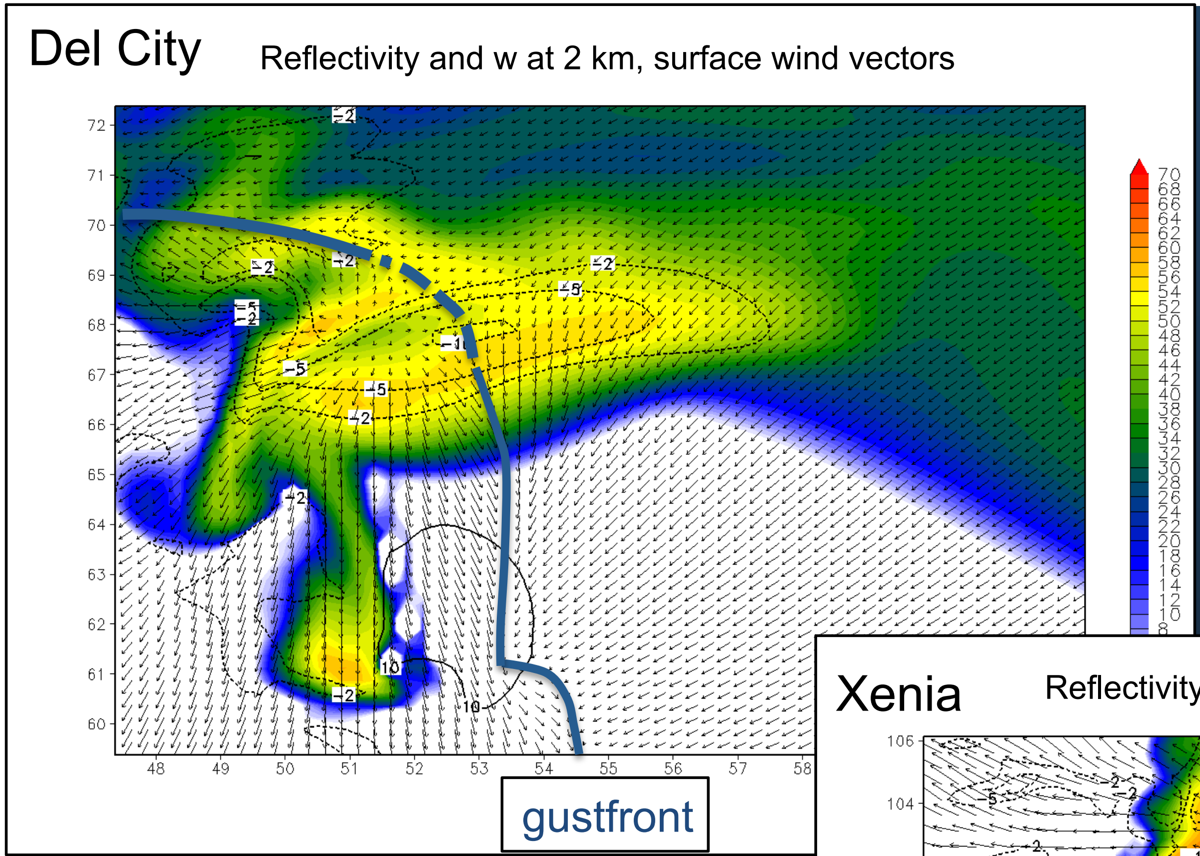


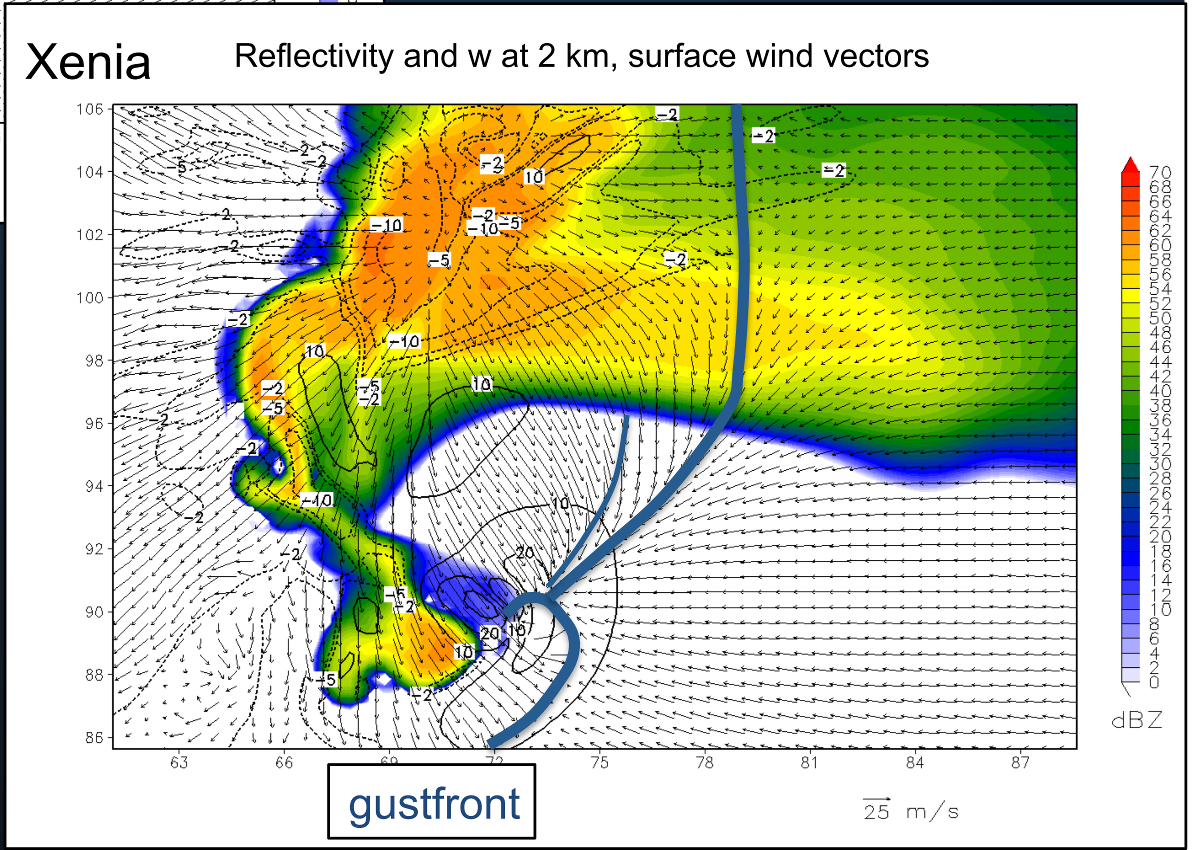
Simulations: overview

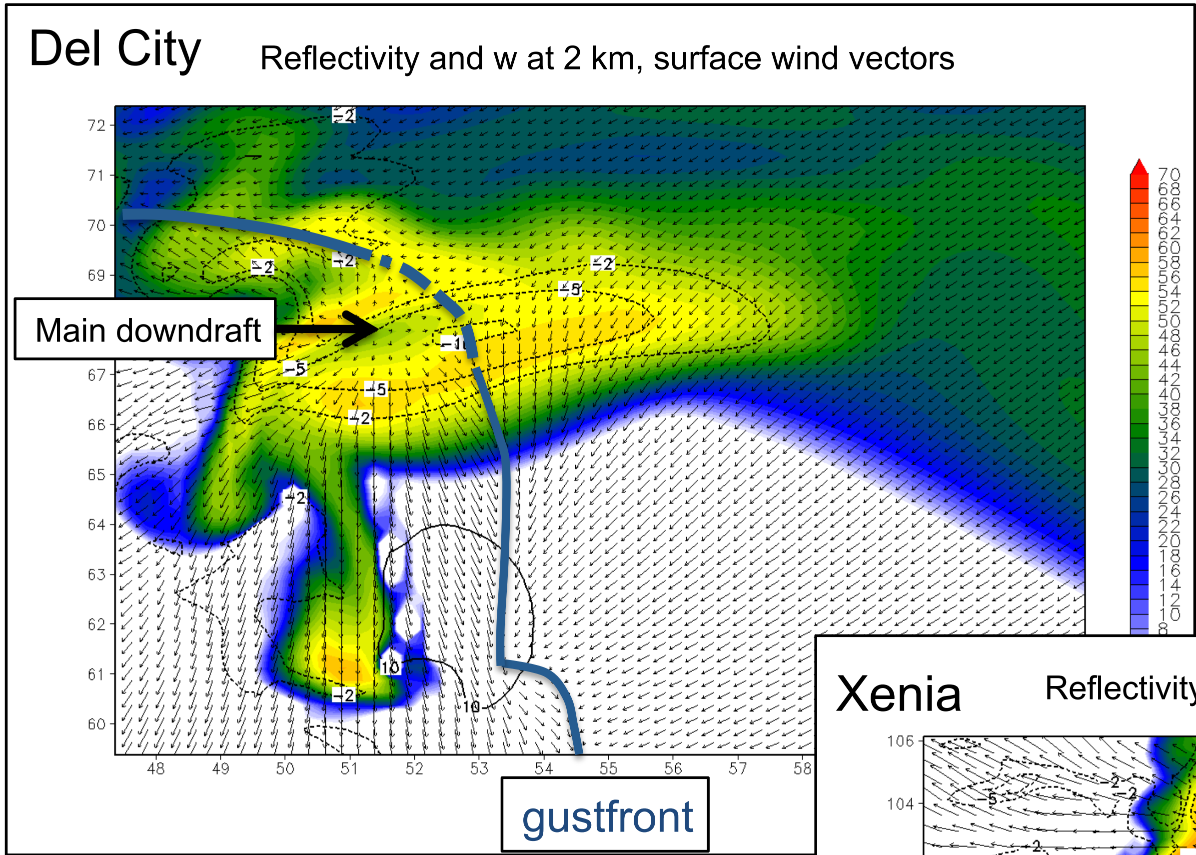
- Bryan cloud model CM1, version 14
- LFO (Gilmore et al.) single-moment microphysics
- Rain intercept: 1E6 (default: 8E6)
- Free-slip lower BC
- Initialization: warm bubble (1 K, 85% rh, R = 6 km)
- dx = dy = 250 m
- 100 m < dz < 250 m
- dt = 2.0
- Lowest model level: 50 m
- Output every 30 s

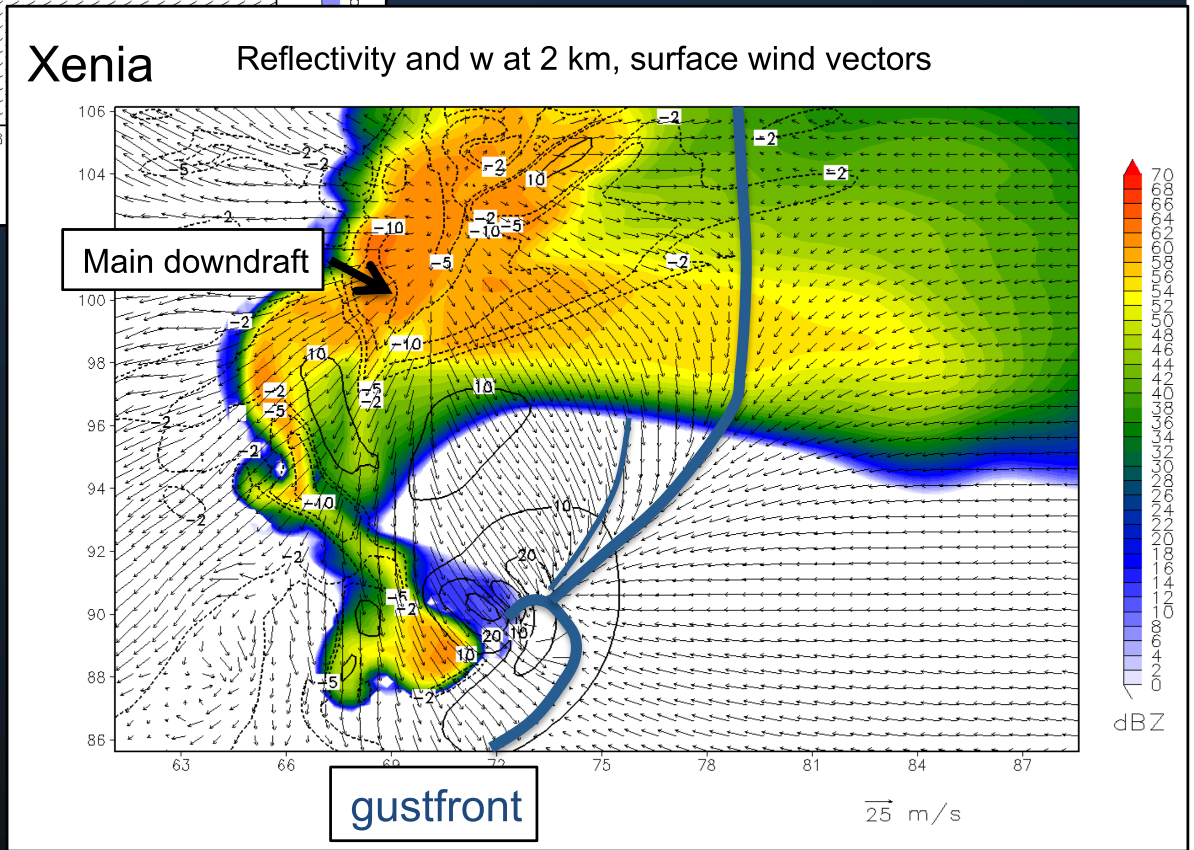

Del City
Reflectivity and w at 2 km, surface wind vectors

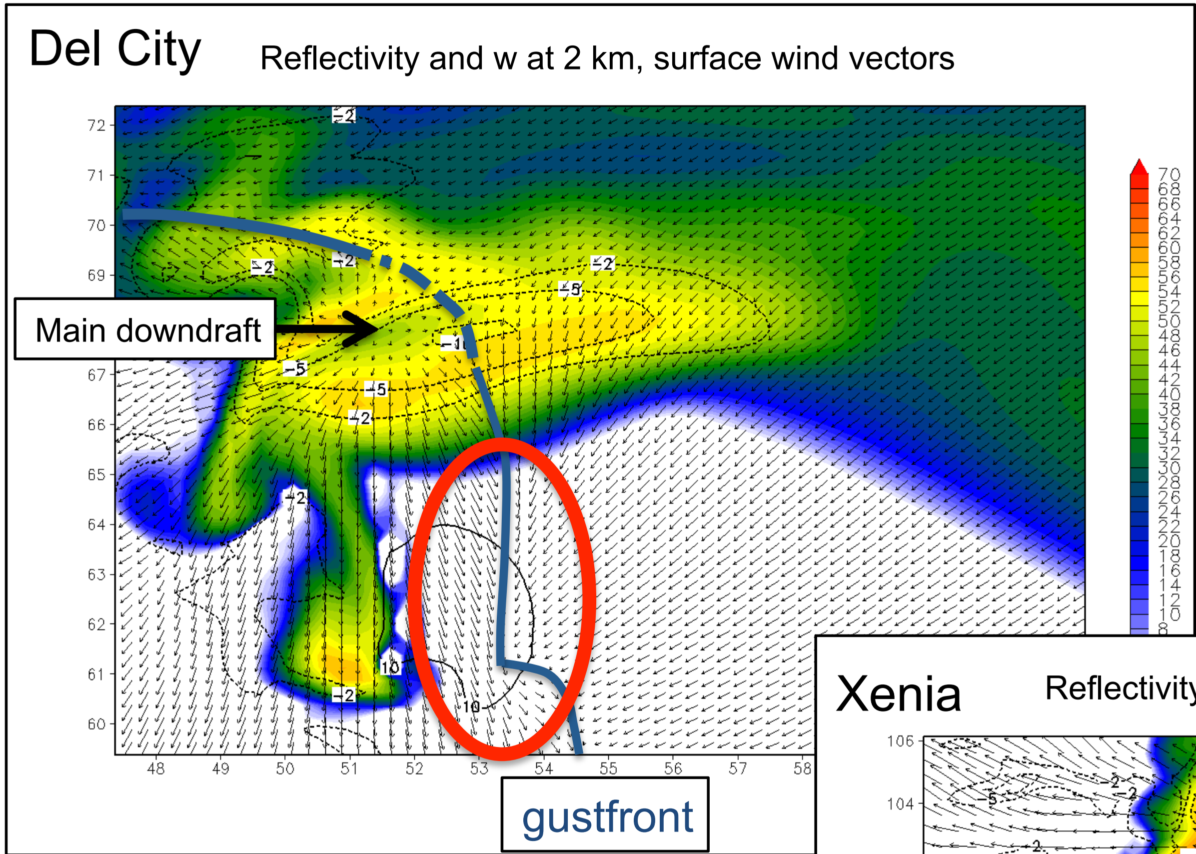

Xenia
Reflectivity and w at 2 km, surface wind vectors
dBZ
25 m/s


Del City
Reflectivity and w at 2 km, surface wind vectors
gustfront

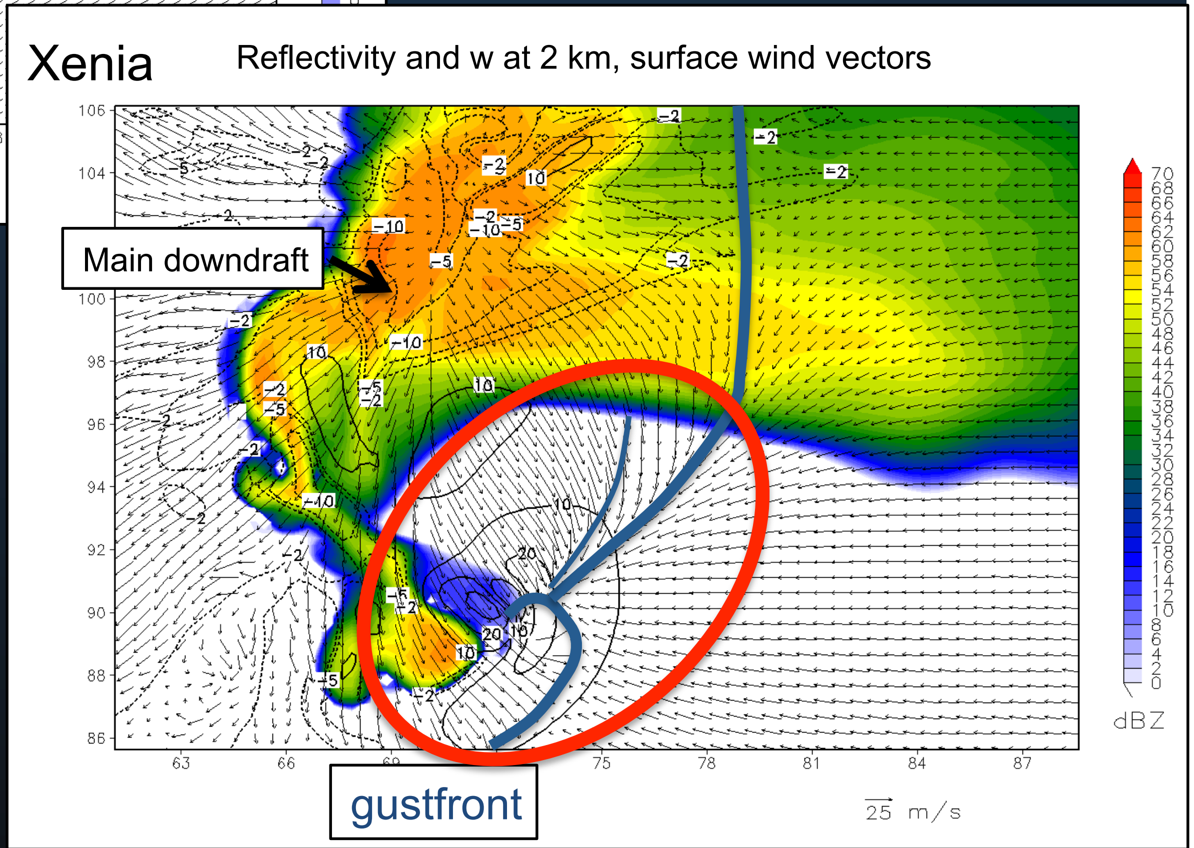

Xenia
Reflectivity and w at 2 km, surface wind vectors
dBZ
25 m/s
gustfront


Del City
Reflectivity and w at 2 km, surface wind vectors
Main downdraft
gustfront


Xenia
Reflectivity and w at 2 km, surface wind vectors
Main downdraft
gustfront
dBZ
25 m/s

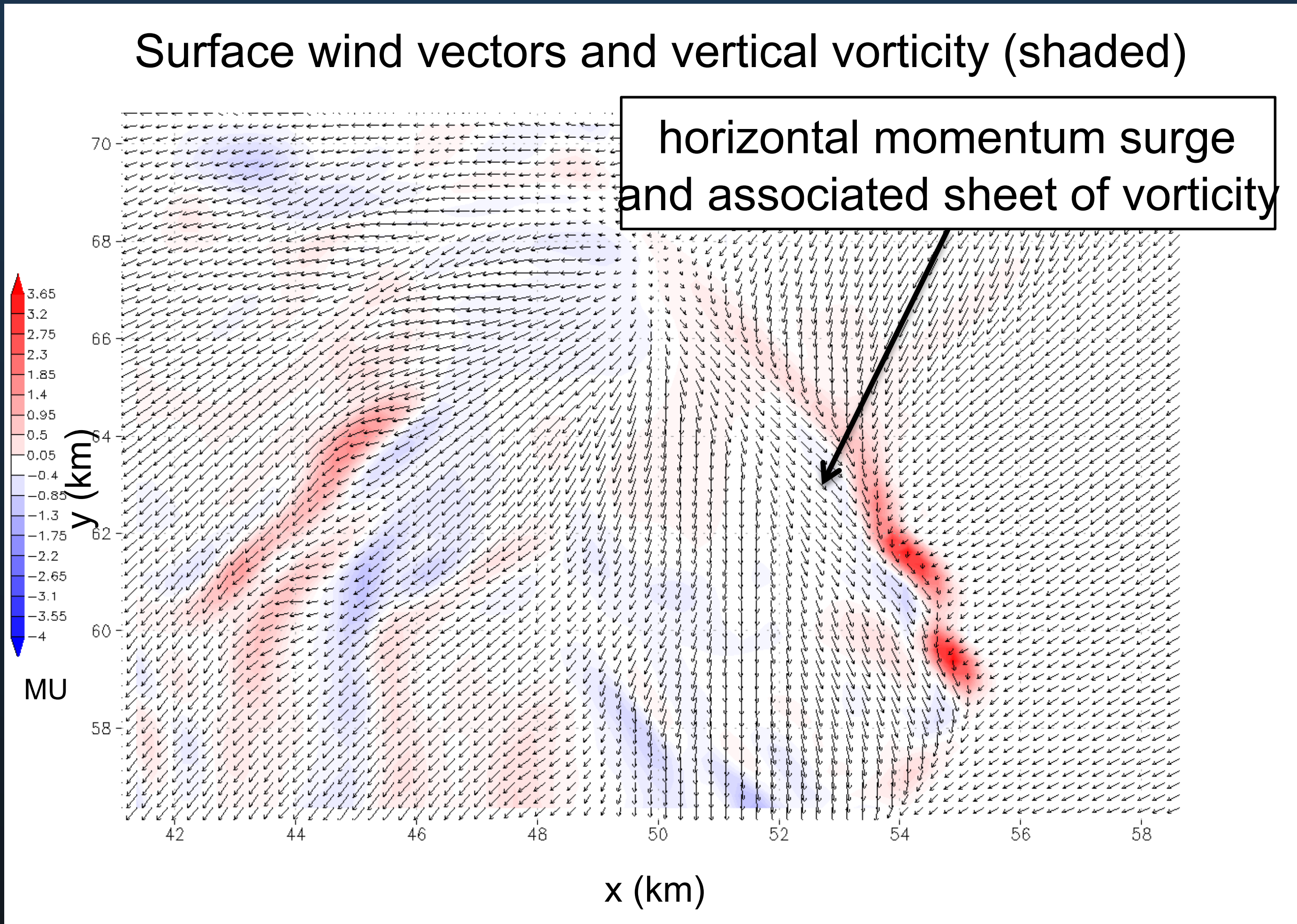


Del City
Reflectivity and w at 2 km, surface wind vectors
Main downdraft
gustfront

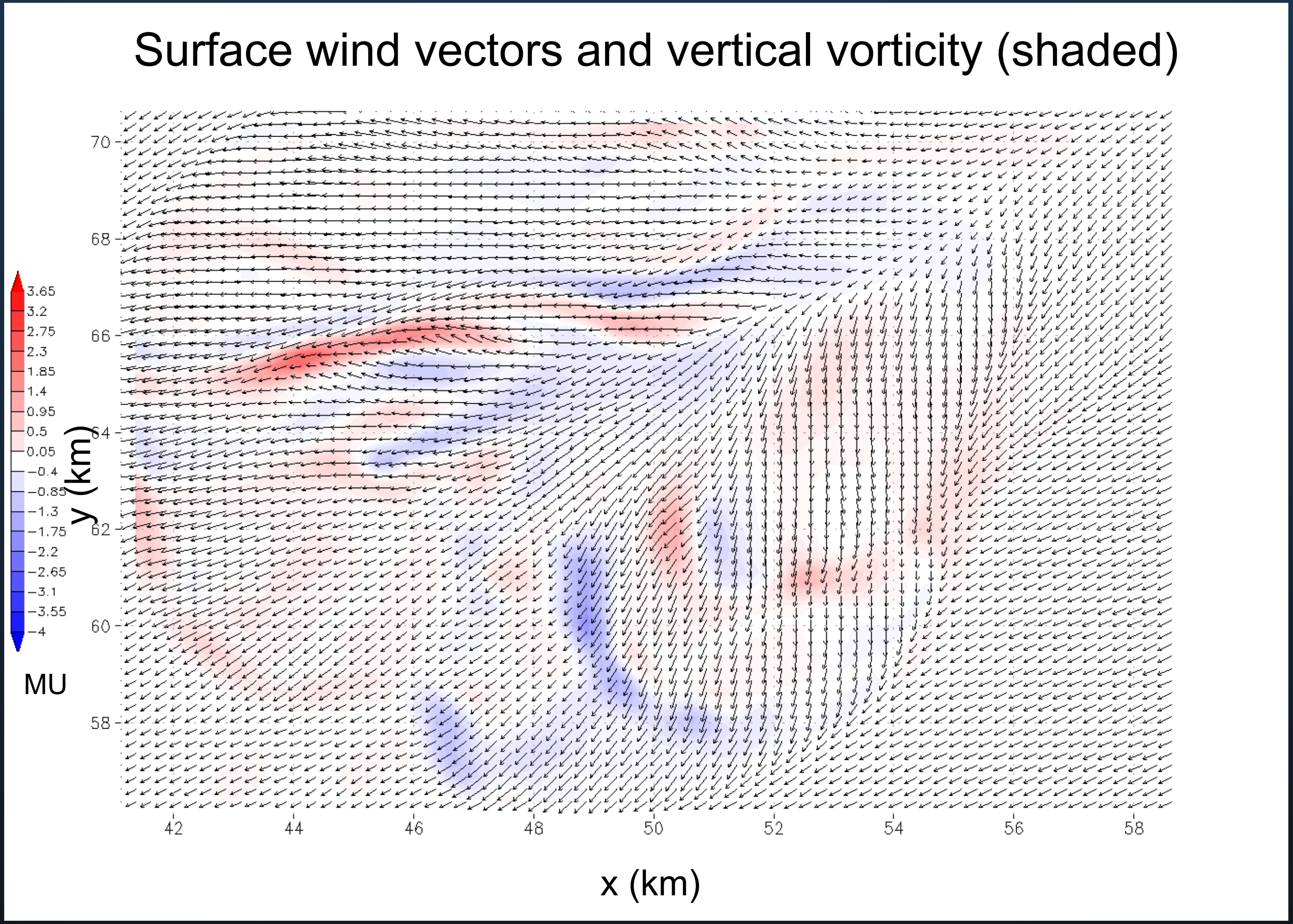


Xenia
Reflectivity and w at 2 km, surface wind vectors
Main downdraft
gustfront
dBZ
25 m/s

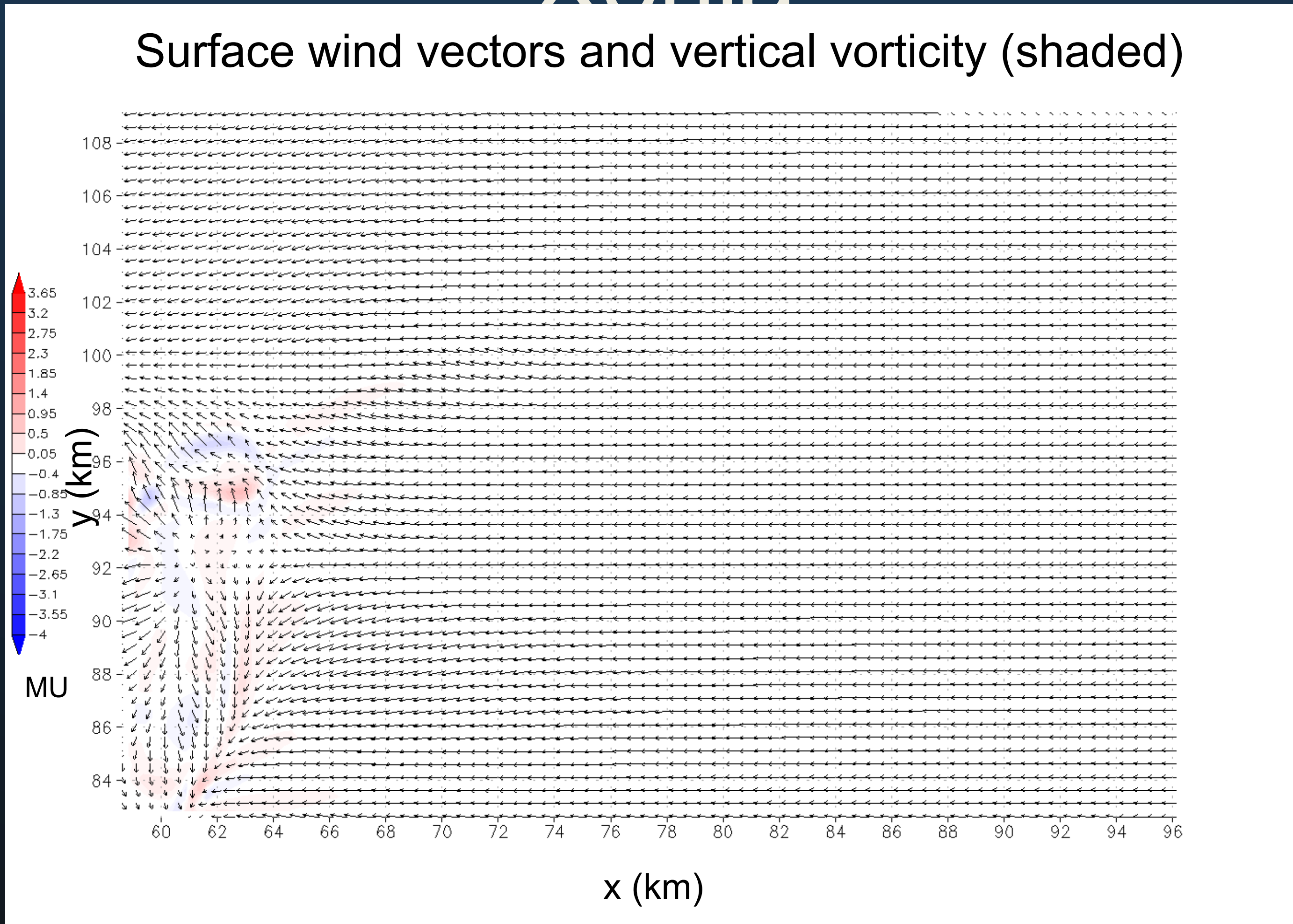
Horizontal Momentum Surges (HMS's) Del City



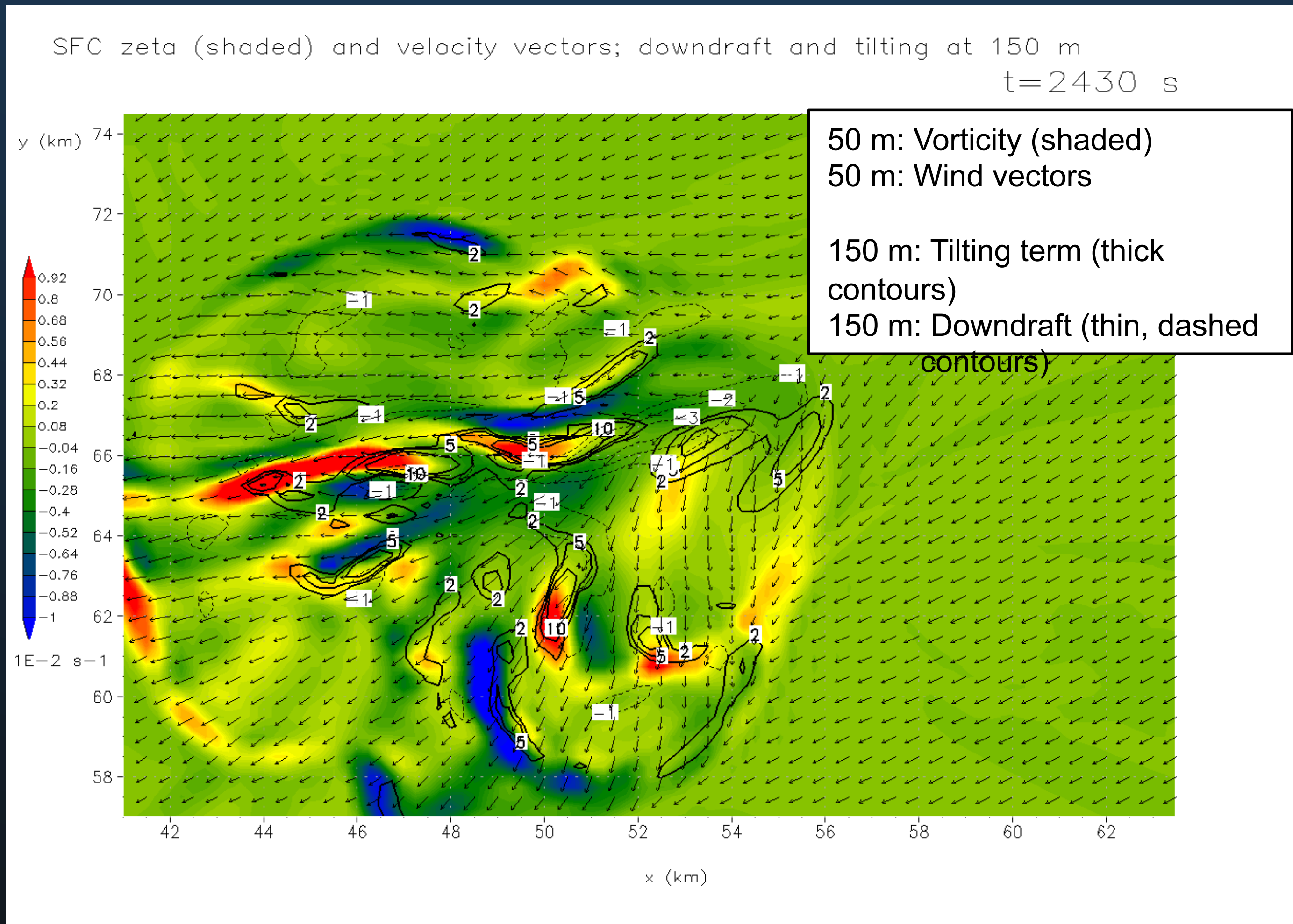
Horizontal Momentum Surges (HMS's) Del City



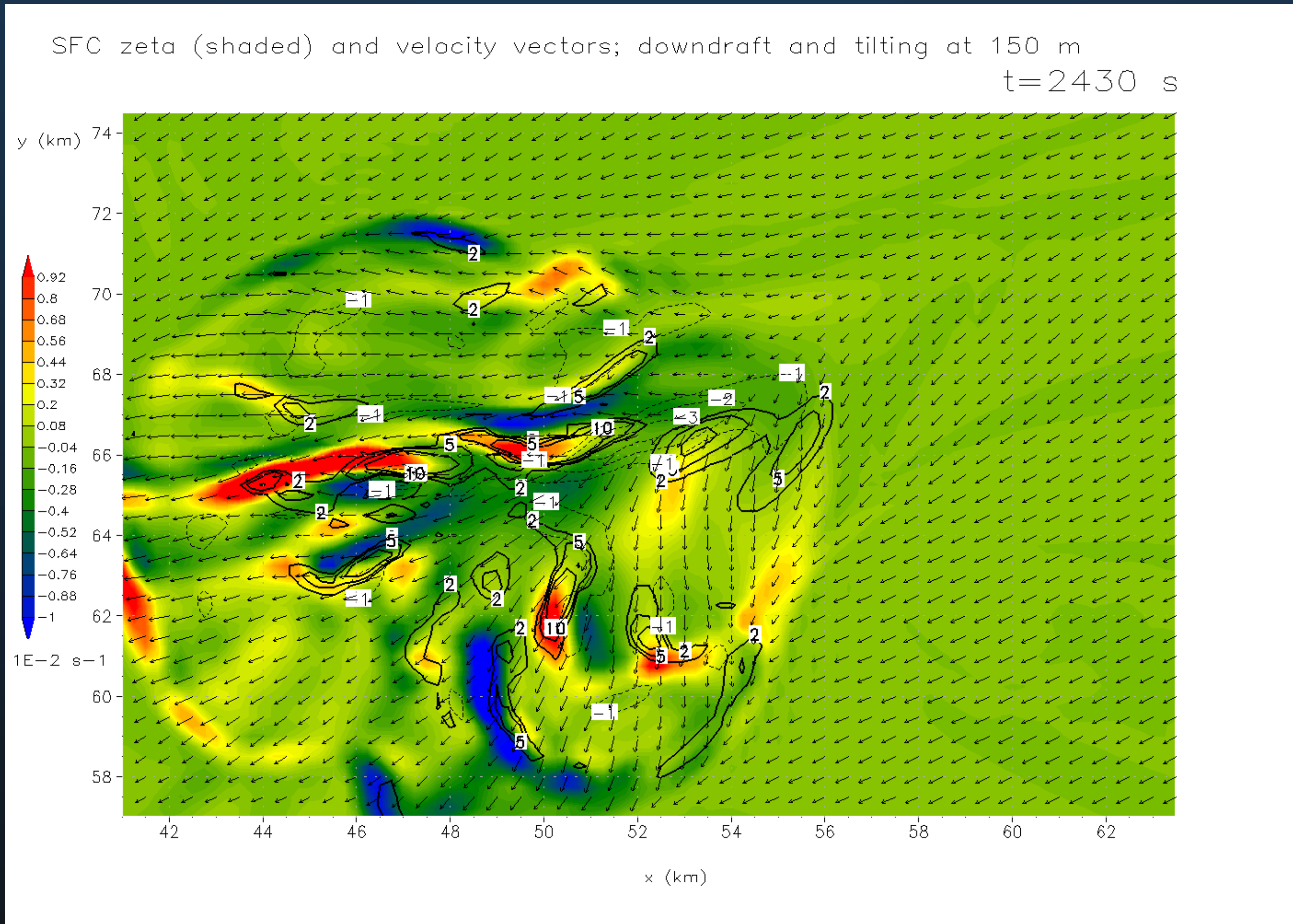
Horizontal Momentum Surges (HMS's) Xenia



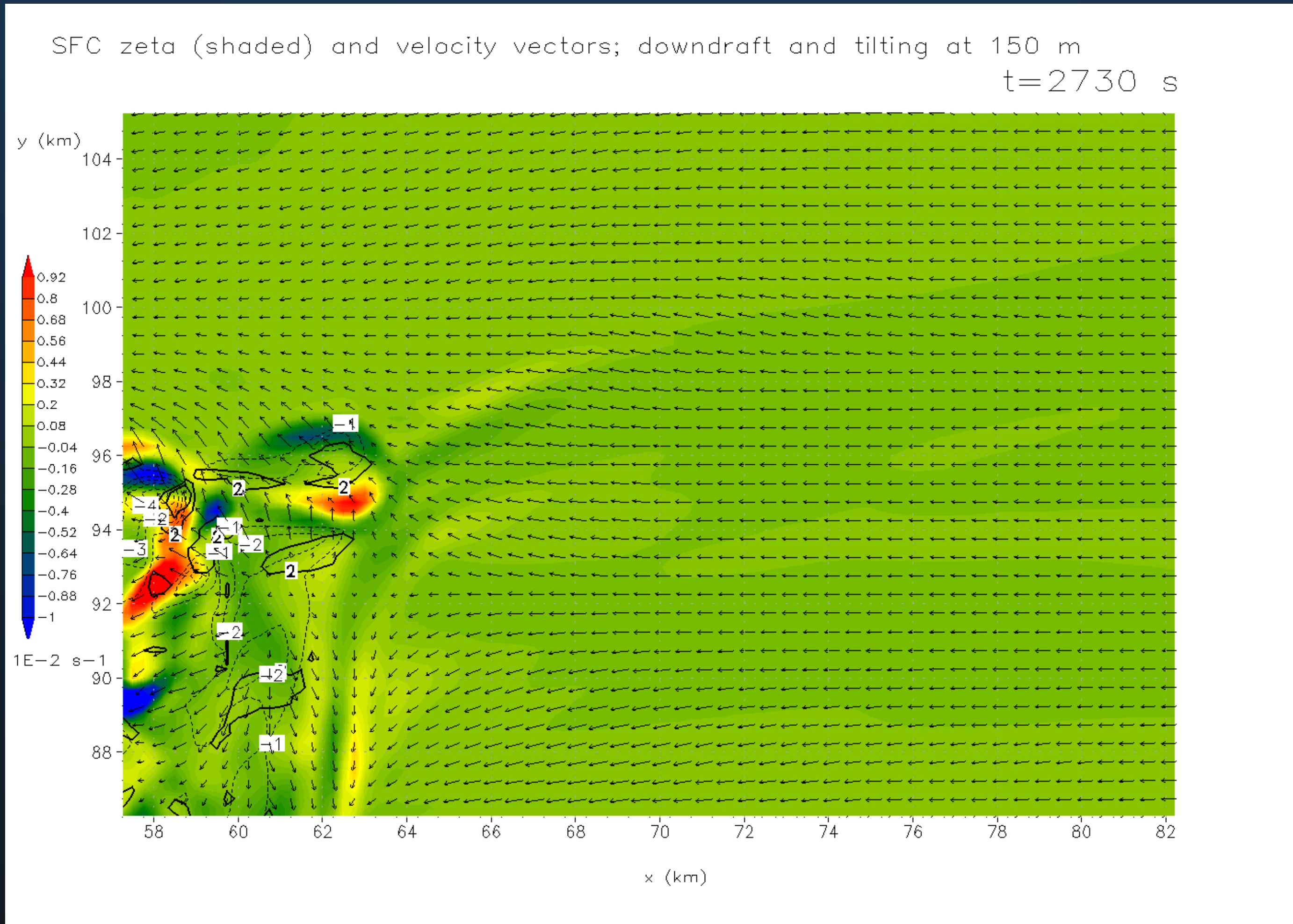
Tilting in downdraft and vorticity streamers (Del City)



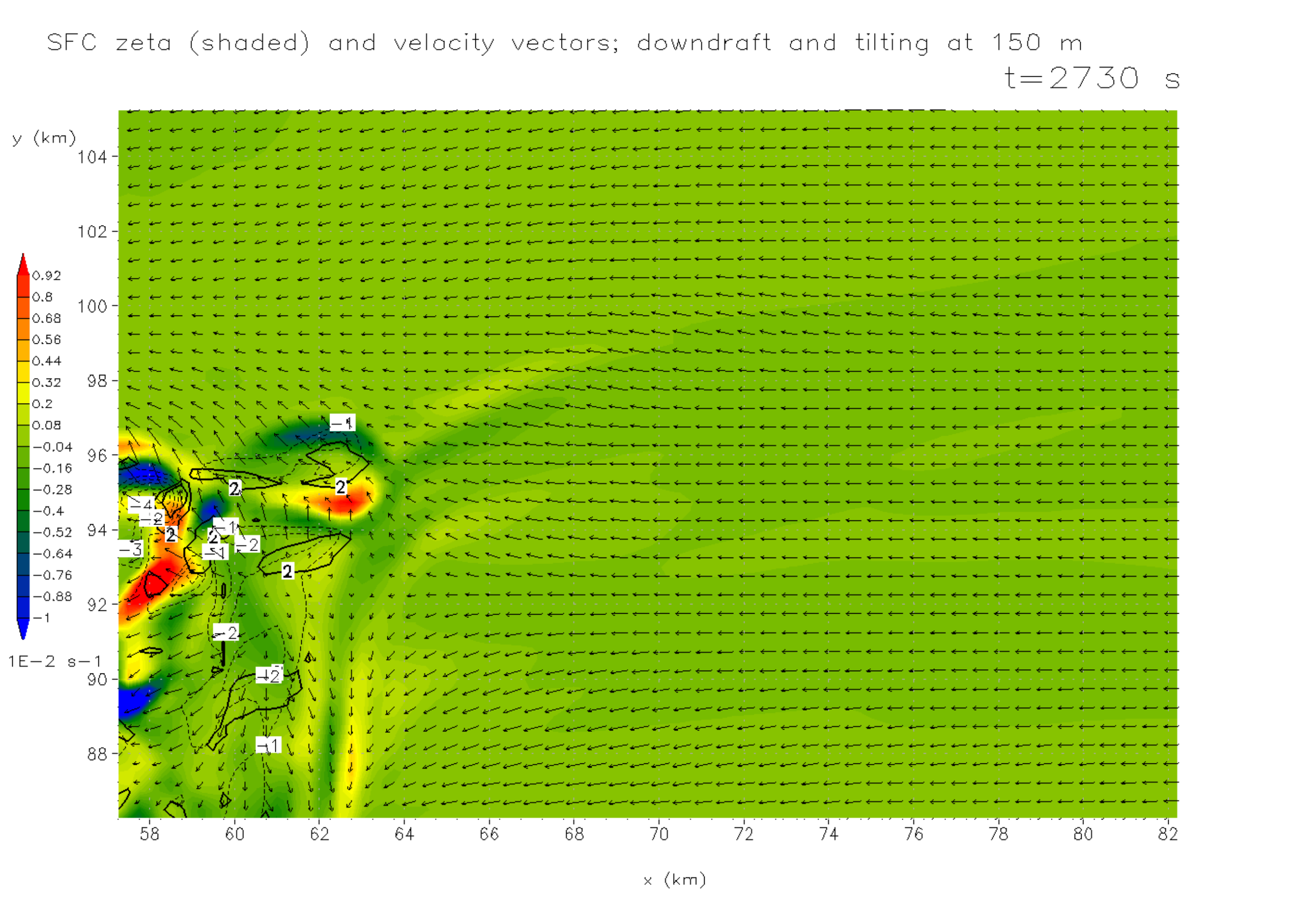
Tilting in downdraft and vorticity streamers (Del City)



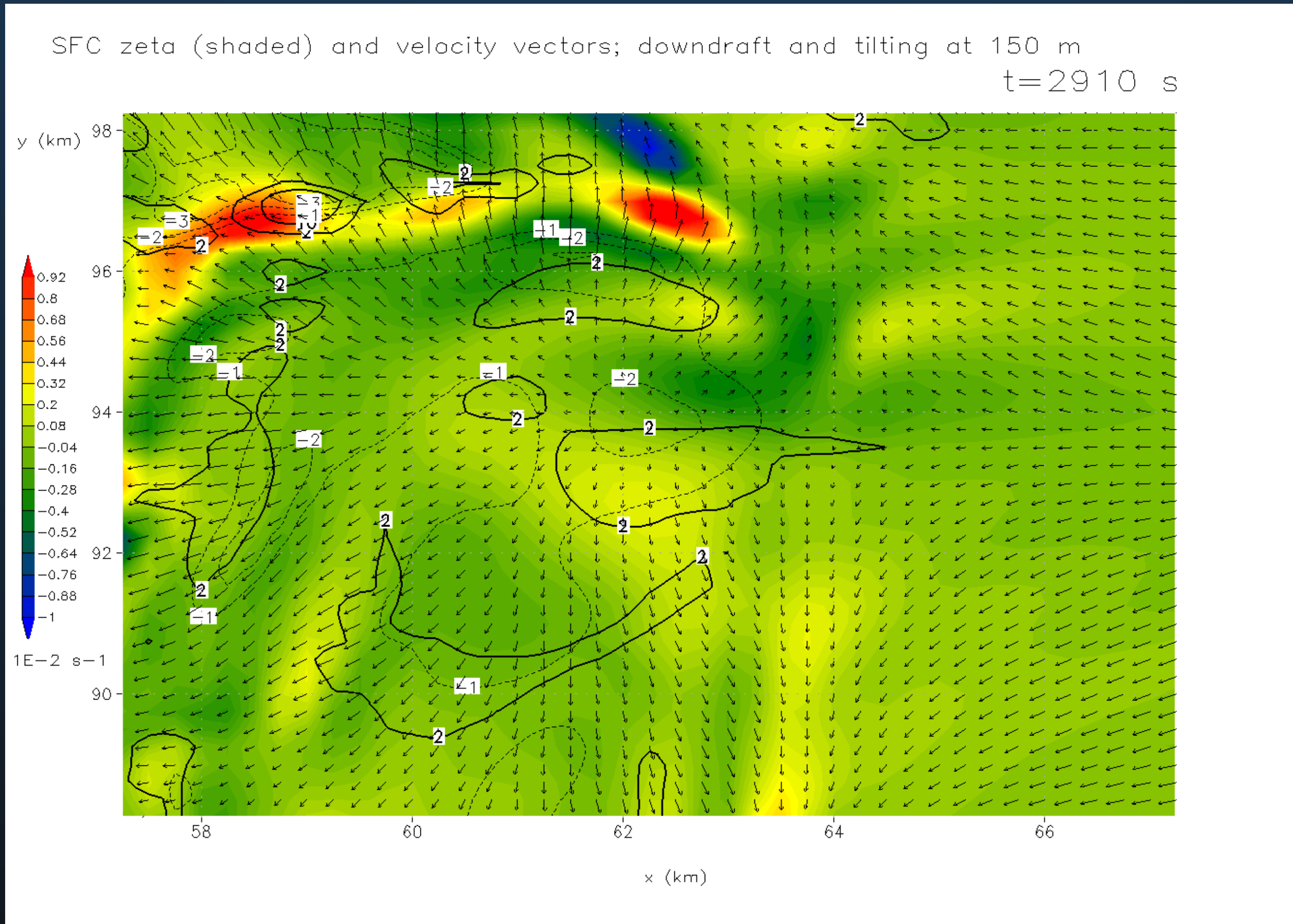
Tilting in downdraft and vorticity streamers (Xenia)



Tilting in downdraft and vorticity streamers (Xenia)



Tilting in downdraft and vorticity streamers (Xenia)

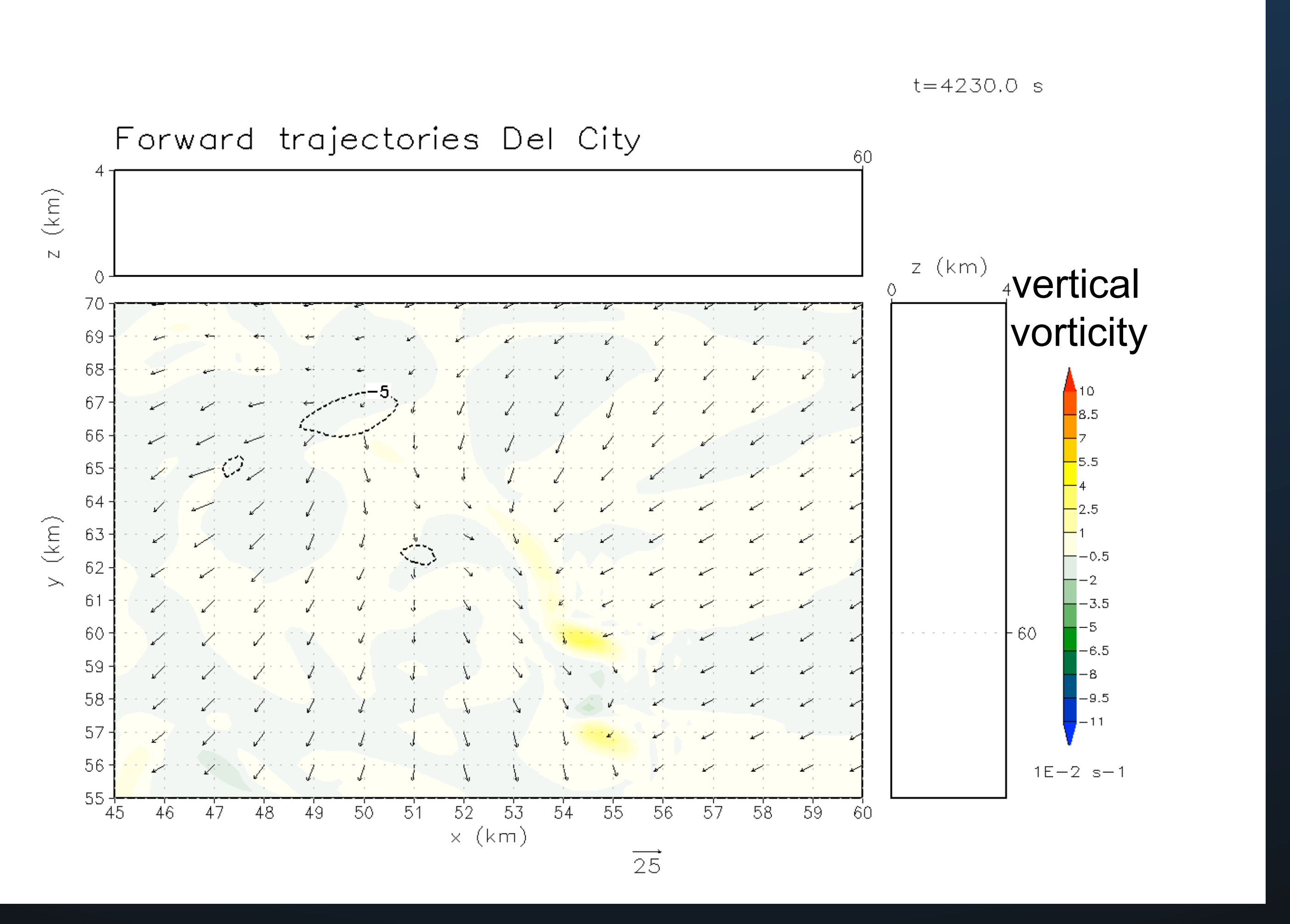


Trajectories

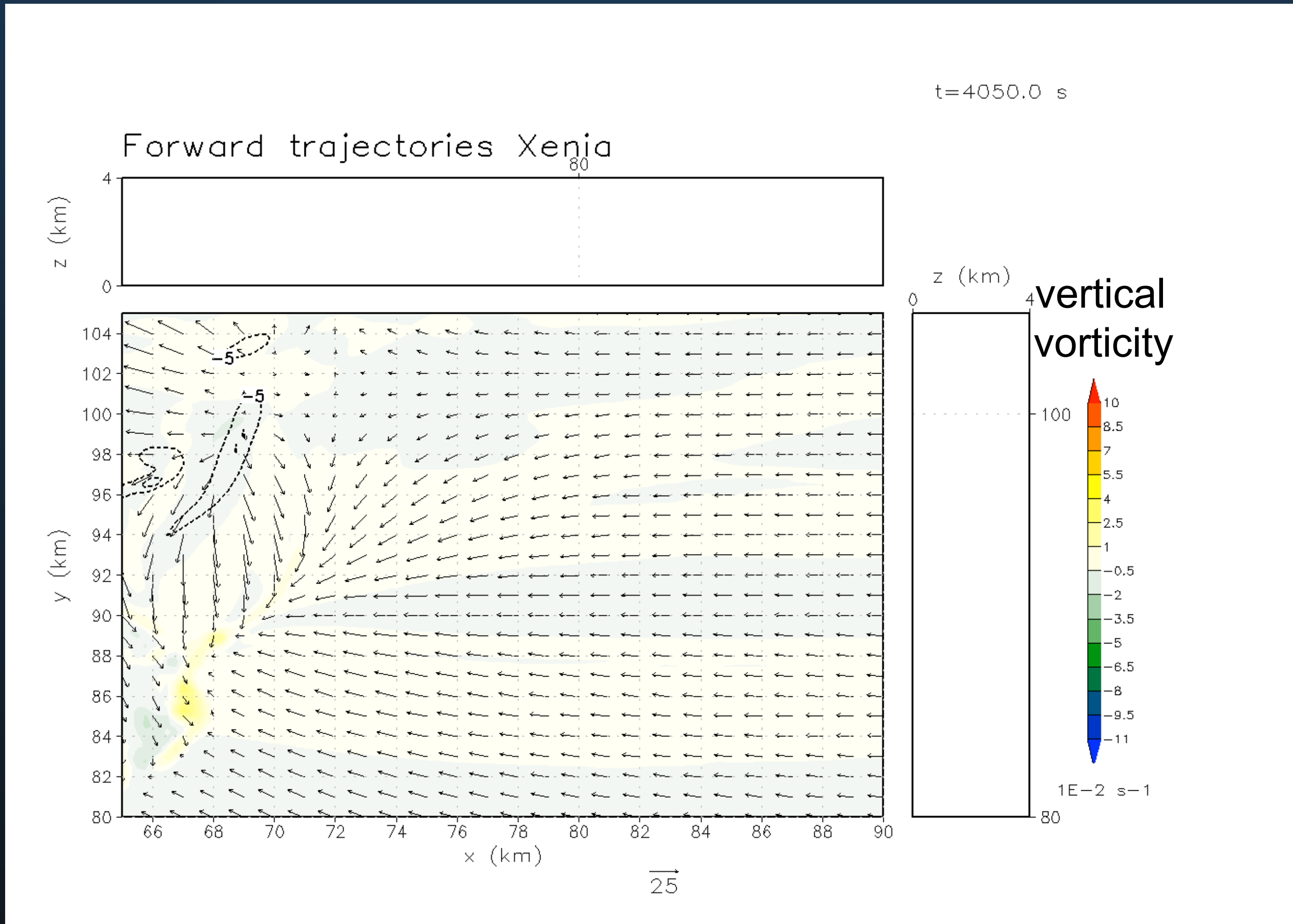
Two sets of experiments for each case

- Forward integration
  - Calculated at each model time step dt = 2 s
  - Hard-wired into CM1
  - 1.8 million parcels released in a box *centered* around the developing circulation at the surface
    - 15 x 15 x 3.5 km (Del City)
    - 45 x 30 x 3.5 km (Xenia)
- Backward trajectories
  - history files every 30 s
  - 2nd-order RK scheme (dt = 2 s)
  - Initial conditions taken from forward trajectories

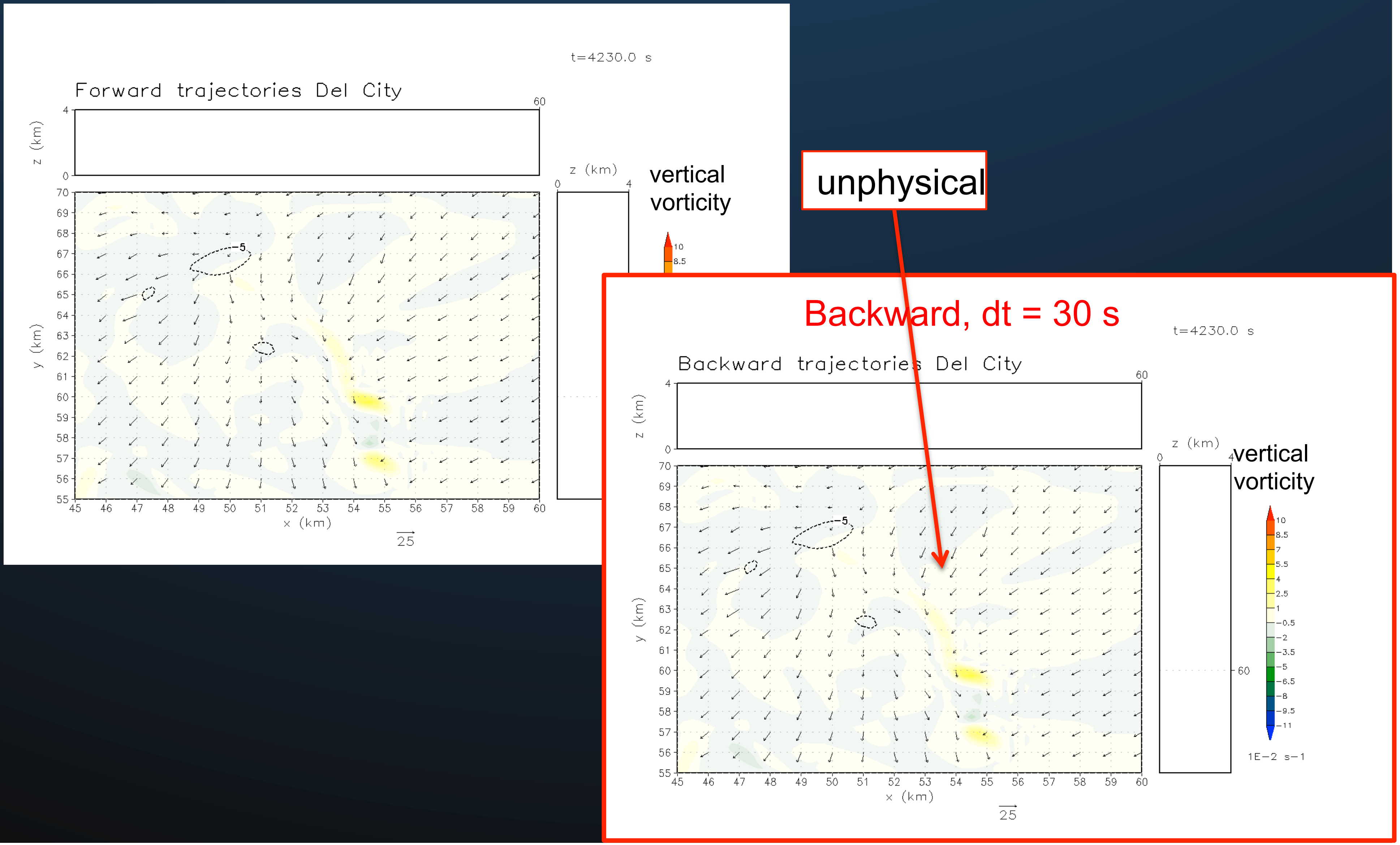
Forward trajectories Del City



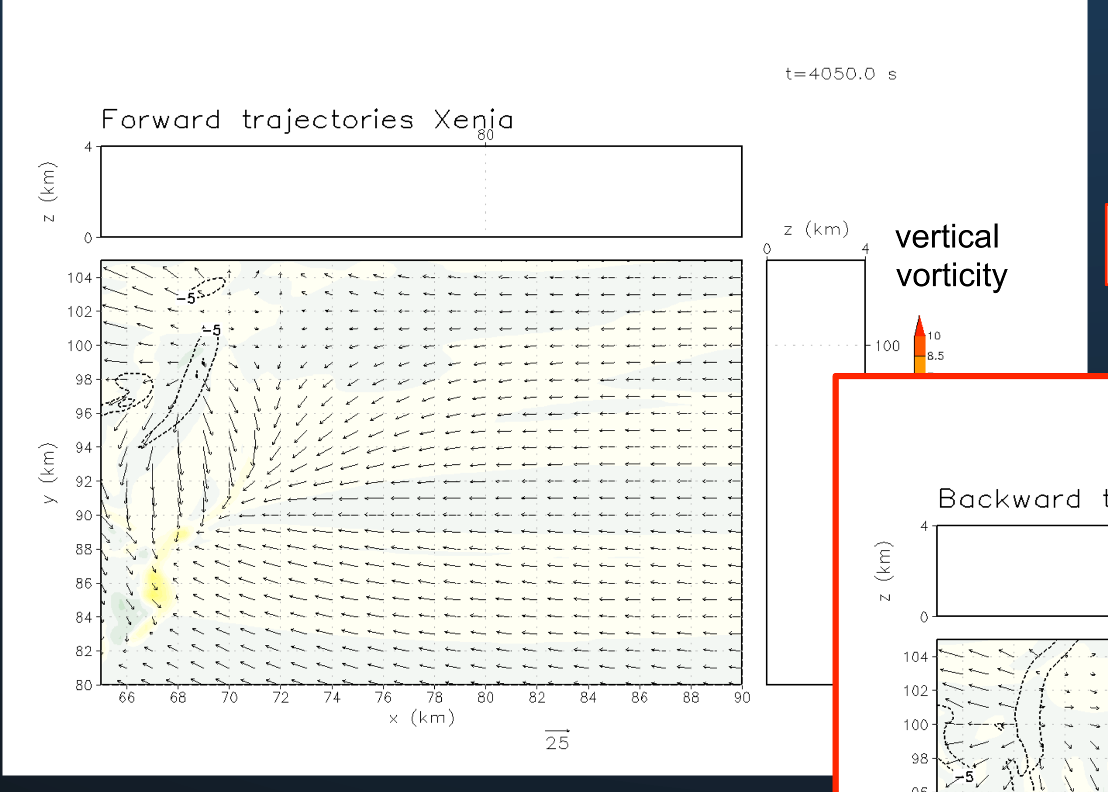
Forward trajectories Xenia



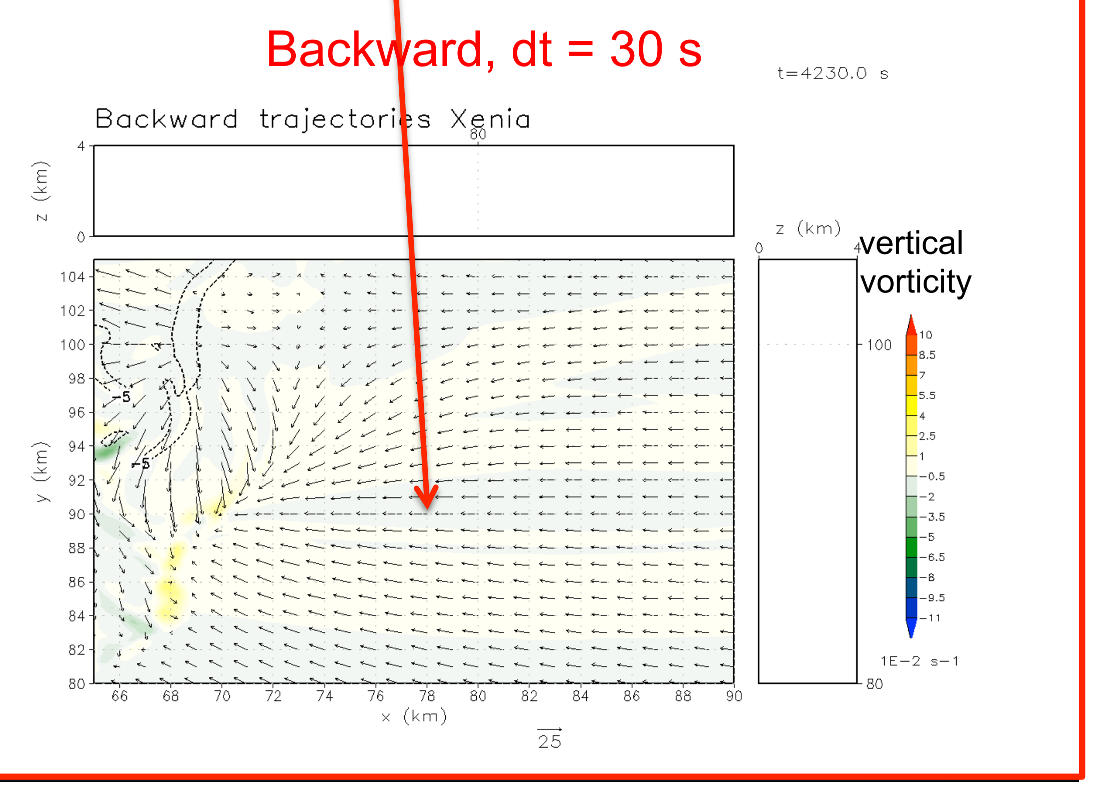
Comparison: forward and backward trajectories Del City



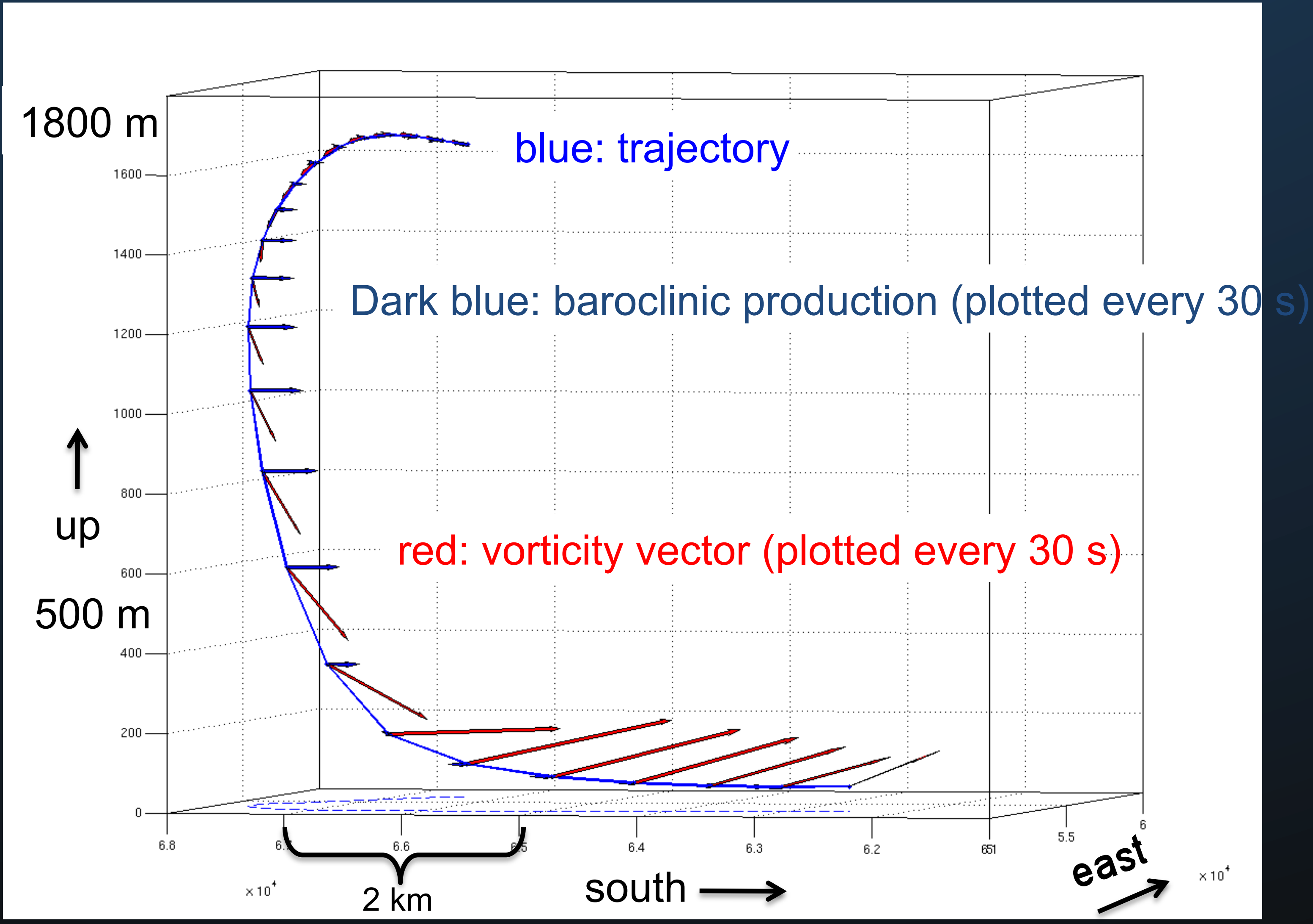
Comparison: forward and backward trajectories Xenia



unphysical

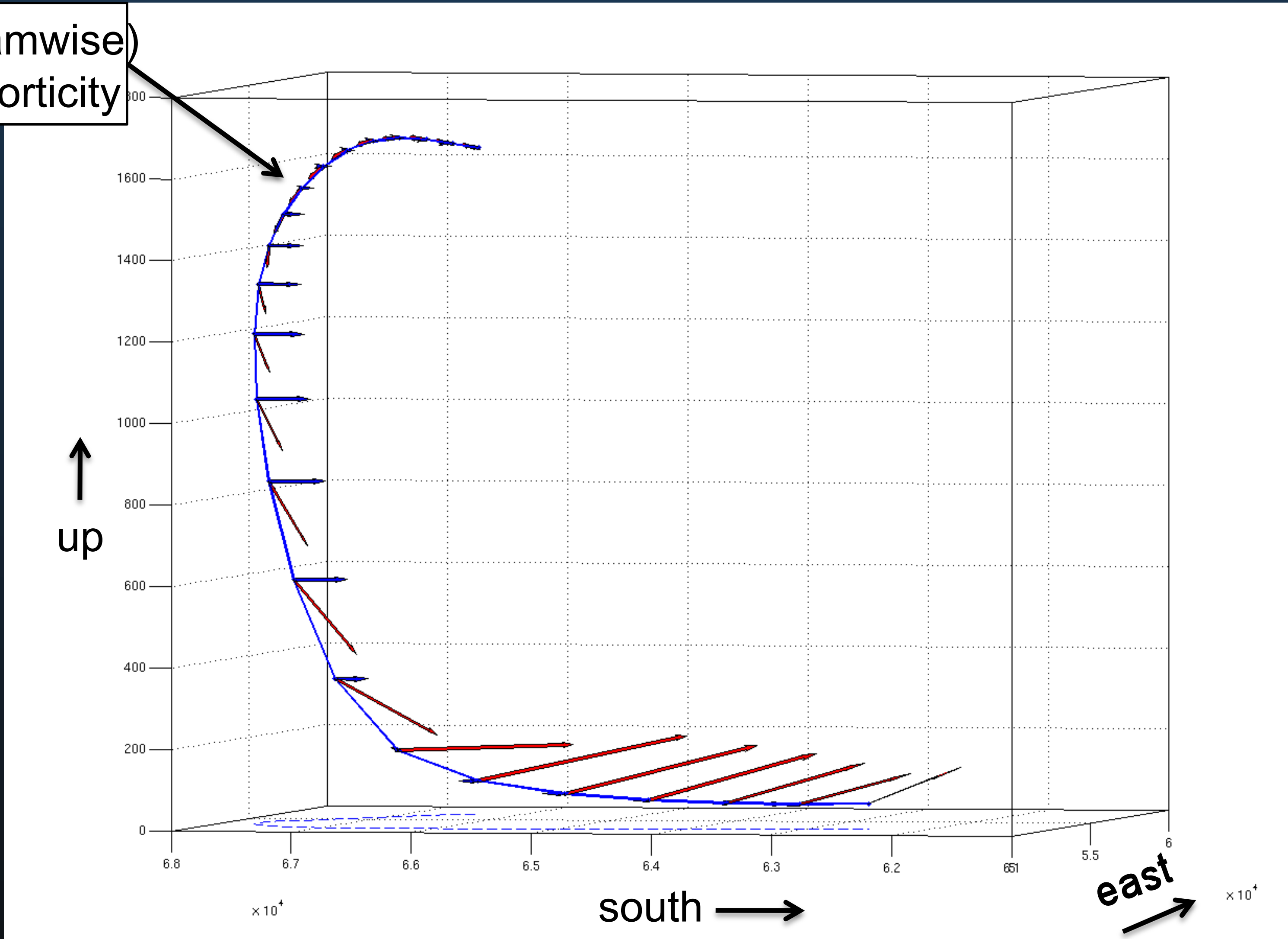


Vorticity and buoyant generation (Del City)

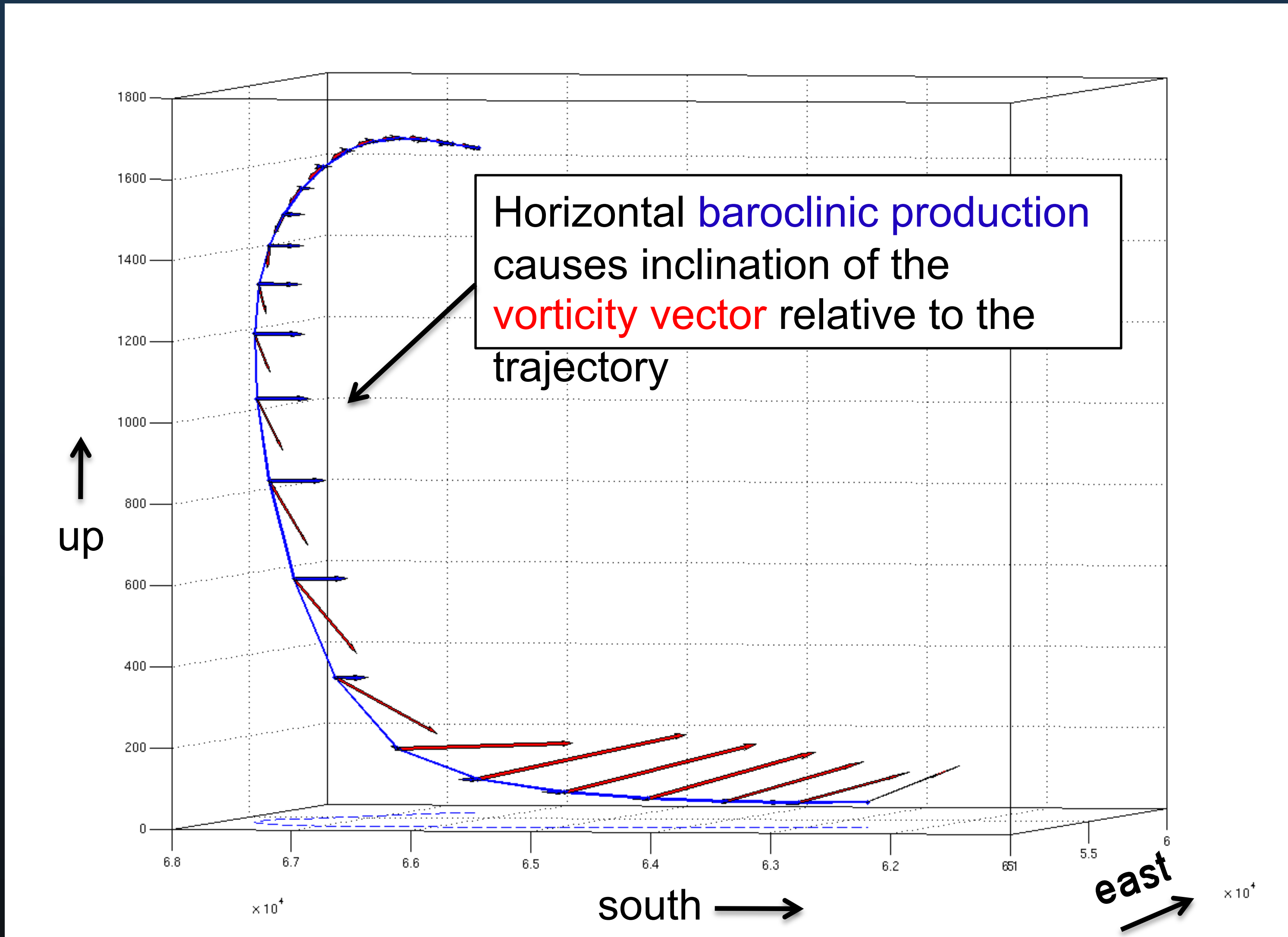


Vorticity and buoyant generation (Del City)

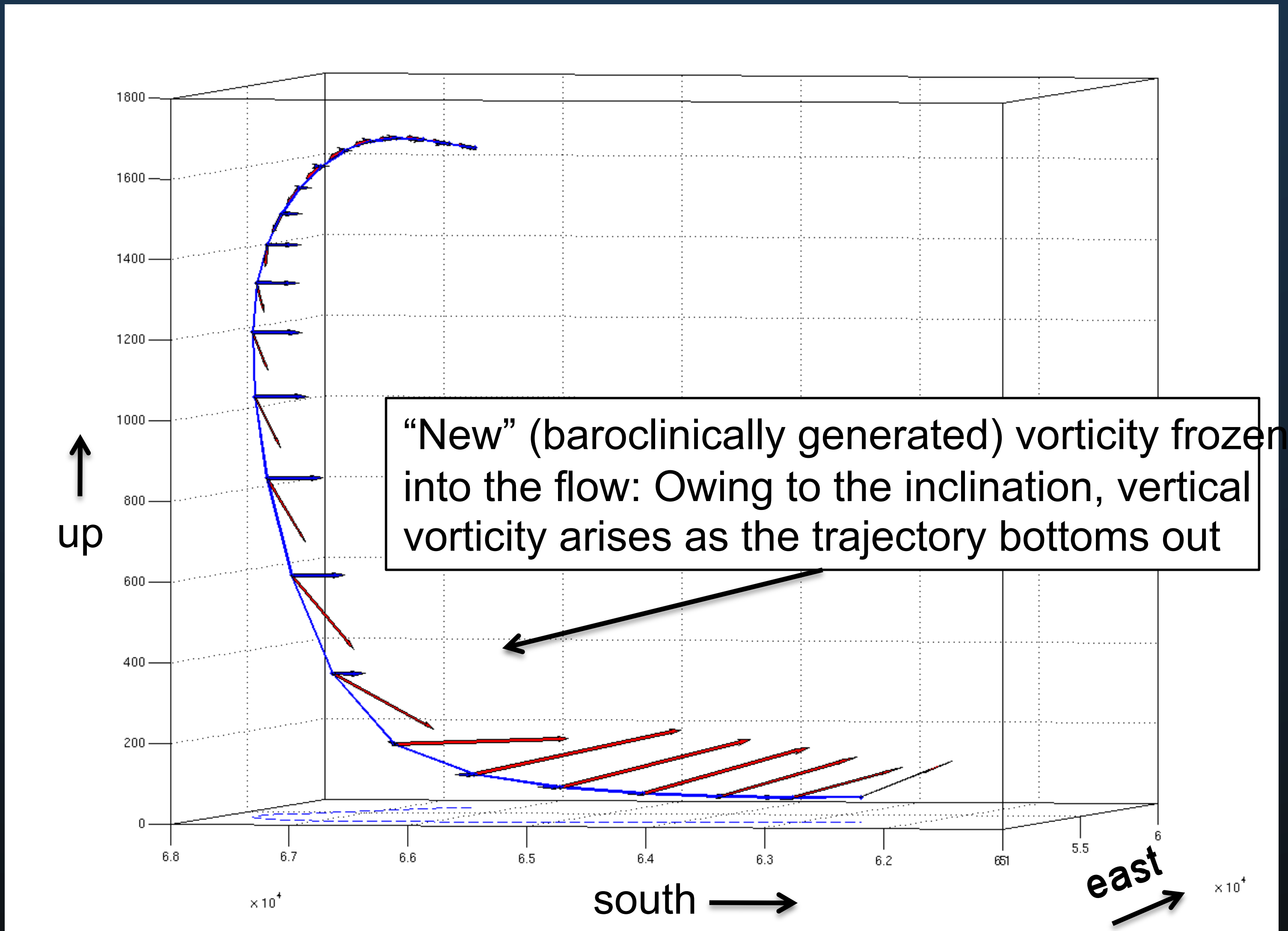
Weak (streamwise) barotropic vorticity



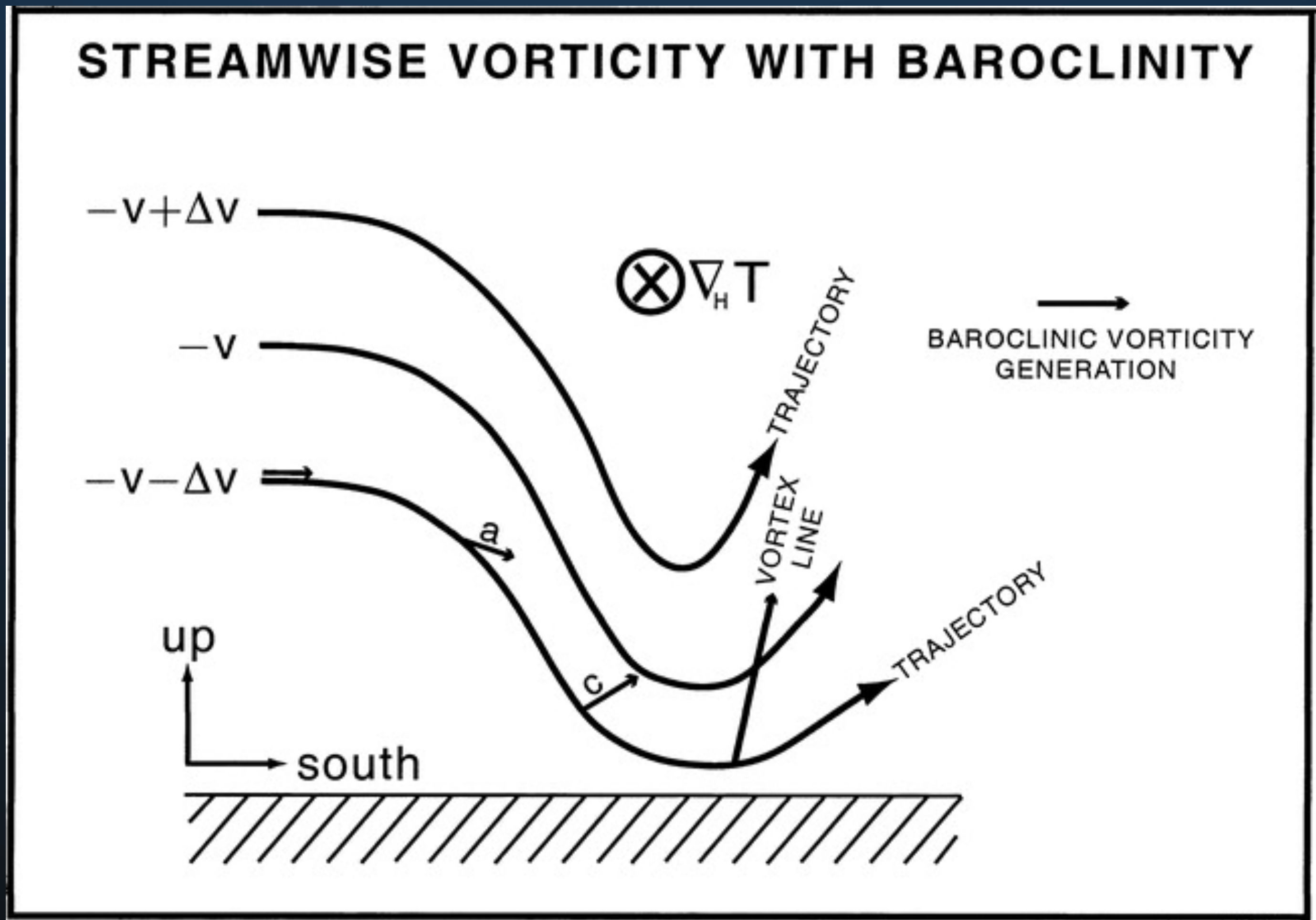
Vorticity and buoyant generation (Del City)



Vorticity and buoyant generation (Del City)



… just as envisioned by Davies-Jones and Brooks (1993)



Barotropic Vorticity

$$\omega_j^{BT}(t;t_0) = \frac{\rho(t)}{\rho(t_0)} \boxed{\frac{\partial x_j(t)}{\partial x_i(t_0)}} \omega_i(t_0)$$

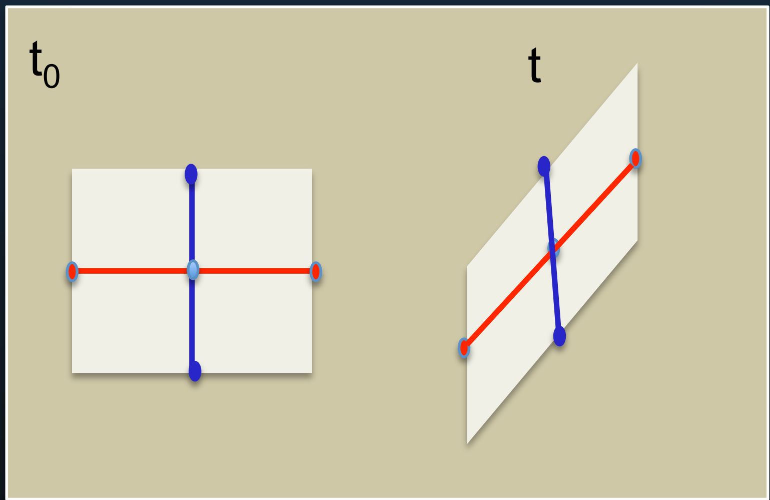
Cauchy formula

Jacobian Matrix between initial (Lagrangian) and later (Eulerian) coordinates

The baroclinic vorticity is simply the difference between the total vorticity and its and barotropic part:

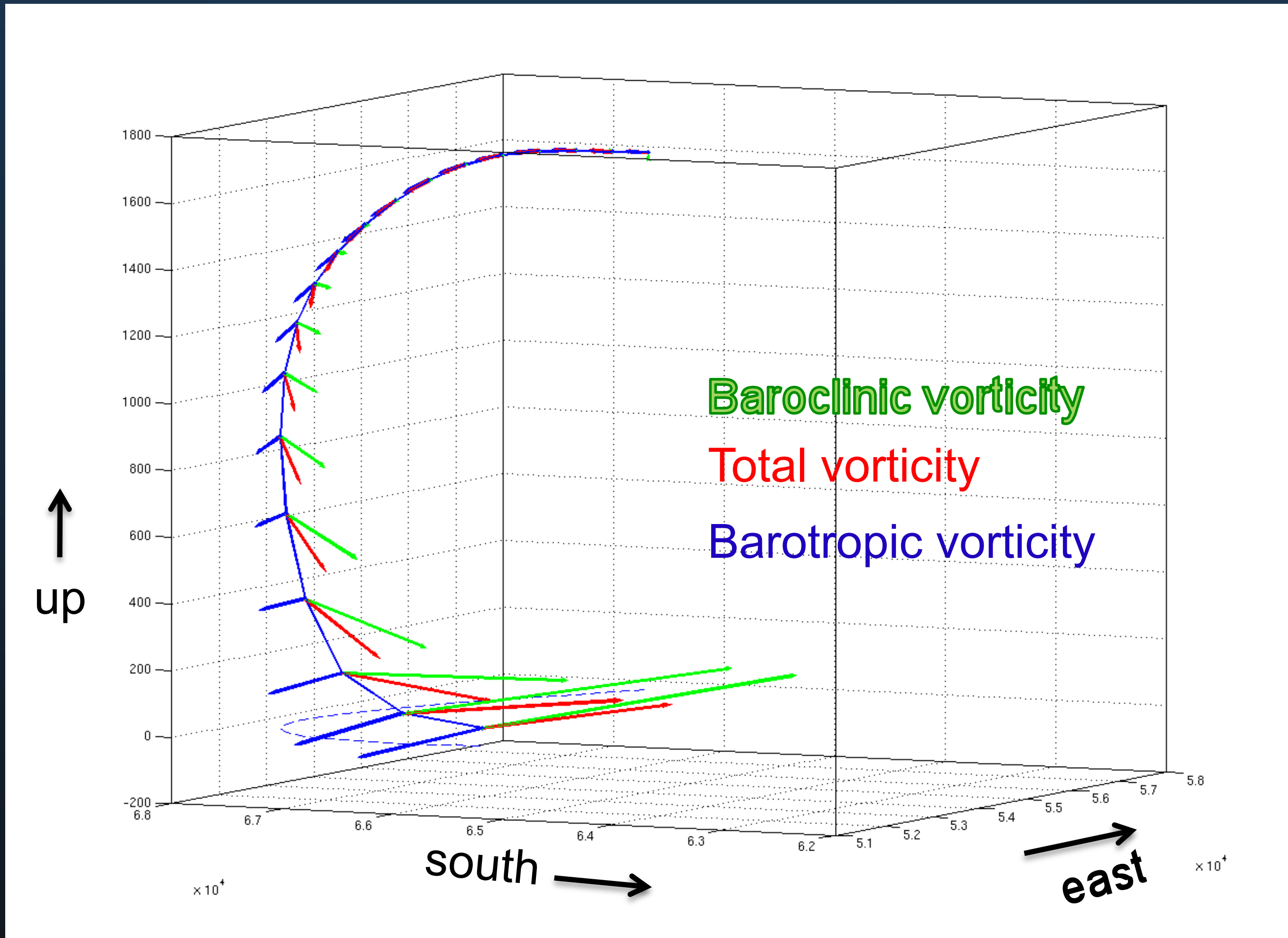
$$\omega_j^{BC}(t;t_0) = \omega_j(t) - \omega_j^{BT}(t;t_0)$$

Define a 3D Cartesian 6-point Stencil around given Parcel at t_0

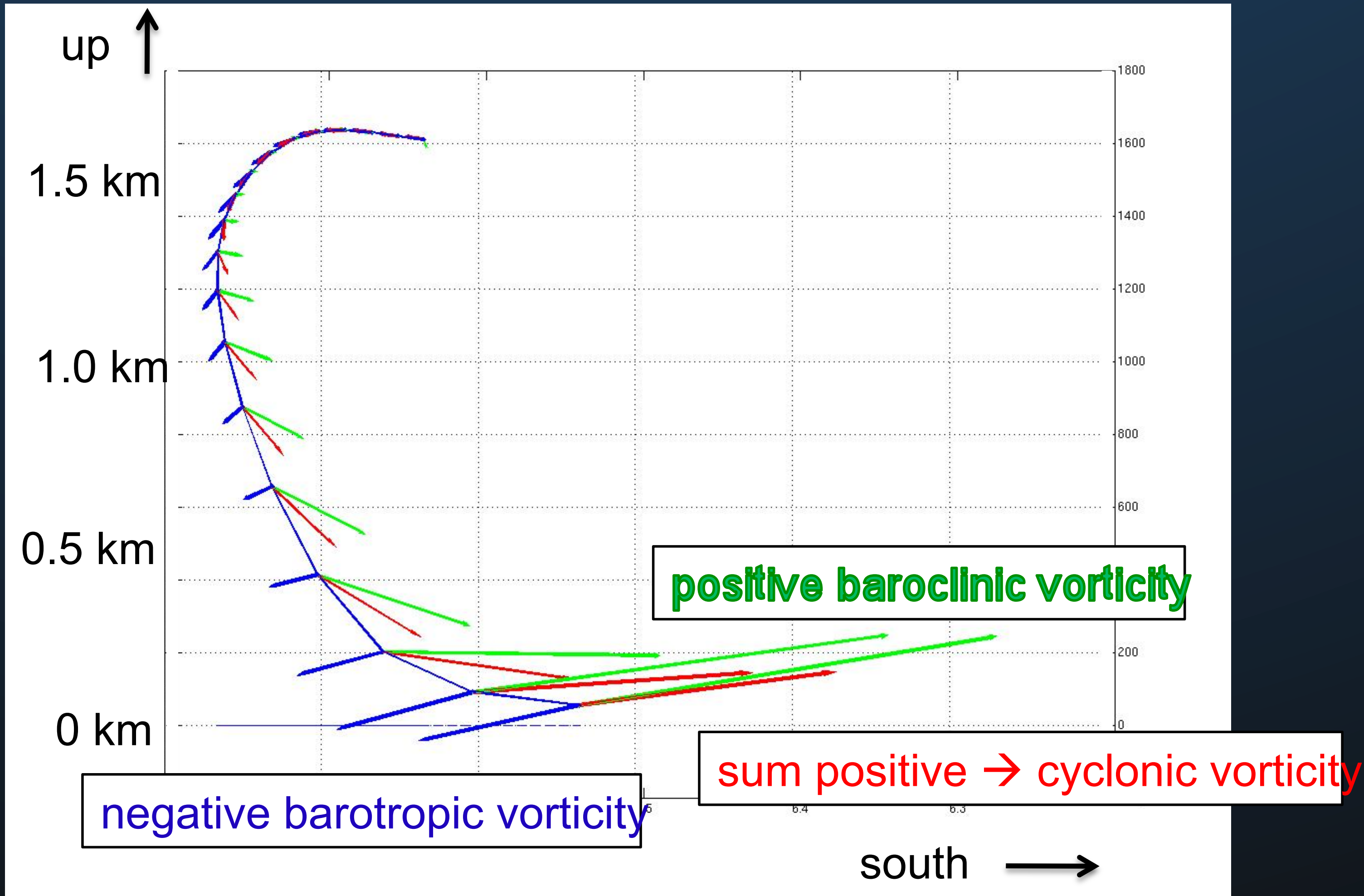


Jacobian matrix describes how the initial Cartesian coordinates can be mapped onto the new (non-Cartesian) grid

Vorticity decomposition Del City (parcel average)



Vorticity decomposition Del City (parcel average)

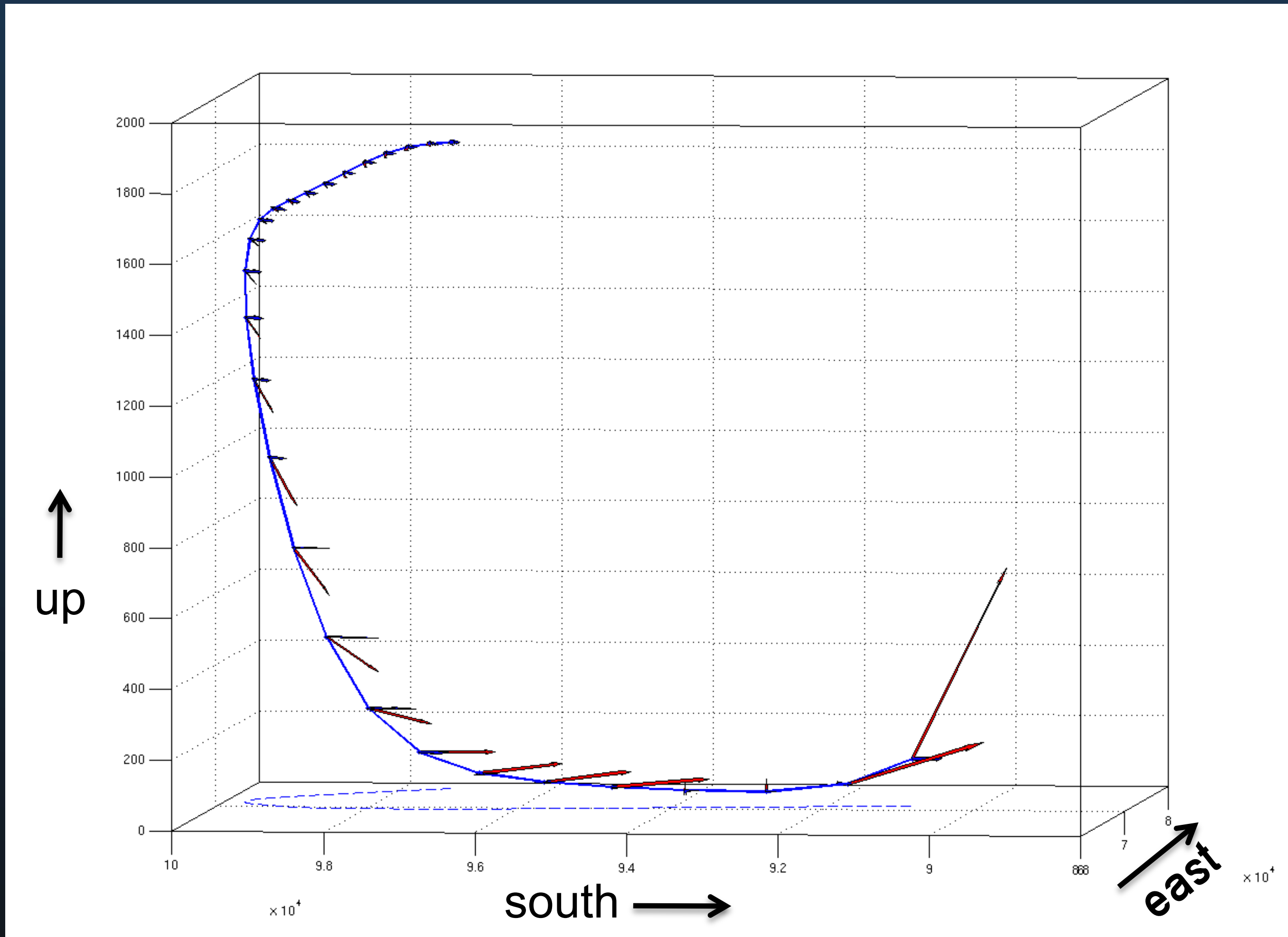


Conclusions

- Surface rotation is preceded by, and associated with multiple horizontal momentum surges (HMS)
- HMSs and the associated vorticity streamers are a result of by baroclinic processes in the downdraft by the mechanism as proposed by Davies-Jones and Brooks (1993) and Davies-Jones (2000)
- Temporal-interpolation errors strongly affect the trajectories: even high-resolution (dt = 30 s) data are insufficient to obtain accurate results
- All trajectories in the low-level circulation are “downdraft processed”; no trajectories from warm inflow side
  - “occlusion” process = cut-off from warm air?
- Barotropic vorticity in the surface circulation is substantial and contributes to negative vorticity
- Baroclinic vorticity dominates and contributes the positive vertical vorticity

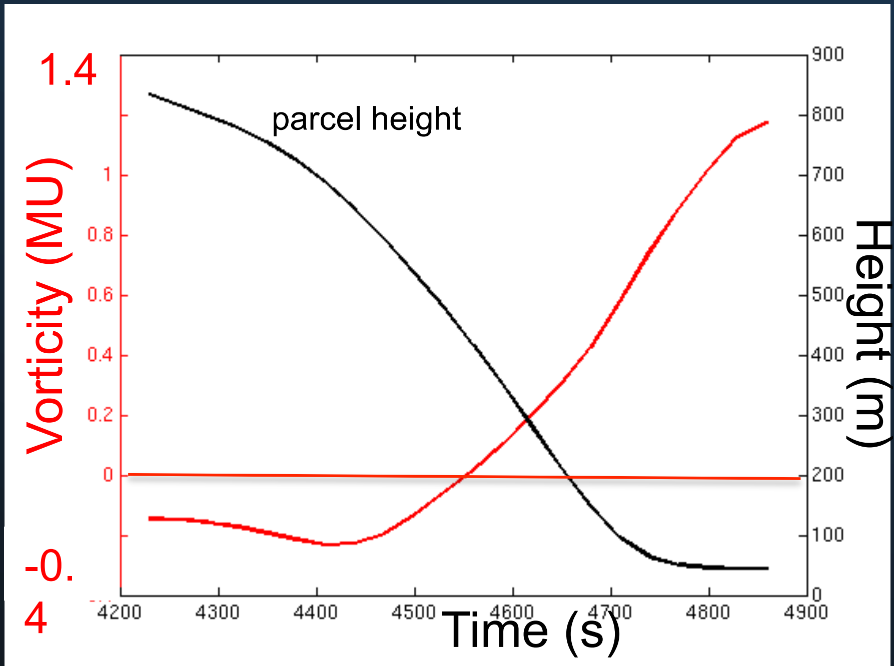
Backup slides …

Vorticity and buoyant generation (Xenia)



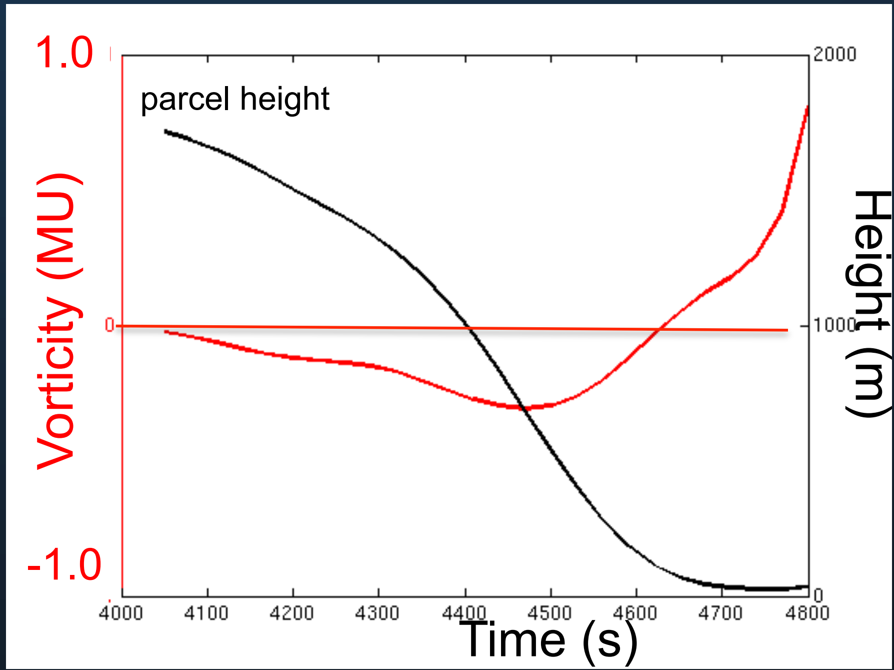
Average vorticity and height vs time

Del City (n = 843)



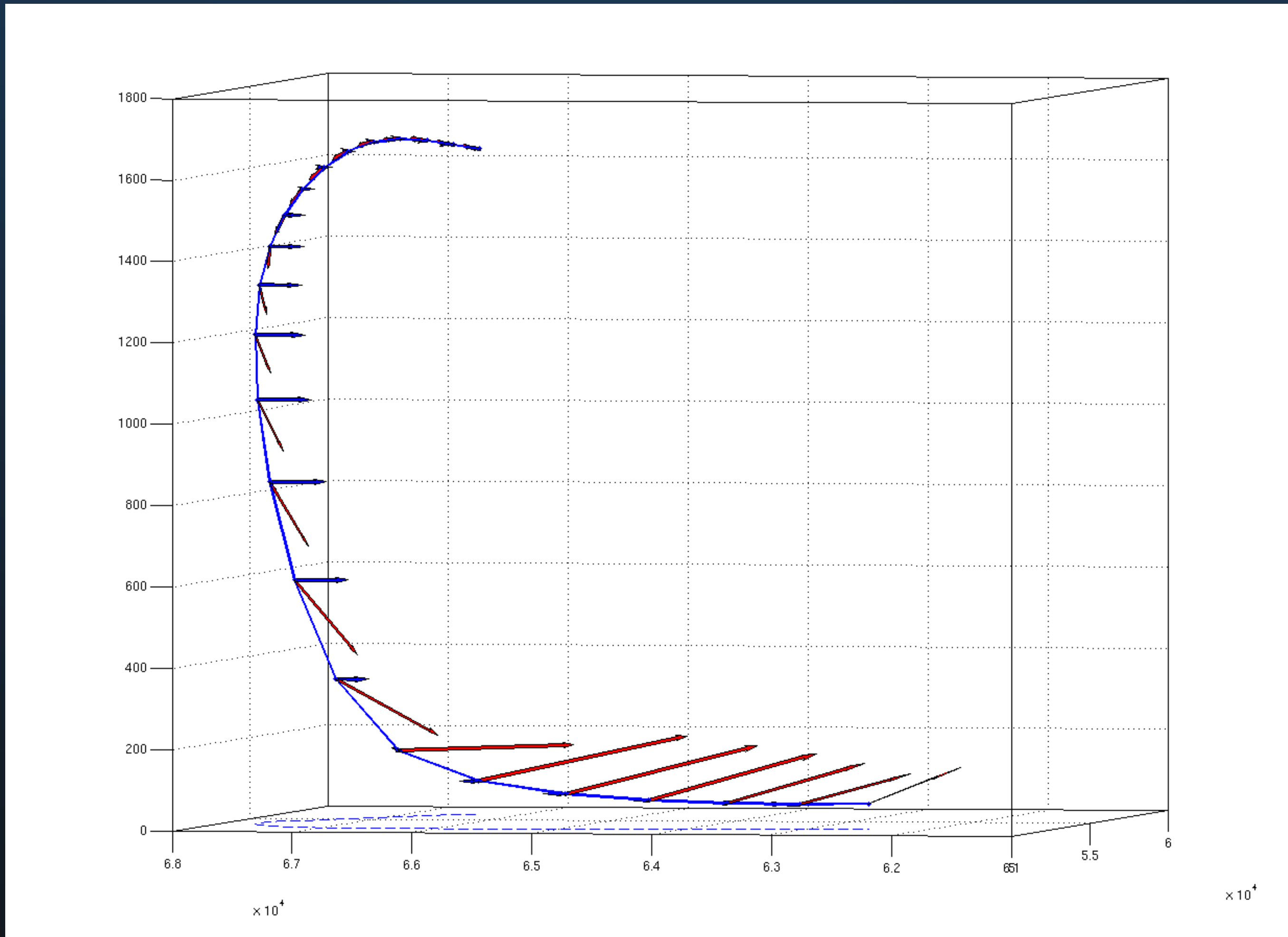
barotropic baroclinic

Xenia (n = 244)

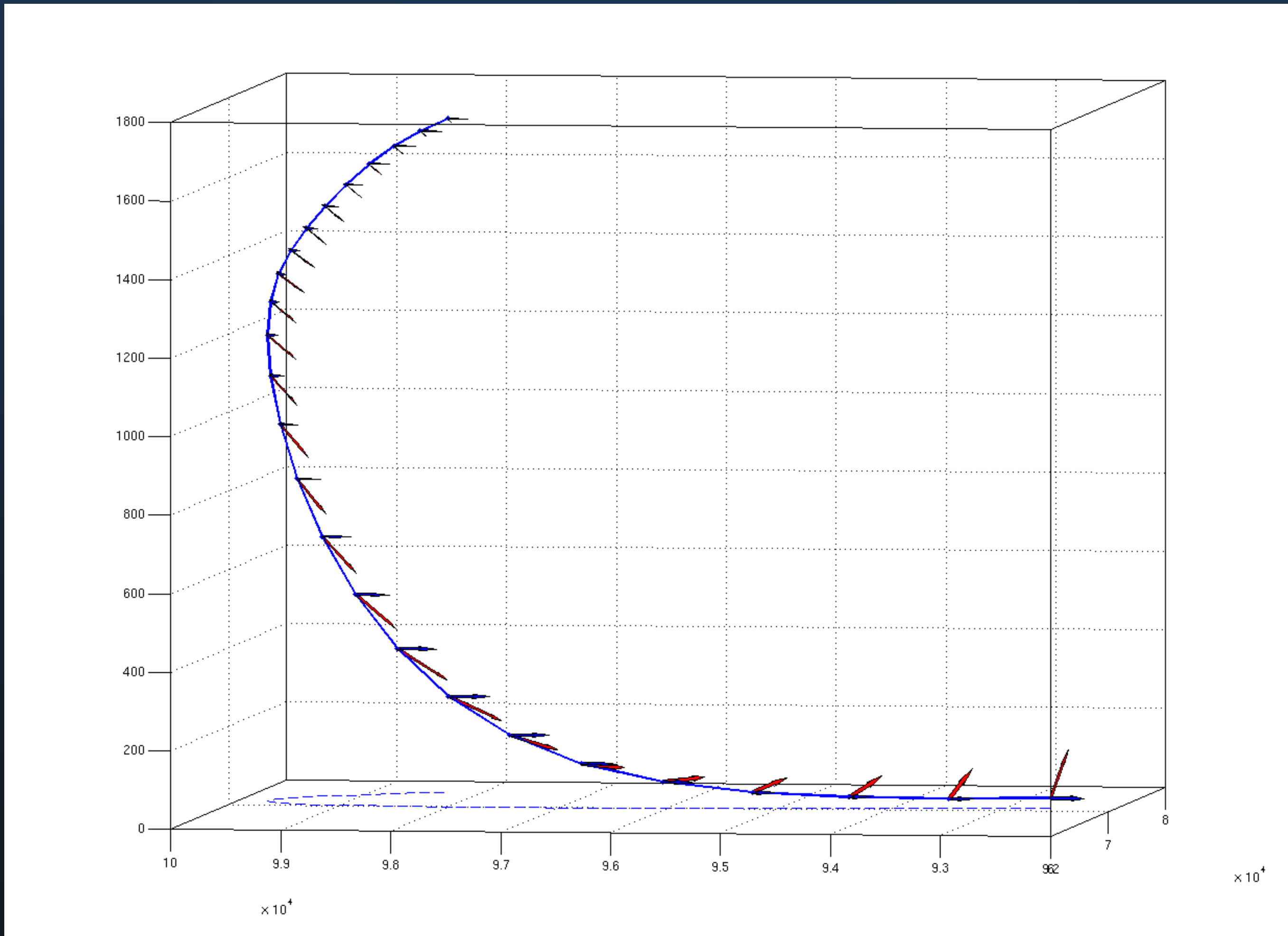


barotropic baroclinic

Mean Del City



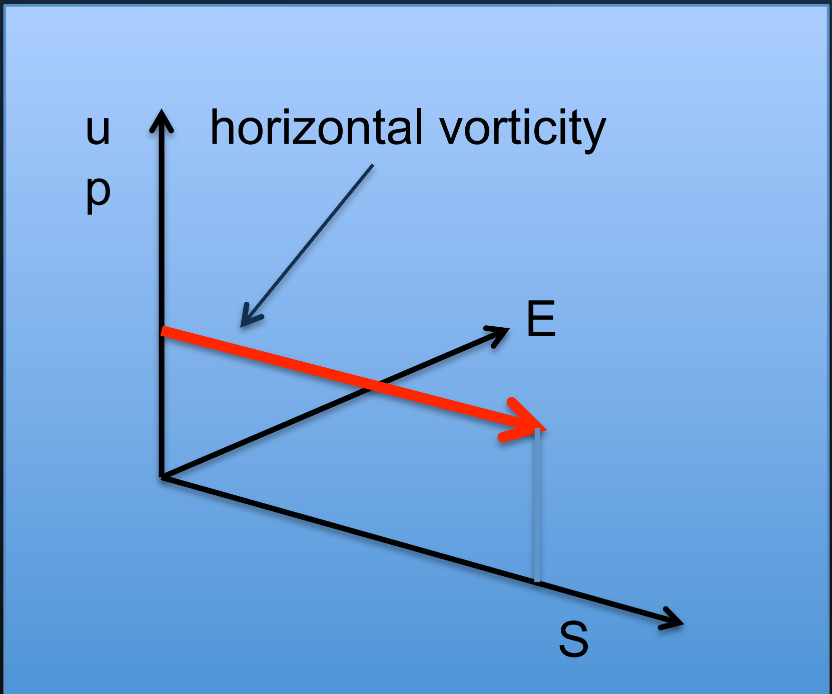
Mean Xenia



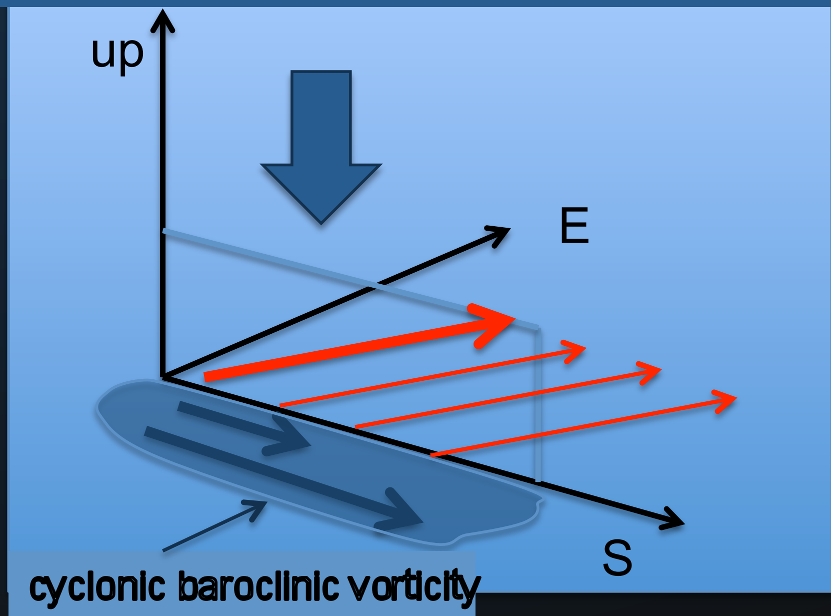
1800
1600
1400
1200
1000
800
600
400
200
0
10
9.9
9.8
9.7
9.6
9.5
9.4
9.3
9.2
7
8
× 10⁴
× 10⁴

baroclinic mechanism

Downdraft reorients vorticity

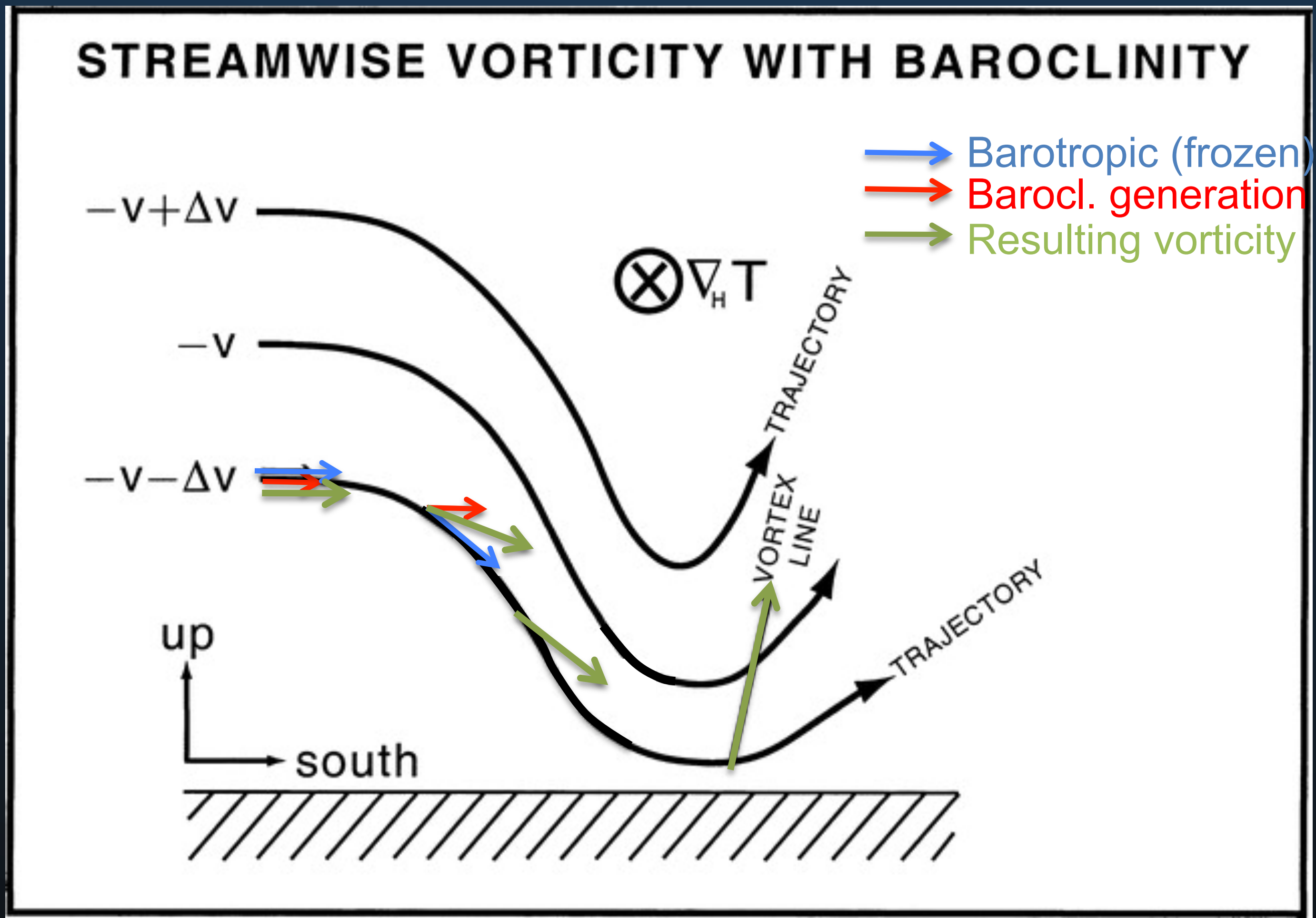


If the vertical vorticity resulting from tilting is manifest as shear, a jet will result



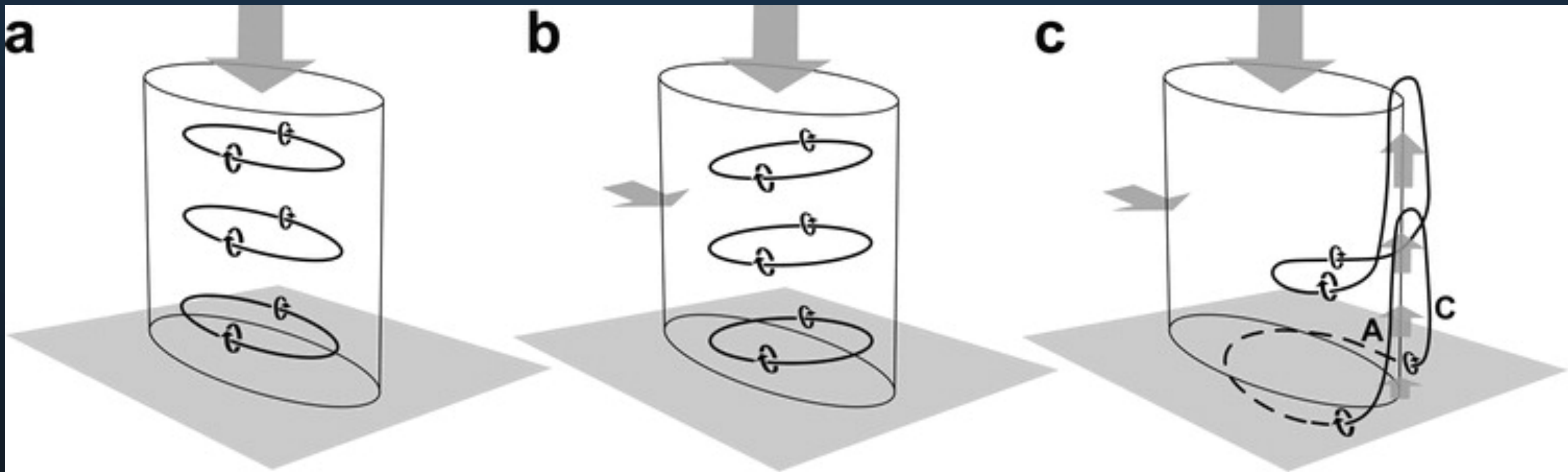
Tilting in the downdraft:

Vorticity vector tugged away from trajectory (reoriented) because of horizontal solenoidal generation



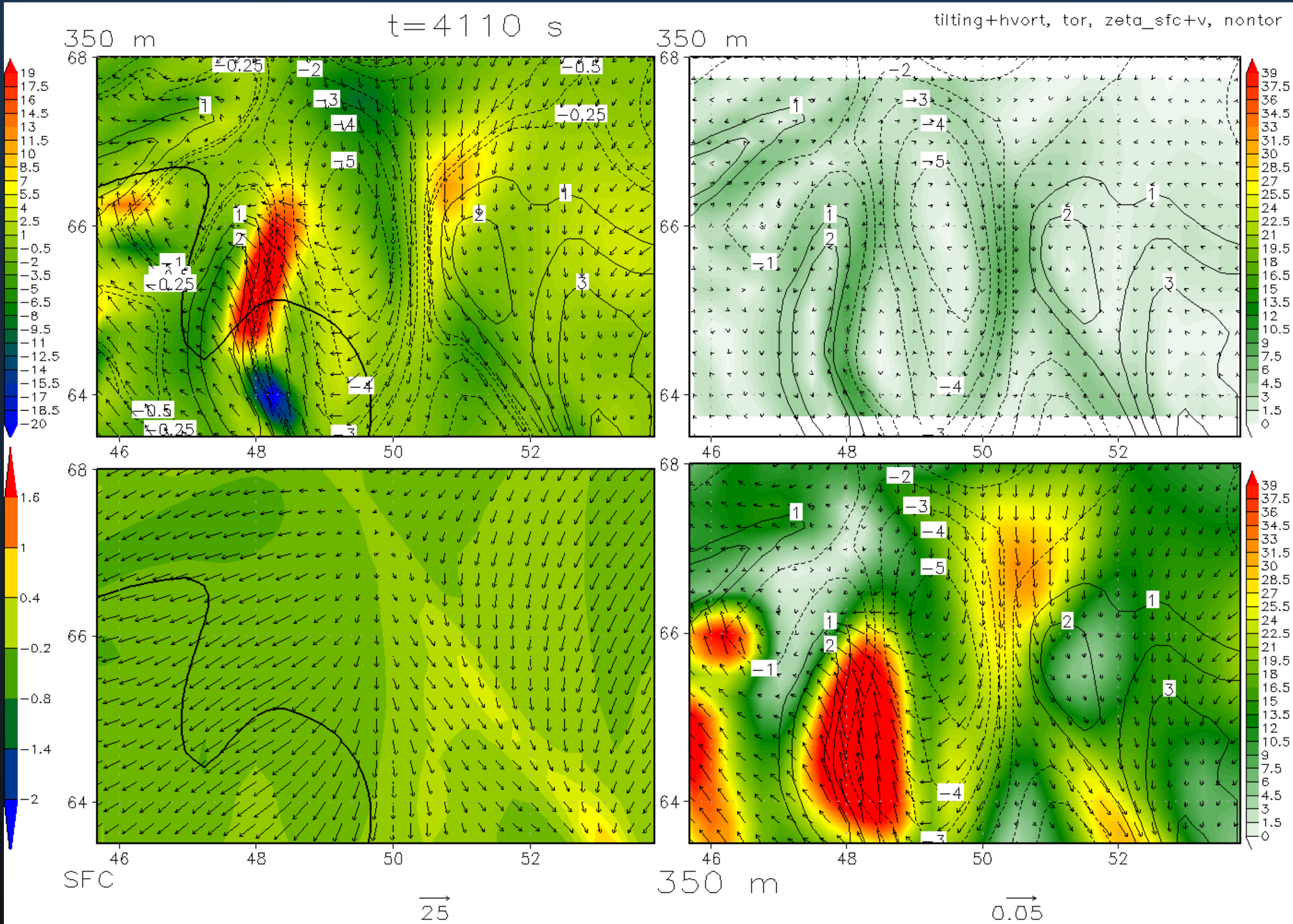
DJB93 and Davies-Jones (2000)

Additional material …



a
b
c
A
C

Vorticity configuration in the simulation



The twisting term

The horizontal vorticity may be split up into two parts:

$$\omega_h = -\mathbf{k} \times \nabla_h w + \mathbf{k} \times \frac{\partial \mathbf{v}_h}{\partial z}$$

"tangential" or "toroidal" part:
- → w is a streamfunction of this part
- → Inescapably parallel to w-contours and
- → Consequently not "tiltable"

"vertical-shear" part:
- → is not necessarily parallel to w-contours
- → may be reoriented

Ergo:

$$T = \omega_h \cdot \nabla_h w = \left[-\mathbf{k} \times \nabla_h w + \mathbf{k} \times \frac{\partial \mathbf{v}_h}{\partial z} \right] \cdot \nabla_h w \equiv \mathbf{k} \times \frac{\partial \mathbf{v}_h}{\partial z} \cdot \nabla_h w$$

Tilting term suggests:
- → Vorticity vector must cut through w-contours in horizontal plane
- → Only vertical-shear component can realize that

How can vortex lines cross w-contours?

- Downdraft: toroidal vortex – no matter how unsteady, this toroidal (buoyantly-generated) vorticity cannot be tilted

- DJ00 used a trick to have buoyantly-generated vorticity cross w-contours: primary-secondary-flow approach
  - w-related horizontal vorticity (“toroidal”) allowed to cross w-contours (kinematically inconsistent)

- Paul: Somewhat unclear about it (horizontal wind drags vortex line through downdraft, which is kinematically inconsistent)

Requirements for zeta generation at the surface (zeta = 0 initially)

- A non-trivial twisting term in a downdraft does not imply vertical vorticity at the surface:

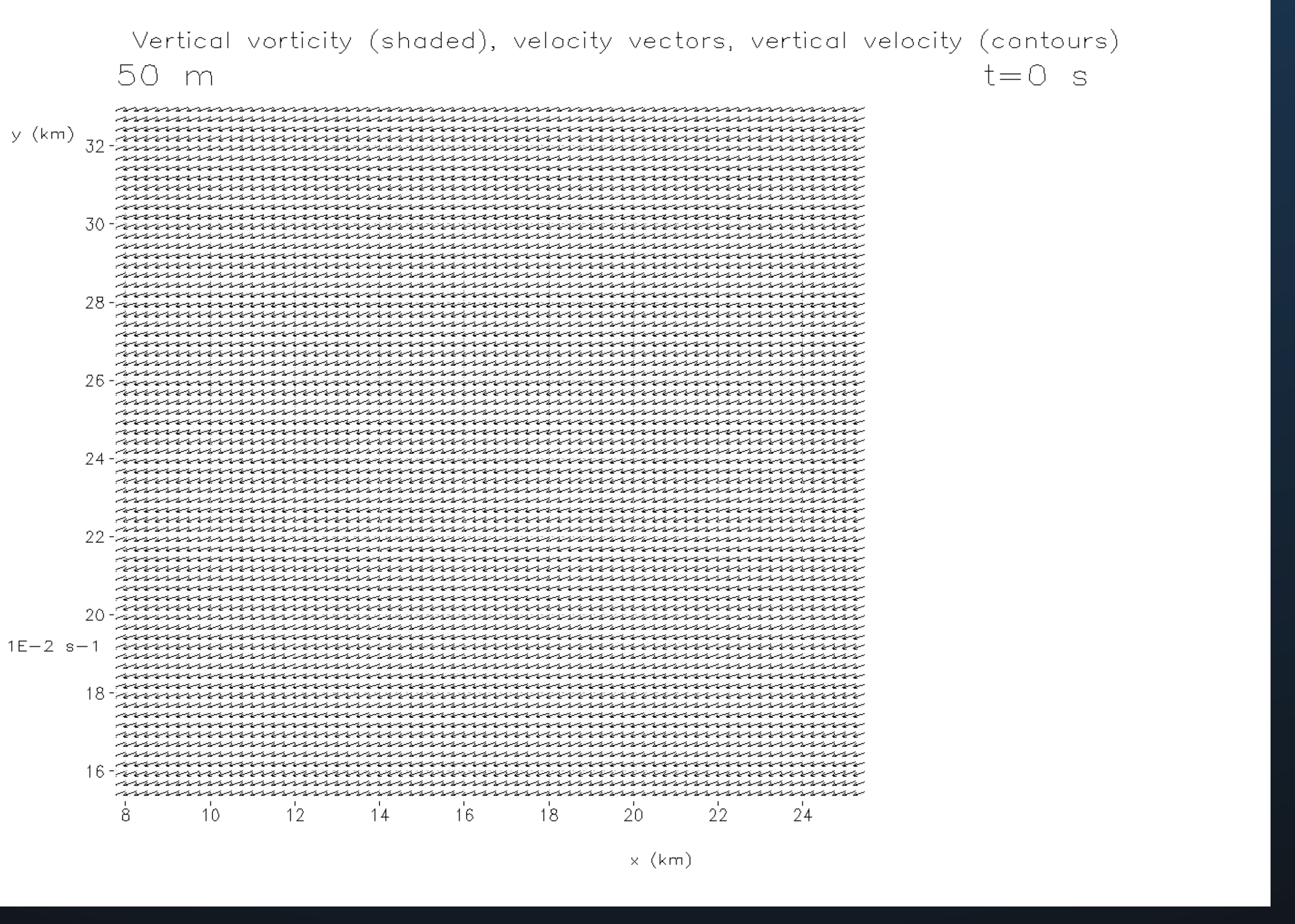
  Vorticity vector must cross trajectory in vertical plane

Two requirements have to be fulfilled:

1. In-situ generation of horizontal *shear* vorticity required while parcels descend
2. This shear vorticity must be non-parallel to w-contours
   (or twisting term remains zero)

All we need for that: Downdraft in shear:

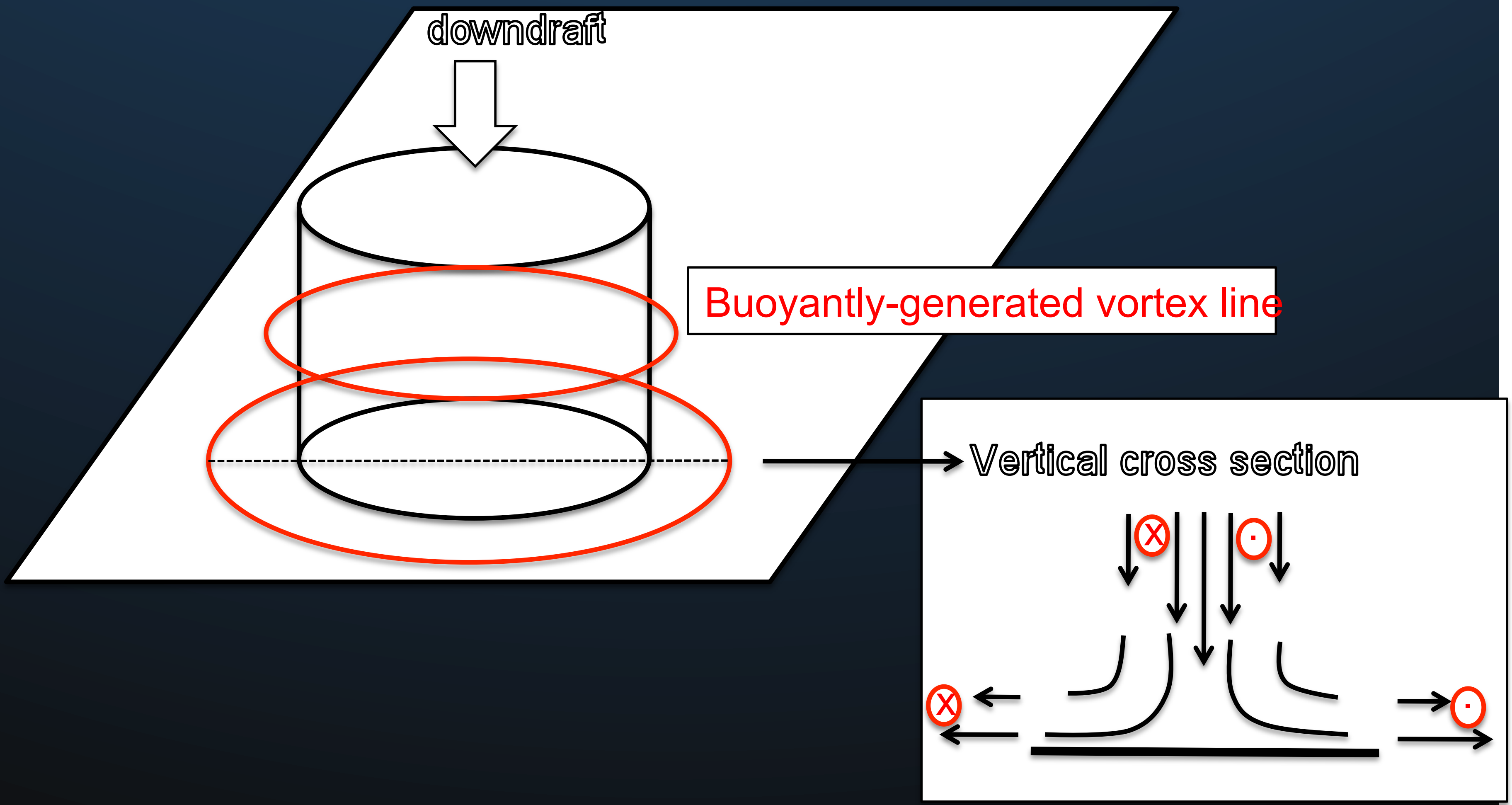
Idealized downdraft



Example 1 (unsheared):

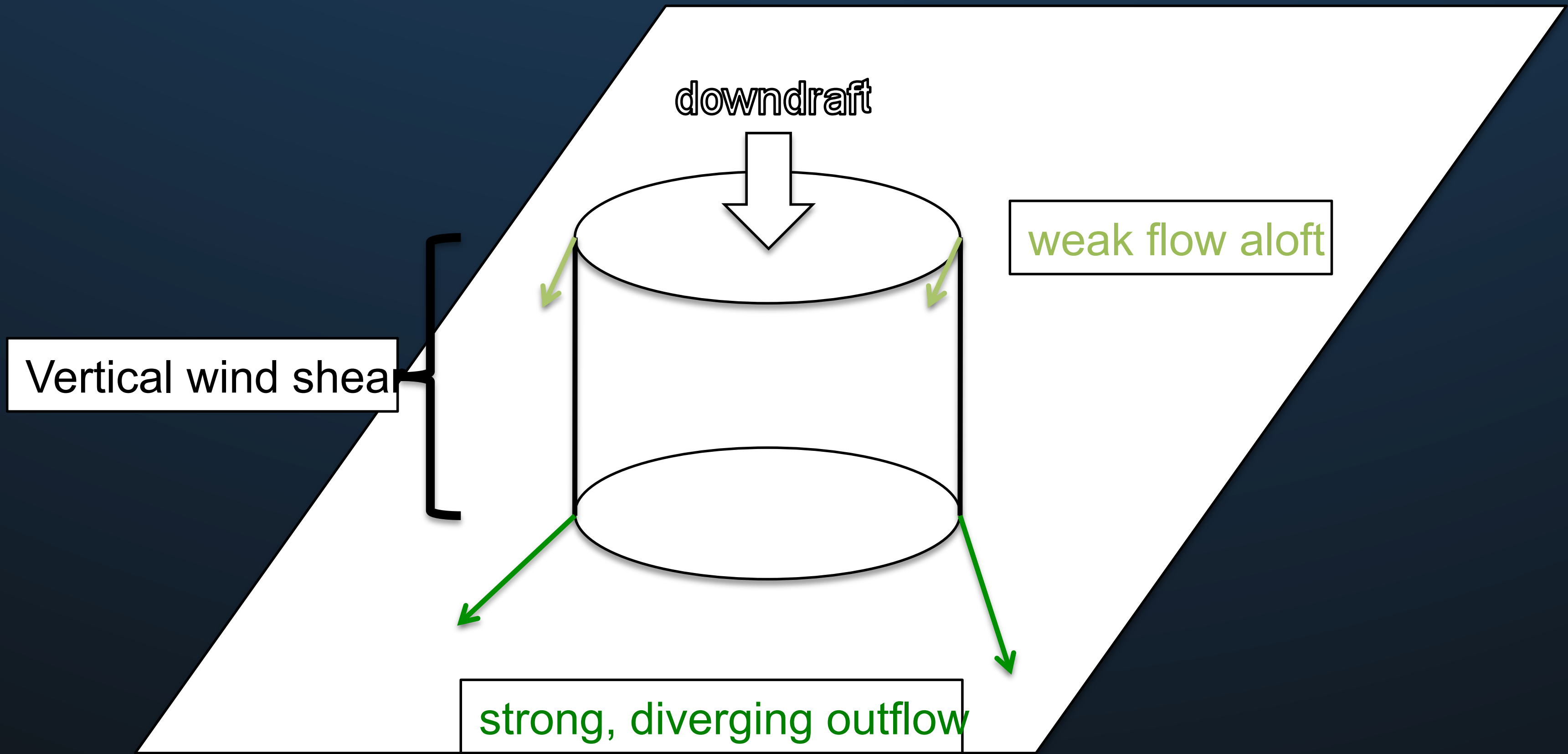
1. Horizontal shear vorticity created during descent
2. This vorticity is parallel to w-contours (requirement 2 not me

→ No vertical vorticity results

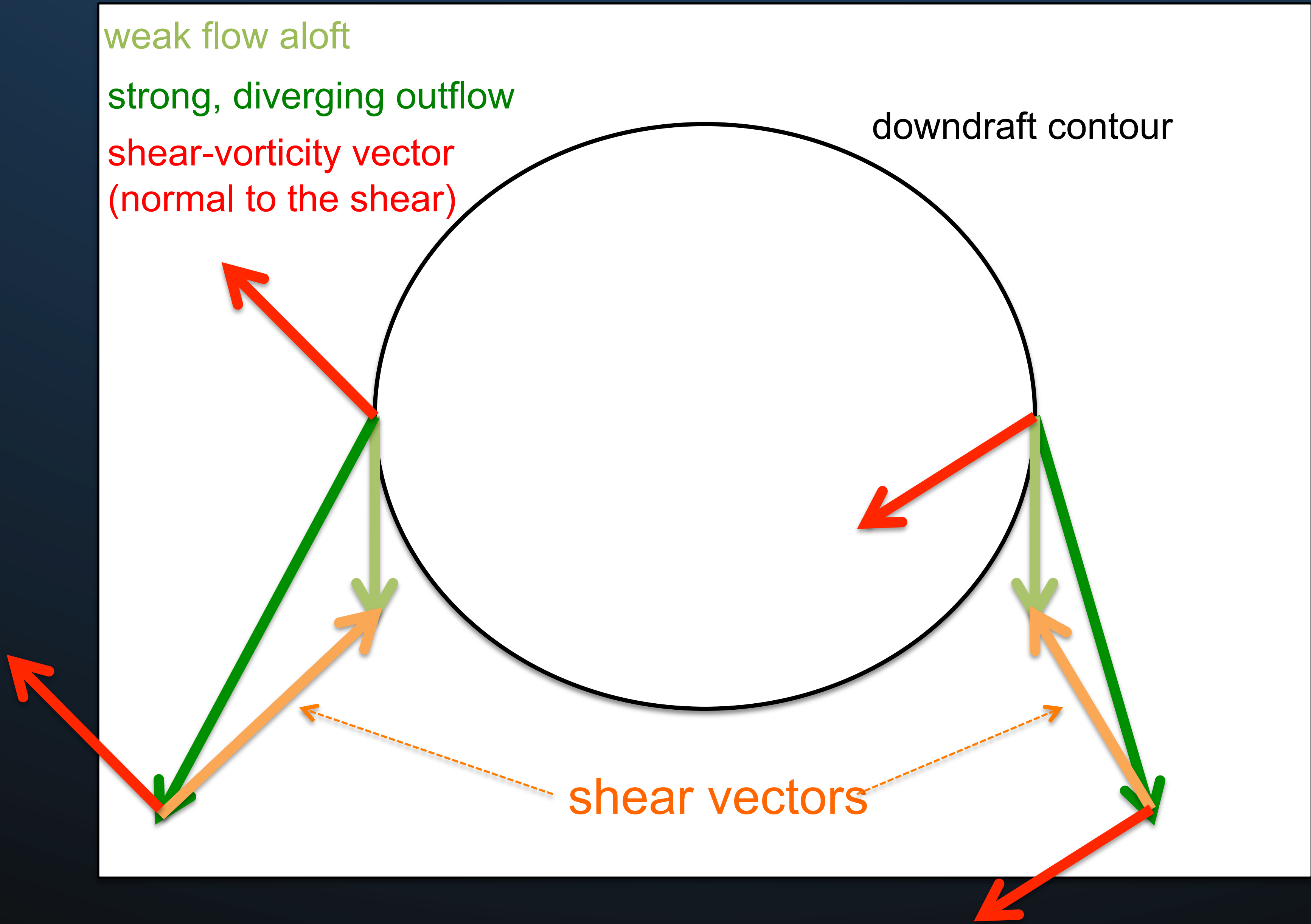


Example 2 (sheared):

1. Horizontal shear vorticity created during descent
3. As will be shown: This vorticity is not parallel to w-contours and thus can be reoriented

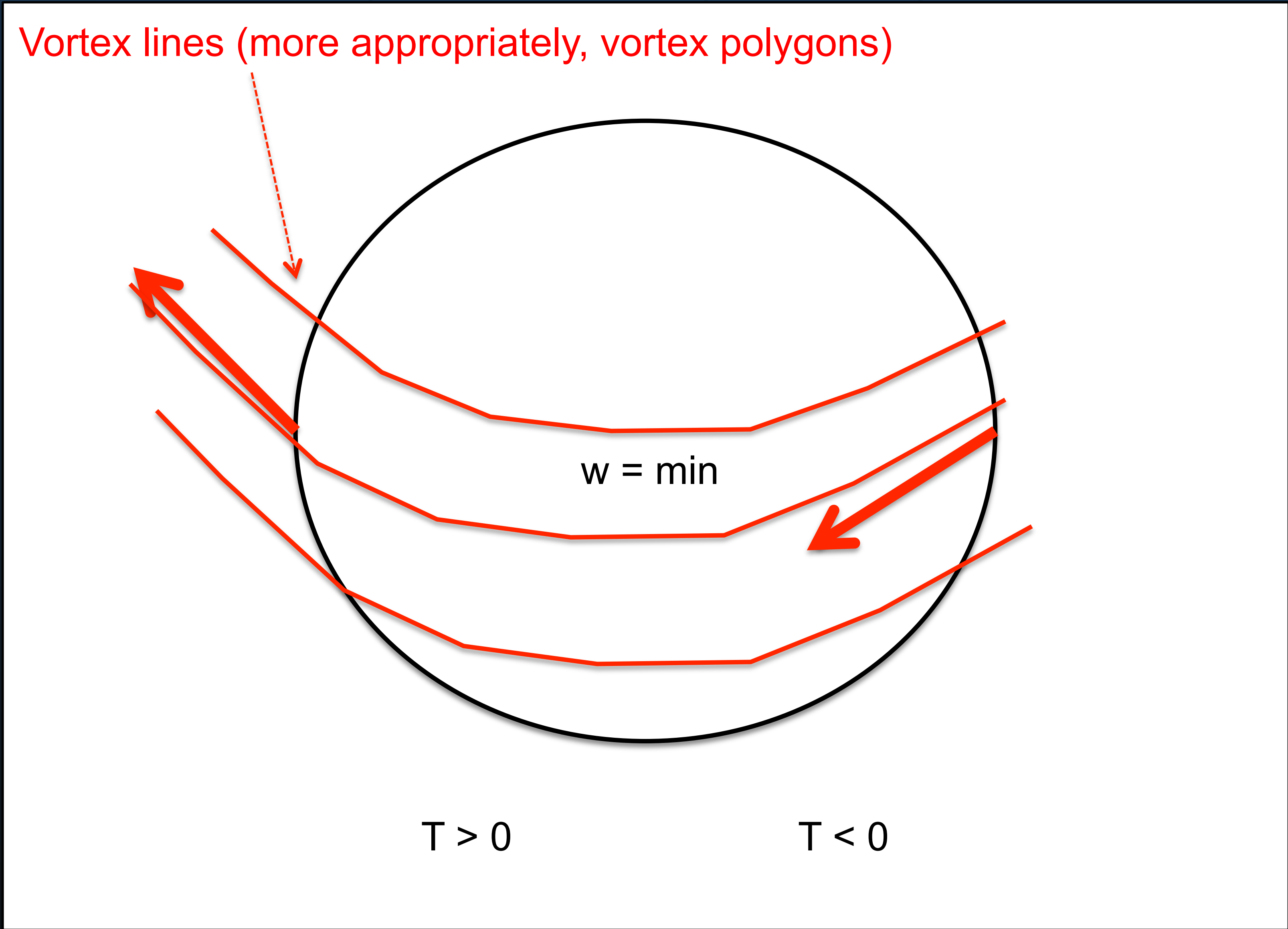


Plan view:

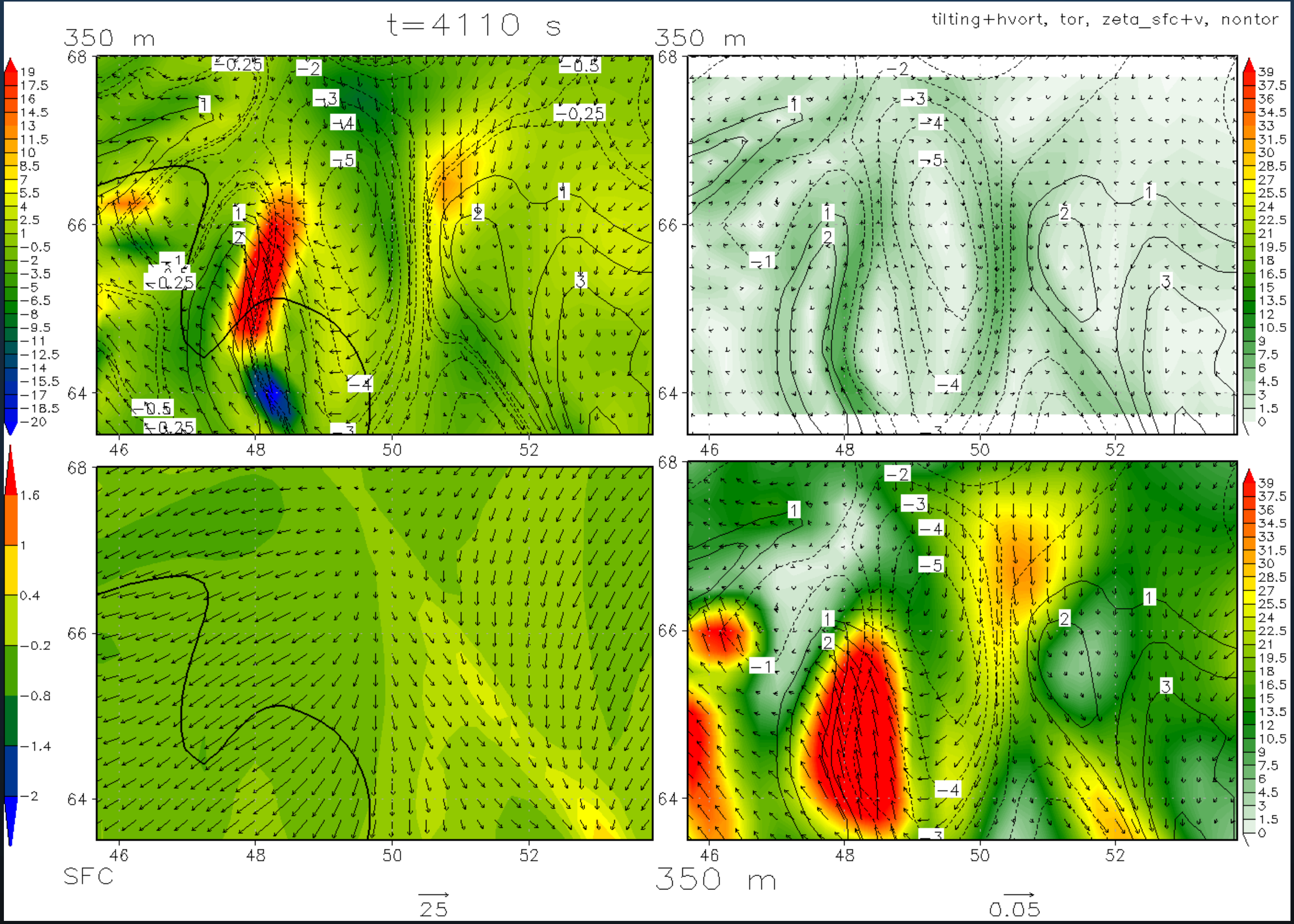


weak flow aloft
strong, diverging outflow
shear-vorticity vector
(normal to the shear)
downdraft contour
shear vectors

Vortex lines now crossing downdraft contours (Paul's configuration)



Vorticity configuration in the simulation



- Vorticity feeding into the circulation due to differential *horizontal* accelerations (splat?) and not *directly* caused by buoyancy gradients

- Low-level shear influencing outflow structure and hence the horizontal shear vorticity

So: Test sensitivity of outflow-generated vorticity to ambient shear using idealized downdrafts (artificial rain source added; in progress)

What about vortex-line arches?

- The simulated hooks are not in downdrafts, so the arches can’t be *generated* around the hook

- Arches may be generated in main downdraft, though

- Hook region: Very complicated and multiple trajectories and vortex lines may, at a given instant, form arches; not necessarily implied that they are formed in situ around the hook

Conclusions 1

- RFD does not seem to instigate low-level rotation but coexist passively at western side of the updraft
  - RFD and associated low-level pressure field may help channeling the trajectories
- Main downdraft generates zeta by the same process as proposed by JDB93/DJ00
- No inflow trajectories into tornado cyclone
  - No "occlusion" (= cut-off from warm air): circulation never fed by warm air