Understanding the Effects of Horizontal Convective Rolls on the Organization of Low-Level Vorticity in Simulated Supercell Thunderstorms

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HCRs result in periodic variations in:

-velocity

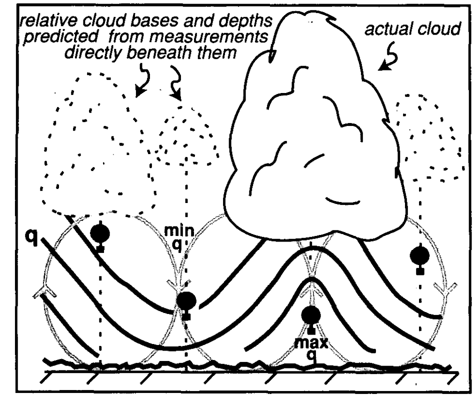
-temperature

-moisture

-instability

-LCL

-wind shear



Weckwerth et al. 1996

20 May 2013

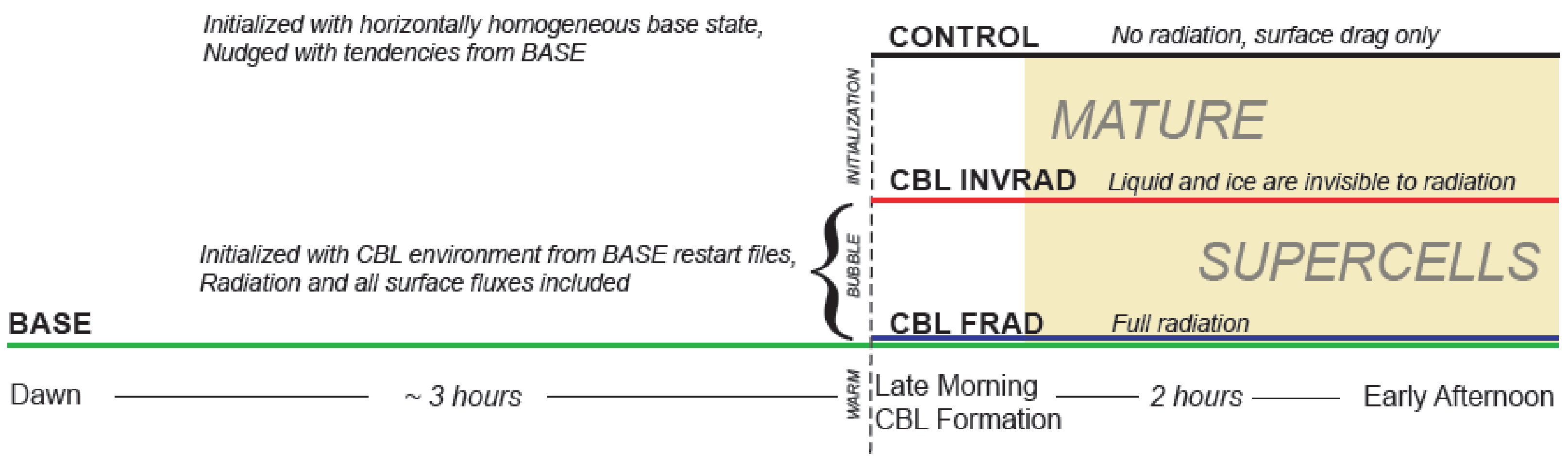
Central Oklahoma

Image Credit: NASA

Experiment Goals

- Simulate a convective boundary layer (CBL) with horizontal convective rolls (HCRs)
- Simulate supercell thunderstorms using this organized CBL as the base state
  - compare with a horizontally homogeneous base state
- Examine effects of HCRs on storm evolution, particularly low-level vorticity structure

Experiment Design



CONTROL

Horizontally homogeneous environment with no radiation or surface heat & moisture fluxes. Base state is nudged using tendencies from the BASE simulation.

CBL INVRAD

Initializes deep convection in an organized CBL with radiation and surface fluxes. Liquid and ice (clouds) are invisible to radiation.

CBL FRAD

Similar to CBL INVRAD, but with full radiation (includes cloud shading).

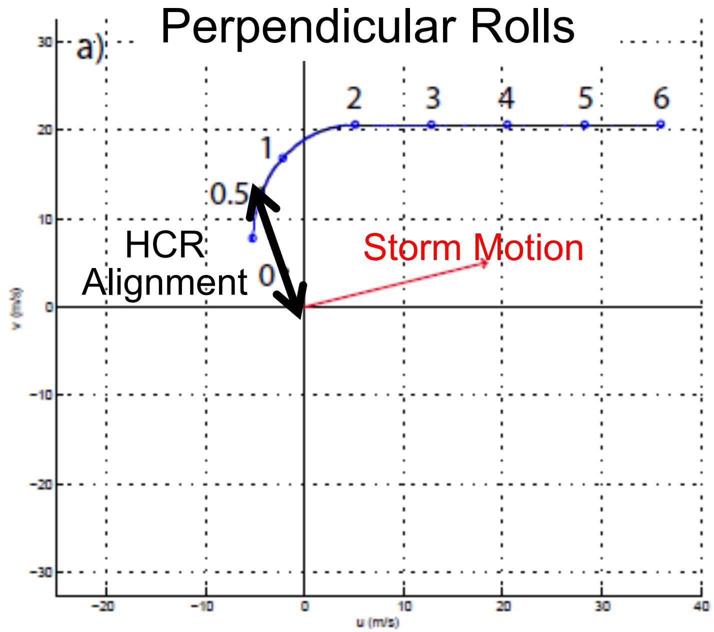
Model Configuration

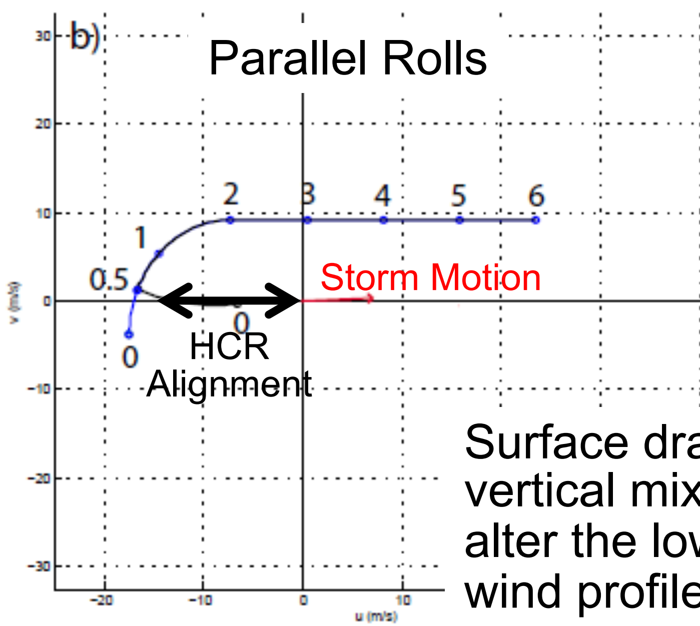
- Model
  - CM1, version 1, release 15 (*Bryan 2002*)
  - $\Delta t = 0.75$ s
  - periodic lateral boundary conditions

- Grid
  - dimensions: 250 km x 200 km x 18 km
  - $\Delta x = 200$ m
  - Δz = stretched from 50 m (below 3 km) to 500 m (above 9.5 km)

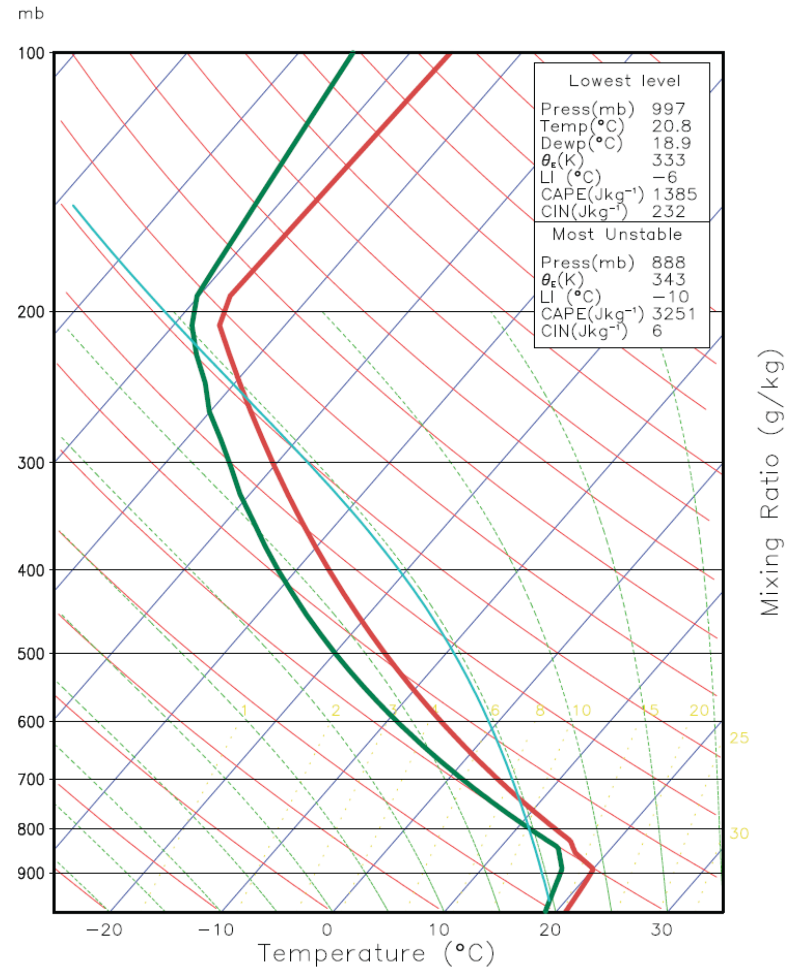
- Parameterizations
  - Single moment LFO ice microphysics *(Lin et al. 1983)*
  - Deardorff (1980) 1.5-order subgrid scale turbulence scheme
  - Land surface scheme using two-layer soil model
  - Independent column approximation radiative transfer *(NASA Goddard Cumulus Ensemble; Chou 1990,1992; Chou et al. 1998;Tao et al. 1996; Chou et al. 1999)*

Generating HCRs



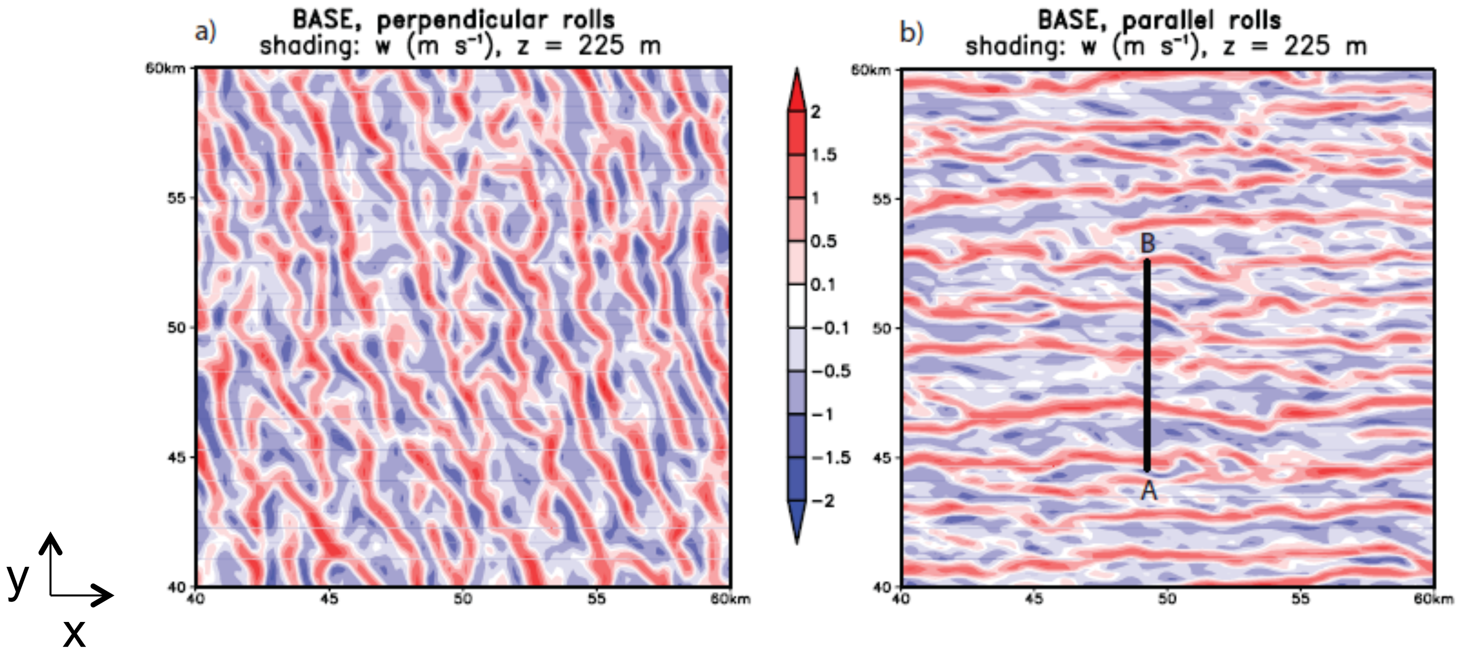


Surface drag and vertical mixing alter the low-level wind profile.



Surface heat and moisture fluxes destabilize the boundary layer, resulting in HCRs aligned with the boundary layer shear vector.

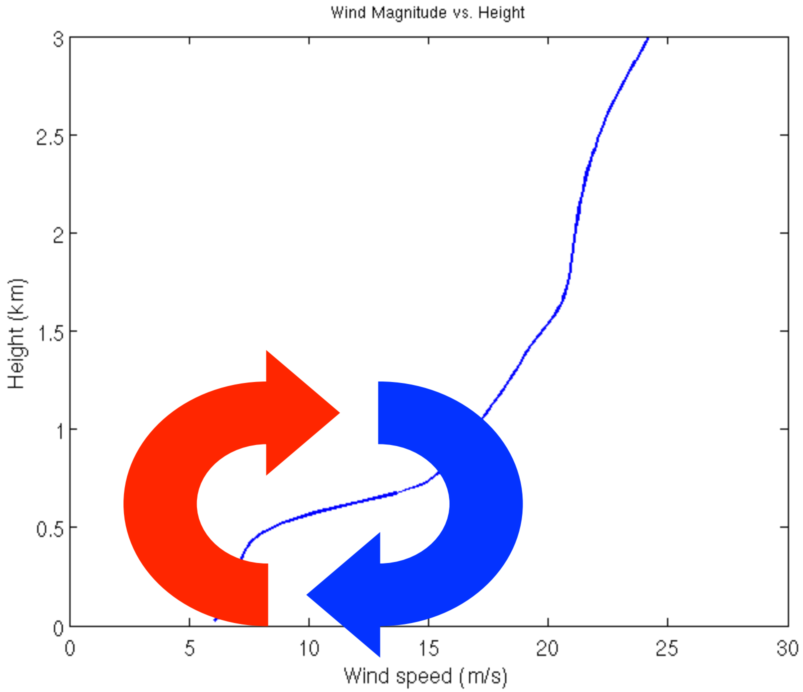
HCR Characteristics

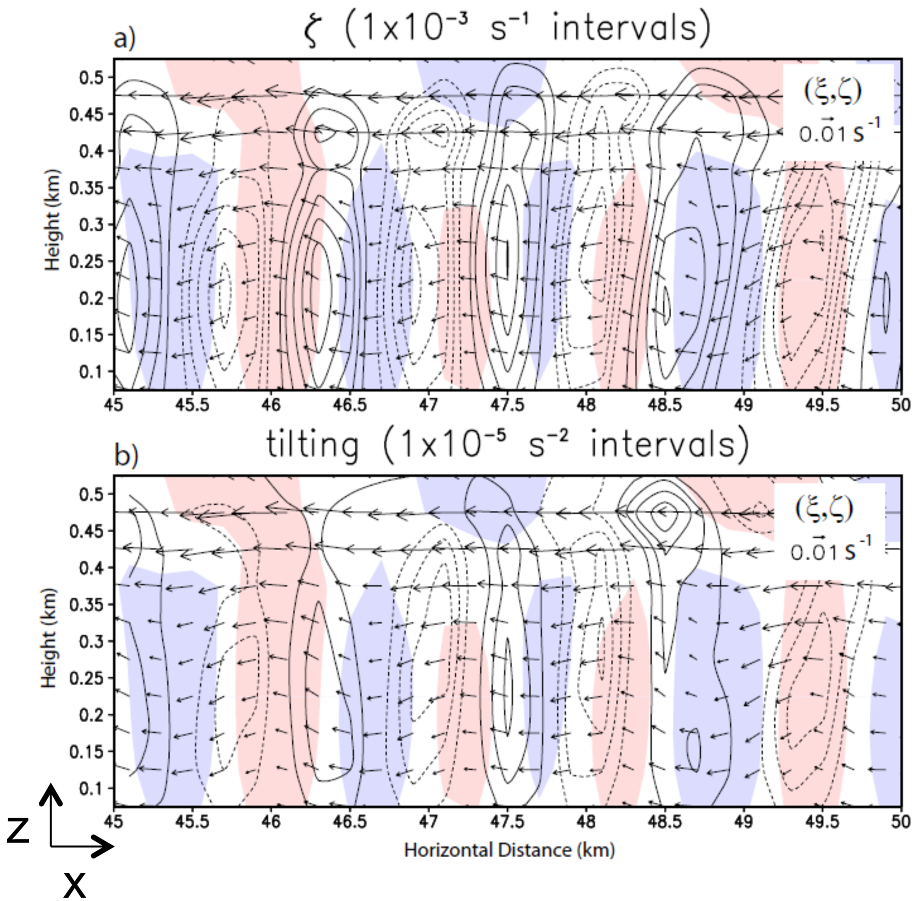


-Simulated HCRs have aspect ratios (wavelength/depth = 2-3) consistent with observations and theory.

-Vertical velocity perturbations are as strong as +/- 2.5 m/s

A source of environmental vertical vorticity





- HCR downdraft branches advect higher momentum air to surface, resulting in alternating vertical vorticity perturbations.

- Put another way, the ambient horizontal vorticity is tilted by HCR vertical velocity perturbations.

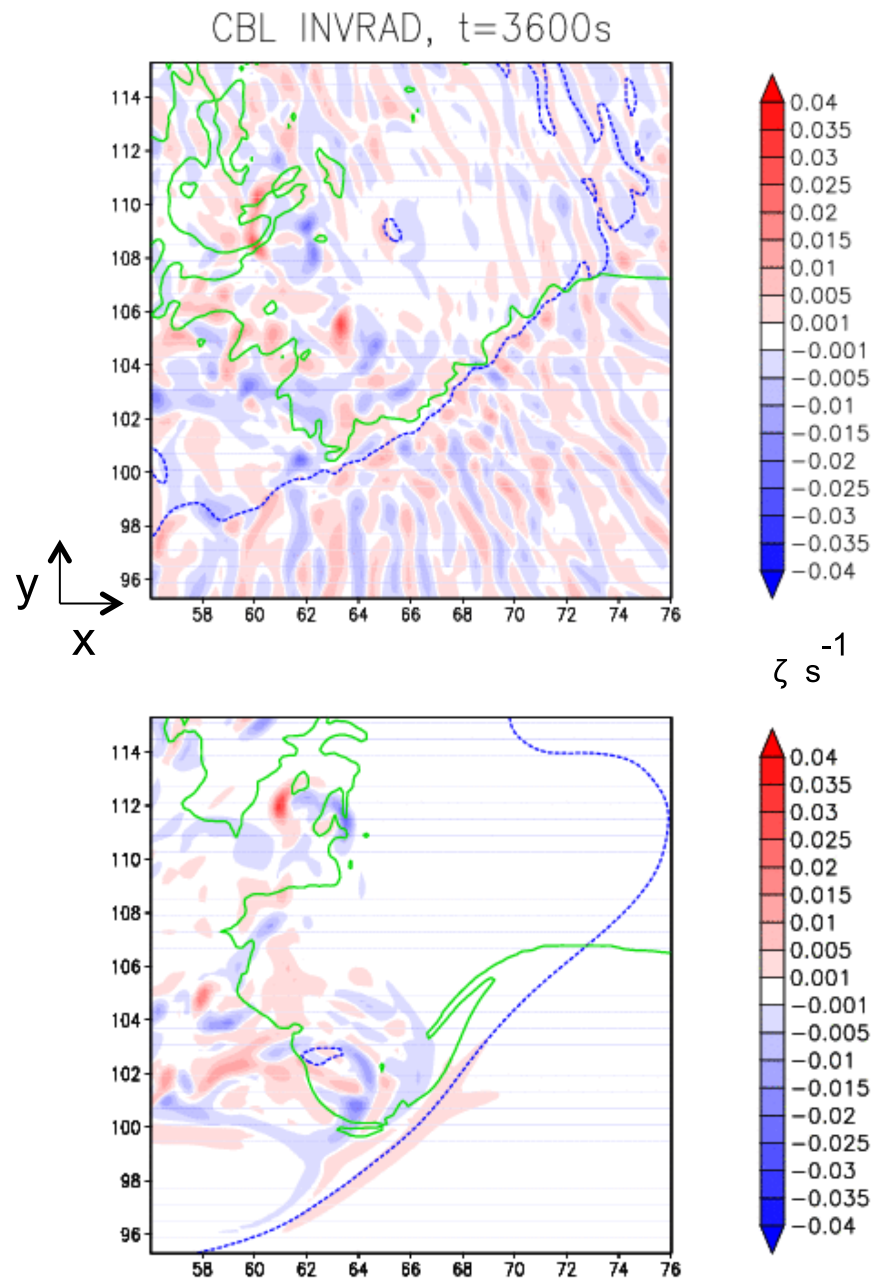
Perpendicular Rolls

Low-Level Mesocyclone

-Before significant vertical vorticity ($>0.01\ s^{-1}$) develops in the CONTROL supercell, vertical vorticity extrema develop beneath the midlevel updraft and along the trailing outflow boundary at HCR intersections.

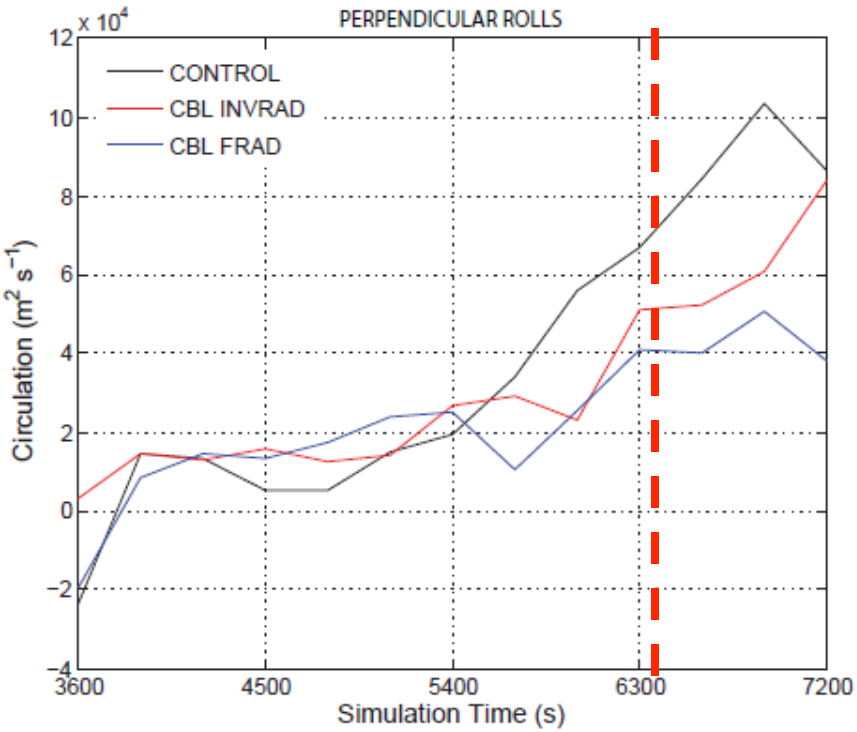
- Eventually (by 5400 s), a sustained low-level mesocyclone begins to develop in the CONTROL supercell.

-HCRs appear to disrupt the development of a persistent low-level mesocyclone in CBL INVRAD.



Perpendicular Rolls

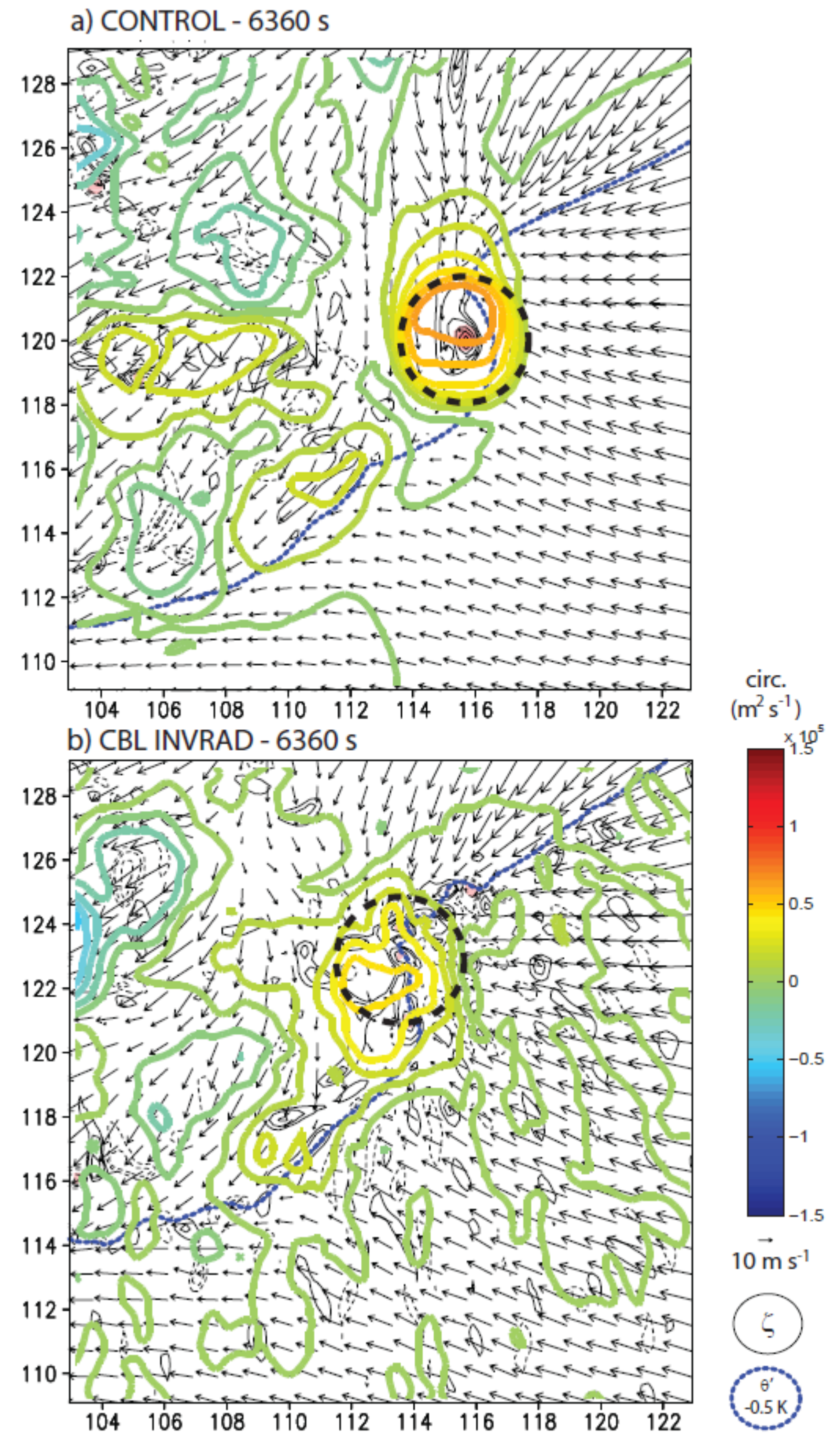
Low-Level Mesocyclone Circulation



$$C \equiv \oint \mathbf{v} \cdot d\mathbf{l} = \iint_A \boldsymbol{\omega} \cdot \mathbf{n} \, dA$$

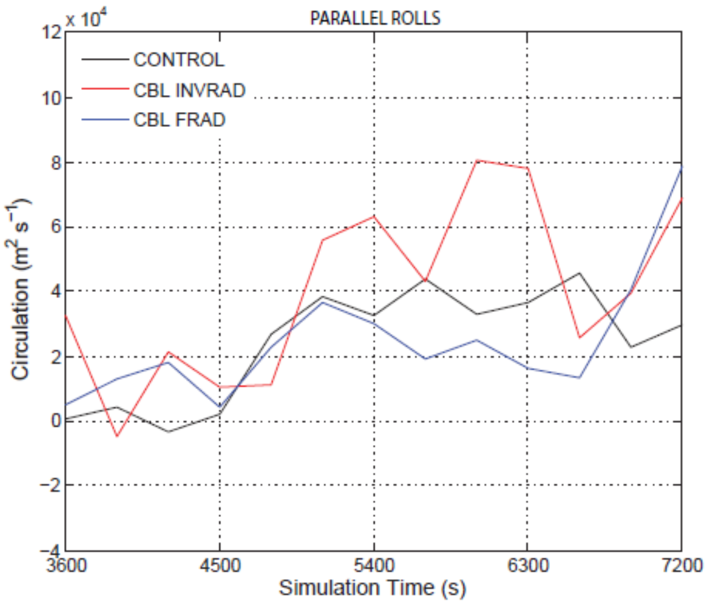
-Circulation is the integral of vertical vorticity over the area of the surface bounded by a horizontal circuit.

- Over last half hour of simulation, CONTROL mesocyclone circulation is consistently stronger than in CBL INVRAD.



Parallel Rolls

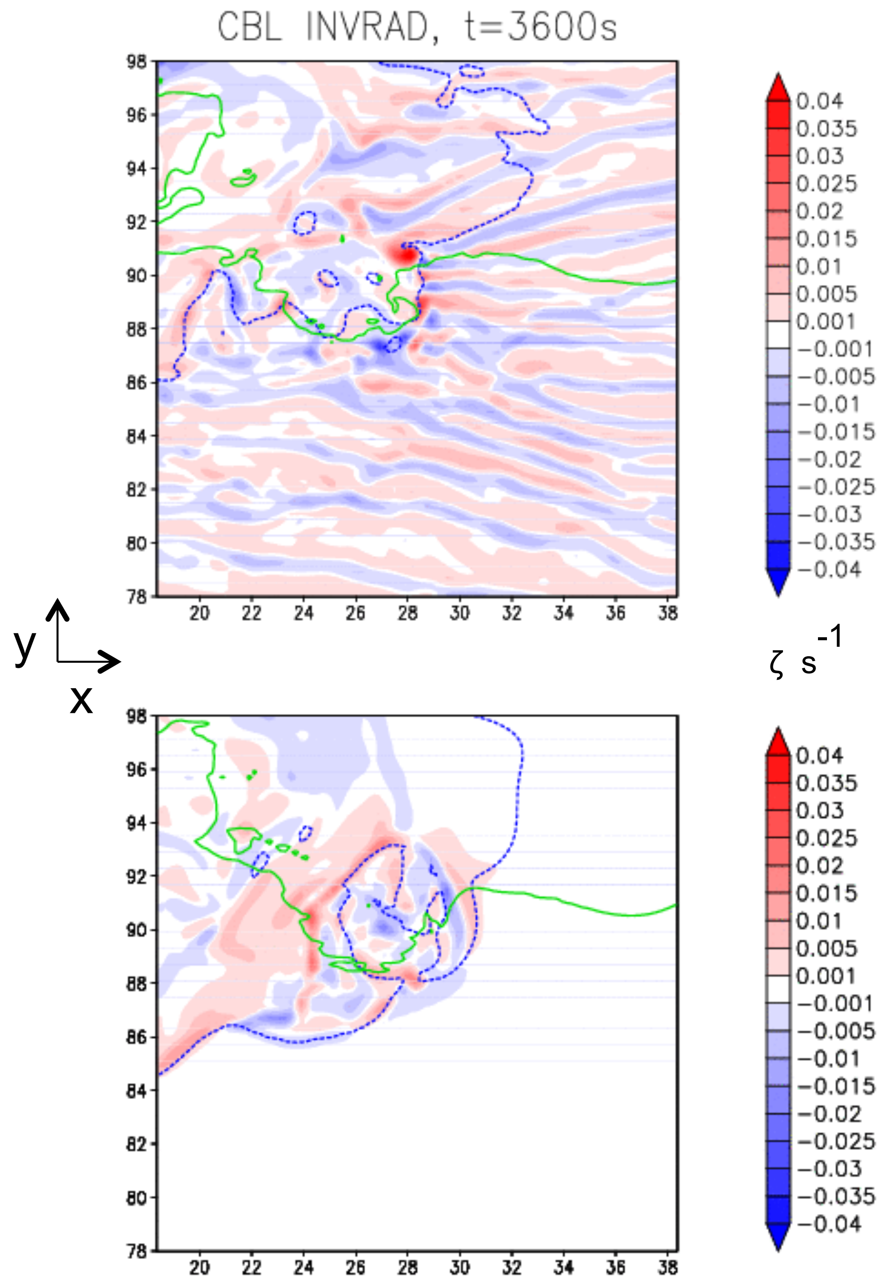
Low-Level Vertical Vorticity



Overall, the parallel-roll hodograph is less conducive to a sustained, strong low-level mesocyclone when compared to the perpendicular-roll hodograph.

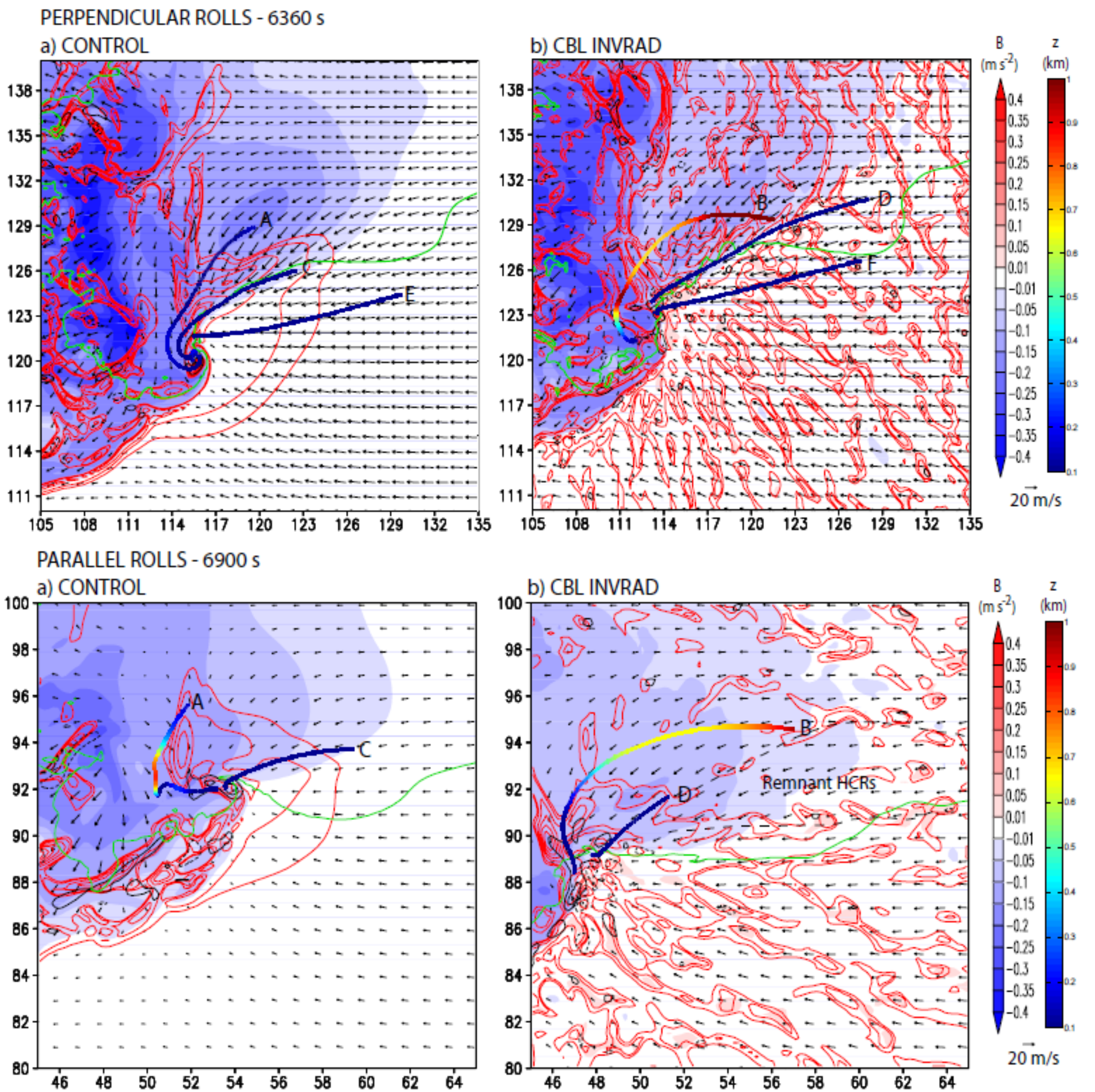
HCR intersections provide favorable locations for vertical vorticity maxima to develop in CBL INVRAD.

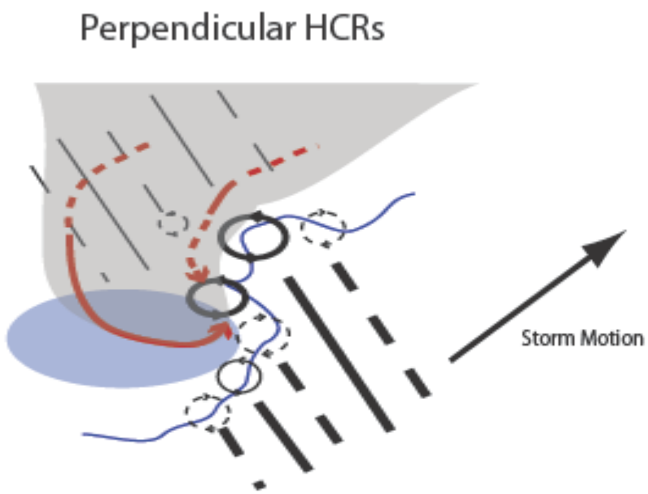
This often enhances the low-level mesocyclone circulation relative to the CONTROL.

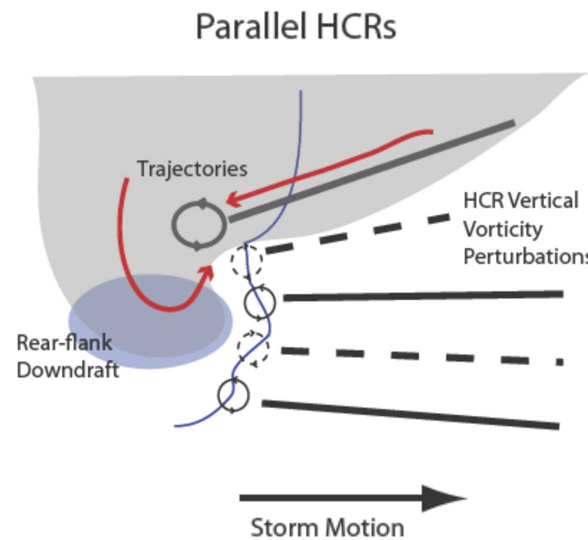


There is considerable heterogeneity associated with HCRs in the forward-flank outflow and along the forward-flank baroclinic zone.

This affects the properties of air parcels entering the mesocyclone, especially from the forward flank.







Perpendicular Rolls:

-Supercell moves across rolls such that low-level mesocyclone encounters varying unfavorable/favorable conditions (i.e., negative/positive tilting and/or stretching) associated with HCR heterogeneity.

-Vorticity budgets show that forward–flank source parcels have variable vortiicty tendency along their trajectories.

-Depending on its HCR-relative position, the cyclonic vorticity maximum may be flanked by anticyclonic vorticity, weakening circulation.

Parallel Rolls:

-Supercell moves along rolls such that the low-level mesocyclone may encounter favorable conditions for a longer period of time.

-Vorticity budgets show that forward-flank source parcels move along HCRs and have prolonged periods of positive vertical vorticity tendency

- Though this hodograph generally leads to a weaker mesocyclone, HCR influences often augment the low-level mesocyclone circulation.

Conclusions

- HCRs can be a source of environmental vertical vorticity.
- HCRs affect both the low-level mesocyclone circulation and misovortices along the trailing outflow boundary.
  - When perpendicular to storm motion, HCRs disrupt the development of a persistent mesocyclone.
  - When parallel to storm motion, HCRs may augment the low-level mesocyclone.
  - Misocyclones and flanking-line updrafts are more frequent when HCRs are present.
- When included, shading from the anvil suppresses boundary layer convection, mitigating its effects on the supercell.
- Implications for tornadogenesis remain unclear and may be situation-dependent.

Future Research Directions

- Exploration of the sensitivity of HCR influence to different hodograph shapes, thermodynamic profiles, and storm types
- Comparison a case study of observed HCR/ thunderstorm interactions
- These findings suggest that future simulations investigating low-level rotation in supercells should include more realistic boundary layers and surface properties.

Acknowledgments

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- Computing facilities and support provided by the National Center for Atmospheric Research.

EXTRA SLIDES

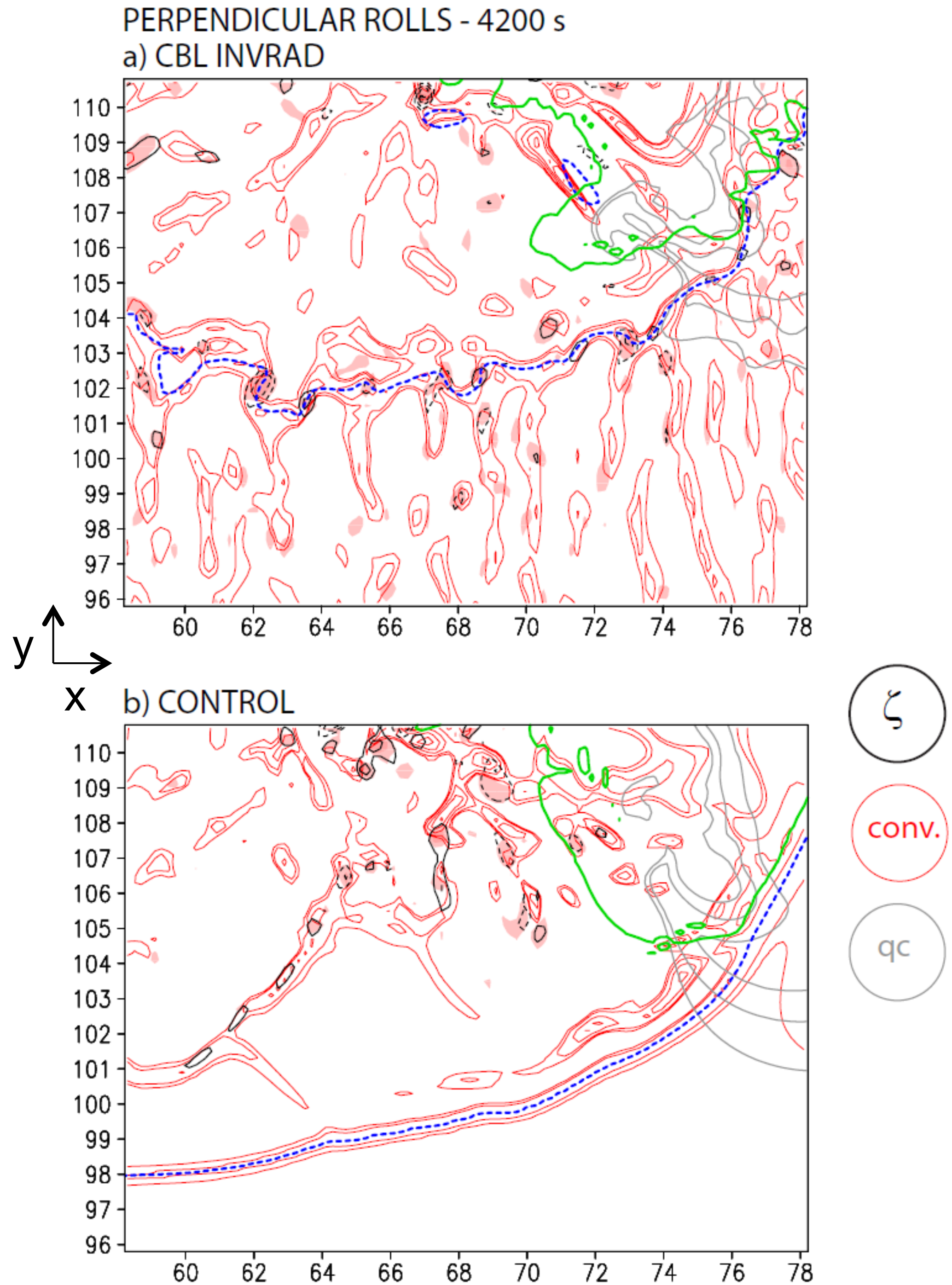
Misovortices

-More frequent misocyclones and misoanticyclones when HCRs are present in environment

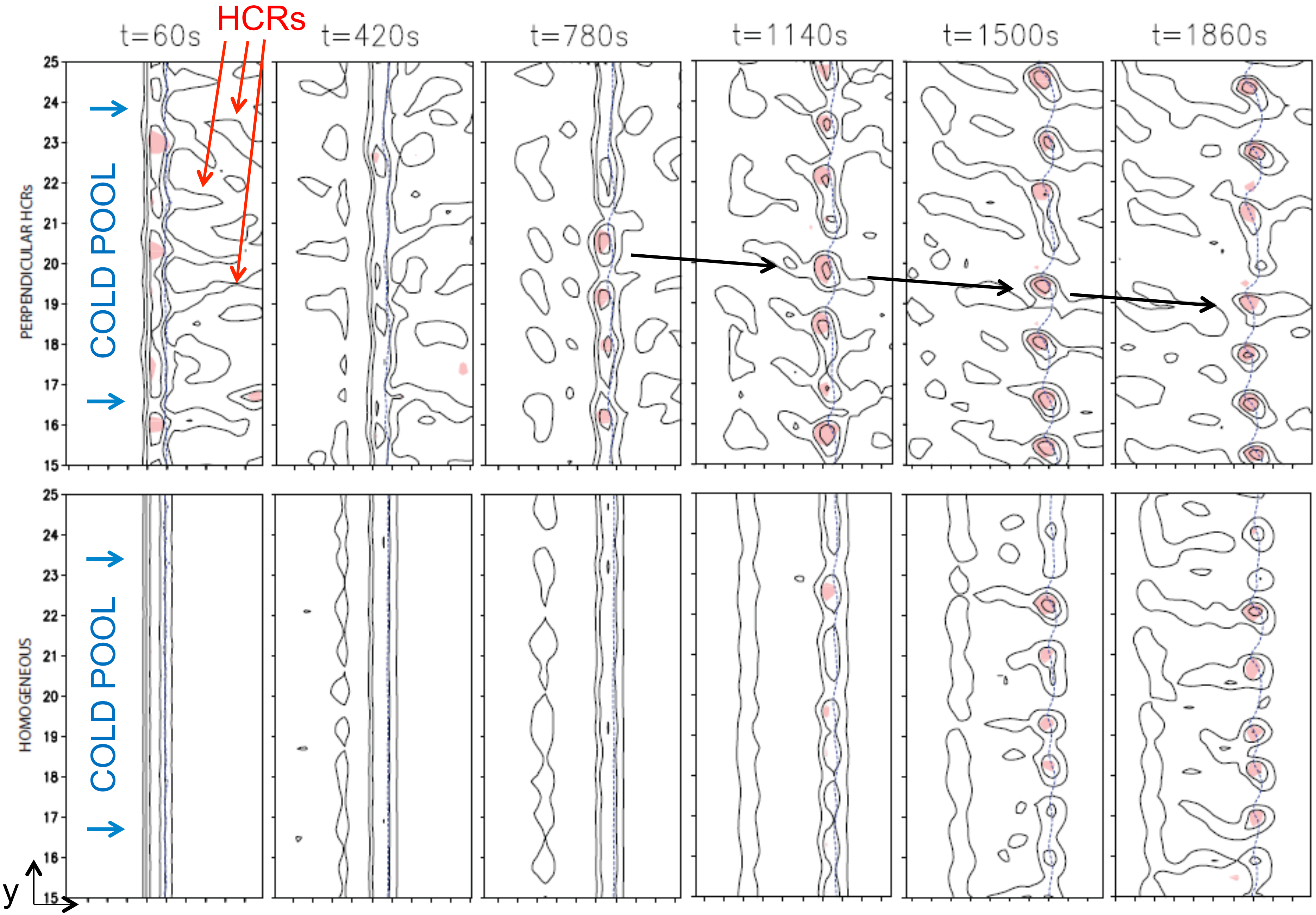
-Misovortices tend to occur where convergence (updraft) band of HCR overlaps with vertical vorticity perturbations and outflow boundary.

-More intersection points where HCRs are perpendicular to the outflow boundary

-In these simulations HCRs were required to develop flanking-line deep convection, suggesting HCRs may play a critical role in gustnadoes and/or non-mesocyclone tornadoes.

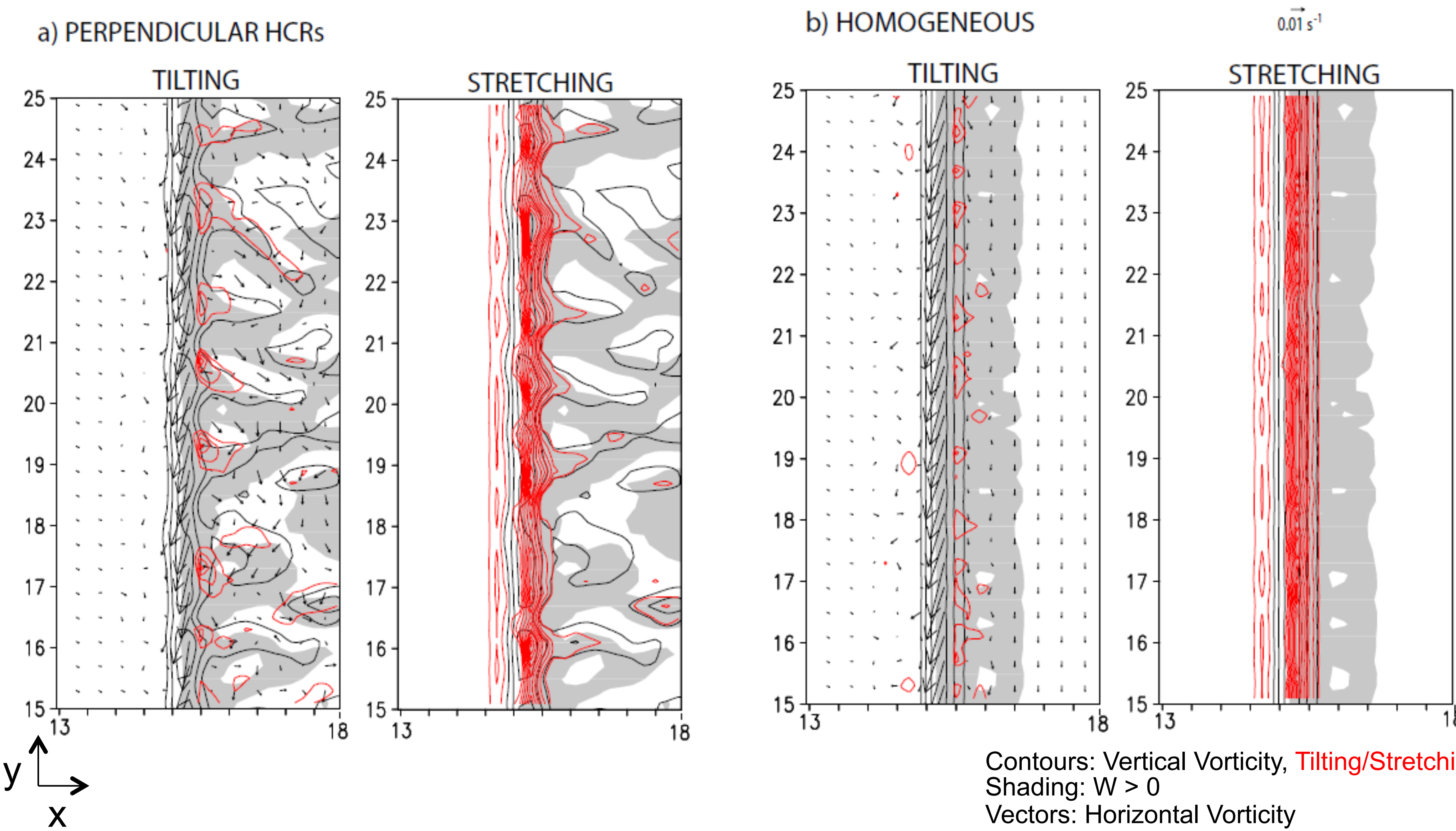


Idealized Density Current Simulation



Contours: Vertical Vorticity

Idealized Density Current Simulation



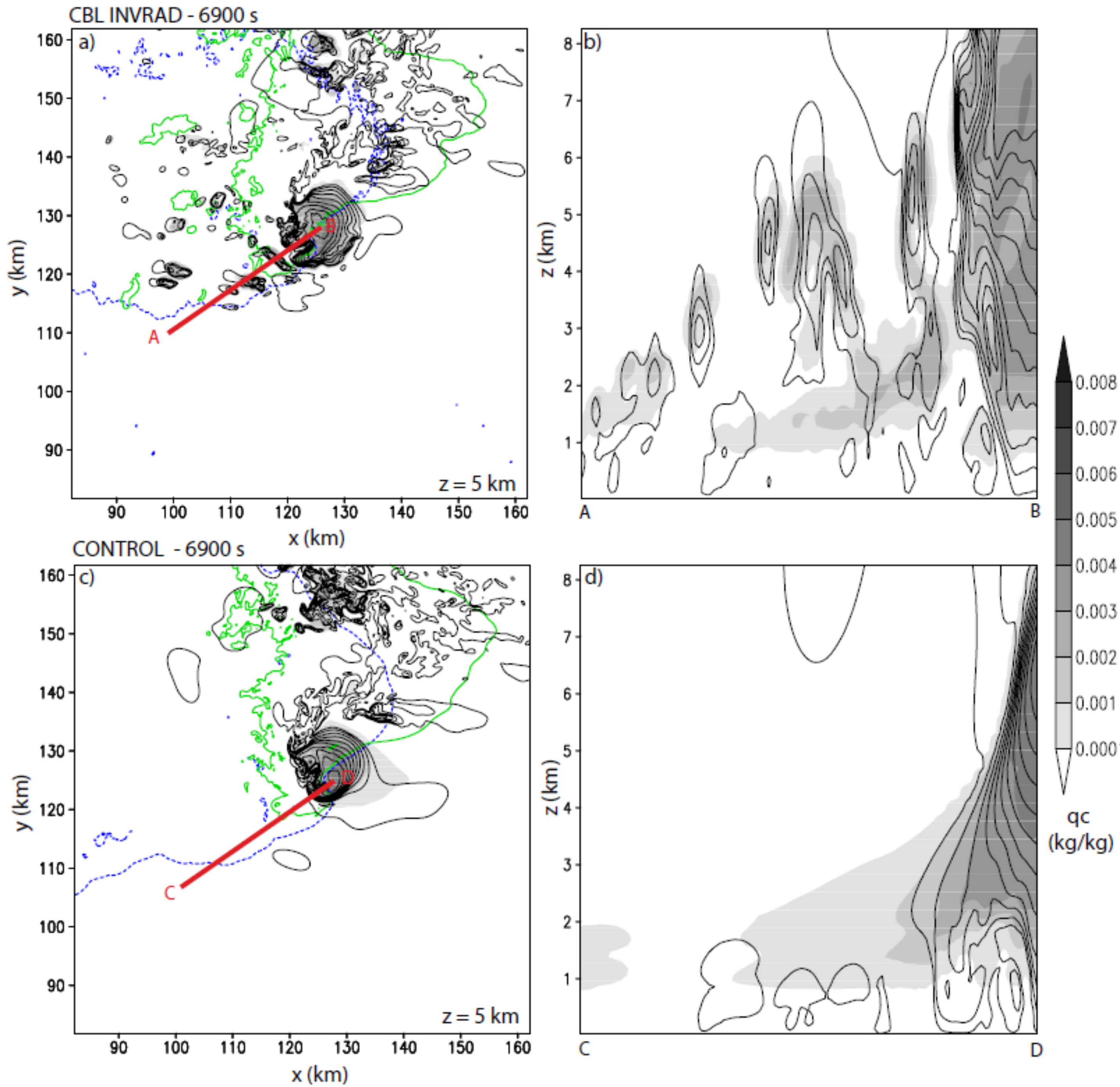
Contours: Vertical Vorticity, Tilting/Stretching
Shading: W > 0
Vectors: Horizontal Vorticity

Greater vertical vorticity tilting and stretching at HCR intersection points promotes more rapid vortex-sheet breakdown, creating favored locations for misocyclone development.

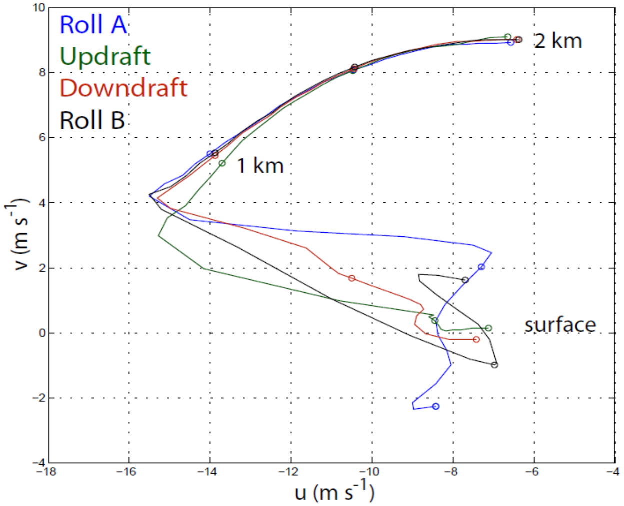
Flanking-Line Convection

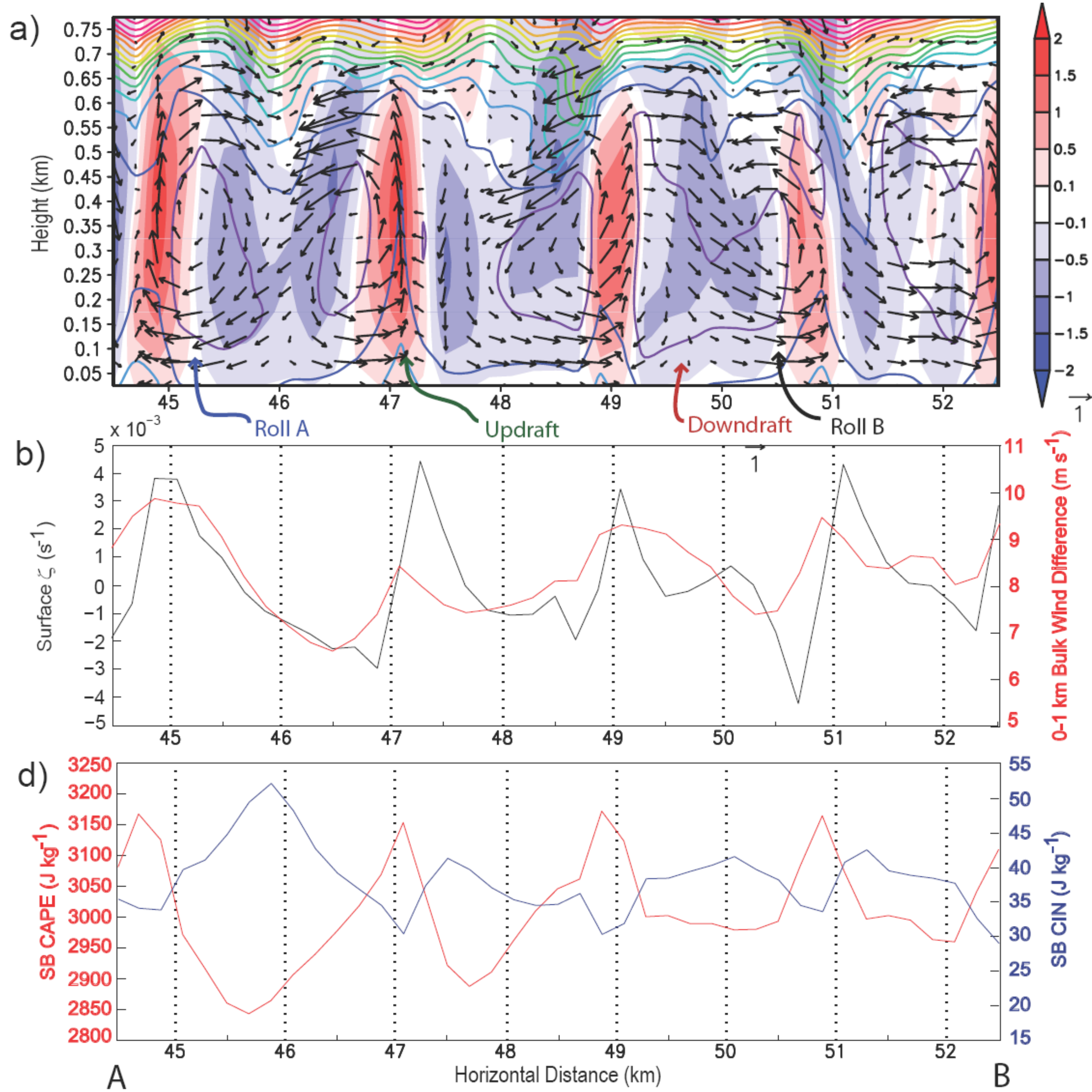
-In these simulations, flanking line cumulus clouds only develop when HCRs are present.

- When they become positioned above misovortices along the outflow boundary, the deeper updrafts enhance vorticity stretching, intensifying the vortex.



Environmental Variability





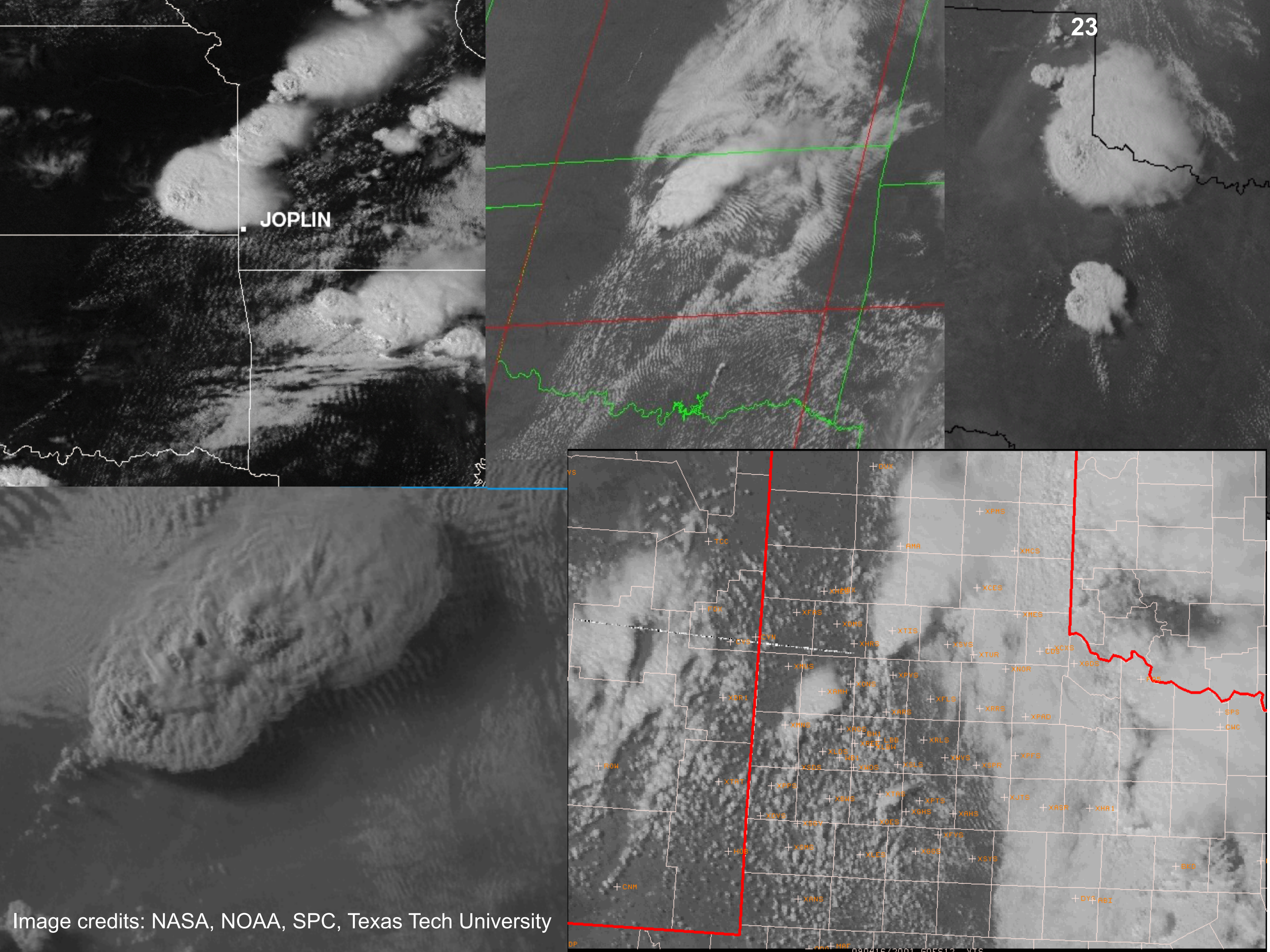
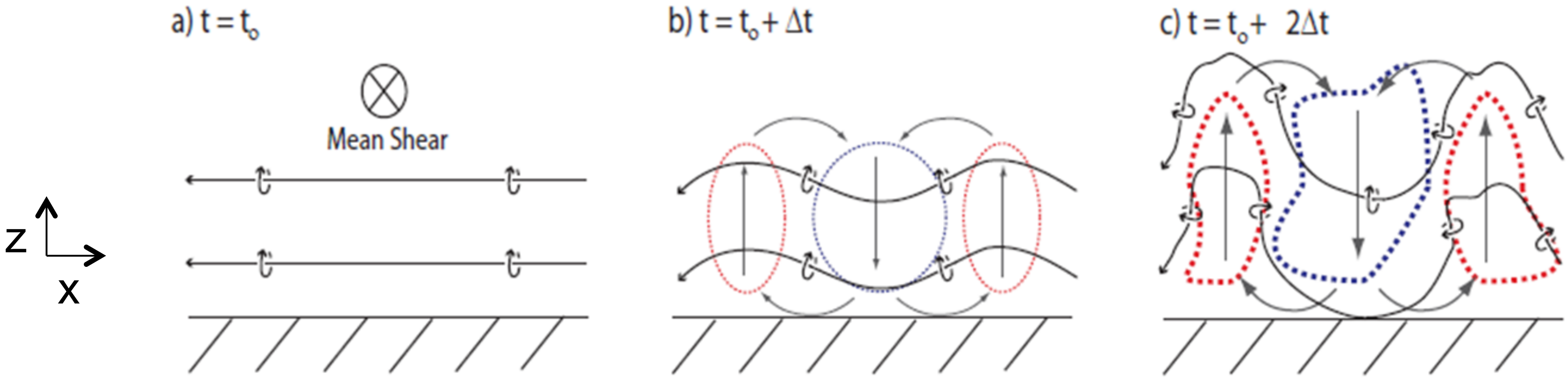


Image credits: NASA, NOAA, SPC, Texas Tech University

A source of environmental vertical vorticity



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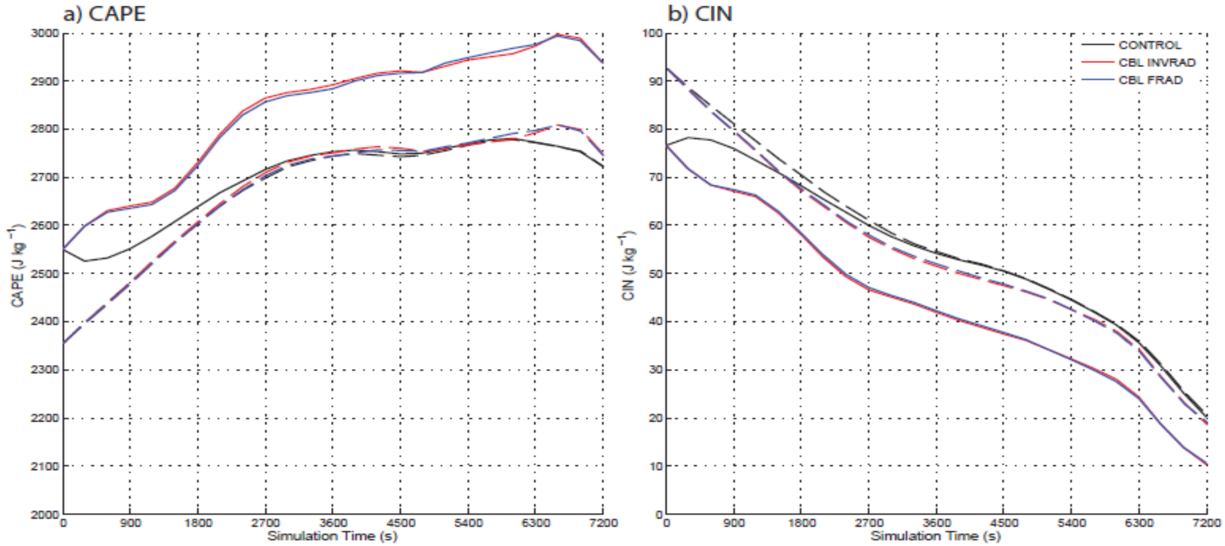
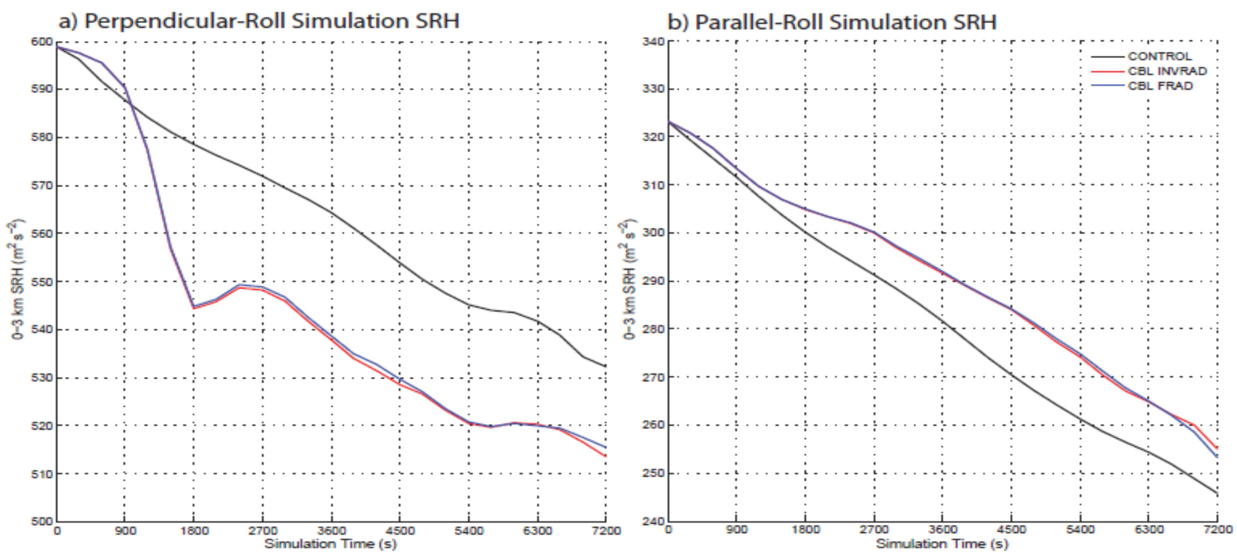
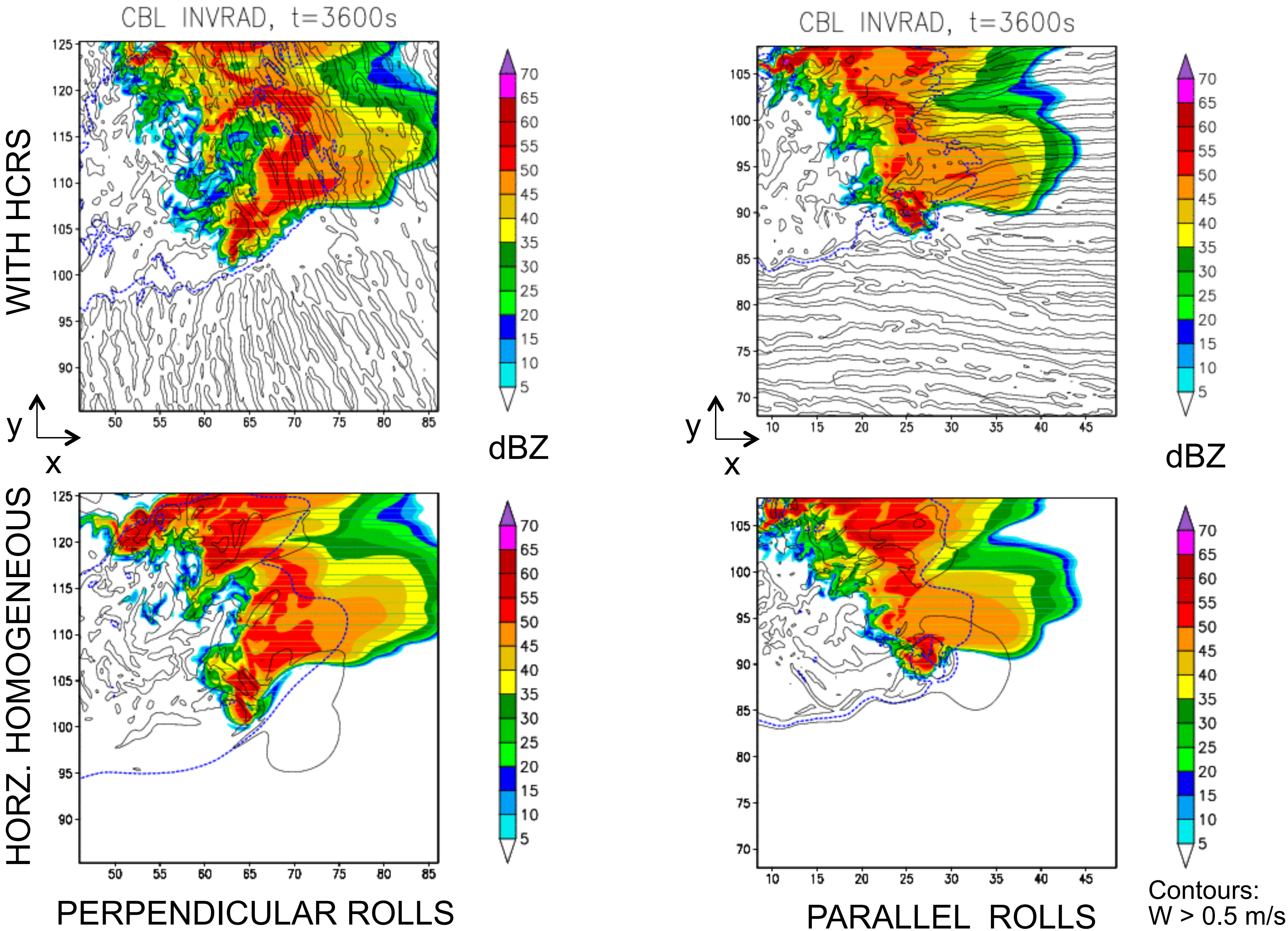
- Put another way, the ambient horizontal vorticity is tilted by HCR vertical velocity perturbations

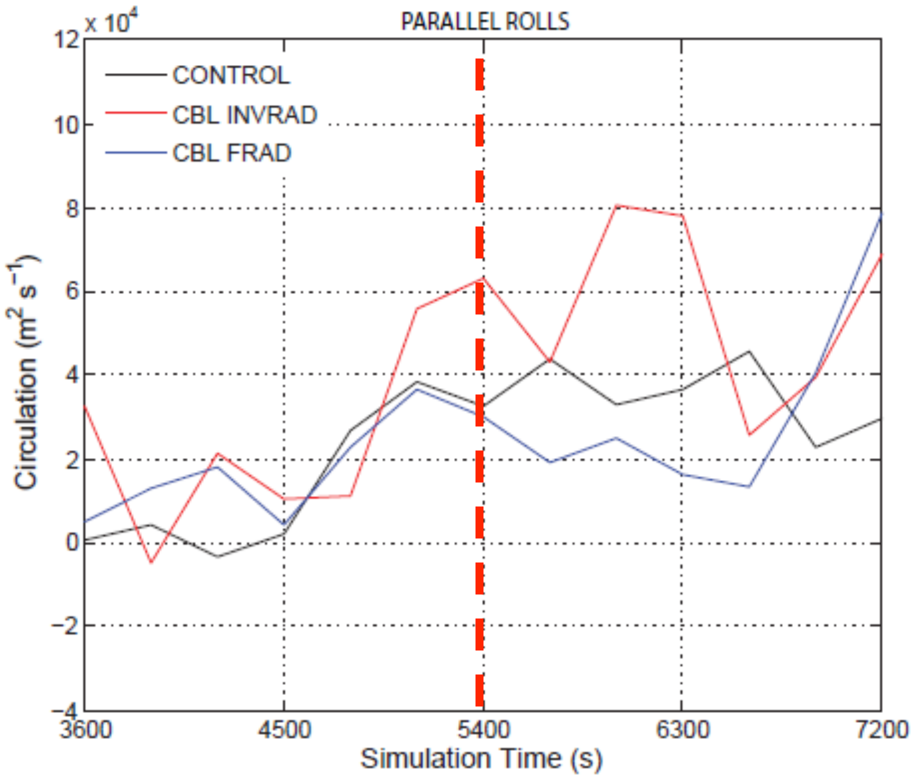

a) CAPE
CAPE (J kg^{-1})
Simulation Time (s)
b) CIN
CIN (J kg^{-1})
Simulation Time (s)
CONTROL
CBL INVRAD
CBL FRAD

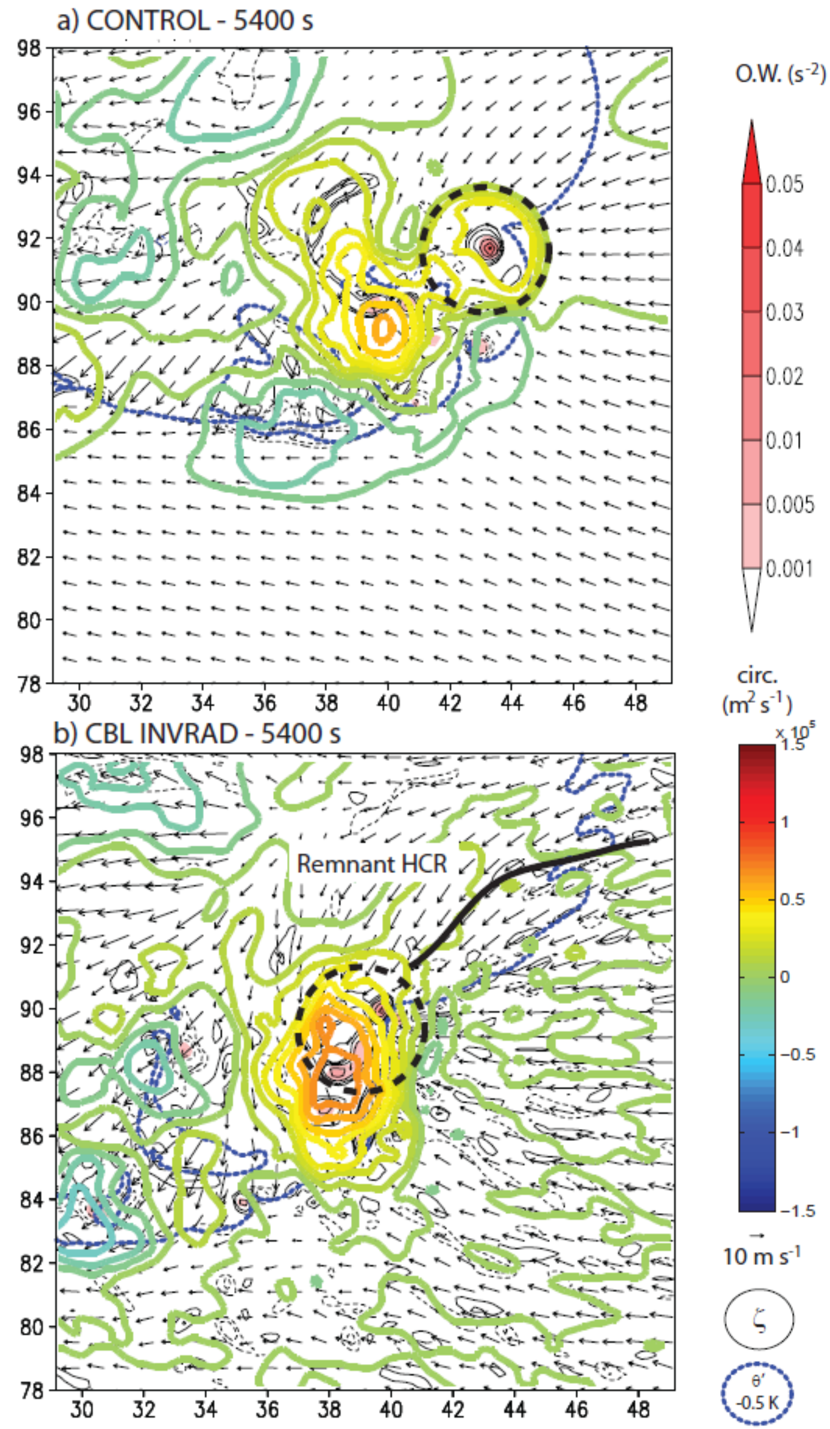

a) Perpendicular-Roll Simulation SRH
0-3 km SRH (m^2 s^{-2})
Simulation Time (s)
b) Parallel-Roll Simulation SRH
0-3 km SRH (m^2 s^{-2})
Simulation Time (s)
CONTROL
CBL INVRAD
CBL FRAD


CBL INVRAD, t=3600s
CBL INVRAD, t=3600s
WITH HCRS
HORZ. HOMOGENEOUS
y
x
dBZ
dBZ
70
65
60
55
50
45
40
35
30
25
20
15
10
5
PERPENDICULAR ROLLS
PARALLEL ROLLS
Contours:
W > 0.5 m/s

Parallel Rolls

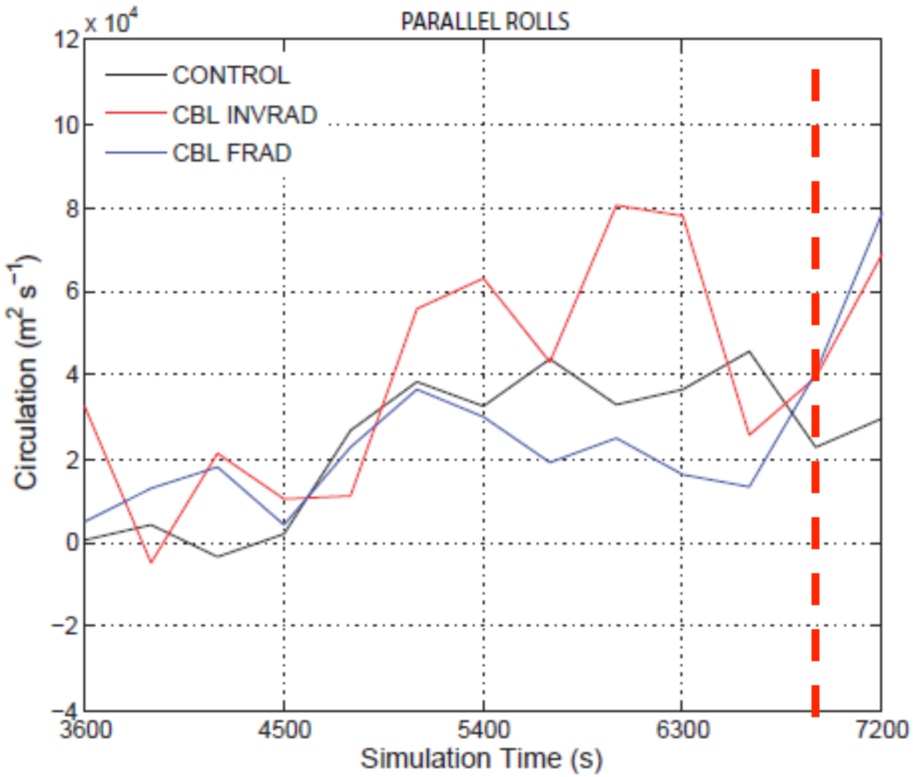
Low-Level Mesocyclone Circulation

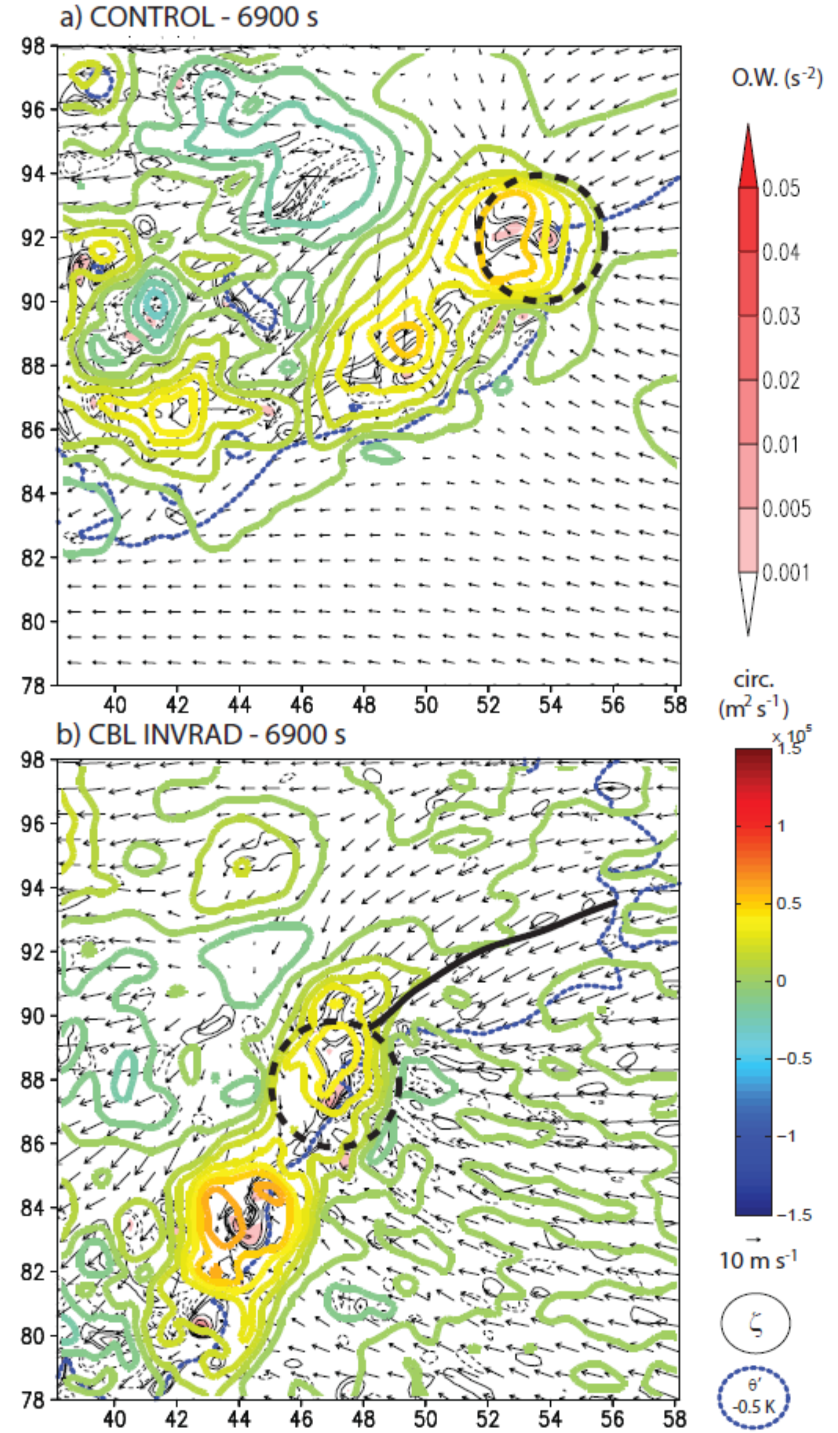


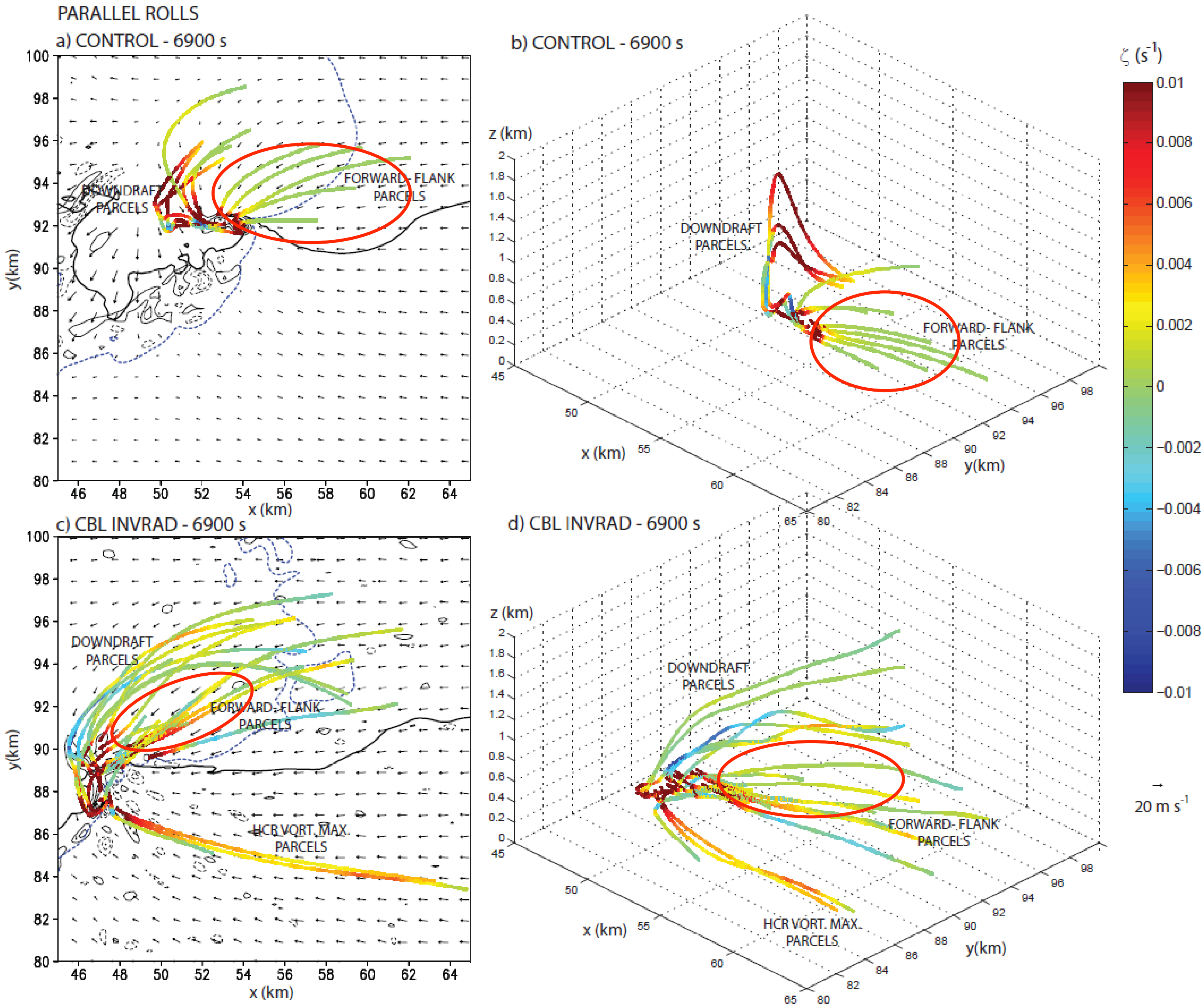


Parallel Rolls

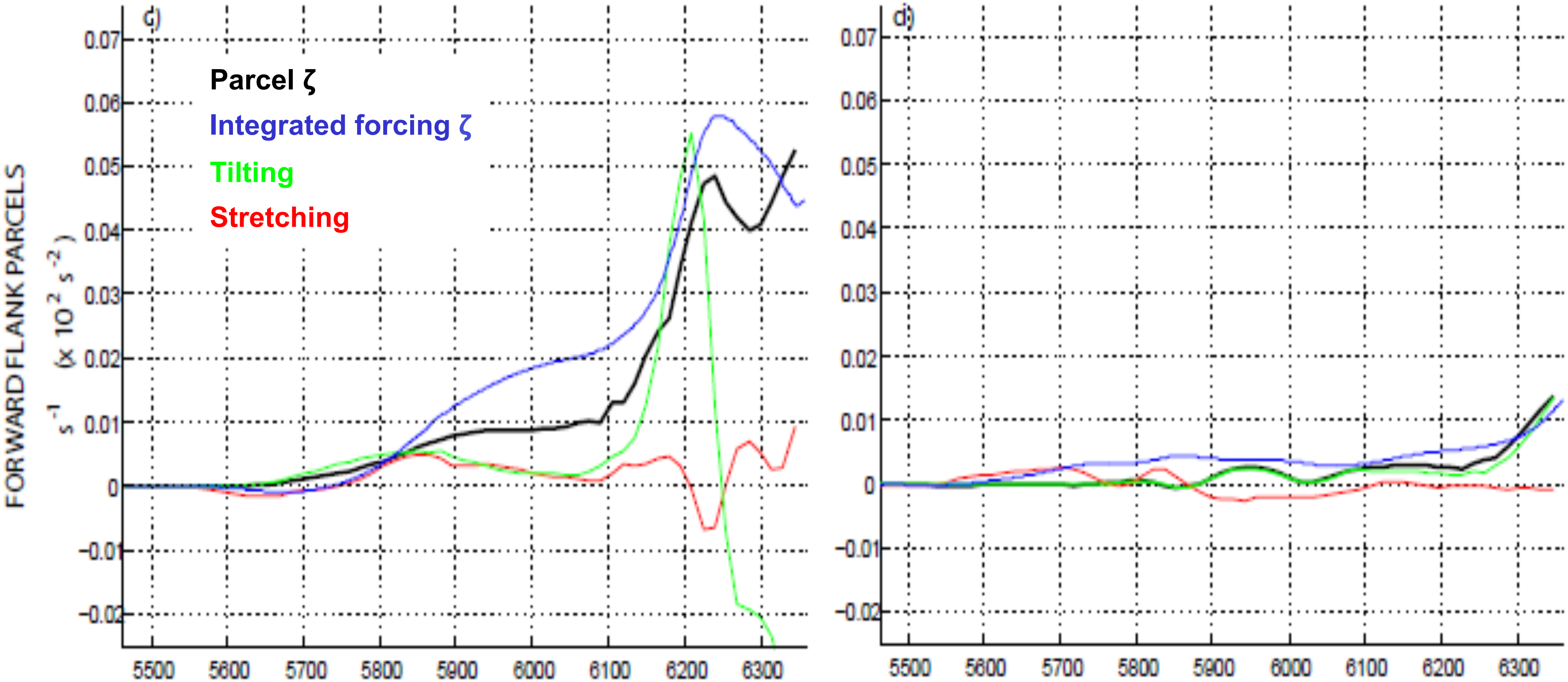
Low-Level Mesocyclone Circulation







PARALLEL ROLLS
a) CONTROL - 6900 s
b) CONTROL - 6900 s
c) CBL INVRAD - 6900 s
d) CBL INVRAD - 6900 s
DOWNDRAFT PARCELS
FORWARD- FLANK PARCELS
HCR VORT. MAX. PARCELS
x (km)
y(km)
z (km)
ζ (s^{-1})
20 m s^{-1}



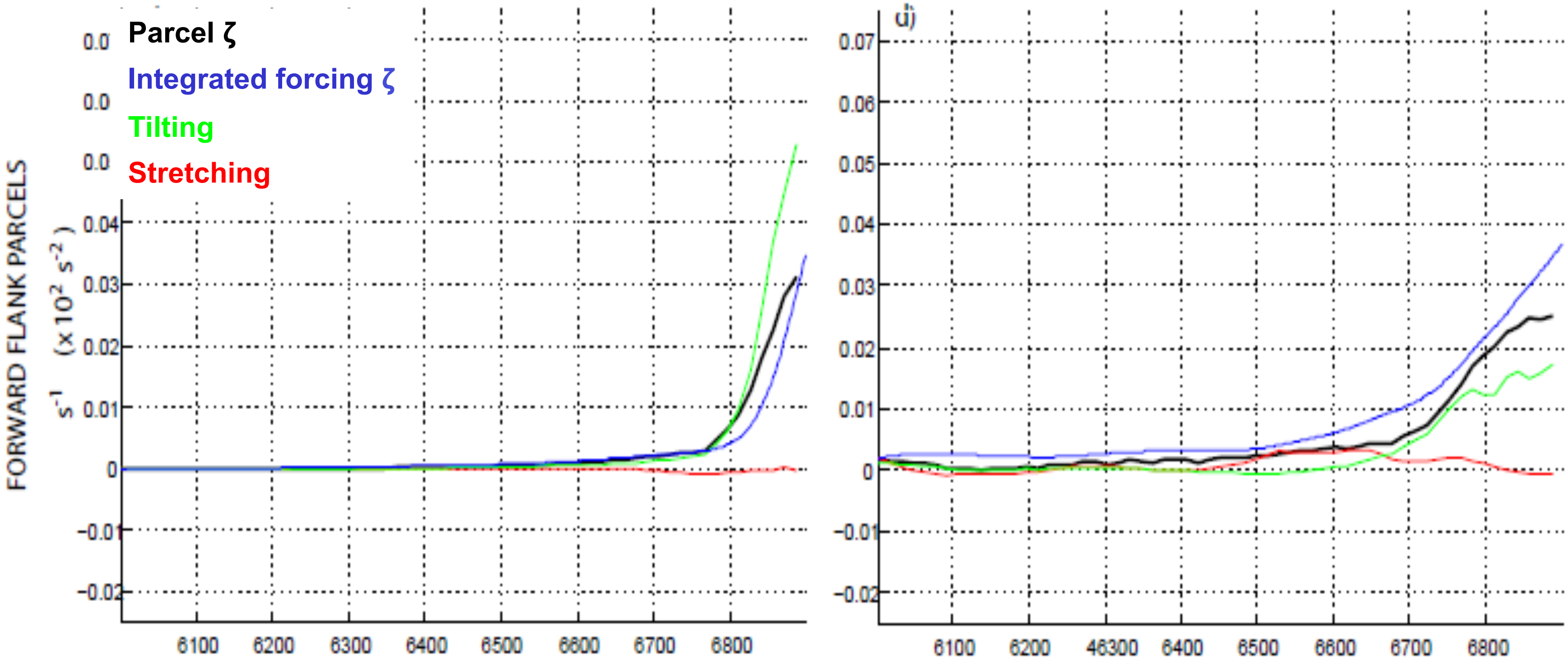
-Three main trajectory “streams”

-HCR influence is most obvious in forward-flank parcels

-Parcels and HCRs have different storm-relative translation velocities, such that parcels may cross HCRs.

-Trajectories encounter considerable horizontal heterogeneity in forward flank baroclinic zone and parcels experience variable vertical vorticity forcing.

-Many parcels terminate with negative vertical vorticity near the low-level mesocyclone from this stream, reducing circulation.



-Parcels acquire vertical vorticity earlier along the forward flank when HCRs are present.

-Because the storm moves along HCRs, it encounters similar HCR-relative conditions for longer periods of time.

-This provides an additional, consistent source of convergence and vertical vorticity to the low-level mesocyclone, causing intensification.

-Fewer parcels with negative vertical vorticity approach the low-level mesocyclone.

-Like the CONTROL, the strongest intensification of vertical vorticity is due to stretching beneath the mid-level updraft.