Tornadogenesis in a High-Resolution Simulation of the 8 May 2003 Oklahoma City Tornadic Supercell

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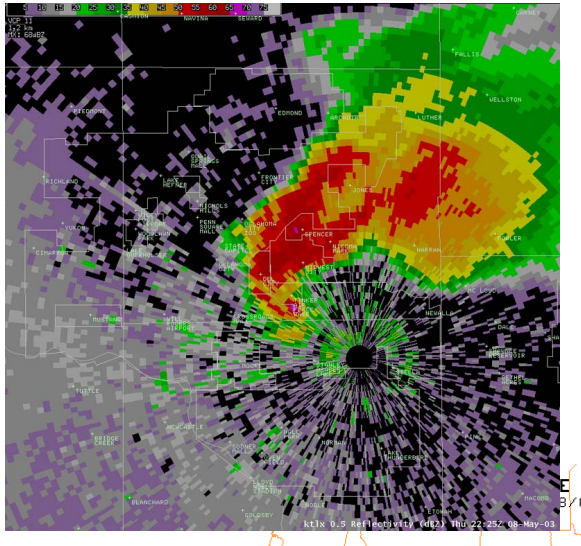
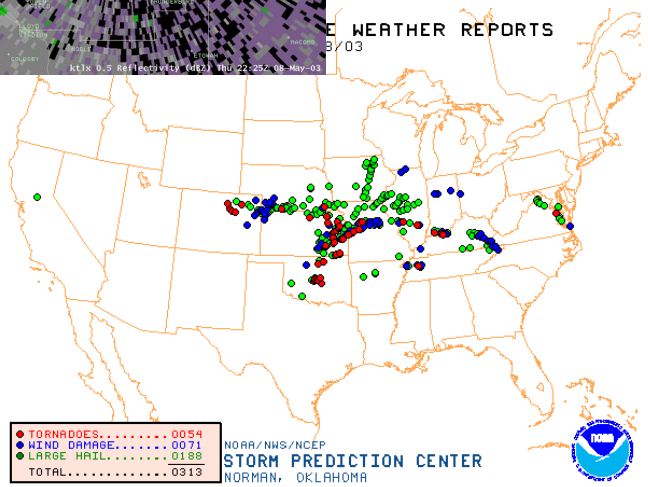
Objective

- Study a high-resolution simulation of a supercell thunderstorm initialized with real data (3DVAR DA) to determine the dynamics behind simulated tornadogenesis.
- **Key Assumption**: If the initial model state is similar to the observations and the free-forecast evolves in a similar manner to the observed event then the dynamics responsible for features of interest (e.g., tornadoes) in the model may be the same as those in the real atmosphere.

Event Overview

- Tornado outbreak in Central US on the afternoon of 8 May 2003.
- Part of a multi-day outbreak of severe weather and tornadoes over the central and eastern US (Hamill et al. 2005)
- A supercell in central Oklahoma produced a long-track F4 tornado in Moore.



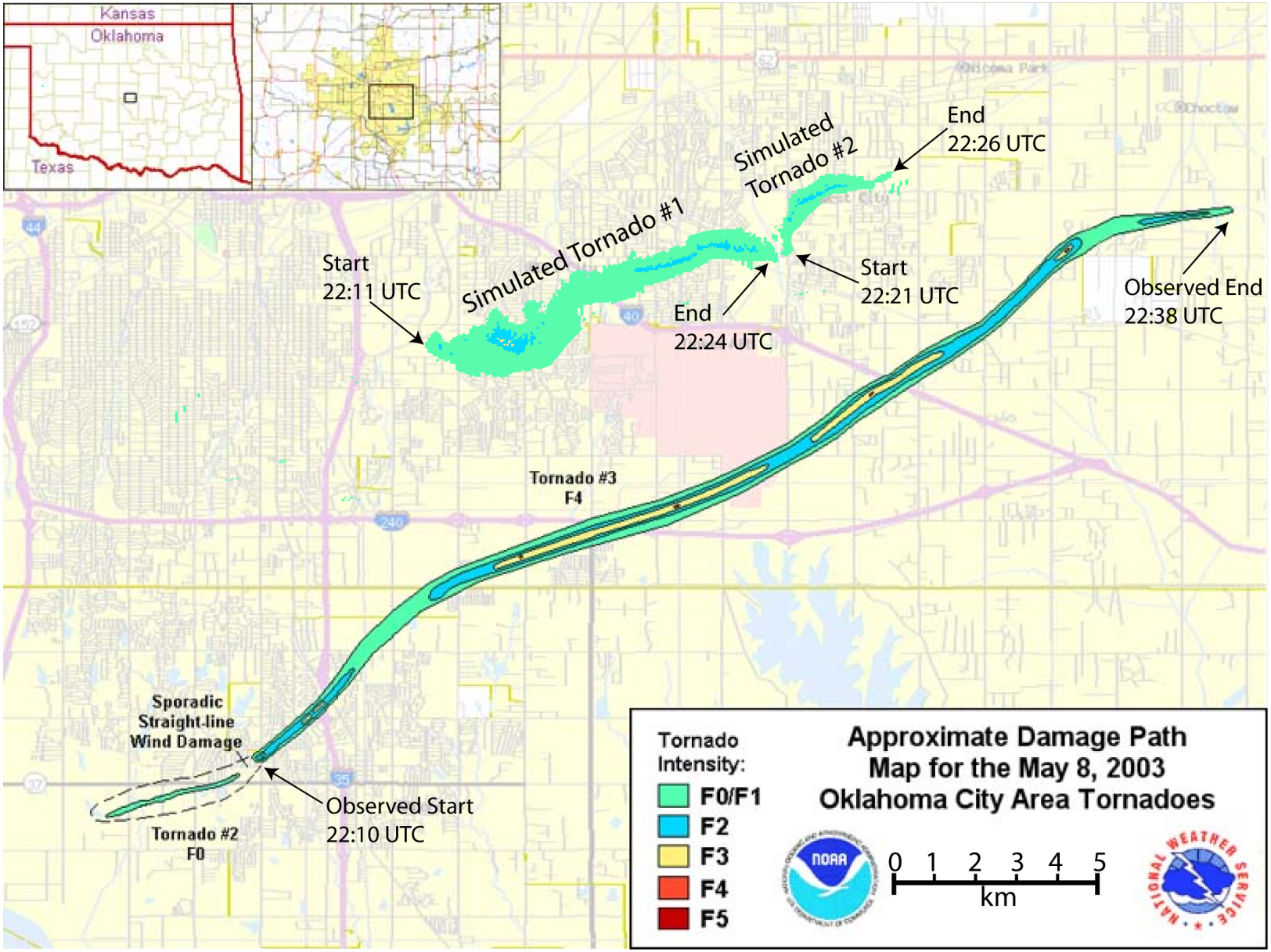


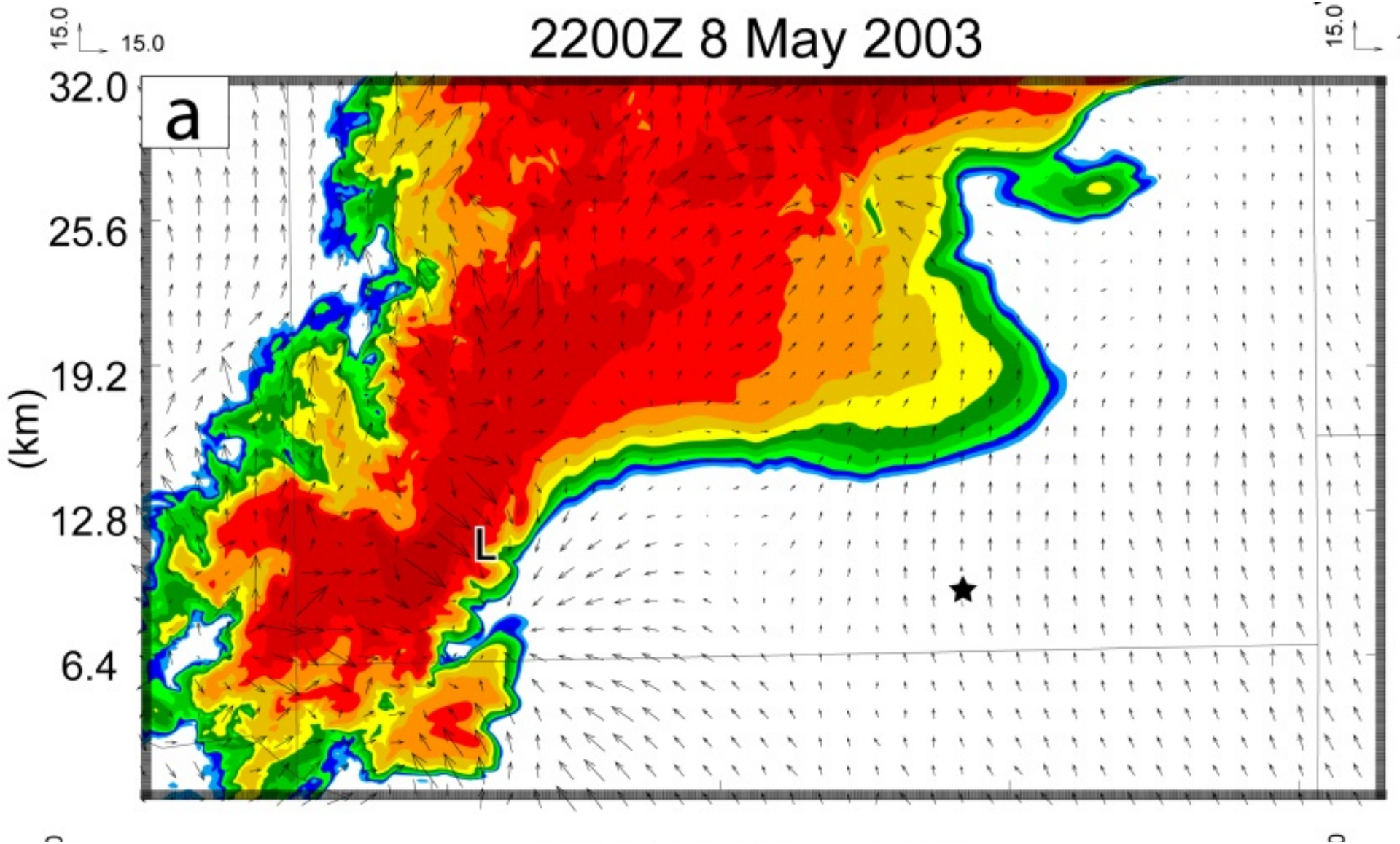
Experiment Design

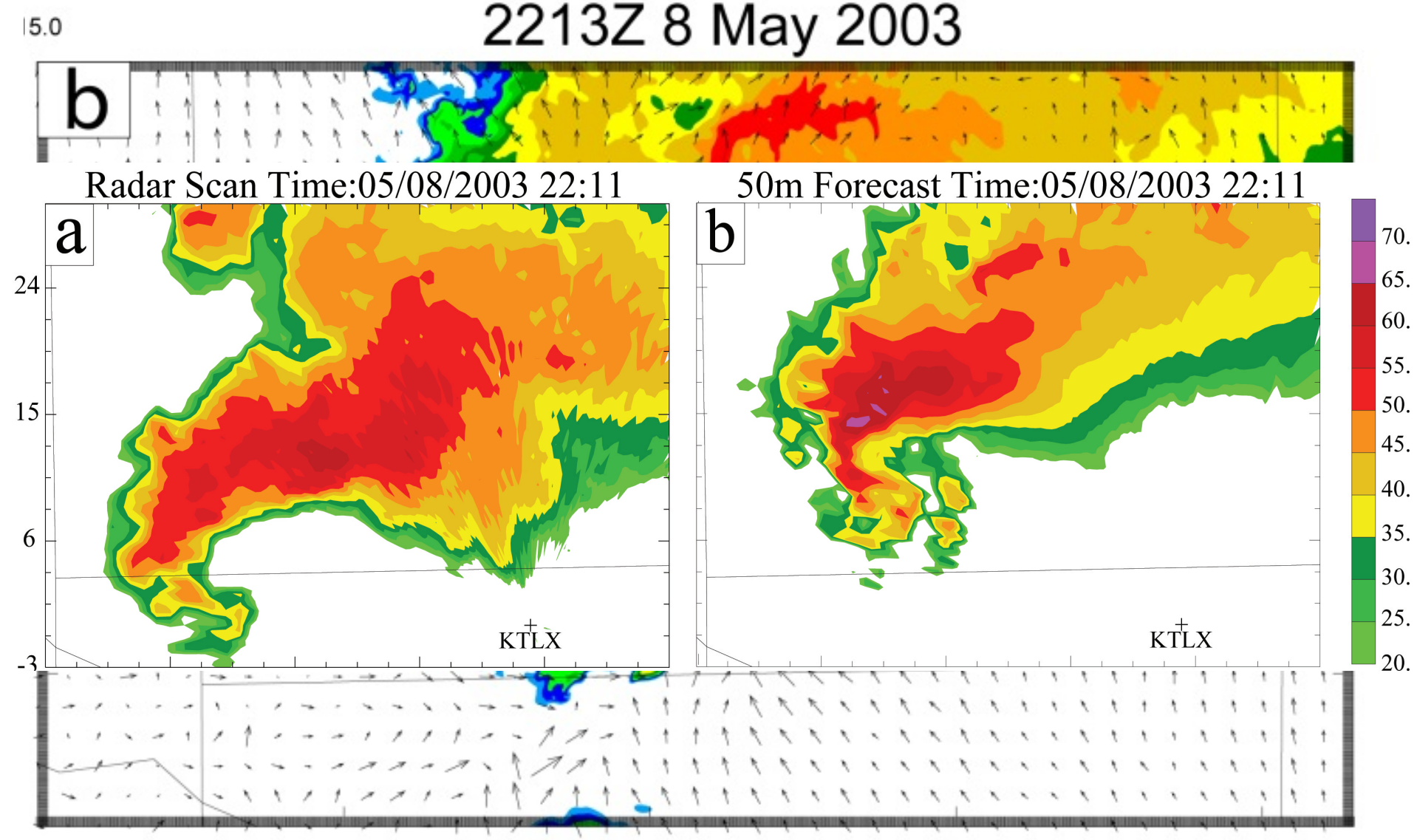
- Advanced Regional Prediction System (ARPS) model is used.
- ARPS 3DVAR + cloud analysis for DA.
- A 50-m grid-spacing simulation is nested within three outer grids:
  - Outermost has 9-km grid spacing, conventional obs. assimilated hourly.
  - Inside the 9-km grid is a 1-km grid spacing domain. Radar data (and conventional obs.) are assimilated every 5 min from 2030-2140 UTC.
  - A 100-m grid spacing domain is initialized by interpolating from the 1-km grid at 2140 UTC.
  - Boundary and initial conditions for the 50-m grid obtained from the 100-m domain forecast at 2200 UTC. Forecast on 50-m grid spacing domain is run from 2200-2240 UTC.

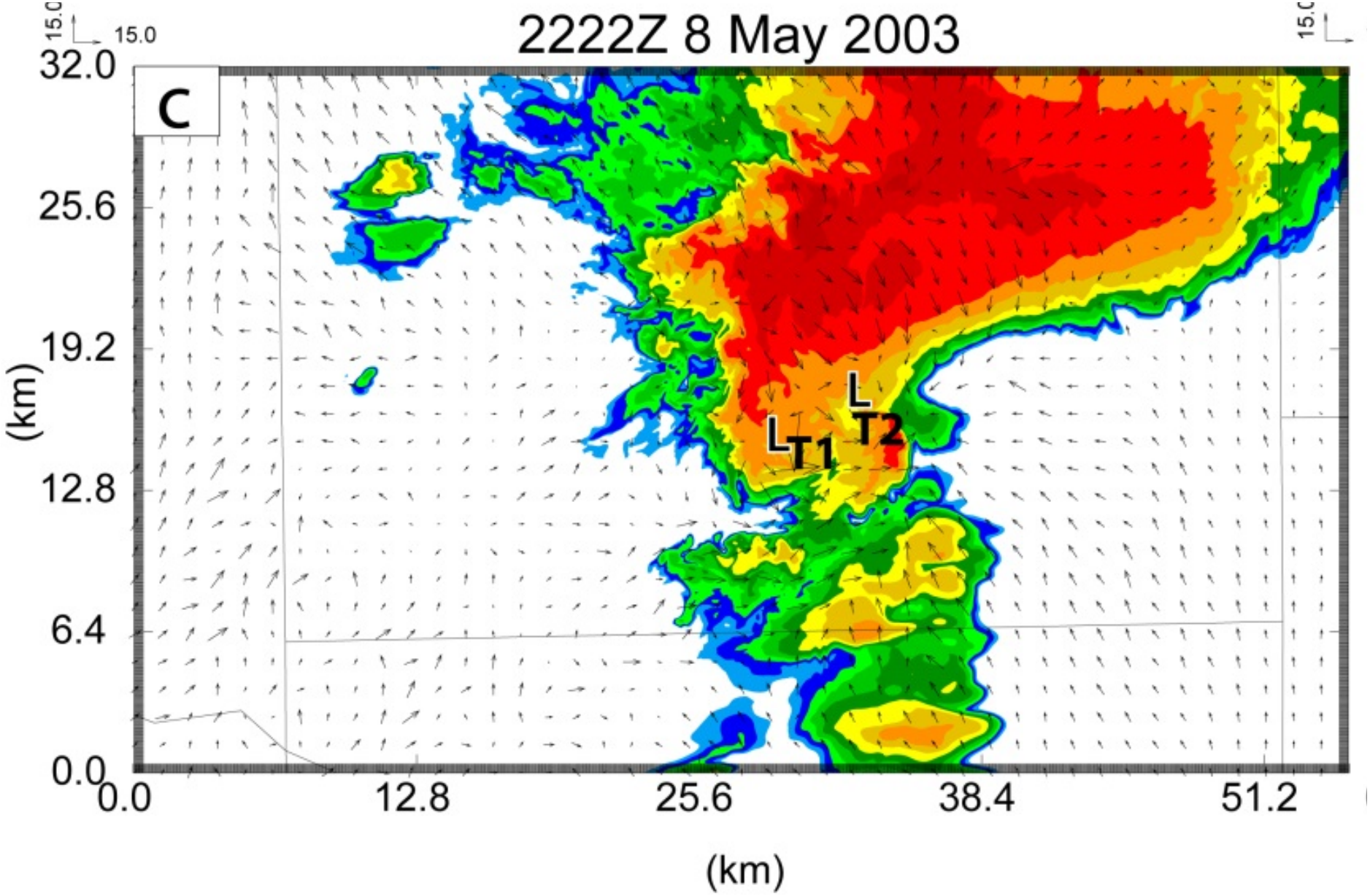
Experiment Design

- All grids are stretched in the vertical with 50 levels and a minimum spacing of 20 m.
- Fourth-order advection.
- Surface fluxes determined according to stability dependent drag coefficients.
- LFO single-moment microphysics


Kansas
Oklahoma
Texas
Simulated Tornado #1
Simulated Tornado #2
Start
22:11 UTC
End
22:24 UTC
Start
22:21 UTC
End
22:26 UTC
Observed End
22:38 UTC
Tornado #3
F4
Sporadic
Straight-line
Wind Damage
Tornado #2
F0
Observed Start
22:10 UTC
Tornado
Intensity:
F0/F1
F2
F3
F4
F5
Approximate Damage Path
Map for the May 8, 2003
Oklahoma City Area Tornadoes
NOAA
0 1 2 3 4 5
km
NATIONAL WEATHER SERVICE

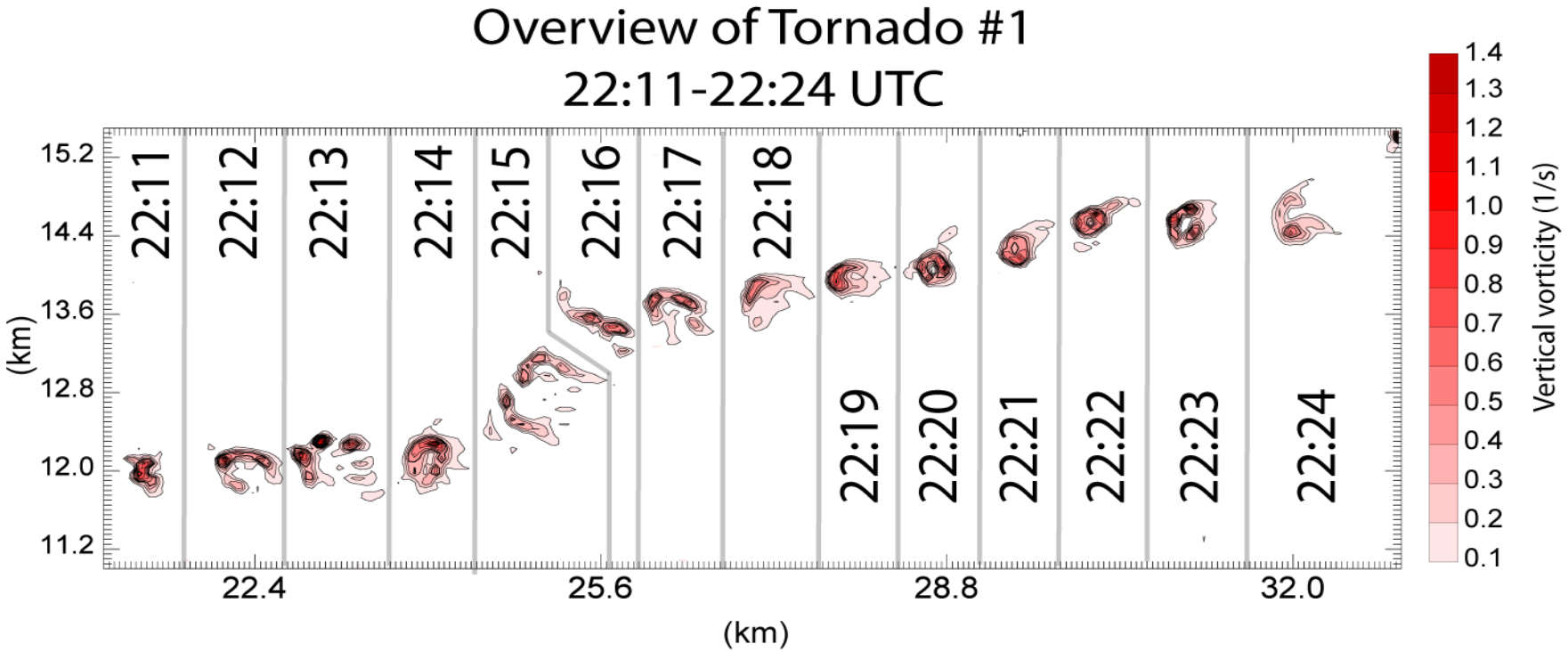

2200Z 8 May 2003
a
15.0
15.0
15.0
32.0
25.6
19.2
12.8
6.4
(km)
L


5.0
2213Z 8 May 2003
b
Radar Scan Time:05/08/2003 22:11
50m Forecast Time:05/08/2003 22:11
a
b
24
15
6
-3
KTLX
KTLX
70.
65.
60.
55.
50.
45.
40.
35.
30.
25.
20.


2222Z 8 May 2003
C
15.0
15.0
32.0
25.6
19.2
12.8
6.4
0.0
(km)
0.0
12.8
25.6
38.4
51.2
(km)
L
T1
L
T2

Tornado #1

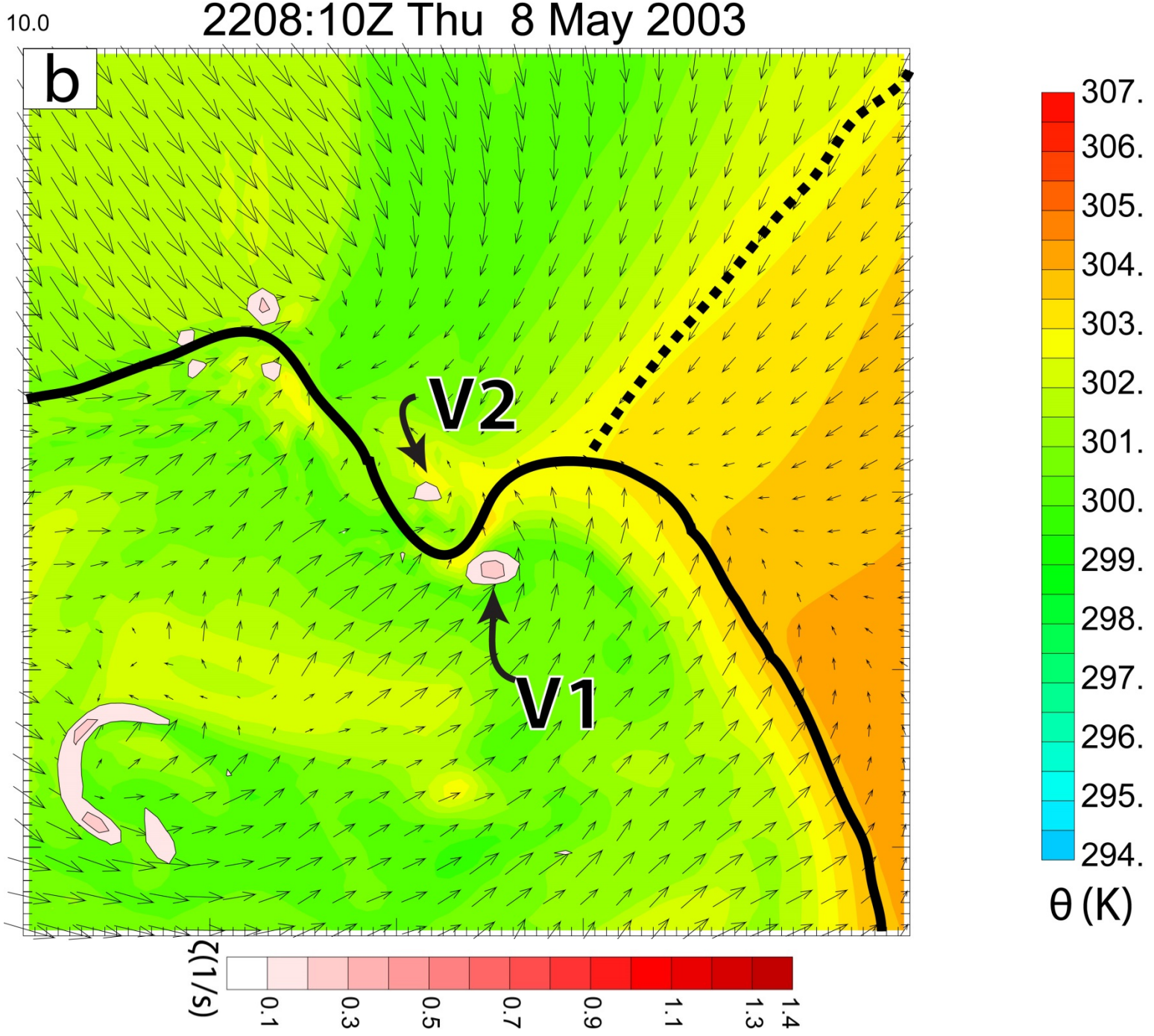
- Persists for 13 min
- Maximum wind speed around 85 m/s (F-3)
- Strongest winds in secondary vortices
- Dissipates well behind the RFGF

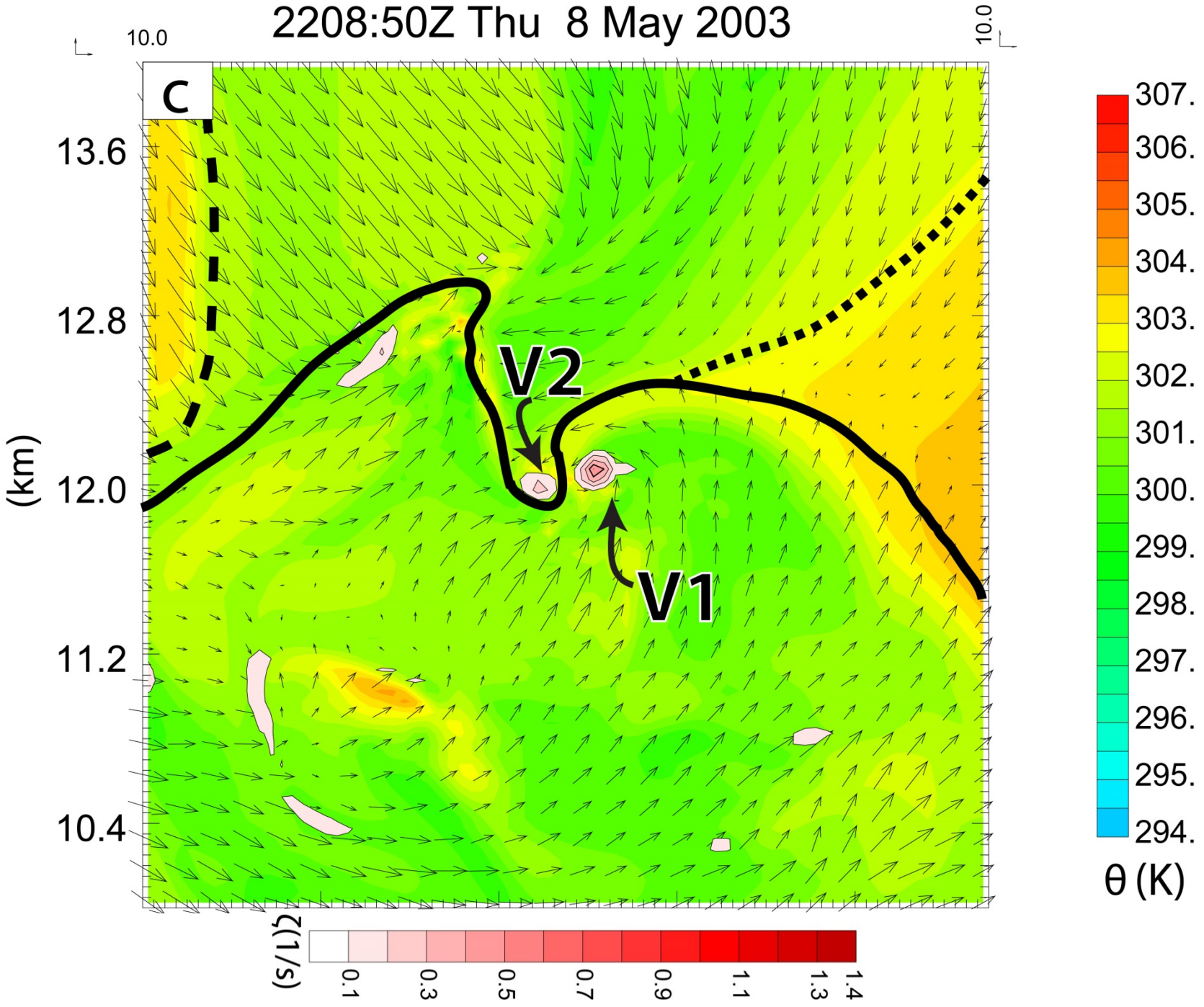


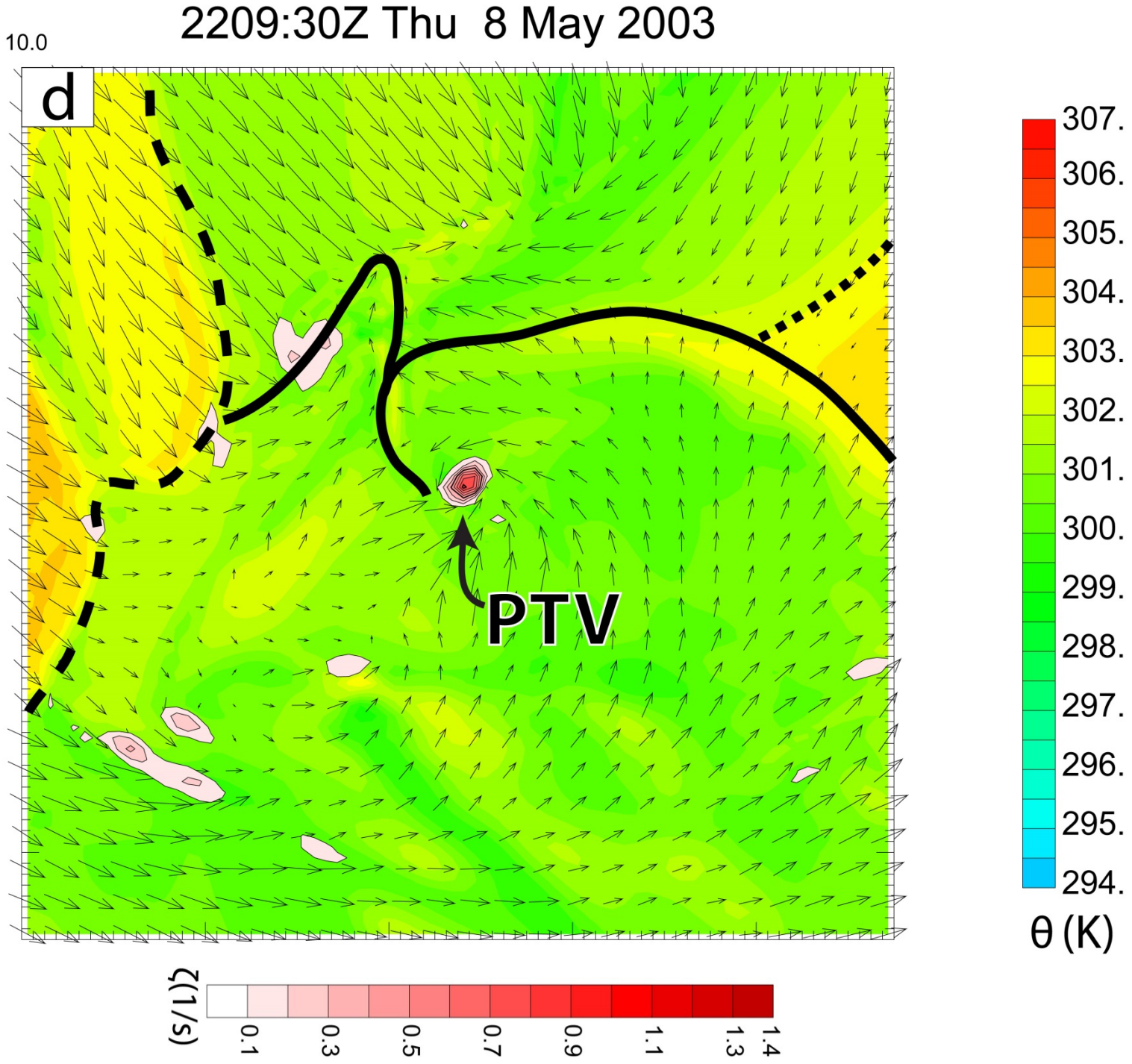
Tornadogenesis for tornado #1

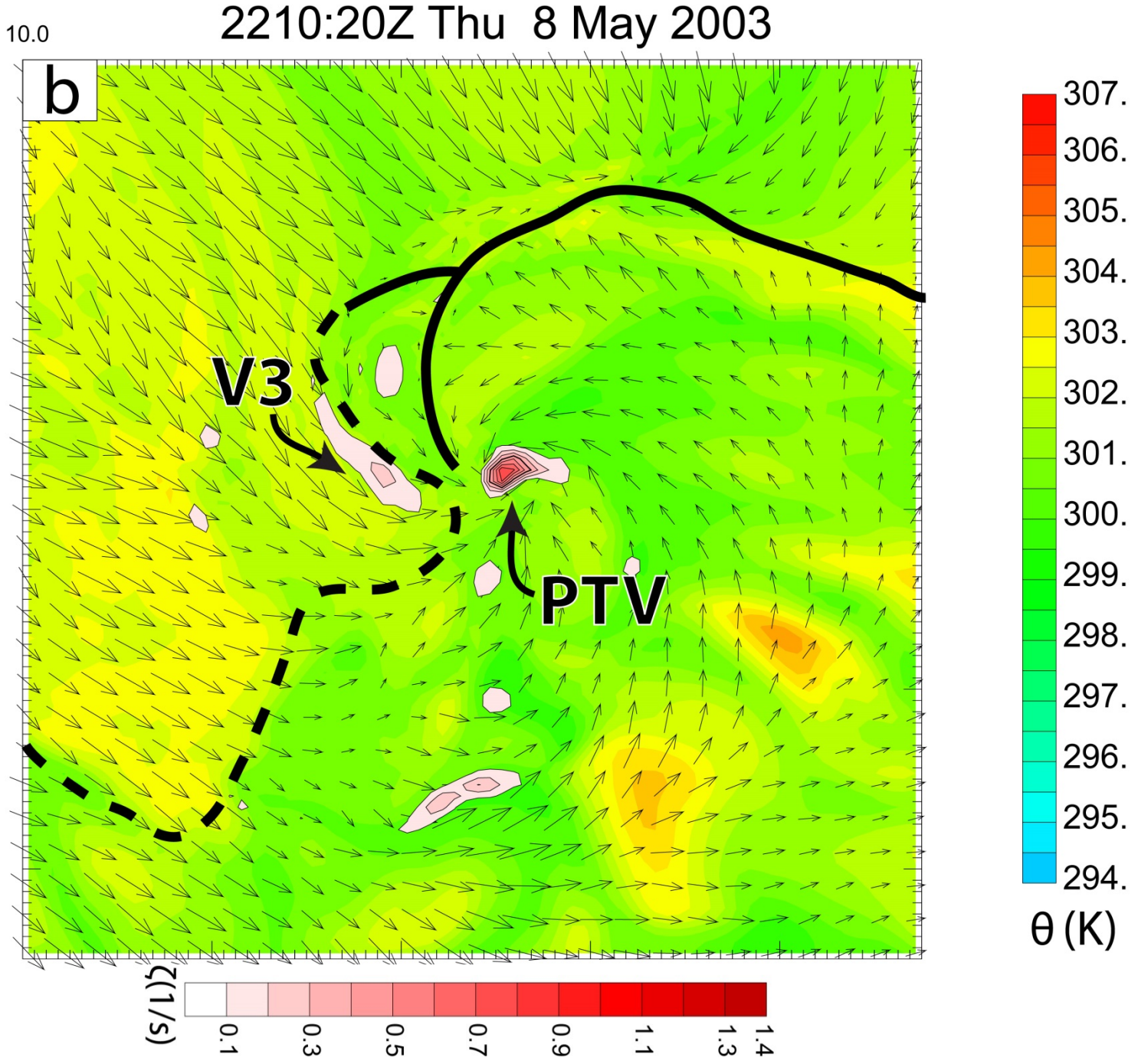
- Look at the development of tornado #1 in detail, focusing on low-level features at the tornado scale.

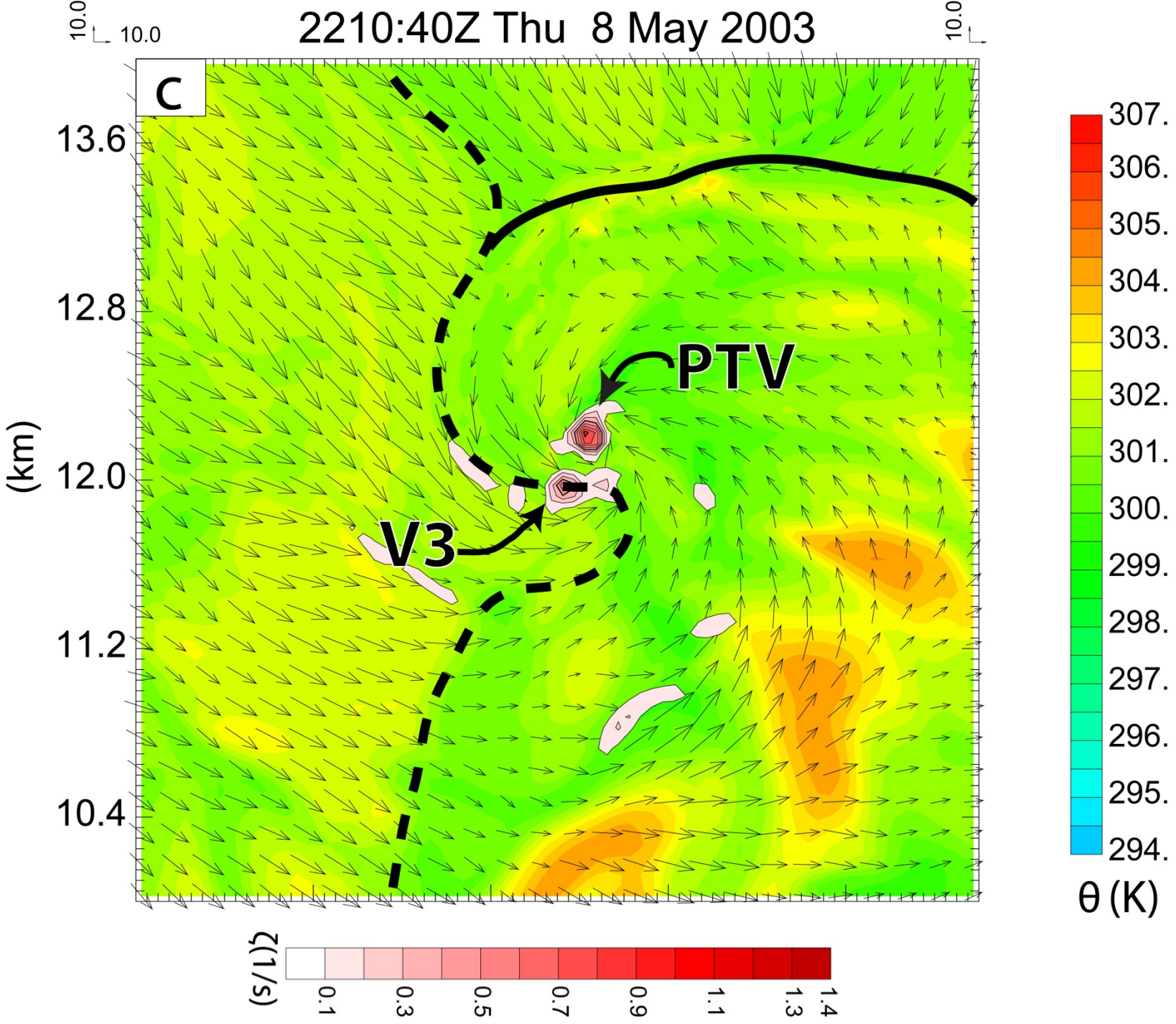
- Use trajectory and vortex line analysis to determine origin of vorticity.

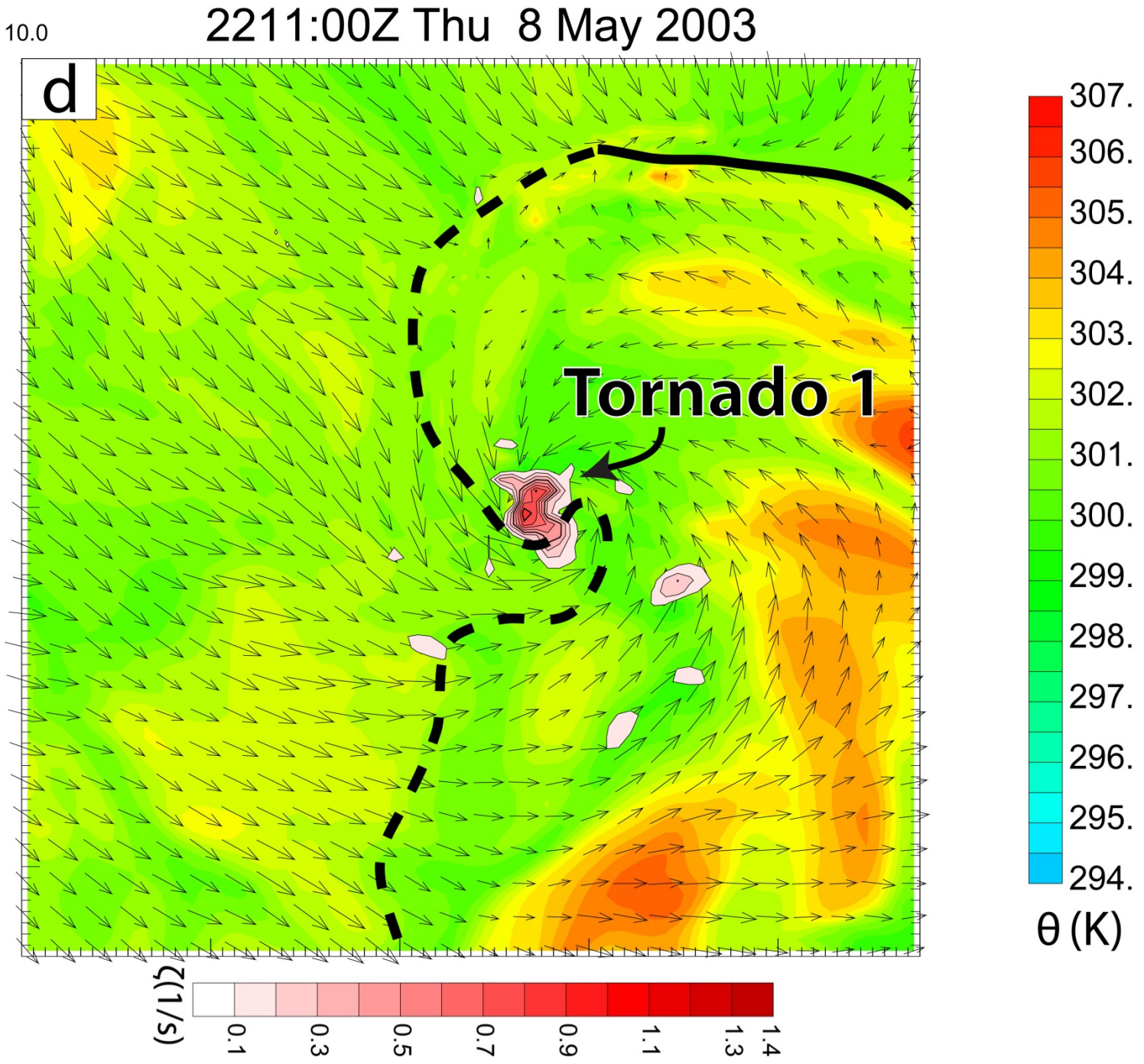

10.0
2208:10Z Thu 8 May 2003
b
V2
V1
307.
306.
305.
304.
303.
302.
301.
300.
299.
298.
297.
296.
295.
294.
θ (K)
ζ(1/s)
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.4


2208:50Z Thu 8 May 2003
10.0
10.0
C
13.6
12.8
12.0
11.2
10.4
(km)
V2
V1
307.
306.
305.
304.
303.
302.
301.
300.
299.
298.
297.
296.
295.
294.
θ (K)
ζ(1/s)
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.4


2209:30Z Thu 8 May 2003
10.0
d
PTV
307.
306.
305.
304.
303.
302.
301.
300.
299.
298.
297.
296.
295.
294.
θ (K)
ζ(1/s)
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.4


10.0
2210:20Z Thu 8 May 2003
b
V3
PTV
307.
306.
305.
304.
303.
302.
301.
300.
299.
298.
297.
296.
295.
294.
θ (K)
ζ(1/s)
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.4


2210:40Z Thu 8 May 2003
C
PTV
V3
13.6
12.8
12.0
11.2
10.4
(km)
10.0
10.0
307.
306.
305.
304.
303.
302.
301.
300.
299.
298.
297.
296.
295.
294.
θ (K)
ζ(1/s)
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.4

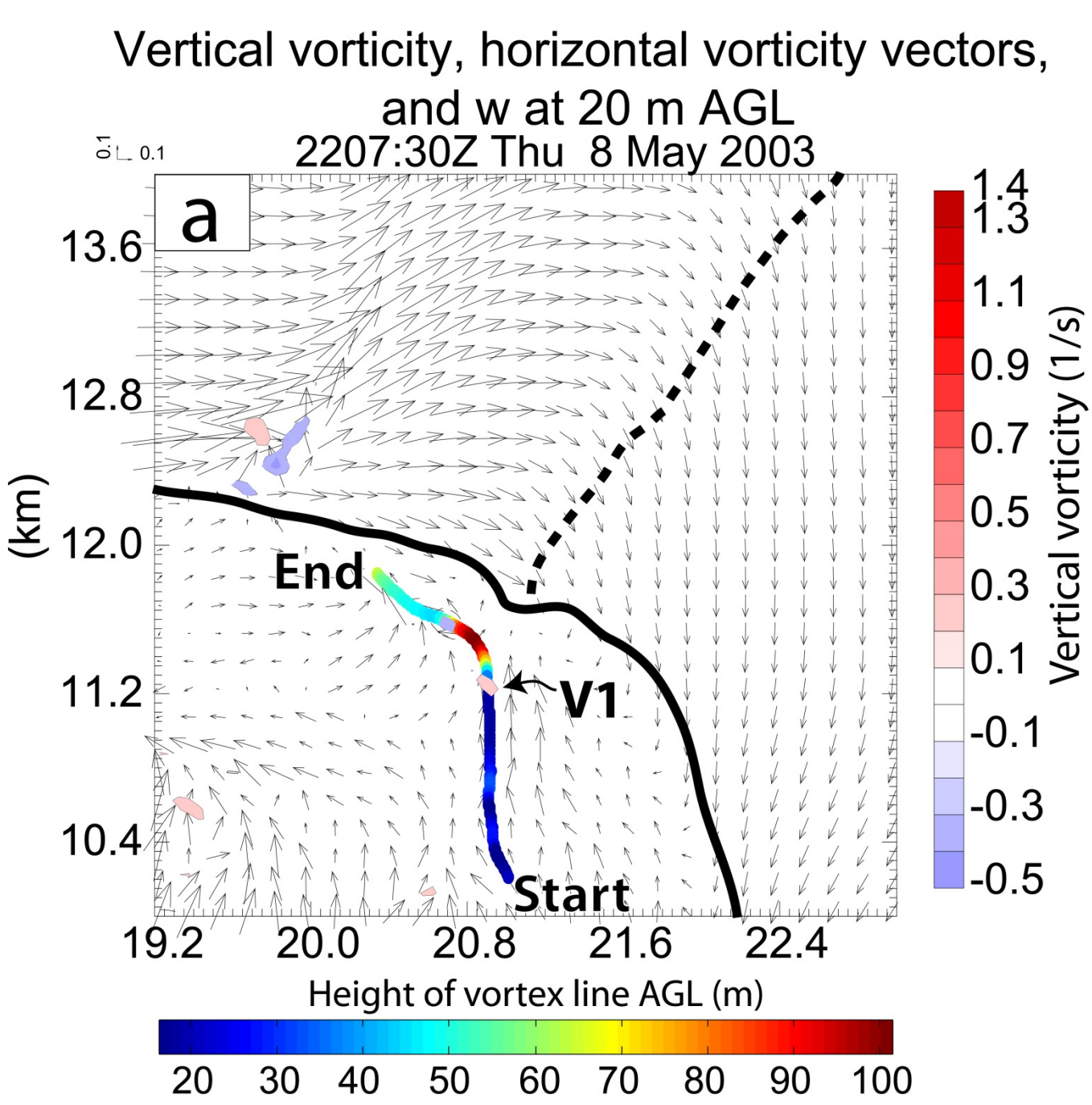

10.0
2211:00Z Thu 8 May 2003
d
Tornado 1
307.
306.
305.
304.
303.
302.
301.
300.
299.
298.
297.
296.
295.
294.
θ (K)
ζ(1/s)
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.4

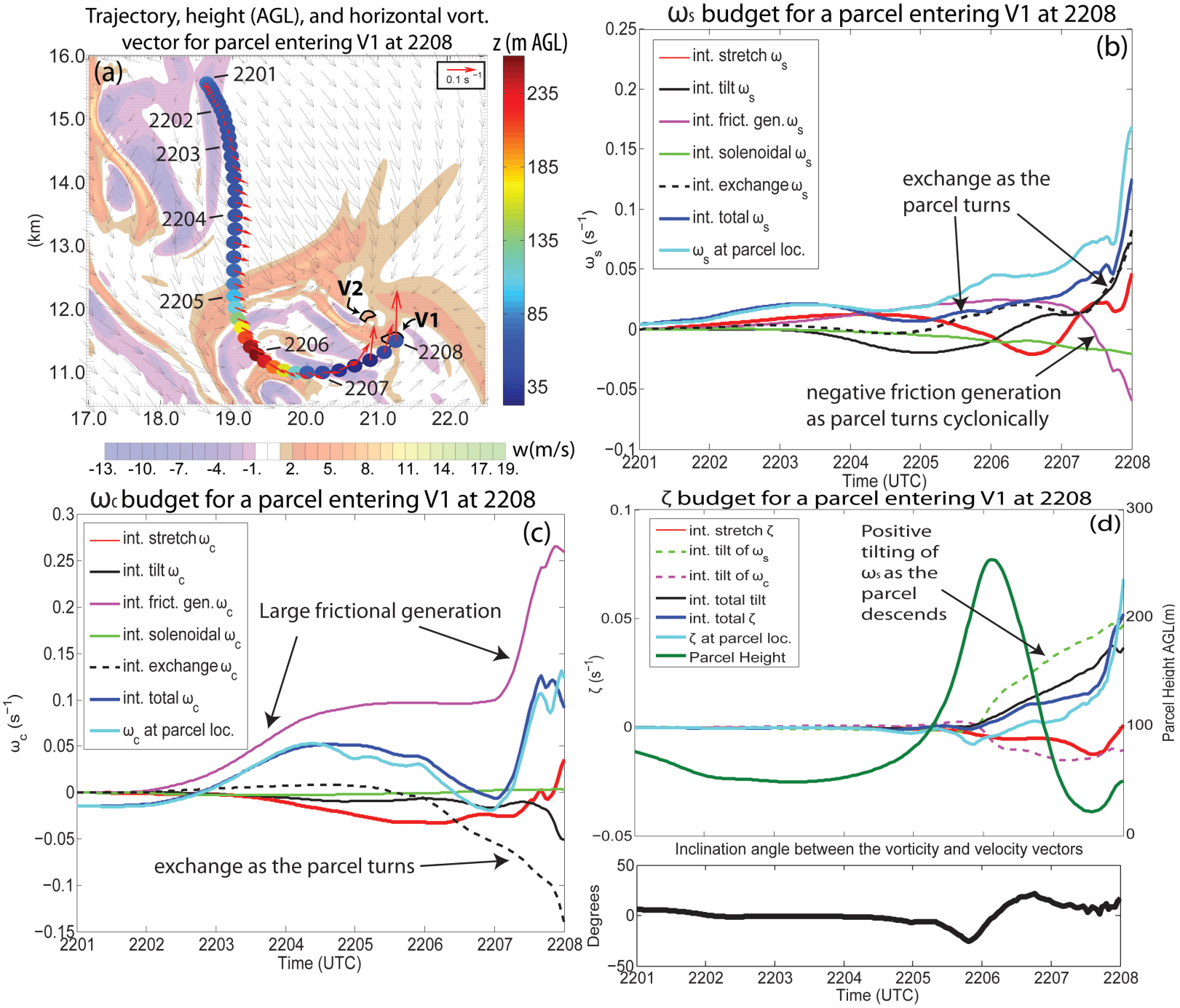
Tornadogenesis

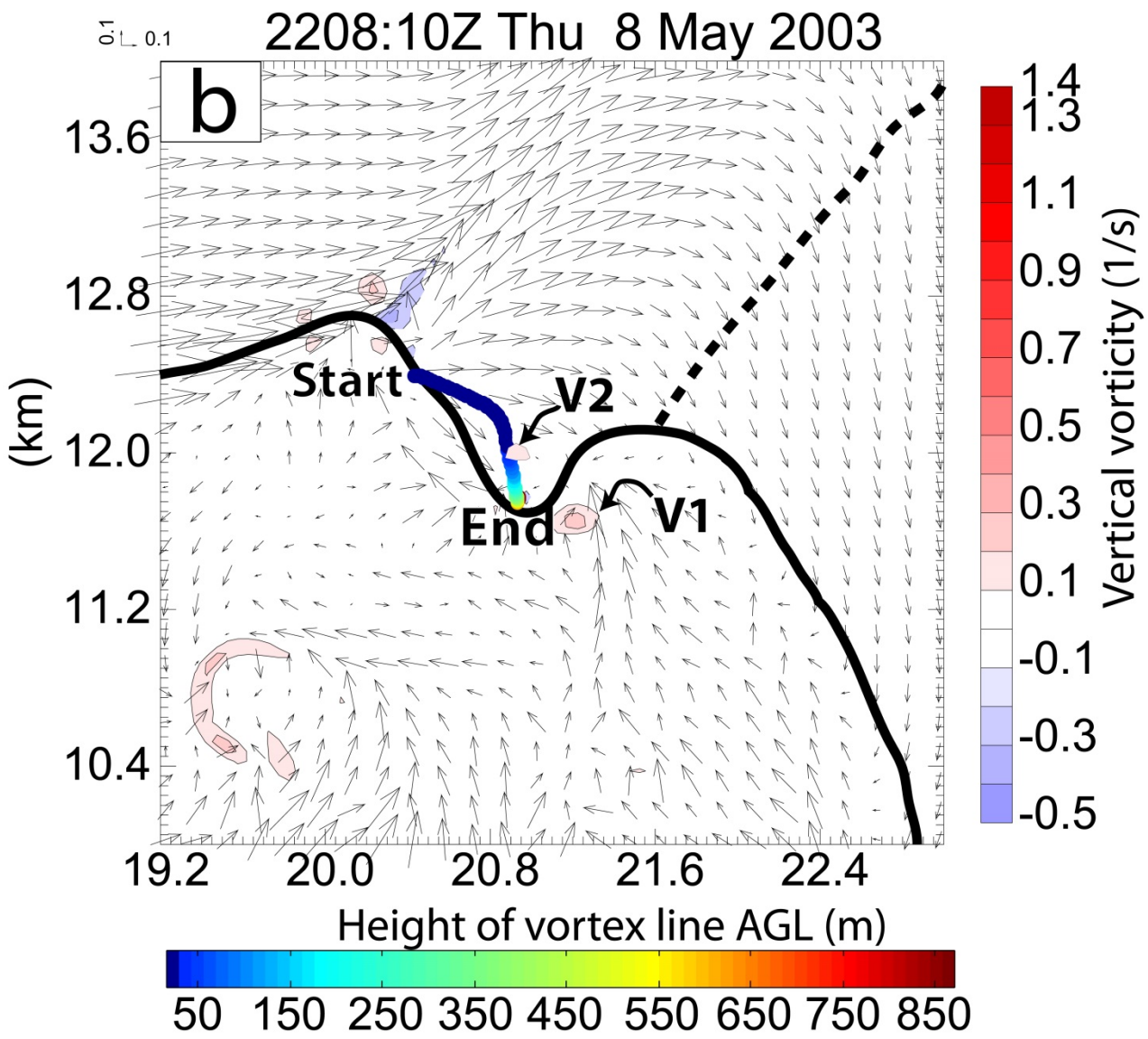
- Tornado #1 forms from at least three main vorticity maxima – V1,V2,V3.
- V1 and V2 form around the same time.
- V1 strongest at the ground.
- V2 develops (and is strongest) a few hundred meters AGL.
- V1 and V2 combine to form a PTV.
- V3 strongest at the ground
- Tornadogenesis is triggered as V3 (and associated internal outflow surge) encounters the PTV.
- Let's examine the development each vorticity maximum separately to simplify the analysis.

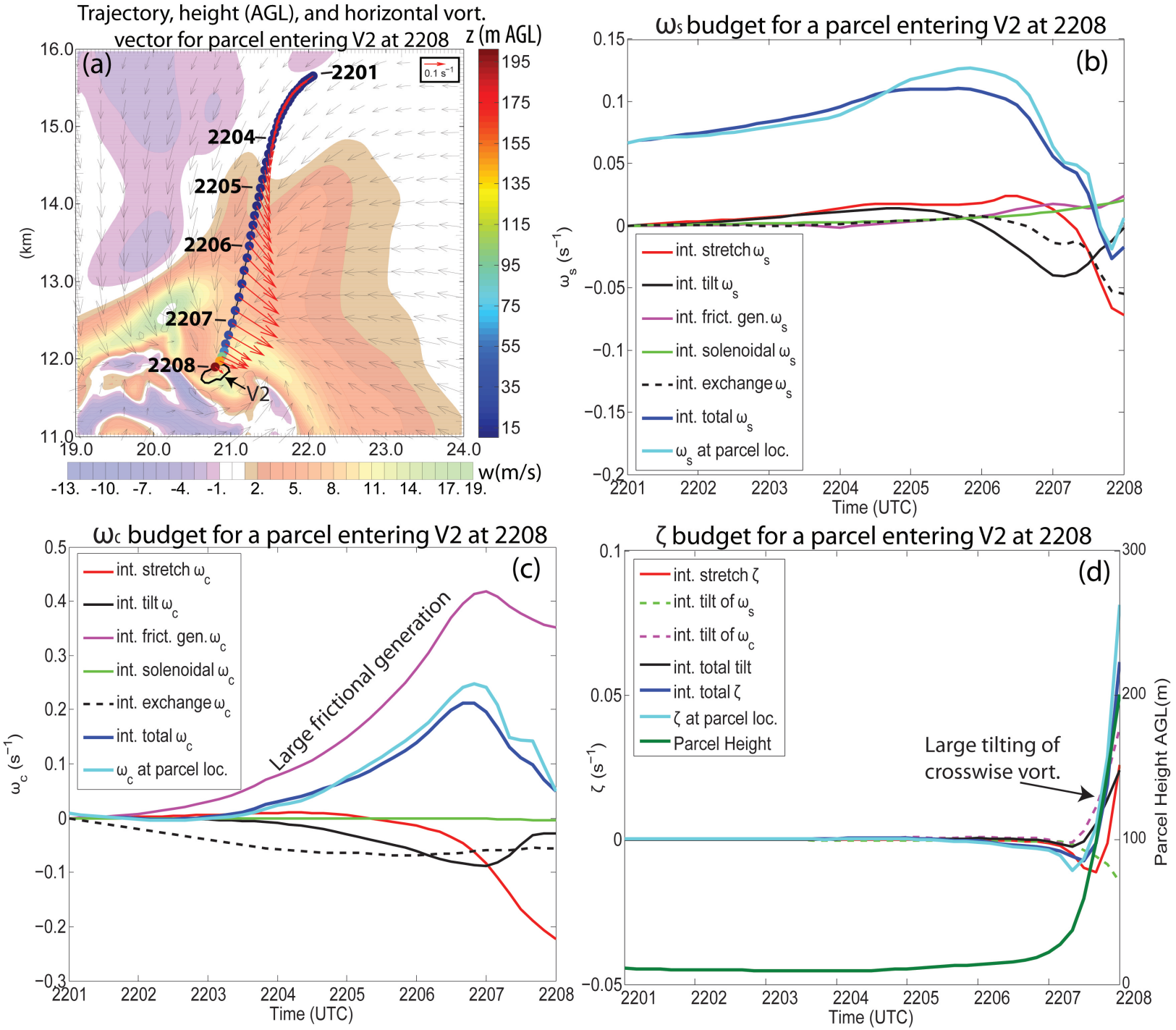
Backward Trajectories

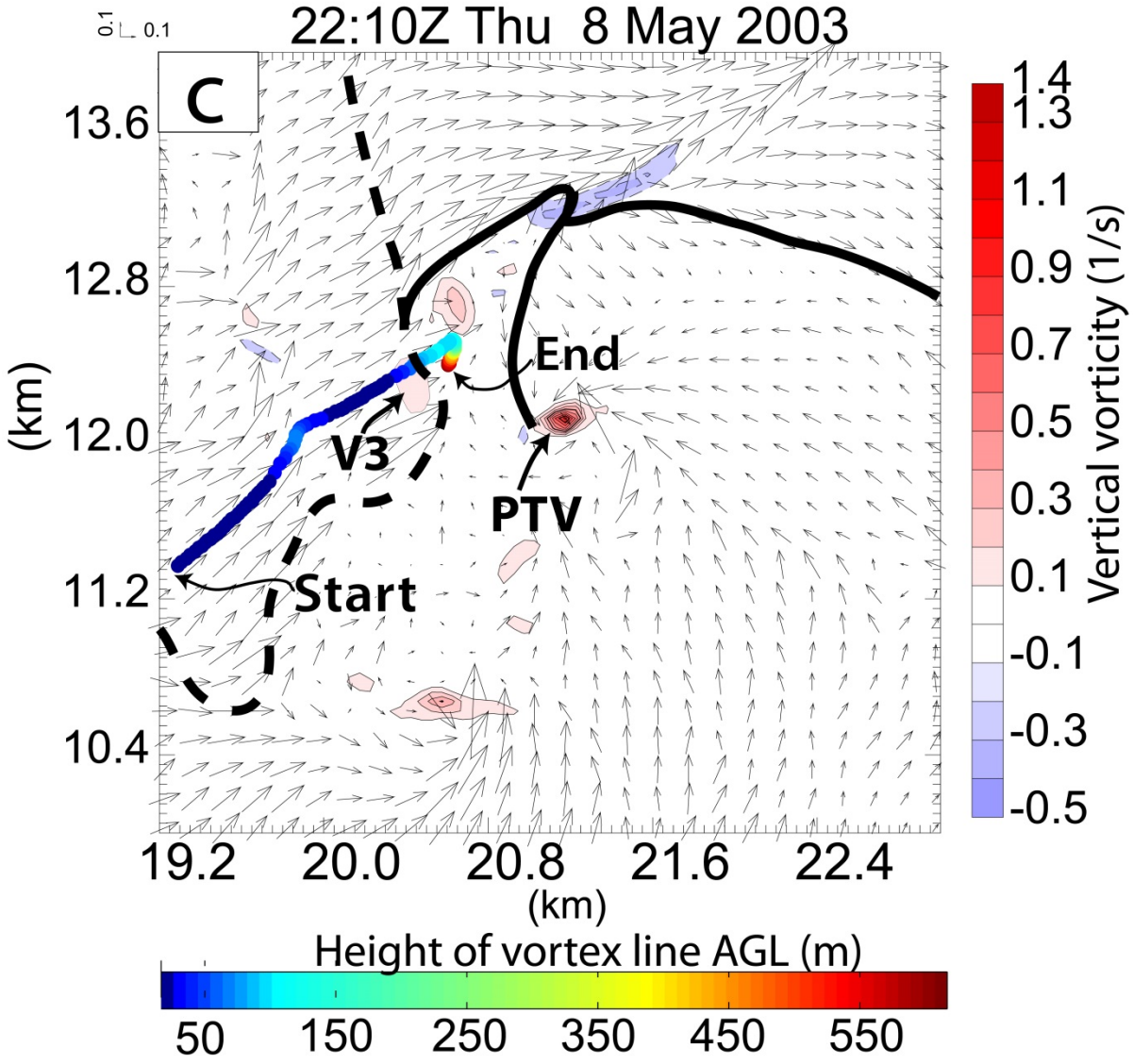
- 4^{th} order Runge-Kutta
- 2-s model output data used for calculations
- For trajs. that drop under lowest scalar point, forcings at lowest scalar point used.
- **Caveat:** Trajectory length limited by tornadogenesis close proximity to model start time.

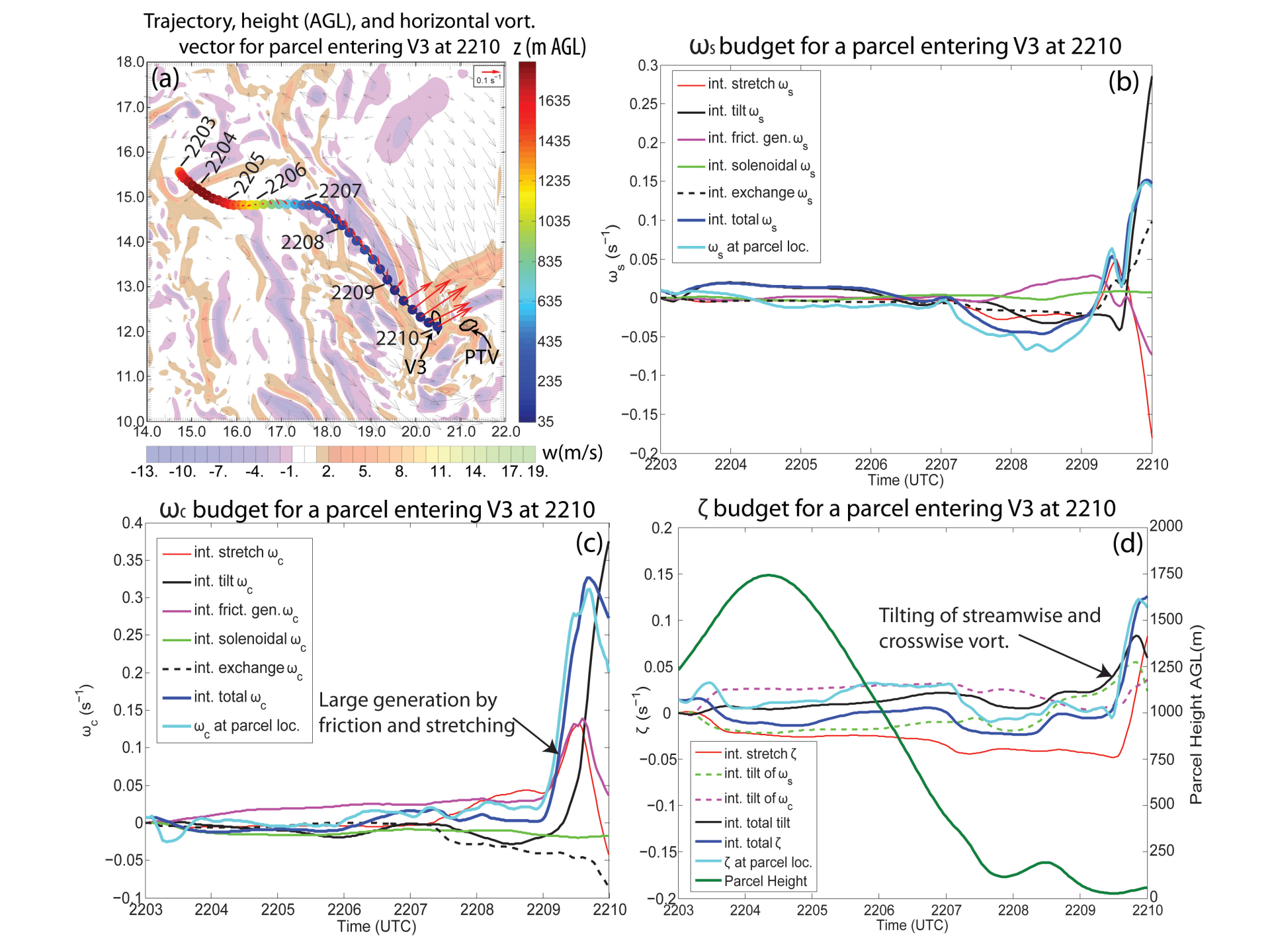

Vertical vorticity, horizontal vorticity vectors,
and w at 20 m AGL
2207:30Z Thu 8 May 2003
0.1
0.1
a
13.6
12.8
12.0
11.2
10.4
(km)
End
V1
Start
19.2
20.0
20.8
21.6
22.4
Height of vortex line AGL (m)
20
30
40
50
60
70
80
90
100
1.4
1.3
1.1
0.9
0.7
0.5
0.3
0.1
-0.1
-0.3
-0.5
Vertical vorticity (1/s)

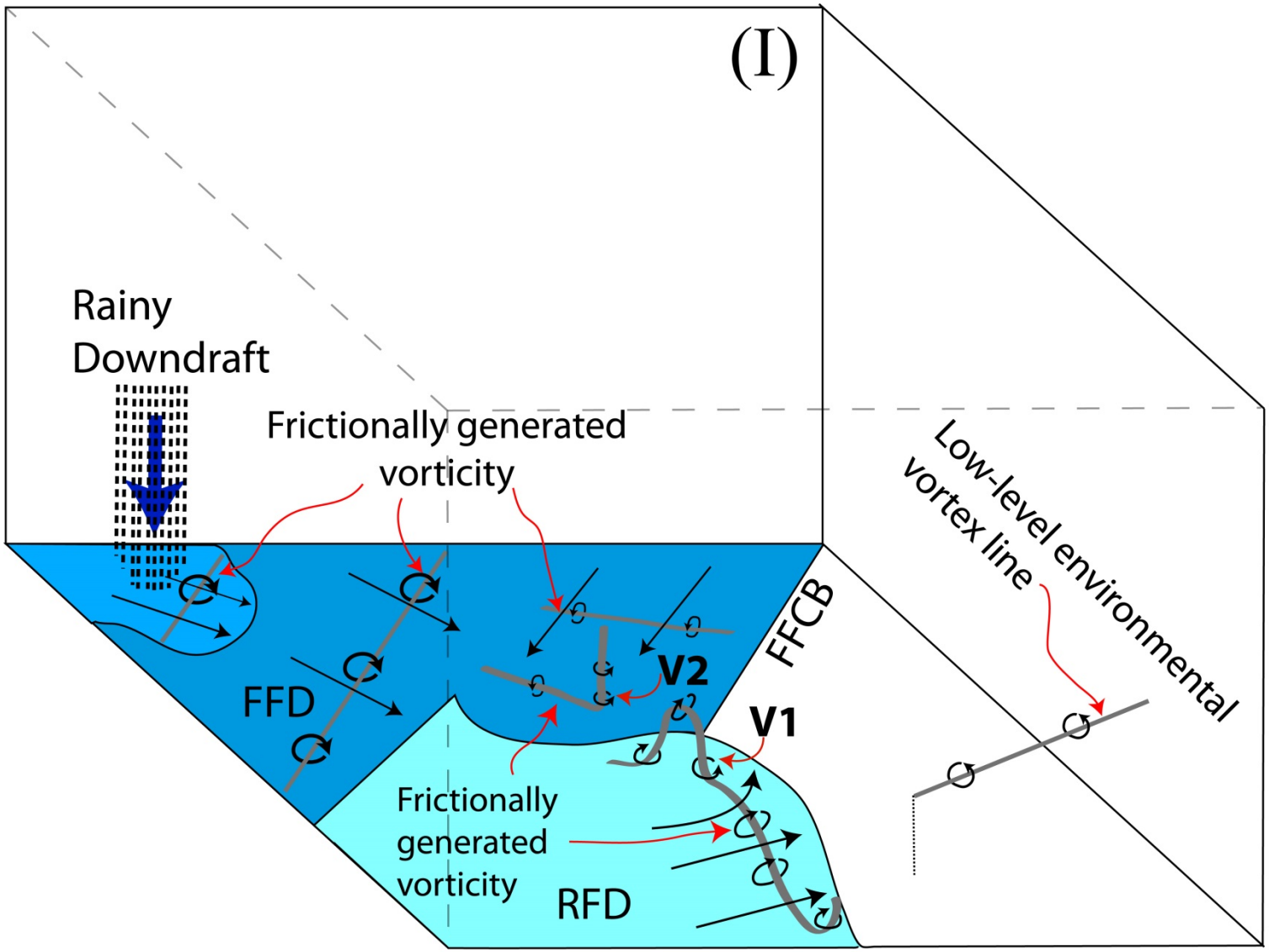

Trajectory, height (AGL), and horizontal vort.
vector for parcel entering V1 at 2208
(a)
z (m AGL)
0.1 s⁻¹
2201
2202
2203
2204
2205
2206
2207
2208
V1
V2
(km)
w(m/s)
-13. -10. -7. -4. -1. 2. 5. 8. 11. 14. 17. 19.
ωs budget for a parcel entering V1 at 2208
(b)
int. stretch ωs
int. tilt ωs
int. frict. gen. ωs
int. solenoidal ωs
int. exchange ωs
int. total ωs
ωs at parcel loc.
exchange as the parcel turns
negative friction generation as parcel turns cyclonically
ωs (s⁻¹)
Time (UTC)
ωc budget for a parcel entering V1 at 2208
(c)
int. stretch ωc
int. tilt ωc
int. frict. gen. ωc
int. solenoidal ωc
int. exchange ωc
int. total ωc
ωc at parcel loc.
Large frictional generation
exchange as the parcel turns
ωc (s⁻¹)
Time (UTC)
ζ budget for a parcel entering V1 at 2208
(d)
int. stretch ζ
int. tilt of ωs
int. tilt of ωc
int. total tilt
int. total ζ
ζ at parcel loc.
Parcel Height
Positive tilting of ωs as the parcel descends
ζ (s⁻¹)
Parcel Height AGL(m)
Inclination angle between the vorticity and velocity vectors
Degrees
Time (UTC)

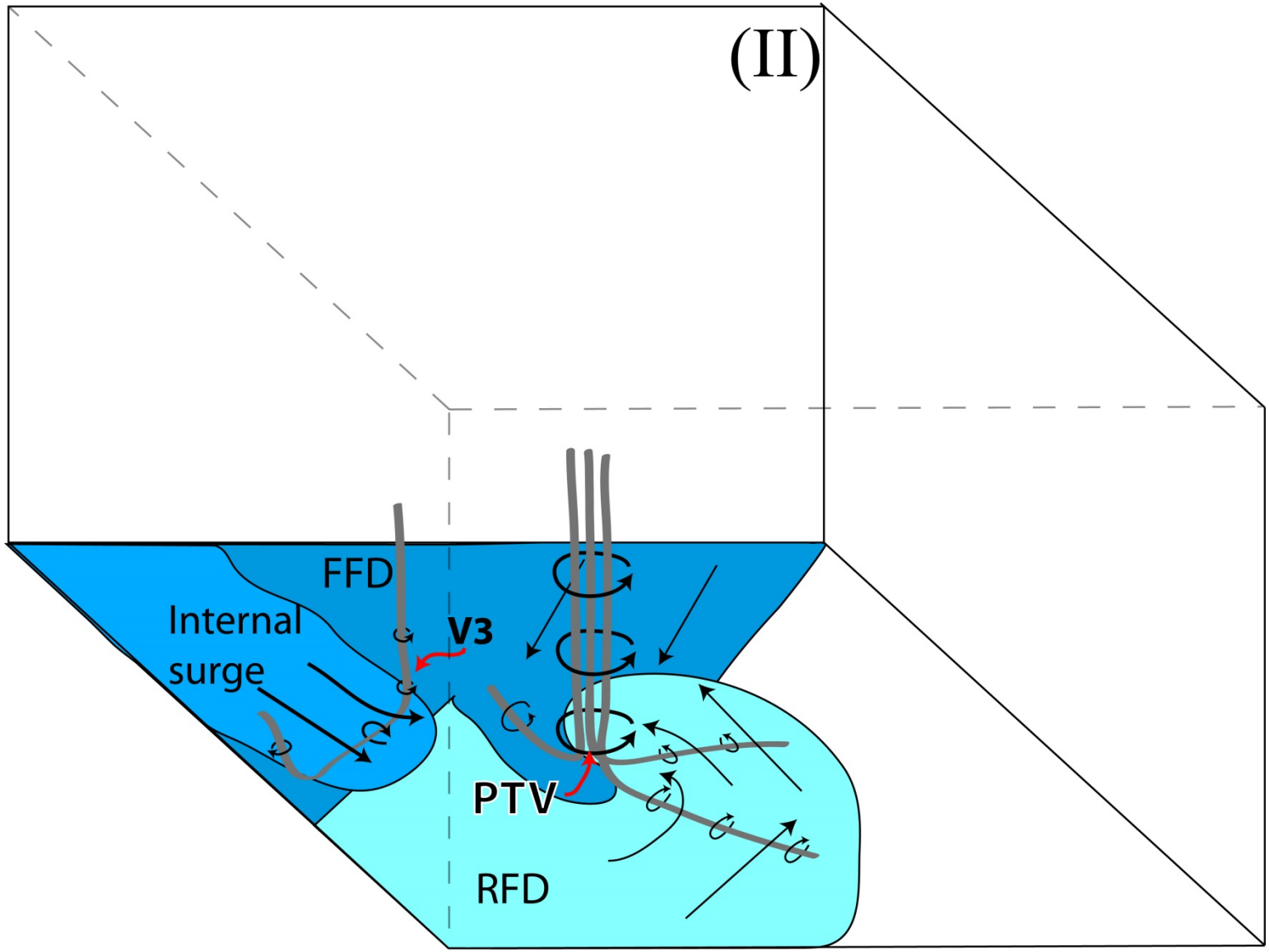

2208:10Z Thu 8 May 2003
b
0.1
0.1
13.6
12.8
12.0
11.2
10.4
(km)
Start
End
V2
V1
19.2
20.0
20.8
21.6
22.4
Height of vortex line AGL (m)
50 150 250 350 450 550 650 750 850
1.4
1.3
1.1
0.9
0.7
0.5
0.3
0.1
-0.1
-0.3
-0.5
Vertical vorticity (1/s)

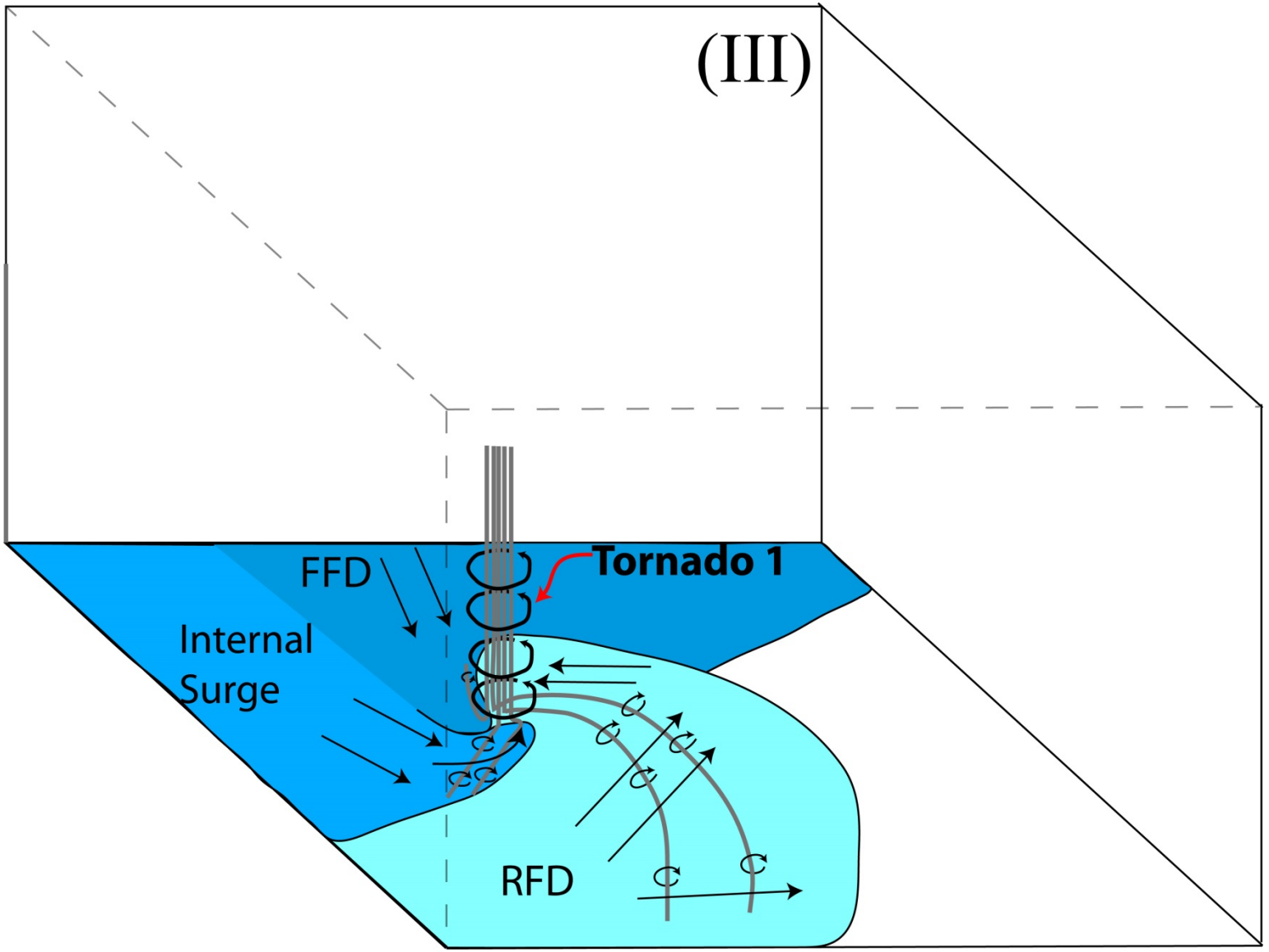

Trajectory, height (AGL), and horizontal vort.
vector for parcel entering V2 at 2208
(a)
2201
2204
2205
2206
2207
2208
V2
0.1 s⁻¹
z (m AGL)
195
175
155
135
115
95
75
55
35
15
(km)
16.0
15.0
14.0
13.0
12.0
11.0
19.0
20.0
21.0
22.0
23.0
24.0
w(m/s)
-13. -10. -7. -4. -1. 2. 5. 8. 11. 14. 17. 19.
ωs budget for a parcel entering V2 at 2208
(b)
int. stretch ωs
int. tilt ωs
int. frict. gen. ωs
int. solenoidal ωs
int. exchange ωs
int. total ωs
ωs at parcel loc.
ωs (s⁻¹)
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
−0.2
2201
2202
2203
2204
2205
2206
2207
2208
Time (UTC)
ωc budget for a parcel entering V2 at 2208
(c)
int. stretch ωc
int. tilt ωc
int. frict. gen. ωc
int. solenoidal ωc
int. exchange ωc
int. total ωc
ωc at parcel loc.
Large frictional generation
ωc (s⁻¹)
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
2201
2202
2203
2204
2205
2206
2207
2208
Time (UTC)
ζ budget for a parcel entering V2 at 2208
(d)
int. stretch ζ
int. tilt of ωs
int. tilt of ωc
int. total tilt
int. total ζ
ζ at parcel loc.
Parcel Height
Large tilting of
crosswise vort.
ζ (s⁻¹)
0.1
0.05
0
−0.05
Parcel Height AGL(m)
300
200
100
0
2201
2202
2203
2204
2205
2206
2207
2208
Time (UTC)


22:10Z Thu 8 May 2003
C
0.1
0.1
13.6
12.8
12.0
11.2
10.4
(km)
19.2
20.0
20.8
21.6
22.4
(km)
End
V3
PTV
Start
1.4
1.3
1.1
0.9
0.7
0.5
0.3
0.1
-0.1
-0.3
-0.5
Vertical vorticity (1/s)
Height of vortex line AGL (m)
50
150
250
350
450
550


Trajectory, height (AGL), and horizontal vort.
vector for parcel entering V3 at 2210
z (m AGL)
(a)
0.1 s⁻¹
2203
2204
2205
2206
2207
2208
2209
2210
V3
PTV
1635
1435
1235
1035
835
635
435
235
35
w(m/s)
-13. -10. -7. -4. -1. 2. 5. 8. 11. 14. 17. 19.
ωs budget for a parcel entering V3 at 2210
(b)
int. stretch ωs
int. tilt ωs
int. frict. gen. ωs
int. solenoidal ωs
int. exchange ωs
int. total ωs
ωs at parcel loc.
ωs (s⁻¹)
Time (UTC)
ωc budget for a parcel entering V3 at 2210
(c)
int. stretch ωc
int. tilt ωc
int. frict. gen. ωc
int. solenoidal ωc
int. exchange ωc
int. total ωc
ωc at parcel loc.
Large generation by
friction and stretching
ωc (s⁻¹)
Time (UTC)
ζ budget for a parcel entering V3 at 2210
(d)
Tilting of streamwise and
crosswise vort.
int. stretch ζ
int. tilt of ωs
int. tilt of ωc
int. total tilt
int. total ζ
ζ at parcel loc.
Parcel Height
ζ (s⁻¹)
Parcel Height AGL(m)
Time (UTC)

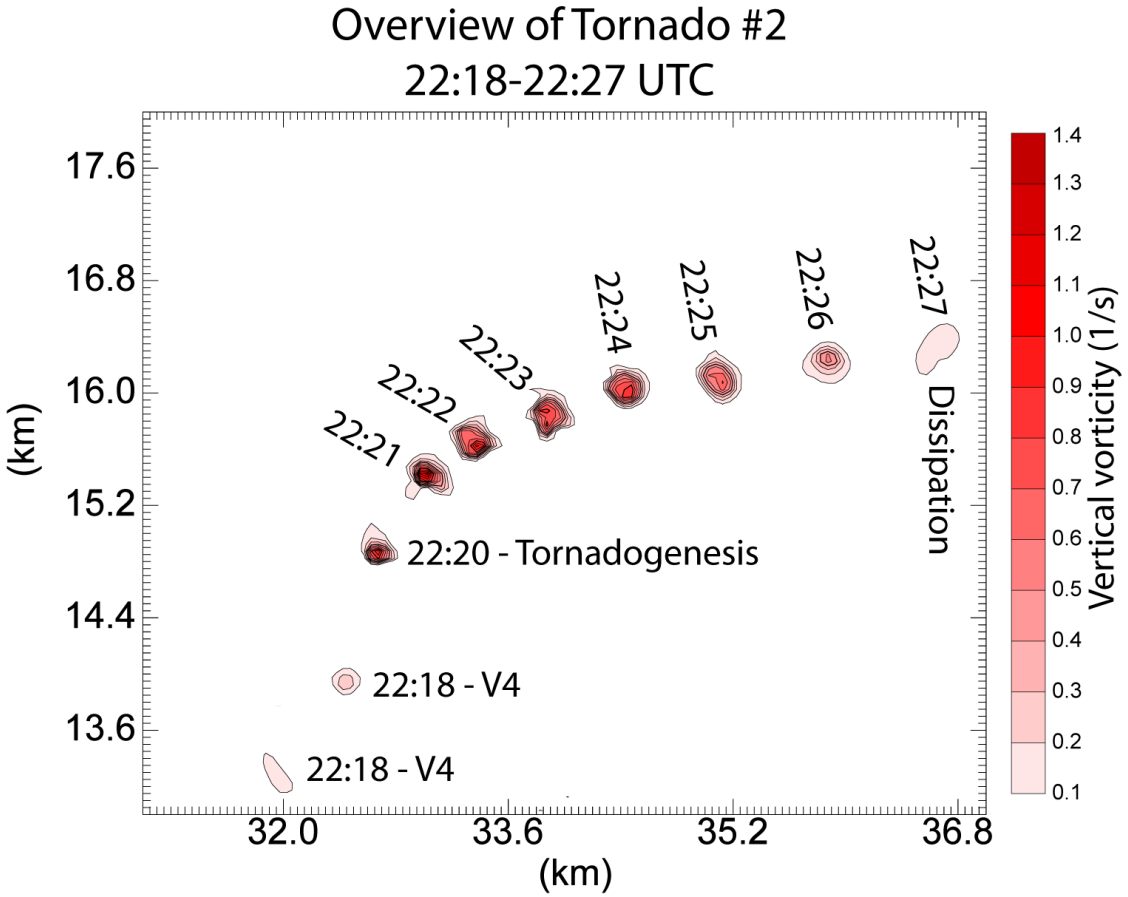

(I)
Rainy
Downdraft
Frictionally generated
vorticity
Low-level environmental
vortex line
FFCB
V2
V1
FFD
Frictionally
generated
vorticity
RFD

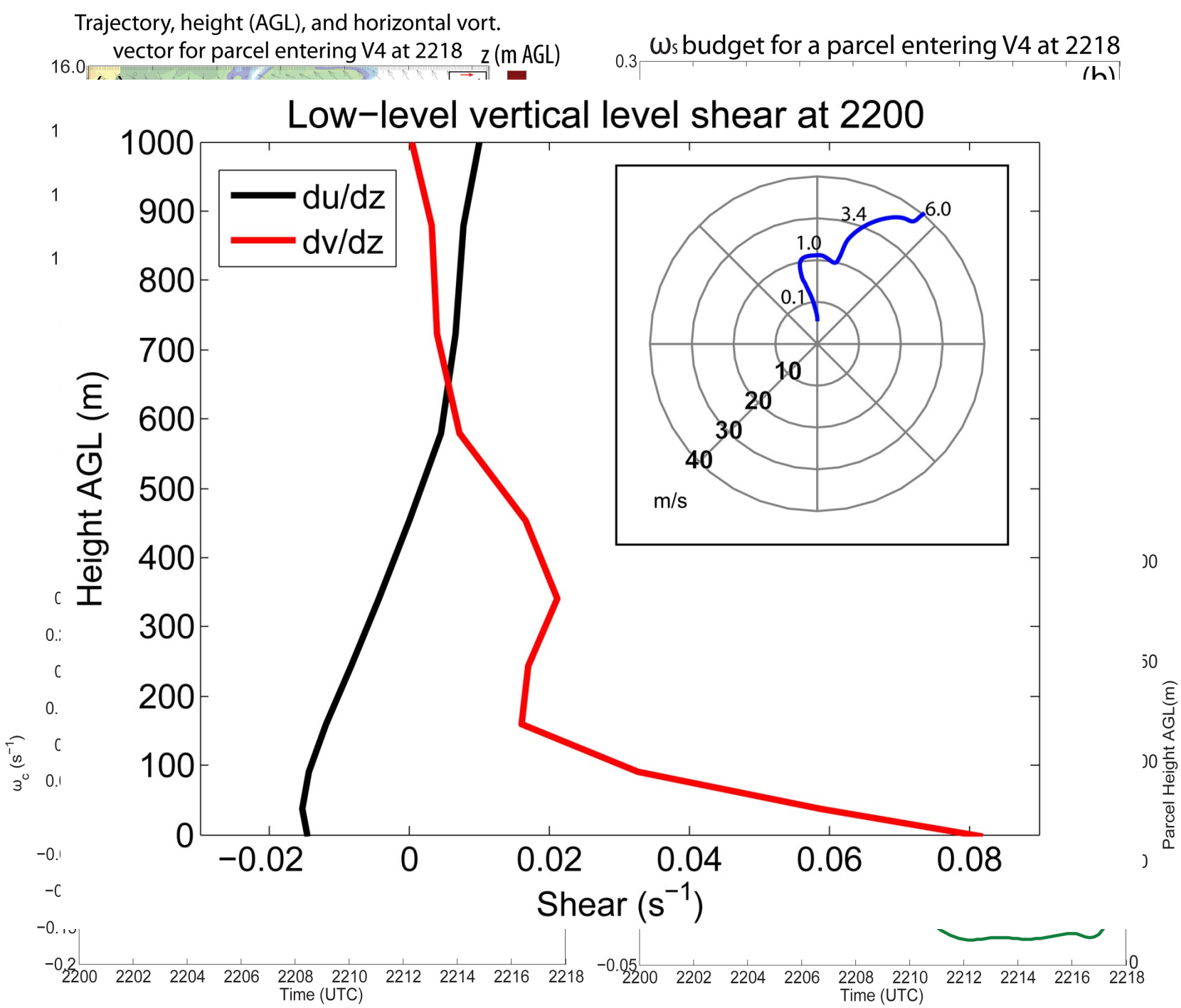

(II)
FFD
Internal
surge
V3
PTV
RFD

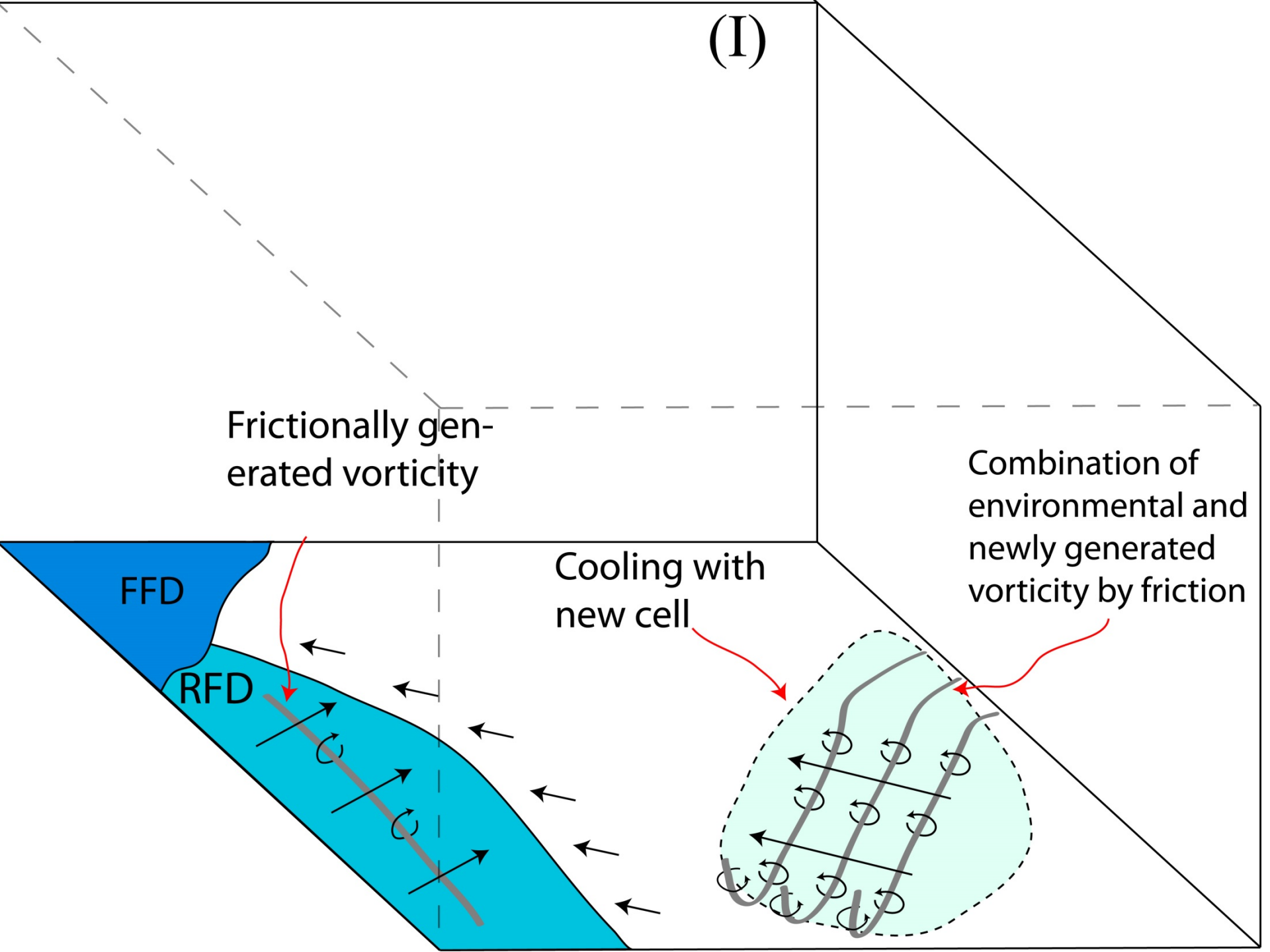

(III)
FFD
Tornado 1
Internal
Surge
RFD

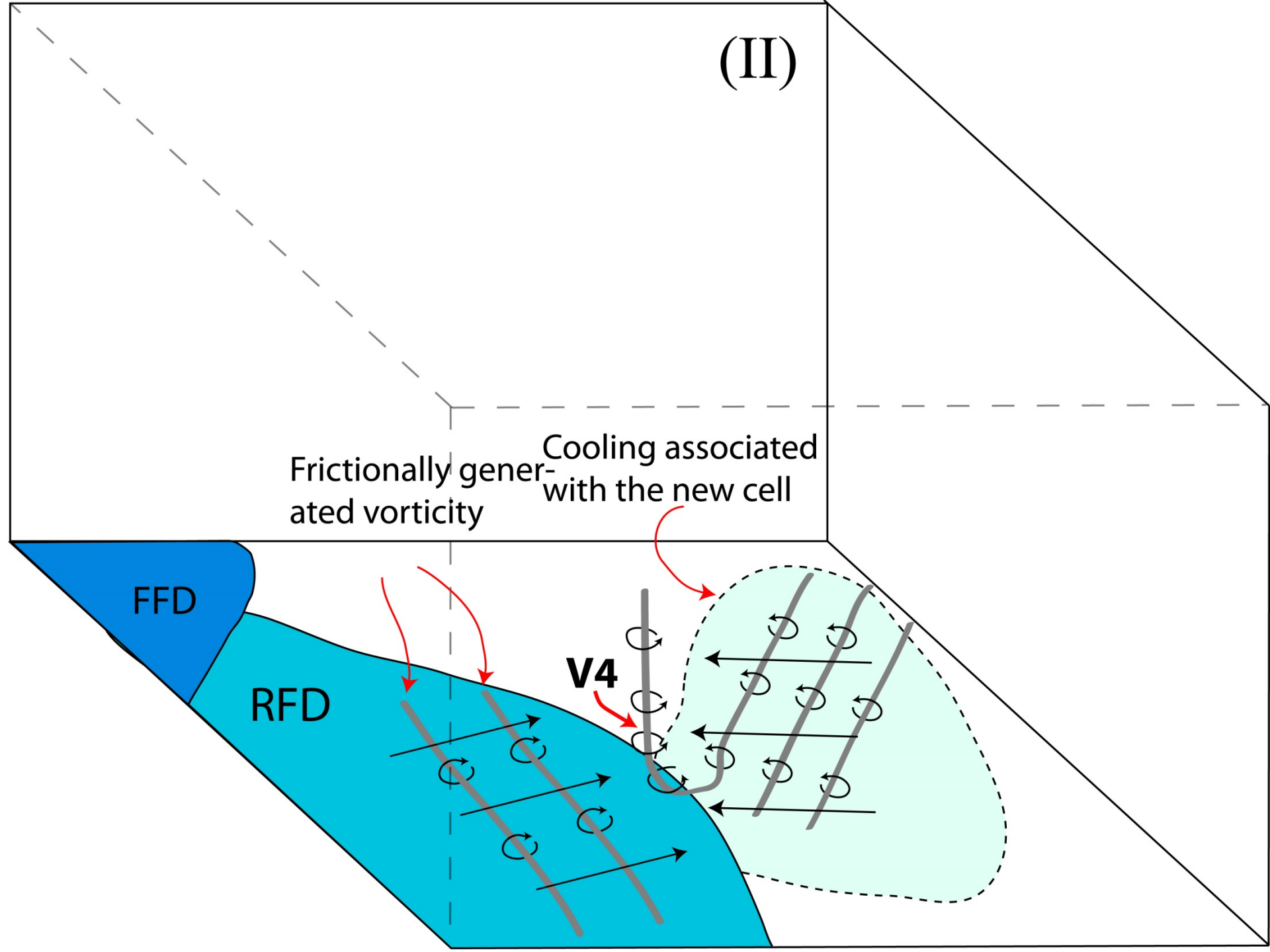
Tornado #2

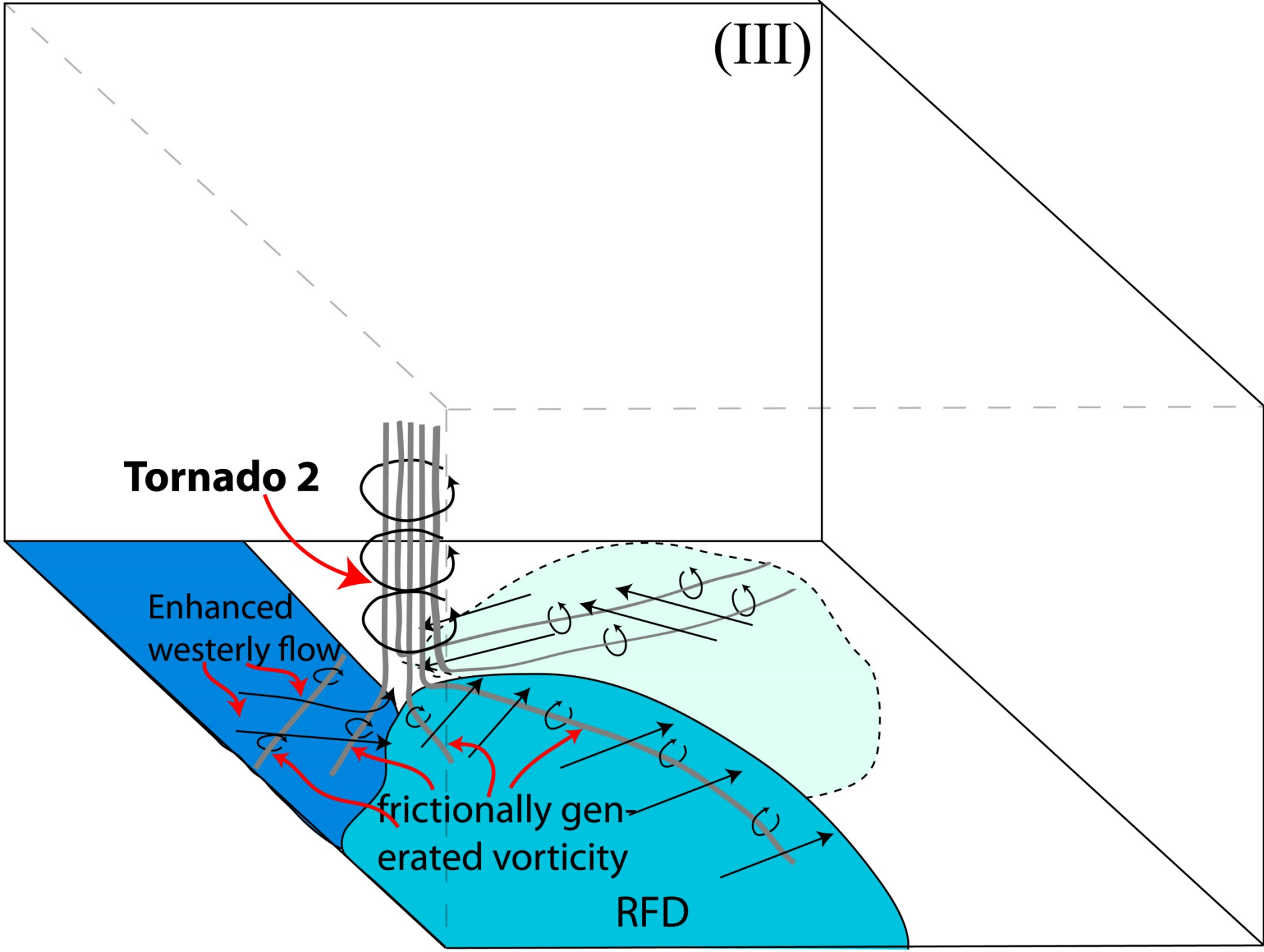
- Forms as weak area of vorticity (V4) in inflow area
- Associated with new cell
- As V4 encounters primary RFGF it rapidly strengthens to tornado-strength
- Max winds ~ 60 m/s




Trajectory, height (AGL), and horizontal vort.
vector for parcel entering V4 at 2218
z (m AGL)
16.0
ωs budget for a parcel entering V4 at 2218
0.3
(b)
Low−level vertical level shear at 2200
du/dz
dv/dz
Height AGL (m)
1000
900
800
700
600
500
400
300
200
100
0
−0.02
0
0.02
0.04
0.06
0.08
Shear (s−1)
3.4
6.0
1.0
0.1
10
20
30
40
m/s
ωc (s−1)
Parcel Height AGL(m)
2200
2202
2204
2206
2208
2210
2212
2214
2216
2218
Time (UTC)
−0.05
0


(I)
Frictionally gen-
erated vorticity
Cooling with
new cell
Combination of
environmental and
newly generated
vorticity by friction
FFD
RFD


(II)
Frictionally gener-
ated vorticity
Cooling associated
with the new cell
FFD
RFD
V4


(III)
Tornado 2
Enhanced
westerly flow
frictionally gen-
erated vorticity
RFD

Conclusions

- Rearrangement and tilting of frictionally generated horizontal vorticity found to play a substantial role in the genesis and intensification of two simulated tornadoes.
- With that said, importance of baroclinic vorticity generation cannot be ruled out owing to short trajectory integrations.
- A simulation without drag also produces a tornado.