High-Resolution Dual-Doppler Analysis of Tornadic Thunderstorms using a New Advection-Correction Technique

Presented by Katherine Willingham

Motivation

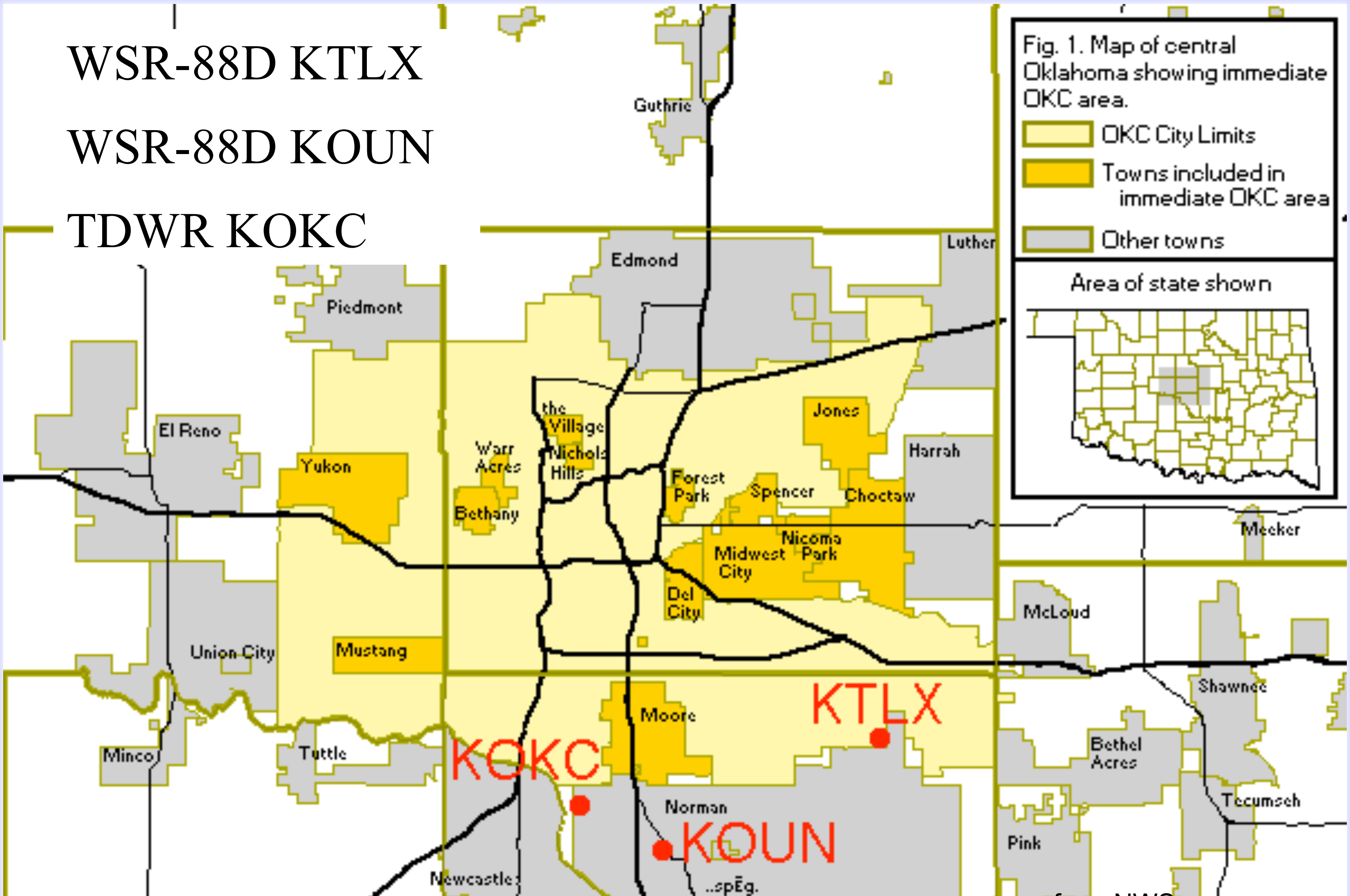
- Verify and complement results of the Neuro-Fuzzy Tornado Detection Algorithm (NFTDA)(Wang et al. 2008)
  - Compare dual-Doppler analysis with NFTDA detections and damage path
- Test a new formulation for advection-correction of radar data
  - Used for small scale features such as mesocyclones and tornadoes
- Compare dual-Doppler results with conceptual models of tornado and mesocyclone structures

Map of Radar Locations

WSR-88D KTLX

WSR-88D KOUN

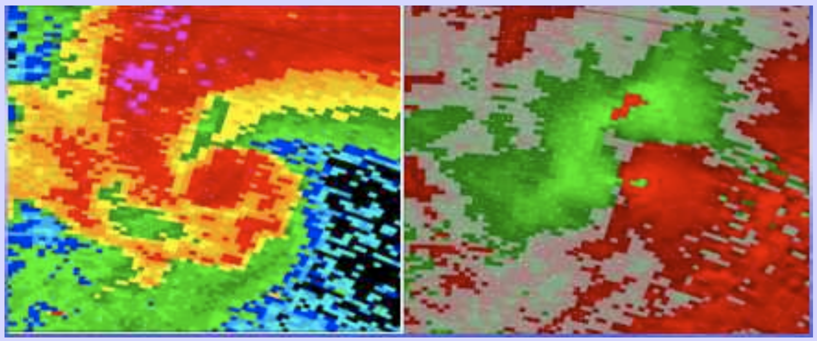
TDWR KOKC

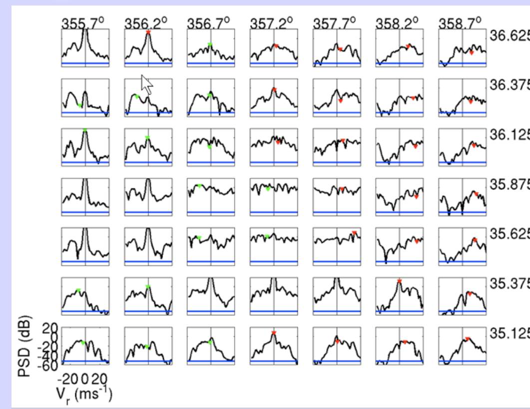


map from NWS

What is the NFTDA?

- The algorithm integrates tornadic signatures in both the velocity and spectral domains

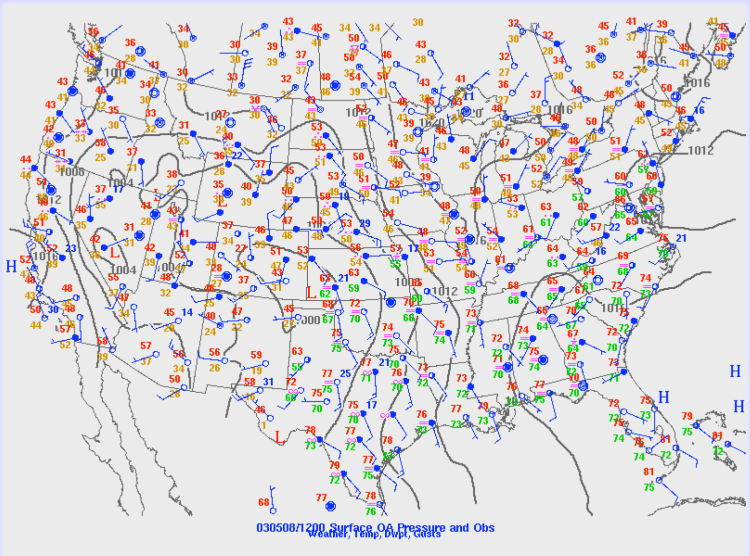


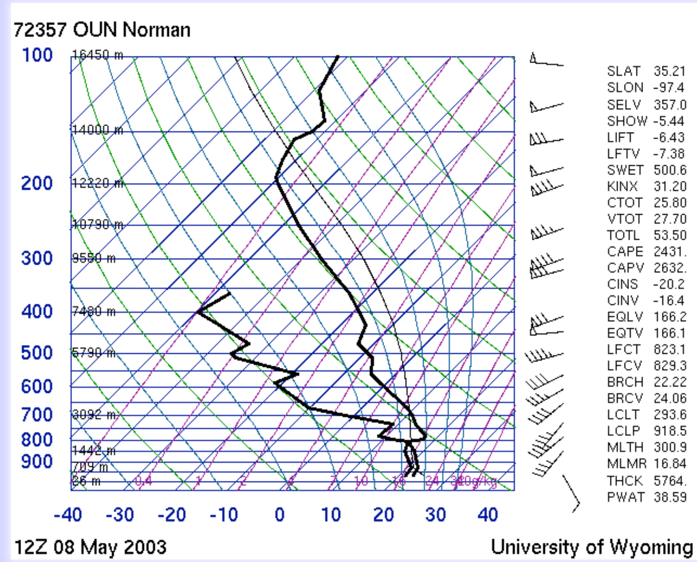


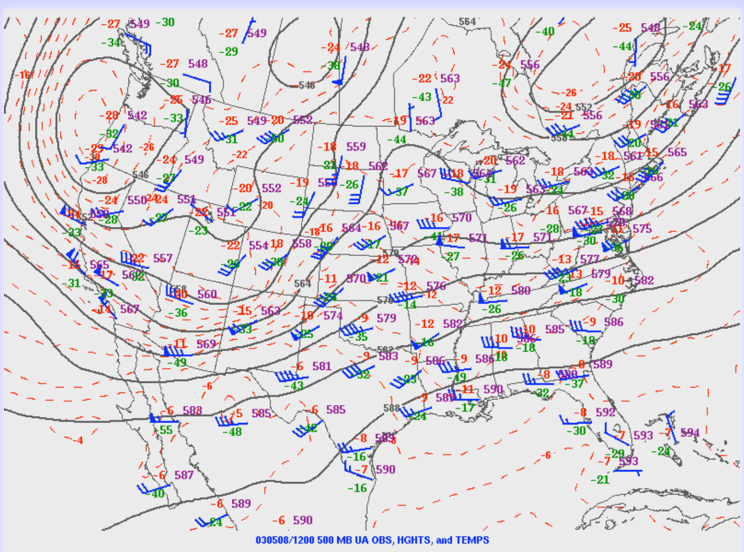
- Verification done by using analytical simulations as well as real data collected by KOUN for two tornadic cases
  - 8 May 2003
  - 10 May 2003
- The NFTDA detects tornadoes even when shear signatures are degraded significantly
- The NFTDA extends the detectable range for tornadoes

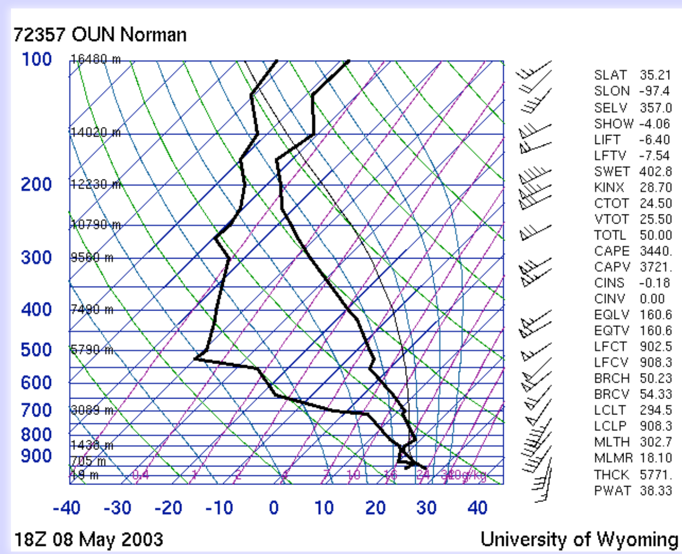
(Wang et al. submitted)

8 May 2003 Overview









figures: SPC

8 May 2003 Tornado Path

- Tornado first reported in Moore, traveled through south OKC, across I-240 and Sooner Rd, across TAFB, across I-40 into SE Midwest City and into Choctaw
- Widespread F3 damage and small areas of F4 damage
- Maximum width 4/10 mi

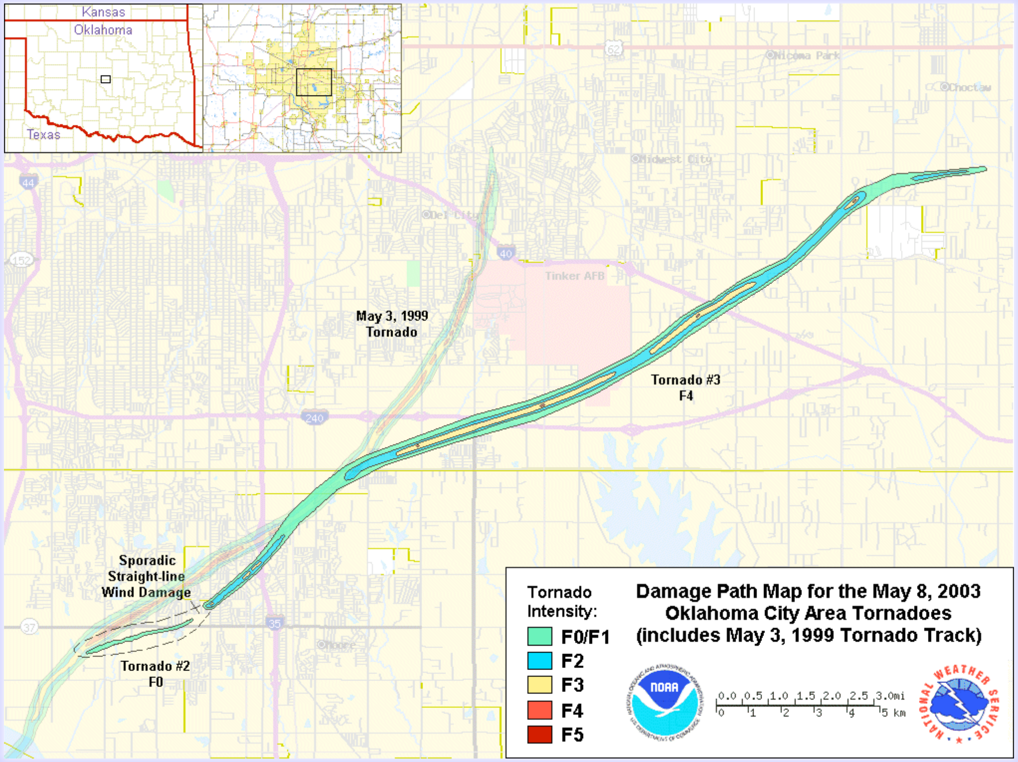
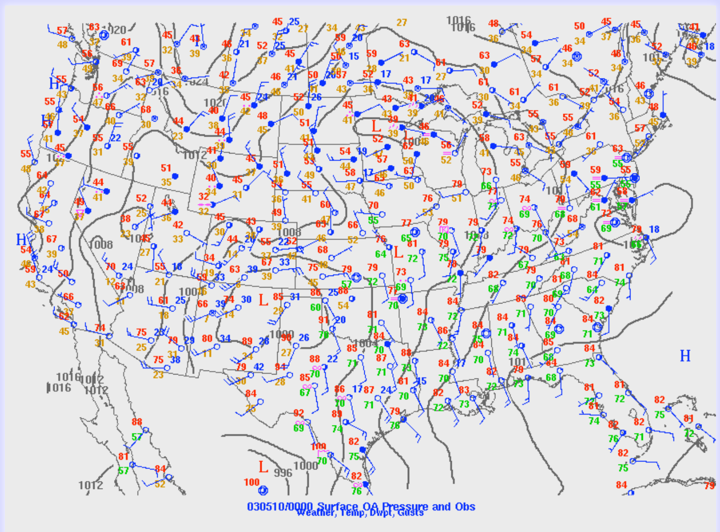
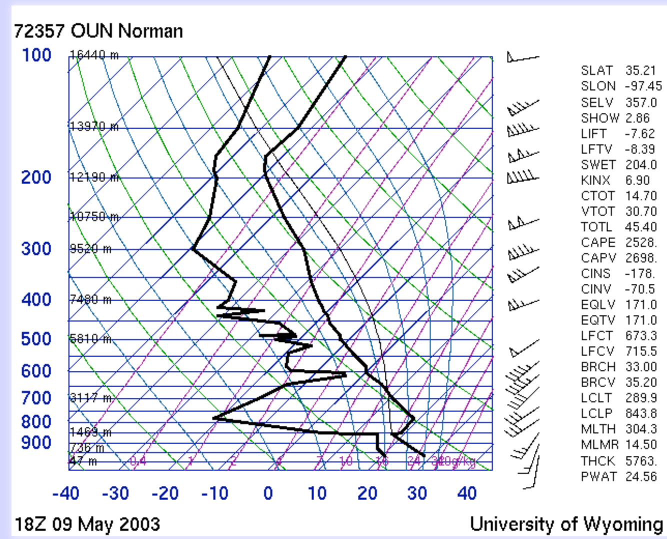
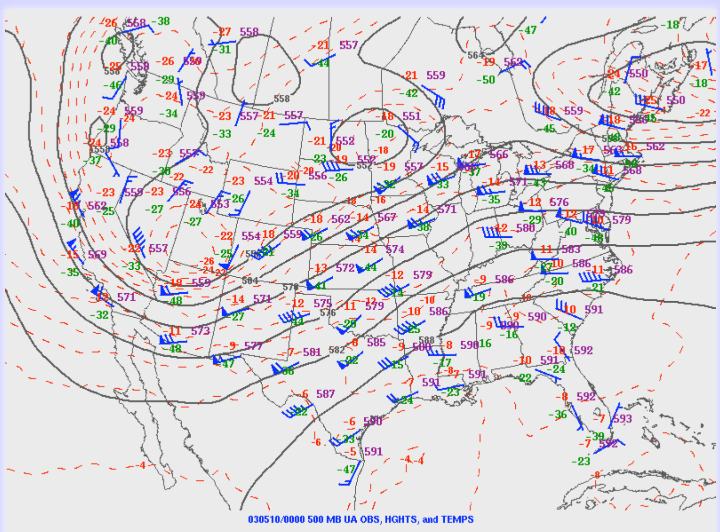


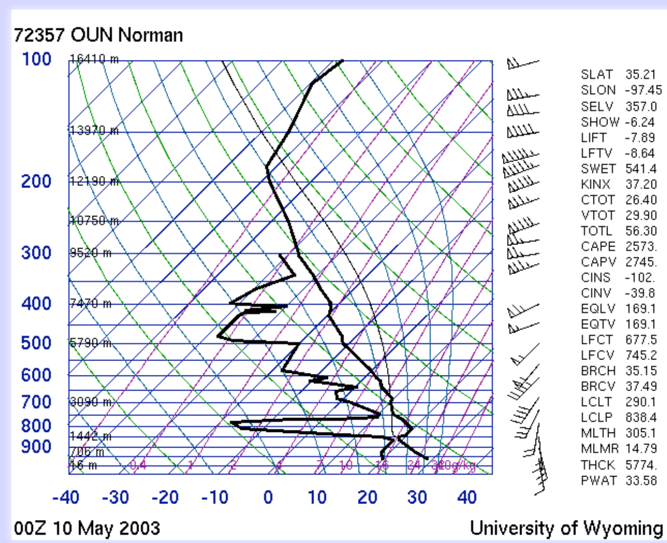
figure from NWS

10 May 2003 Overview



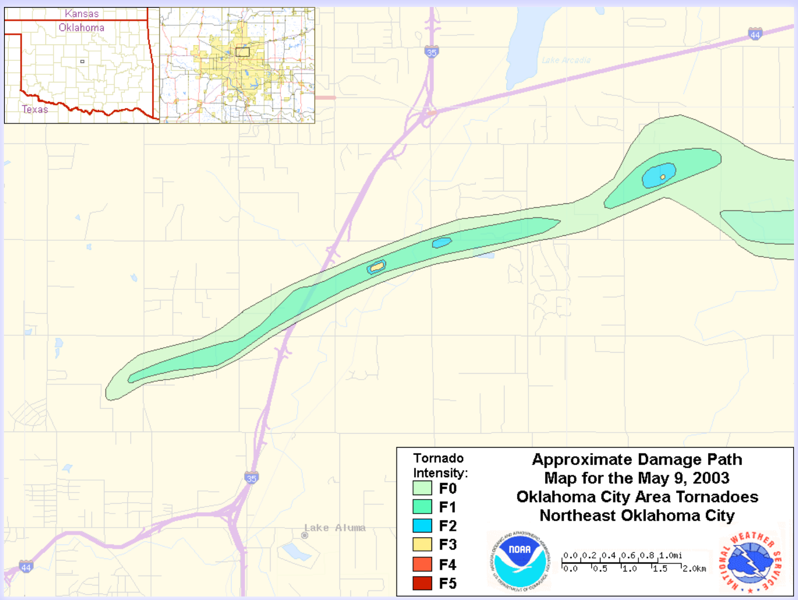


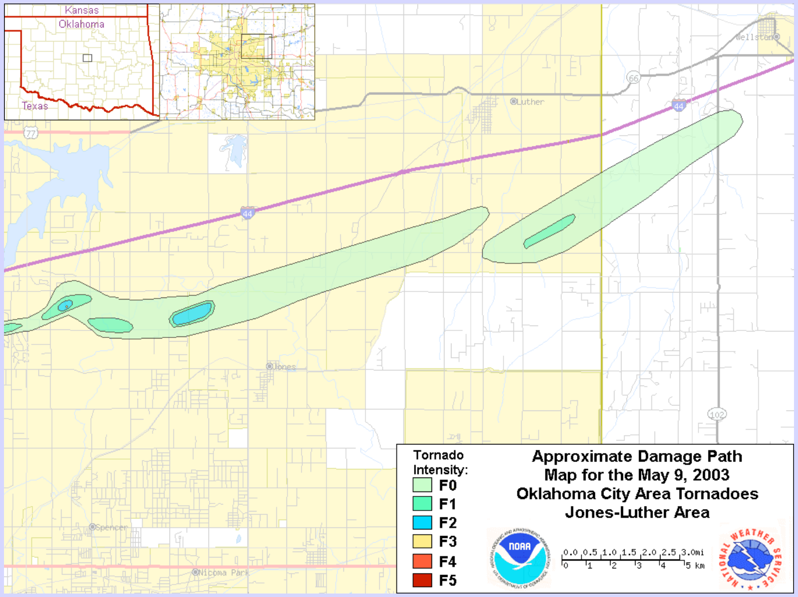




figures: SPC

10 May 2003 Tornado Path





figures from NWS

- Widespread F2 damage with a small area of F3 damage.
- Maximum width 1/2 mi

Data Processing

- Data was edited for quality and dealiasing was completed.
- A Cressman interpolation was used for coordinate transformation.
- A range dependent radius of influence n was used:

	WSR-88D data	TDWR data
Azimuthal Component	0.9°	0.9°
Elevation Component	0.9°	2.6°
Range Component	r*dA	r*dA

- The weight W for a particular gate value is calculated from

$$W = \frac{n^2 - r^2}{n^2 + r^2},$$

where n is the radius of influence and r is the range from the radar.

Analysis Grid and Data

8 May 2003

- $\delta x = \delta y = 250$m
- $\delta z = 500$m
- Radars used:
  - KOKC and KTLX
- Time analyzed:
  - 22:26 - 22:43 UTC

10 May 2003

- $\delta x = \delta y = 250$m
- $\delta z = 500$m
- Radars used:
  - KTLX and KOUN
- Time analyzed:
  - 03:19 - 03:43 UTC

Patterns on the Go

Two types of unsteadiness:

Propagation. Pattern of unchanging for translates horizontally.

Evolution. Pattern changes in size, shape or intensity.

- Temporal-resolution-sensitive analysis products are prone to errors if the flow is sufficiently unsteady (flow time scales ≤ volume scan period).
- Examples of volume scan periods:

WSR-88D: 10 min clear air mode, 4-6 min precip mode

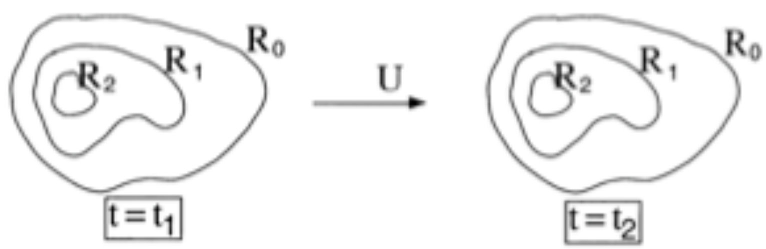
TDWR: 6 min, but 1 min for lowest tilt

Research radars (DOW, SMART-R, CASA, NWRT): <1min

Mitigating Temporal Errors

- Dual-Doppler wind analysis is a temporal-resolution-sensitive analysis product
- Advection-correction is used to mitigate propagation error
- Traditional methods use the frozen-turbulence hypothesis.

Frozen-turbulence hypothesis



For R: $\frac{DR}{Dt} = 0$, or equivalently $\frac{\partial R}{\partial t} + U\frac{\partial R}{\partial x} + V\frac{\partial R}{\partial y} = 0.$

For $\vec{v}$: $\frac{D\vec{v}}{Dt} = 0$, or equivalently $\frac{\partial \vec{v}}{\partial t} + U\frac{\partial \vec{v}}{\partial x} + V\frac{\partial \vec{v}}{\partial y} = 0.$

For v_r: $\frac{D^2(rv_r)}{Dt^2} = 0$, or equivalently $\left(\frac{\partial}{\partial t} + U\frac{\partial}{\partial x} + V\frac{\partial}{\partial y}\right)^2 (rv_r) = 0.$

A New Formulation of Advection-Correction

(Shapiro et al. submitted)

Goal: Improve analysis of small scale features embedded within (and advected by) larger-scale features.

Idea: Spatially-variable U,V may improve analyses of tornadoes and other small/mesoscale phenomena

Method: Apply a weak frozen-turbulence constraint on R with R-data supplied at two time levels. Determine U, V and advection corrected R, then use U, V to advection correct v_r

A New Formulation of Advection-Correction

(Shapiro et al. submitted)

- U,V,R are the fields that minimize a cost-function J_i, defined for the i^{th} analysis surface as

$$J_i \equiv \iiint \left[\alpha \left(\frac{\partial R}{\partial t} + U \frac{\partial R}{\partial x} + V \frac{\partial R}{\partial y} \right)^2 + \beta \left| \nabla_h U \right|^2 + \beta \left| \nabla_h V \right|^2 \right] dxdydt$$

with R imposed at two effective data times, $t=t_1$ and $t=t_1 + T$

- α is a binary analysis coverage footprint function imposed with a strong constraint

$$\frac{\partial \alpha}{\partial t} + U \frac{\partial \alpha}{\partial x} + V \frac{\partial \alpha}{\partial y} = 0$$

- There must be data at both the start and end times for a trajectory to be calculated
  - α depends on the topology of data voids

A New Formulation of Advection-Correction

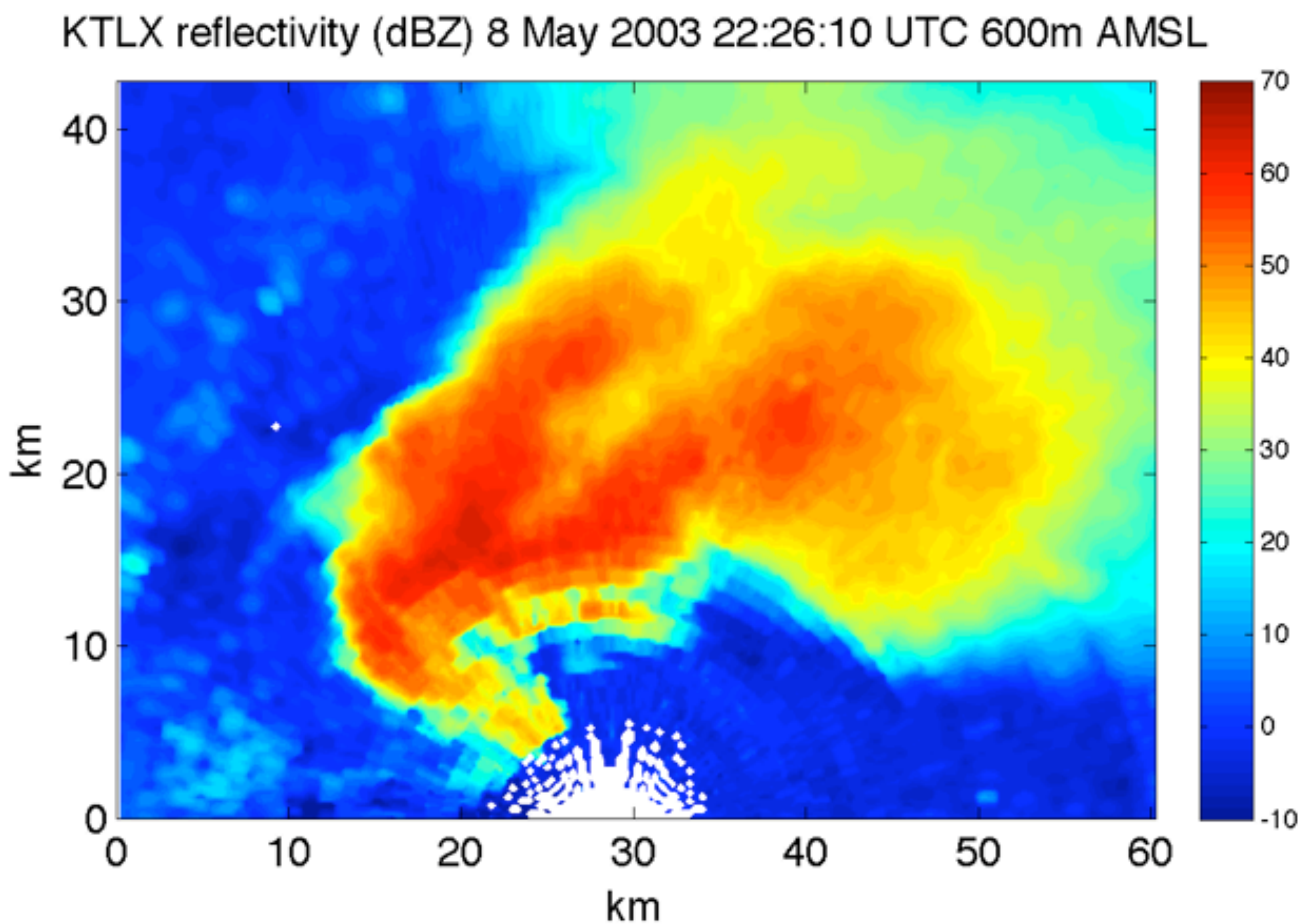
(Shapiro et al. submitted)

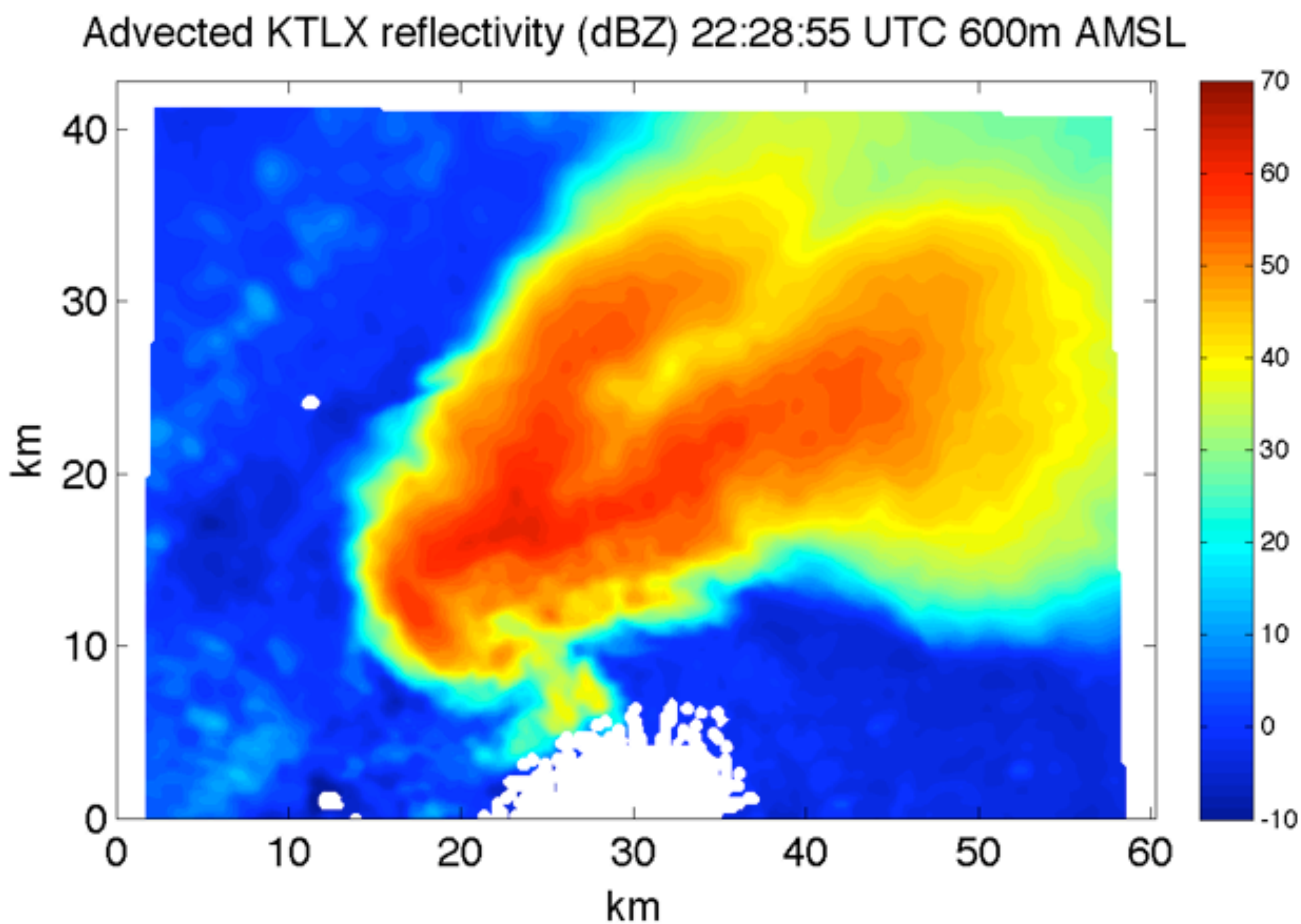
- Set δJ=0, integrate by parts. Leads to Euler-Lagrange equations for U,V and R:

$$\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial y^2}-\frac{\alpha}{\beta T}\left[\int \frac{\partial R}{\partial t}\frac{\partial R}{\partial x}dt+U\int\left(\frac{\partial R}{\partial x}\right)^2 dt+V\int\frac{\partial R}{\partial x}\frac{\partial R}{\partial y}dt\right]=0$$

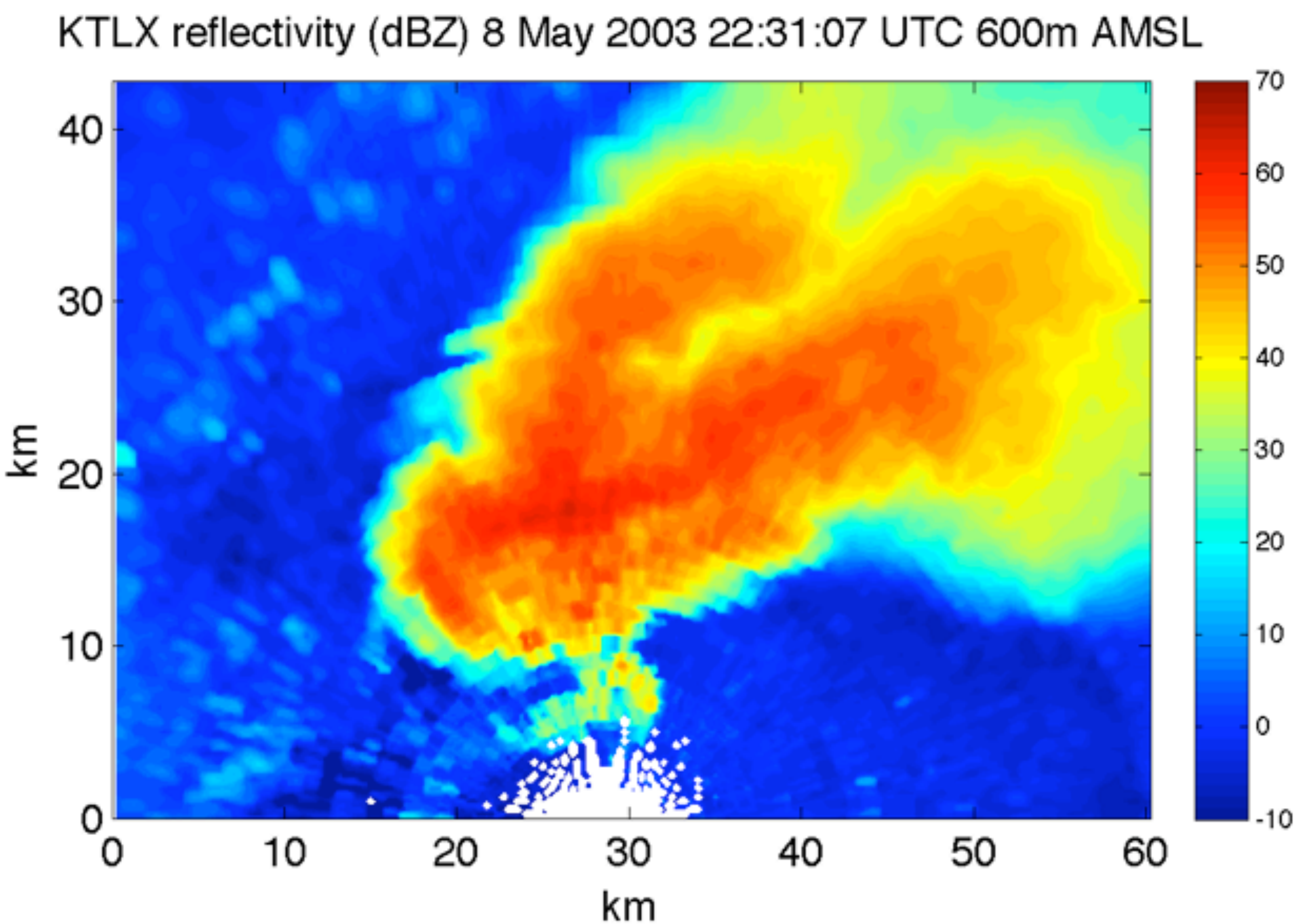
$$\frac{\partial^2 V}{\partial x^2}+\frac{\partial^2 V}{\partial y^2}-\frac{\alpha}{\beta T}\left[\int \frac{\partial R}{\partial t}\frac{\partial R}{\partial y}dt+U\int\frac{\partial R}{\partial x}\frac{\partial R}{\partial y}dt+V\int\left(\frac{\partial R}{\partial y}\right)^2 dt\right]=0$$

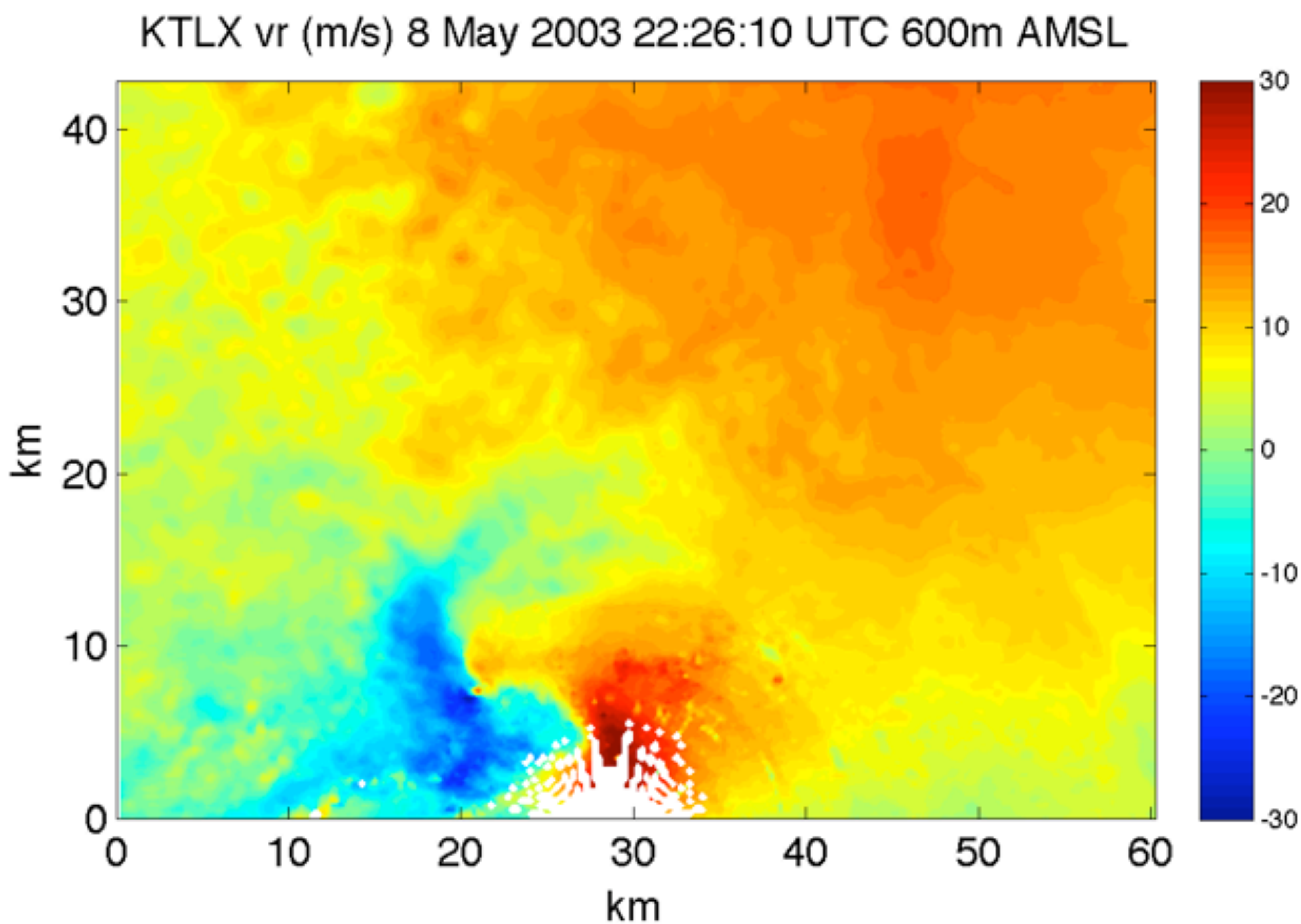
$$\alpha\left(\frac{\partial}{\partial t}+U\frac{\partial}{\partial x}+V\frac{\partial}{\partial y}\right)^2 R+\alpha\left(\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}\right)\left(\frac{\partial R}{\partial t}+U\frac{\partial R}{\partial x}+V\frac{\partial R}{\partial y}\right)$$
$$+\left(\frac{\partial \alpha}{\partial t}+U\frac{\partial \alpha}{\partial x}+V\frac{\partial \alpha}{\partial y}\right)\left(\frac{\partial R}{\partial t}+U\frac{\partial R}{\partial x}+V\frac{\partial R}{\partial y}\right)=0$$

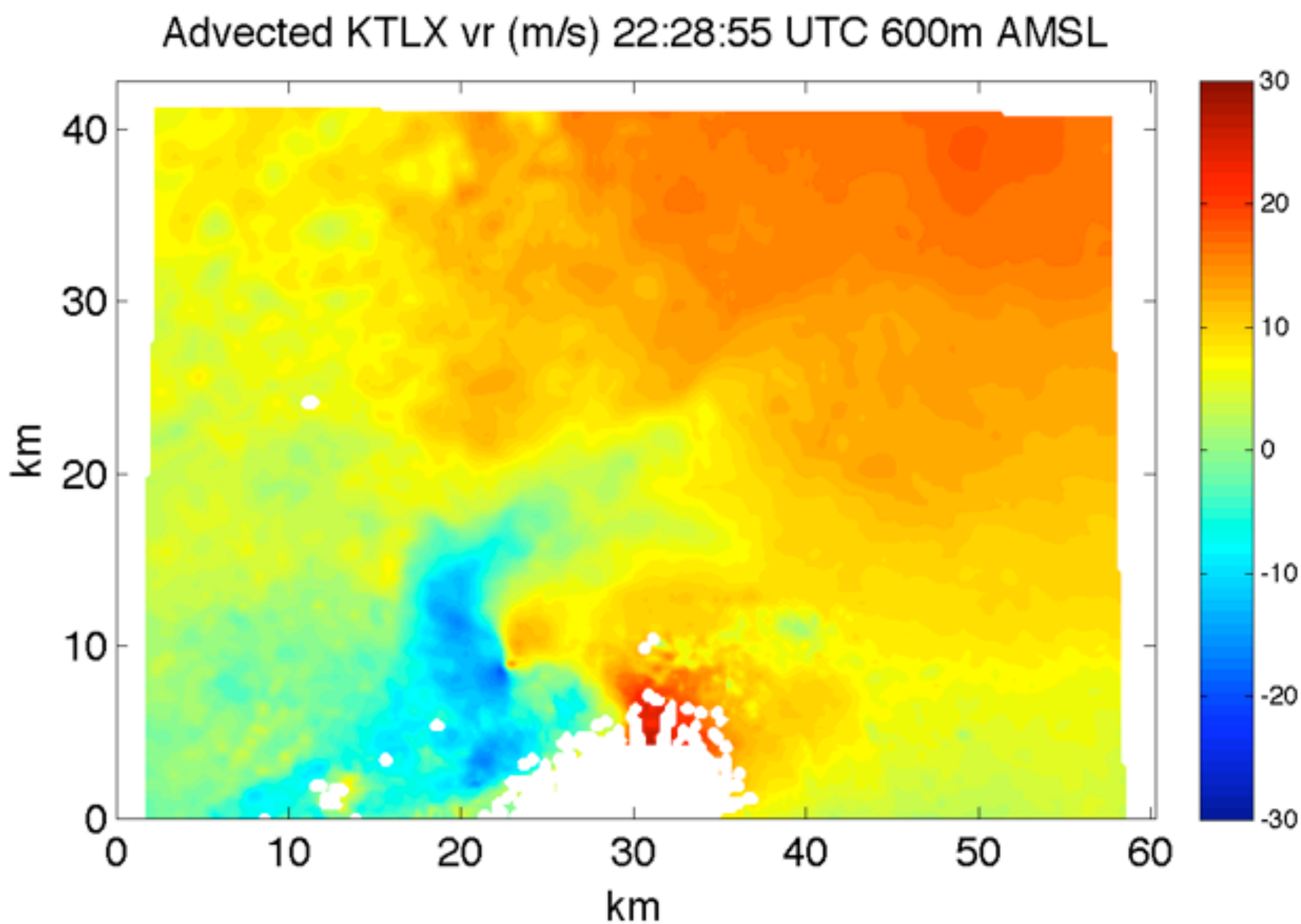

KTLX reflectivity (dBZ) 8 May 2003 22:26:10 UTC 600m AMSL
km
km
0
10
20
30
40
50
60
70
60
50
40
30
20
10
0
-10



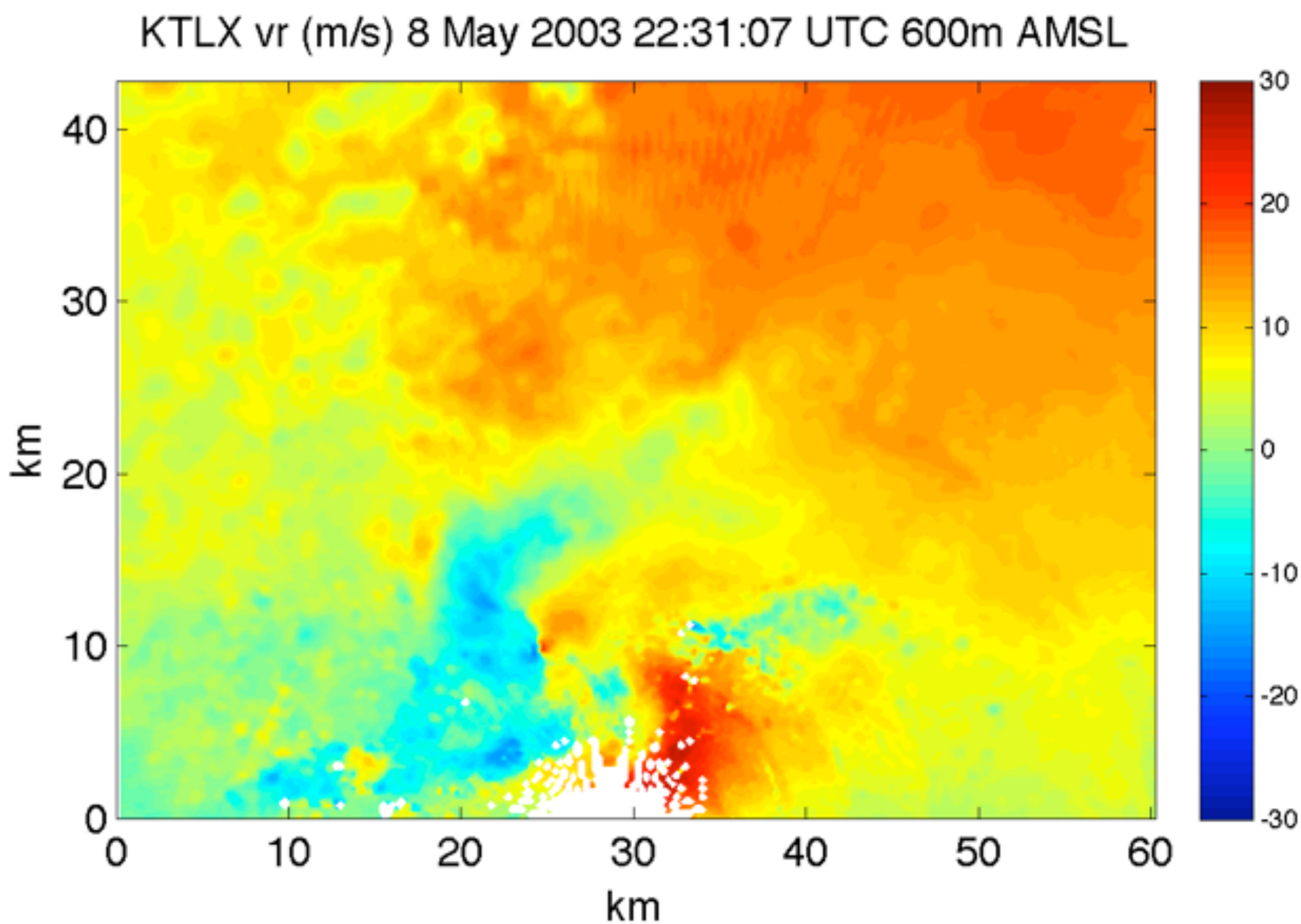
Advected KTLX reflectivity (dBZ) 22:28:55 UTC 600m AMSL
km
0
10
20
30
40
0
10
20
30
40
50
60
km
70
60
50
40
30
20
10
0
-10


KTLX reflectivity (dBZ) 8 May 2003 22:31:07 UTC 600m AMSL
km
km
0
10
20
30
40
50
60
70
-10

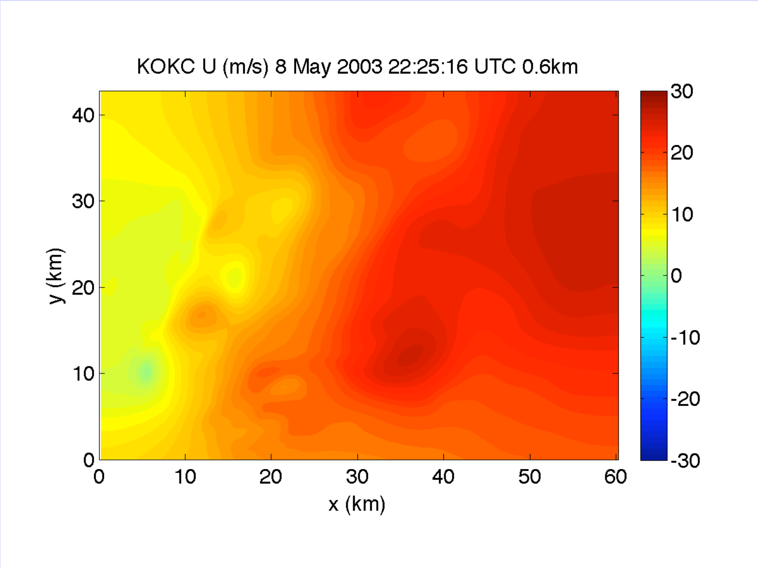

KTLX vr (m/s) 8 May 2003 22:26:10 UTC 600m AMSL
km
km
0
10
20
30
40
50
60
-30
-20
-10
0
10
20
30

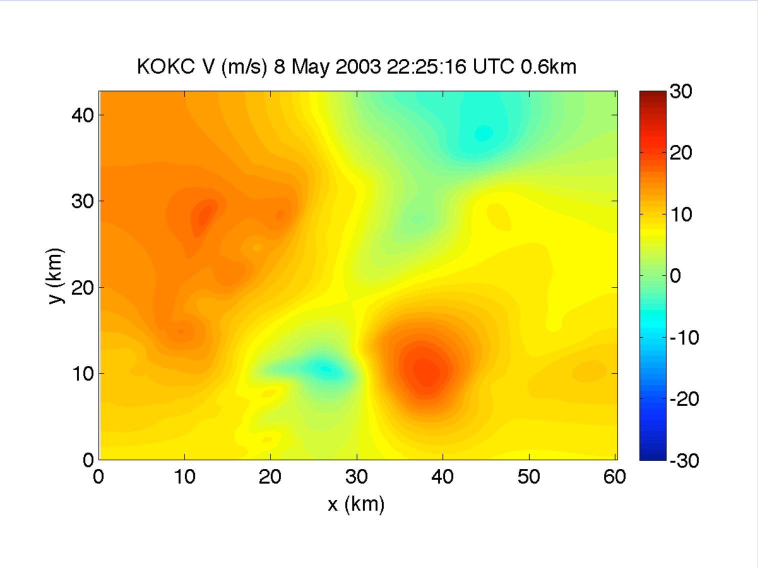


Advected KTLX vr (m/s) 22:28:55 UTC 600m AMSL
km
km
0
10
20
30
40
50
60
0
10
20
30
40
30
20
10
0
-10
-20
-30


KTLX vr (m/s) 8 May 2003 22:31:07 UTC 600m AMSL
km
km
0
10
20
30
40
0
10
20
30
40
50
60
30
20
10
0
-10
-20
-30

Advection-Correction Results

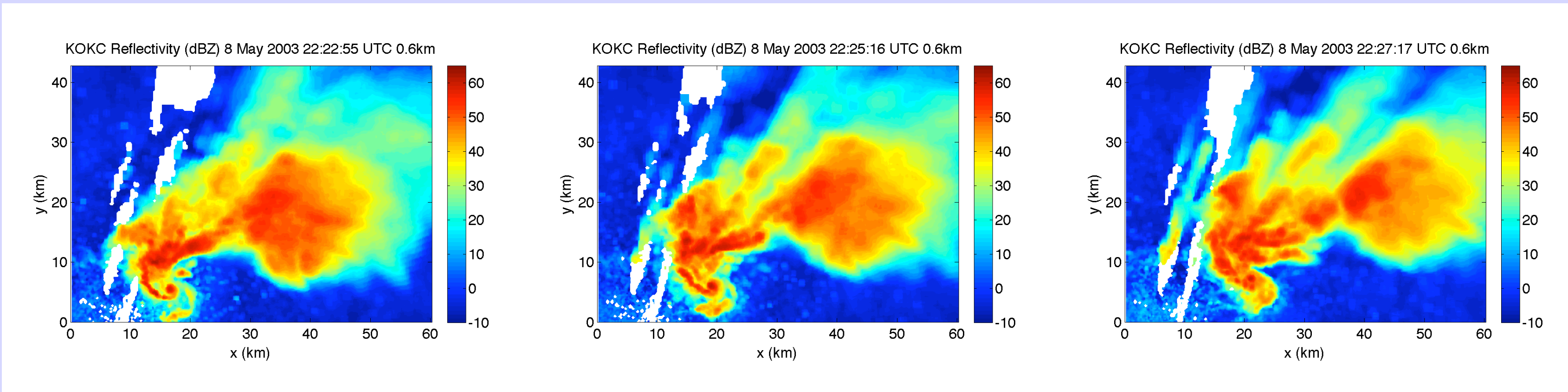




Spatially-variable pattern-translation components U,V for the following example scans

- Variability from about -8 to 25 m/s

Advection-Correction Results

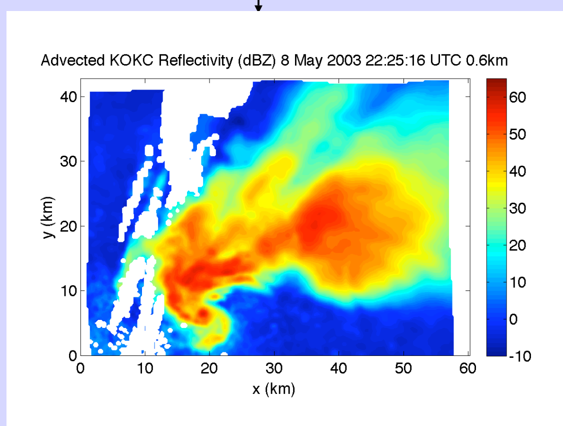


reflectivity 22:22:55

observed 22:25:16

reflectivity 22:27:17

advected 22:25:16



Advection Parameters

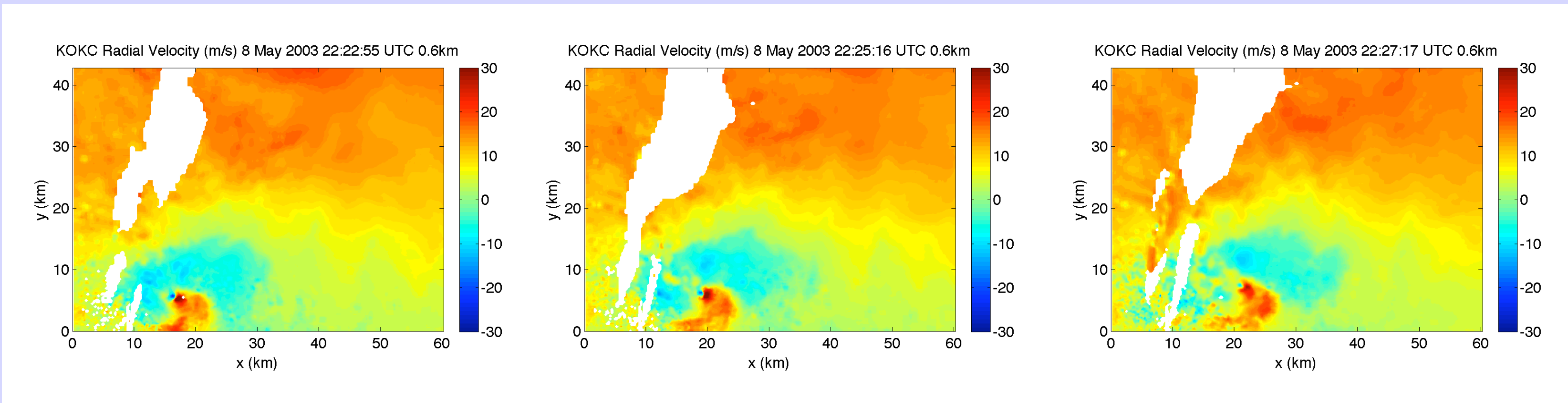
T=262s

TE=141s

nt=16

b=100

Advection-Correction Results

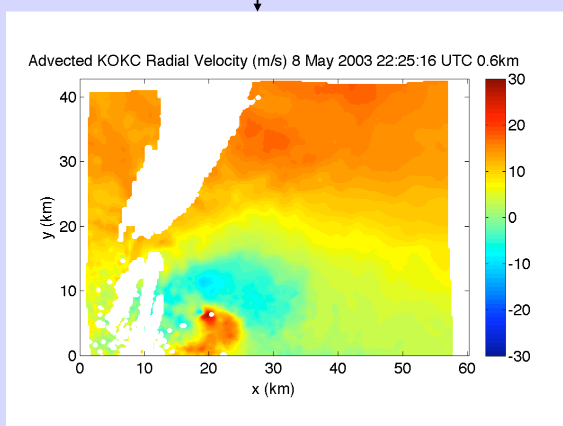


radial velocity 22:22:55

observed vr 22:25:16

radial velocity 22:27:17

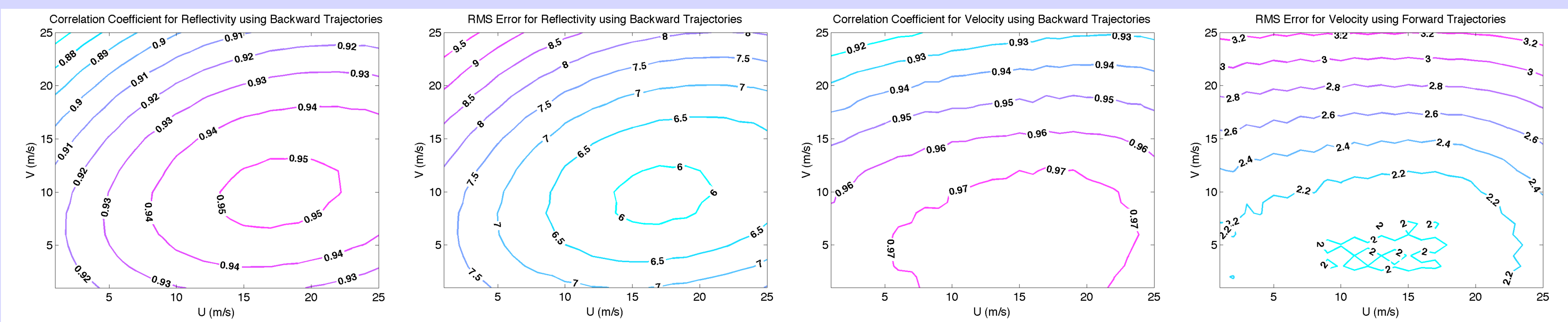
advected vr 22:25:16



Advection-Correction Results

The advection correction using spatially-variable pattern-translation components for this case is an improvement over any constant pattern-translation.

	Reflectivity Correlation	Radial Velocity Correlation	Reflectivity RMS Error	Radial Velocity RMS Error
Spatially Variable *U*, *V*	0.9764	0.9839	4.2307	1.4233
Constant *U*, *V* using Backward Trajectories	0.9528	0.9784	5.8740	1.7218
Constant *U*, *V* using Forward Trajectories	0.9330	0.9706	6.9547	1.9684



Dual-Doppler Wind Analysis

- Simple, traditional dual-Doppler method intended for low elevation angles (< 10º)

$$u = \frac{(y - y_2) r_1 v_{r1} - (y - y_1) r_2 v_{r2}}{(x - x_1)(y - y_2) - (x - x_2)(y - y_1)}$$

$$v = \frac{(x - x_2) r_1 v_{r1} - (x - x_1) r_2 v_{r2}}{(x - x_2)(y - y_1) - (x - x_1)(y - y_2)}$$

- x and y are Cartesian coordinates for the analysis point, (x_1,y_1), (x_2,y_2) are locations of radars 1 and 2, r_1, r_2 are distances of the analysis point from radars 1 and 2, v_{r1}, v_{r2} are the radial velocities

Dual-Doppler Vertical Velocity Analysis

- Vertical velocity is calculated from mass conservation (Brandes 1977)

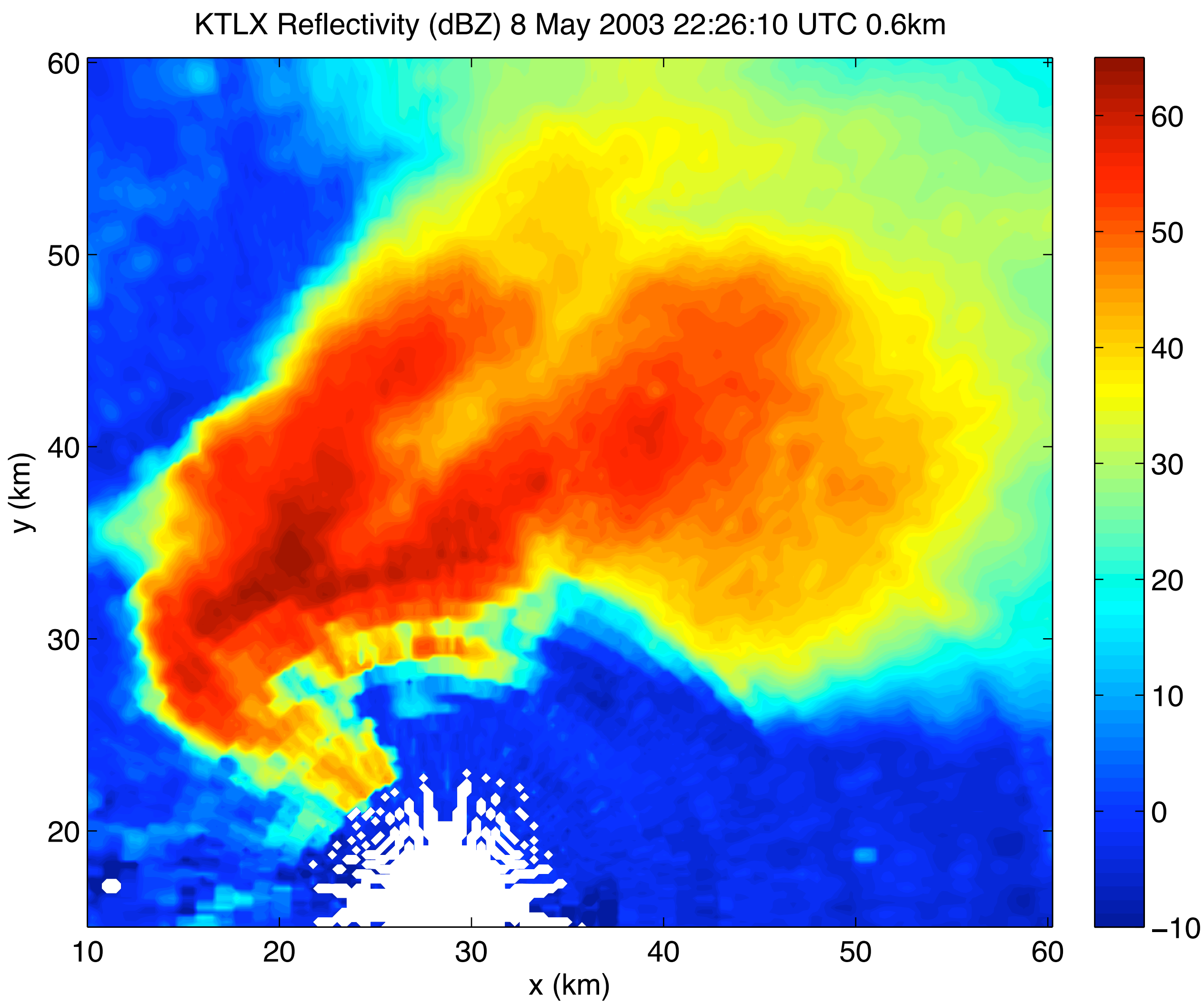
$$w = -e^{-kz} \int_{z_o}^{z} \delta e^{-kz'} dz'$$

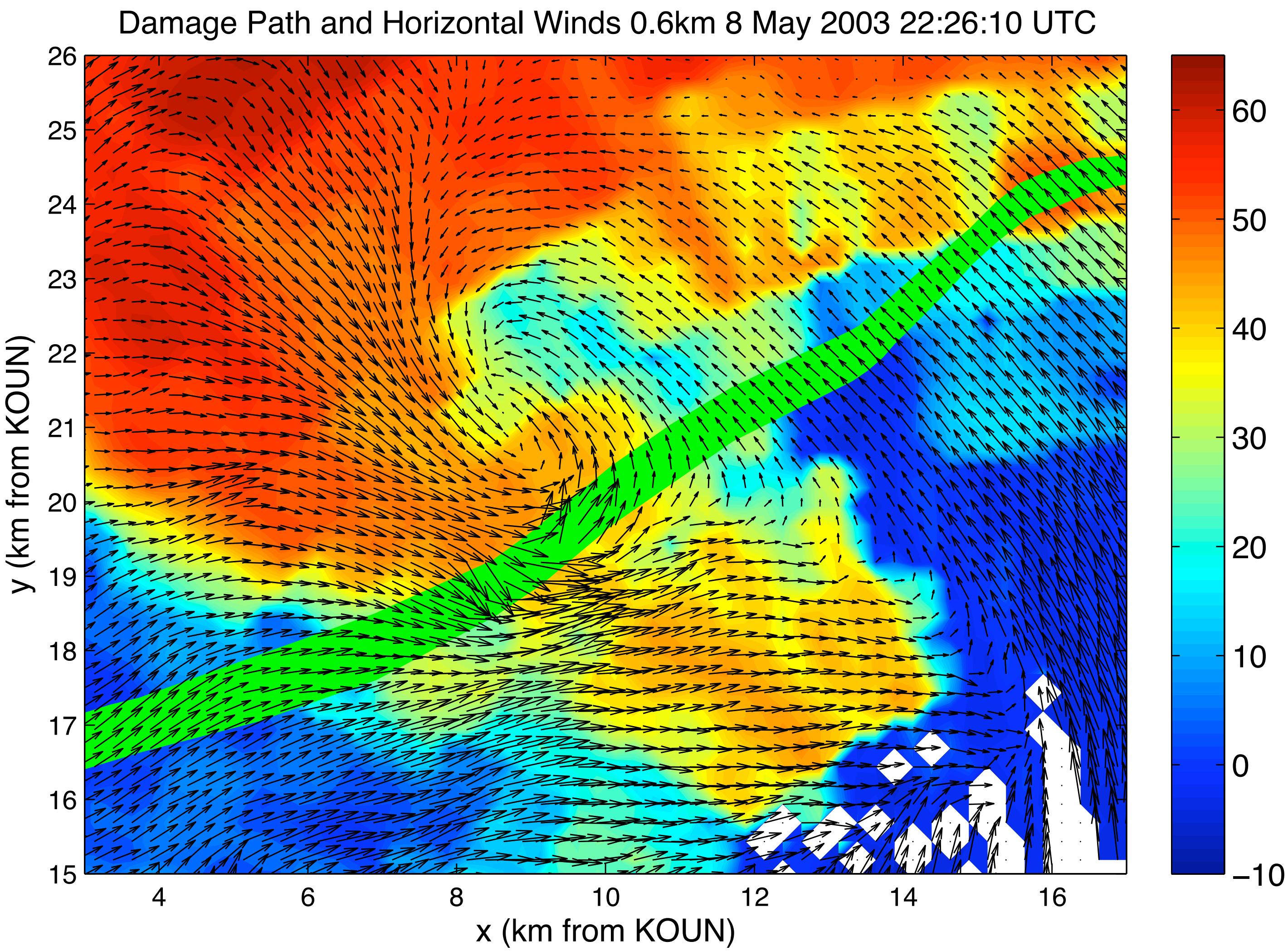
where $\delta = \dfrac{\partial u}{\partial x} + \dfrac{\partial v}{\partial y}$ and $k = -\dfrac{\partial}{\partial z} \ln \rho = \dfrac{1}{H}$

Scale height H is set to 10km.

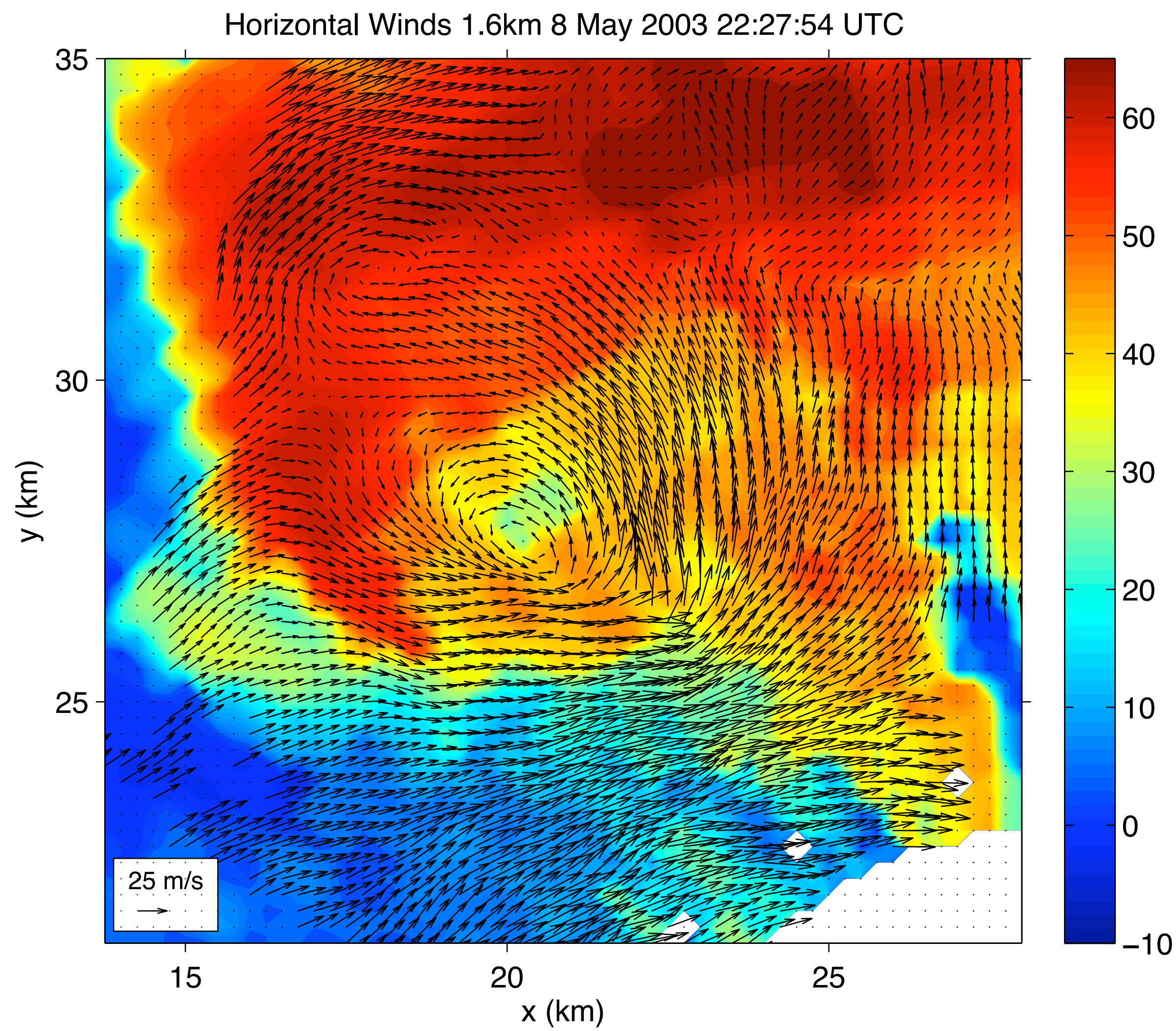
Dual-Doppler Results

8 May 2003
22:26

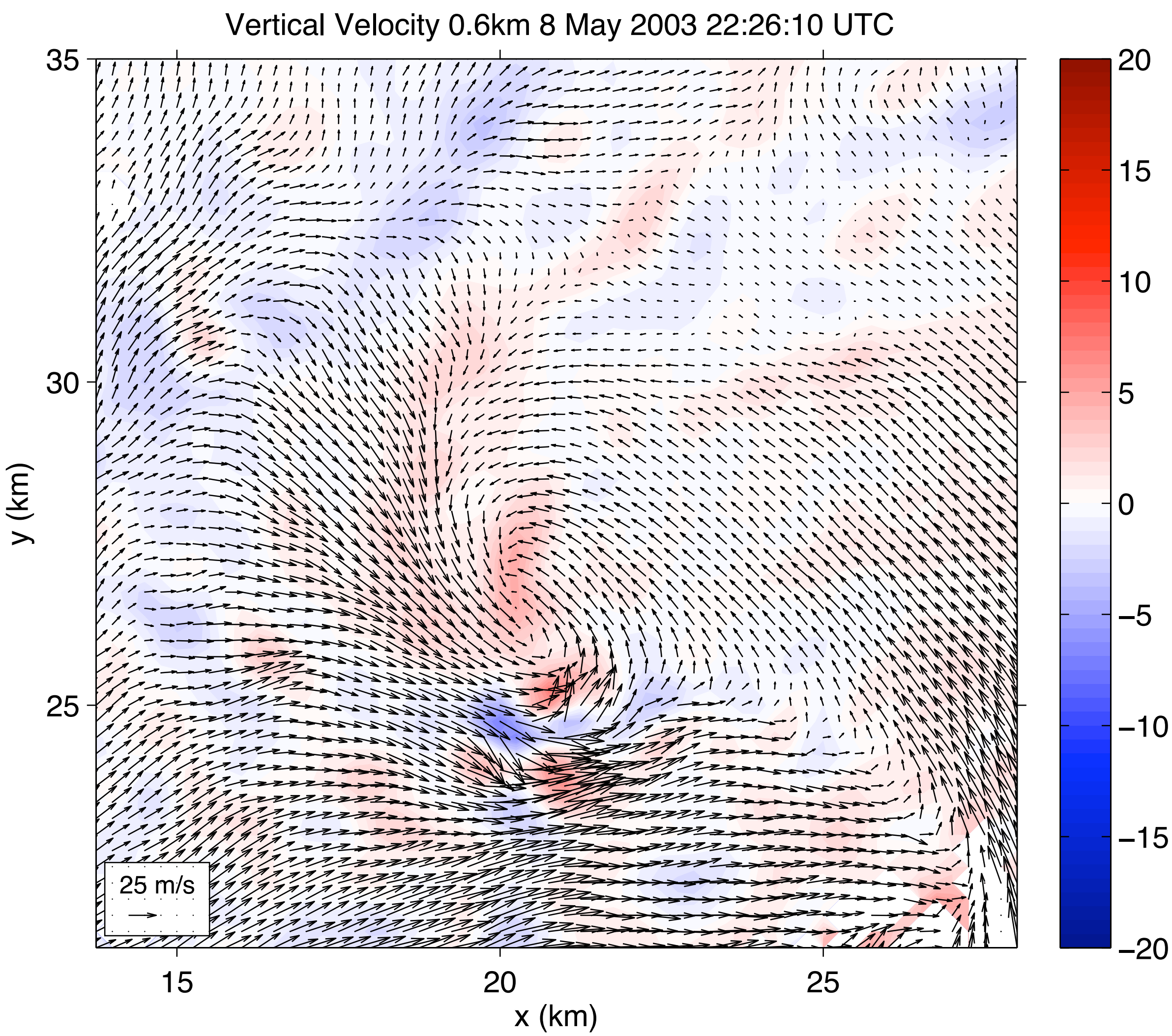

KTLX Reflectivity (dBZ) 8 May 2003 22:26:10 UTC 0.6km
y (km)
x (km)
10
20
30
40
50
60
60
50
40
30
20
10
0
−10



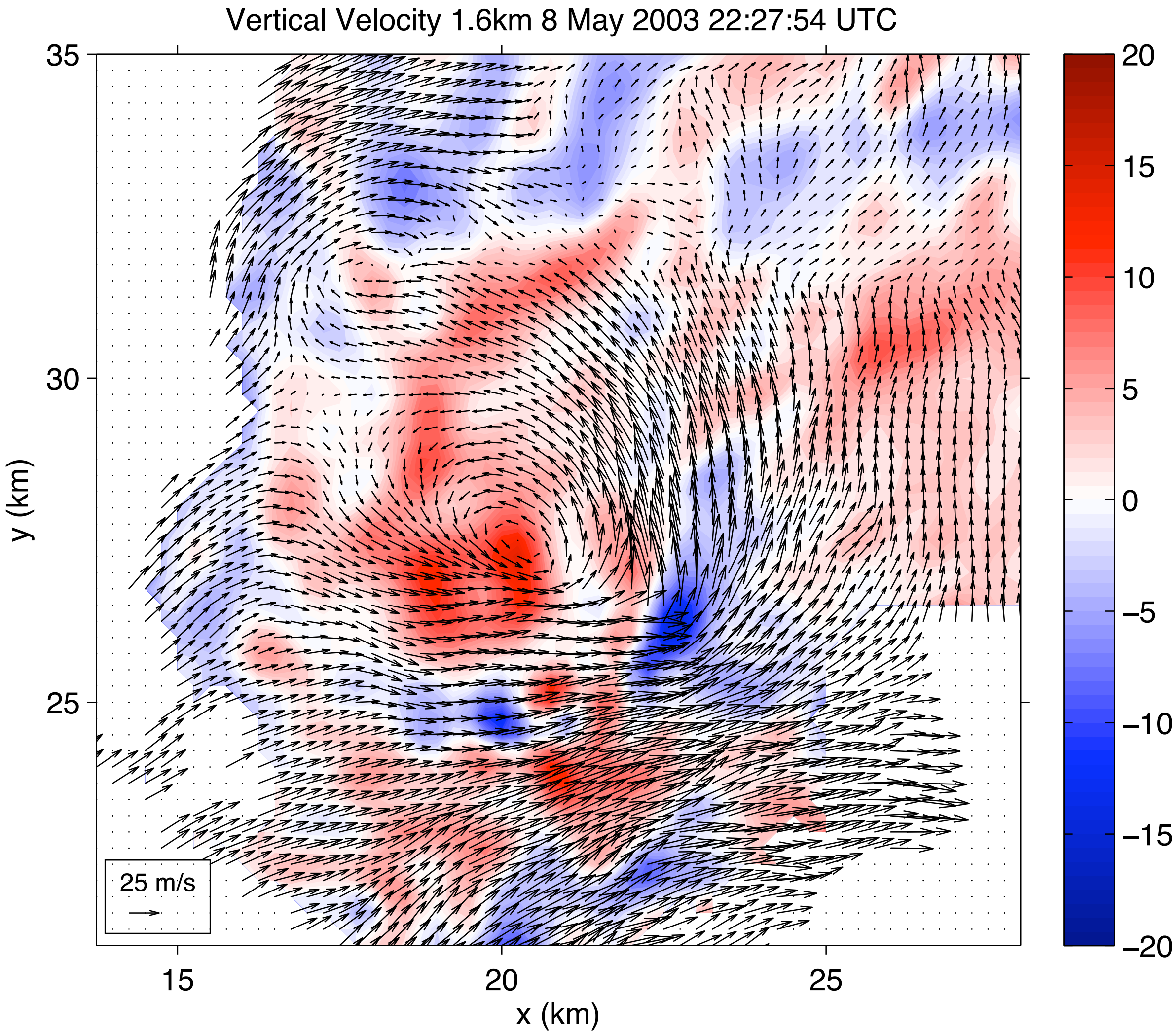
Damage Path and Horizontal Winds 0.6km 8 May 2003 22:26:10 UTC
y (km from KOUN)
26
25
24
23
22
21
20
19
18
17
16
15
4
6
8
10
12
14
16
x (km from KOUN)
60
50
40
30
20
10
0
−10



Horizontal Winds 1.6km 8 May 2003 22:27:54 UTC
35
30
25
y (km)
15
20
25
x (km)
25 m/s
60
50
40
30
20
10
0
−10

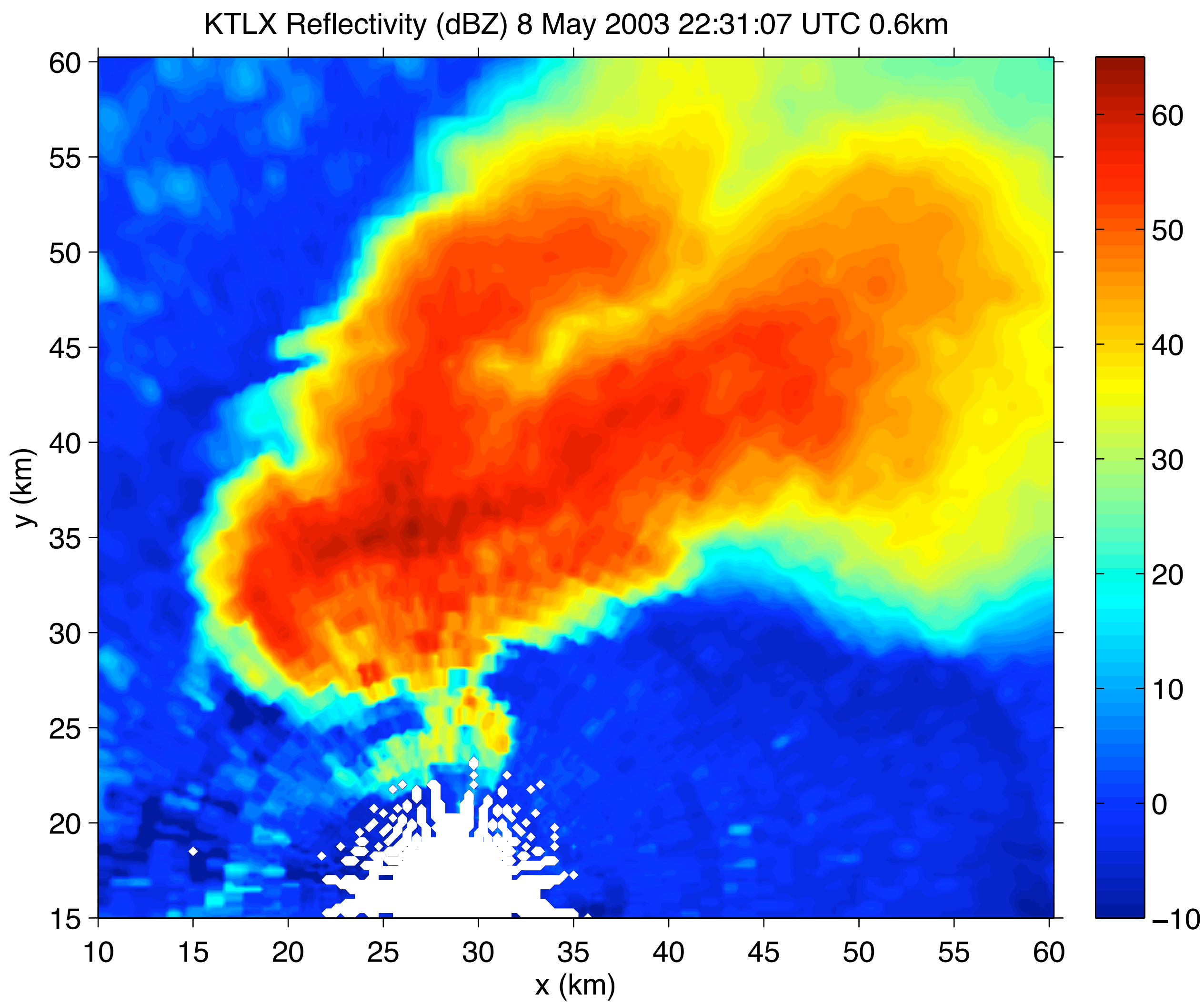


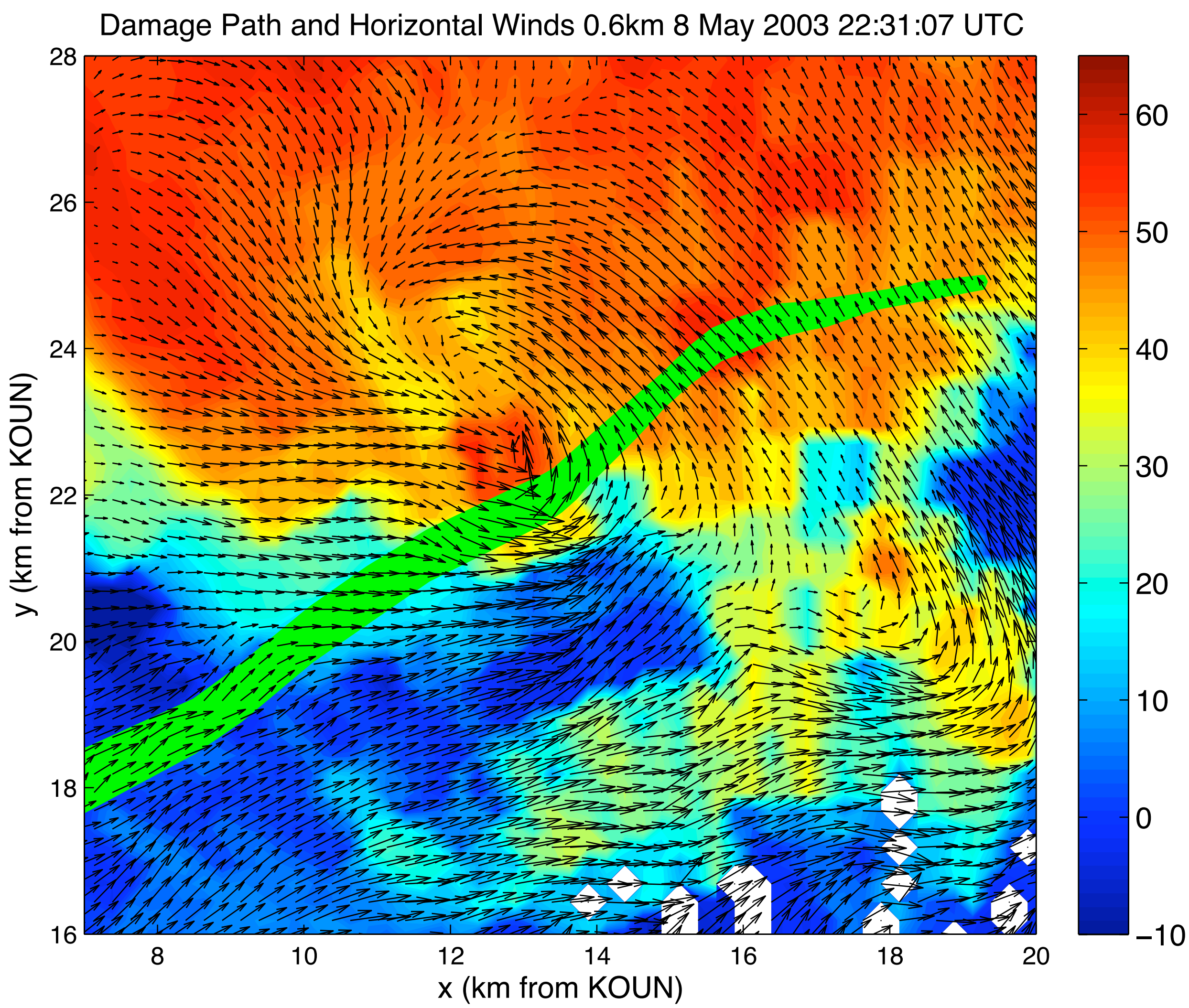
Vertical Velocity 0.6km 8 May 2003 22:26:10 UTC
35
30
25
y (km)
15
20
25
x (km)
25 m/s
20
15
10
5
0
−5
−10
−15
−20



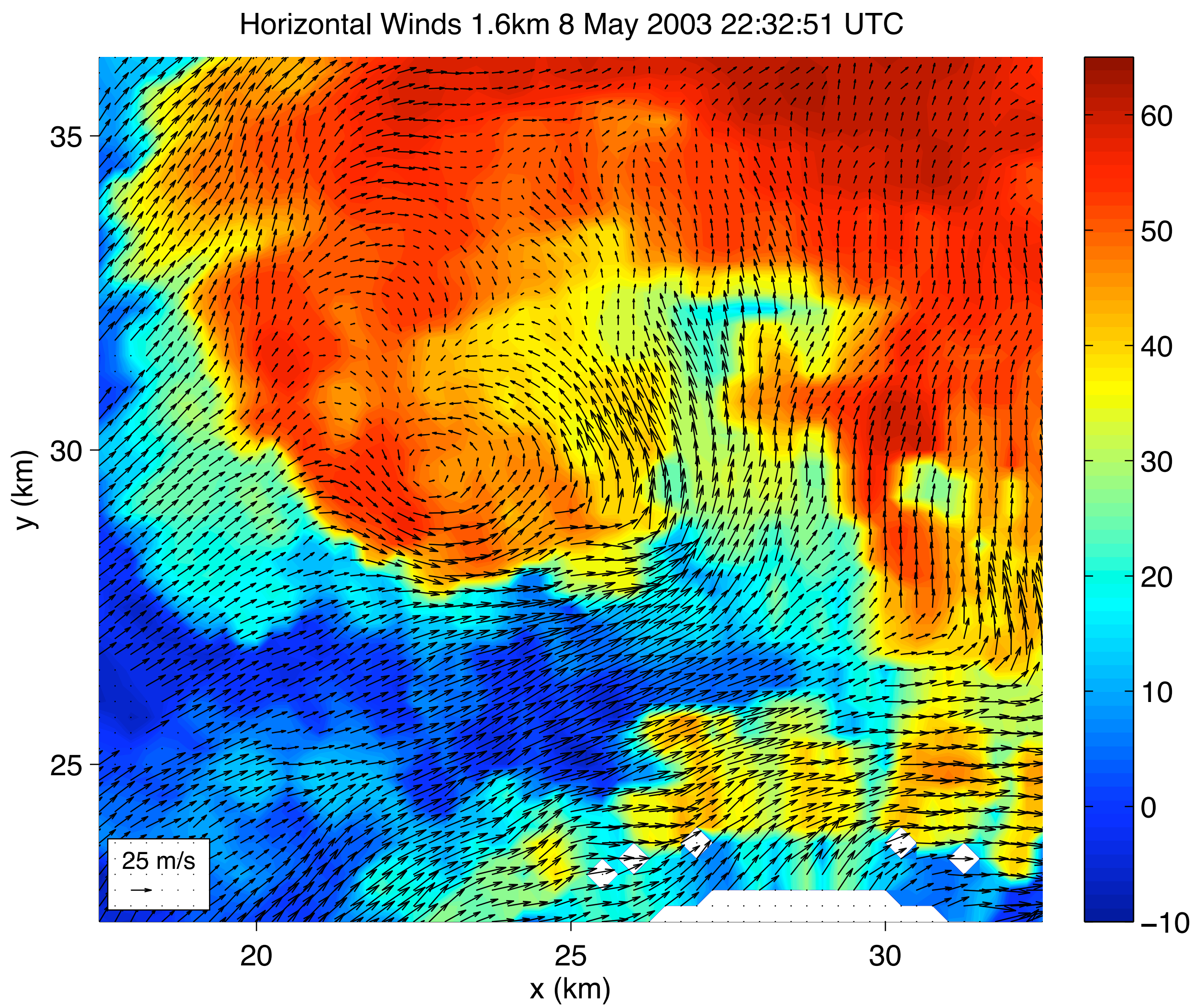
Vertical Velocity 1.6km 8 May 2003 22:27:54 UTC
y (km)
x (km)
35
30
25
15
20
25
25 m/s
20
15
10
5
0
−5
−10
−15
−20

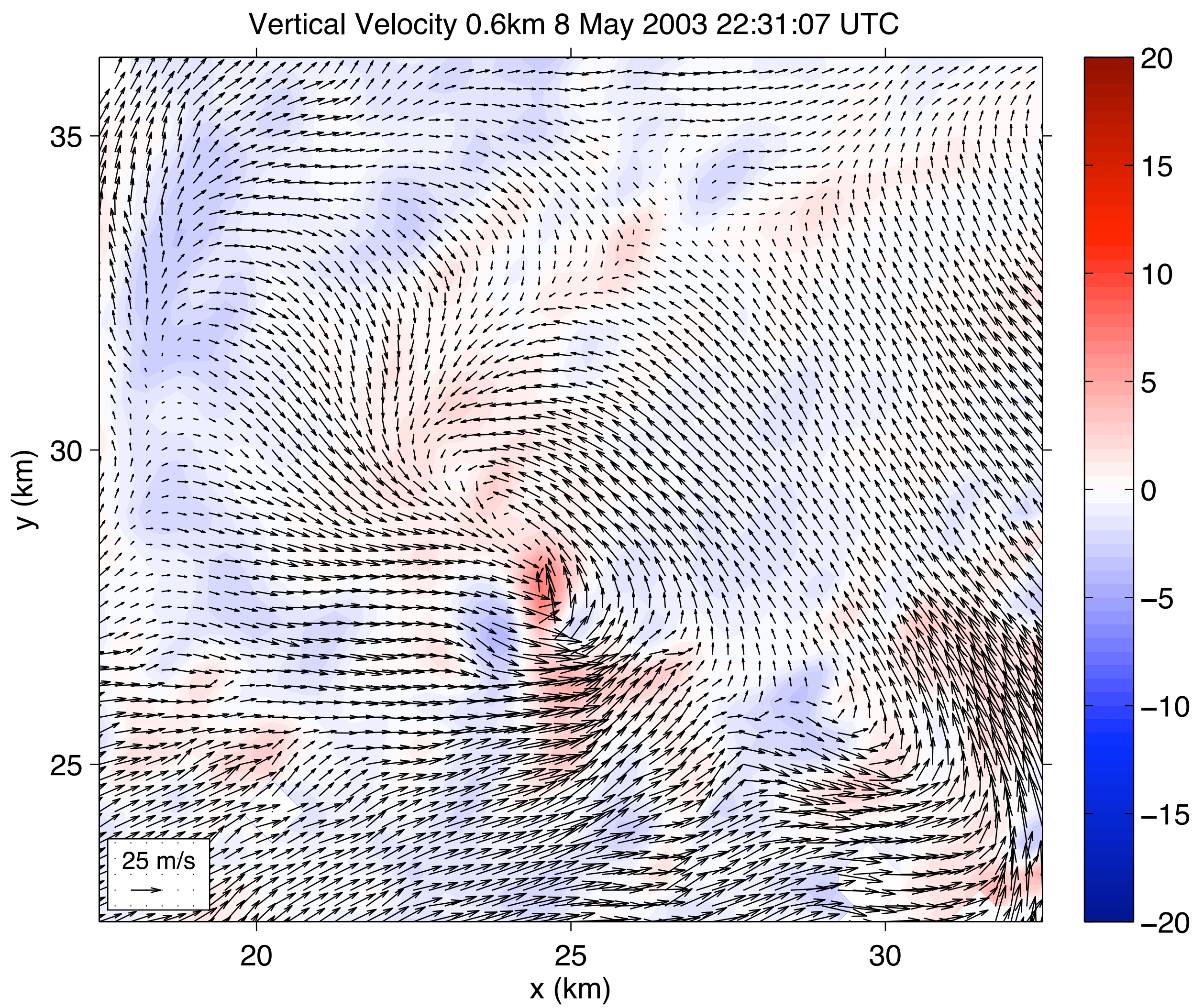
8 May 2003
22:31


KTLX Reflectivity (dBZ) 8 May 2003 22:31:07 UTC 0.6km
y (km)
x (km)
10
15
20
25
30
35
40
45
50
55
60
60
55
50
45
40
35
30
25
20
15
60
50
40
30
20
10
0
−10

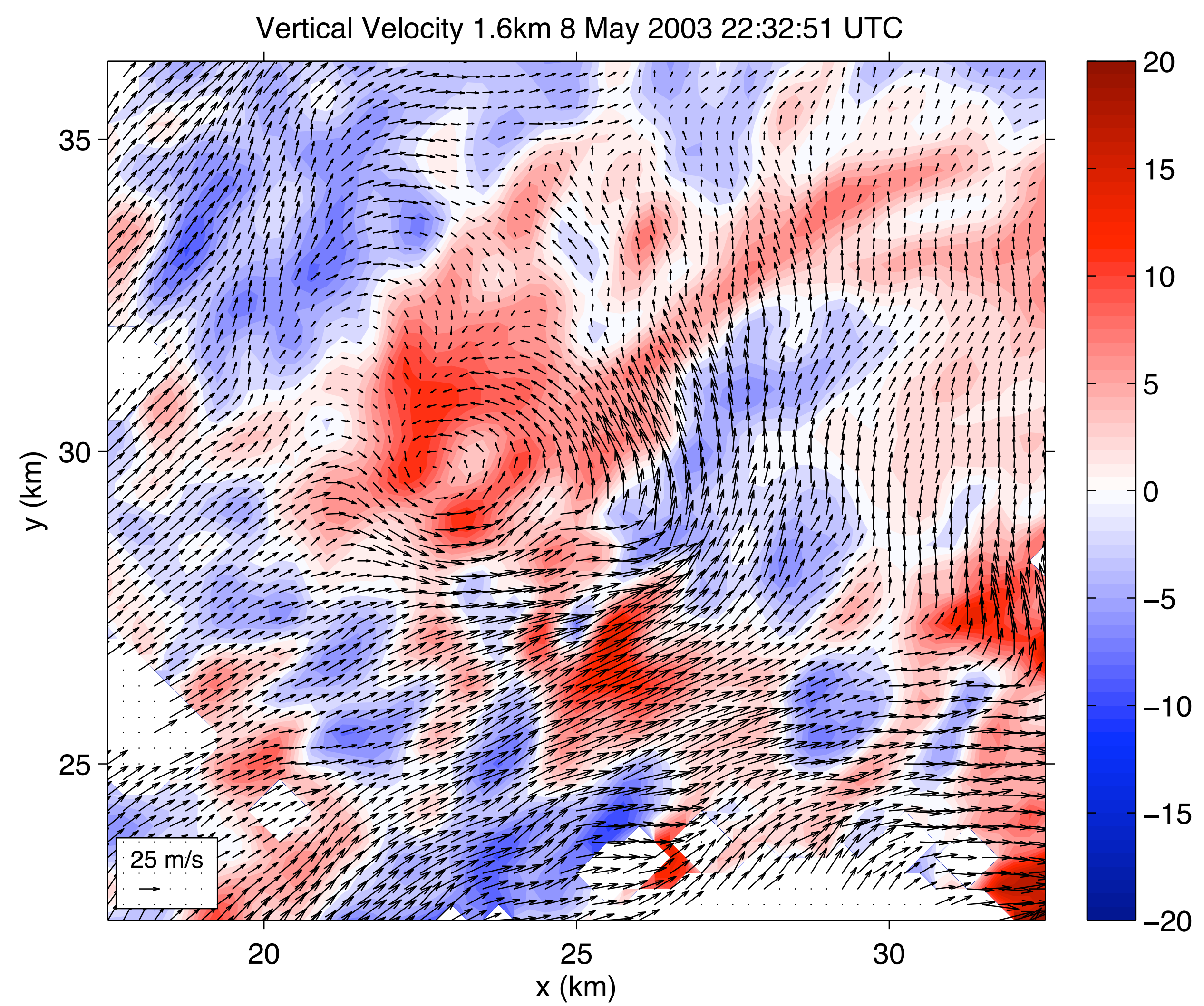


Damage Path and Horizontal Winds 0.6km 8 May 2003 22:31:07 UTC
y (km from KOUN)
x (km from KOUN)
28
26
24
22
20
18
16
8
10
12
14
16
18
20
60
50
40
30
20
10
0
−10


Horizontal Winds 1.6km 8 May 2003 22:32:51 UTC
y (km)
x (km)
35
30
25
20
25
30
25 m/s
60
50
40
30
20
10
0
−10

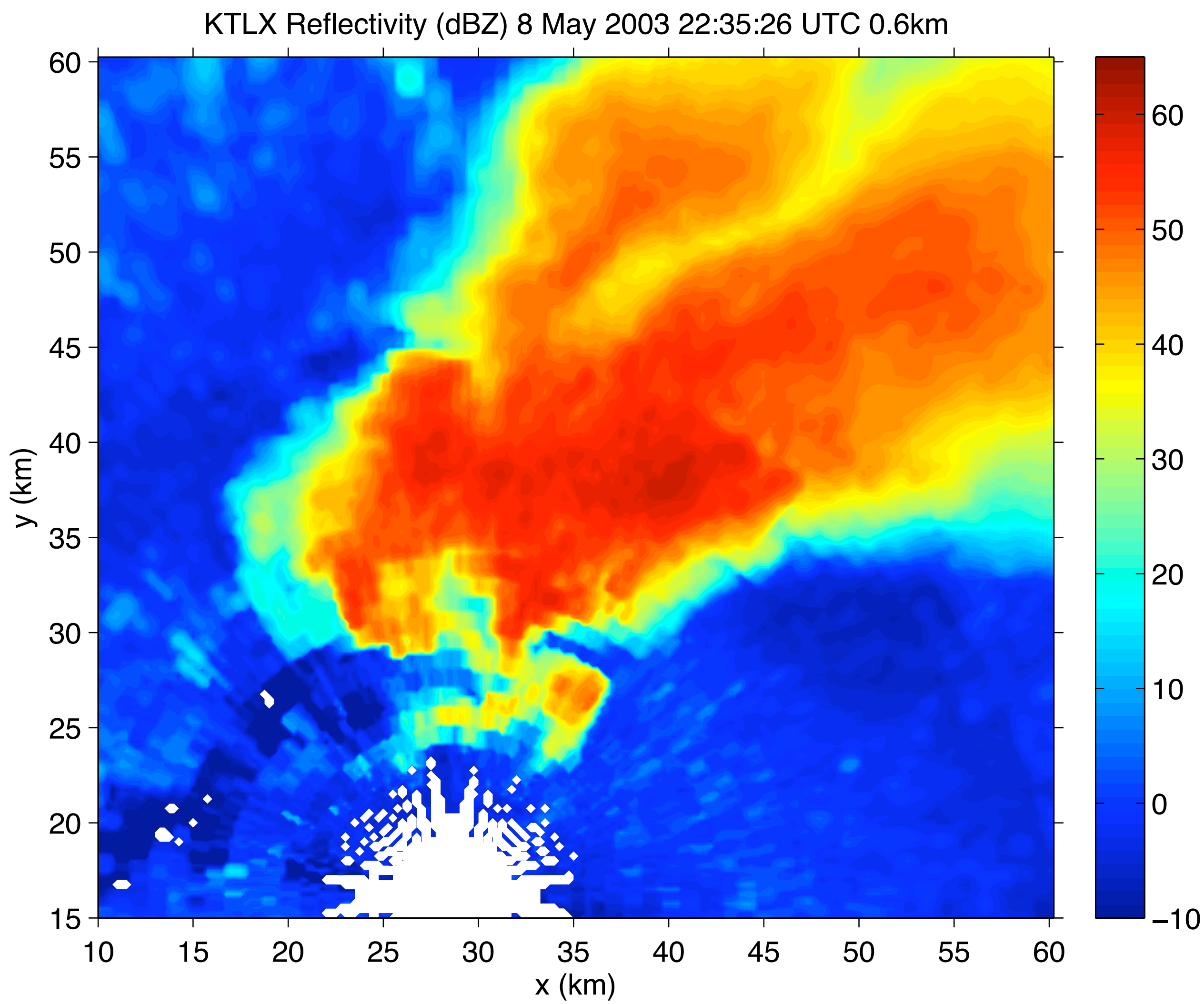


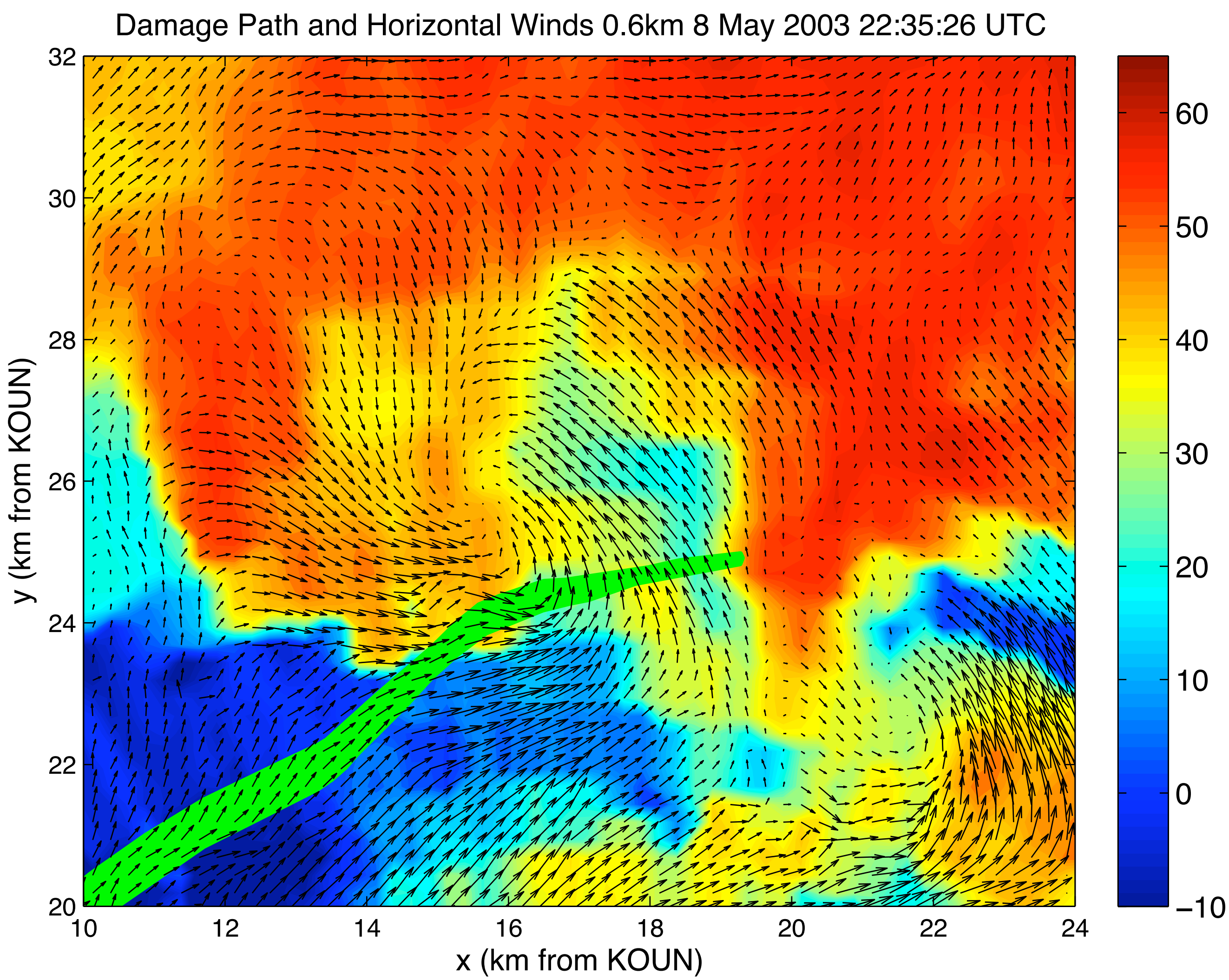
Vertical Velocity 0.6km 8 May 2003 22:31:07 UTC
y (km)
x (km)
25 m/s
35
30
25
20
25
30
20
15
10
5
0
−5
−10
−15
−20



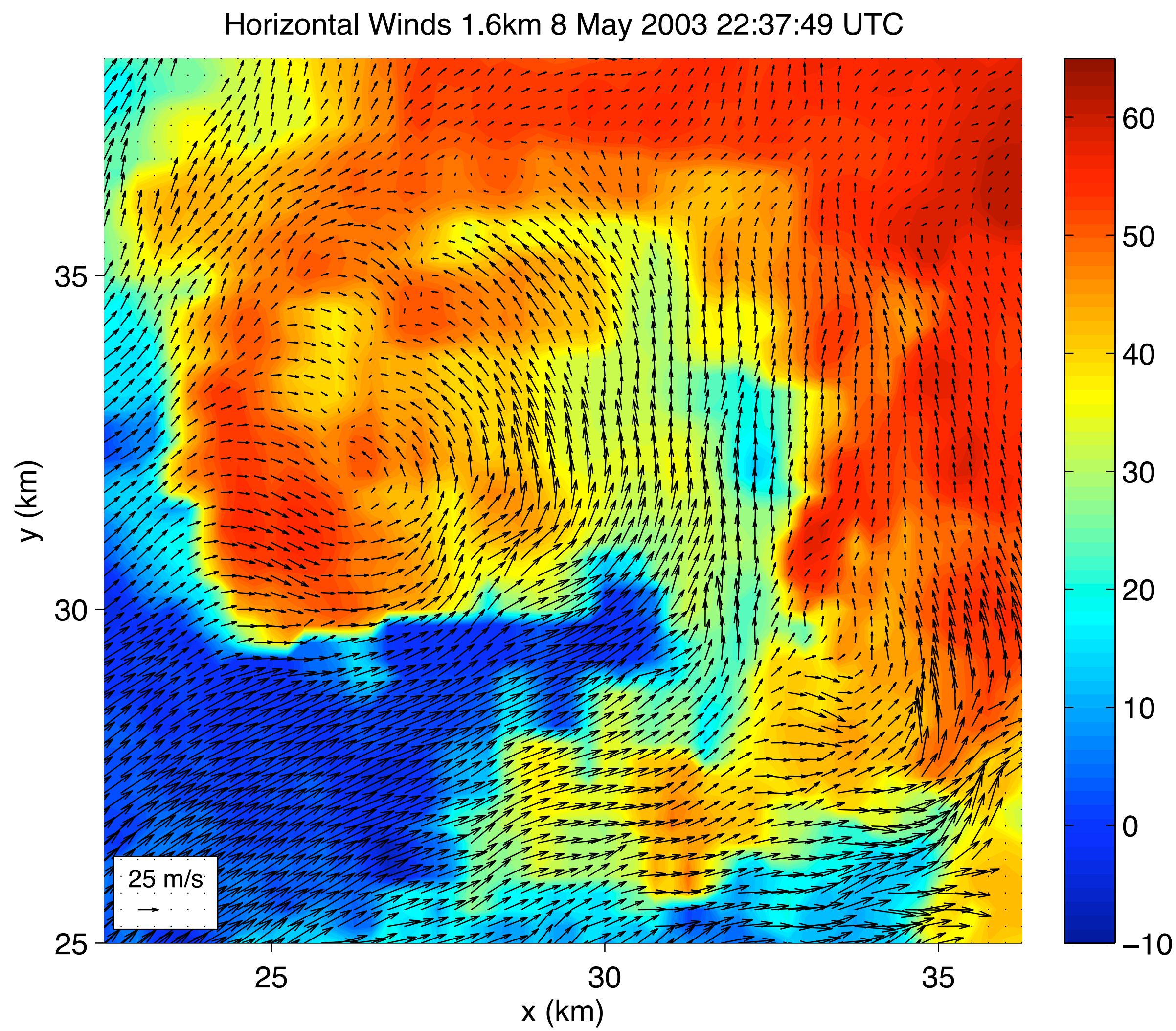
Vertical Velocity 1.6km 8 May 2003 22:32:51 UTC
y (km)
x (km)
25 m/s
35
30
25
20
25
30
20
15
10
5
0
−5
−10
−15
−20

8 May 2003
22:35

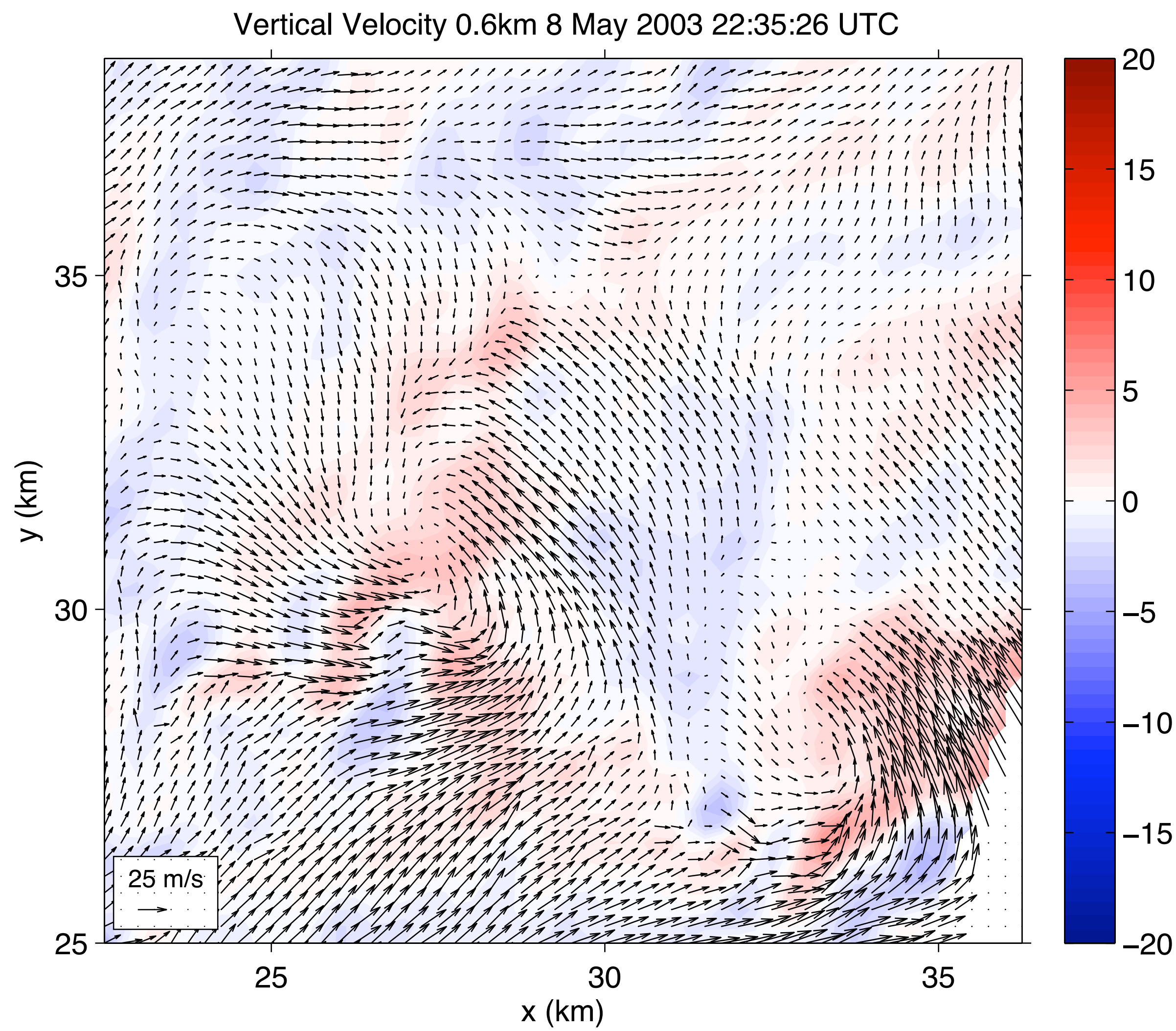

KTLX Reflectivity (dBZ) 8 May 2003 22:35:26 UTC 0.6km
60
55
50
45
40
35
30
25
20
15
y (km)
10
15
20
25
30
35
40
45
50
55
60
x (km)
60
50
40
30
20
10
0
−10



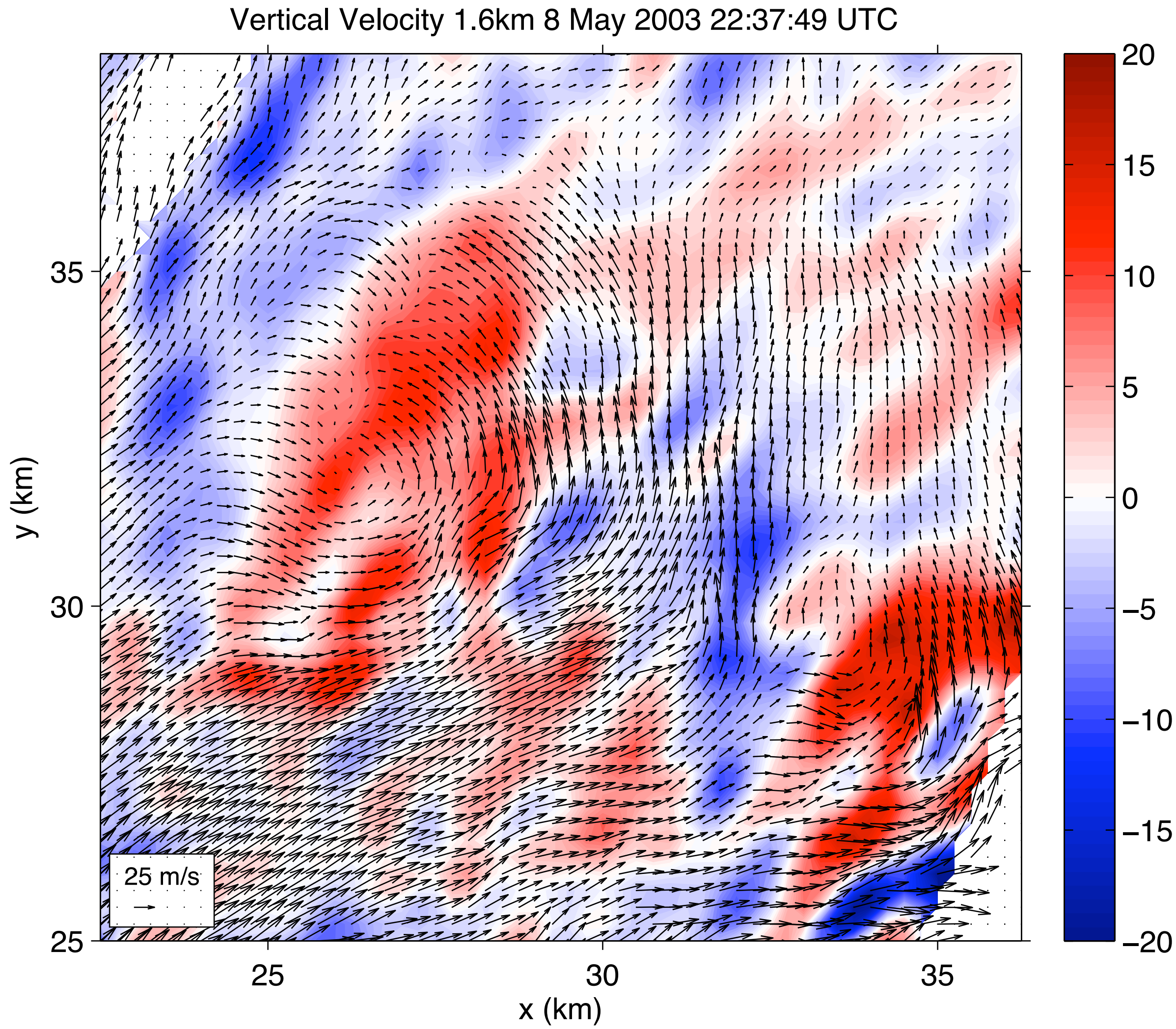
Damage Path and Horizontal Winds 0.6km 8 May 2003 22:35:26 UTC
y (km from KOUN)
x (km from KOUN)
32
30
28
26
24
22
20
10
12
14
16
18
20
22
24
60
50
40
30
20
10
0
−10



Horizontal Winds 1.6km 8 May 2003 22:37:49 UTC
y (km)
35
30
25
x (km)
25
30
35
25 m/s
60
50
40
30
20
10
0
−10

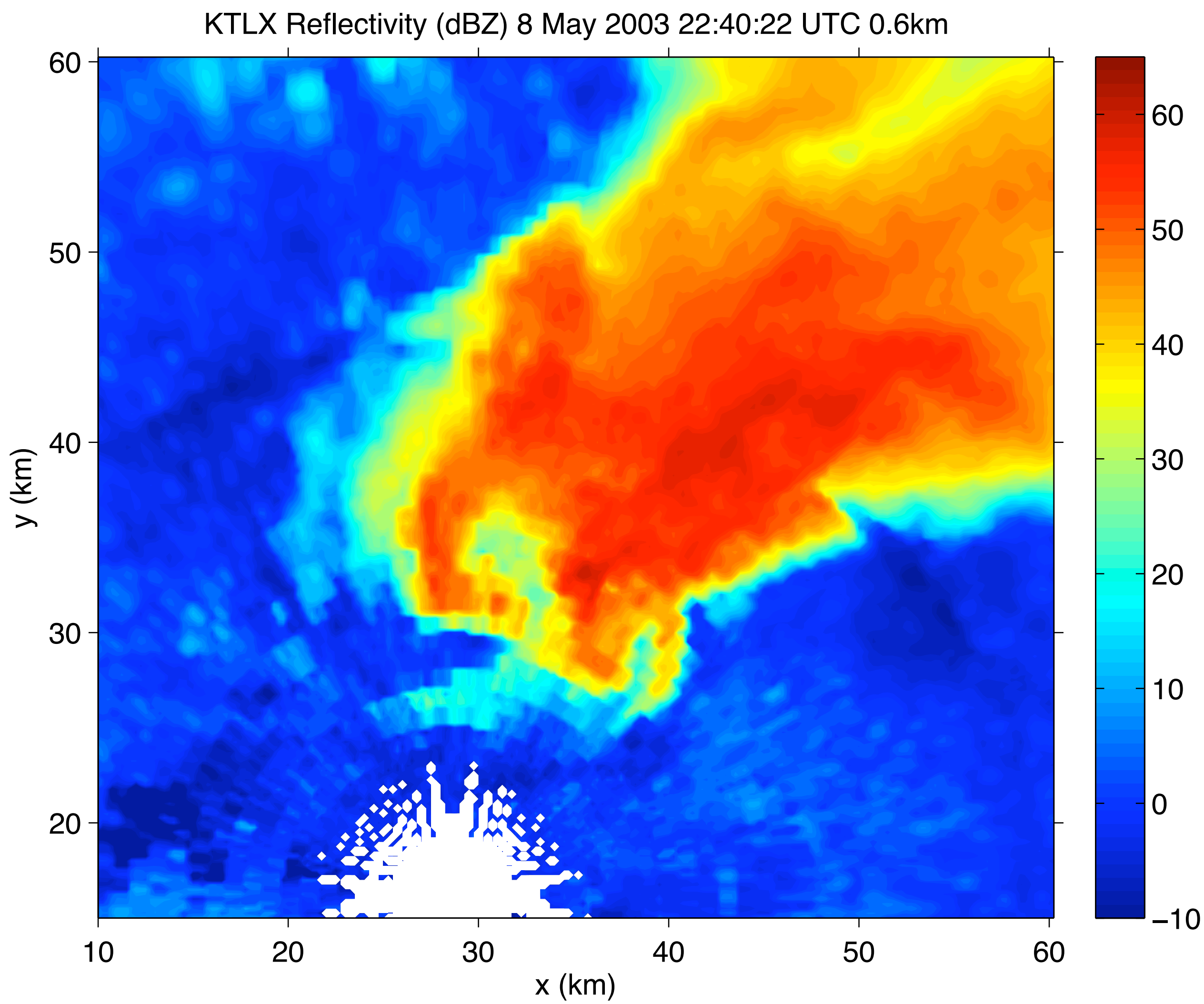


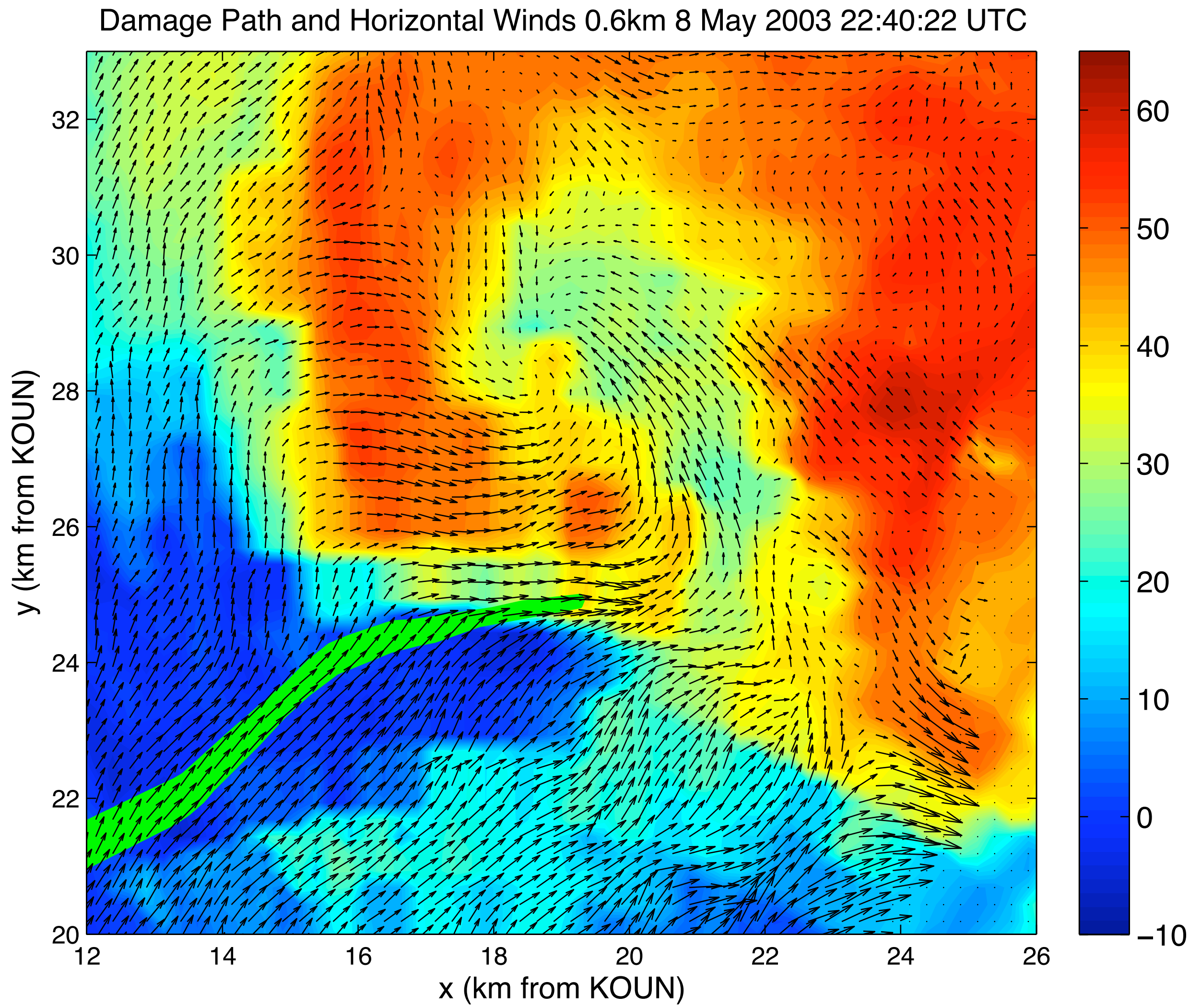
Vertical Velocity 0.6km 8 May 2003 22:35:26 UTC
y (km)
x (km)
25 m/s
25
30
35
25
30
35
20
15
10
5
0
−5
−10
−15
−20

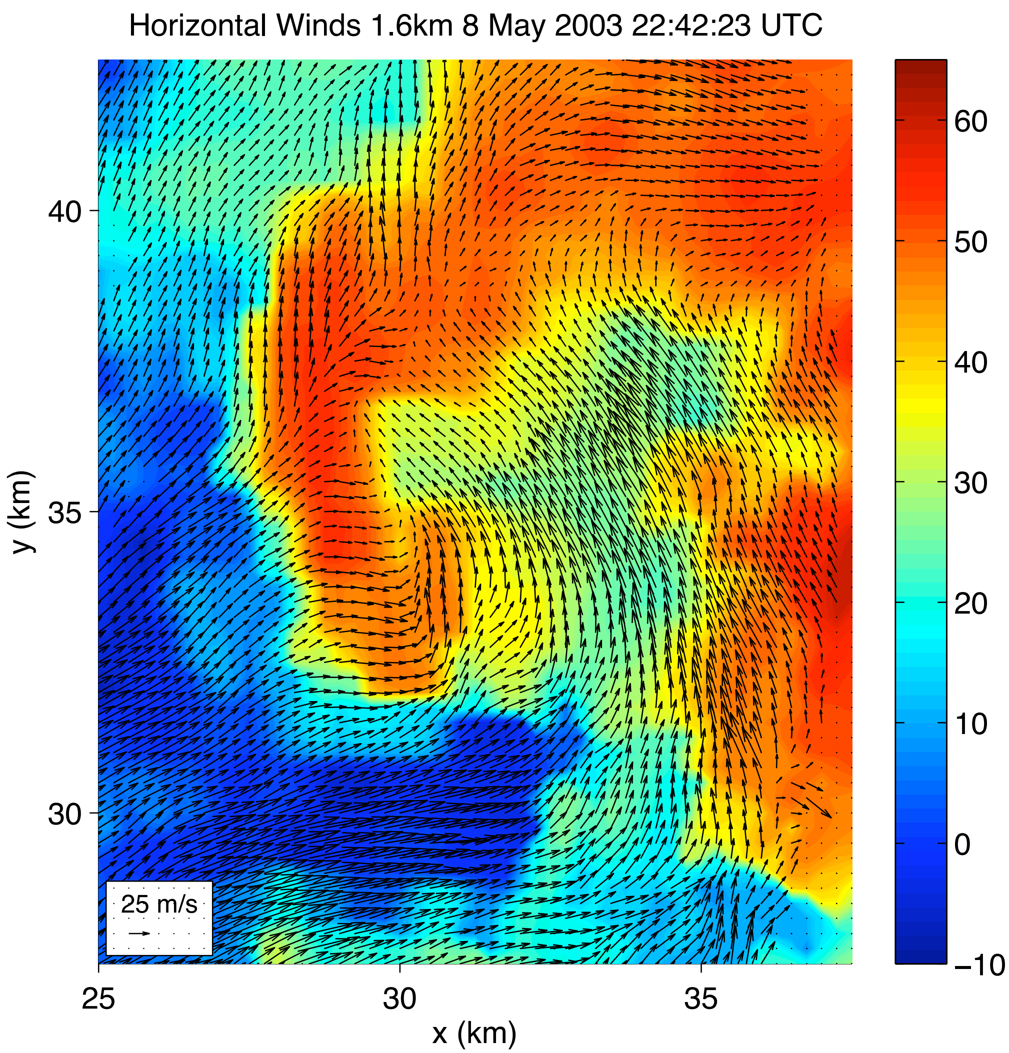


Vertical Velocity 1.6km 8 May 2003 22:37:49 UTC
y (km)
x (km)
25 m/s
25
30
35
20
15
10
5
0
−5
−10
−15
−20

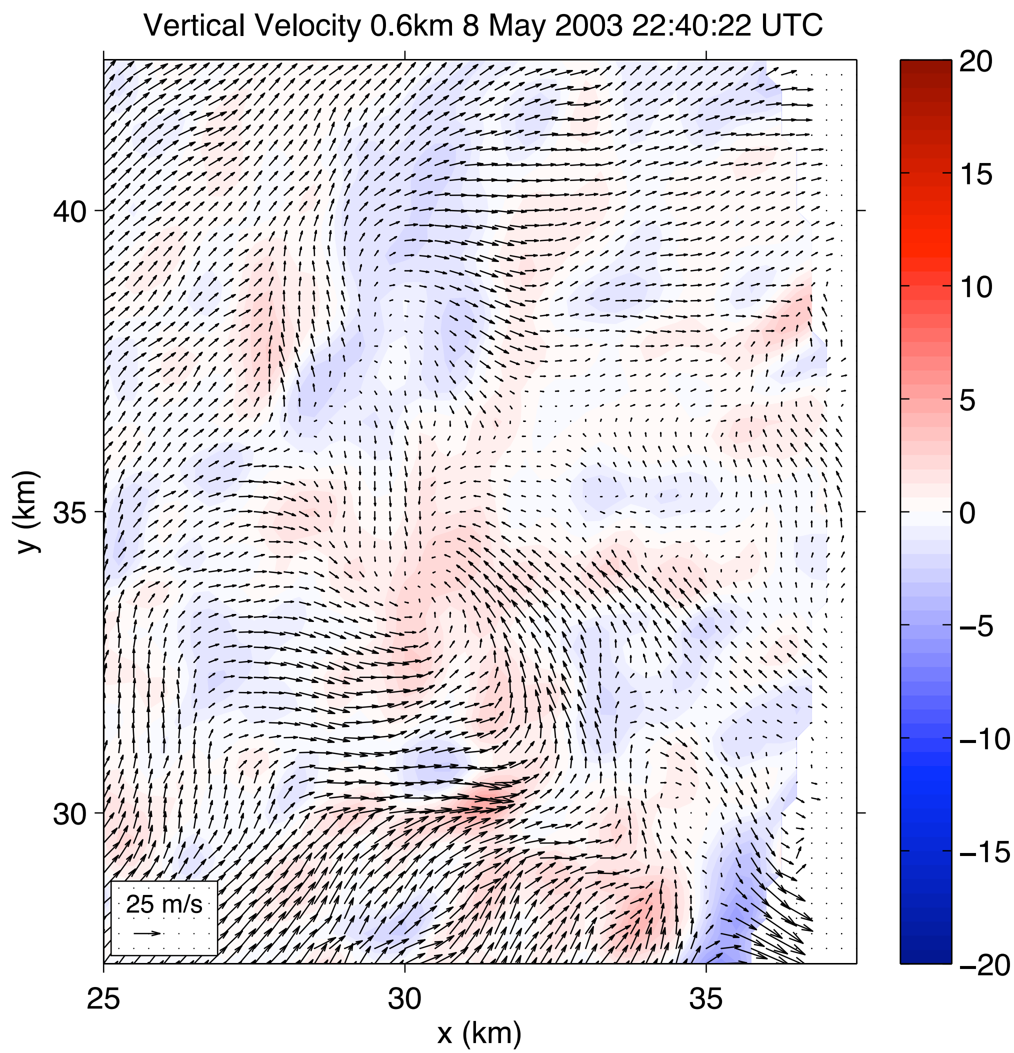
8 May 2003
22:40


KTLX Reflectivity (dBZ) 8 May 2003 22:40:22 UTC 0.6km
y (km)
x (km)
10
20
30
40
50
60
−10
0
10
20
30
40
50
60

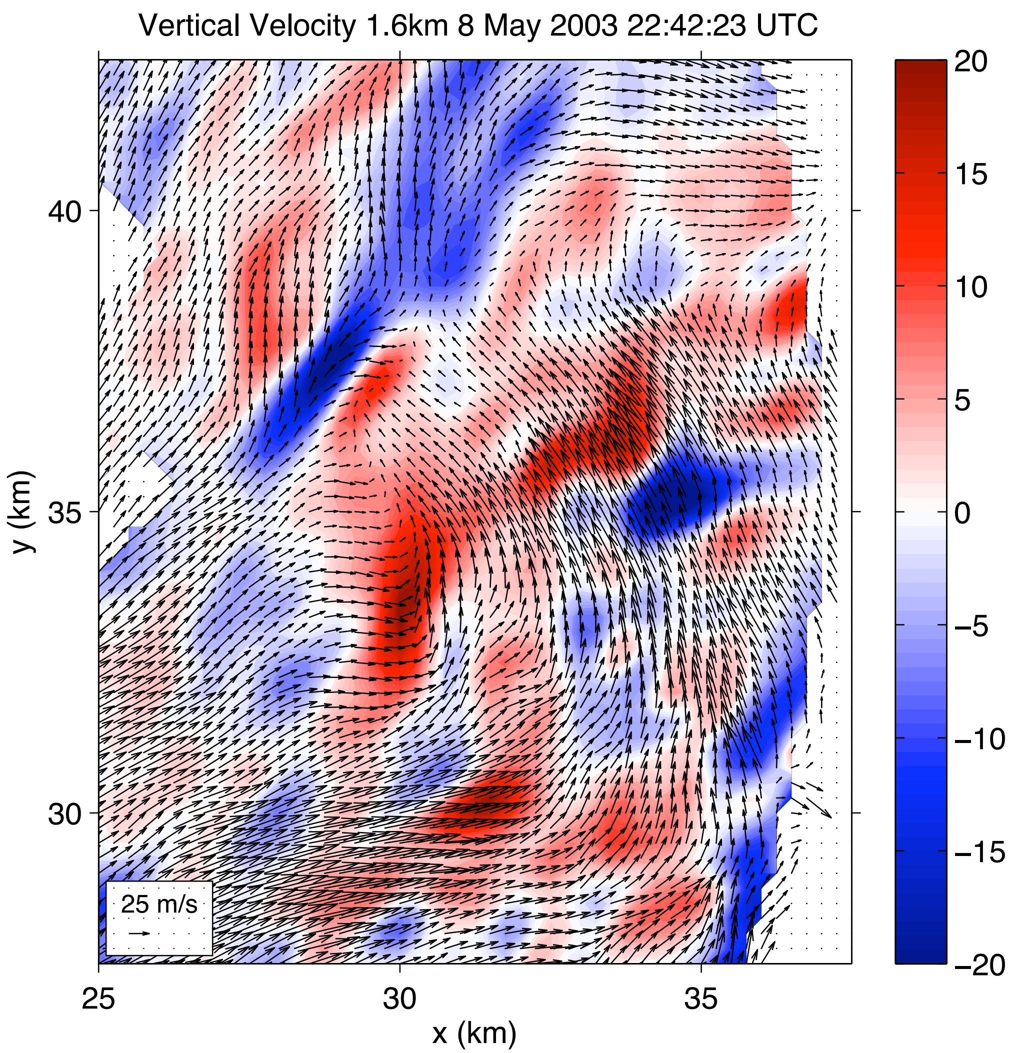

Damage Path and Horizontal Winds 0.6km 8 May 2003 22:40:22 UTC
y (km from KOUN)
x (km from KOUN)
32
30
28
26
24
22
20
12
14
16
18
20
22
24
26
60
50
40
30
20
10
0
−10



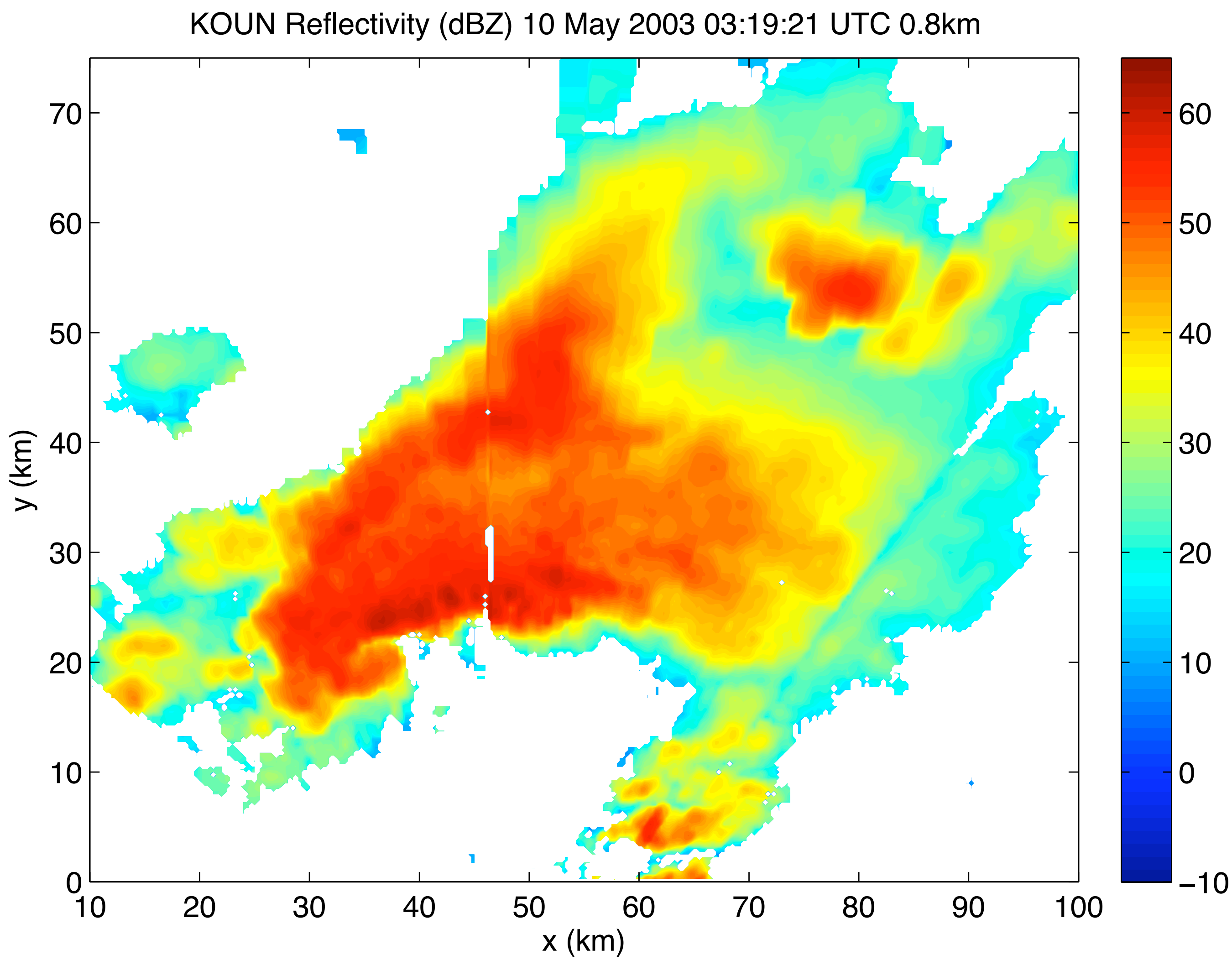
Horizontal Winds 1.6km 8 May 2003 22:42:23 UTC
y (km)
x (km)
40
35
30
25
30
35
25 m/s
60
50
40
30
20
10
0
−10

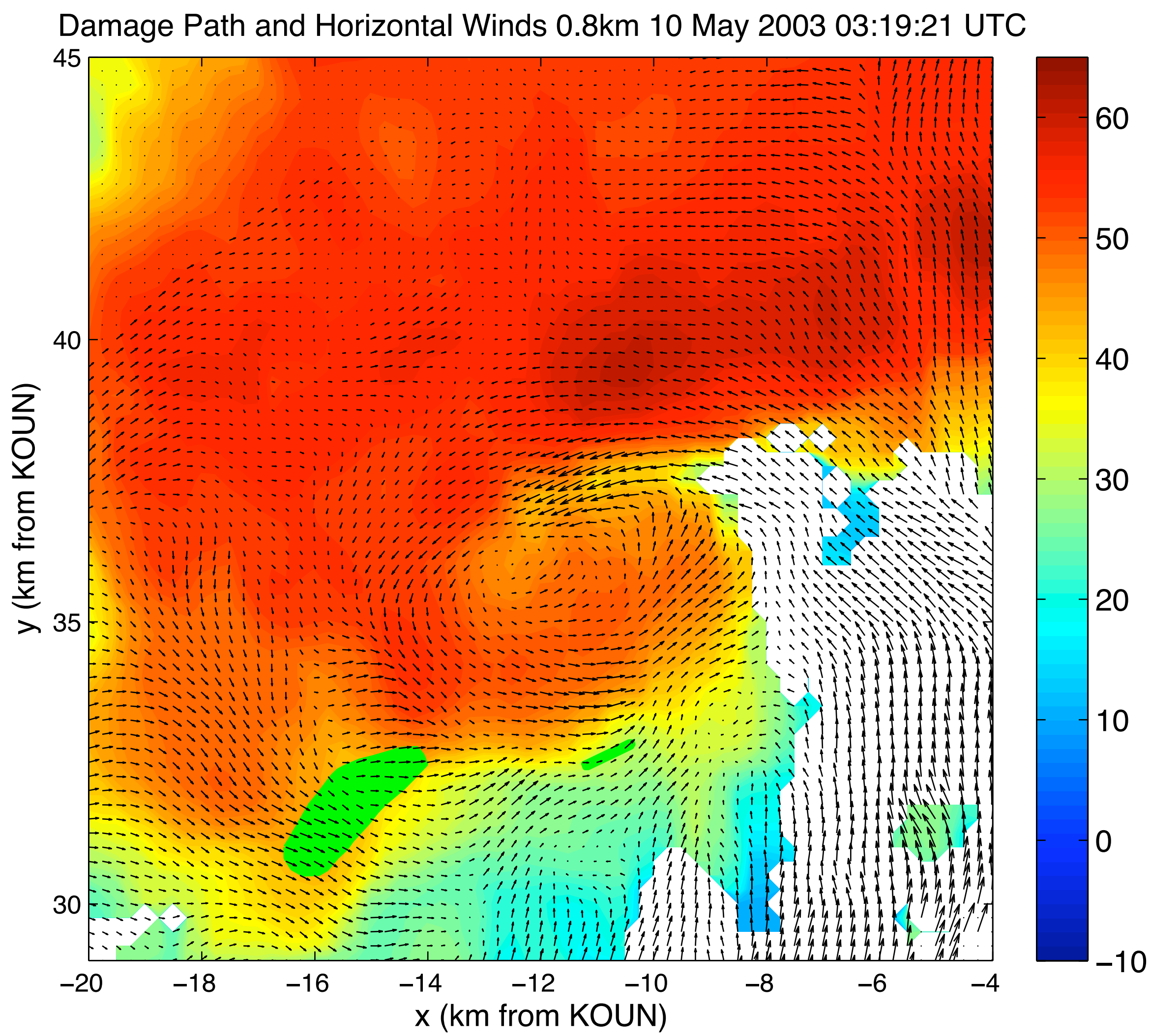


Vertical Velocity 0.6km 8 May 2003 22:40:22 UTC
y (km)
x (km)
25 m/s
40
35
30
25
20
15
10
5
0
−5
−10
−15
−20

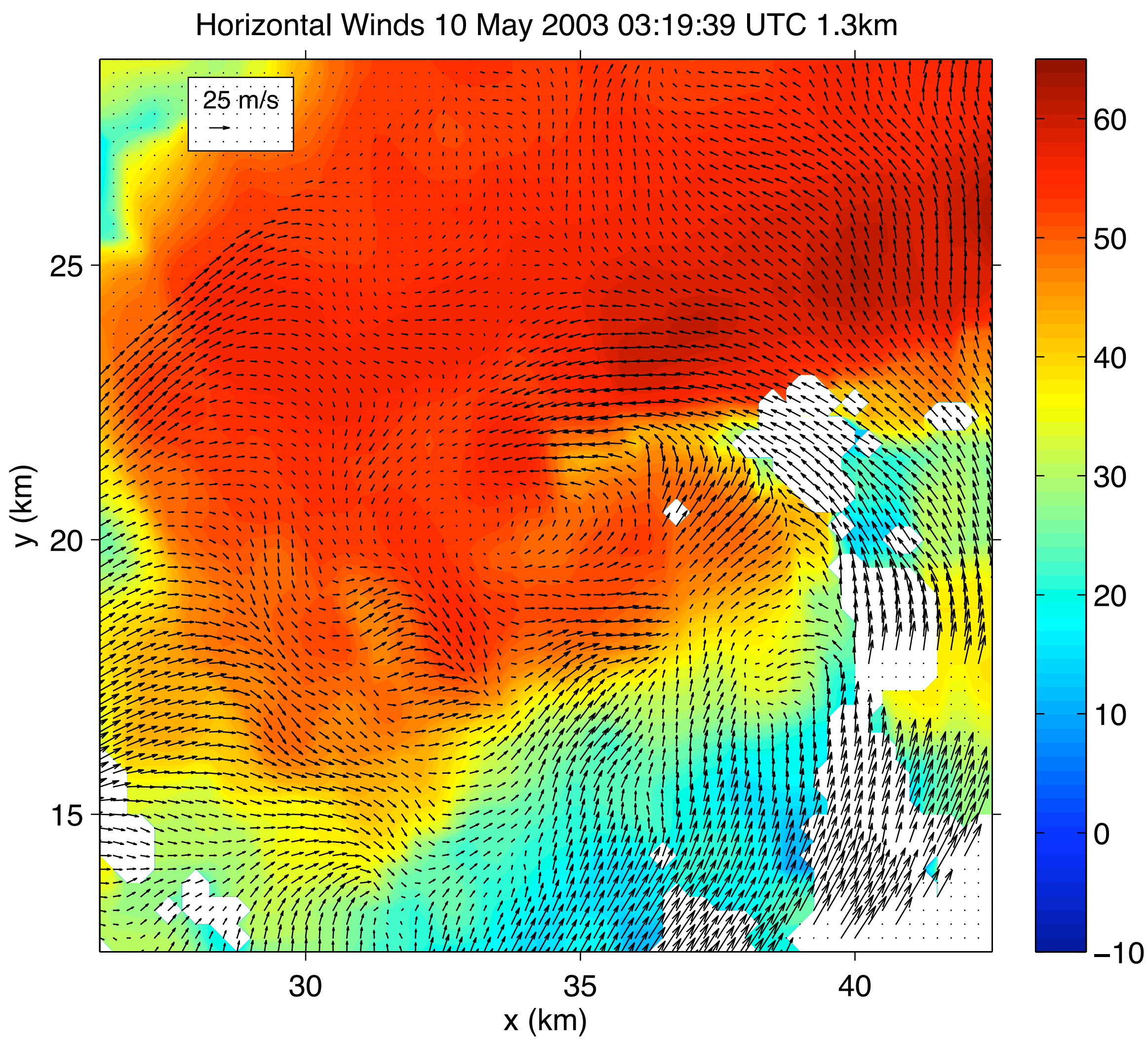

Vertical Velocity 1.6km 8 May 2003 22:42:23 UTC
y (km)
x (km)
25
30
35
40
35
30
25 m/s
20
15
10
5
0
−5
−10
−15
−20

10 May 2003
03:19

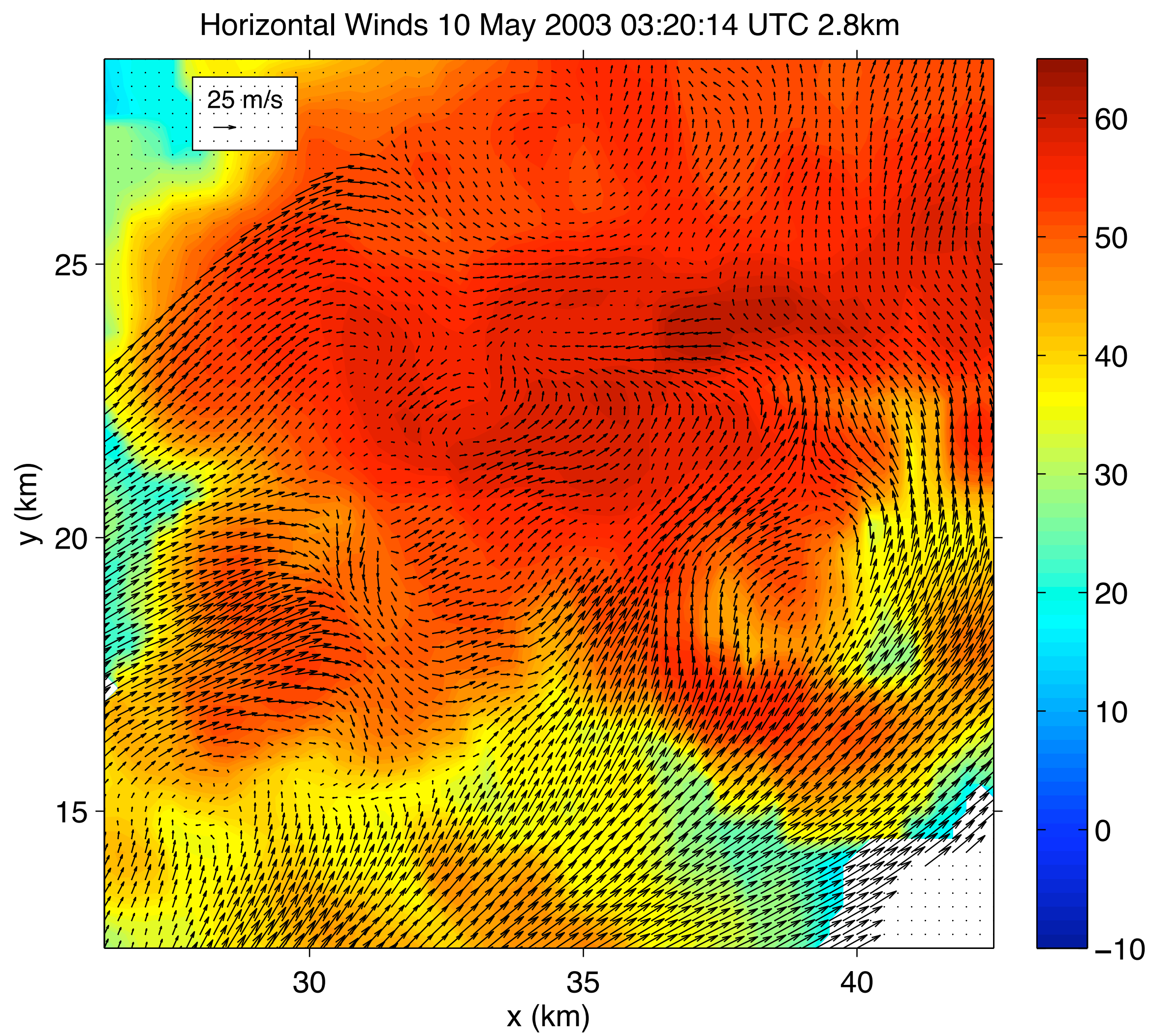

KOUN Reflectivity (dBZ) 10 May 2003 03:19:21 UTC 0.8km
y (km)
x (km)
0
10
20
30
40
50
60
70
10
20
30
40
50
60
70
80
90
100
−10
0
10
20
30
40
50
60

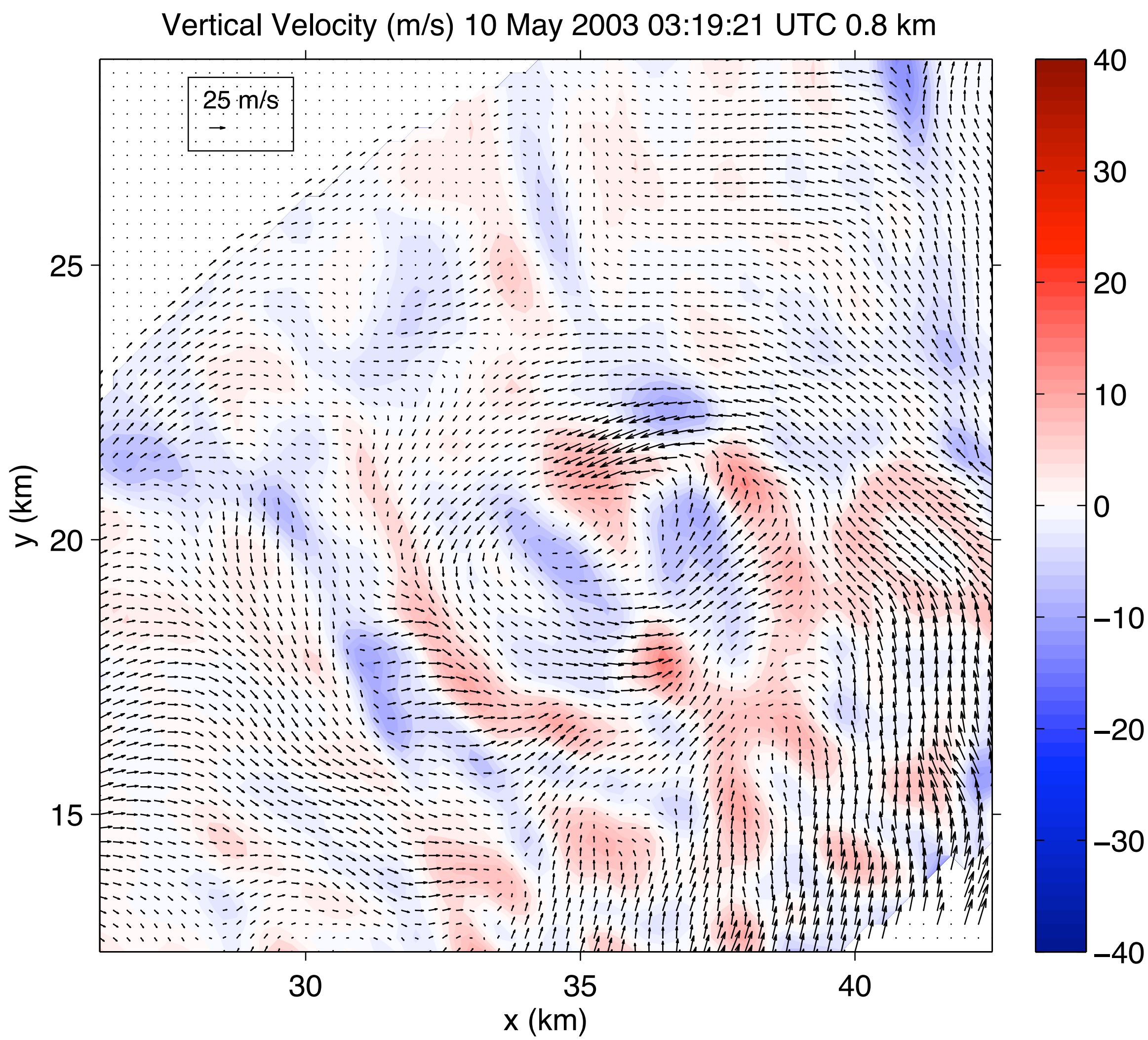


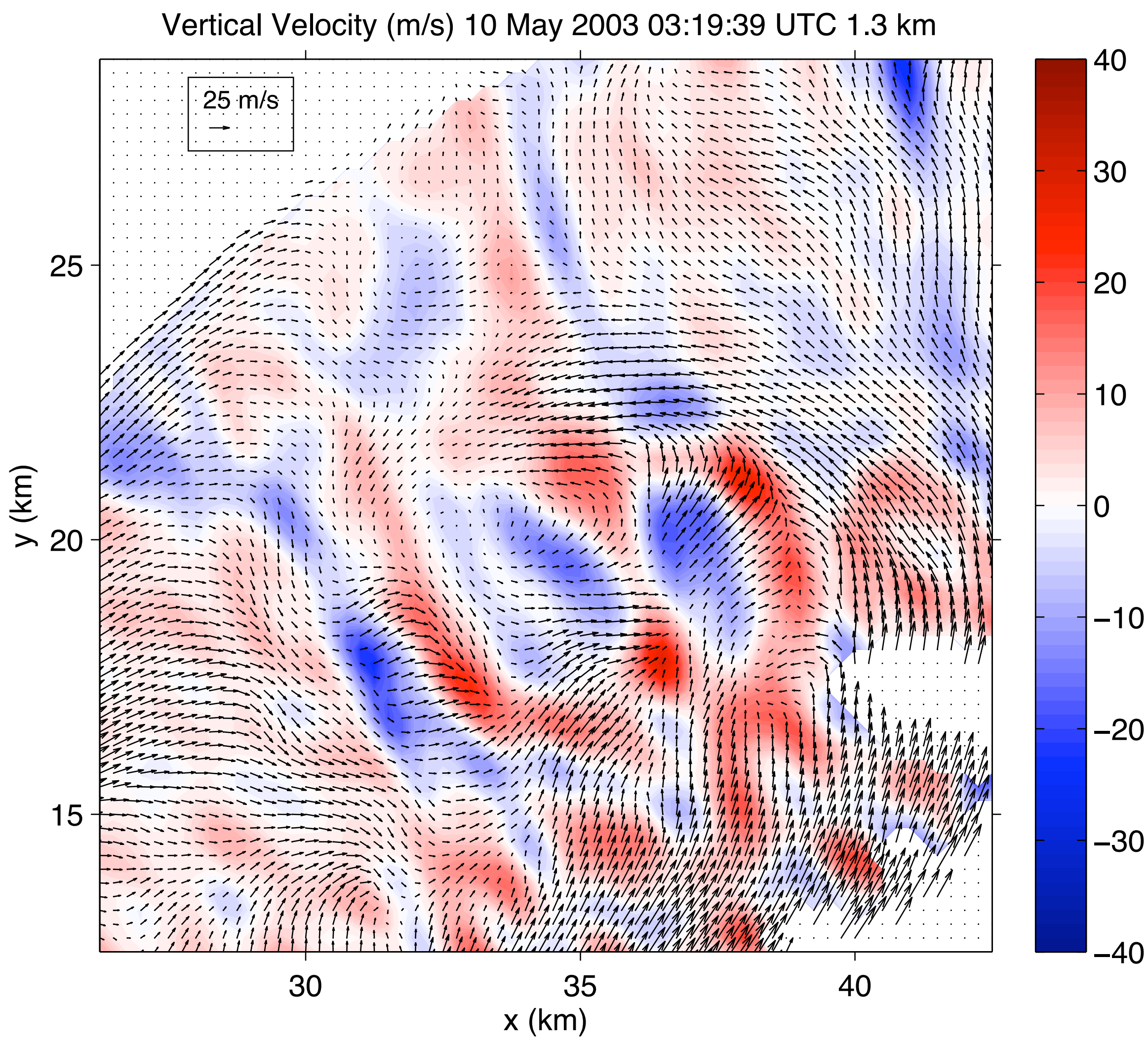
Damage Path and Horizontal Winds 0.8km 10 May 2003 03:19:21 UTC
45
40
35
30
y (km from KOUN)
−20
−18
−16
−14
−12
−10
−8
−6
−4
x (km from KOUN)
60
50
40
30
20
10
0
−10

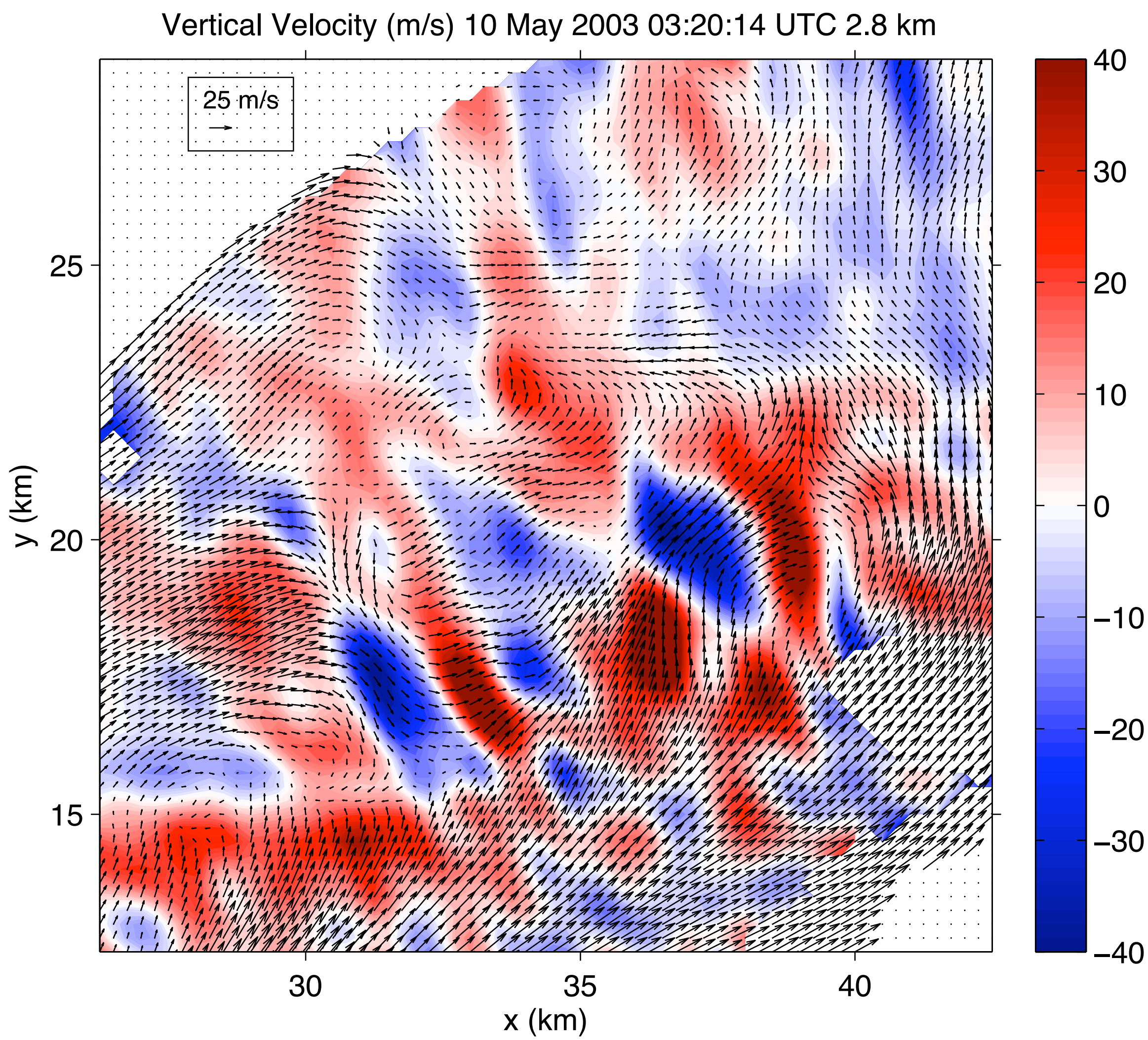


Horizontal Winds 10 May 2003 03:19:39 UTC 1.3km
25 m/s
y (km)
25
20
15
30
35
40
x (km)
60
50
40
30
20
10
0
−10

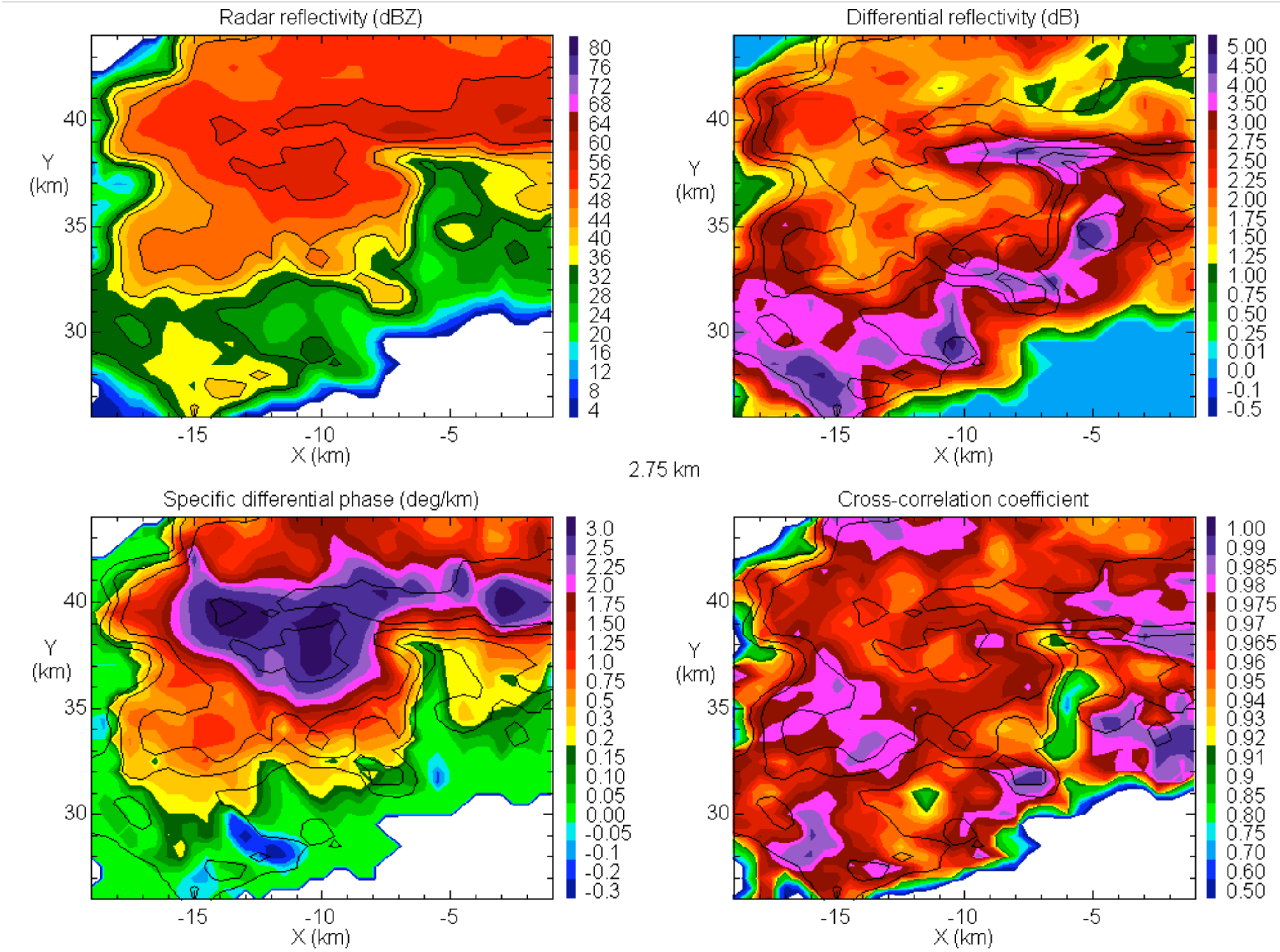

Horizontal Winds 10 May 2003 03:20:14 UTC 2.8km
25 m/s
y (km)
25
20
15
30
35
40
x (km)
60
50
40
30
20
10
0
−10


Vertical Velocity (m/s) 10 May 2003 03:19:21 UTC 0.8 km
25 m/s
y (km)
25
20
15
x (km)
30
35
40
40
30
20
10
0
−10
−20
−30
−40


Vertical Velocity (m/s) 10 May 2003 03:19:39 UTC 1.3 km
25 m/s
y (km)
x (km)
15
20
25
30
35
40
40
30
20
10
0
−10
−20
−30
−40

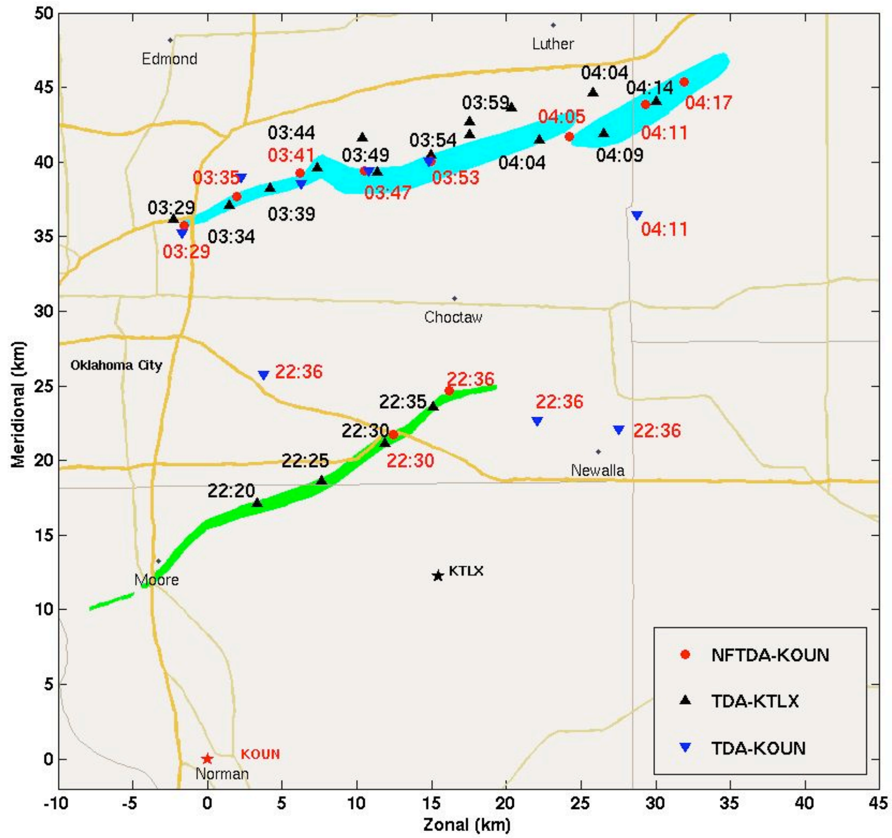


Vertical Velocity (m/s) 10 May 2003 03:20:14 UTC 2.8 km
25 m/s
y (km)
x (km)
25
20
15
30
35
40
40
30
20
10
0
−10
−20
−30
−40



Radar reflectivity (dBZ)
Differential reflectivity (dB)
Specific differential phase (deg/km)
Cross-correlation coefficient
2.75 km
Y (km)
X (km)
80 76 72 68 64 60 56 52 48 44 40 36 32 28 24 20 16 12 8 4
5.00 4.50 4.00 3.50 3.00 2.75 2.50 2.25 2.00 1.75 1.50 1.25 1.00 0.75 0.50 0.25 0.01 0.0 -0.1 -0.5
3.0 2.5 2.25 2.0 1.75 1.50 1.25 1.0 0.75 0.5 0.3 0.2 0.15 0.10 0.05 0.00 -0.05 -0.1 -0.2 -0.3
1.00 0.99 0.985 0.98 0.975 0.97 0.965 0.96 0.95 0.94 0.93 0.92 0.91 0.9 0.85 0.80 0.75 0.70 0.60 0.50

NFTDA Detections



Wang et. al. submitted

Conclusions

- Quantitative verification of advection-correction using spatially-variable pattern-translation components in this case is an improvement on any constant pattern-translation.

- The tornado shear anomaly present in dual-Doppler horizontal winds consistent is with the damage path.

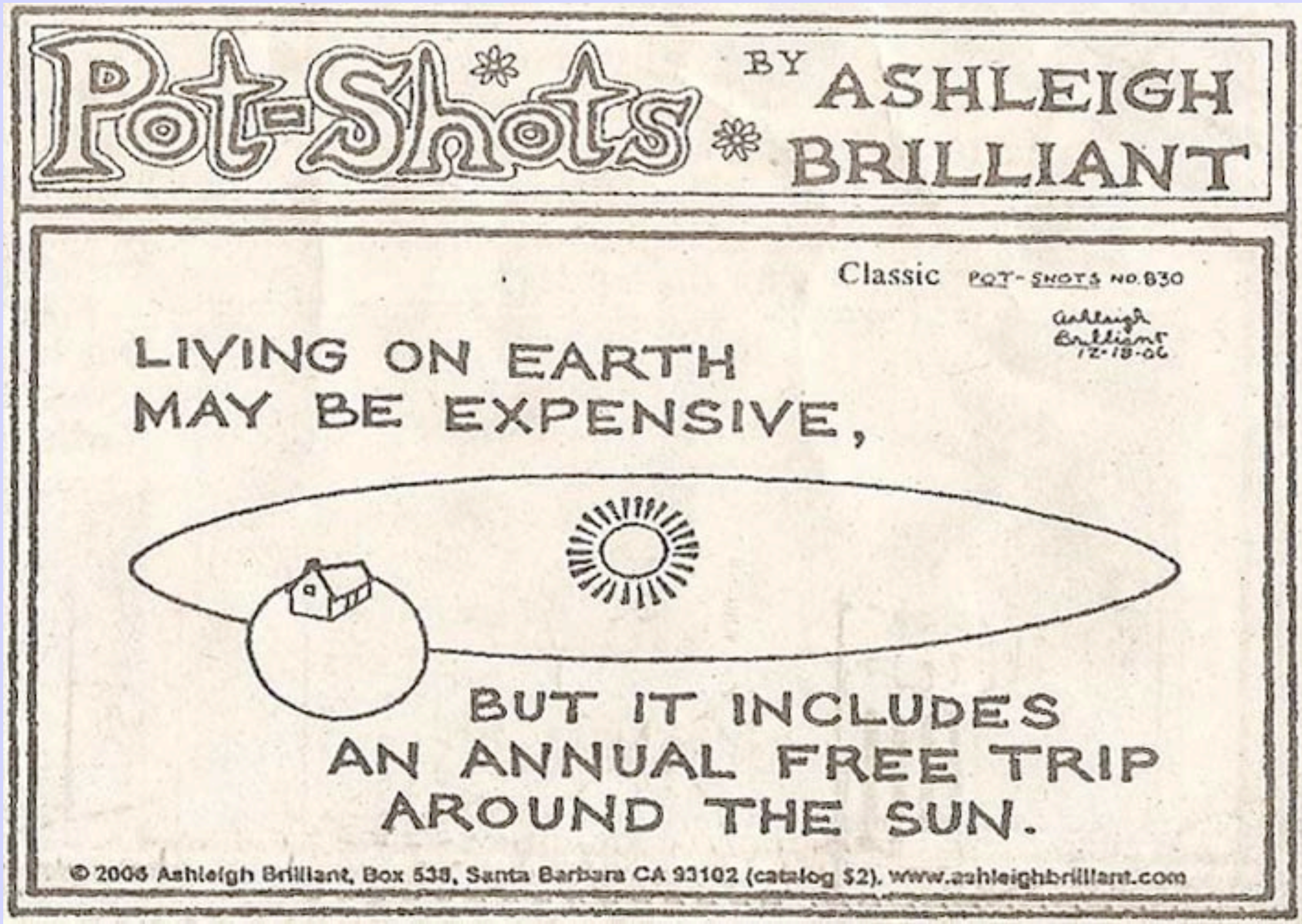
- The NFTDA detections were consistent with the damage path
  - The NFTDA did not detect the secondary, non-tornadic mesocyclone circulation 8 May 22:35
  - For this case and for the data analyzed, the NFTDA performed better than the TDA.

- Vertical velocity 10 May 03:19 shows arc shaped updraft
  - The arc shape is consistent with Differential Reflectivity from KOUN, indicating a precipitating flanking line.
  - Evaporational cooling from precipitation could have reinforced the RFD from the storm that led to enhanced convergence before the tornado

References

- Armijo, Larry, 1969: A Theory for the Determination of Wind and Precipitation Velocities with Doppler Radars. *J. Atmos. Sci.*, **26**, 570-573.
- Brandes, Edward A., 1977: Flow in Severe Thunderstorms Observed by Dual- Doppler Radar. *Mon. Wea. Rev.*, **105**, 113-120.
- Cressman, G. P., 1959: An Operational Objective Analysis System. *Mon. Wea. Rev.*, **87**, 367-374.
- National Weather Service, <www.nws.noaa.gov>
- Shapiro, Alan, et al., submitted: A New Formulation of Advection-Correction for Radar Data.
- Storm Prediction Center, <www.spc.noaa.gov>
- Wang, Yadong, et. al., 2008: Tornado Detection Using a Neuro-Fuzzy System to Integrate Shear and Spectral Signatues.

Questions?


Pot-Shots BY ASHLEIGH BRILLIANT
Classic POT-SHOTS NO. 830
LIVING ON EARTH MAY BE EXPENSIVE,
BUT IT INCLUDES AN ANNUAL FREE TRIP AROUND THE SUN.
© 2006 Ashleigh Brilliant, Box 538, Santa Barbara CA 93102 (catalog $2). www.ashleighbrilliant.com