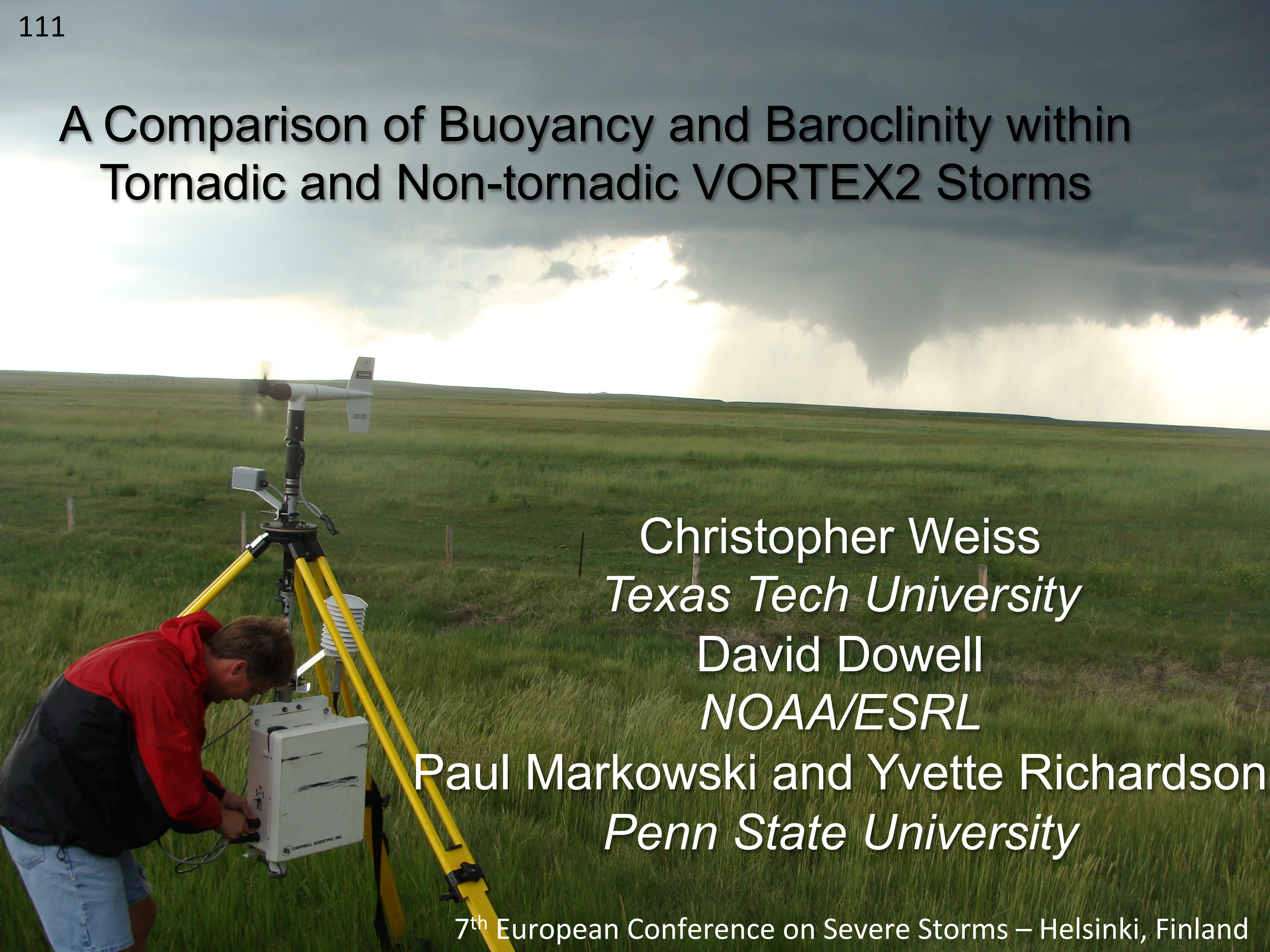


A Comparison of Buoyancy and Baroclinity within Tornadic and Non-tornadic VORTEX2 Storms

Christopher Weiss

Texas Tech University

David Dowell

NOAA/ESRL

Paul Markowski and Yvette Richardson

Penn State University

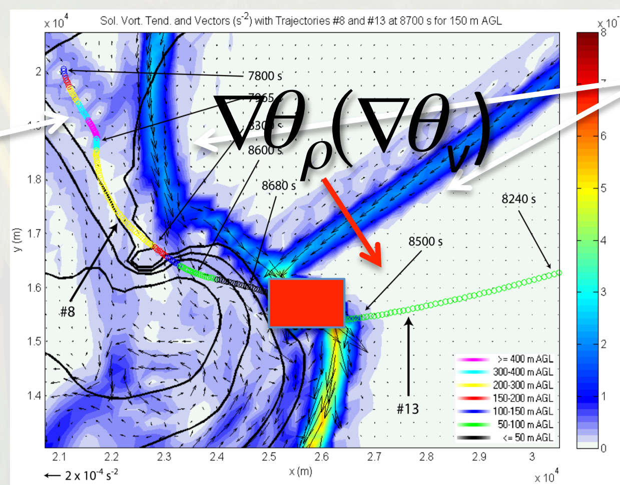
7th European Conference on Severe Storms – Helsinki, Finland

Introduction

- Baroclinic generation of horizontal vorticity $(\nabla\rho \times \nabla P)$ implicated in vorticity budget of low-level mesocyclone by a number of numerical studies (e.g., Klemp and Rotunno 1983; Rotunno and Klemp 1983; Davies-Jones and Brooks 1993; Wicker and Wilhelmson 1995)

- Issue: zones for baroclinic vorticity production are not ubiquitous across simulations, can be narrow and transient (e.g., Beck and Weiss 2013 (below))

Inbound trajectory to low-level mesocyclone (red rectangle)



Bifurcated zones of baroclinic vorticity production north/ east of low-level mesocyclone

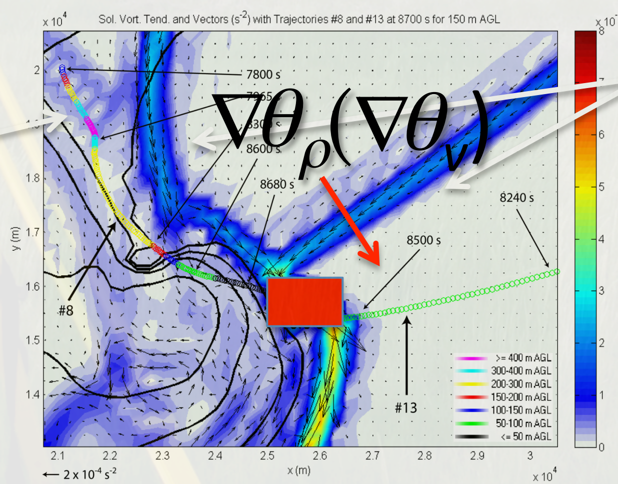
Colored: Solenoidal horizontal vorticity generation (s $^{-2}$)

Introduction

- Baroclinic generation of horizontal vorticity $(\nabla\rho \times \nabla P)$ implicated in vorticity budget of low-level mesocyclone by a number of numerical studies (e.g., Klemp and Rotunno 1983; Rotunno and Klemp 1983; Davies-Jones and Brooks 1993; Wicker and Wilhelmson 1995)

- Issue #1: cold pool required for baroclinic vorticity generation, but also dictates that many parcels entering updraft region have elevated level of free convection (common mechanism for tornado failure)

- Issue #2: zones for baroclinic vorticity production are not ubiquitous across simulations, can be narrow and transient (e.g., Beck and Weiss 2013 (below))

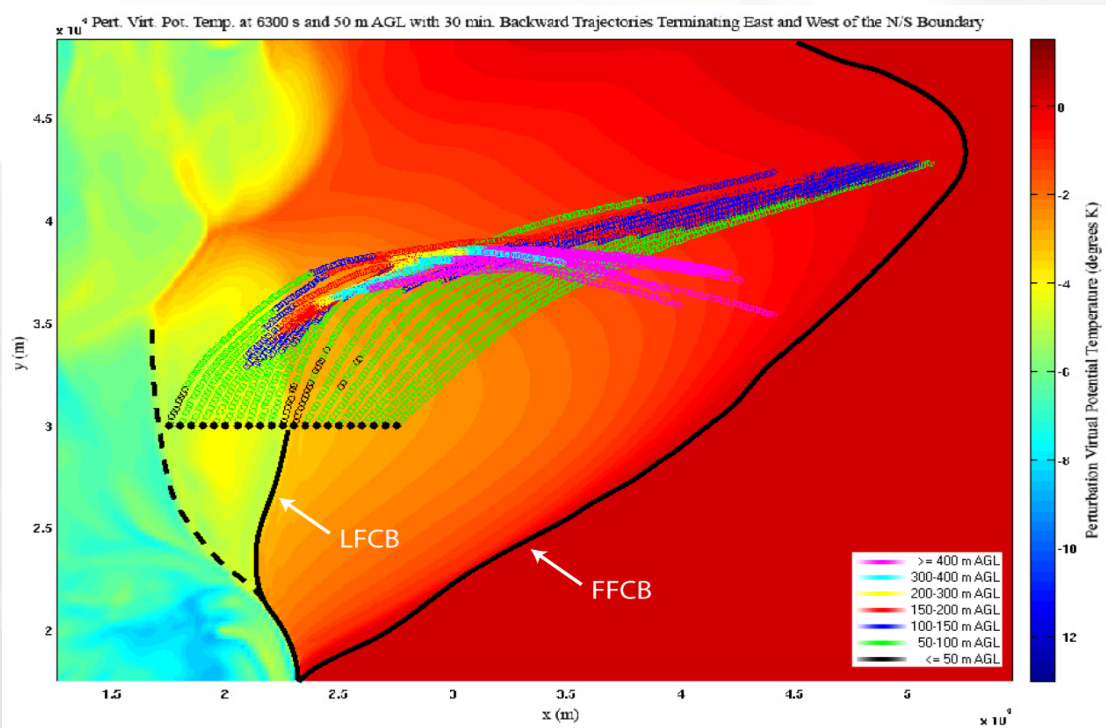


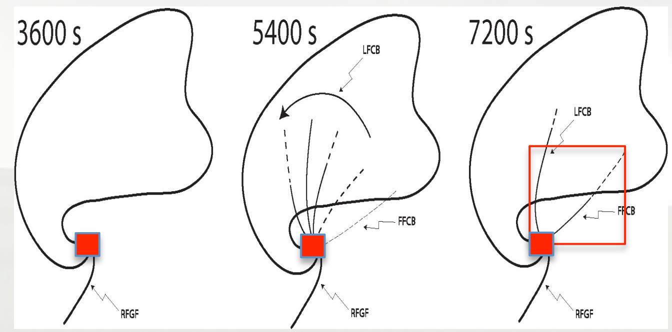
Inbound trajectory to low-level mesocyclone (red rectangle)

Bifurcated zones of baroclinic vorticity production north/ east of low-level mesocyclone

Colored: Solenoidal horizontal vorticity generation (s $^{-2}$)

Forward/Left Flank Baroclinic Zones





θ_v' (colored, K); 15-min backward trajectories (altitude colored, m AGL)

Beck and Weiss 2013

- Numerous transient baroclinic zones develop and traverse the left side of the updraft
- Vorticity budget reveals many of these zones are relevant to low-level mesocyclone

Introduction

- Issue #2: Limited observational mapping of thermodynamics on entire storm scale

Objectives of StickNet during VORTEX2

- Map spatio-temporal variability in storm-scale buoyancy
- Diagnose impacts on low-level vertical vorticity
- Verify numerically simulated cold pools



StickNet Analysis Methodology

- StickNet data analysis
  - Data quality controlled and debiased according to mass test the previous day
  - Time-to-space conversion - motion determined at time low-level mesocyclone passes through the StickNet array
  - Objectively analyzed with isotropic two-pass Barnes filter
    - 500 m grid spacing
    - $\gamma = 0.1$, $\kappa = (1.33\ \Delta y)^2$ Δy = along-deployment line station spacing
- Mobile radar data moments subject to separate Barnes filter
- Analyses centered on objectively determined maximum in azimuthal shear of radial velocity
  - Aggregate from 1-10 km diameter
  - Origin (0,0) of all analyses set to this position
- θ_e calculated as by Bolton (1980)
- Base state determined by (Dumas/Bowlegs) observation 2 hr before updraft passage – just ahead of anvil shadow
- Composite analyses produced

18 May 2010 Deployment Overview

- Long-lived, weakly tornadic supercell
- Two StickNet arrays deployed
  - #1 – US-287 north/south from Dumas, TX
    - Weak tornadoes reported near and west of Dumas
  - #2 – FM 1060 north/south between Dumas and Stinnett, TX
    - Non-tornadic, strong low-level mesocyclone
- Coarse deployments each cover ~30-40 km swath, with nested fine array centered near low-level mesocyclone
- Town of Dumas interferes with deployment #1
- Significant hail damages a few StickNet probes, particularly in deployment #2
- Hail cover is substantial at time of probe pickup (tennis balls at +1 hr), hail fog

18 May 2010 Deployment Overview

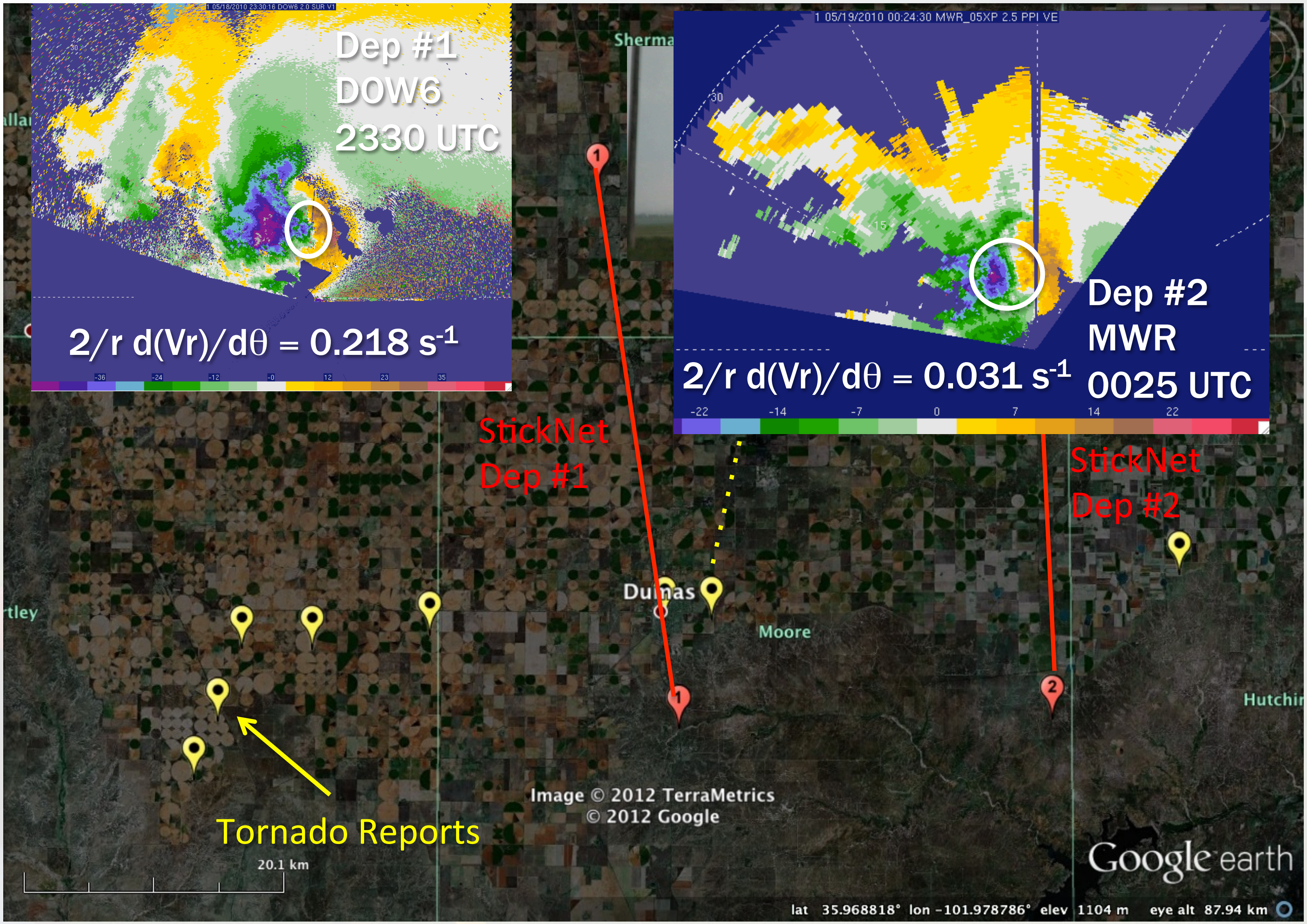


Photo Credit: Curtis McDonald

18 May 2010 Deployment Overview

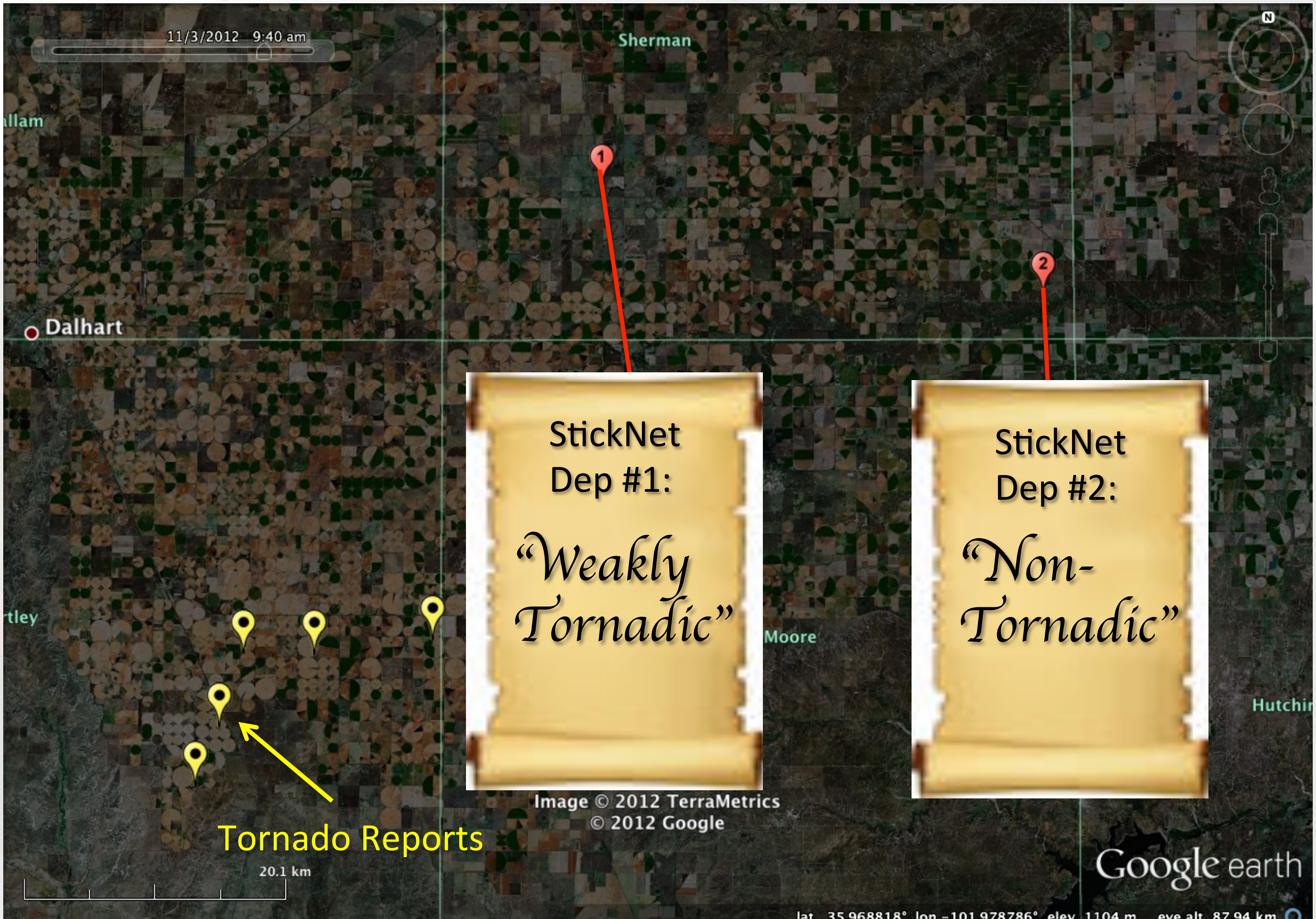
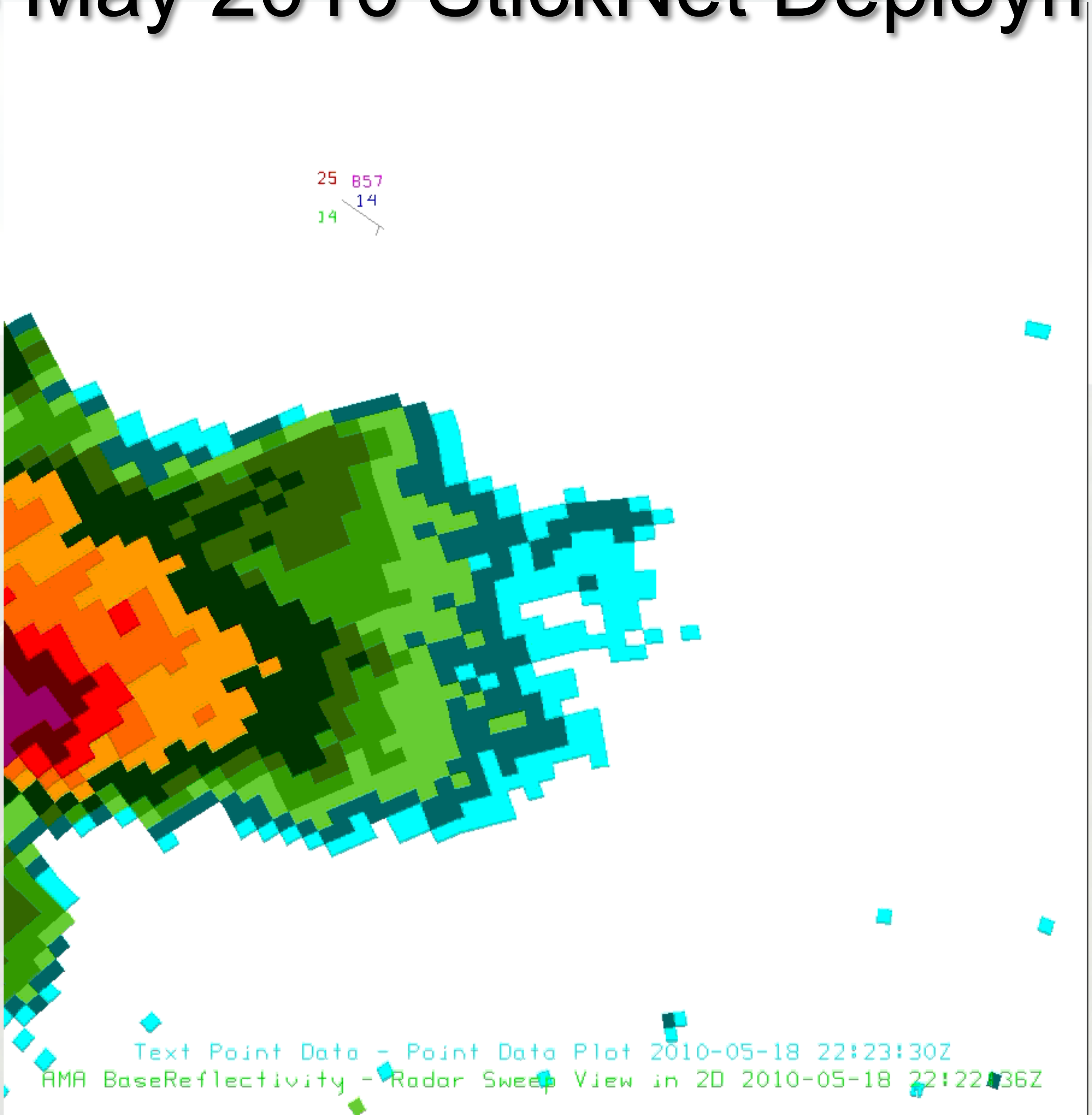
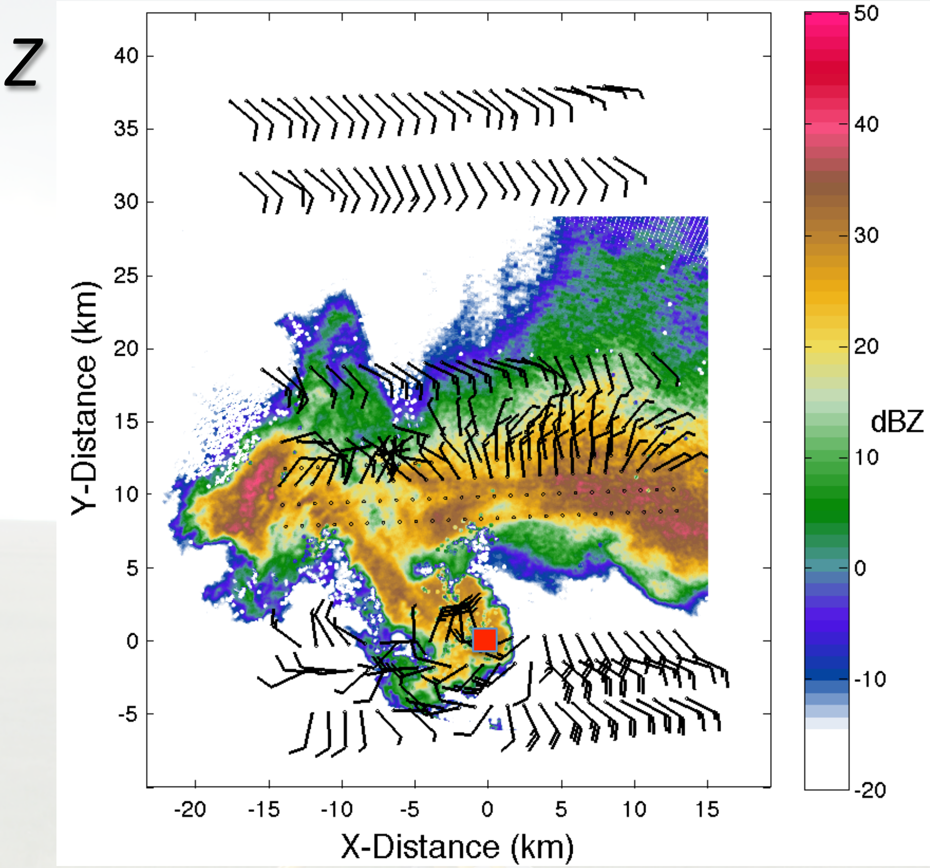


Photo Credit: Curtis McDonald

18 May 2010 StickNet Deployments

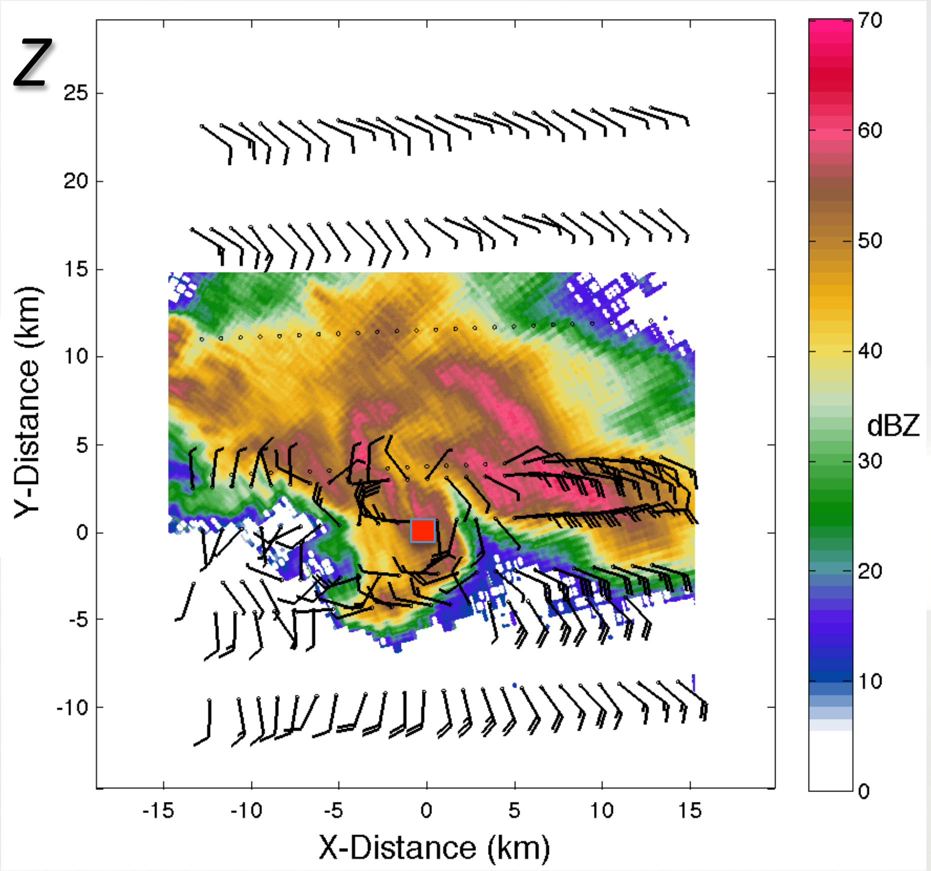


KAMA WSR-88D 0.5 deg reflectivity with StickNet obs 2233-0031 UTC, 18-19 May 2010



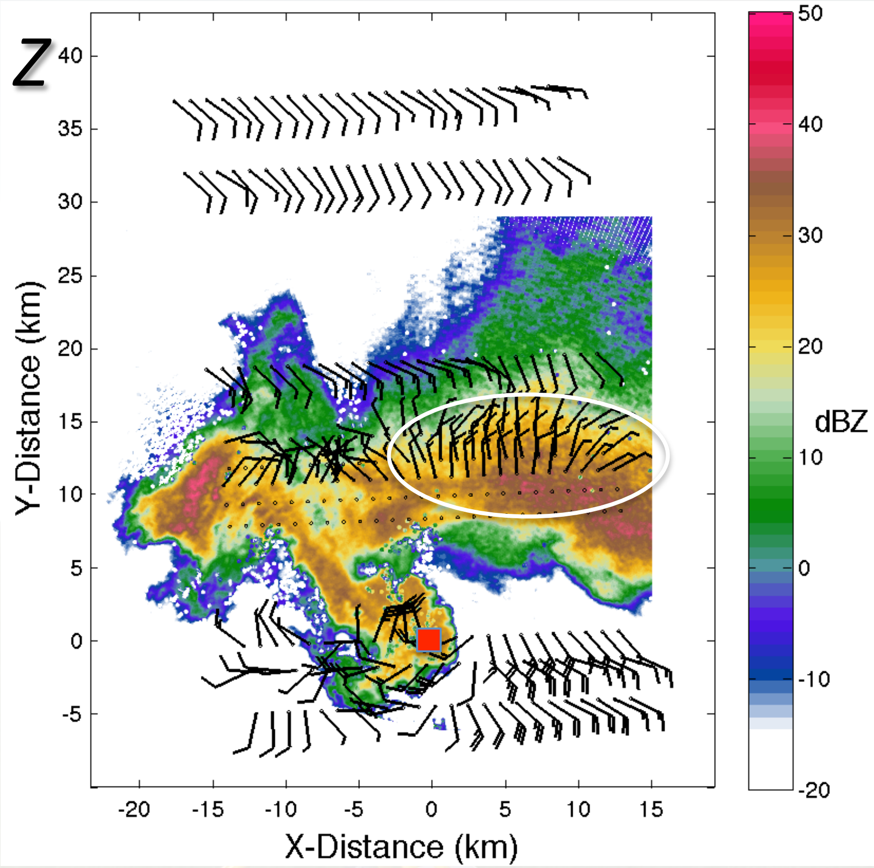
Colored: DOW6 2.0 deg reflectivity, 18 May 2010 2330 UTC
GR-winds: StickNet obs (kts), 18 May 2010, 2305-2355 UTC

Deployment #1
(weakly tornadic)

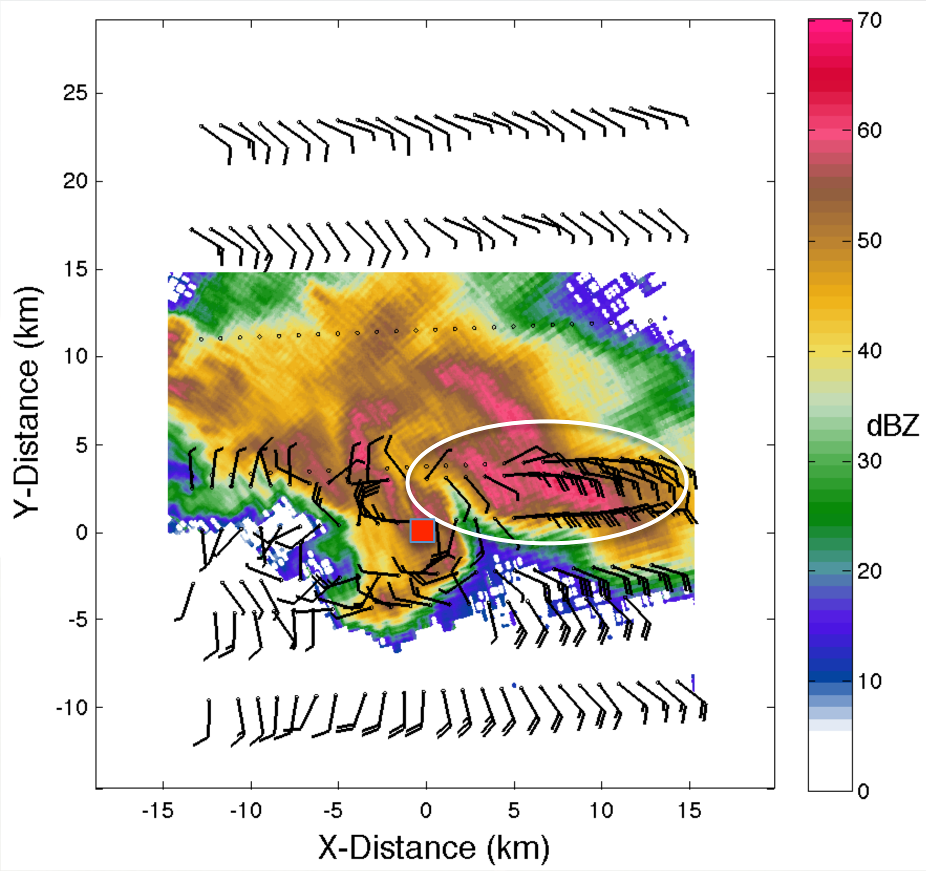


Colored: SMART-R 2.5 deg reflectivity, 19 May 2010 0025 UTC
GR-winds: StickNet obs (kts), 19 May 2010, 0000-0050 UTC

Deployment #2
(non-tornadic)



Colored: DOW6 2.0 deg reflectivity, 18 May 2010 2330 UTC
GR-winds: StickNet obs (kts), 18 May 2010, 2305-2355 UTC



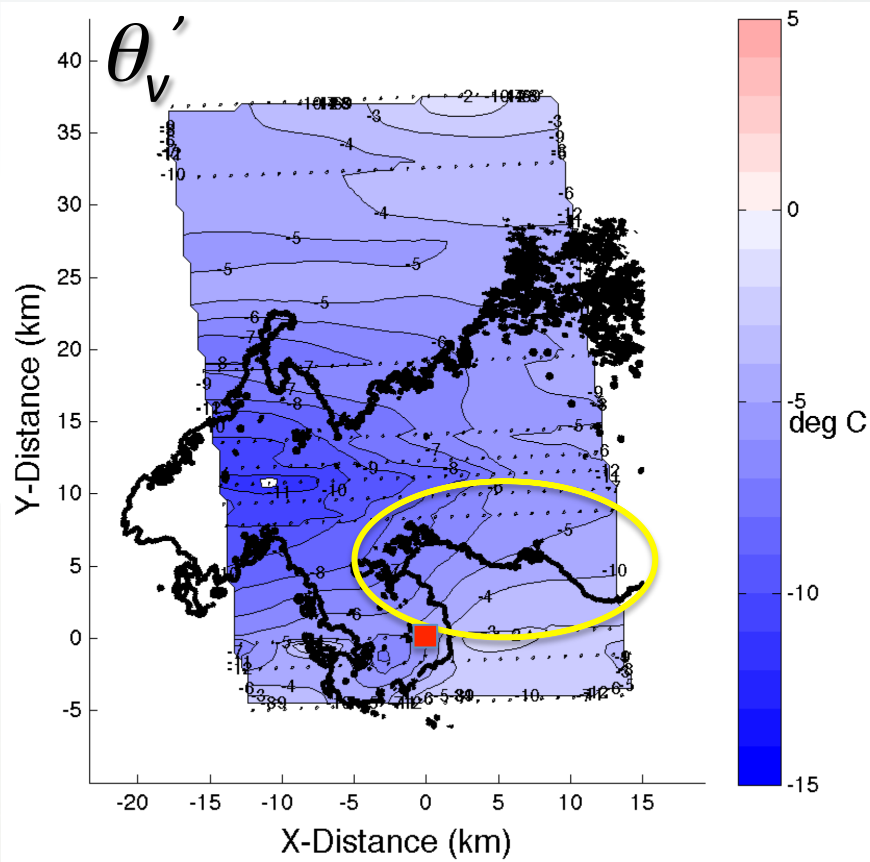
Colored: SMART-R 2.5 deg reflectivity, 19 May 2010 0025 UTC
GR-winds: StickNet obs (kts), 19 May 2010, 0000-0050 UTC

Deployment #1
(weakly tornadic)

Deployment #2
(non-tornadic)

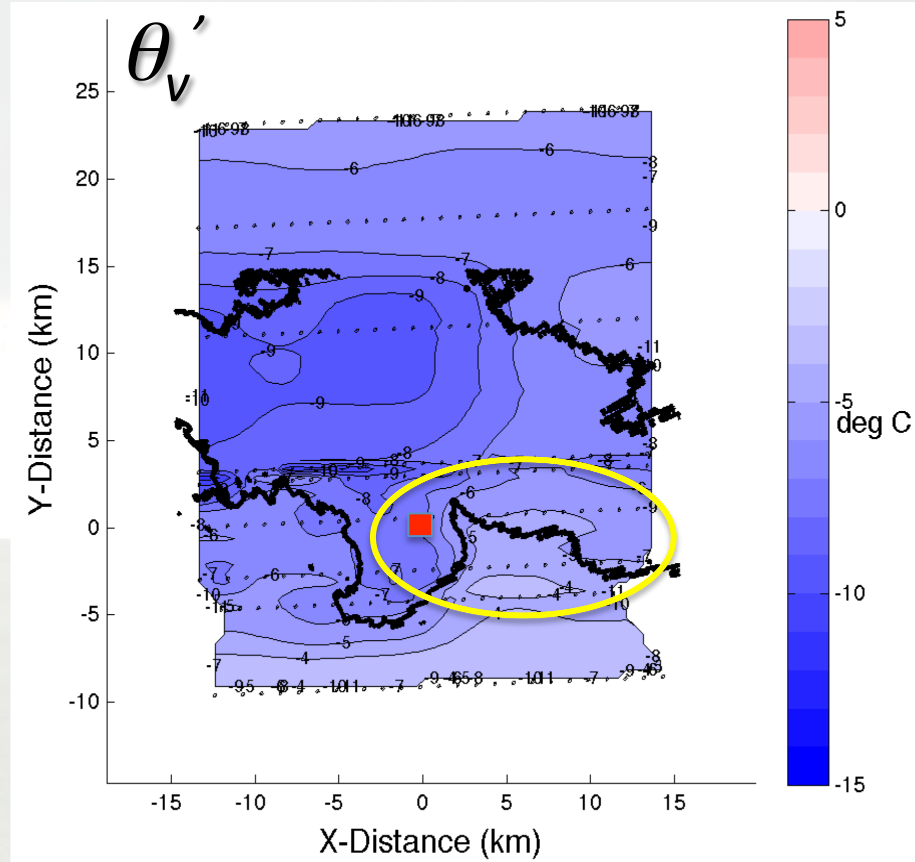
Notes:

- Winds near forward-flank reflectivity gradient (FFRG) in WT case more consistent with traditional notion of a forward-flank gust front (relevance to baroclinity?)



Contour: 0 dBZ DOW6 2.0 deg reflectivity, 2330 UTC
Colored: StickNet θ_v' (K), 18 May 2010, 2305-2355 UTC

Deployment #1
(weakly tornadic)

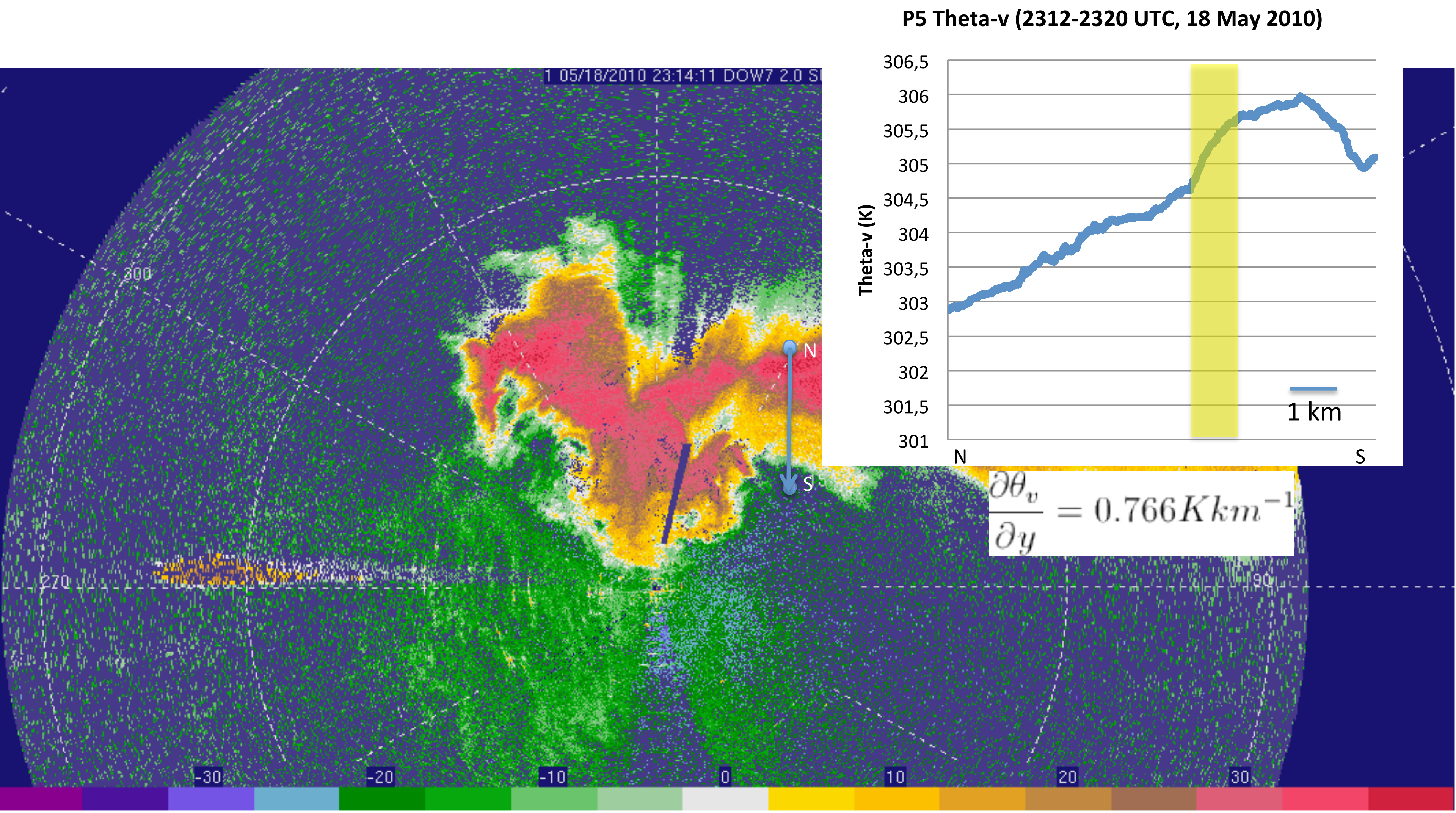


Contour: 30 dBZ SMART-R 2.5 deg reflectivity, 0025 UTC
Colored: StickNet θ_v' (K), 19 May 2010, 0000-0050 UTC

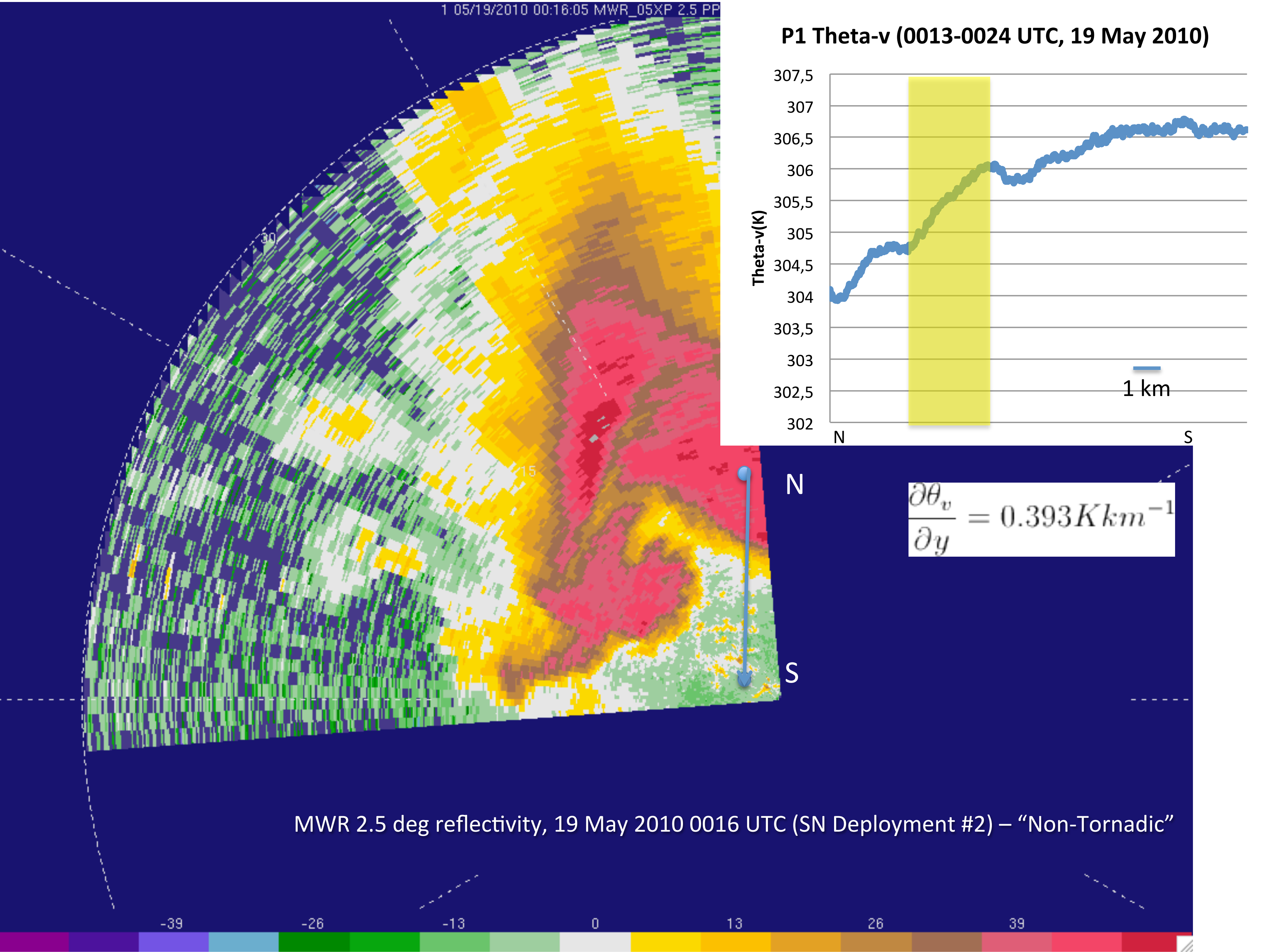
Deployment #2
(non-tornadic)

Notes:

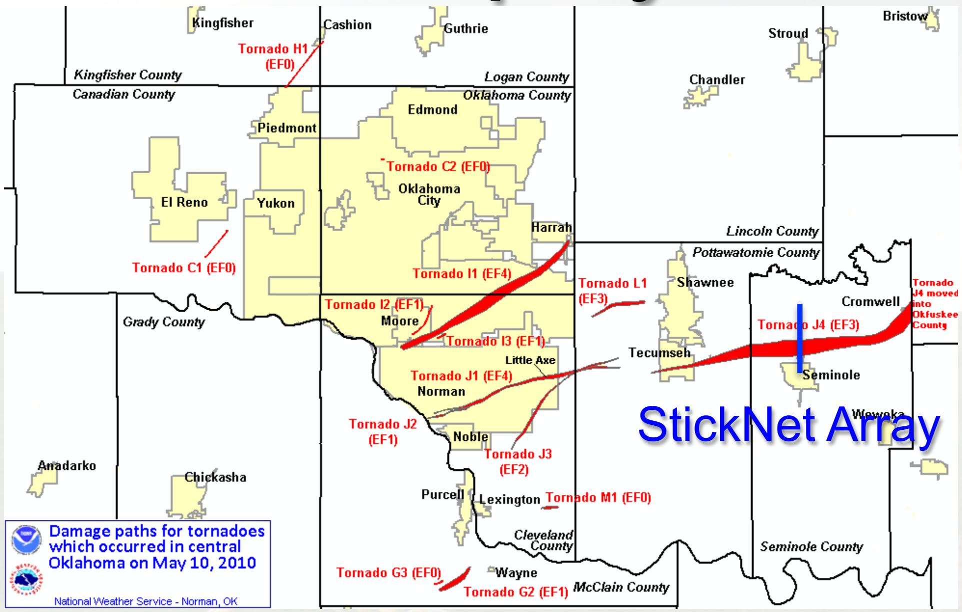
- Shape of virtual potential temperature gradient differs near FFRG, low-level mesocyclone



DOW7 2.0 deg reflectivity, 18 May 2010 2314 UTC (SN Deployment #1 – "Weakly Tornadic")


1 05/19/2010 00:16:05 MWR_05XP 2.5 PP
P1 Theta-v (0013-0024 UTC, 19 May 2010)
Theta-v(K)
307,5
307
306,5
306
305,5
305
304,5
304
303,5
303
302,5
302
N
S
1 km
N
S
$\frac{\partial \theta_v}{\partial y} = 0.393 K km^{-1}$
-39
-26
-13
0
13
26
39
MWR 2.5 deg reflectivity, 19 May 2010 0016 UTC (SN Deployment #2) – "Non-Tornadic"

10 May 2010 (Seminole, OK) Deployment Overview

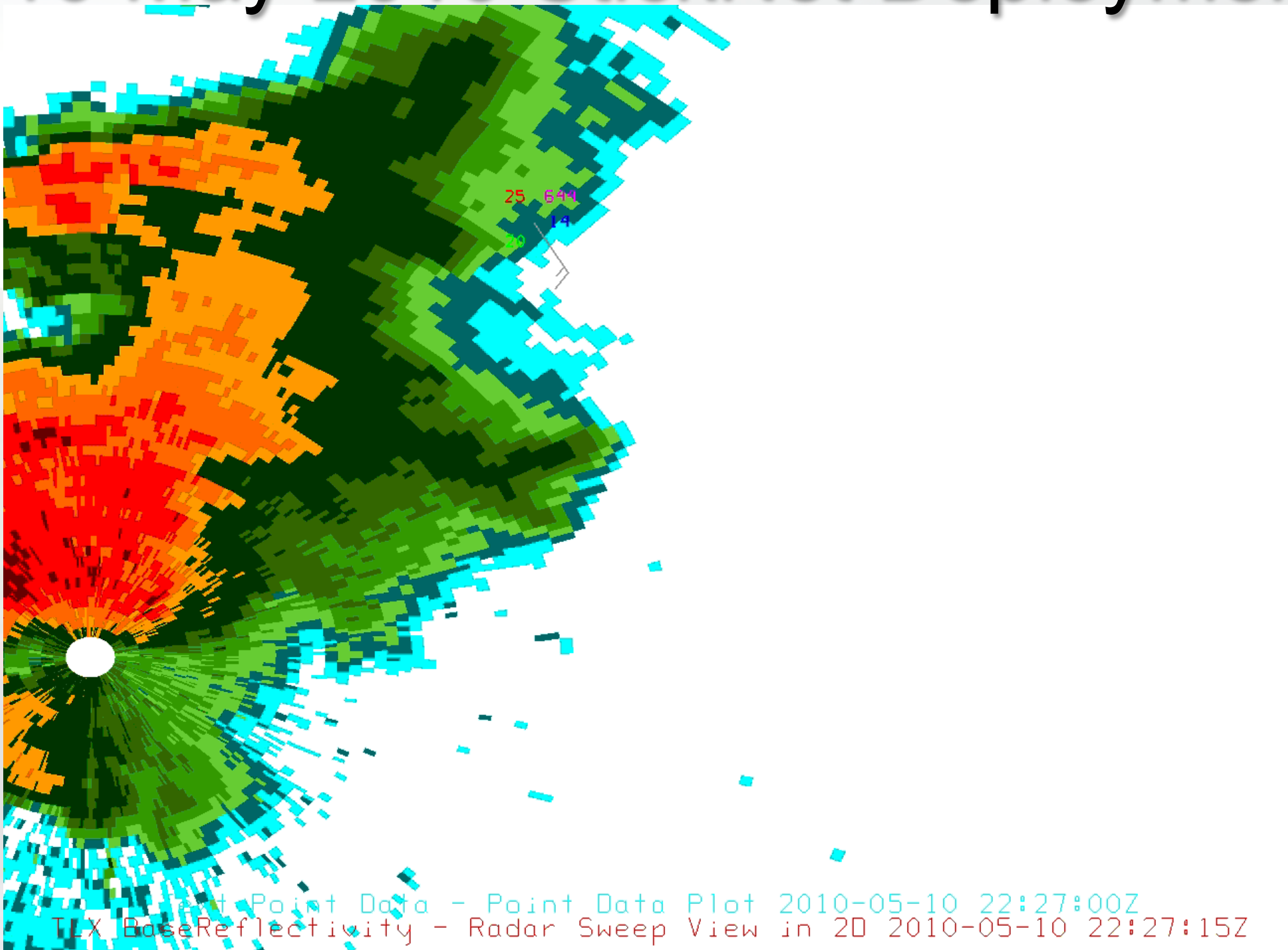


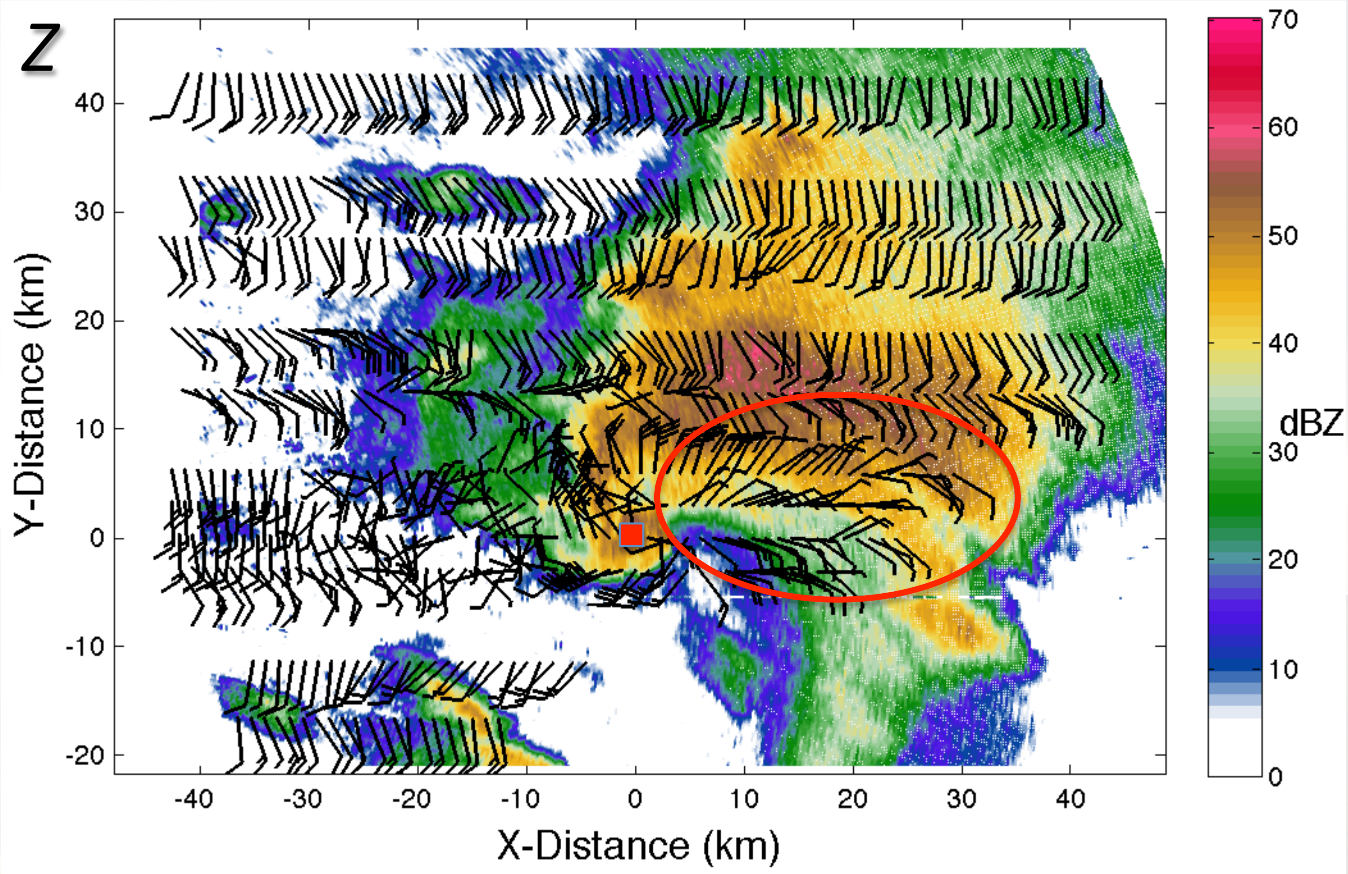
Damage survey, NWSFO Norman, OK

Photo: Greg Forbes / Weather Channel

- Outbreak of rapidly moving tornadic supercells
- 1.25 StickNet arrays deployed
  - #1 – Aborted attempt along US-177 (longitude of Tecumseh, OK)
  - #2 – 10-probe array along US-377 (longitude of Seminole, OK)
    - EF-3 tornado propagates through deployment

10 May 2010 StickNet Deployments

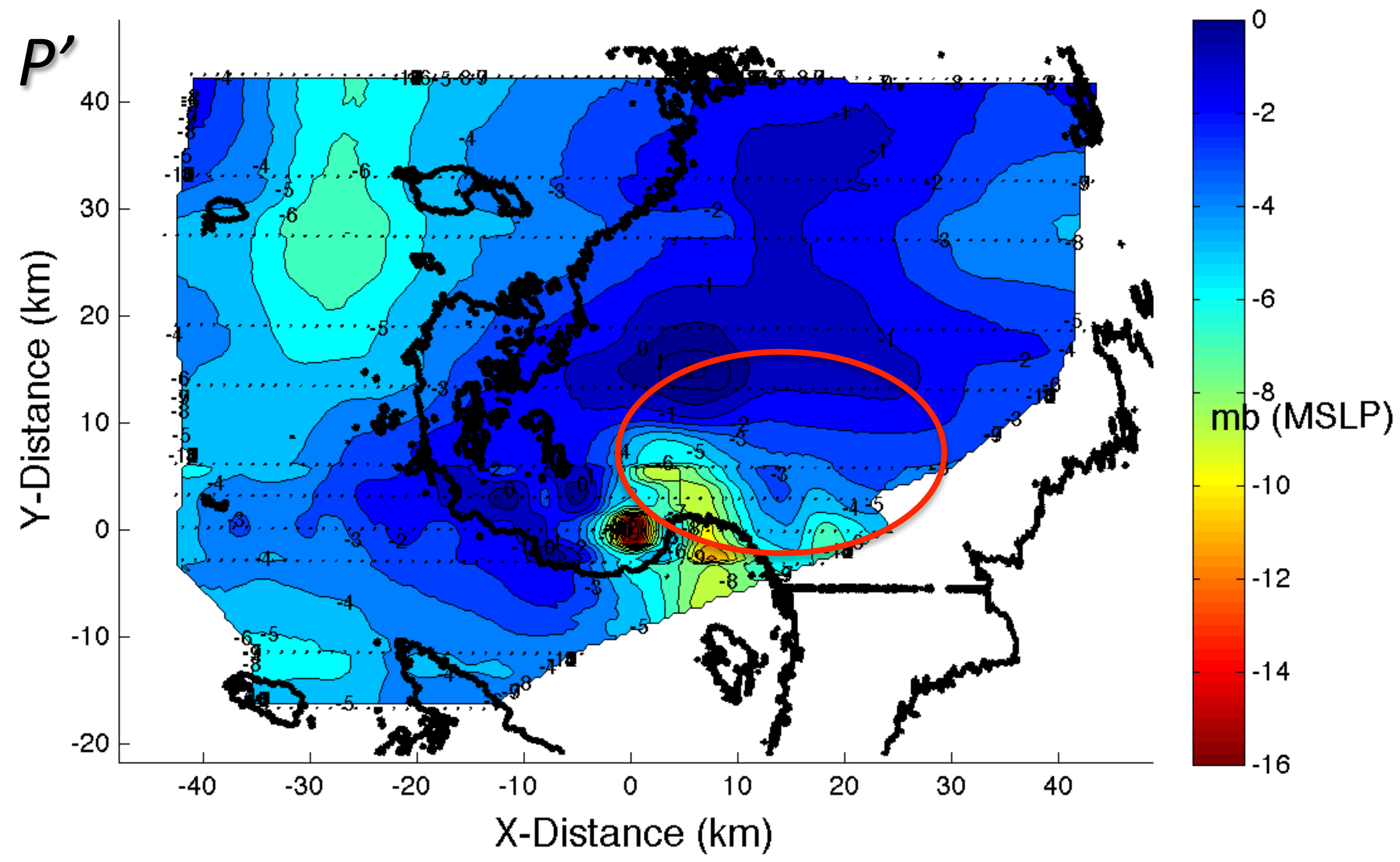




Colored: KOUN 0.5 deg reflectivity, 10 May 2010 2316 UTC
Winds (ground-relative): StickNet obs (kts), 10 May 2010, 2248-2348 UTC

Notes:

- Sharp confluence along FFRG

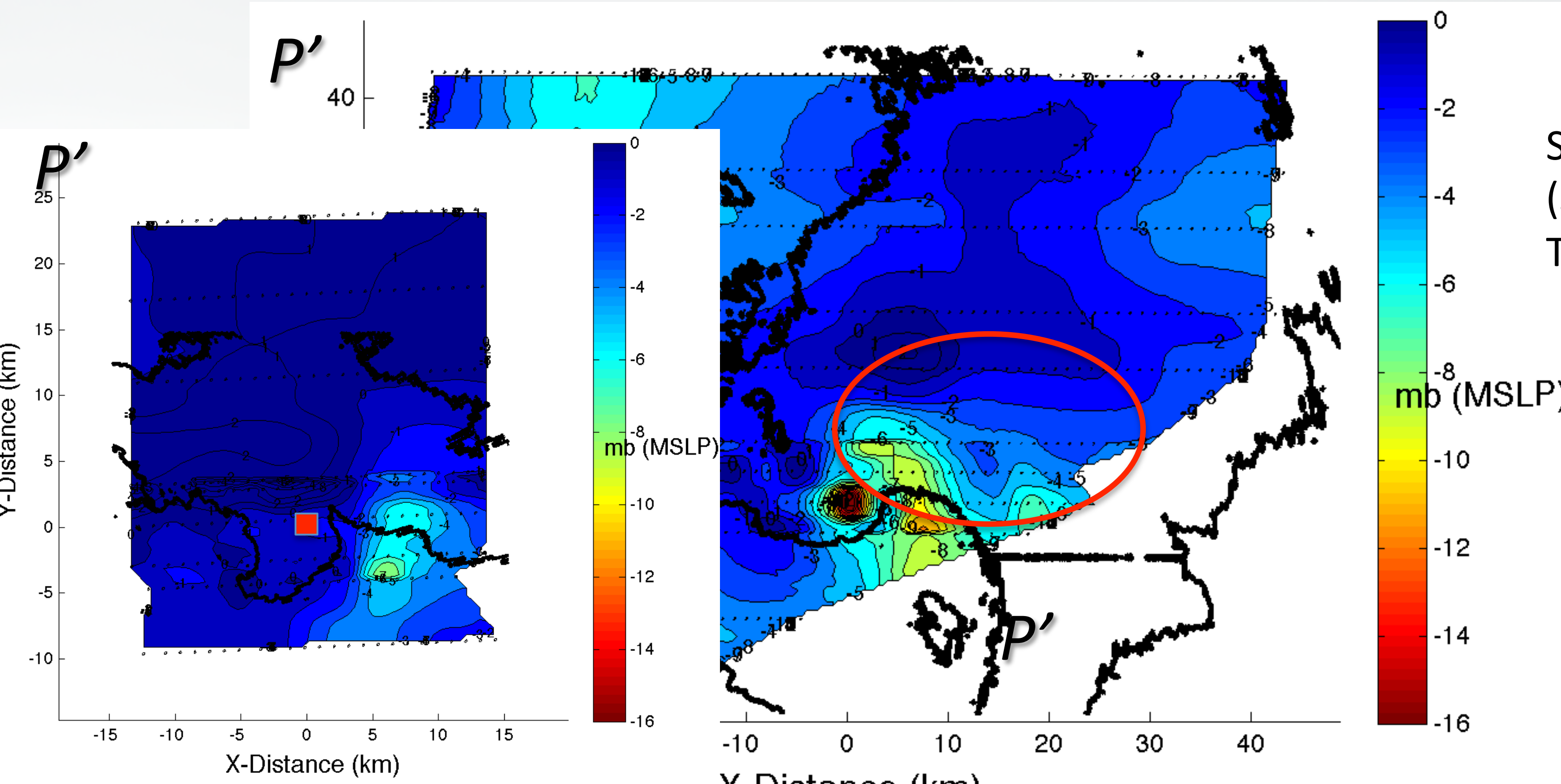


Contour: 20 dBZ KOUN 0.5 deg reflectivity, 2316 UTC
Colored: StickNet MSLP (mb), 18 May 2010, 2248-2348 UTC

Notes:

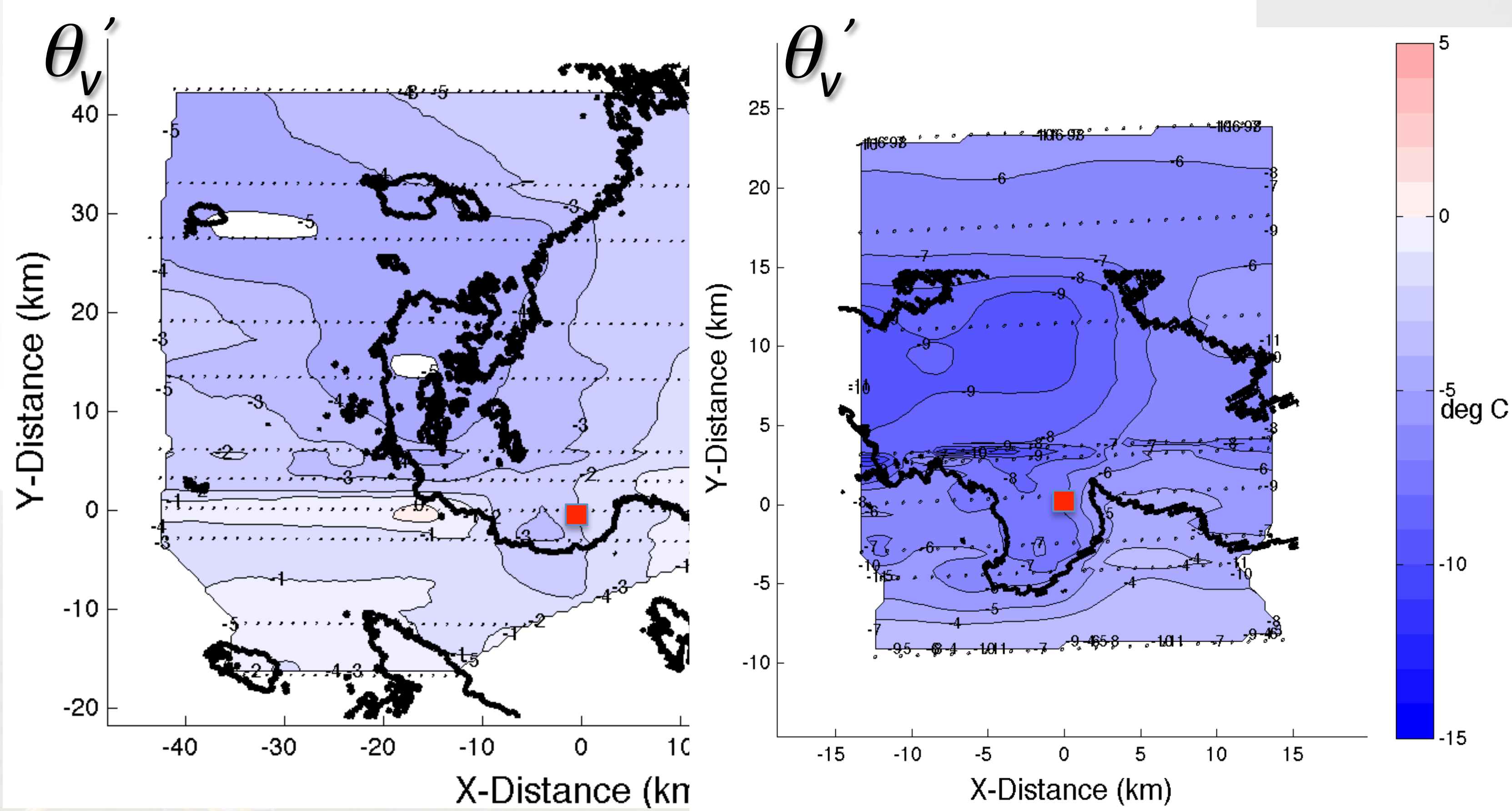
- Sharp confluence along FFRG, consistent within latitudinal storm-scale pressure gradient

Seminole (Strongly Tornadic)



Dumas #2 (Non-Tornadic)

Contour: 20 dBZ KOUN 0.5 deg reflectivity, 2316 UTC
Colored: StickNet MSLP (mb), 18 May 2010, 2248-2348 UTC

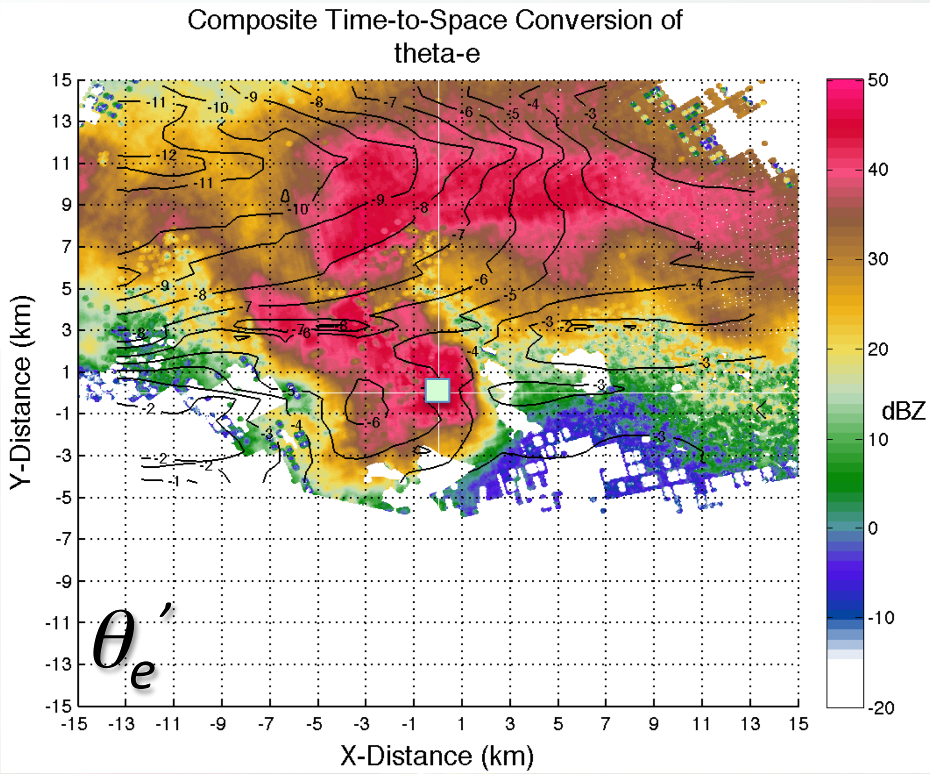


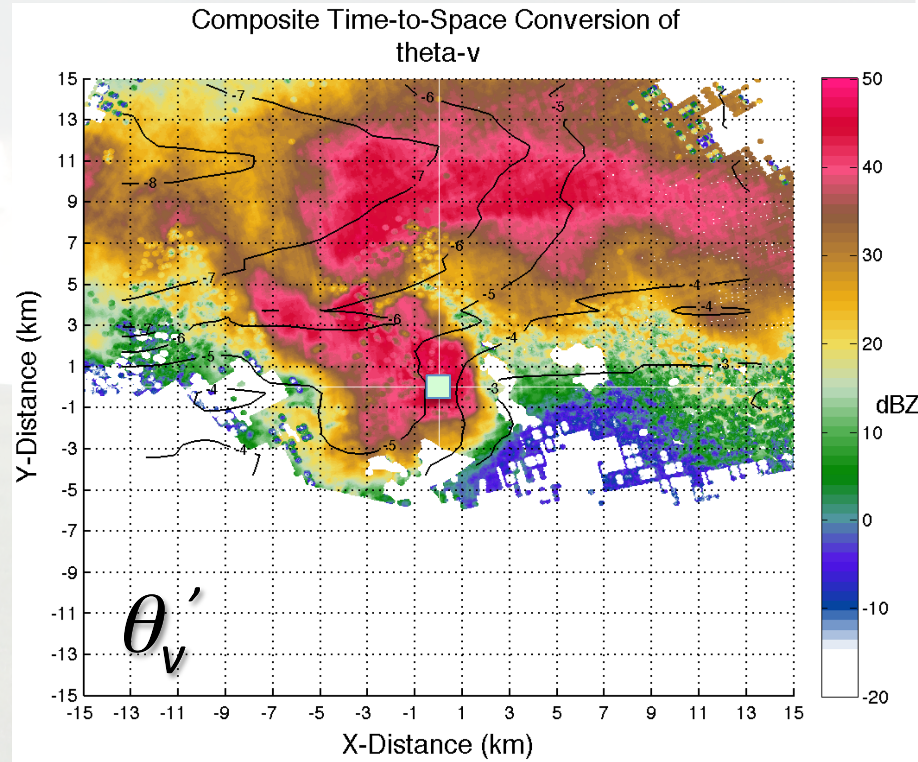
Contour: 20 dBZ KOUN 0.5 deg reflectivity, 2316 UTC
Colored: StickNet θ_v' (K), 18 May 2010, 2248-2348 UTC

Notes:

- Sharp confluence along FFRG, consistent within latitudinal storm-scale pressure gradient
- Thermodynamic deficits weaker and positioned well to rear of highest reflectivity

Composite Profiles – Dumas (2) + Seminole



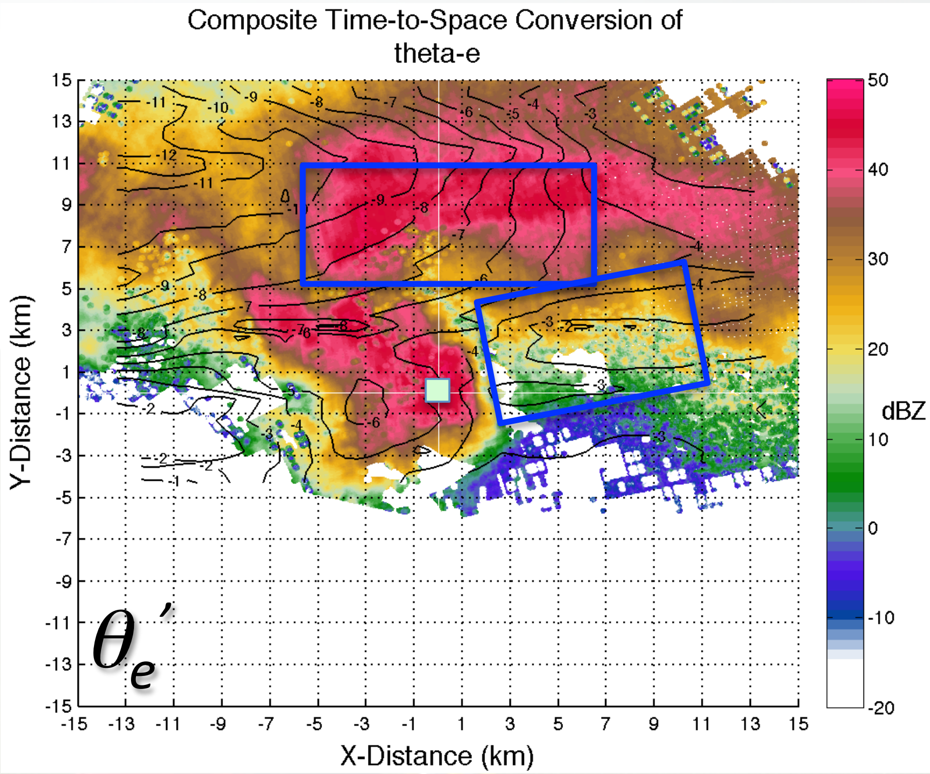


Colored: Mean reflectivity (dBZ)
Contoured: Mean θ_e' (K)

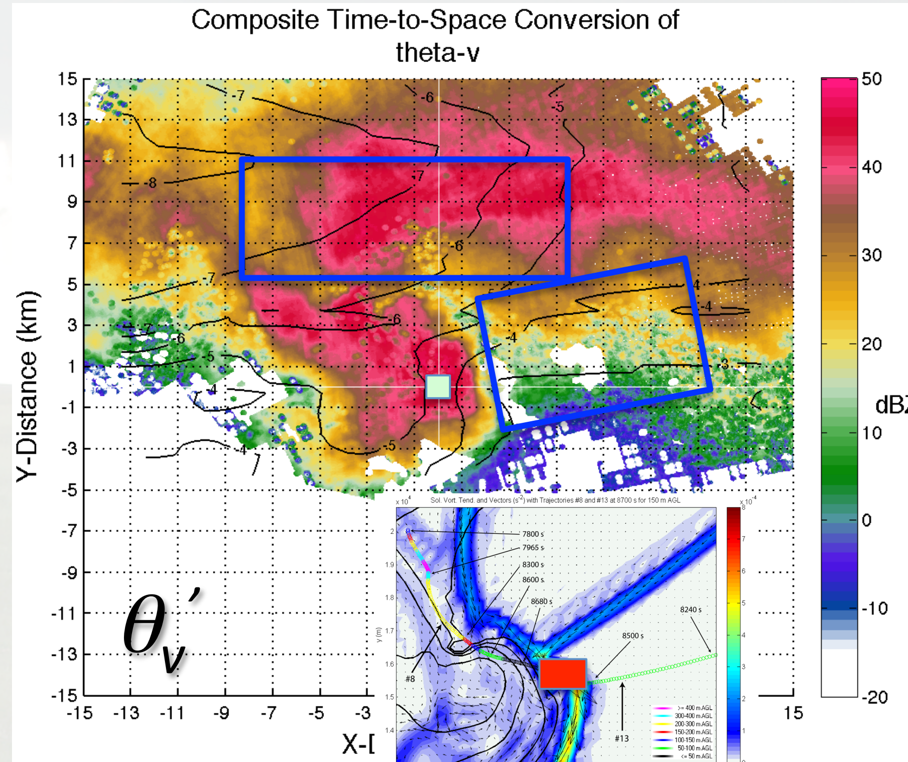
Colored: Mean reflectivity (dBZ)
Contoured: Mean θ_v' (K)

- Gradients related to deficits in forward flank are bifurcated

Composite Profiles – Dumas (2) + Seminole



Colored: Mean reflectivity (dBZ)
Contoured: Mean θ_e' (K)



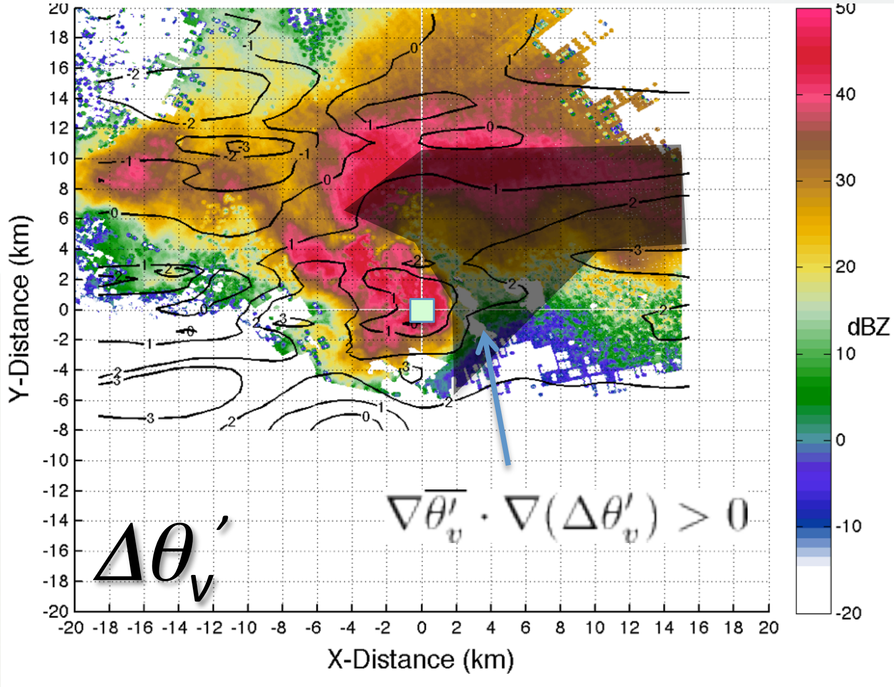
Beck and Weiss 2013

Colored: Mean reflectivity (dBZ)
Contoured: Mean θ_v' (K)

- Gradients related to deficits in forward flank are bifurcated
    - (Longitudinal) gradient steady within core, max deficits rearward of highest *Z*
    - Gradient strengthens near FFRG

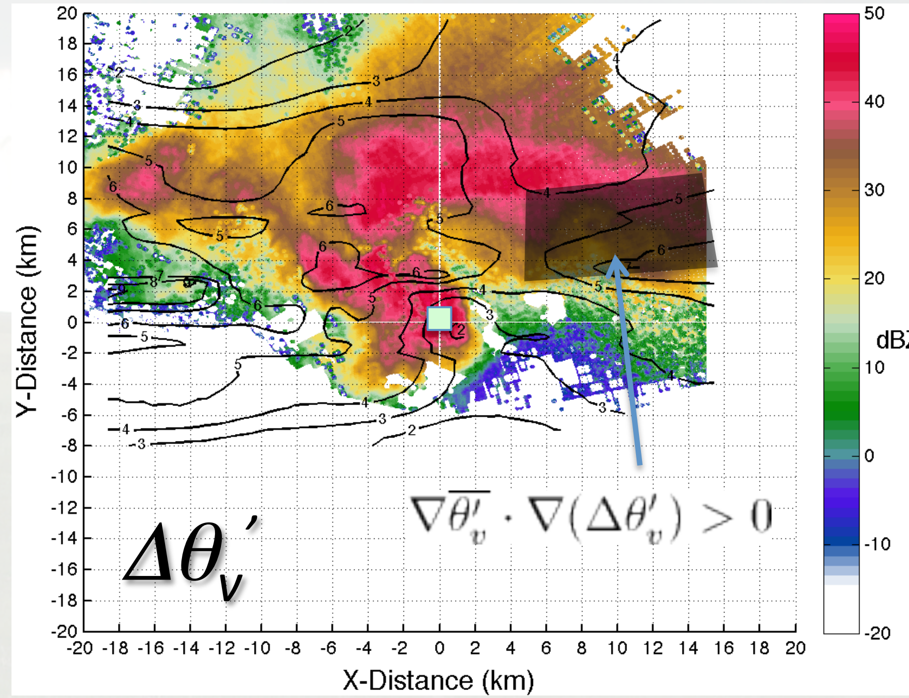
θ_v' Difference Profiles

Dumas 1 (WT) – Dumas 2 (NT)



Colored: Mean reflectivity (dBZ)
Contoured: Difference θ_v' (K)

Seminole (T) – Dumas 2 (NT)

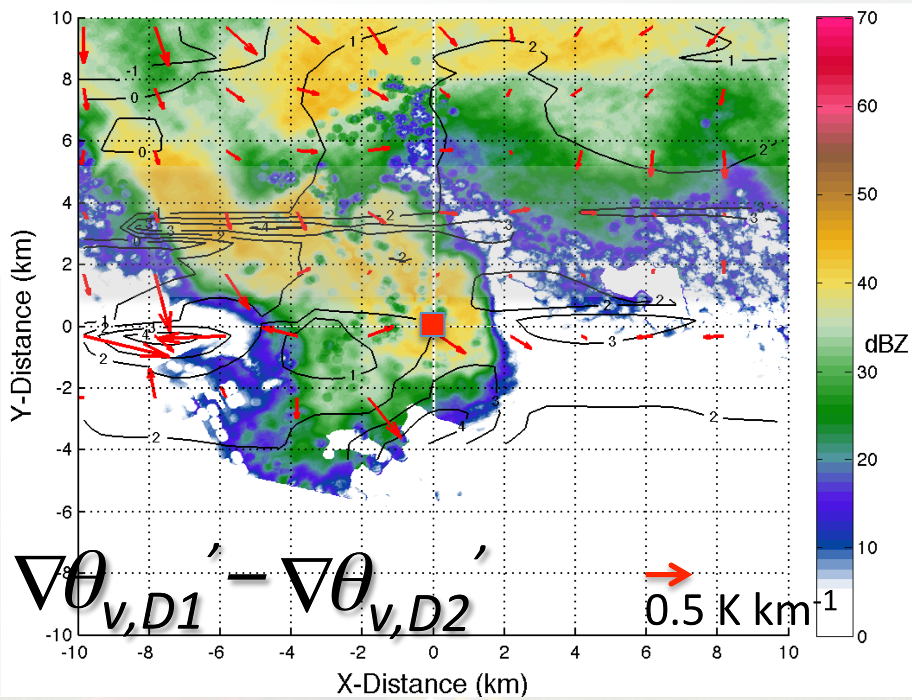


Colored: Mean reflectivity (dBZ)
Contoured: Difference θ_v' (K)

- Gradients related to deficits in forward flank are bifurcated
  - (Longitudinal) gradient steady within core, max deficits rearward of highest *Z*
  - Gradient strengthens near FFRG
- FFRG θ_v' gradient tends to be stronger for the tornadic cases in this study

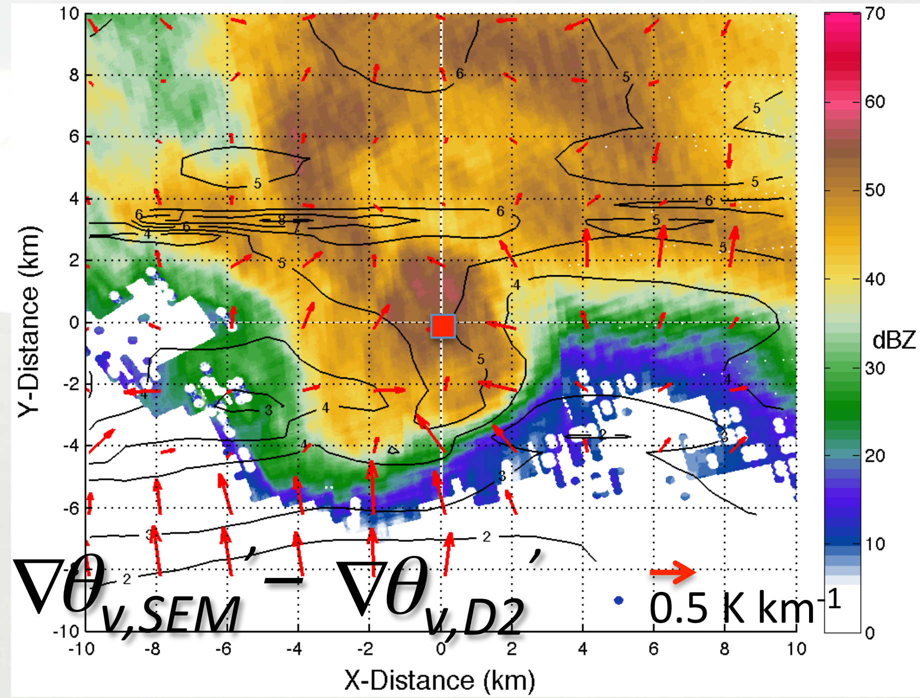
$\theta_v{}'$ Difference Profiles

Dumas 1 (WT) – Dumas 2 (NT)



Colored: Mean reflectivity (dBZ) (Dumas1, Dumas2)
Contoured: Difference $\theta_v{}'$ (K)
Vectors: Difference $\nabla\theta_v{}'$

Seminole (T) – Dumas 2 (NT)



Colored: Mean reflectivity (dBZ)
Contoured: Difference $\theta_v{}'$ (K)
Vectors: Difference $\nabla\theta_v{}'$

- $\theta_v{}'$ gradient tends to be stronger through FFRG and left flank for weakly tornadic case (compared to non-tornadic sample with similar environment)
- However, $\theta_v{}'$ gradients and deficits are weaker throughout these critical zones in strongly-tornadic (Seminole) case

Conclusions

- Baroclinic vorticity appears to contribute to the low-level mesocyclone in the examined cases
  - Composites of θ_v' reveal a bifurcated distribution related to the position of the precipitation core and the FFRG
    - Baroclinic zones located where previous studies have identified trajectories relevant to the low-level mesocyclone / tornado
    - In comparing two samples with a similar environment (Dumas), θ_v' gradients are stronger throughout the FFRG and left flank for the weakly tornadic deployment
    - However, much weaker θ_v' gradients (and deficits overall) throughout the strongly tornadic (Seminole) storm highlight the principal importance of buoyancy
  - Varied kinematic presentation along FFRG
    - These cases reveal stronger confluence along FFRG for tornadic deployments
    - Confluence appears consistent with distribution of pressure and, to some degree, latitudinal gradients of θ_v'

This work is supported by NSF Grant AGS-0800542

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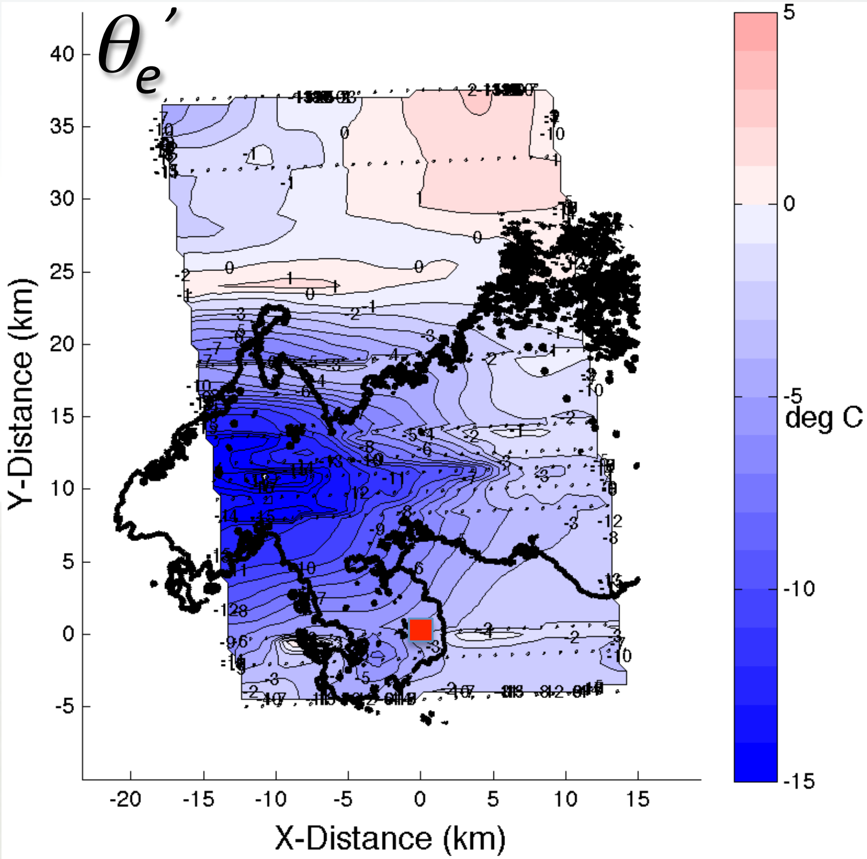
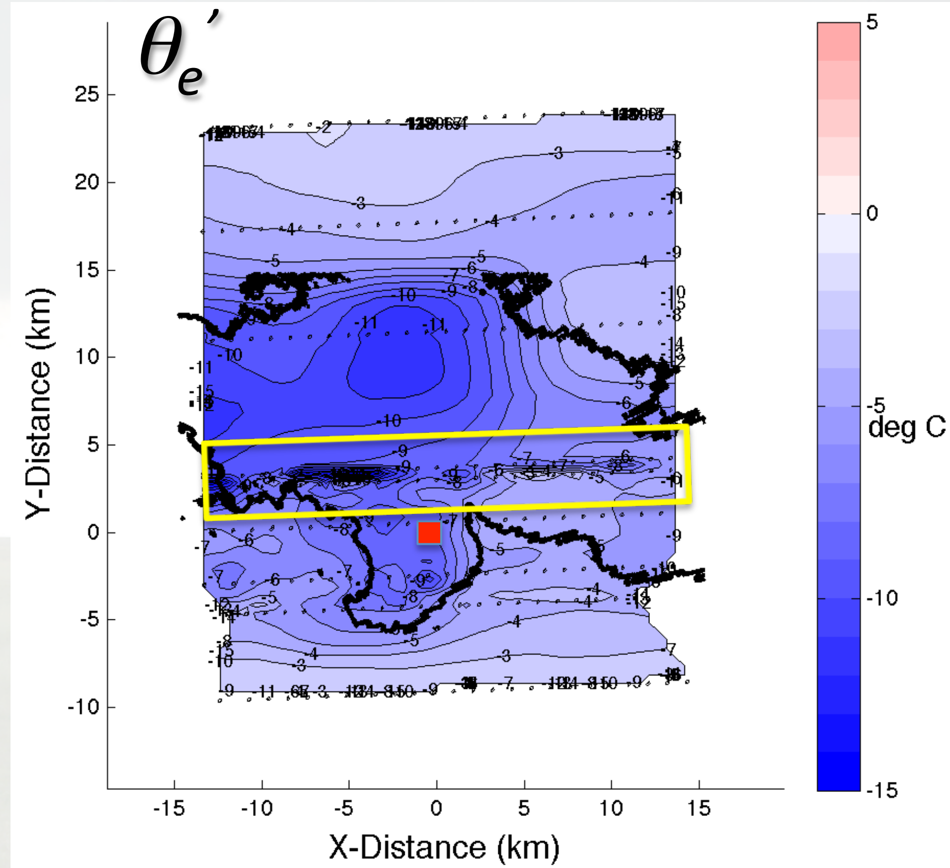
  - Varied kinematic presentation along FFRG
    - These cases reveal stronger confluence along FFRG for tornadic deployments
    - Confluence appears consistent with distribution of pressure and, to some degree, latitudinal gradients of θ_v'
- Baroclinic zones can locally have vorticity tendency comparable to that indicated in recent simulations (e.g., Beck and Weiss 2013)
  - Magnitudes are comparable in isolated zones of <=1 km width, mostly to northwest of low-level mesocyclone
  - Strongest tendency seen for probes affected by hailfall (hailfall locally influences thermodynamic deficits; impact on vorticity budget?)

This work is supported by NSF Grant AGS-0800542



Contour: 0 dBZ DOW6 2.0 deg reflectivity, 2330 UTC
Colored: StickNet θ_e' (K), 18 May 2010, 2305-2355 UTC

Deployment #1
(weakly tornadic)

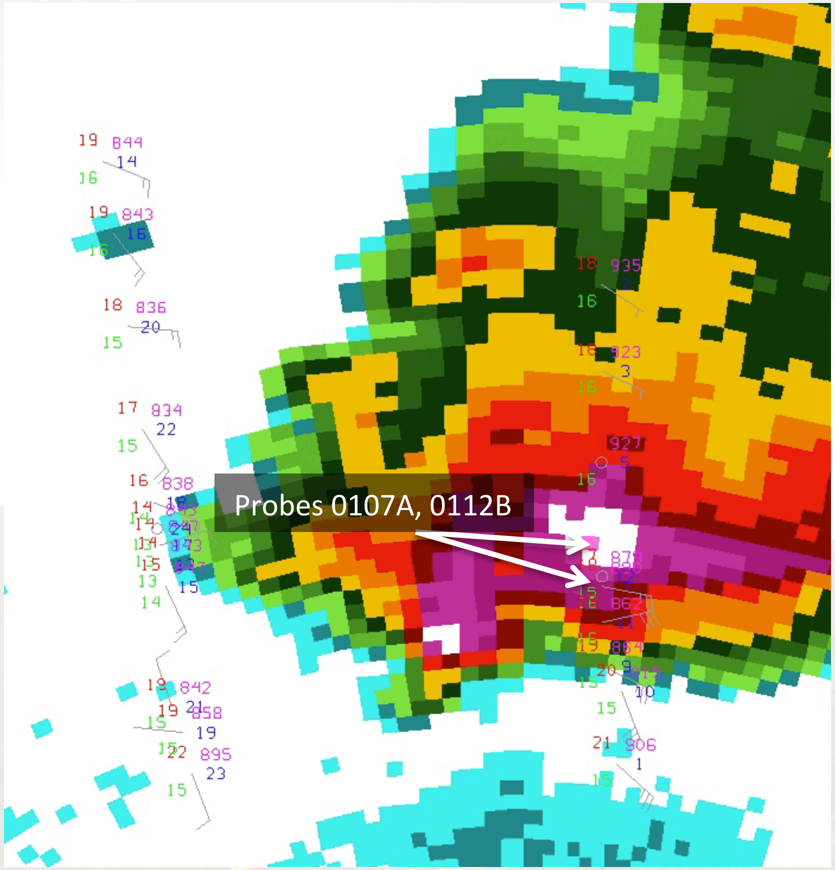


Contour: 30 dBZ SMART-R 2.5 deg reflectivity, 0025 UTC
Colored: StickNet θ_e' (K), 19 May 2010, 0000-0050 UTC

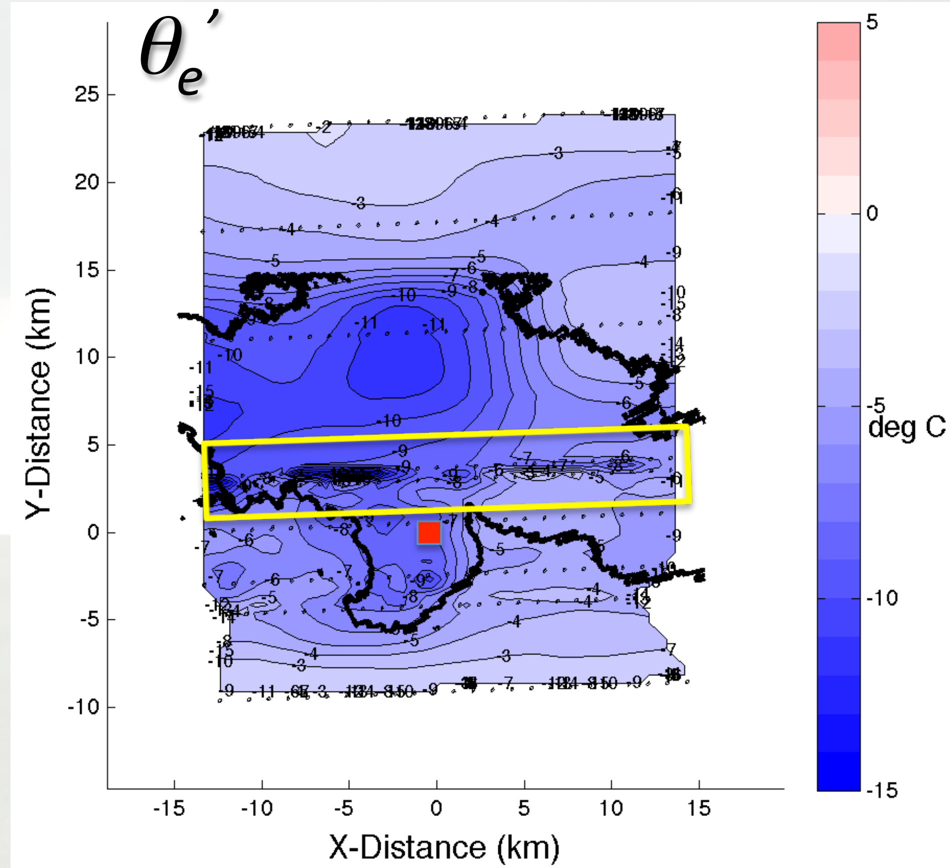
Deployment #2
(non-tornadic)

Notes:

- Some influence of hailfall on deficits



KAMA WSR-88D Base Reflectivity – 19 May 2010, 0013 UTC



Contour: 30 dBZ SMART-R 2.5 deg reflectivity, 0025 UTC
Colored: StickNet θ_e' (K), 19 May 2010, 0000-0050 UTC

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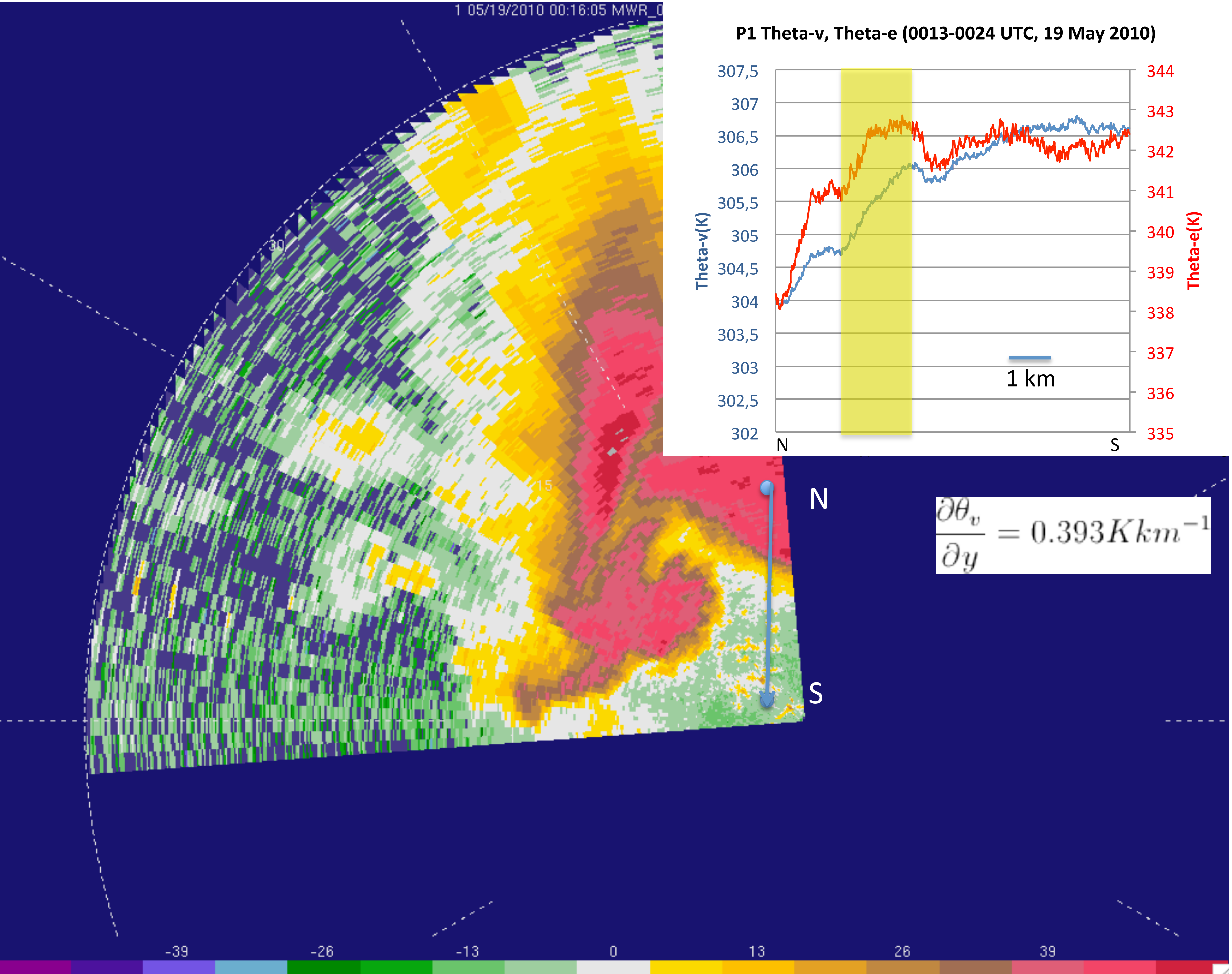
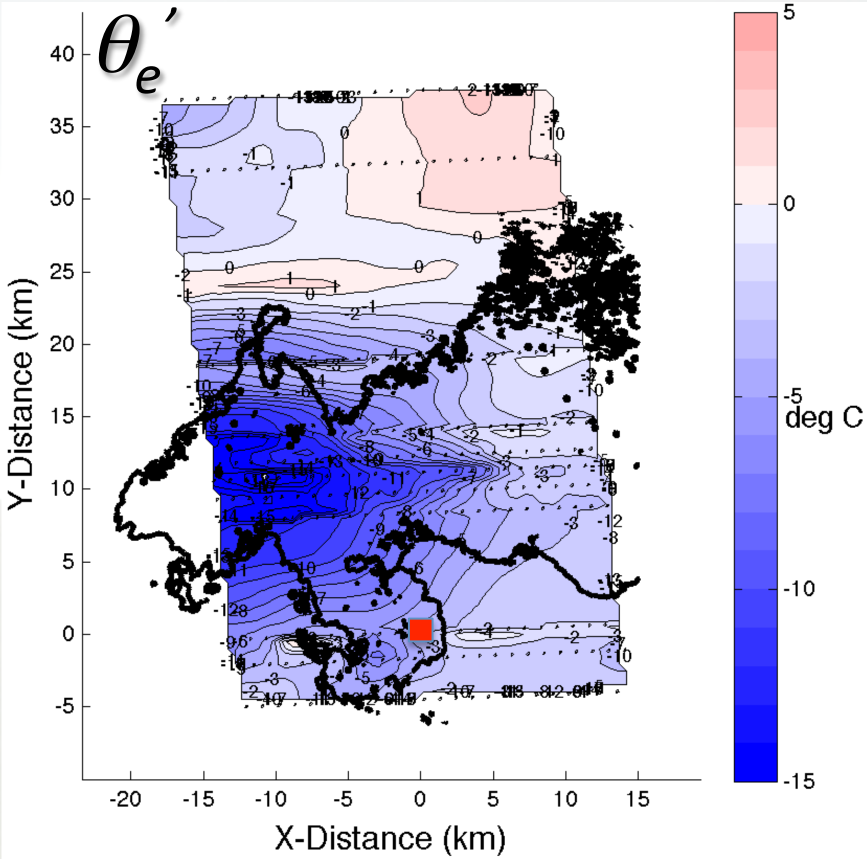
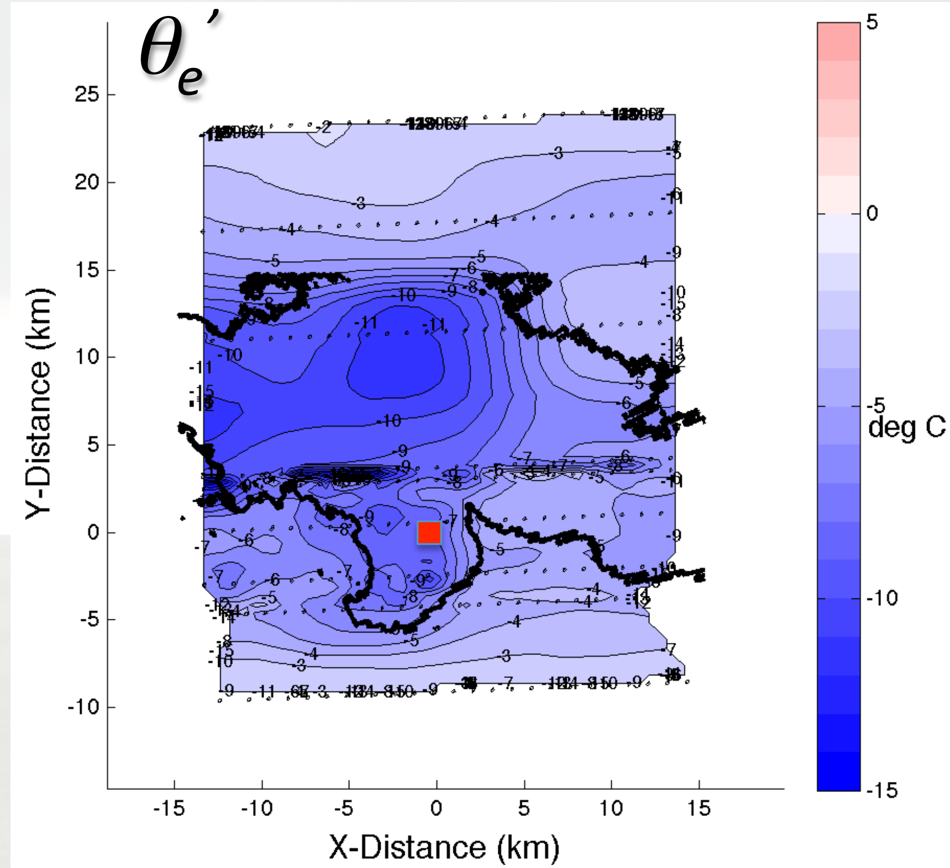

1 05/19/2010 00:16:05 MWR_
P1 Theta-v, Theta-e (0013-0024 UTC, 19 May 2010)
307,5
307
306,5
306
305,5
305
304,5
304
303,5
303
302,5
302
Theta-v(K)
344
343
342
341
340
339
338
337
336
335
Theta-e(K)
1 km
N
S
30
15
N
S
$\frac{\partial \theta_v}{\partial y} = 0.393 K km^{-1}$
-39
-26
-13
0
13
26
39



Contour: 0 dBZ DOW6 2.0 deg reflectivity, 2330 UTC
Colored: StickNet θ_e' (K), 18 May 2010, 2305-2355 UTC



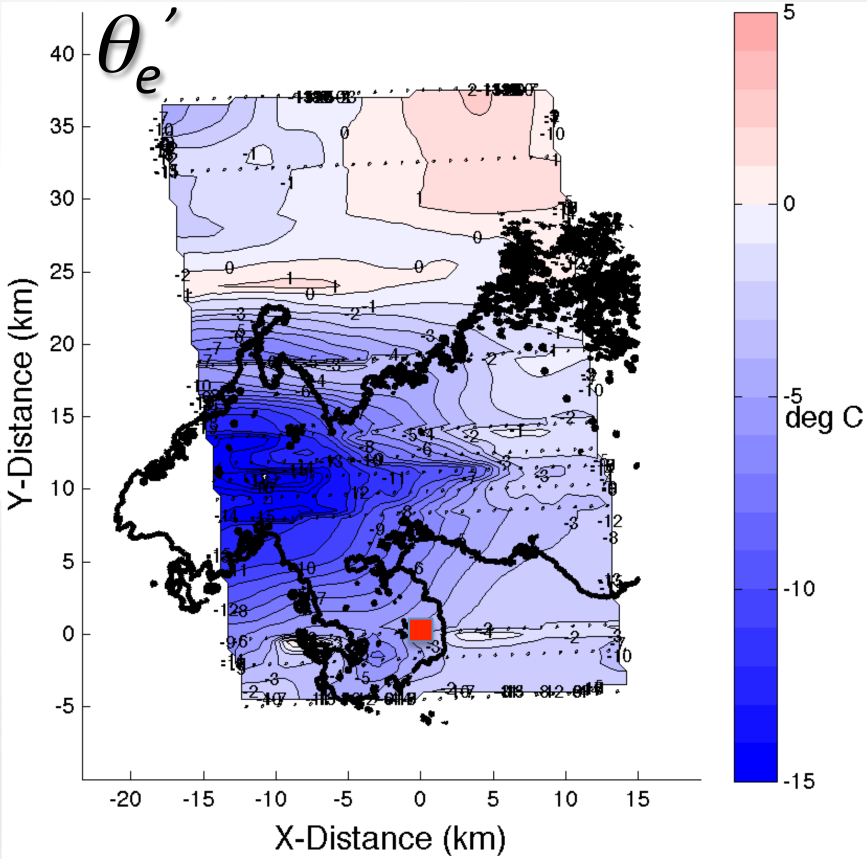
Contour: 30 dBZ SMART-R 2.5 deg reflectivity, 0025 UTC
Colored: StickNet θ_e' (K), 19 May 2010, 0000-0050 UTC

Deployment #1
(weakly tornadic)

Deployment #2
(non-tornadic)

Notes:

- Thermodynamic deficits strongest in rear of storm; deficits somewhat stronger near low-level mesocyclone for NT case



Contour: 0 dBZ DOW6 2.0 deg reflectivity, 2330 UTC
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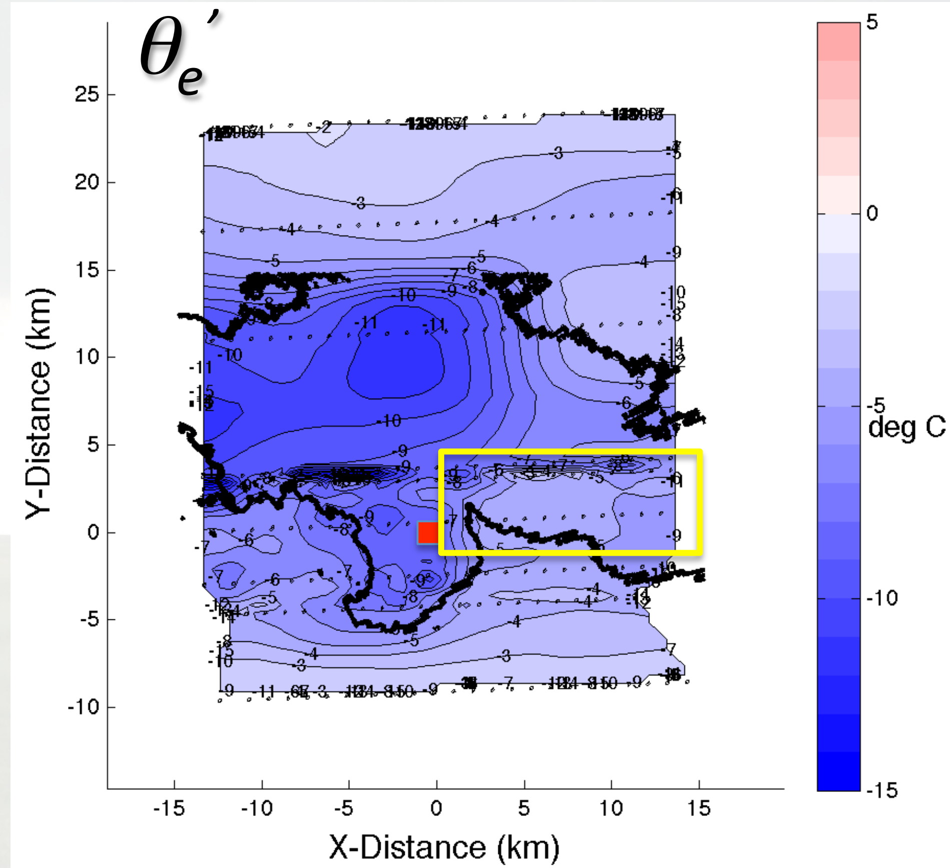
(weakly tornadic)

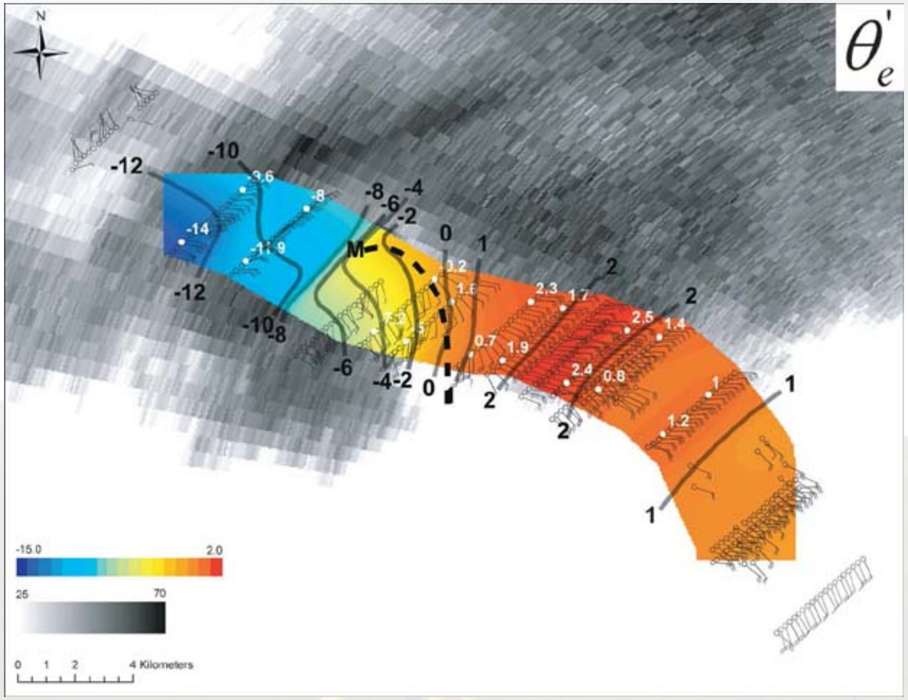


Contour: 30 dBZ SMART-R 2.5 deg reflectivity, 0025 UTC
Colored: StickNet θ_e' (K), 19 May 2010, 0000-0050 UTC

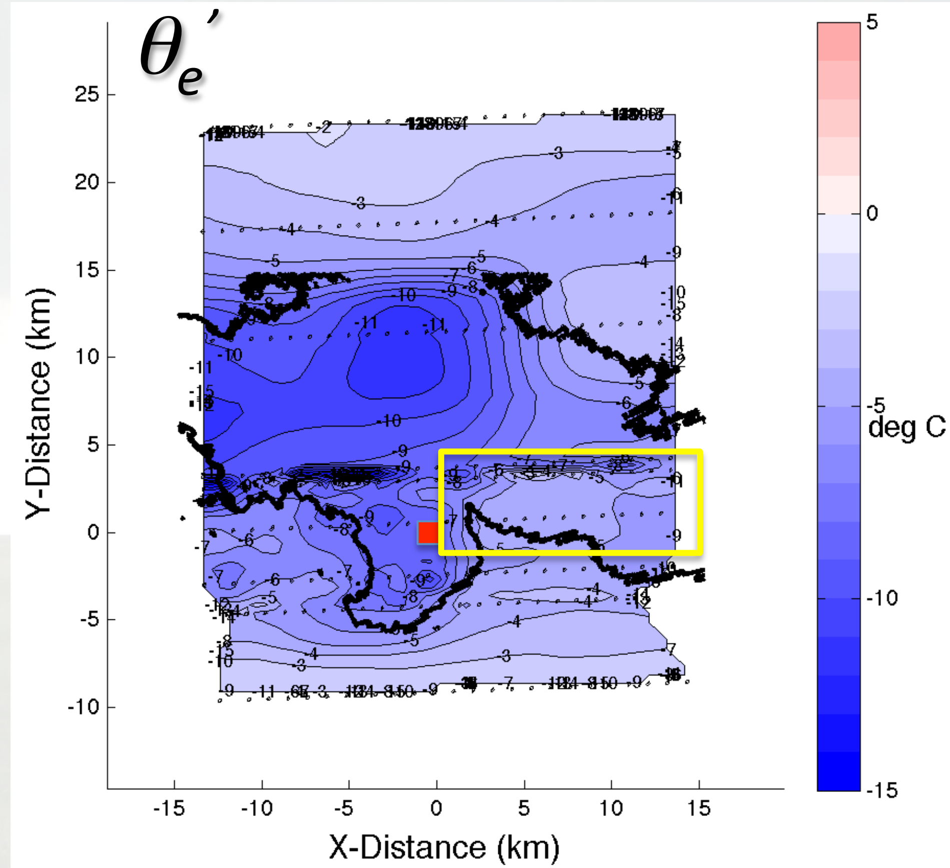
Deployment #2
(non-tornadic)

Notes:

- Weakness in θ_e deficit near FFRG in NT dep #2 (similar to Skinner et al. 2011)



Skinner et al. 2011 (Perryton, TX 2007)
Grey-shade: WSR-88D 0.5 deg Reflectivity
Colored: StickNet θ_e' (K)



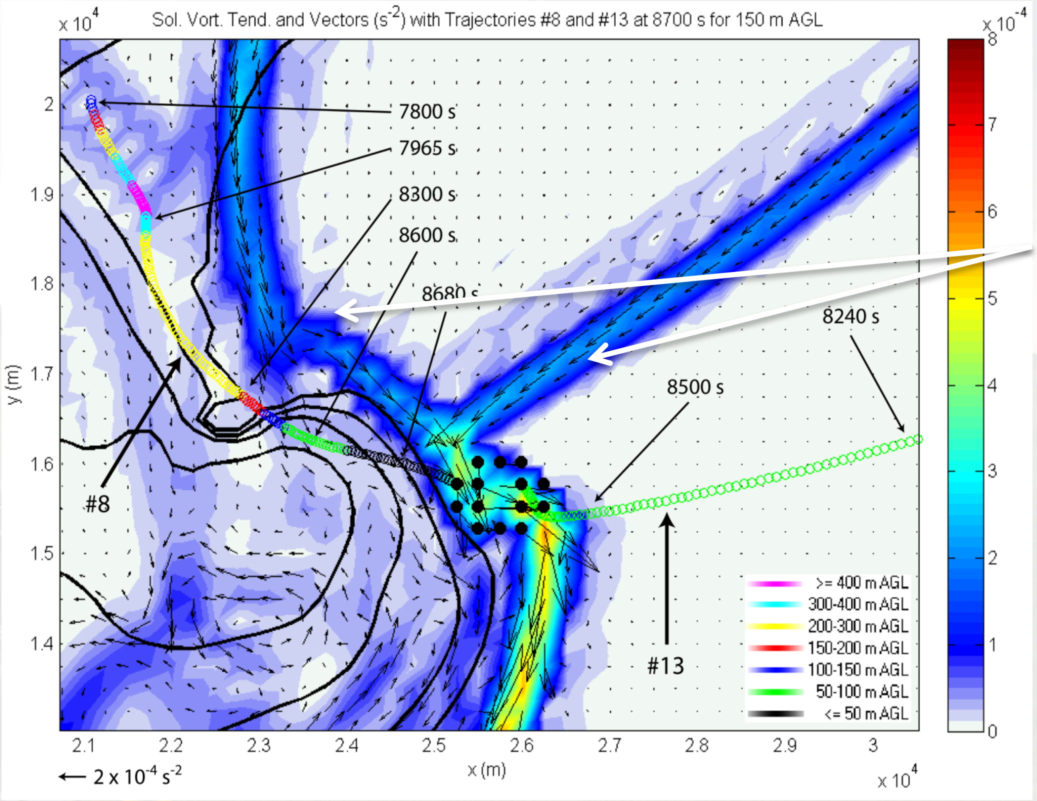
Contour: 30 dBZ SMART-R 2.5 deg reflectivity, 0025 UTC
Colored: StickNet θ_e' (K), 19 May 2010, 0000-0050 UTC

Deployment #2
(non-tornadic)

Notes:

- Weakness in θ_e deficit near FFRG in NT dep #2 (similar to Skinner et al. 2011)

What about the magnitude of the baroclinic zones?



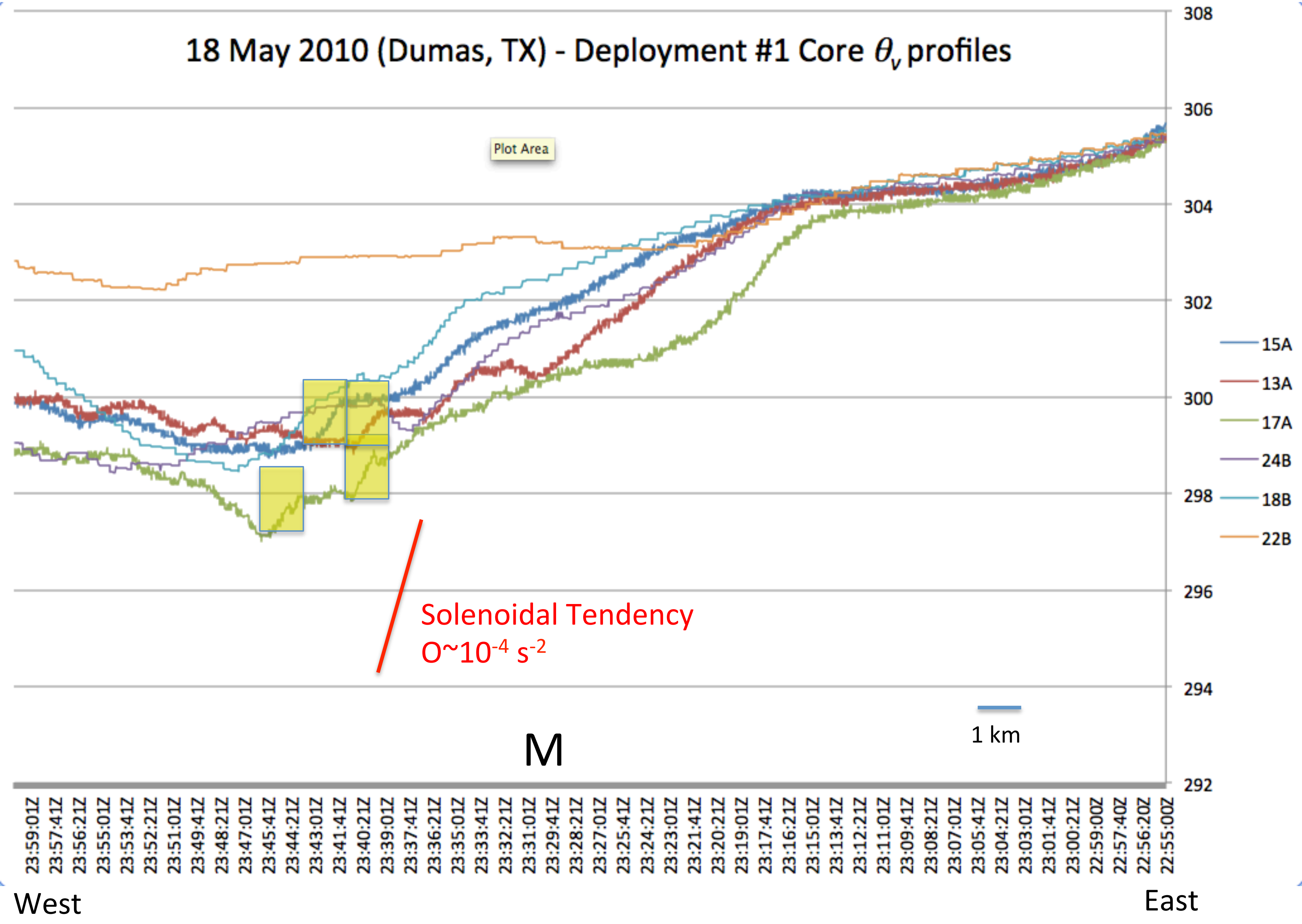
Simulated solenoidal vorticity tendency (s^{-2}) of order 10^{-4}.

Beck and Weiss 2013

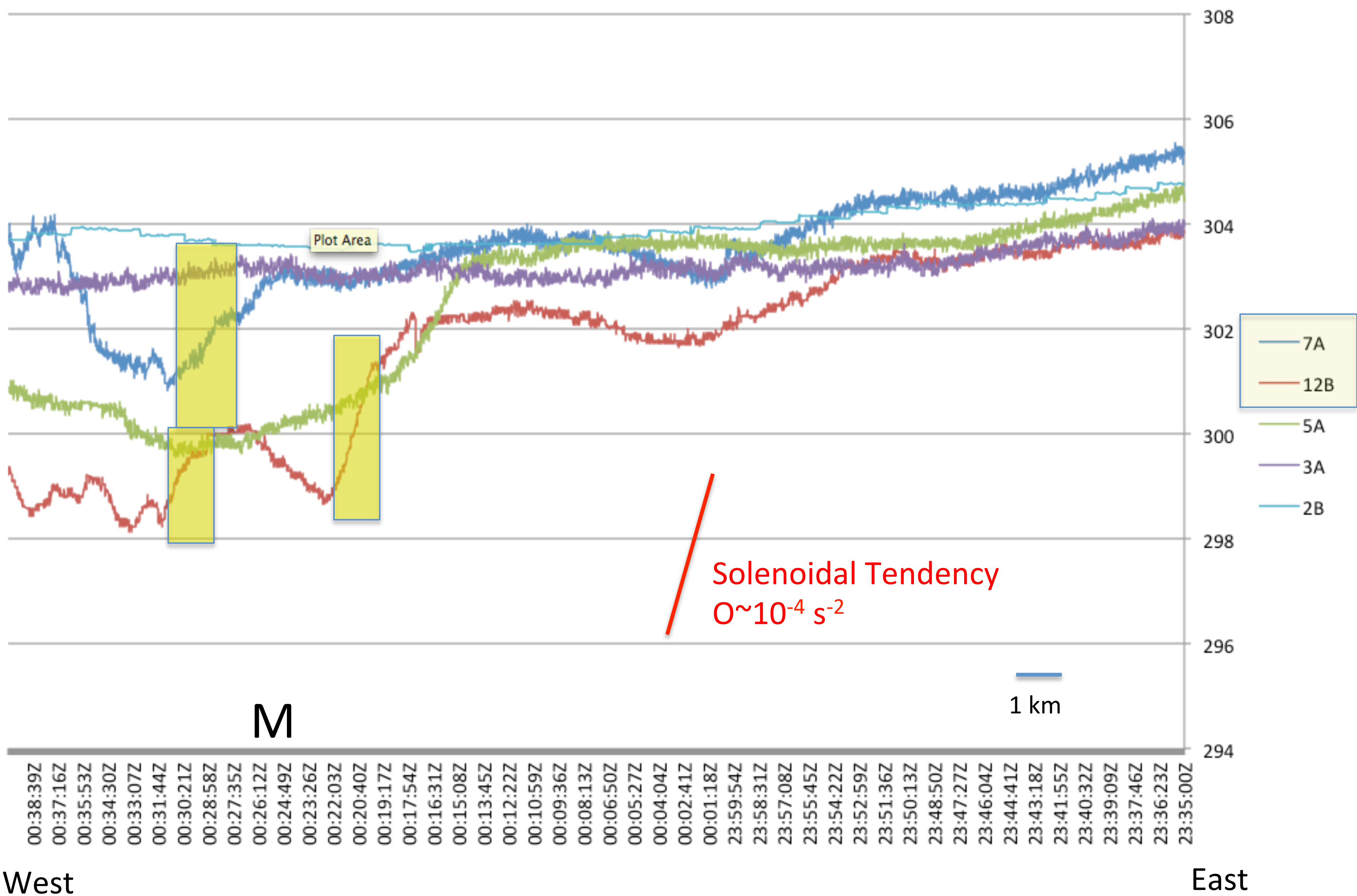
How do StickNet obs compare?

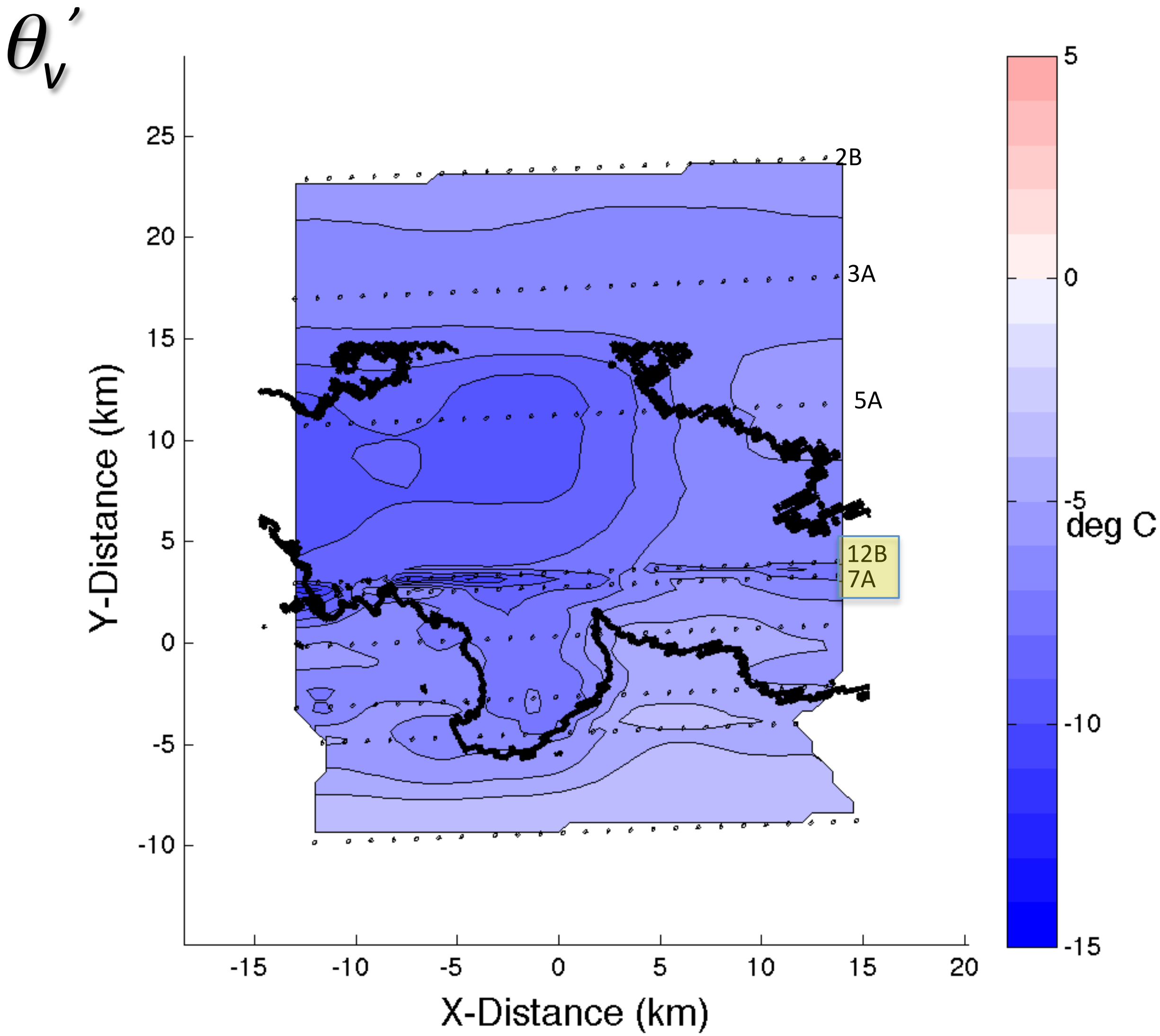
Use scaling of Klemp and Rotunno (1983), where:

$$\Delta\omega_s \approx \frac{g}{\theta}\frac{\partial\theta}{\partial n}\frac{\Delta_s}{\upsilon_s}$$

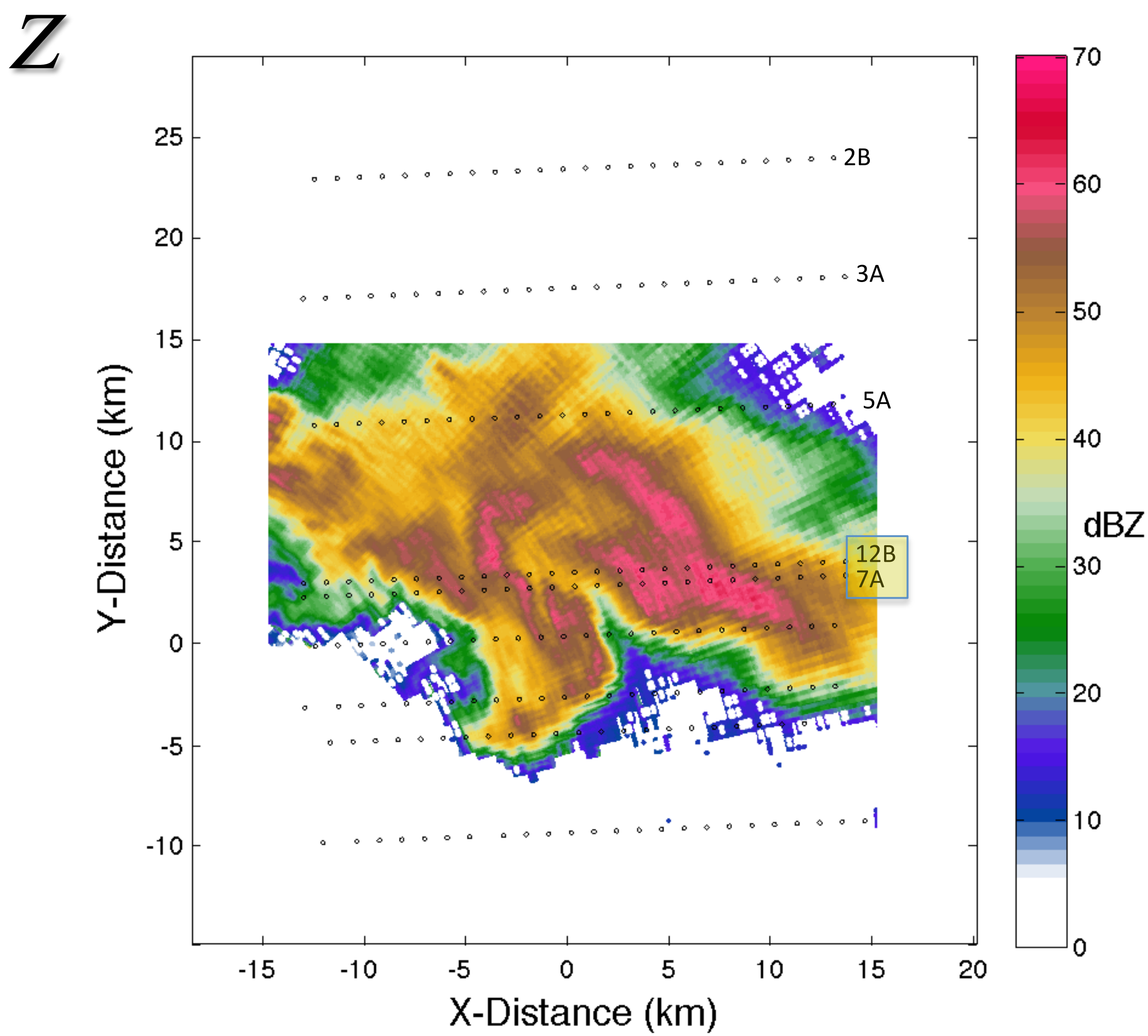

18 May 2010 (Dumas, TX) - Deployment #1 Core θv profiles
Plot Area
Solenoidal Tendency
O~10-4 s-2
M
1 km
15A
13A
17A
24B
18B
22B
308
306
304
302
300
298
296
294
292
23:59:01Z
23:57:41Z
23:56:21Z
23:55:01Z
23:53:41Z
23:52:21Z
23:51:01Z
23:49:41Z
23:48:21Z
23:47:01Z
23:45:41Z
23:44:21Z
23:43:01Z
23:41:41Z
23:40:21Z
23:39:01Z
23:37:41Z
23:36:21Z
23:35:01Z
23:33:41Z
23:32:21Z
23:31:01Z
23:29:41Z
23:28:21Z
23:27:01Z
23:25:41Z
23:24:21Z
23:23:01Z
23:21:41Z
23:20:21Z
23:19:01Z
23:17:41Z
23:16:21Z
23:15:01Z
23:13:41Z
23:12:21Z
23:11:01Z
23:09:41Z
23:08:21Z
23:07:01Z
23:05:41Z
23:04:21Z
23:03:01Z
23:01:41Z
23:00:21Z
22:59:00Z
22:57:40Z
22:56:20Z
22:55:00Z
West
East

18 May 2010 (Dumas, TX) - Deployment #2 Core θ_v profiles



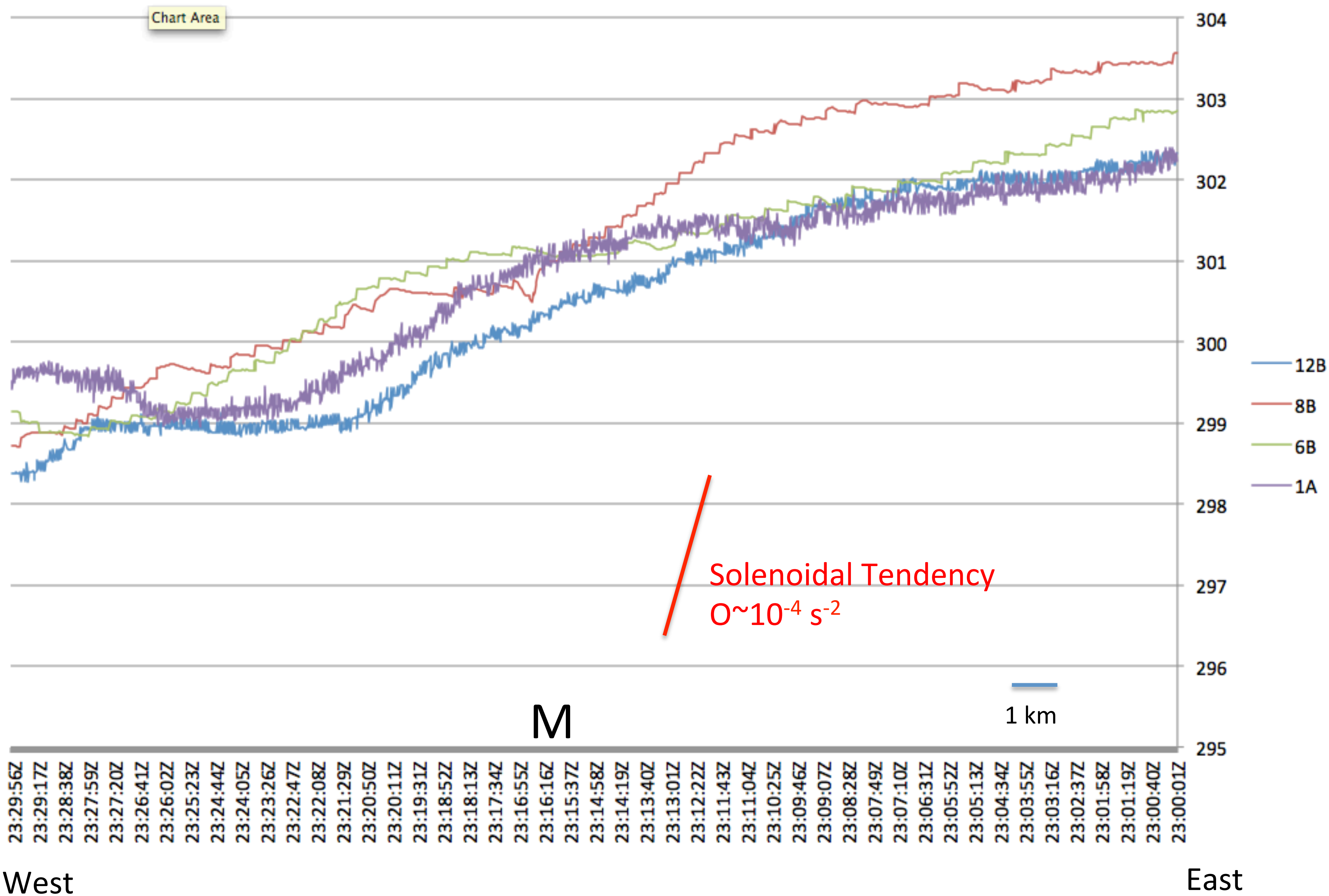


θ_v'
2B
3A
5A
12B
7A
Y-Distance (km)
X-Distance (km)
deg C
25
20
15
10
5
0
-5
-10
-15
20
5
-15



Z
2B
3A
5A
12B
7A
Y-Distance (km)
X-Distance (km)
dBZ
25
20
15
10
5
0
-5
-10
-15
20
70
60
50
40
30

10 May 2010 (Seminole, OK) - Core θ_v profiles



Conclusions

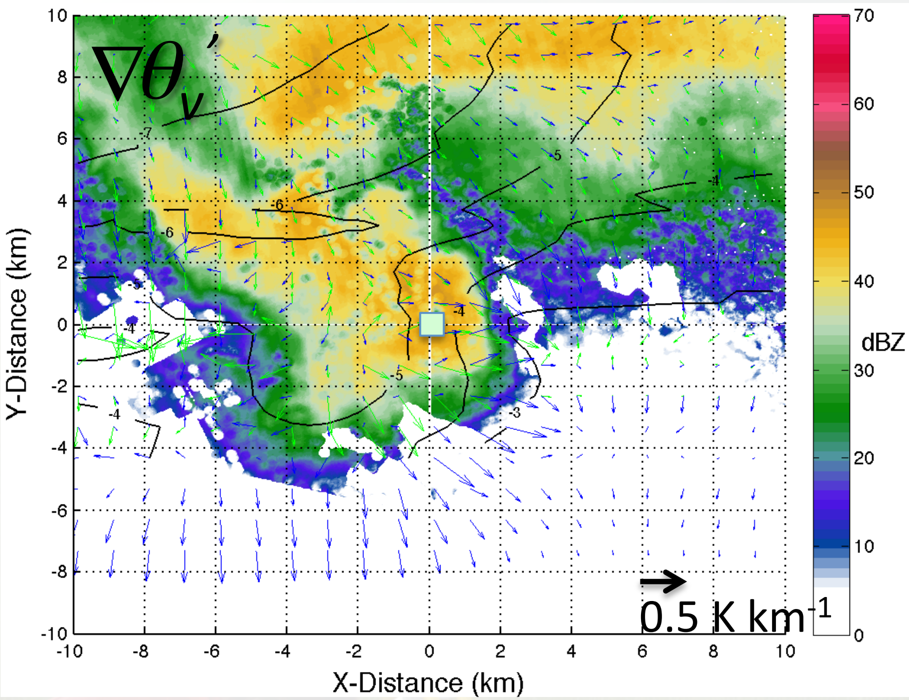
- Baroclinic vorticity appears to contribute to the low-level mesocyclone in the examined cases
  - Composites of θ_v' reveal a bifurcated distribution related to the position of the precipitation core and the FFRG
    - FFRG θ_v' gradients stronger for tornadic deployments (esp. 18 May 2010, Dumas, TX)
    - Baroclinic zones located where previous studies have identified trajectories relevant to the low-level mesocyclone / tornado
  - Varied kinematic presentation along FFRG
    - These cases reveal stronger confluence along FFRG for tornadic deployments
    - Confluence appears consistent with distribution of pressure and latitudinal gradients of θ_v'
- Baroclinic zones can locally have vorticity tendency comparable to that indicated in recent simulations (e.g., Beck and Weiss 2013)
  - Magnitudes are comparable in isolated zones of <=1 km width, mostly to northwest of low-level mesocyclone
  - Strongest tendency seen for probes affected by hailfall (hailfall locally influences thermodynamic deficits; impact on vorticity budget?)
- Thermodynamic deficits weaker overall in the significant tornado case (10 May 2010, Seminole, OK)

Moving Forward…

- Expand sample, e.g., quality null cases from 2009; incorporate mobile mesonet
- Resolve any thermodynamic footprint of radar signatures (e.g., LRR)
- Resolve relevant baroclinic zones aloft (UAS is a **key** player)
- "BHAG" – To construct a low-level mesocyclone vorticity budget driven by in situ and radar observations
  - ➢ Challenges:
    - Stationarity assumption
    - Observation error, in situ time constants
    - Liquid condensate estimation
    - Accurate, resolute trajectories
  - ➢ Compromise: EnKF-driven analysis constrained by observations?

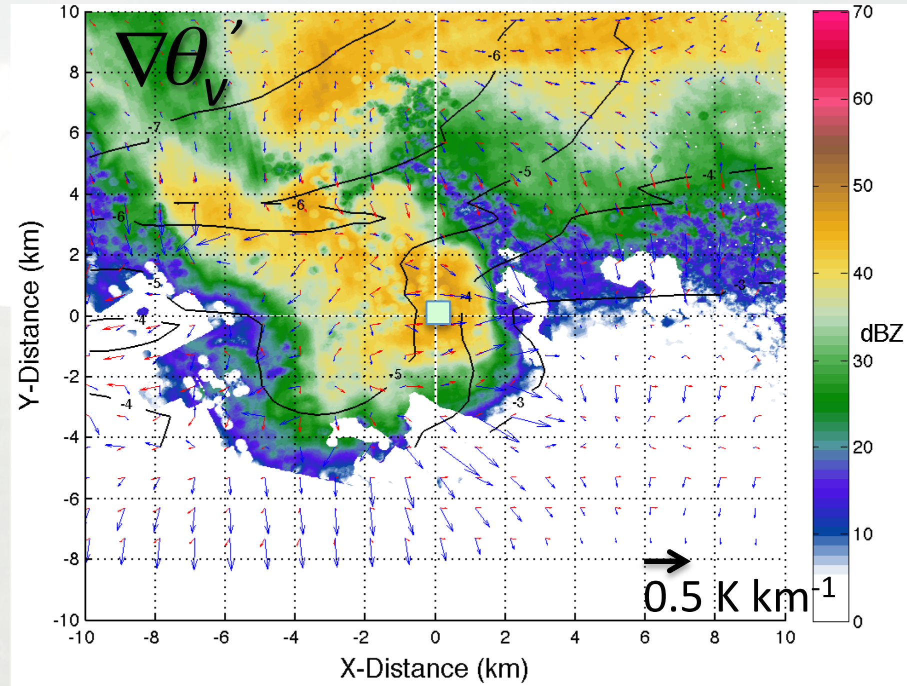
θ_v' Difference Profiles

Dumas 1 (WT) – Dumas 2 (NT)



Colored: Mean reflectivity (dBZ) (all three cases)
Contoured: Difference θ_v' (K)
Vectors: $\nabla\theta_v'$ Dumas 1 (green), $\nabla\theta_v'$ Dumas 2 (blue)

Seminole (T) – Dumas 2 (NT)

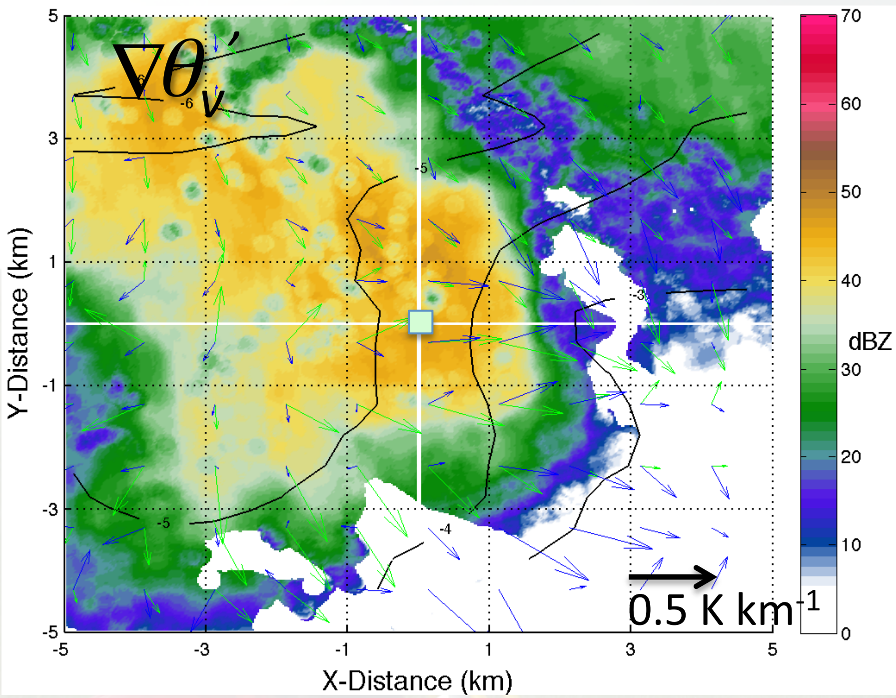


Colored: Mean reflectivity (dBZ) (all three cases)
Contoured: Difference θ_v' (K)
Vectors: $\nabla\theta_v'$ Seminole (red), $\nabla\theta_v'$ Dumas 2 (blue)

- Gradients related to deficits in forward flank are bifurcated
  - (Longitudinal) gradient steady within core, max deficits rearward of highest *Z*
  - Gradient strengthens near FFRG

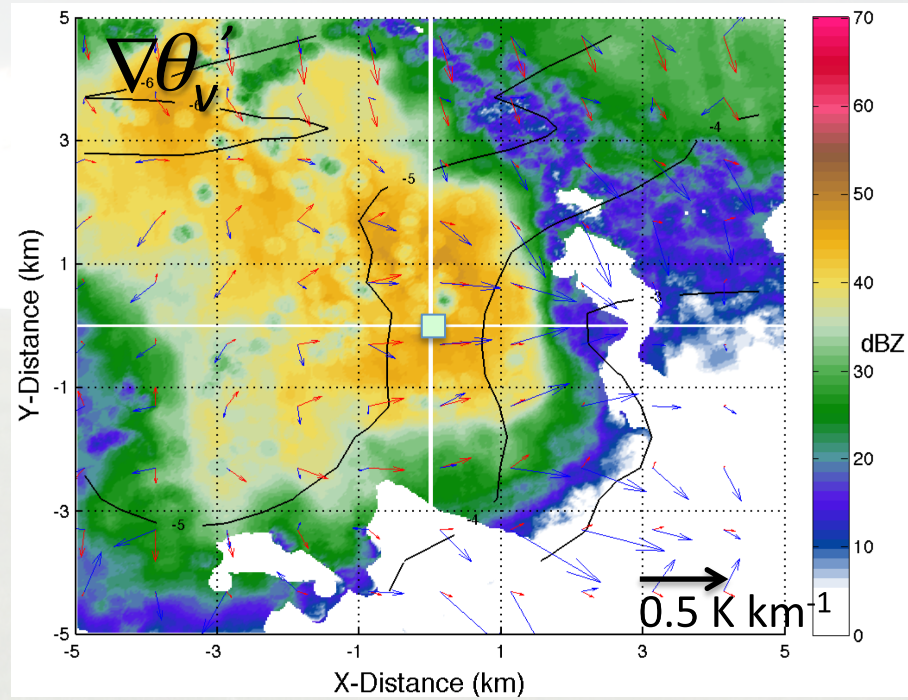
θ_v' Difference Profiles

Dumas 1 (WT) – Dumas 2 (NT)



Colored: Mean reflectivity (dBZ) (all three cases)
Contoured: Difference θ_v' (K)
Vectors: $\nabla\theta_v'$ Dumas 1 (green), $\nabla\theta_v'$ Dumas 2 (blue)

Seminole (T) – Dumas 2 (NT)



Colored: Mean reflectivity (dBZ) (all three cases)
Contoured: Difference θ_v' (K)
Vectors: $\nabla\theta_v'$ Seminole (red), $\nabla\theta_v'$ Dumas 2 (blue)

- Gradients related to deficits in forward flank are bifurcated
  - (Longitudinal) gradient steady within core, max deficits rearward of highest *Z*
  - Gradient strengthens near FFRG
- FFRG θ_v' gradient tends to be stronger for the tornadic cases in this study