Dynamics and microphysics in elevated convective systems

Russ S. Schumacher Department of Atmospheric Science, Colorado State University

Matthew Parker, North Carolina State University
Conrad Ziegler and Mike Coniglio, NOAA/NSSL

Along with: John Peters, Kelly Keene, Charles Yost, Richard Johnson

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NCAR MMM Seminar, 24 April 2014

A tale of two papers…

Published February 1988

A Theory for Strong, Long-Lived Squall Lines

RICHARD ROTUNNO, JOSEPH B. KLEMP AND MORRIS L. WEISMAN

National Center for Atmospheric Research, Boulder, Colorado*

(Manuscript received 27 February 1987, in final form 7 September 1987)

Cited 651 times!

Published December 1988

The Effect of Large-Scale Convergence on the Generation and Maintenance of Deep Moist Convection

N. ANDREW CROOK AND MITCHELL W. MONCRIEFF

*The National Center for Atmospheric Research, Boulder, Colorado**

(Manuscript received 10 February 1988, in final form 15 June 1988)

Cited 61 times

Citation counts from Web of Science, 18 April 2014

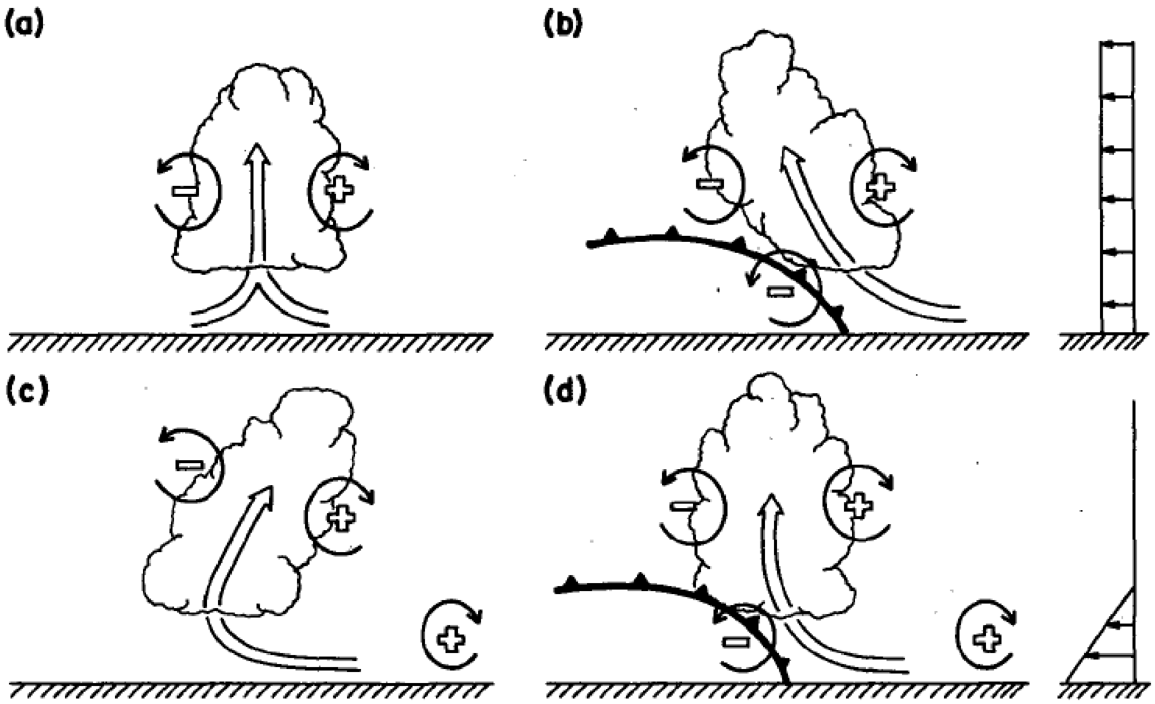
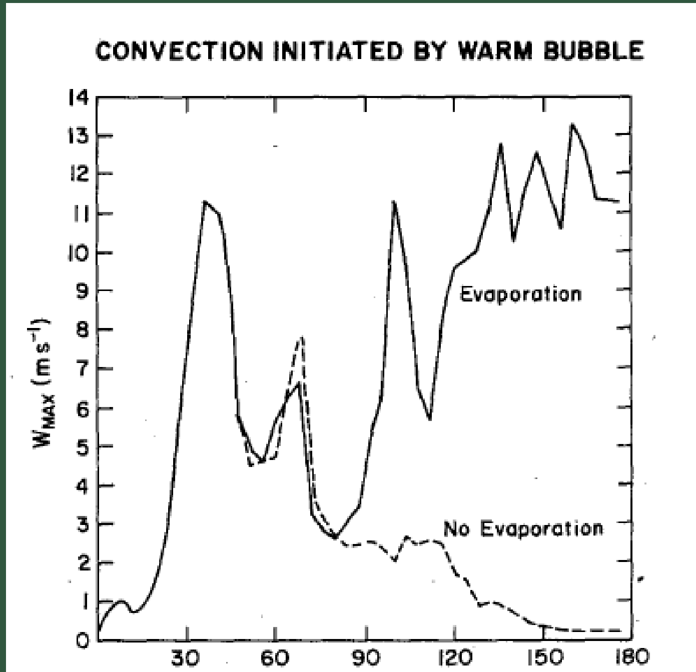
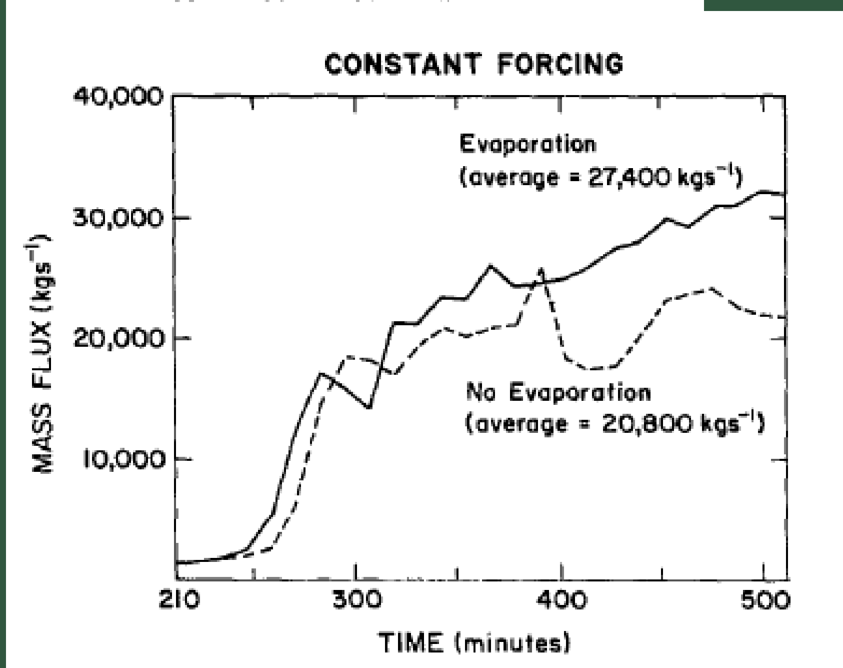


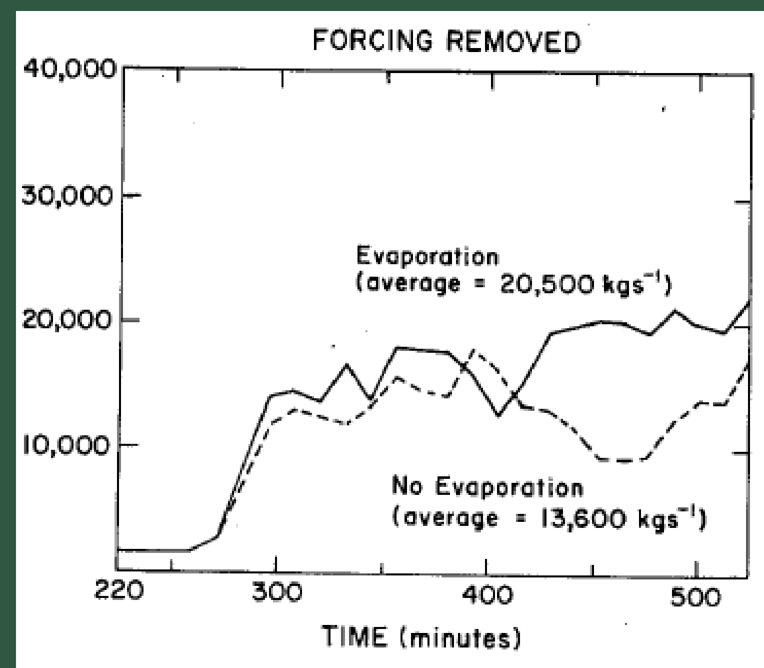
FIG. 18. Schematic diagram showing how a buoyant updraft may be influenced by wind shear and/or a cold pool. (a) With no shear and no cold pool, the axis of the updraft produced by the thermally created, symmetric vorticity distribution is vertical. (b) With a cold pool, the distribution is biased by the negative vorticity of the underlying cold pool and causes the updraft to lean upshear. (c) With shear, the distribution is biased toward positive vorticity and this causes the updraft to lean back over the cold pool. (d) With both a cold pool and shear, the two effects may negate each other, and allow an erect updraft.

From Rotunno et al. (1988)



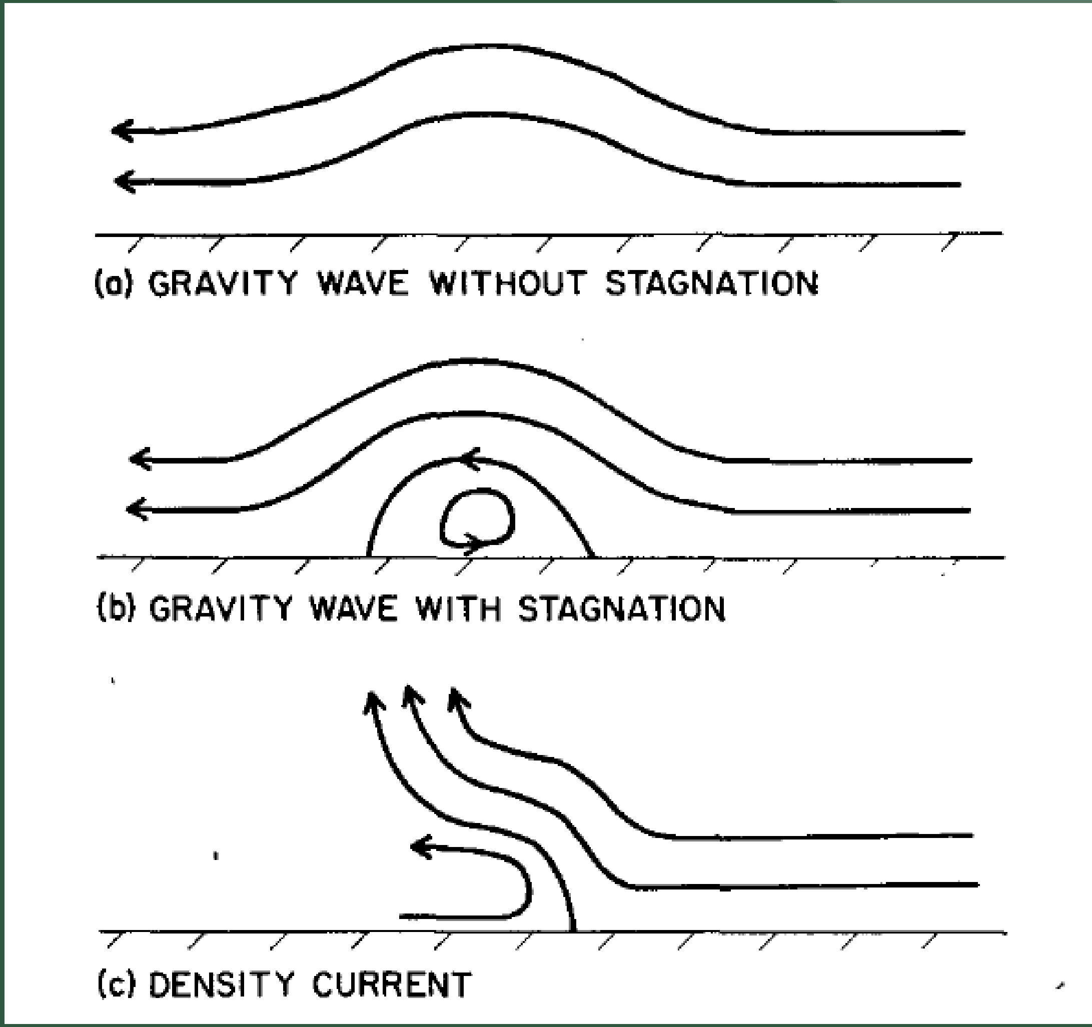
"If the environmental air is lifted to its level of saturation over a wide region before the initiation of convection, then the lifting at the cold pool is no longer critical in maintaining the convective system."



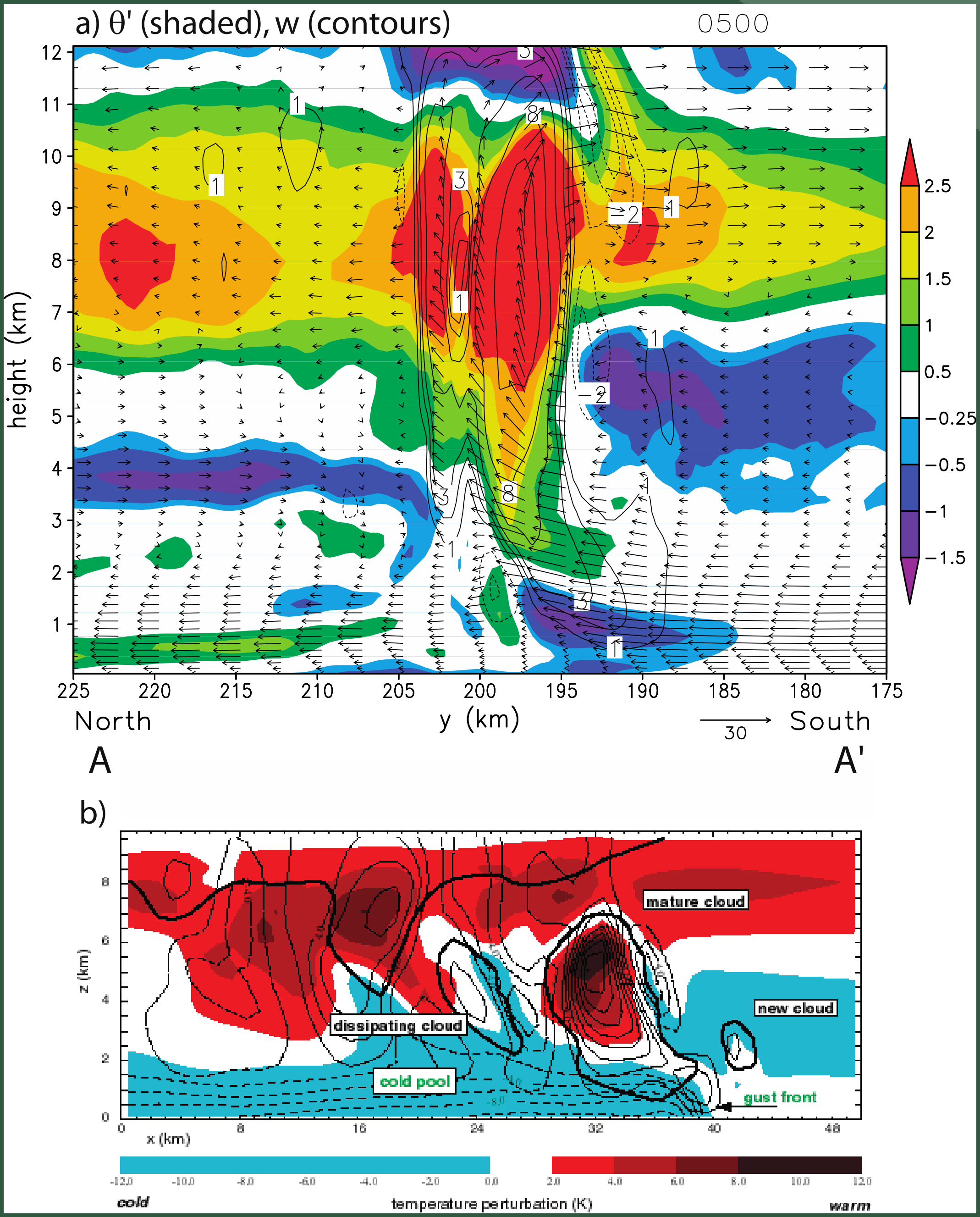


From Crook and Moncrieff (1988)

Low-level structures in MCSs



From Crook and Moncrieff (1988); see also Raymond and Rotunno (1989); Schmidt and Cotton (1990); and Haertel et al. (2001)



Vertical section through MCS initiated with large-scale ascent and organized by low-level wave

(Schumacher 2009)

Vertical section through cold-pool-driven MCS

(Fovell and Tan 1998)

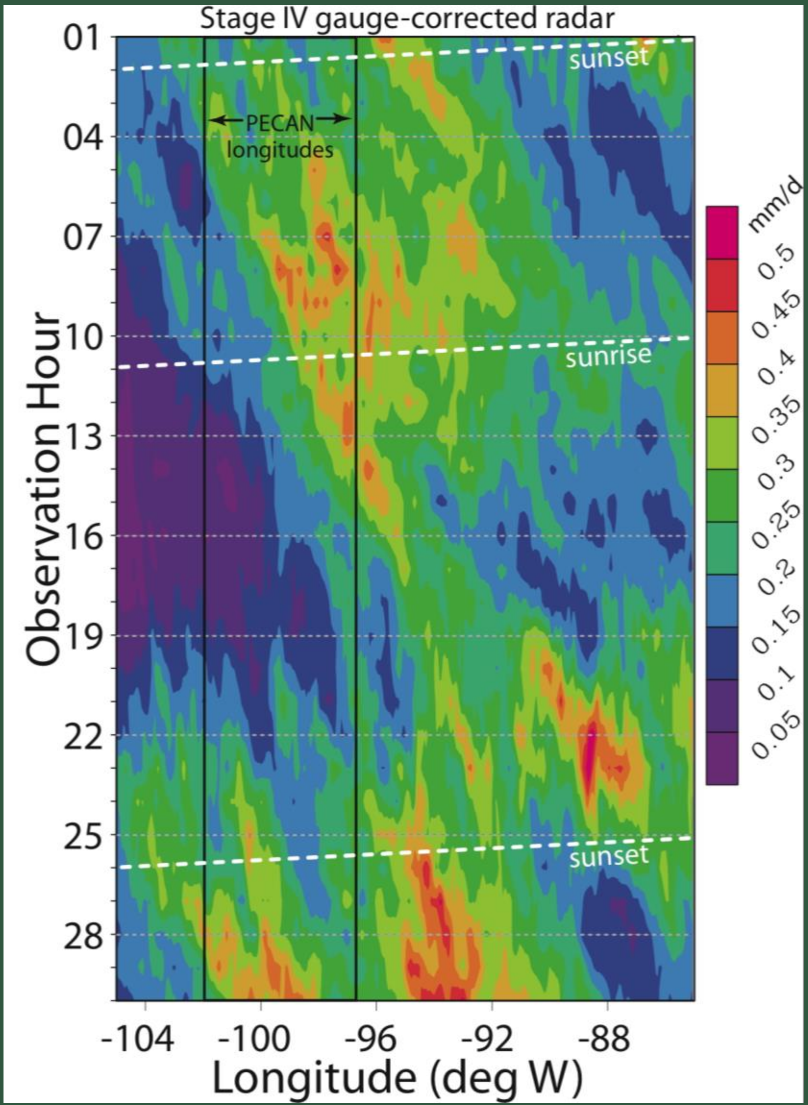
Why do we care?

- Nocturnal MCSs are responsible for the majority of warm-season extreme rain events in the central U.S. (e.g., Maddox et al. 1979; Schumacher and Johnson 2006; Stevenson and Schumacher 2014)
- **“Warm-season quantitative precipitation forecasts are, certifiably, the poorest performance area of forecast systems worldwide”** -- Fritsch and Carbone (2004, *BAMS*)
- Whether a nocturnal MCS will produce severe winds at the surface creates a major forecast challenge: will the strong winds make it through the stable layer to the ground?

Some questions…

- What environmental factors govern the low-level structures in a given nocturnal MCS?
- What internal storm processes (e.g., microphysics → downdrafts → cold pool) are responsible for transitions from cold pool to wave/bore or vice versa?
- Can we use information about these questions to better understand and predict:
  - Whether a nocturnal, elevated MCS will produce severe winds at the surface?
  - Whether a nocturnal, elevated MCS will produce locally extreme rainfall amounts?

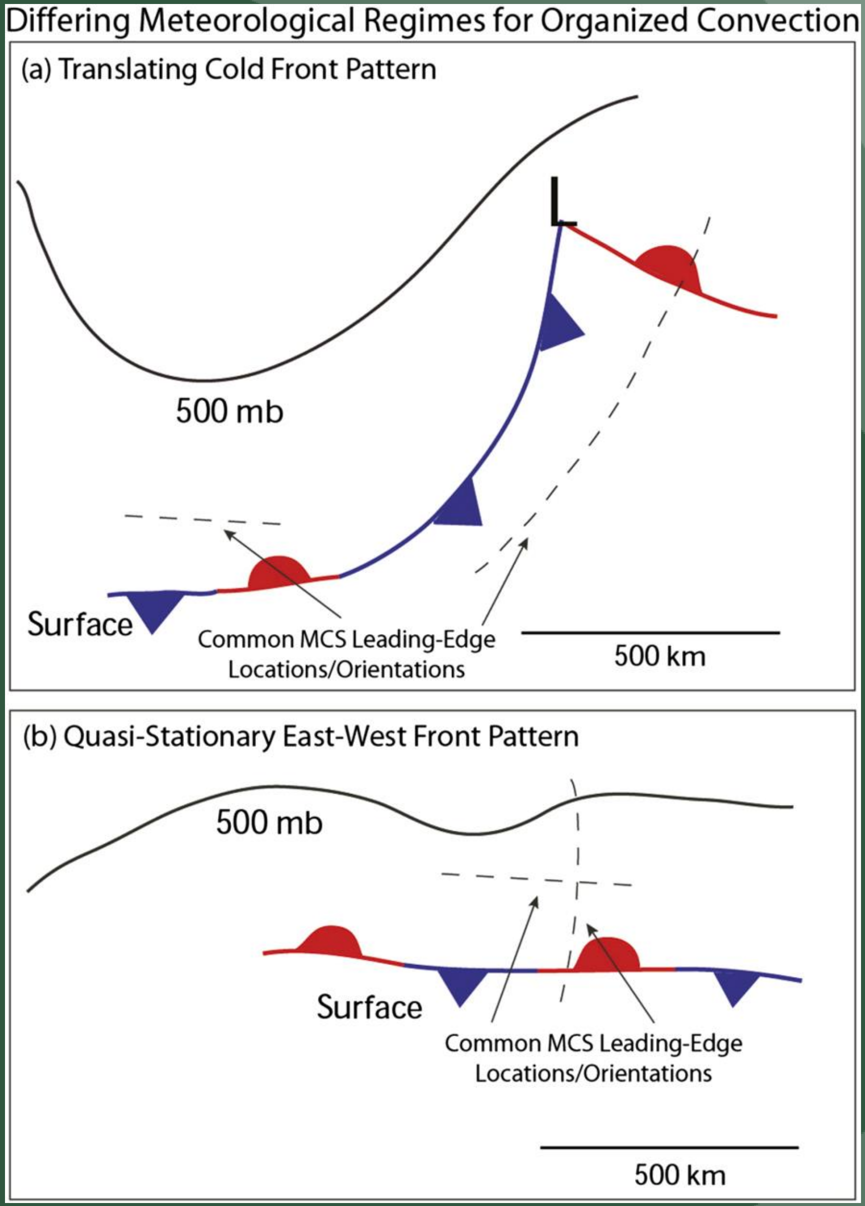
Background



Diurnal cycle of precipitation in late spring 2010
From PECAN EDO

The Great Plains has a well-known nocturnal precipitation maximum in the warm season

Typical synoptic patterns for warm-season MCSs

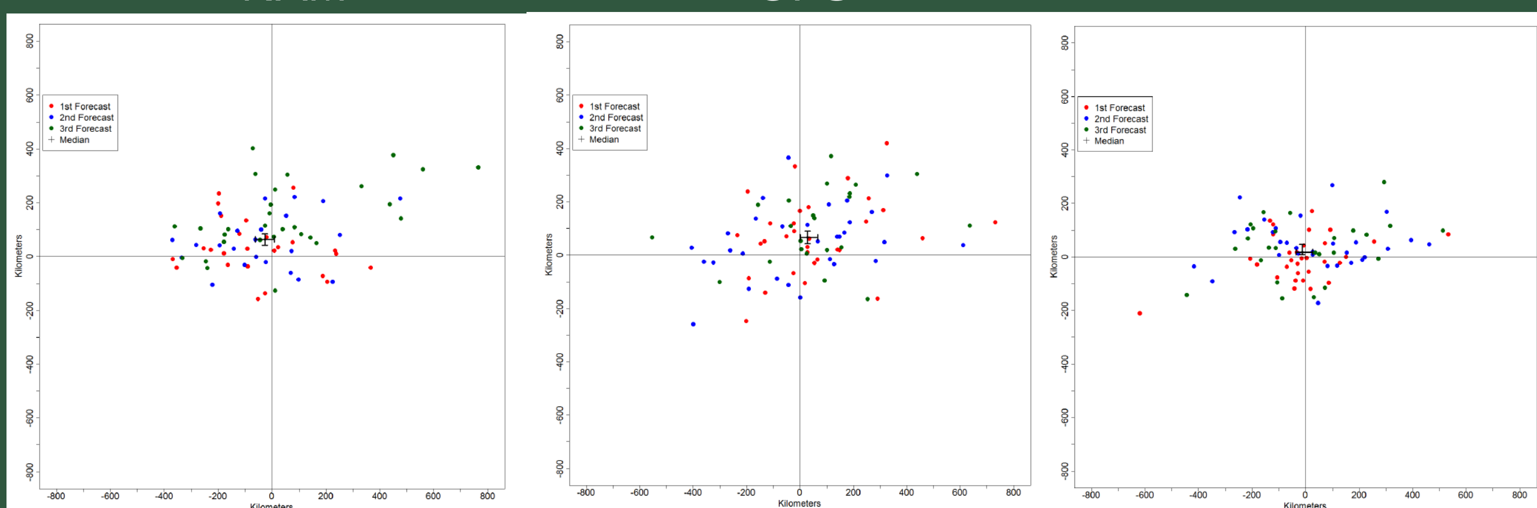


From Trier et al. (2014, MWR)

Model forecast displacement errors

- In a study of MCSs from 2009-2011, Yost (2013) found that operational models (with parameterized convection) were biased toward predicting TL/AS MCSs too far north (i.e., too far on the cool side of the initiating boundary)
- Limited analysis of convection-allowing forecasts suggests improvement in some cases, but not all!

NAM GFS ECMWF



Each dot represents the centroid of a predicted MCS, with the observed centroid at the origin
~6-36-h forecast lead times are shown here

Hypothesis 1

The propagation characteristics of MCSs after the nocturnal transition will depend on the relative influence of changes in environmental shear above the surface layer (e.g., from the developing NLLJ), as well as the changing stratification of the ambient convective and downdraft inflow layers

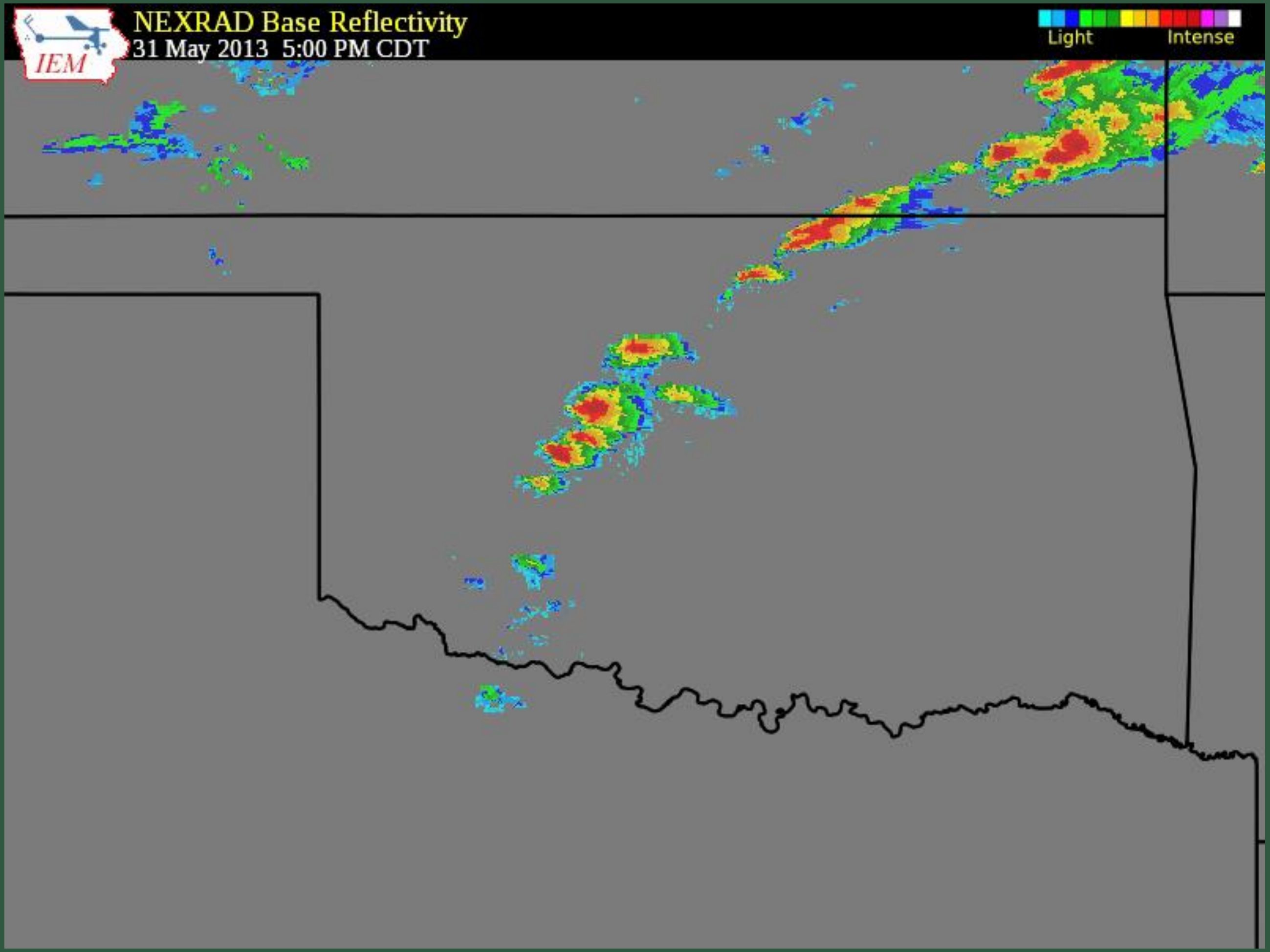
(from Ziegler et al. NSF proposal)

Hypothesis 2

Nocturnal MCS outflow character is controlled by the static stability of the air within and closely above the NBL, by the vertical wind shear in the outflow layer, and by the history of the convection itself (including the type and distribution of hydrometeors in the convective region)

(from Ziegler et al. NSF proposal)

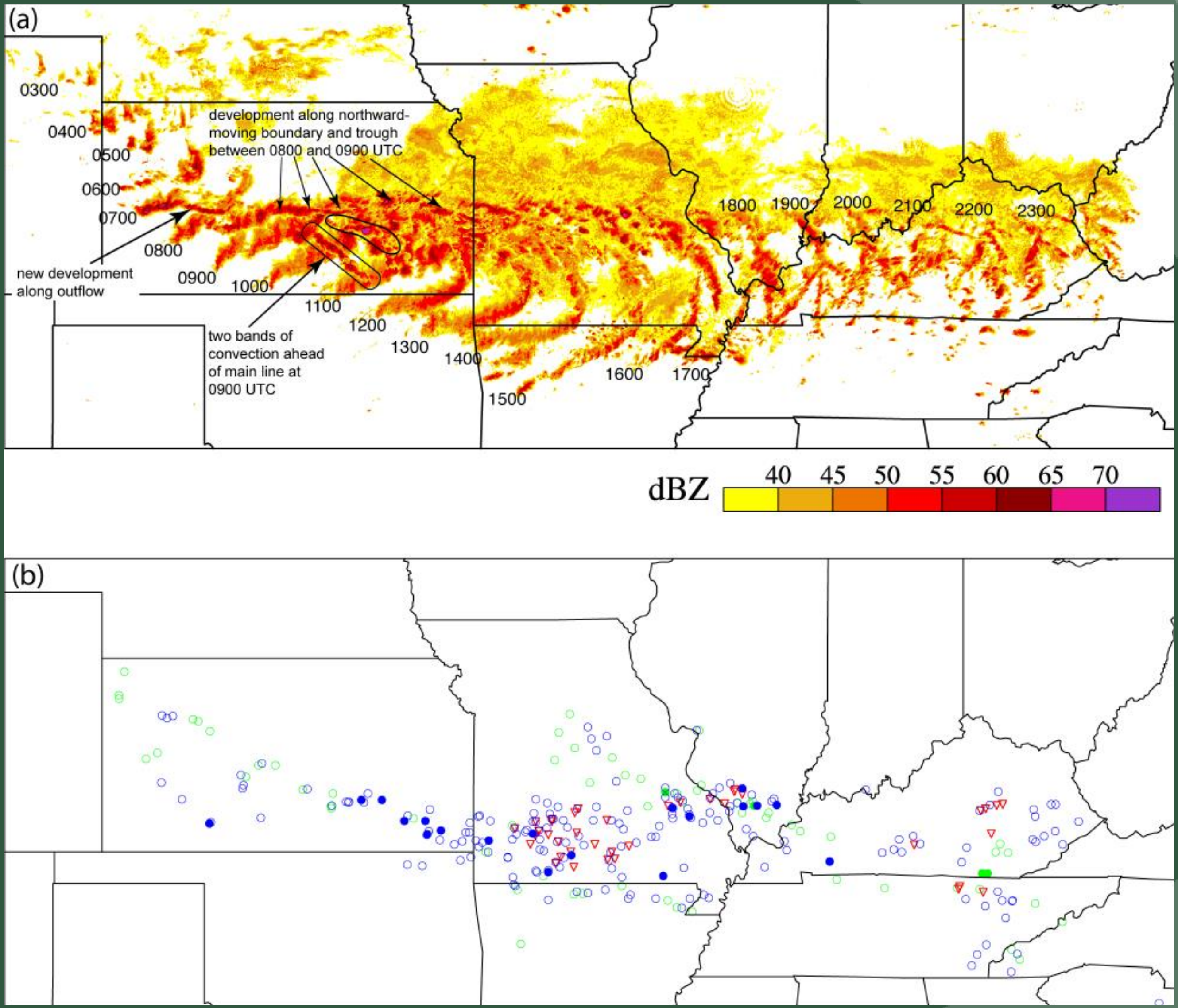
One example:



31 May 2013 – central Oklahoma flash flood
Images from Iowa Environmental Mesonet

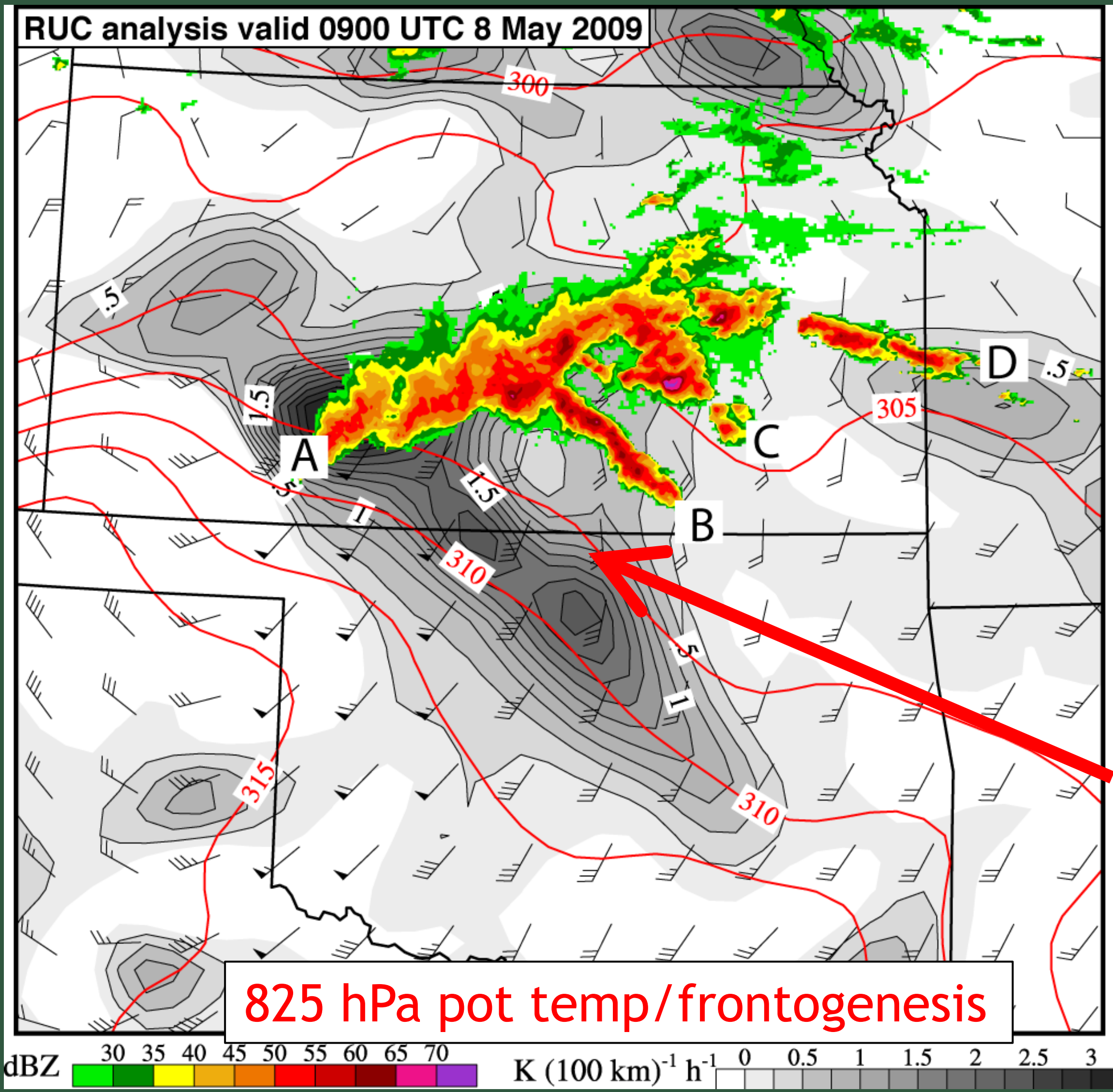
And another:

8 May 2009 derecho



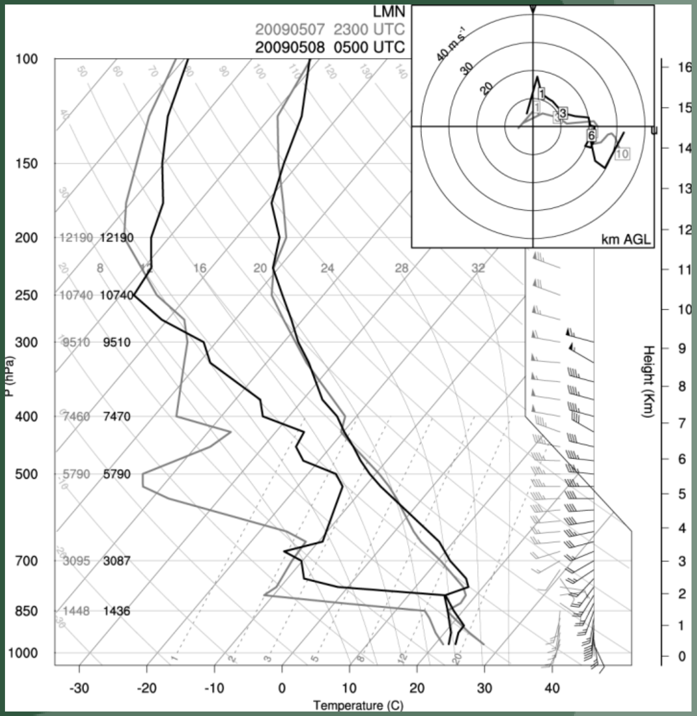
Coniglio et al. (2011)

Is this system elevated?

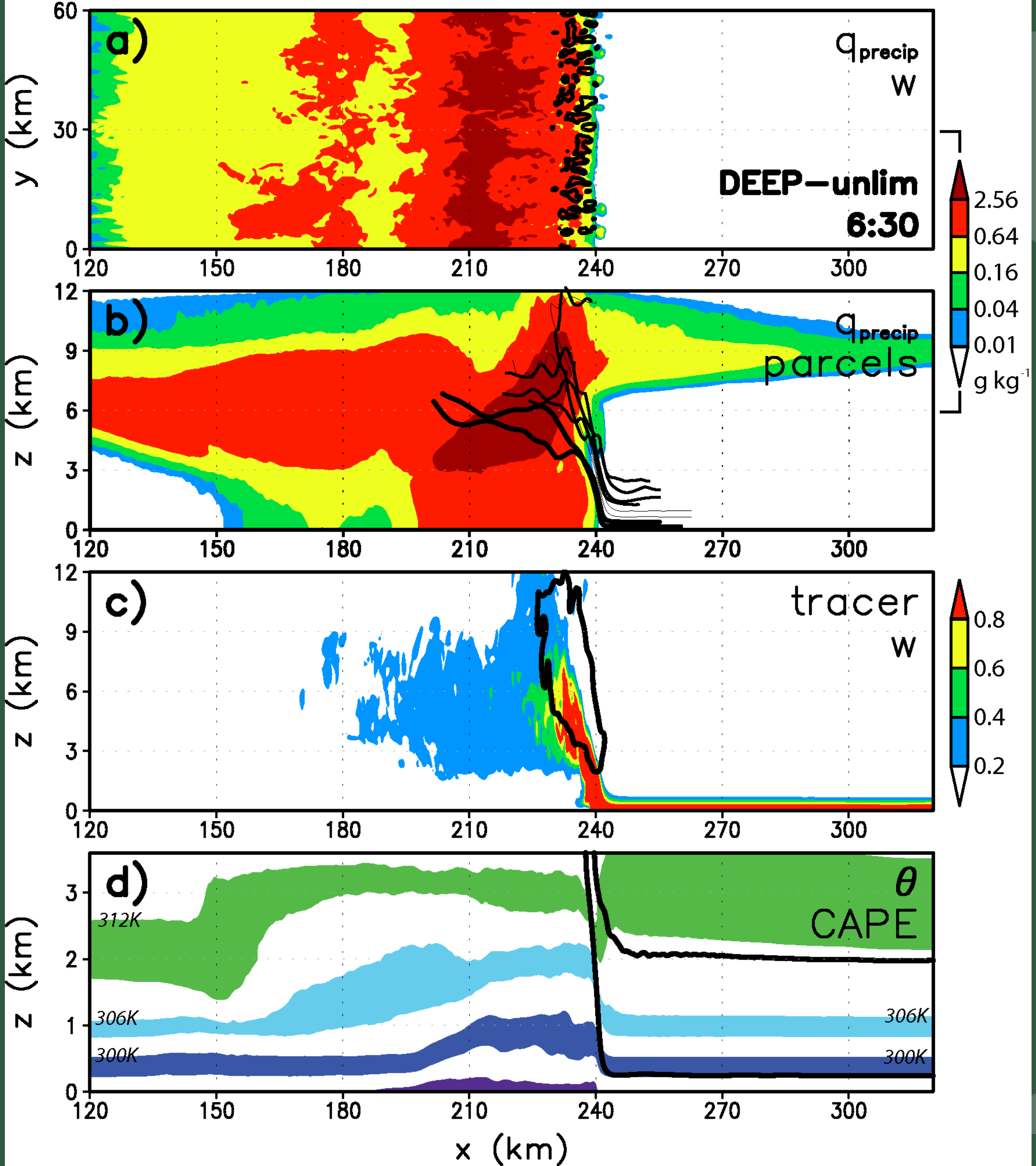


Much of MCS is north/east of baroclinic zone and apparently forced by strong isentropic lift from the strong LLJ and frontogenesis, but nocturnal stable layer is weak and moist residual layer is deep (LMN 0500 UTC sounding).

For cases when severe winds reach the surface, what does the nocturnal stability profile look like?

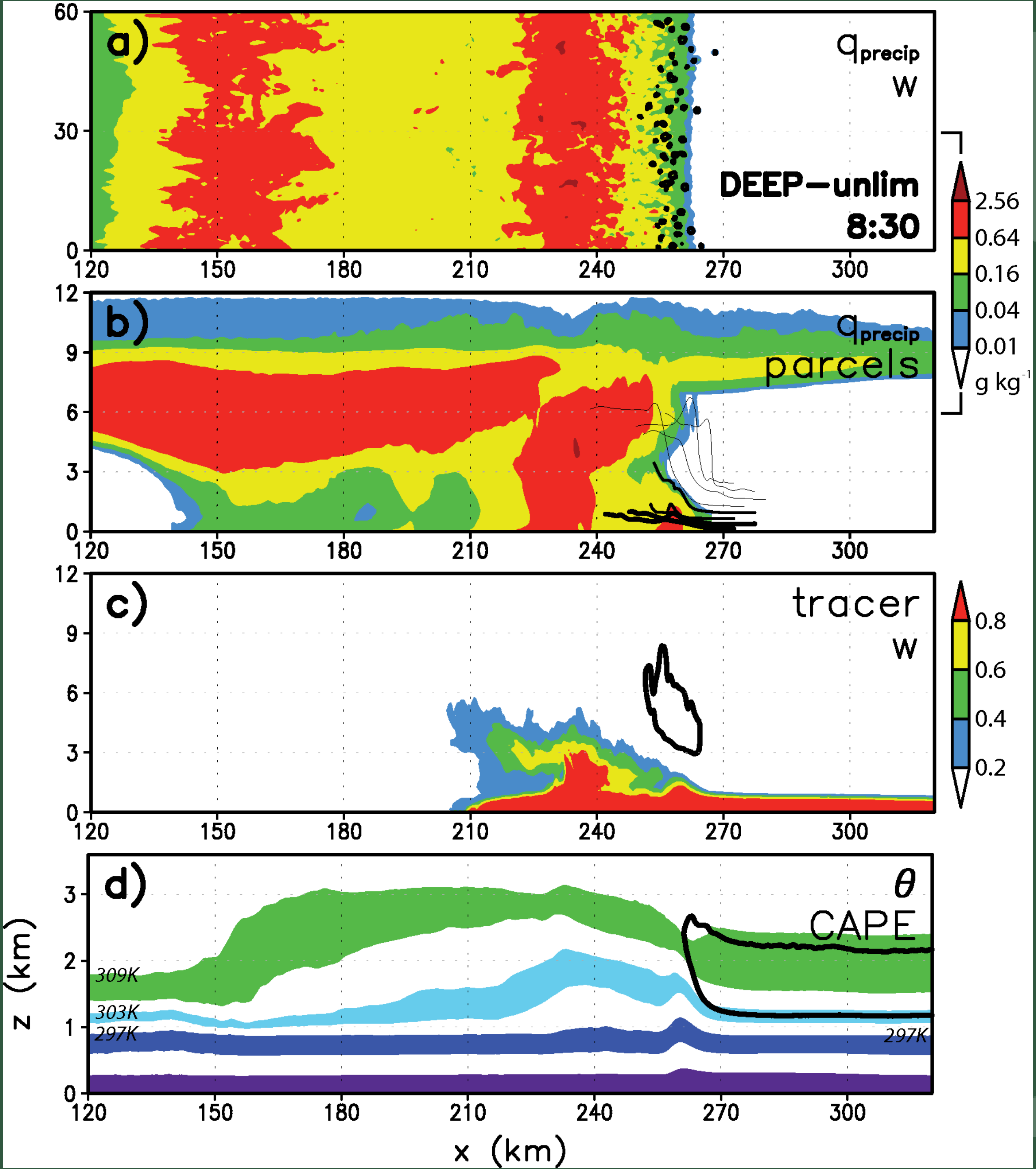


Coniglio et al. (2011)



Surface-based squall line

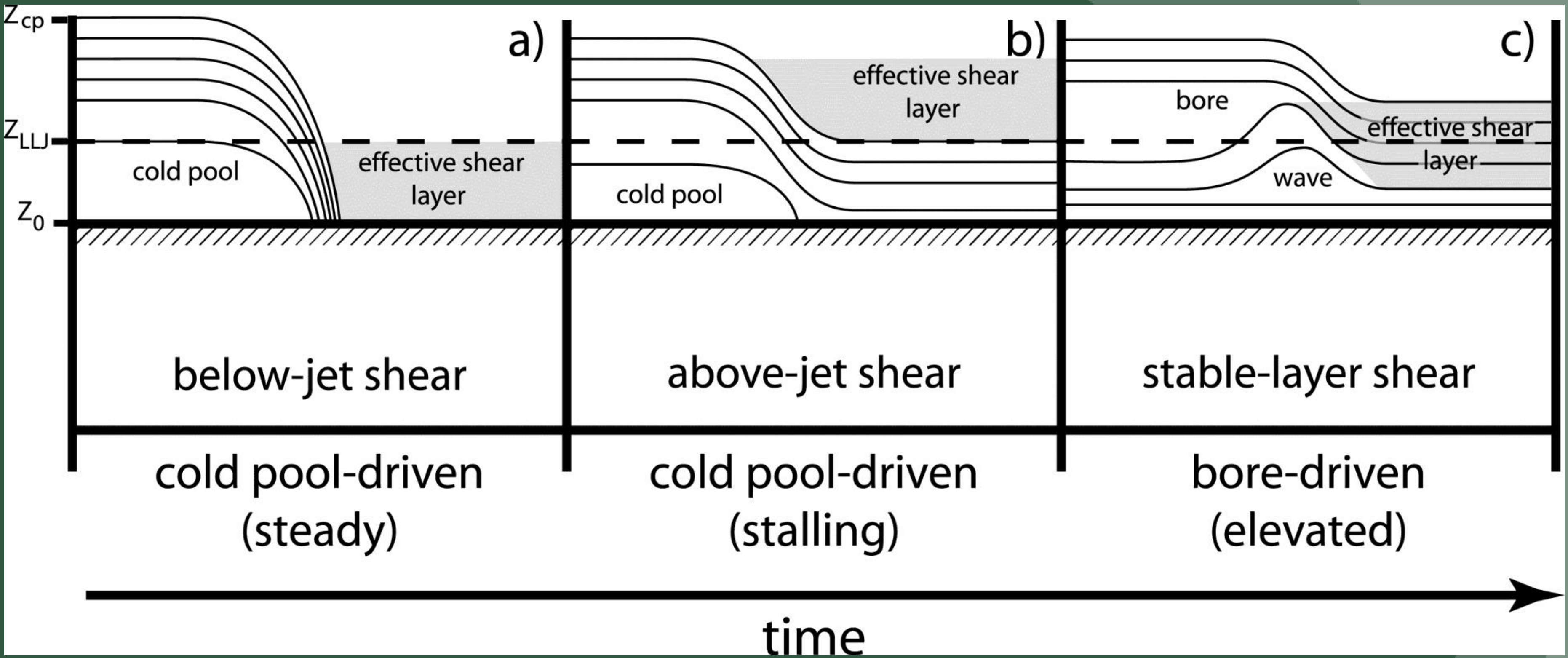
Adapted from Parker (2008)



Squall line that has become elevated after moving into stable low-level environment

Adapted from Parker (2008)

As low-level jet increases, the stability and effective shear layers change…



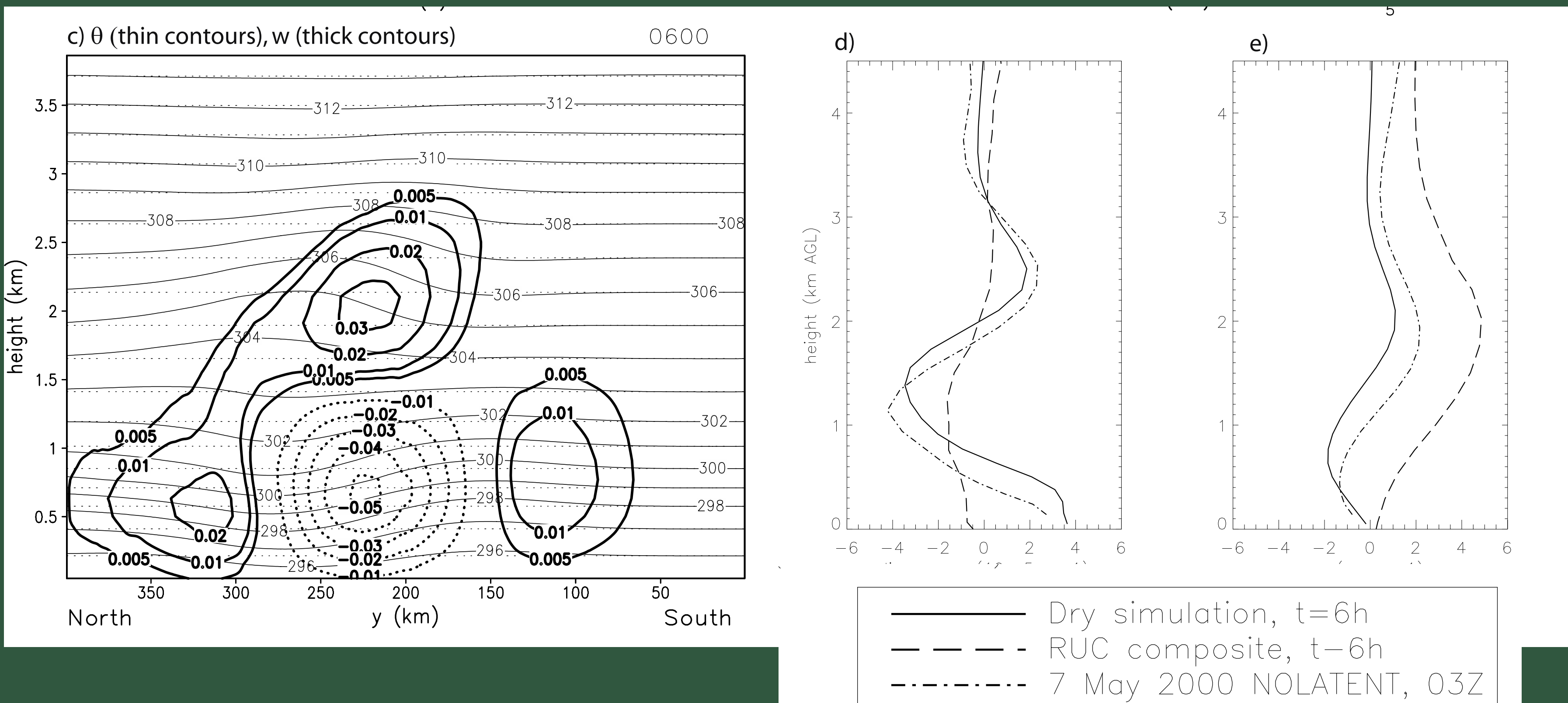
From French and Parker (2010)

Initiation and evolution of MCS in imposed mesoscale ascent

Cross-section of potential temperature and w after 6 h in dry simulation

divergence

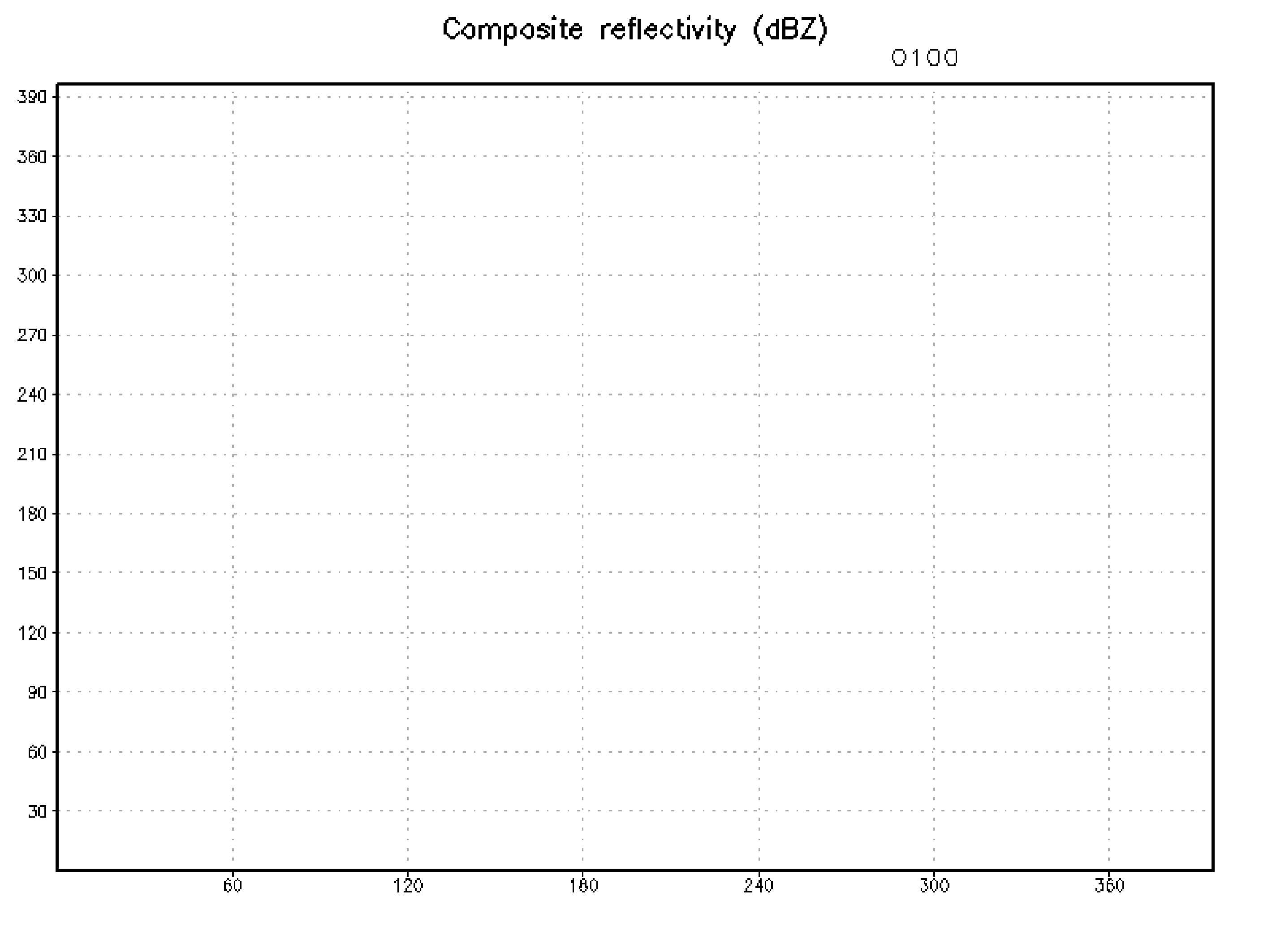
w



From Schumacher (2009, *JAS*)

Simulation with 500-m grid spacing

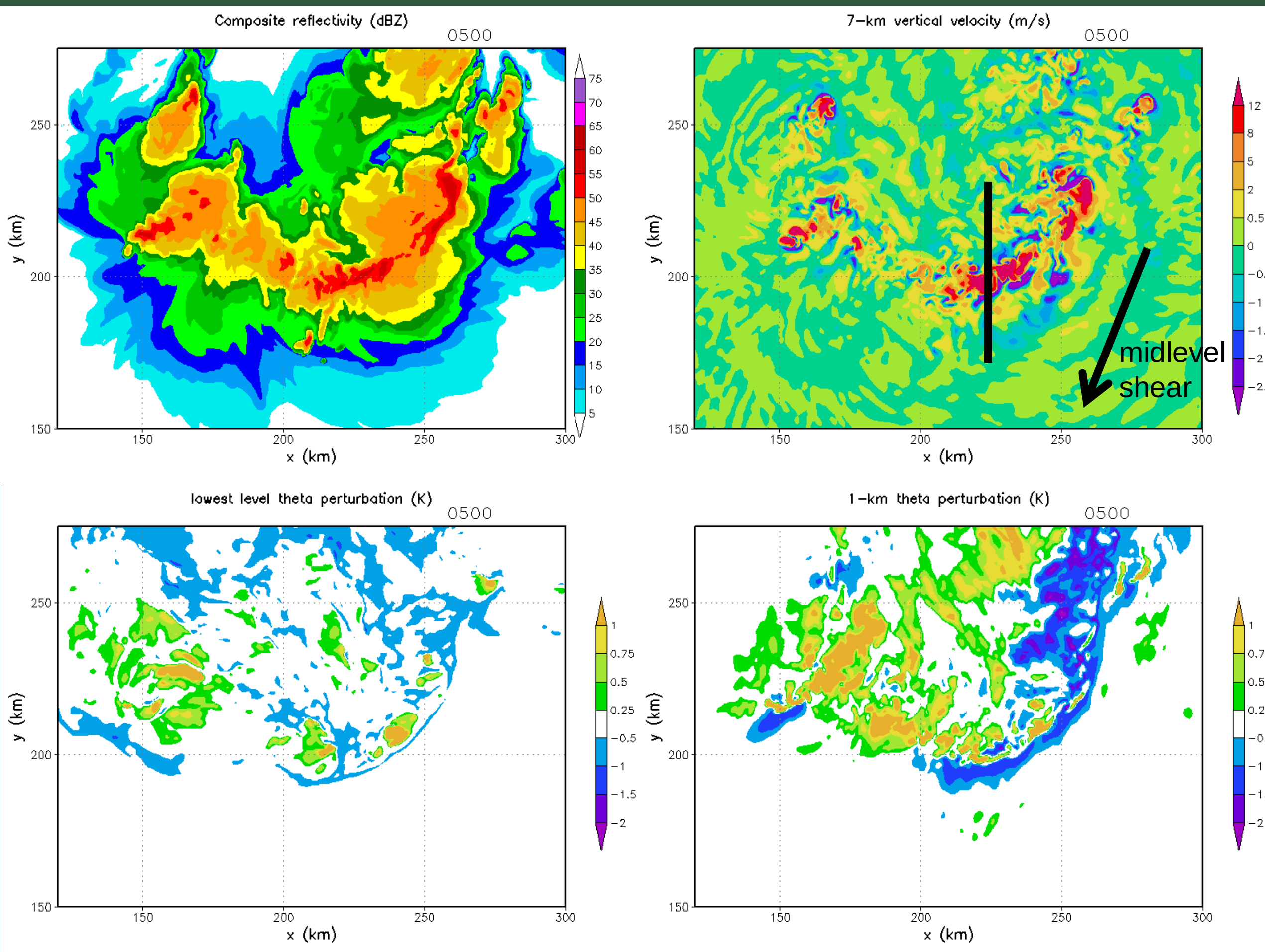
Composite reflectivity every 30 minutes for 9 hrs

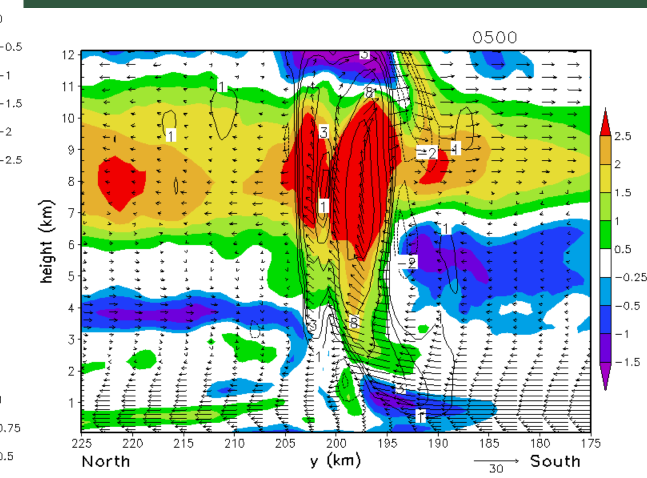


Domain translating at ~7.9 m/s

Simulation is nearly identical to Schumacher (2009), except with CM1 version 17 and Morrison microphysics

- A key finding of Schumacher (2009) was that in very moist environments like these, convection is not organized by a cold pool, but by a low-level gravity wave

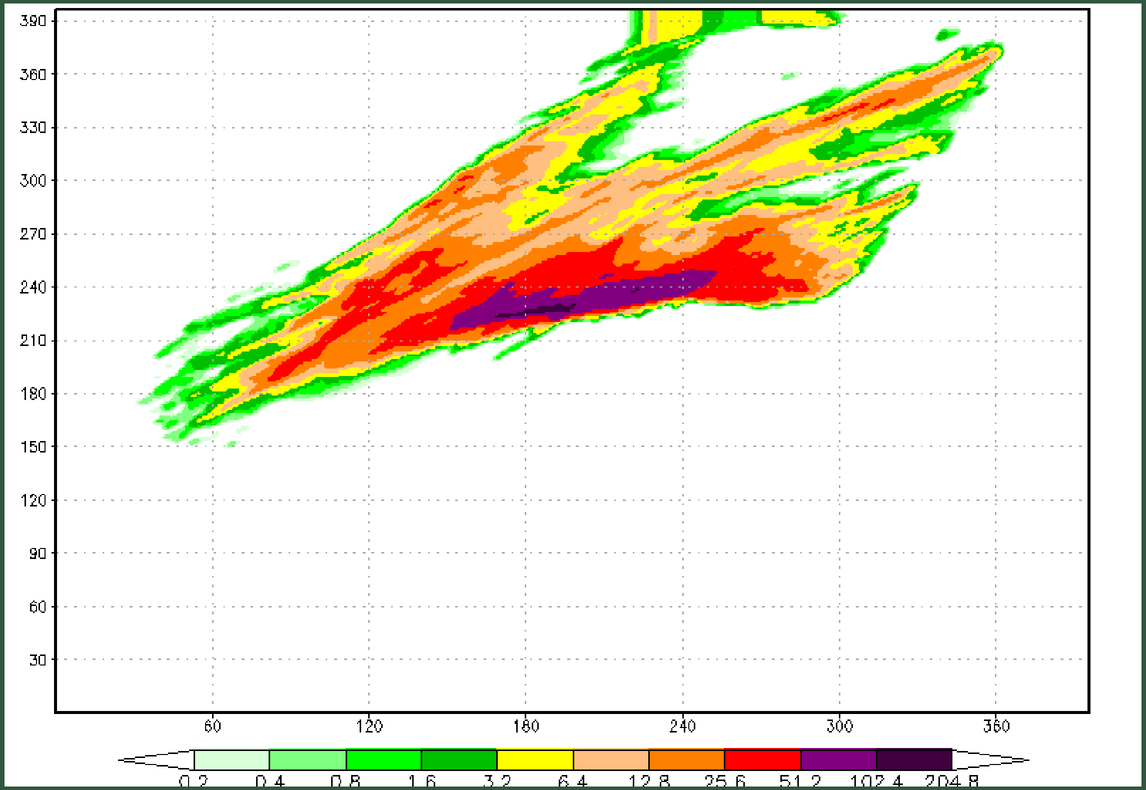




No surface cold pool… **…but a low-level wave**

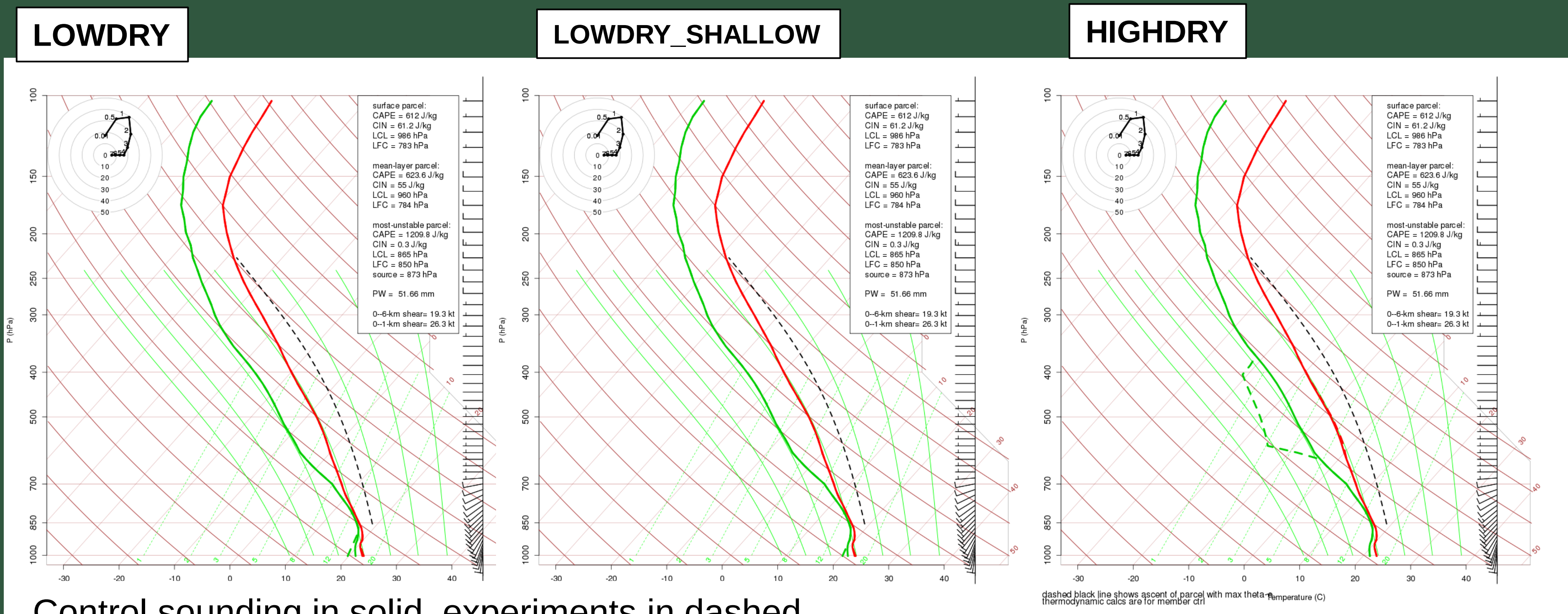
Rainfall production

- The simulated MCS produces a local rainfall maximum of ~125 mm in ~5 hrs, a reasonable replication of observed systems
- But how sensitive are these results to the specifics of the initial sounding?



Total 9-h translated rainfall accumulation (mm); though convection didn't initiate until t≈4 h

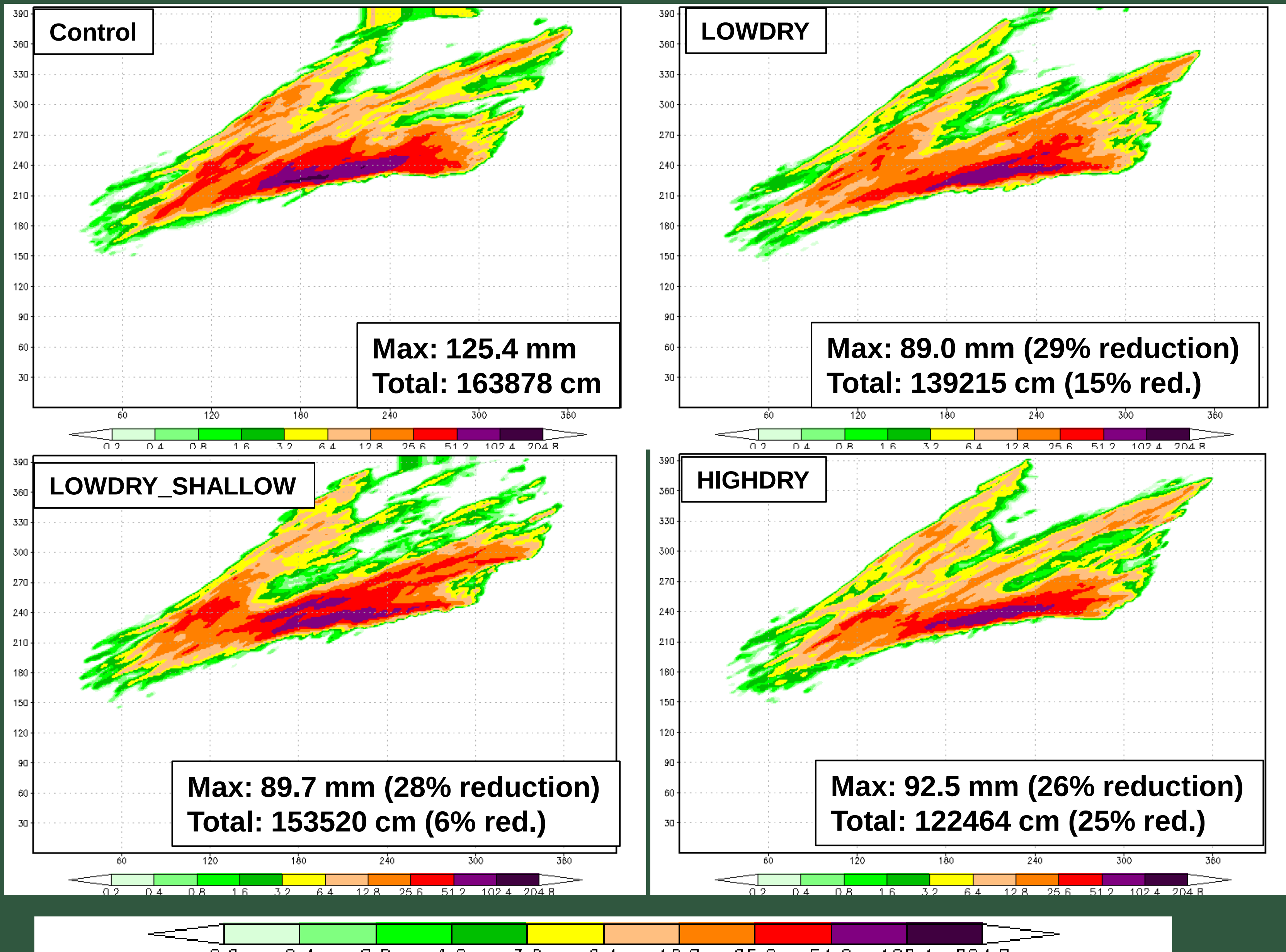
Moisture sensitivity experiments



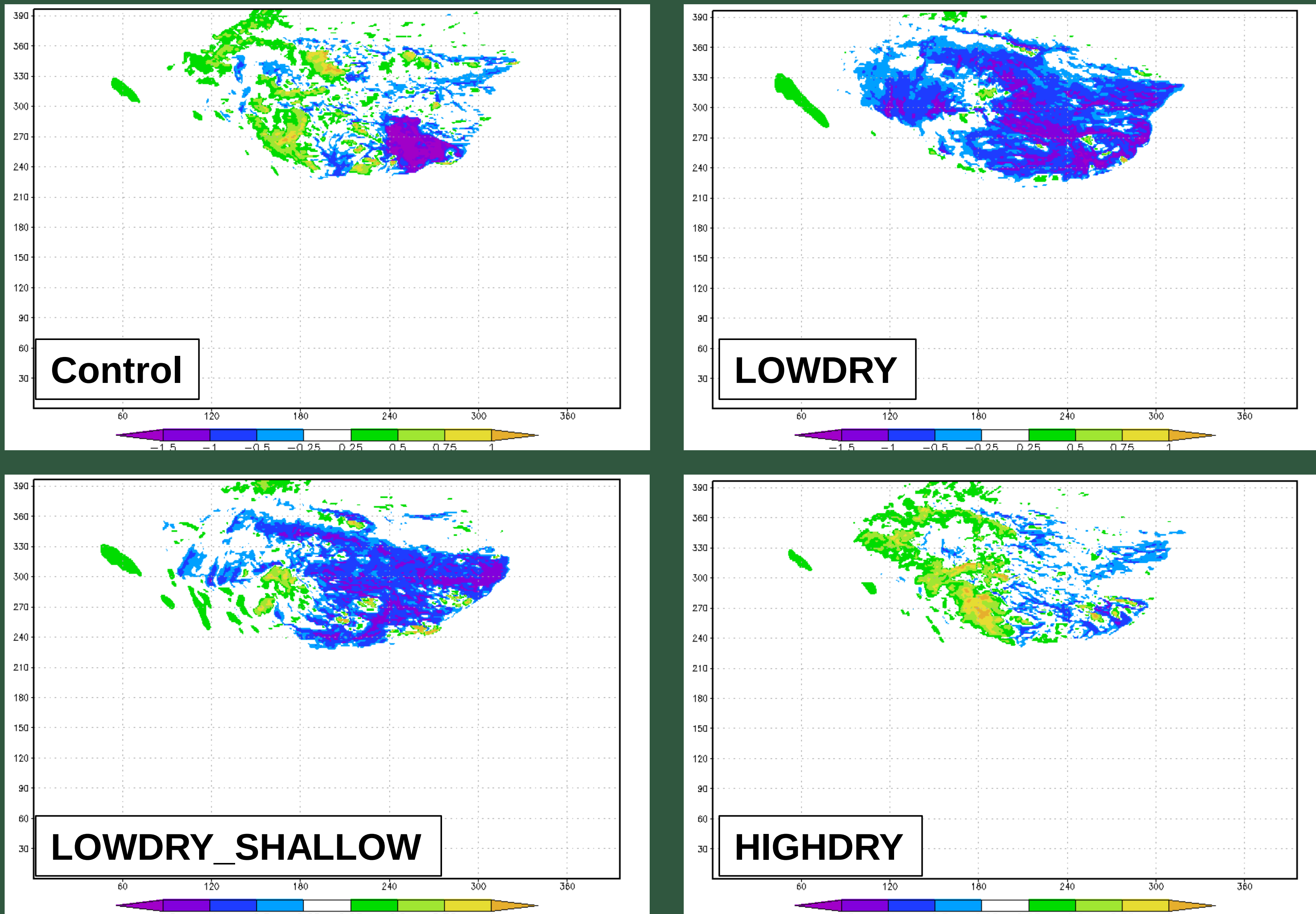
Control sounding in solid, experiments in dashed

Simulation	**Description**	**Precipitable water**
Control	**From Schumacher (2009)**	**51.7 mm**
LOWDRY	**Constant mixing ratio in lowest 1.1 km**	**51.0 mm (~1.5% reduction)**
LOWDRY_SHALLOW	**Constant mixing ratio in lowest 750 m**	**51.4 mm (~0.6% reduction**
HIGHDRY	**Midlevel RH reduced to 35%**	**49.4 mm (~4.5% reduction)**

Total accumulated rainfall



Cold pool structure



Hypothesis 3

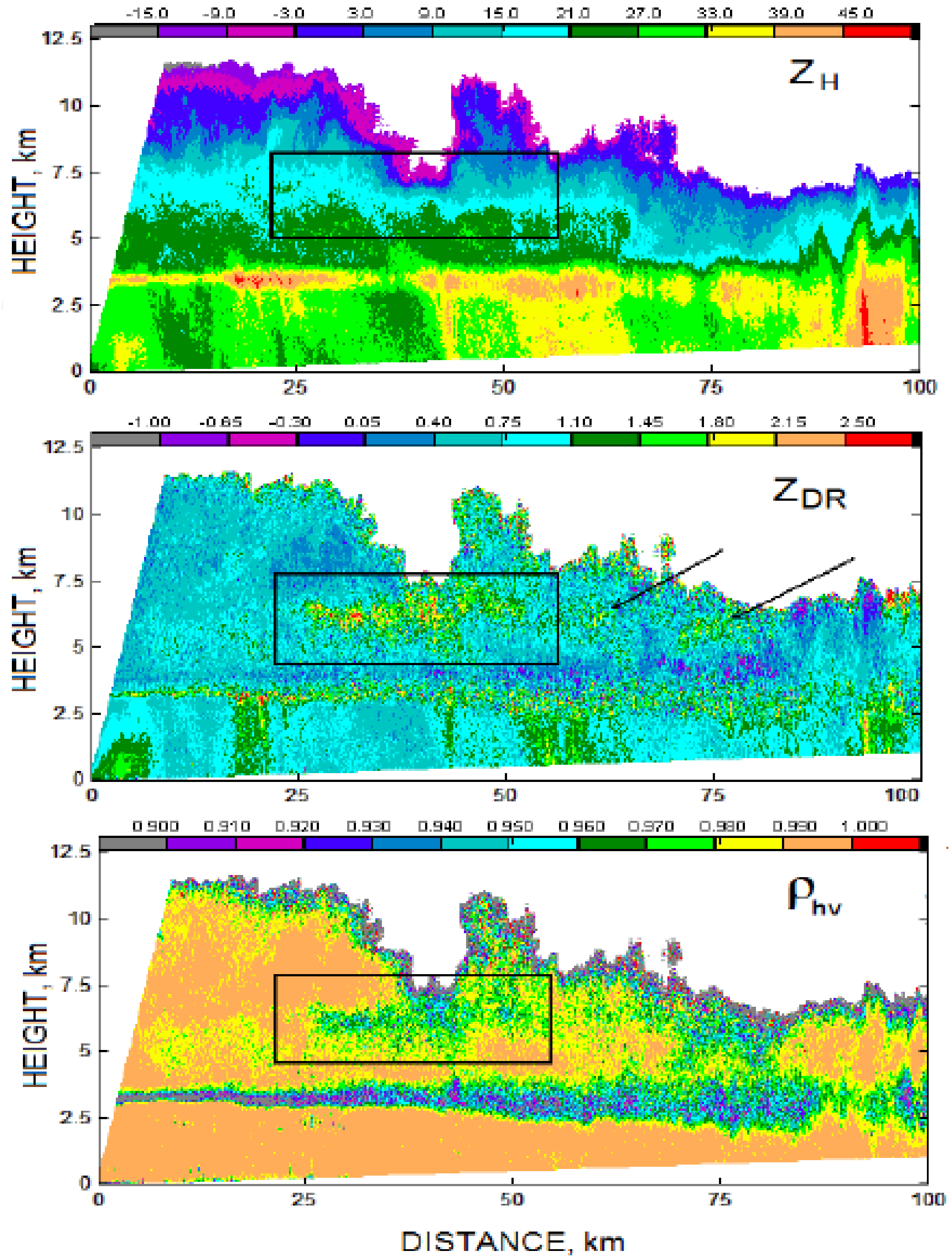
Nocturnal MCS stratiform regions contain (polarimetric-radar-inferred) large, growing or sublimating ice precipitation particles that are spatially and temporally colocated with strong mesoscale updrafts and downdrafts respectively, intense bright bands, high surface precipitation rates, and the meso-β-scale cold pool core

(from Ziegler et al. NSF proposal)

Boxes highlight enhanced depositional growth aloft; associated with heavier surface precip

Radar measurements of microphysical details should reveal connections to cold pool strength and depth

Andric (2011)



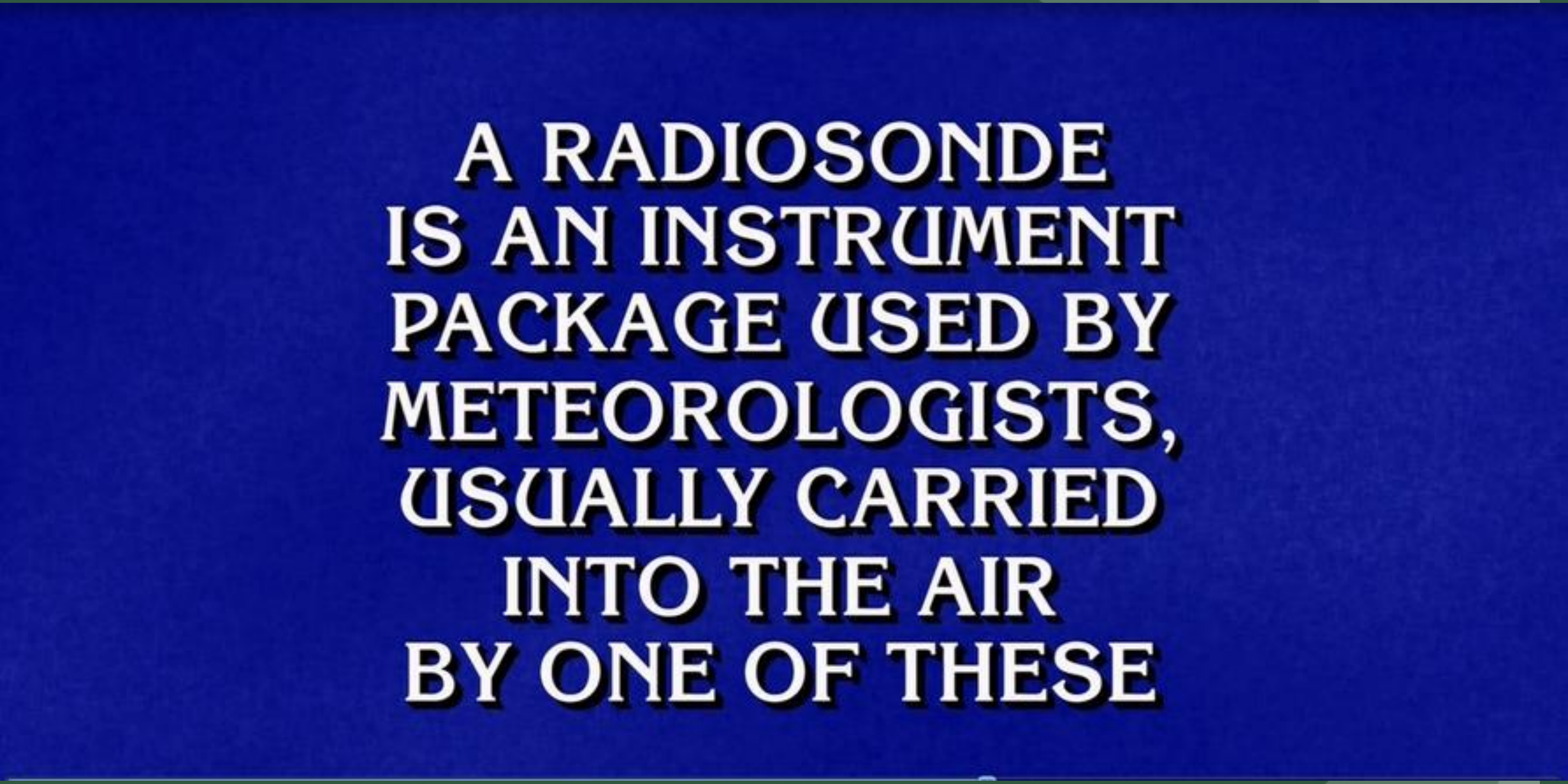
PECAN work plan for NSSL/CSU/NCSU collaborative project

Instruments for field phase:

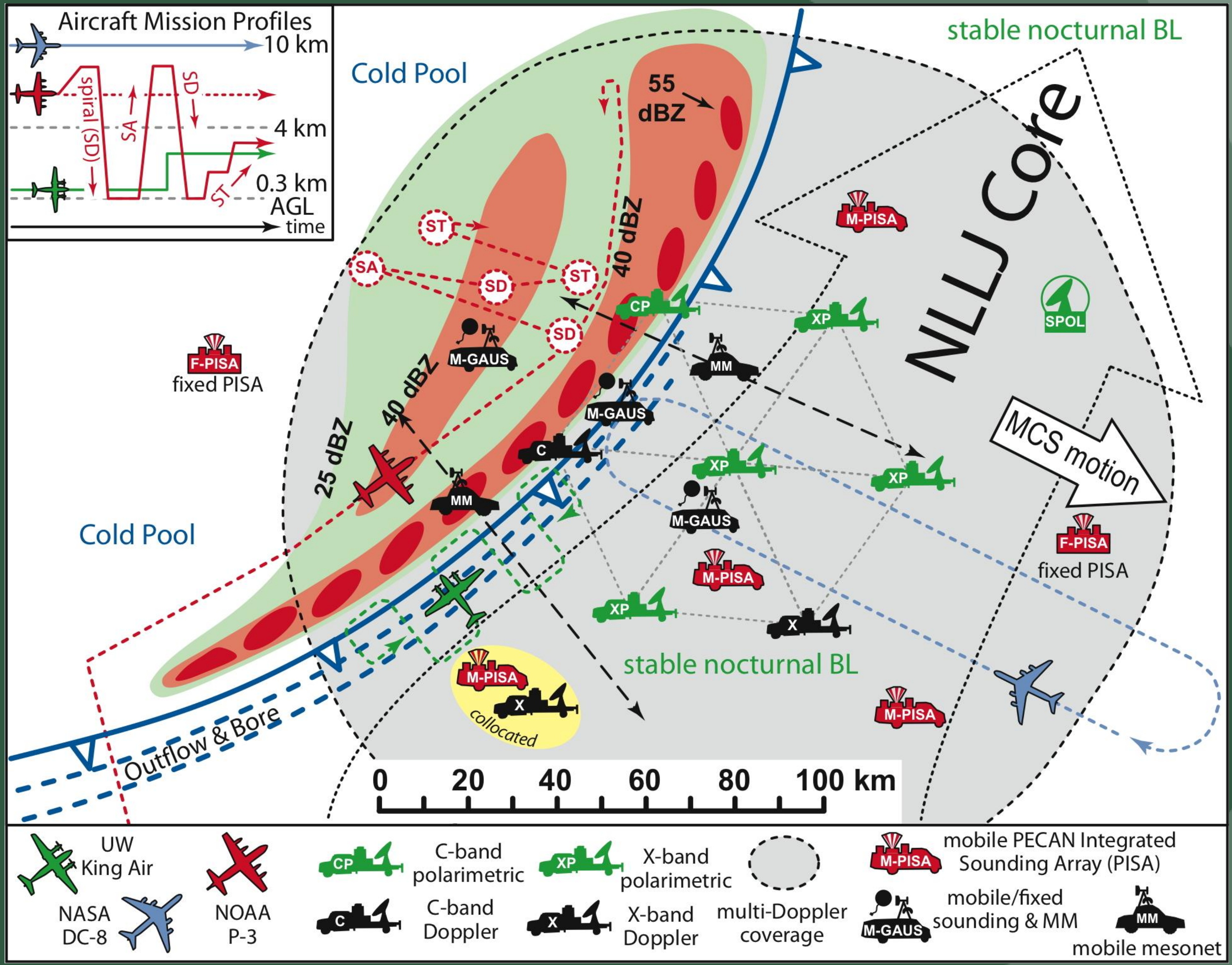
- SMART and NOXP radars
- Highly mobile sounding systems and mobile mesonets (Conrad Ziegler is leading the effort to pre-scout locations for mobile sounding launches at night)

Post-field analysis:

- Synthesized analysis of MCS observations: multi-Doppler airflow; environmental soundings and surface observations; polarimetric variables
- Case-study and idealized numerical modeling studies

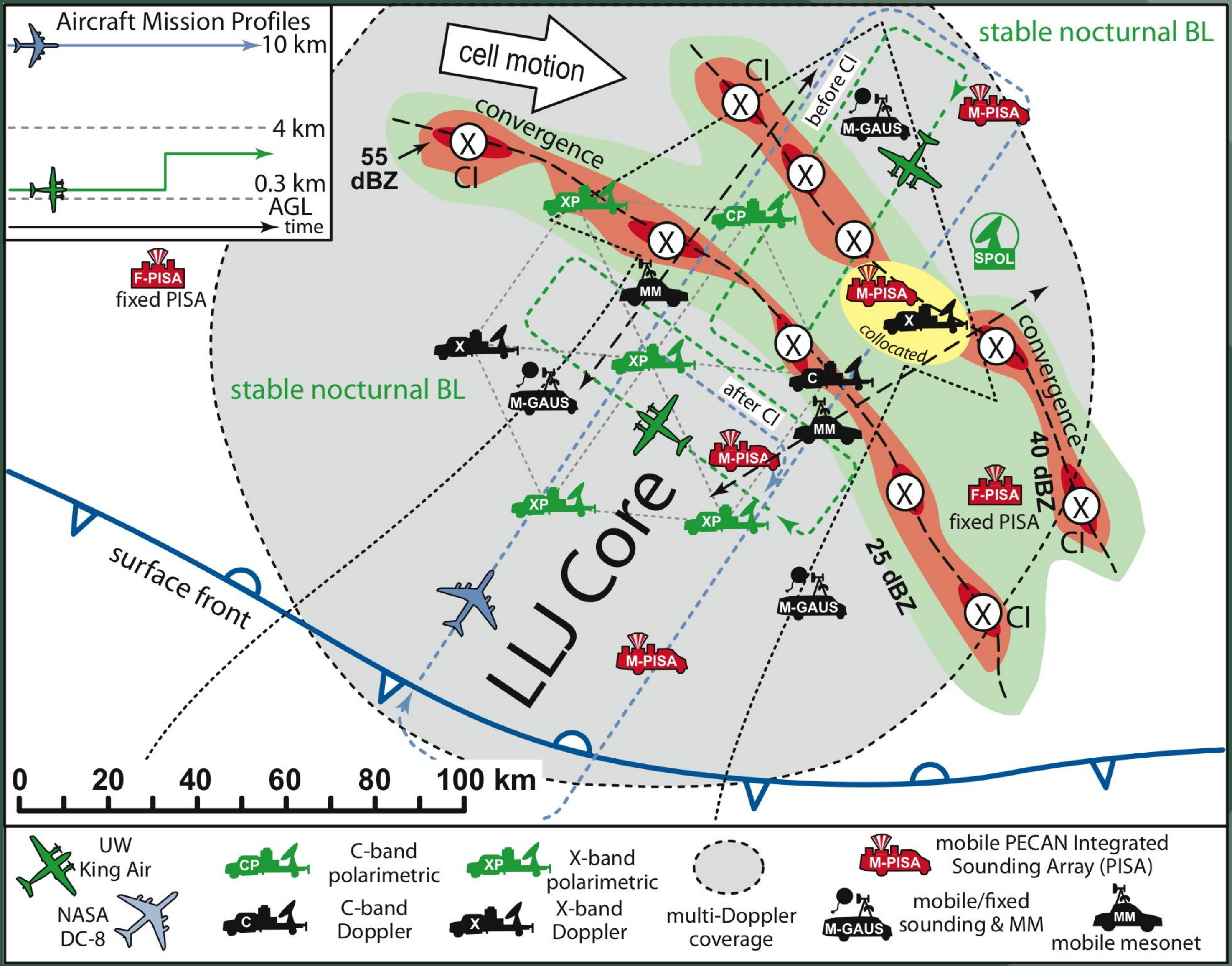

A RADIOSONDE
IS AN INSTRUMENT
PACKAGE USED BY
METEOROLOGISTS,
USUALLY CARRIED
INTO THE AIR
BY ONE OF THESE

MCS deployment strategy

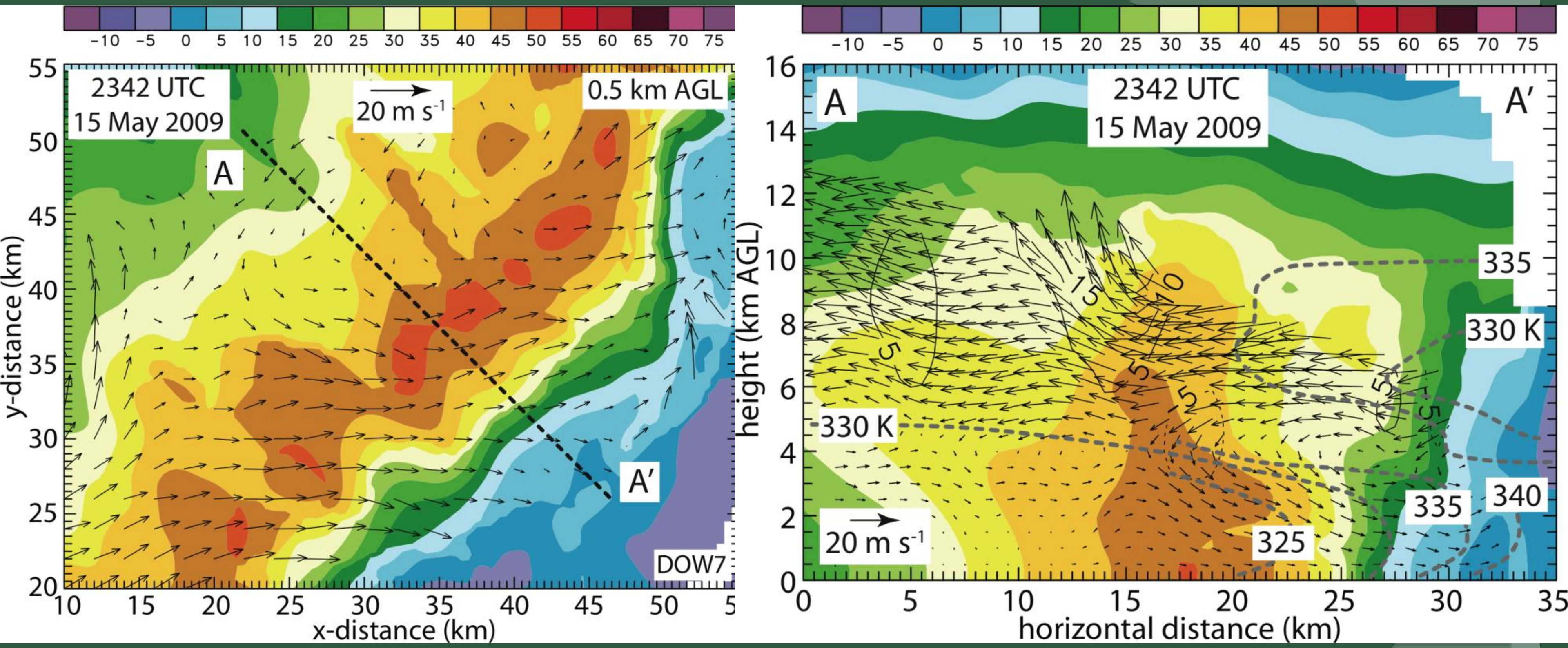


From PECAN EDO

Convection initiation deployment strategy



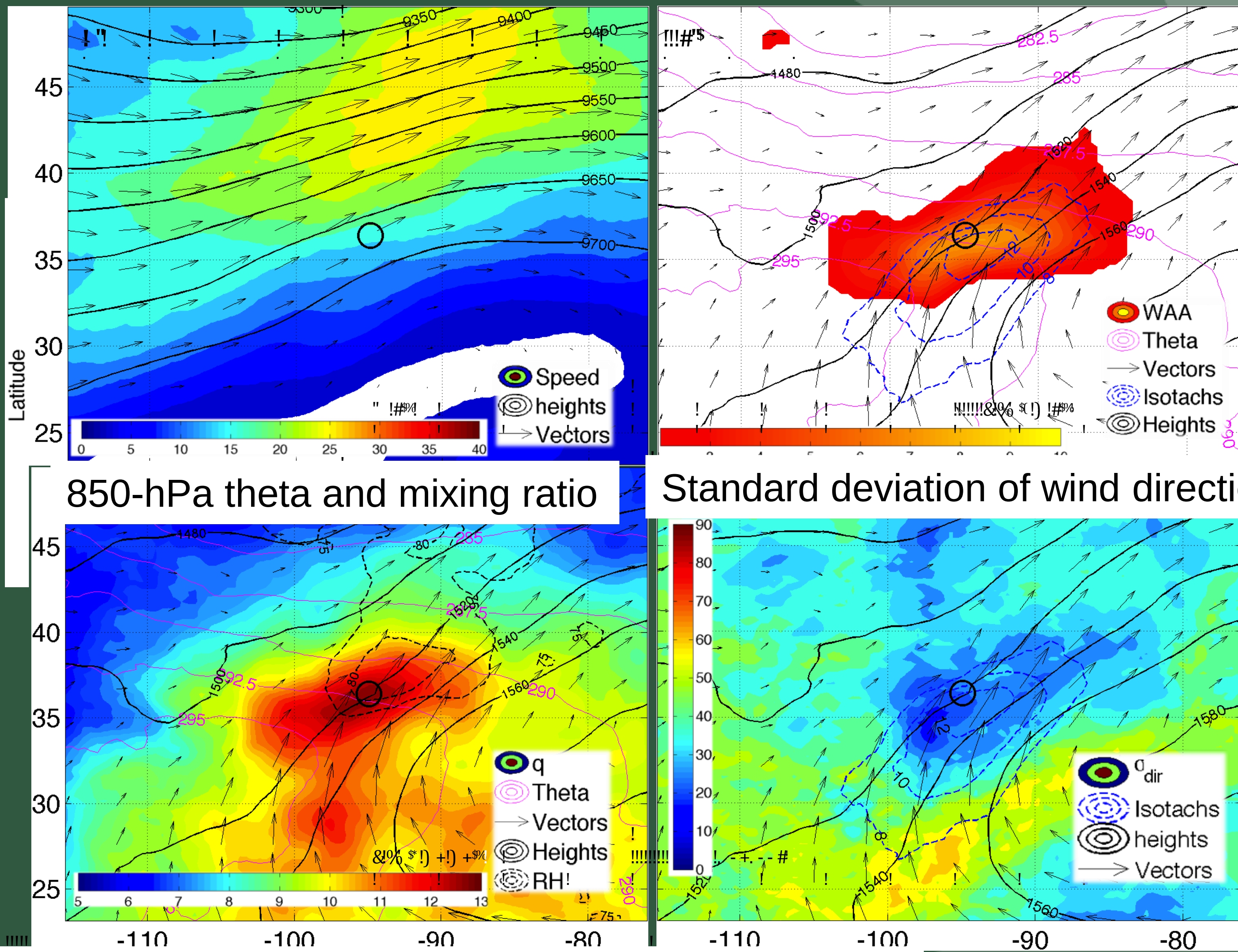
From PECAN EDO



Plan view and cross-section of a VORTEX2 MCS: Radar analysis courtesy C. Ziegler, thermodynamic analysis adapted from Bryan and Parker (2010)

"Warm-season" composite at t=0

250-hPa heights and isotachs   850-hPa theta and WAA

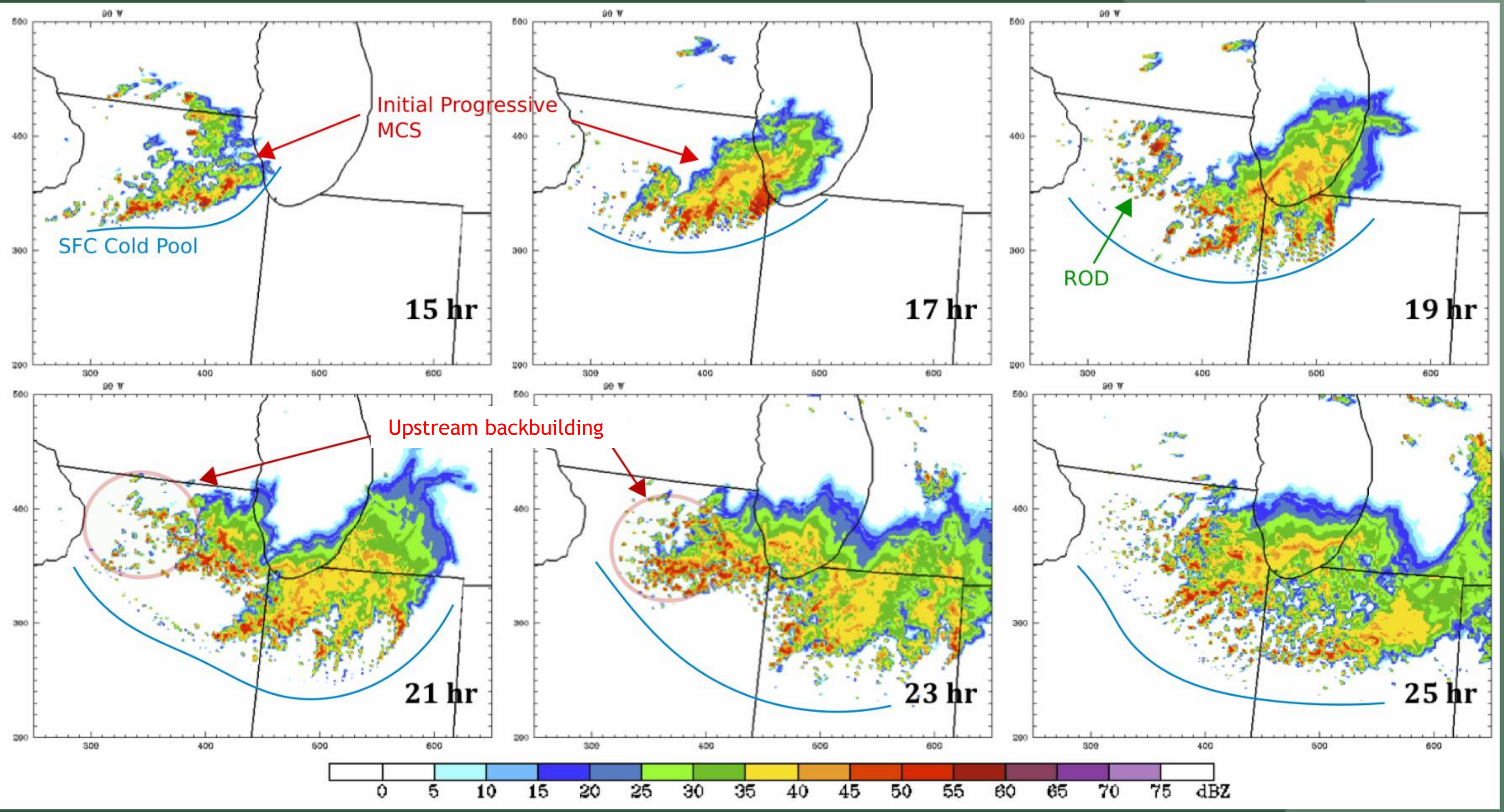


Adapted from Peters and Schumacher (2014, May issue of *MWR*)

Composite initial conditions

- These composites were then used as initial conditions for WRF-ARW simulations at 1.33-km horizontal grid spacing
- The simulations are initialized from the composite at 15 h prior to the peak 1-h rainfall time, and the lateral boundary conditions are updated every 3 h with the corresponding composite grids
- The model configuration is idealized in other ways, with a homogeneous underlying land surface and land-surface fluxes turned off

Reflectivity in quasi-idealized simulation from composite of numerous MCS cases: can we use the same method from composites of PECAN observations?



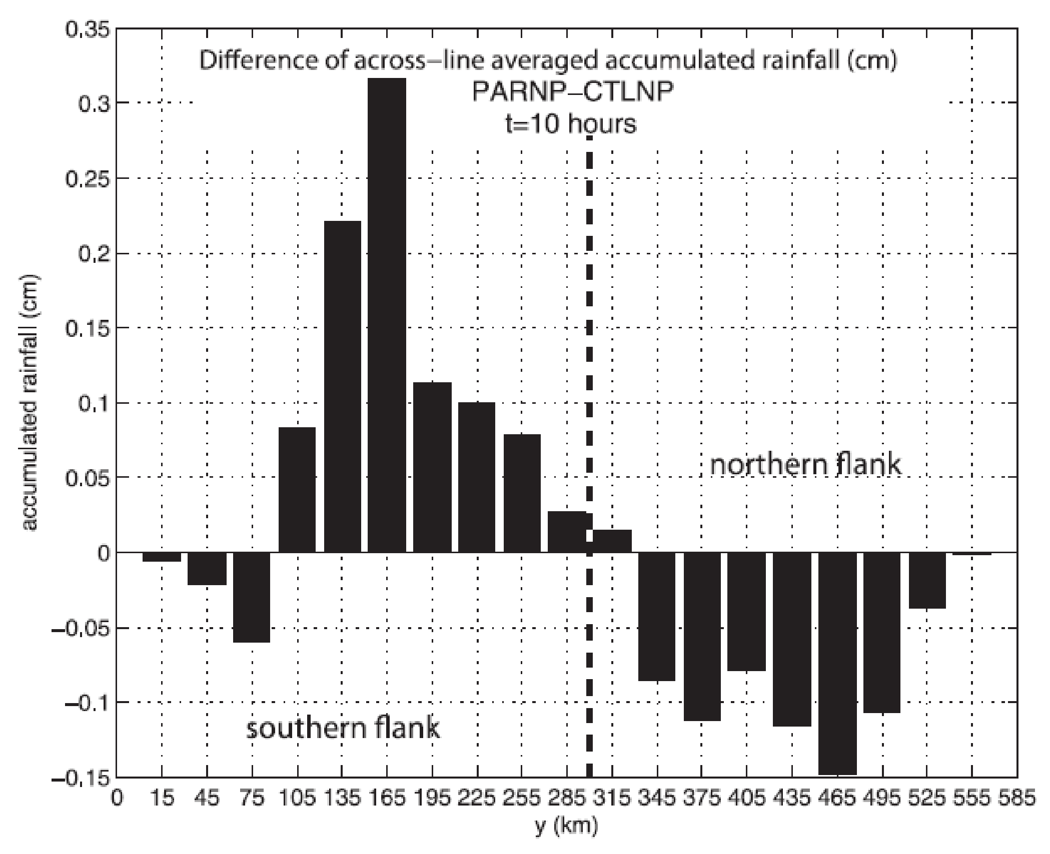
(From Peters and Schumacher, 2014, in prep.)

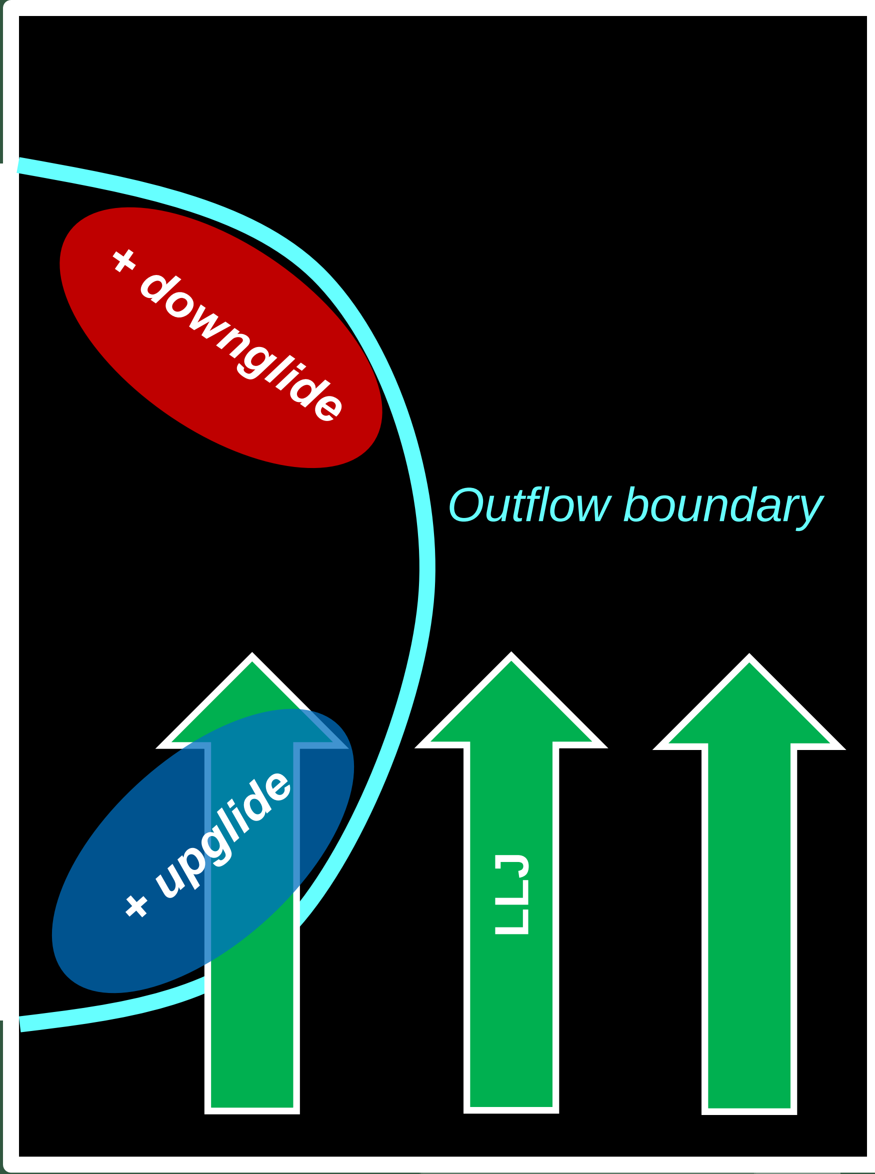
Summary/conclusions

- In comparison to surface-based squall lines, elevated MCSs (which typically occur at night) have received less attention, but are often poorly predicted and are responsible for most of the heavy rainfall production in the US
- Analysis of observations and model simulations reveal the importance of both mesoscale ascent and storm-scale features such as gravity waves in maintaining and organizing nocturnal, elevated MCSs
- Observations from PECAN should provide crucial information about the structures in elevated MCSs and their sensitivities to environmental conditions

Backup slides

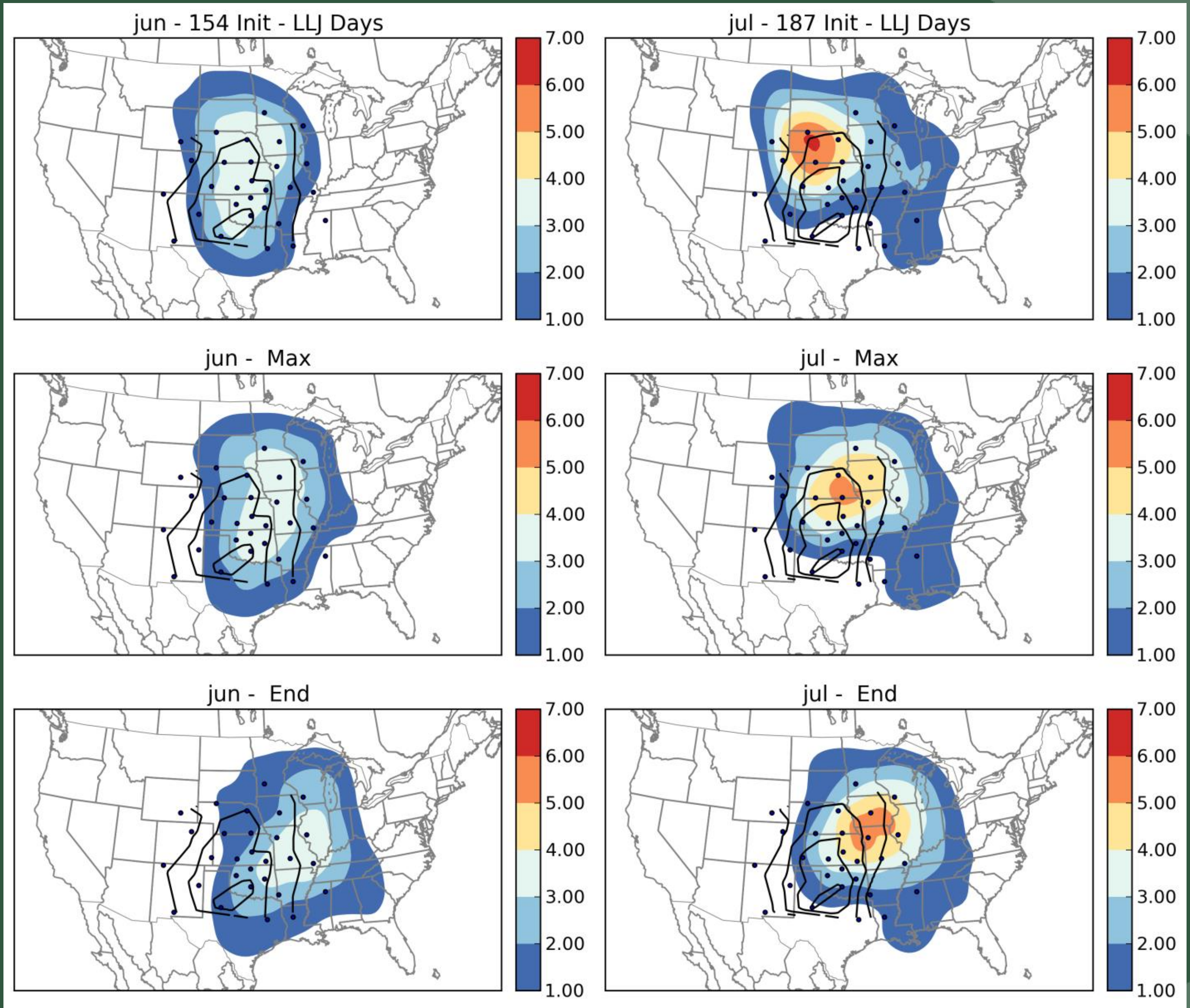
Non-periodic run with line-parallel LLJ





French and Parker (2010)

Nocturnal MCS frequency in PECAN domain



Colors: number of nocturnal MCSs per month within driving distance of PECAN domain

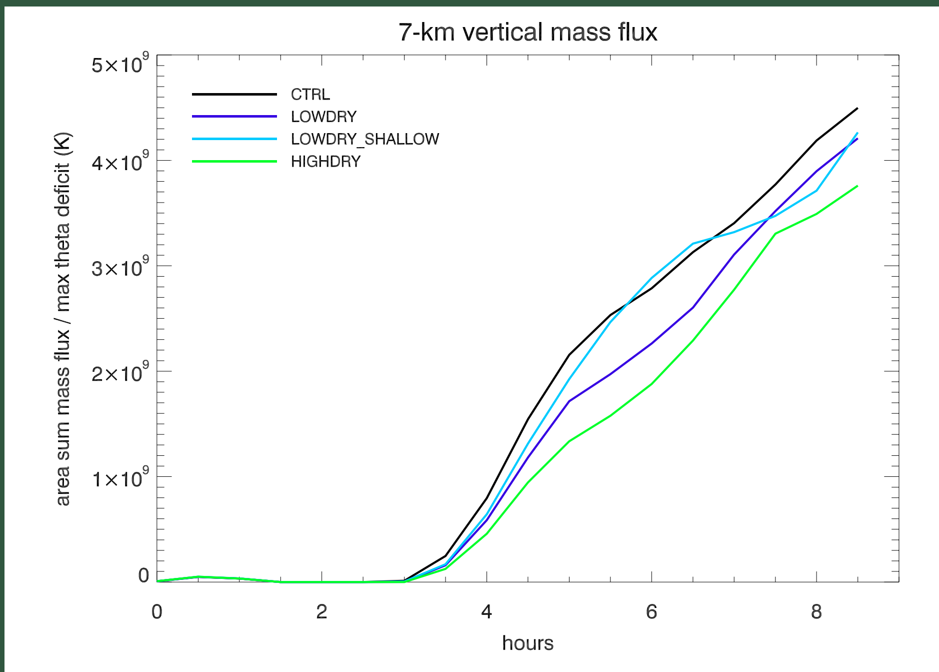
Contours: number of days with nocturnal LLJ (c.i. is 4 days)

Dots are NOAA wind profilers

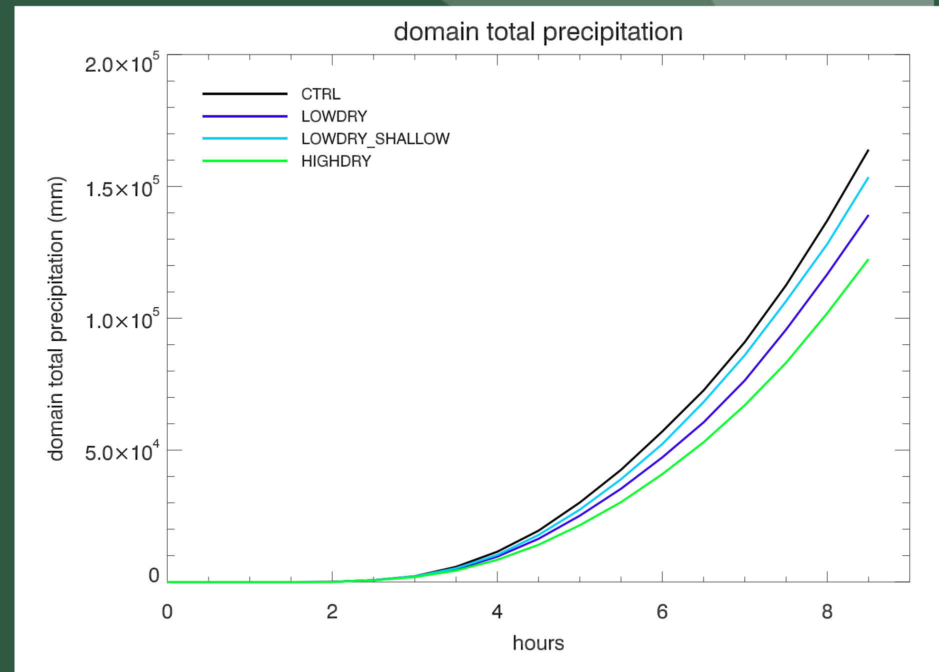
From PECAN EDO

CTRL
LOWDRY
LOWDRY_SHALLOW
HIGHDRY

Vertical mass flux at 7 km AGL



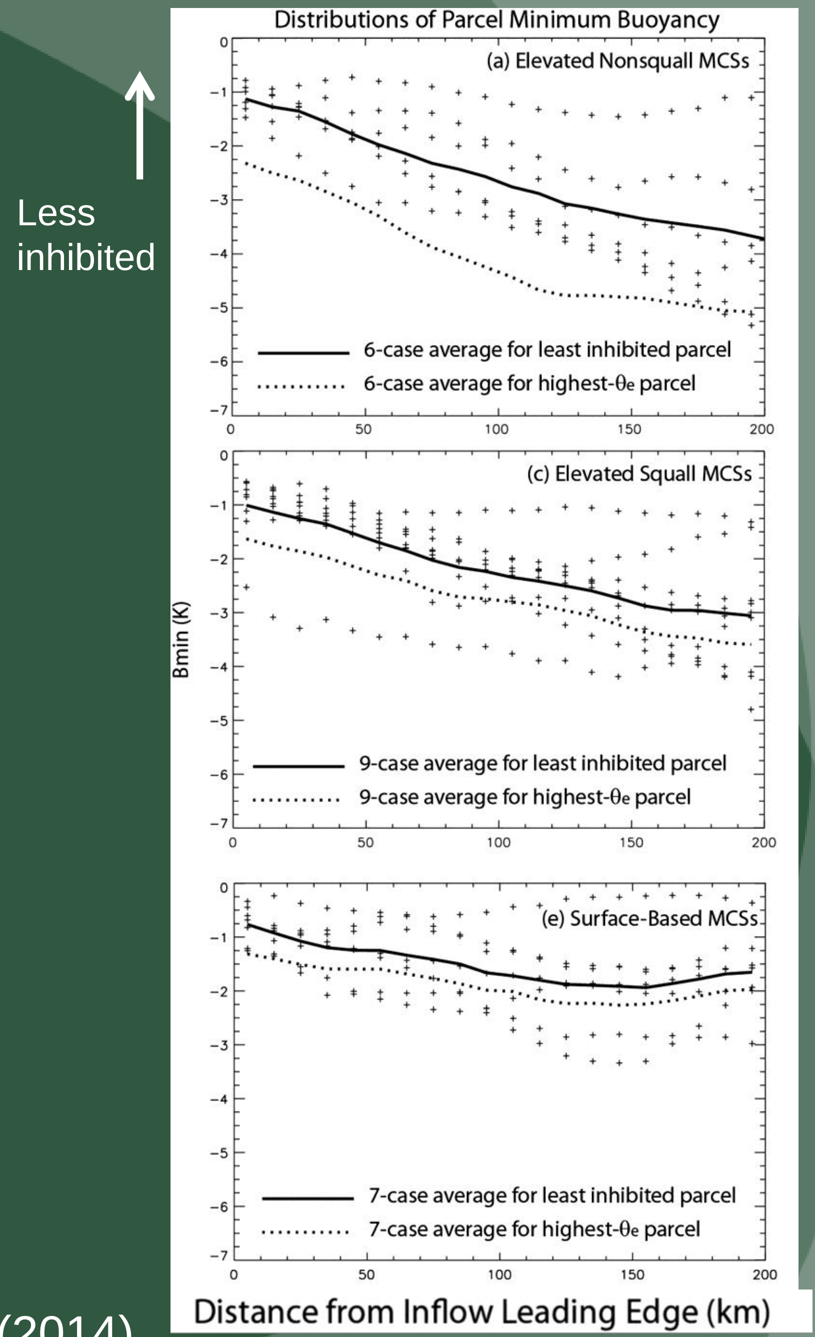
Domain total precipitation



Summary/conclusions

- In comparison to surface-based squall lines, elevated MCSs have received less attention, but are responsible for most of the heavy rainfall production in the US
- Analysis of observations and model simulations reveal the importance of both mesoscale ascent and storm-scale features such as gravity waves in maintaining and organizing heavy-rain-producing MCSs
- Elevated MCSs are often poorly predicted, and forecasts are very sensitive to low-level atmospheric structures and the distribution of moisture

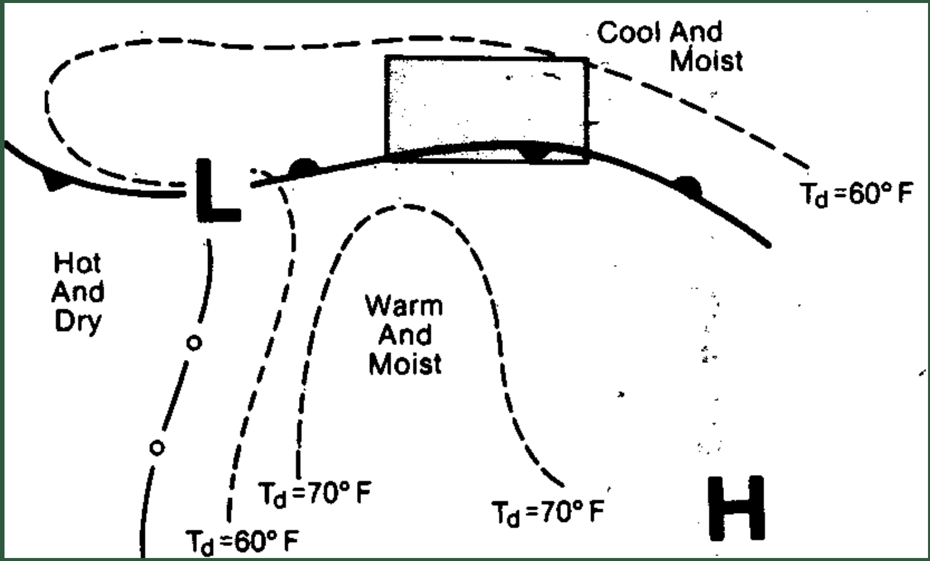
In a recent study, Trier et al. (2014, *MWR*) found that the parcel buoyancy minimum is reduced gradually over scales > 100 km in elevated MCS environments – lending further support to the importance of mesoscale ascent and destabilization, even for squall lines



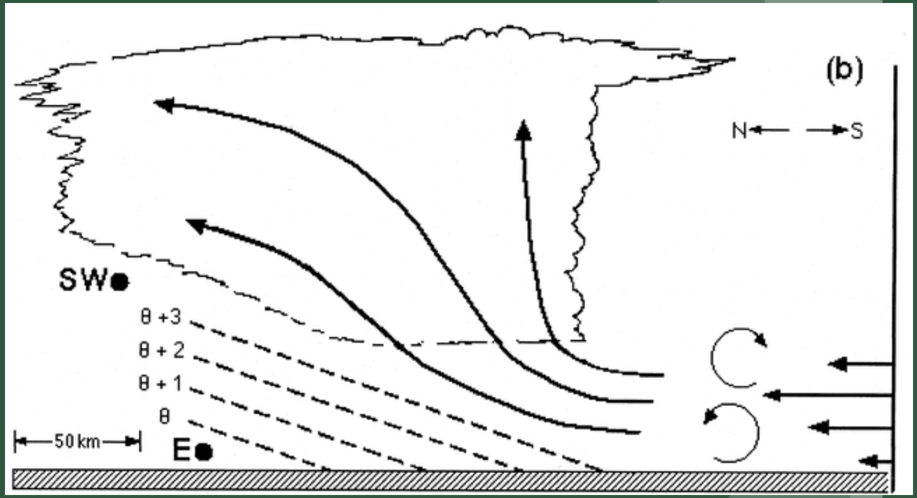
From Trier et al. (2014)

Extreme-rain-producing MCSs

- TL/AS MCSs generally form on the cool side of a boundary, corresponding to the Maddox et al. (1979) “frontal” pattern



Maddox et al. (1979)

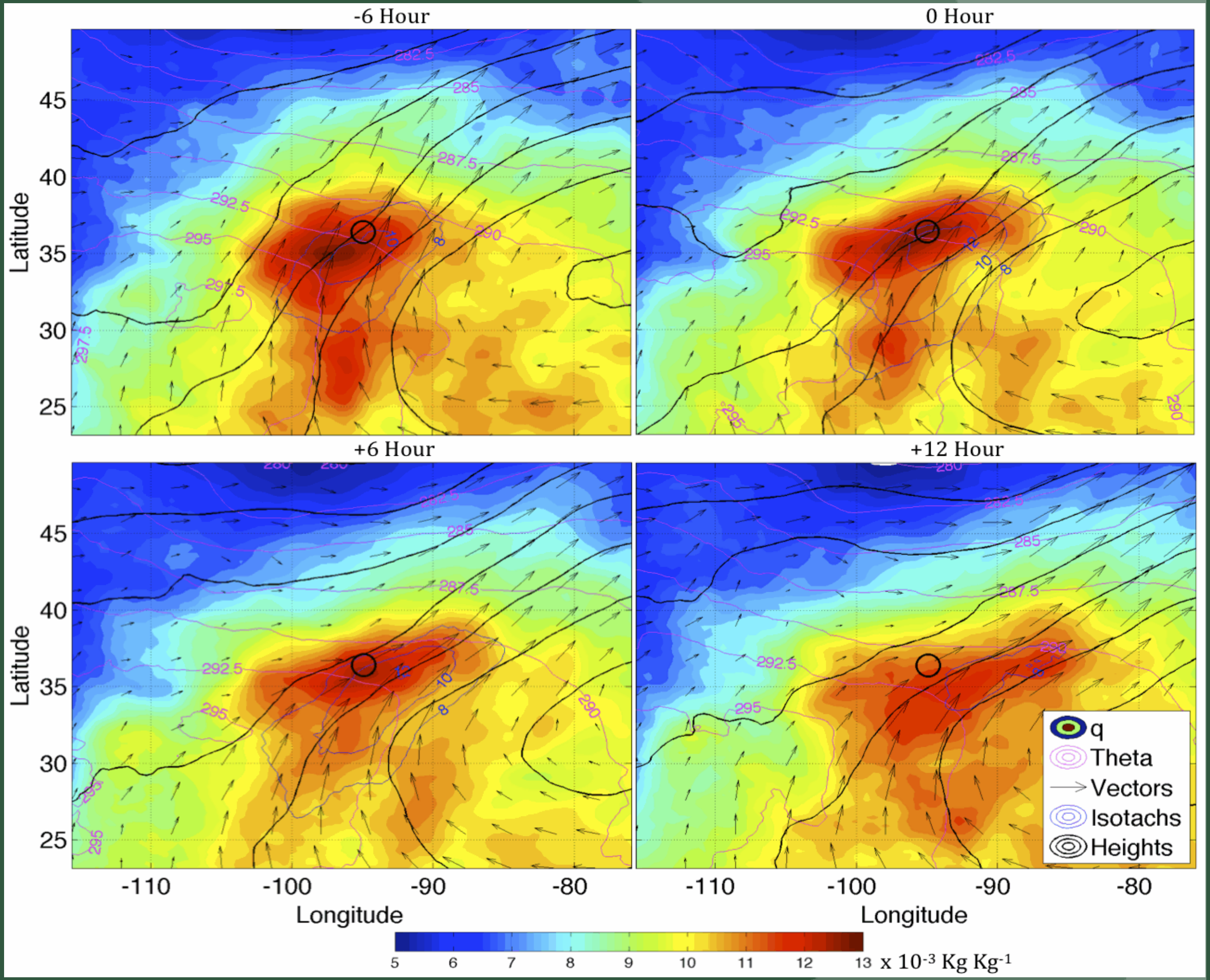


Laing and Fritsch (2000)

Extreme-rain-producing MCSs

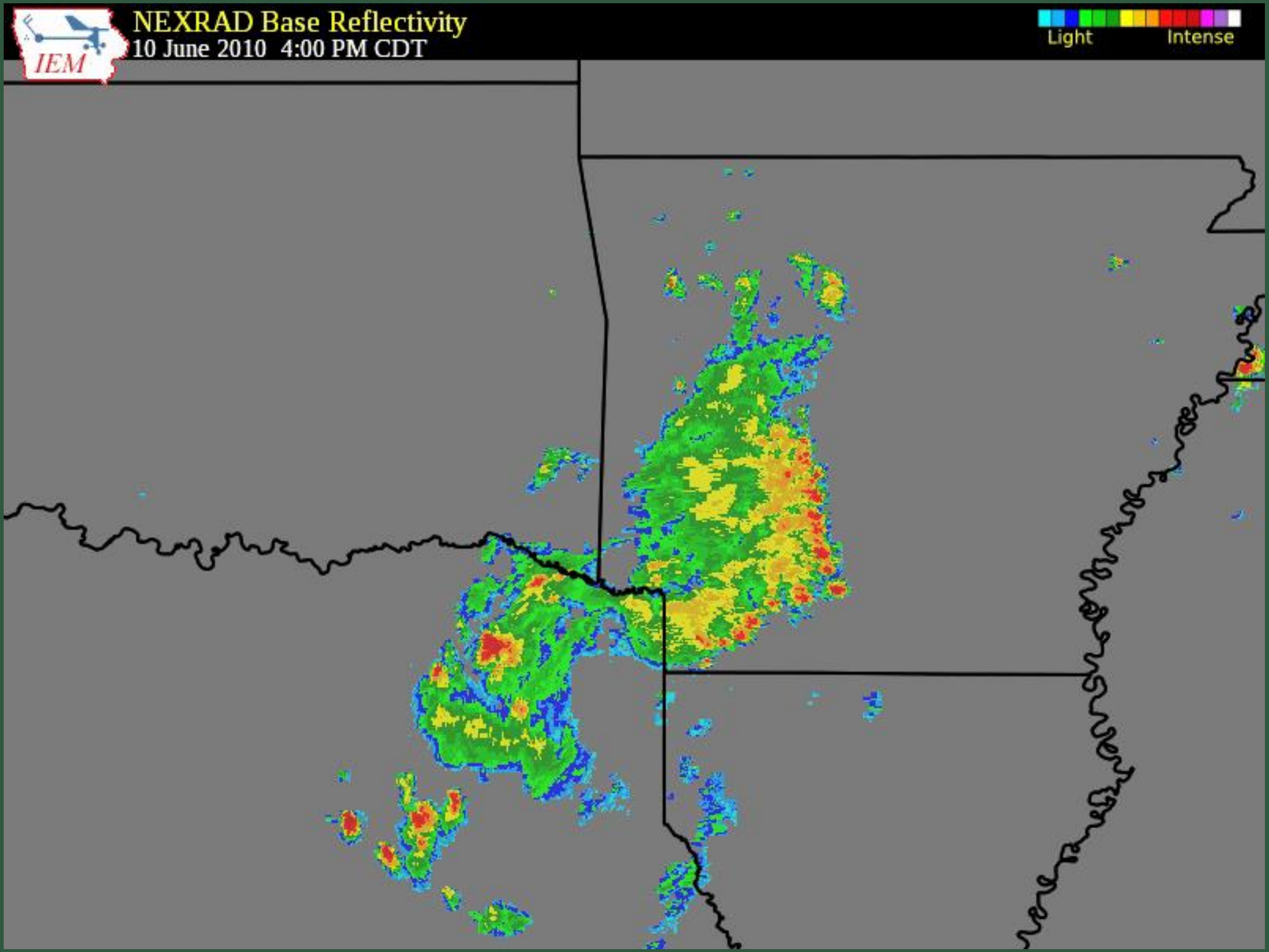
Composite 850-mb evolution of 26 warm-season TL/AS events

Colors: mixing ratio
Potential temperature
Isotachs
Heights



From Peters and Schumacher (2014, *MWR*, in press)

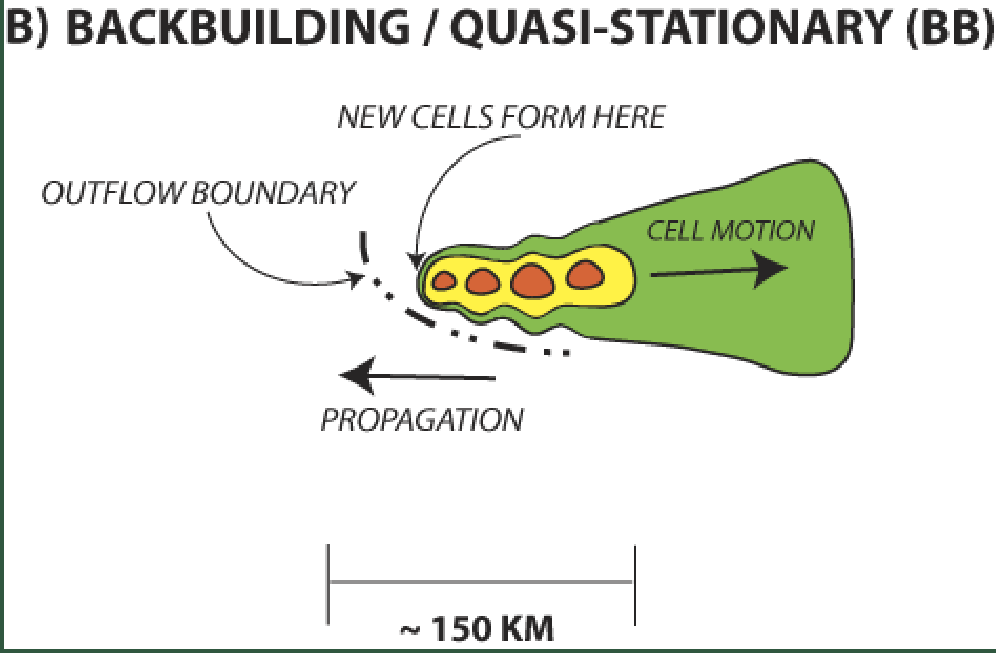
Back-building/quasi-stationary

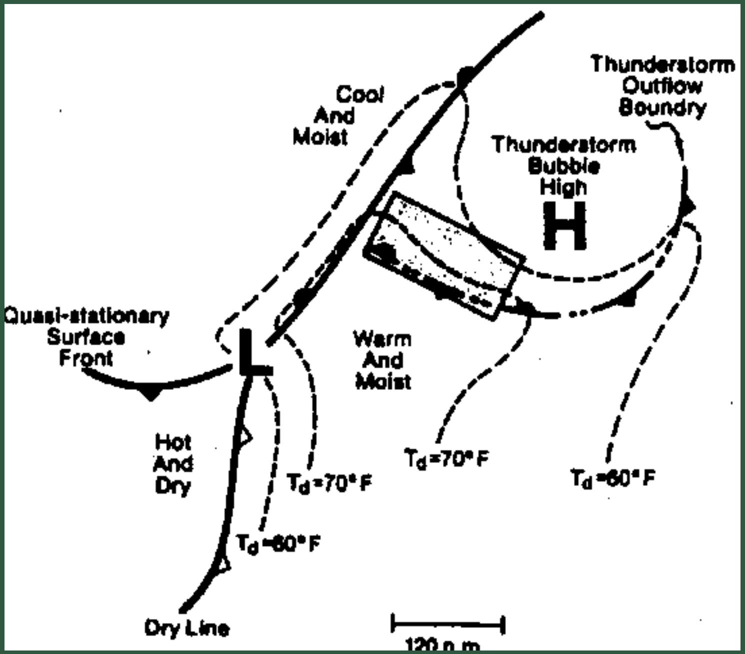


10-11 June 2010

Back-building/Quasi-stationary MCSs

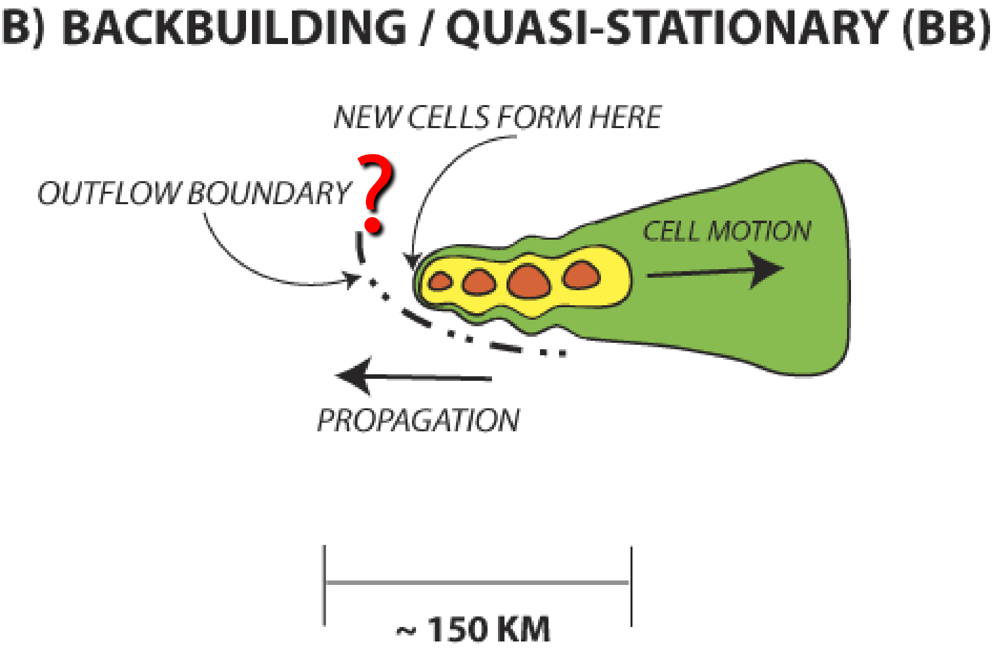
- In some BB MCSs, lifting along an outflow boundary/cold pool causes the repeated cell development, consistent with Maddox et al.'s (1979) "mesohigh" flash flood type

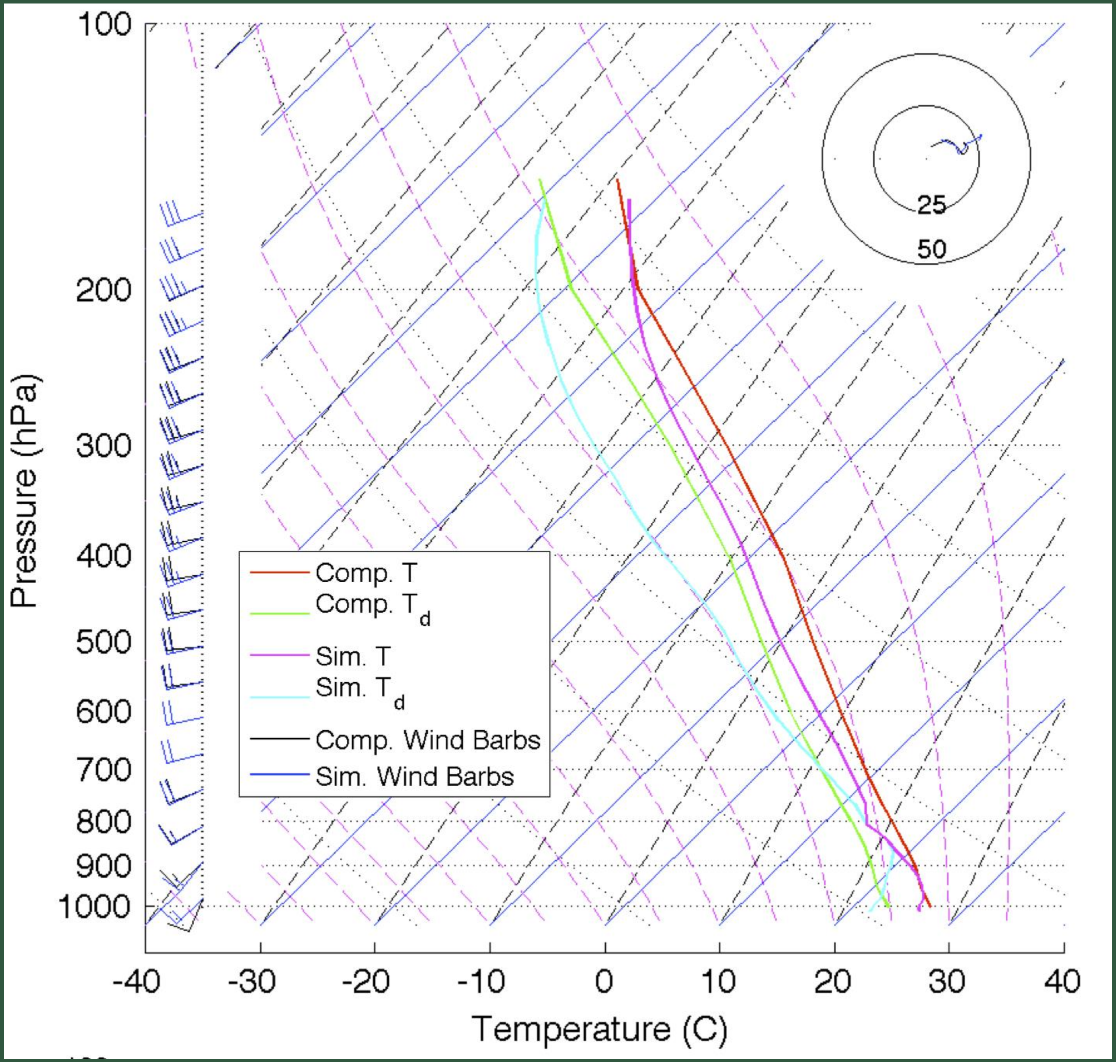




Back-building/Quasi-stationary MCSs

- In some BB MCSs, lifting along an outflow boundary/cold pool causes the repeated cell development, consistent with Maddox et al.'s (1979) "mesohigh" flash flood type
- In others, it was difficult to identify any boundaries at the surface, yet the convection kept linear organization and remained nearly stationary for extended periods




100
200
300
400
500
600
700
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900
1000
Pressure (hPa)
-40
-30
-20
-10
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25
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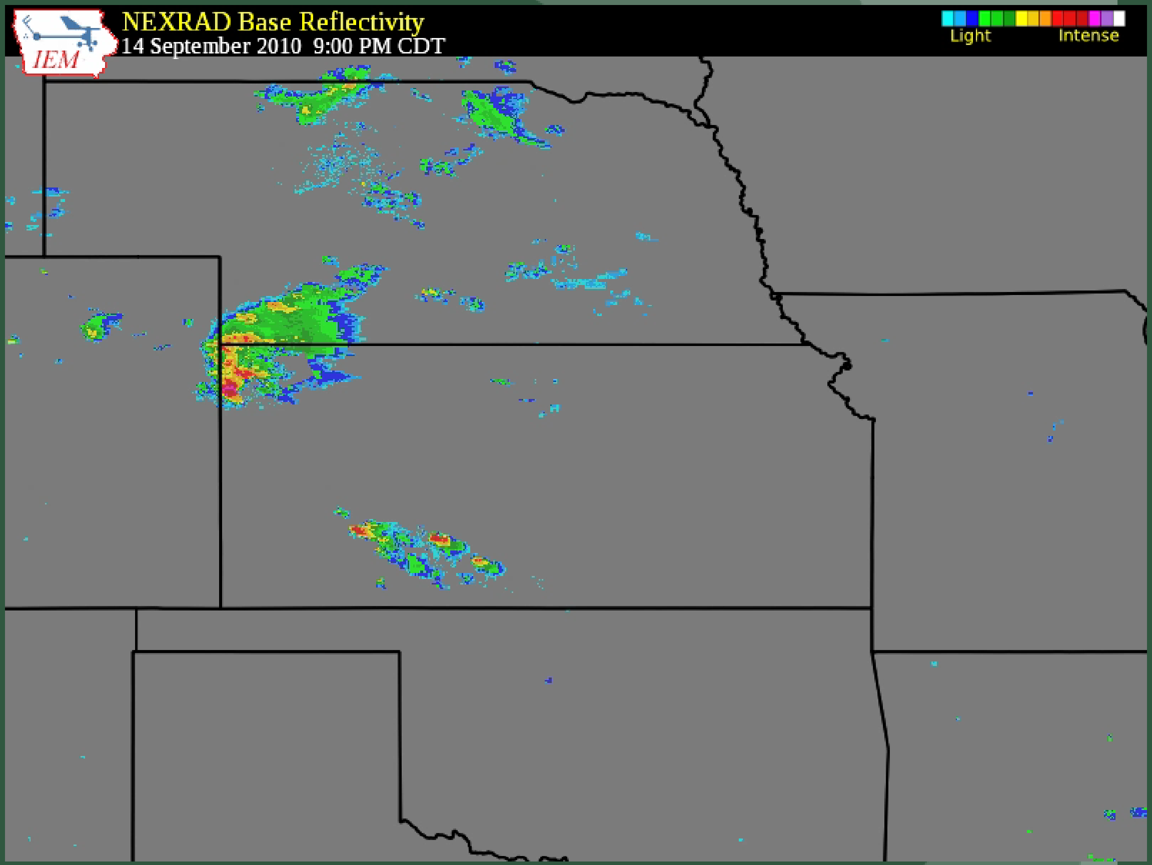
Comp. T_d
Sim. T
Sim. T_d
Comp. Wind Barbs
Sim. Wind Barbs

The “bow and arrow”

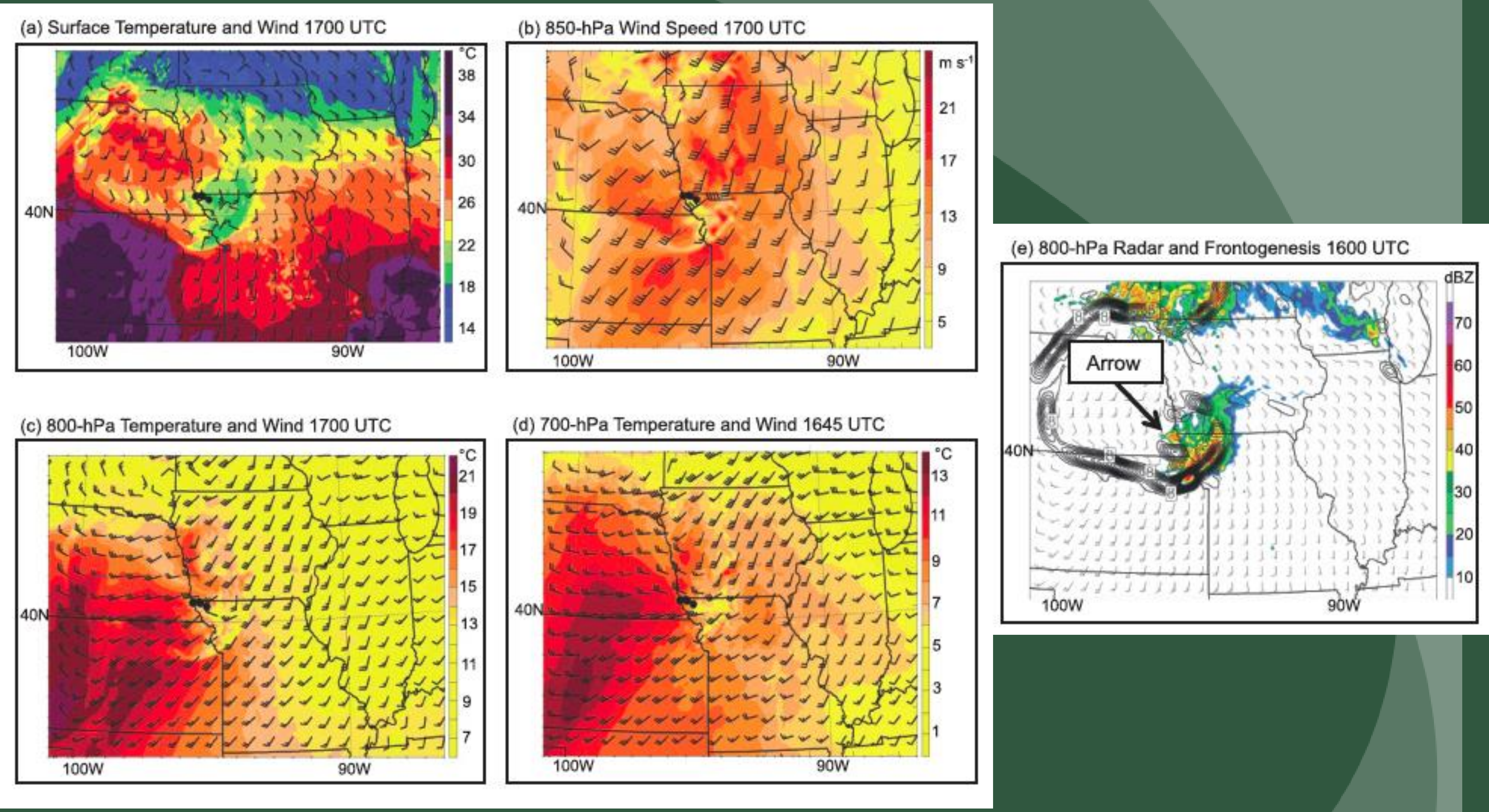
- It is sometimes observed that new convective lines form behind, and perpendicular to, bow echoes
- The new convection does **not** form on the outflow boundary, but instead within/above the cold pool
- We refer to this structure as the “bow and arrow”



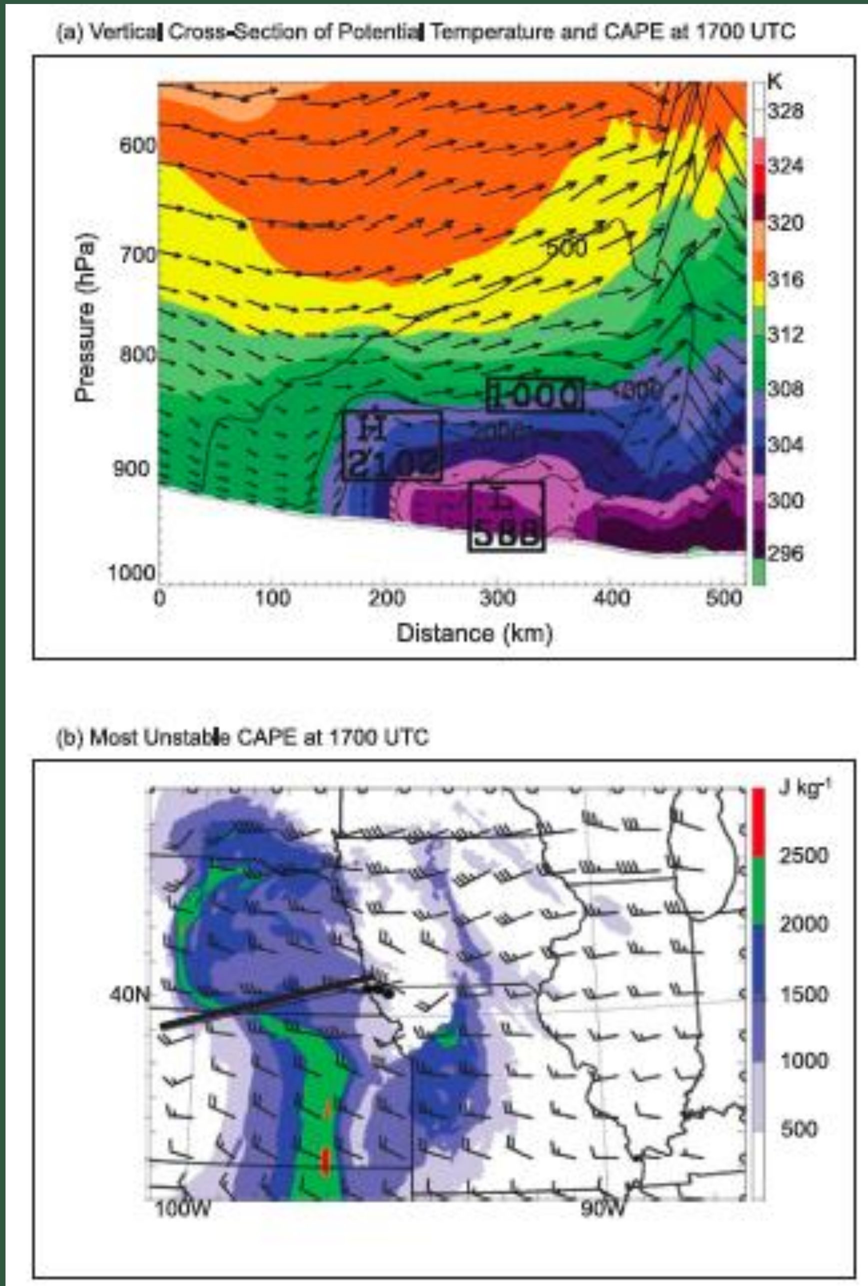
15 September 2010

The “bow and arrow”

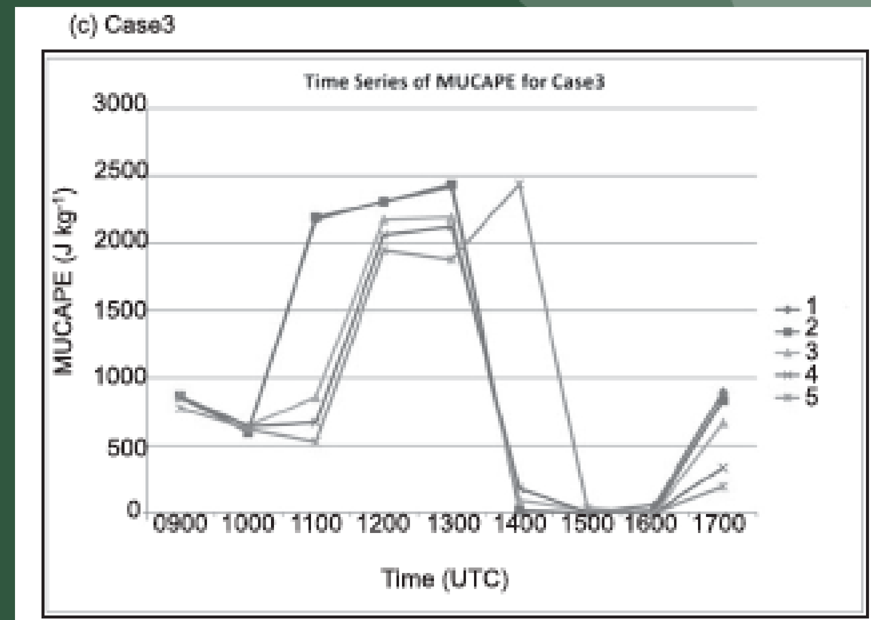
- Keene and Schumacher (2013) used observations and case-study simulations to examine the processes associated with bow-and-arrow events
- We identified 14 cases, and analyzed simulations of 3 of them (2 of which were NCAR WRF-ARW real-time forecasts)



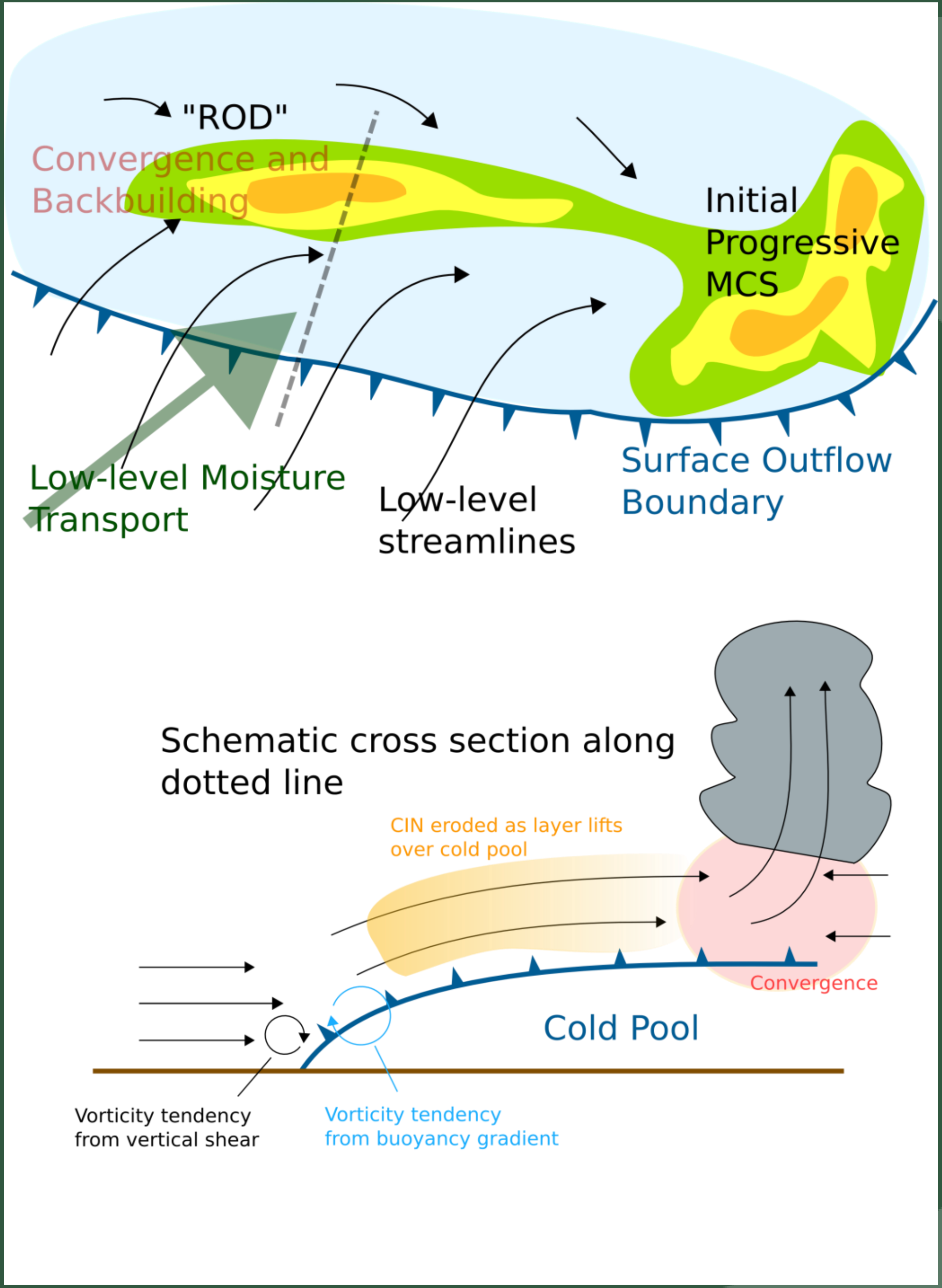
From Keene and Schumacher (2013, *MWR*)



Time series of MUCAPE along parcels



From Keene and Schumacher (2013, *MWR*)



From Peters and Schumacher (2014, submitted to MWR)

Methods for idealized simulations of elevated MCSs

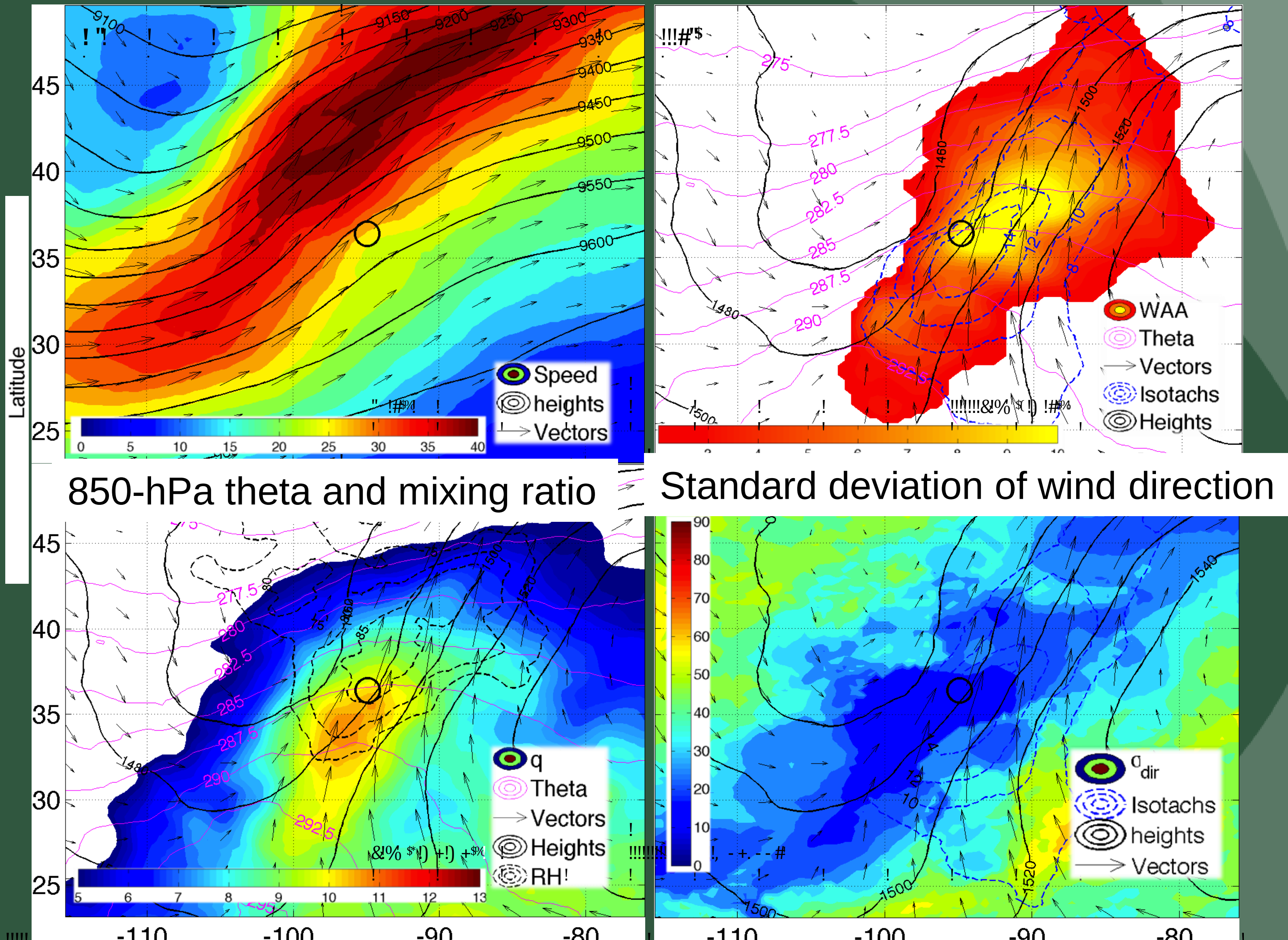
- Parker (2008) and French and Parker (2010) analyzed the response of an MCS as it moved into an environment that is being cooled
- Mahoney et al. (2009) initiated convection with a warm bubble within an environment with a balanced jet-front system
- Crook and Moncrieff (1988); Loftus et al. (2008); and Schumacher (2009) applied a large-scale momentum forcing to initiate and maintain convection (more on this in a bit…)
- **Coniglio and Stensrud (2001) used a gridded composite of multiple cases as initial/boundary conditions**

Composite initial conditions

- Peters and Schumacher (2014, *MWR*, in press) identified 50 “training line-adjoining stratiform” MCSs
- Applied rotated principal component analysis (RPCA) to the North American Regional Reanalysis for these cases, which objectively categorized them into “synoptically forced” and “warm-season” subcategories
- Storm-centered composites were created for each of these subcategories

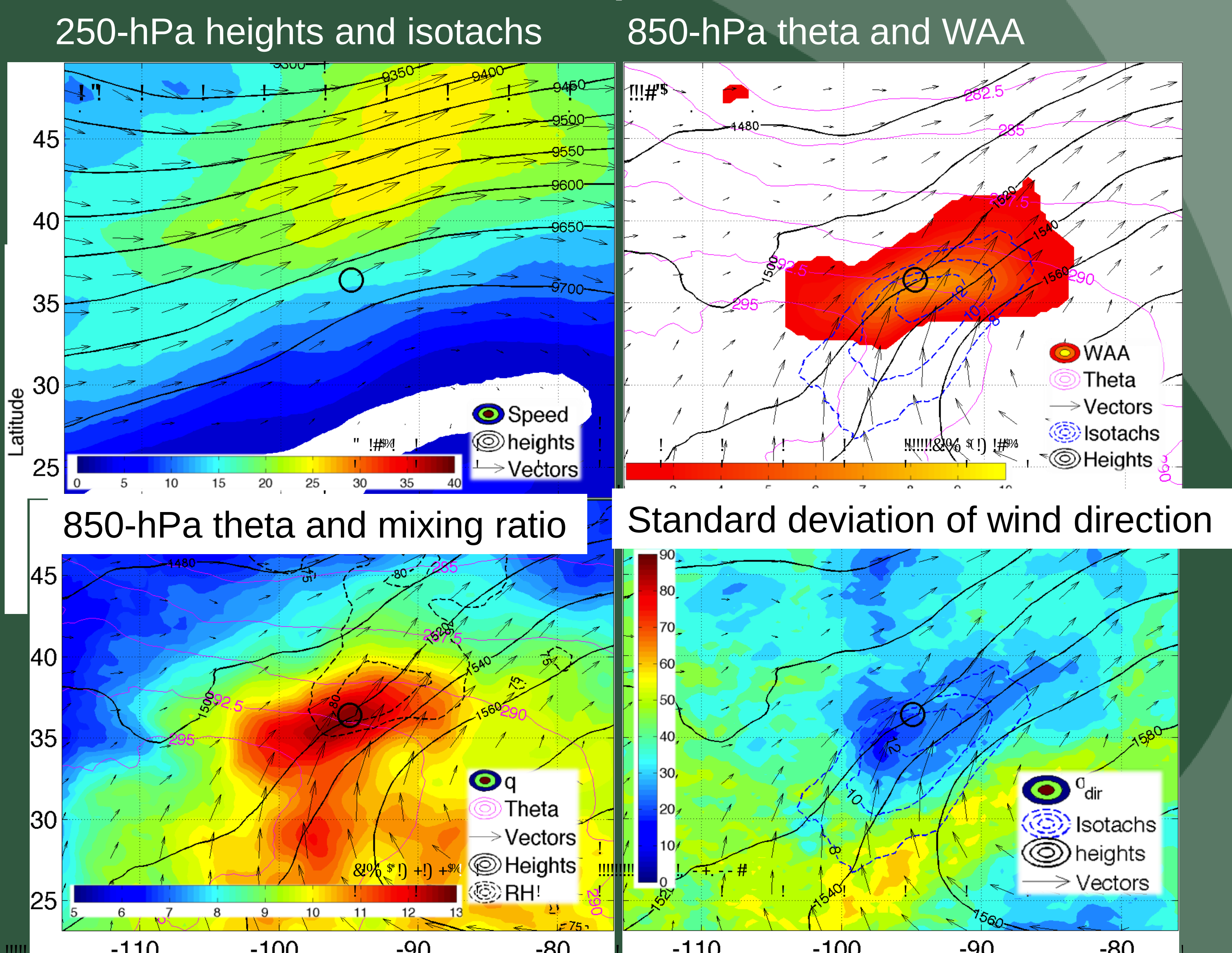
“Synoptically forced” composite at t=0

250-hPa heights and isotachs   850-hPa theta and WAA



Adapted from Peters and Schumacher (2014, MWR, in press)

“Warm-season” composite at t=0



Adapted from Peters and Schumacher (2014, MWR, in press)

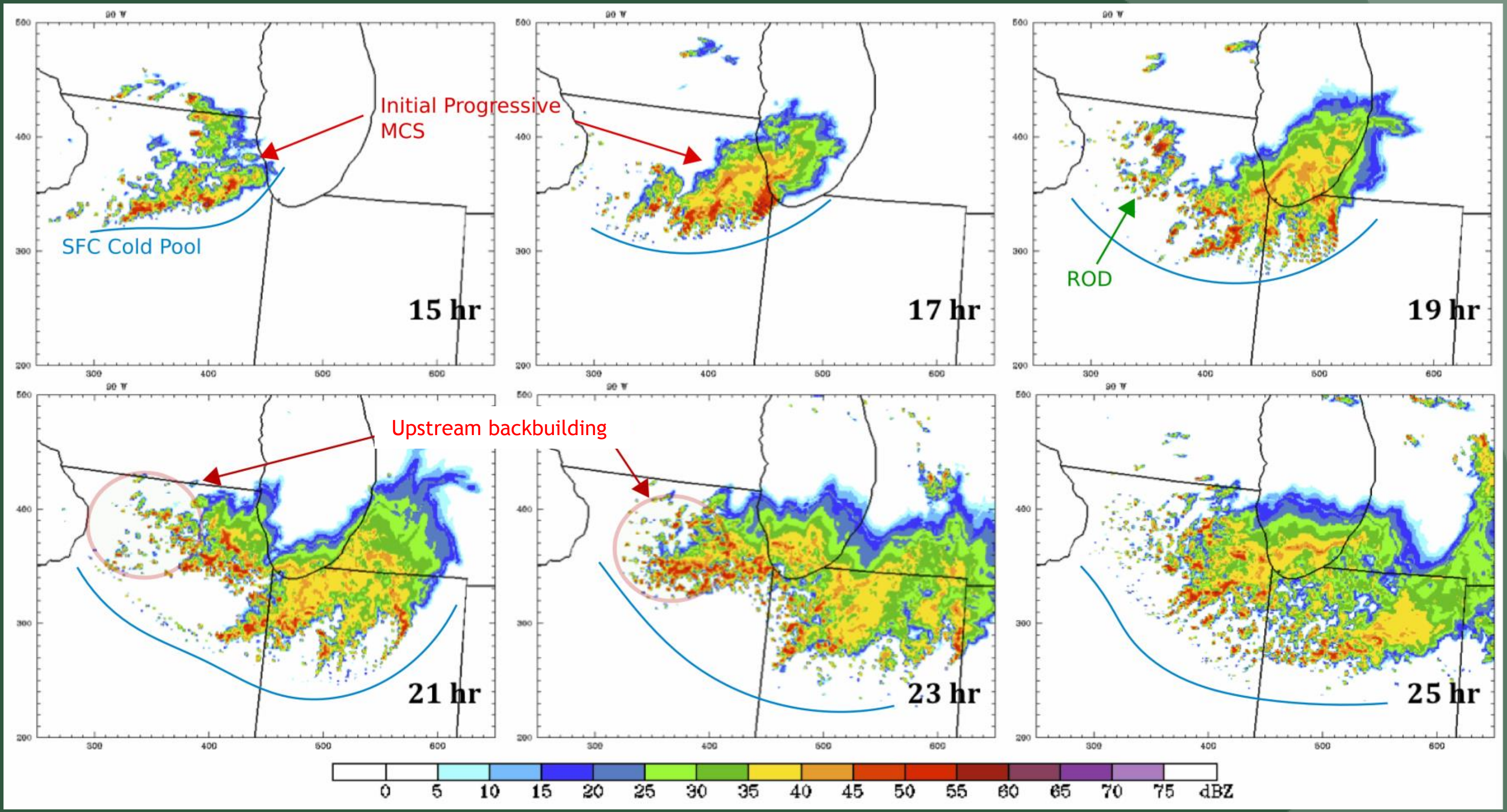
Composite initial conditions

- These composites were then used as initial conditions for WRF-ARW simulations at 1.33-km horizontal grid spacing
- The simulations are initialized from the composite at 15 h prior to the peak 1-h rainfall time, and the lateral boundary conditions are updated every 3 h with the corresponding composite grids
- The model configuration is idealized in other ways, with a homogeneous underlying land surface and land-surface fluxes turned off
- The MYJ boundary layer and Thompson microphysics parameterizations were used

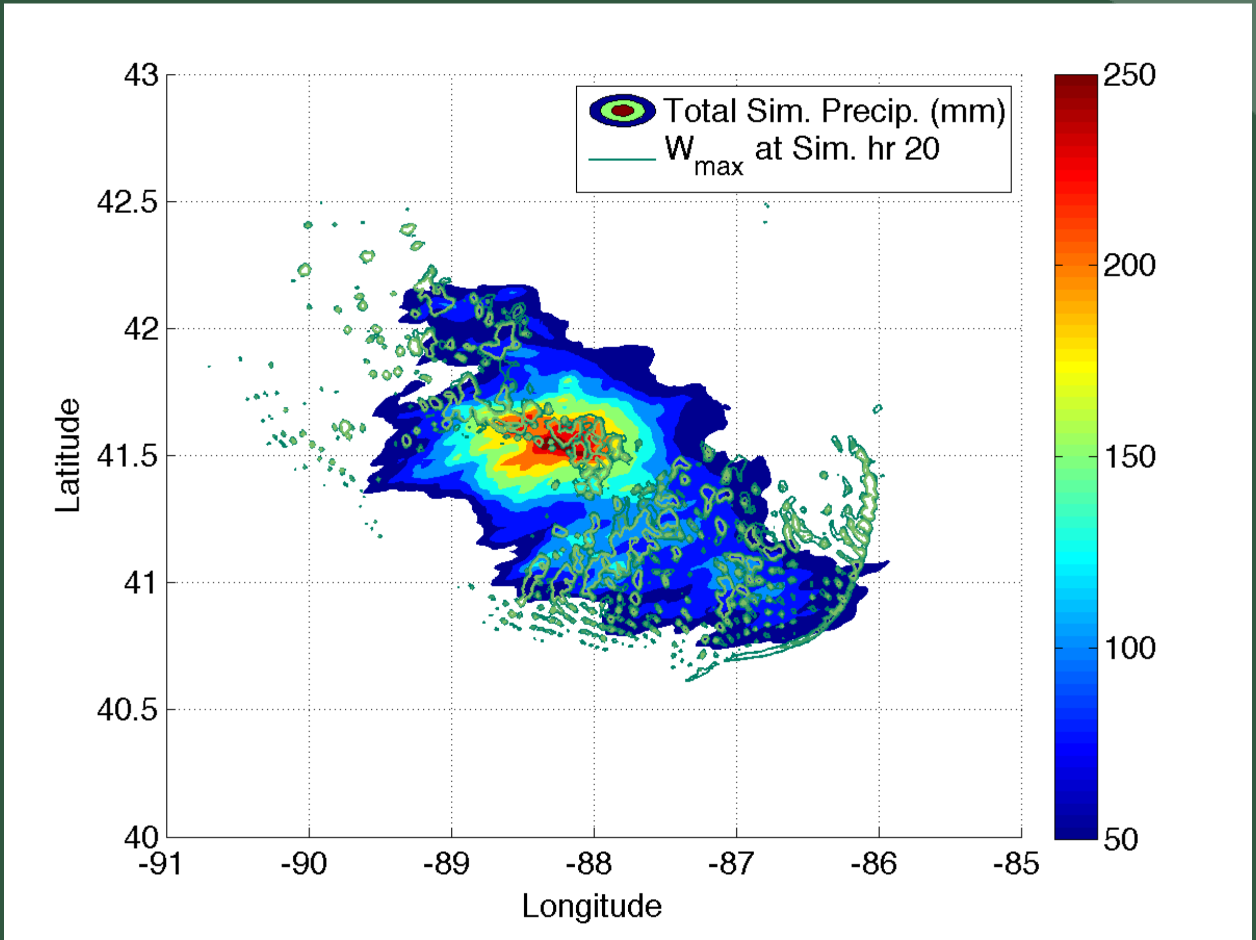
Initiation of convection

- Convection is allowed to initiate "naturally" in the simulation; in other words, no warm bubbles or cold pools are used
- However, to speed up the initiation process, it was found that the initial relative humidity needed to be increased slightly
  - The maximum RH increase was 10% at 900 hPa, with a Gaussian decrease over the 50 hPa above and below

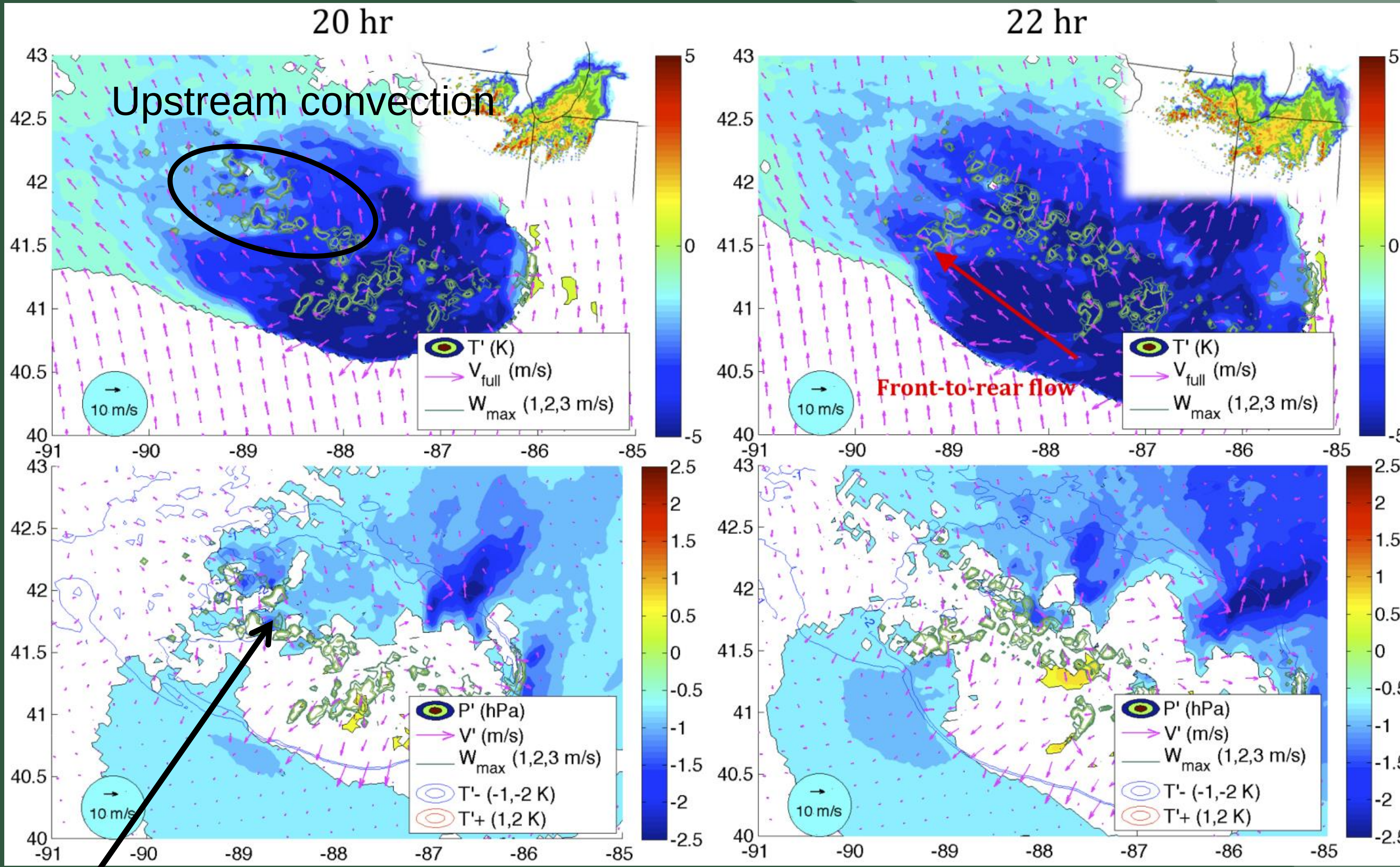
Simulated reflectivity



Simulated precipitation



Surface temperature perturbations and wind vectors

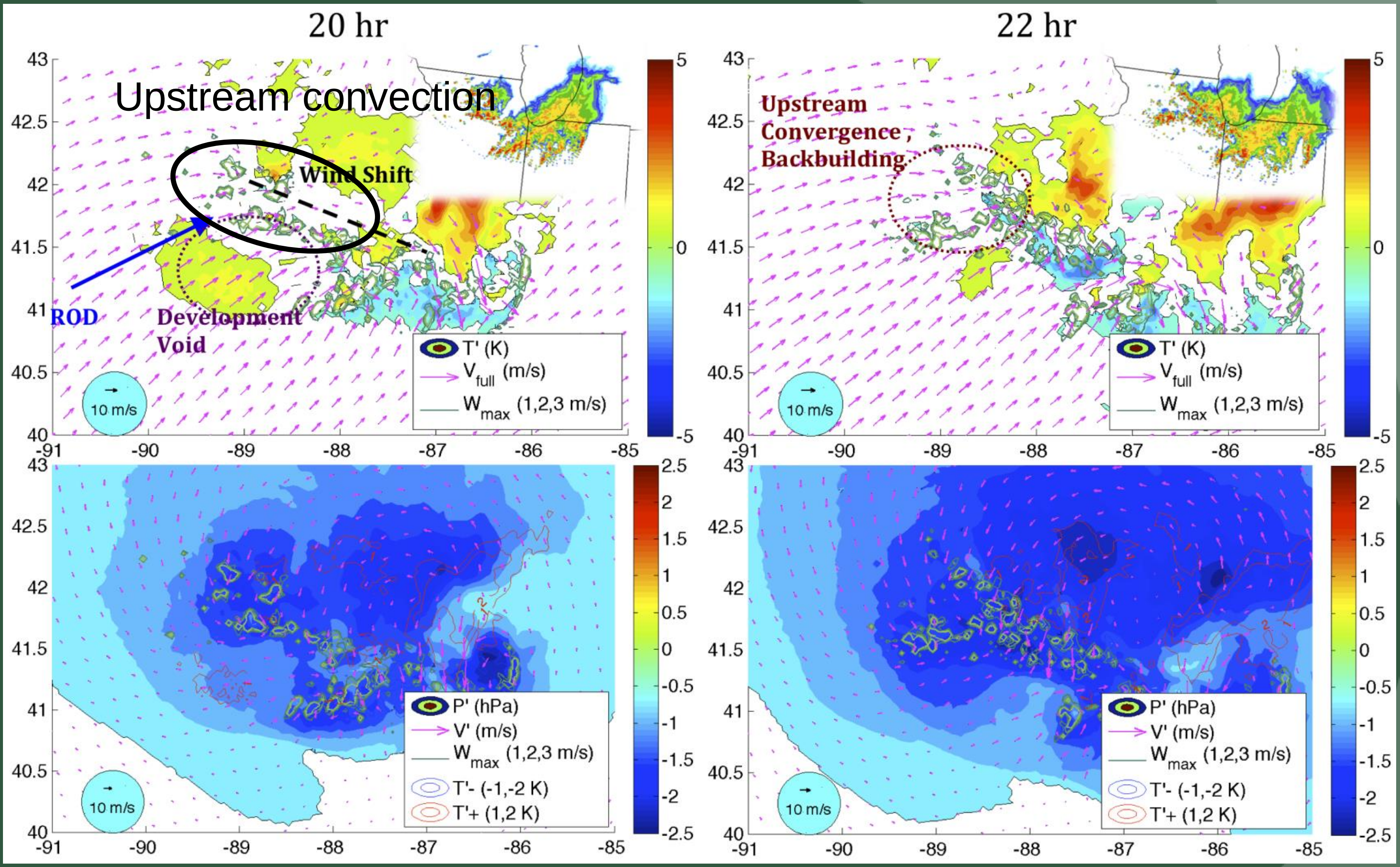


Surface pressure and wind perturbations

Low pressure perturbations associated with midlevel latent heating

Perturbations calculated relative to an analogous simulation with no latent heating

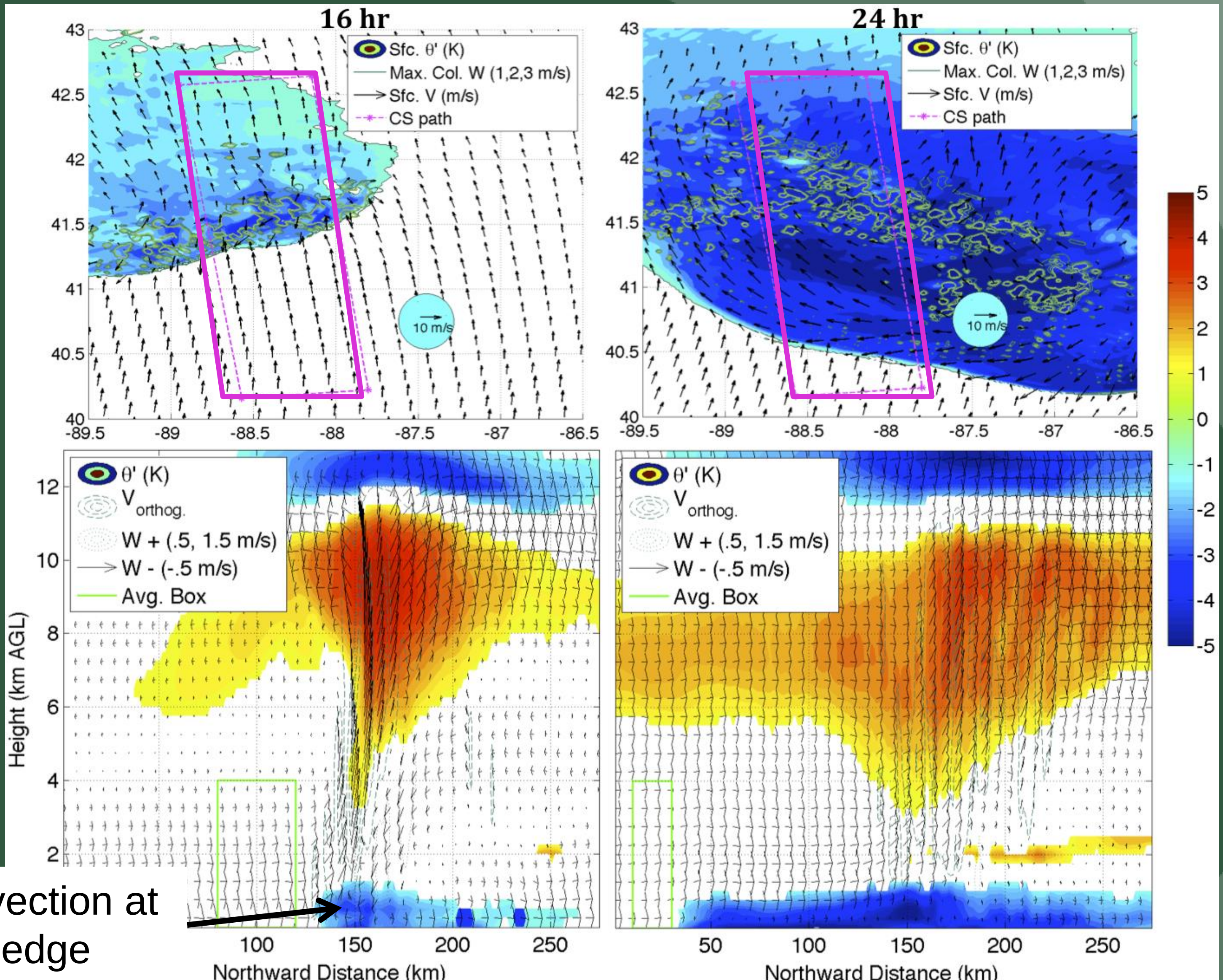
1.5-km AGL temperature perturbations and wind vectors



1.5-km AGL pressure and wind perturbations

Perturbations calculated relative to an analogous simulation with no latent heating

Surface theta perturbations and full wind

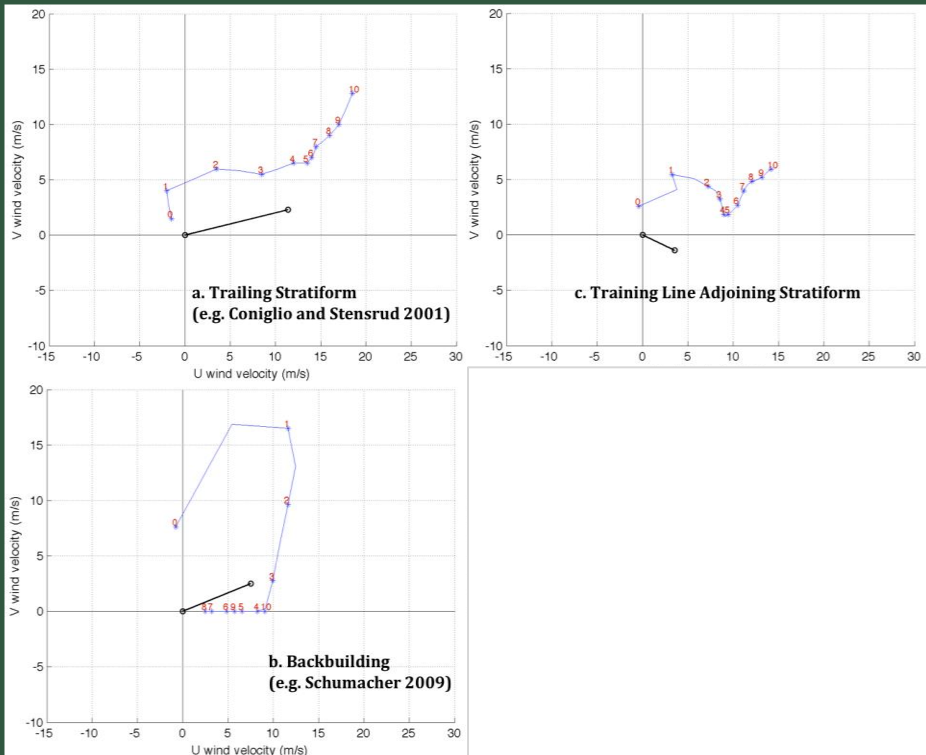


New convection at cold pool edge

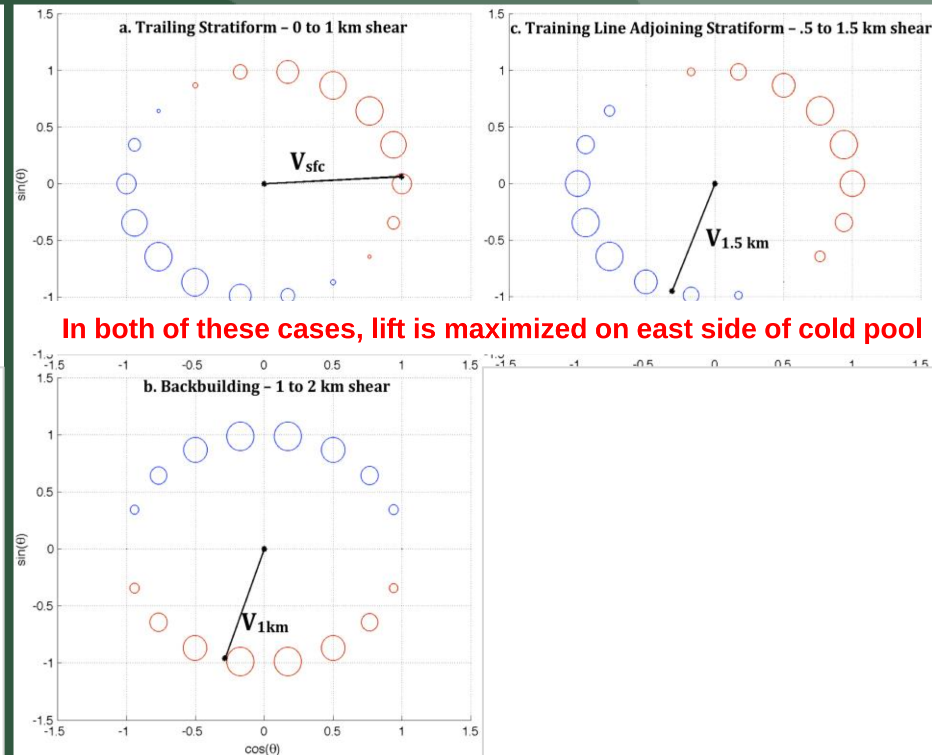
Cross-sections of theta perturbation and flow perpendicular to x-section

Perturbations calculated relative to an analogous simulation with no latent heating

Location of maximized lifting along hypothetical circular cold pool



Hodographs from observed MCS archetypes



In both of these cases, lift is maximized on east side of cold pool

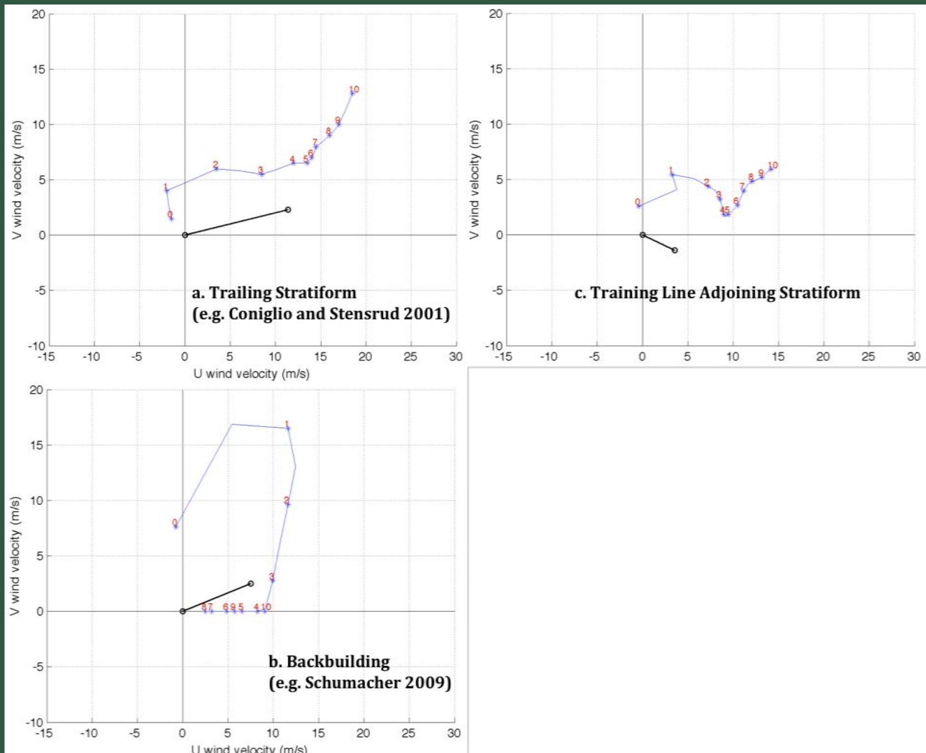
Magnitude of ascent along the gust front
Red circles indicate ascent, blue descent
Black lines indicate direction of max. inflow
Size of circle is the magnitude of this quantity, which is related to the ratio c/Δu from RKW theory:

$$DU_n\left(b\right) = \frac{DU\left(b\right)}{\max\left(\left|DU\left(b\right)\right|\right)}$$

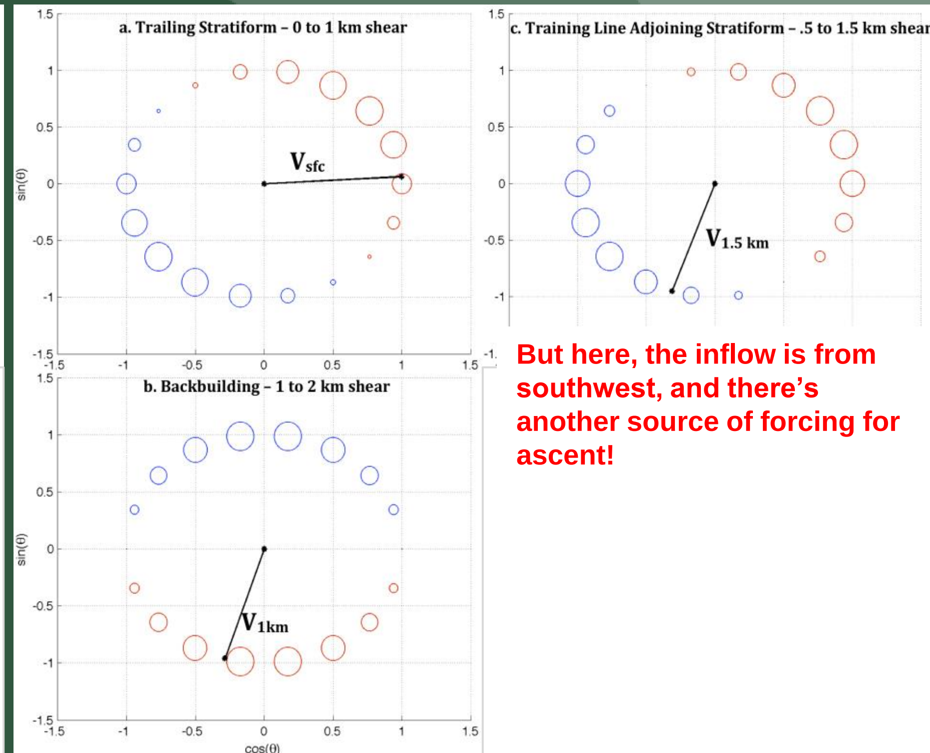
where

$$DU \equiv \left(\frac{\mathbf{V}_{z_2} - \mathbf{V}_{z_1}}{z_2 - z_1}\right) \cdot \left(- \frac{\nabla T'_b}{\left|\nabla T'_b\right|}\right)$$

Location of maximized lifting along hypothetical circular cold pool



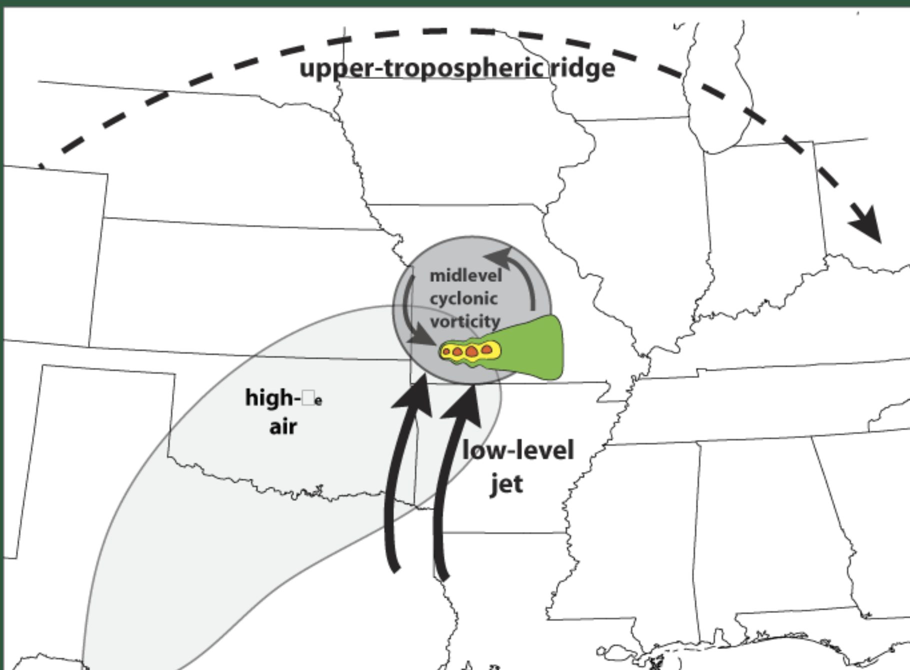
Hodographs from observed MCS archetypes

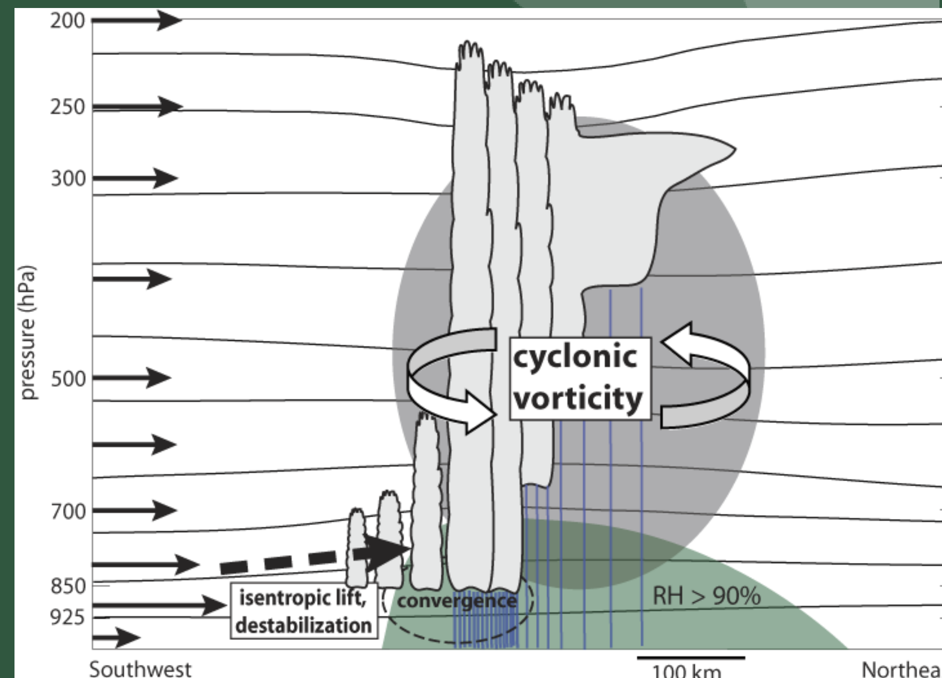


Magnitude of ascent along the gust front
Red circles indicate ascent, blue descent
Black lines indicate direction of max. inflow
Size of circle is the magnitude of this quantity, which is related to the ratio c/Δu from RKW theory:

$$\Delta U_n(b) = \frac{\Delta U(b)}{\max\left(\left|\Delta U(b)\right|\right)}$$ where $$\Delta U \equiv \left(\frac{\mathbf{V}_{z_2} - \mathbf{V}_{z_1}}{z_2 - z_1}\right) \cdot \left(-\frac{\nabla T'_b}{\left|\nabla T'_b\right|}\right)$$

Extreme local rainfall near MCVs





Schumacher, R. S. and R. H. Johnson, 2009: Quasi-stationary, extreme-rain-producing convective systems associated with midlevel cyclonic circulations. *Weather and Forecasting*, **24**, 555-574.

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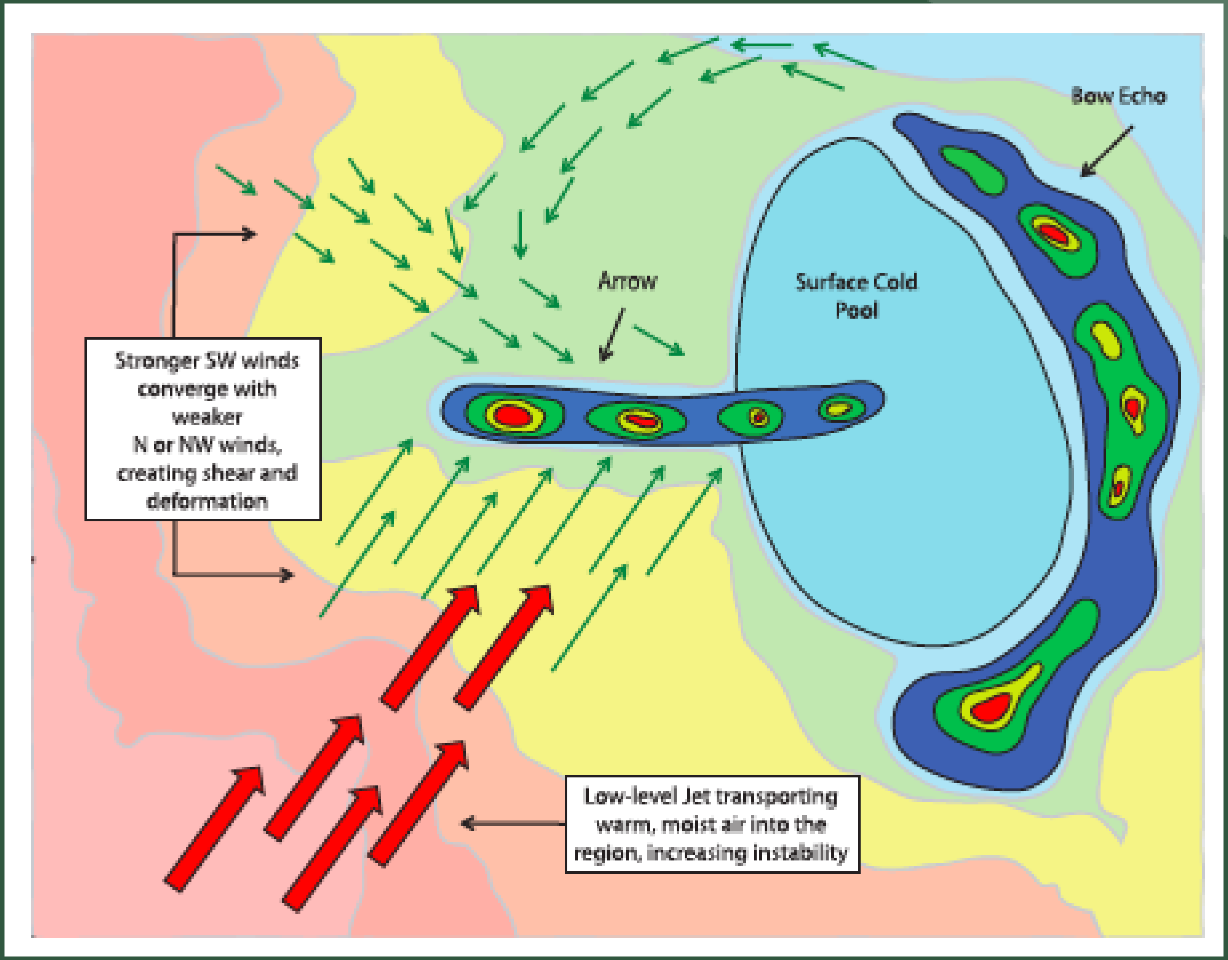
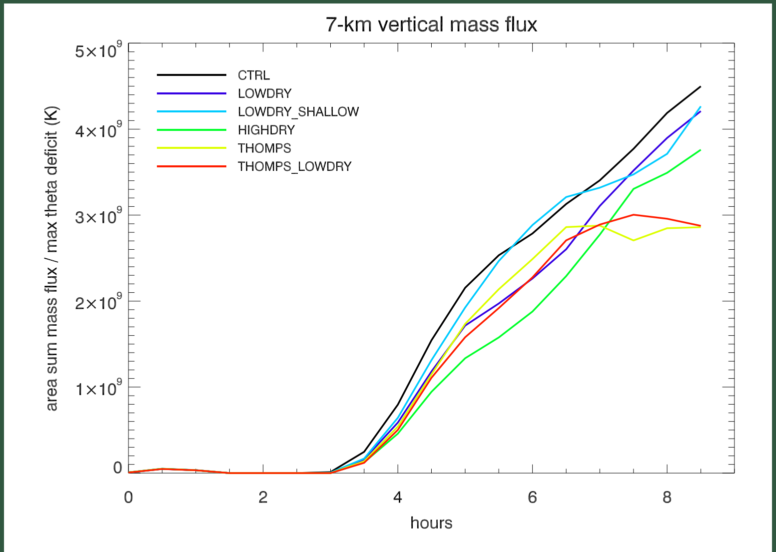
Schematic depiction of the bow and arrow



From Keene and Schumacher (2013, *MWR*)


7-km vertical mass flux
area sum mass flux / max theta deficit (K)
hours
CTRL
LOWDRY
LOWDRY_SHALLOW
HIGHDRY
THOMPS
THOMPS_LOWDRY
5×10^9
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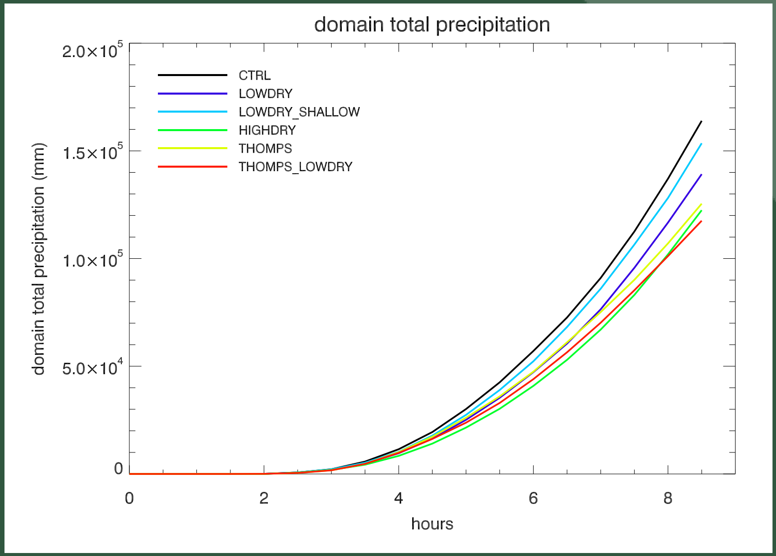
0
2
4
6
8


domain total precipitation
domain total precipitation (mm)
hours
CTRL
LOWDRY
LOWDRY_SHALLOW
HIGHDRY
THOMPS
THOMPS_LOWDRY
2.0×10^5
1.5×10^5
1.0×10^5
5.0×10^4
0
0
2
4
6
8