Reconciling Observations and Numerical Simulations of a Mesoscale Convective System

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Seminar at University of Reading

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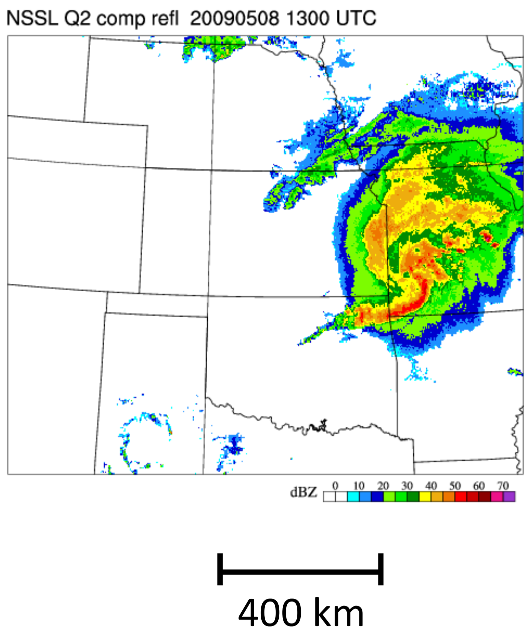
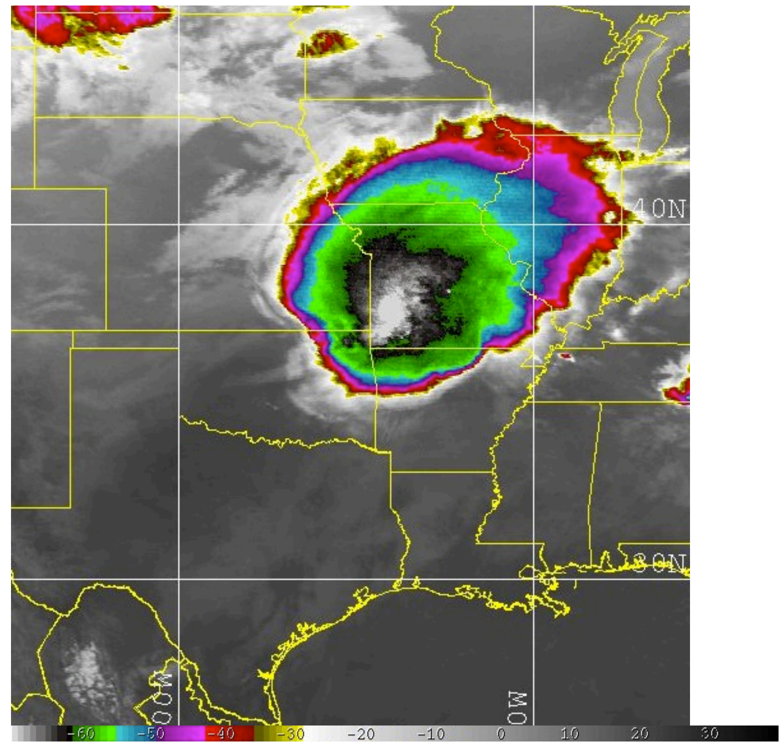
Example of a Mesoscale Convective System (MCS)

Radar reflectivity

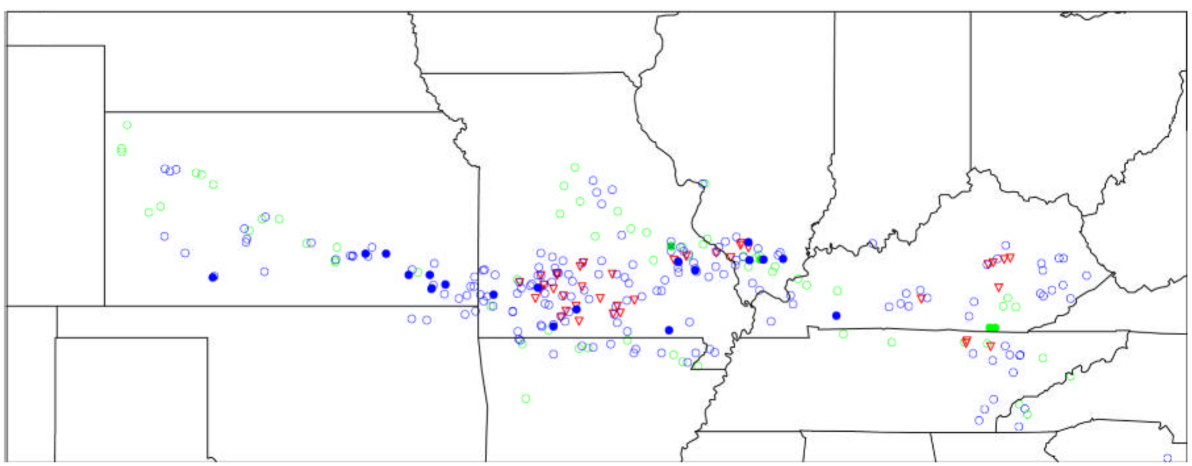


Satellite IR

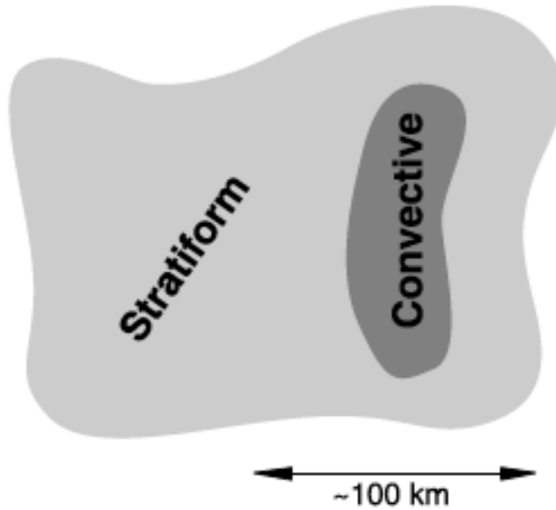


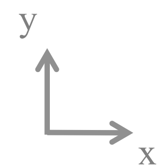
Severe Reports:

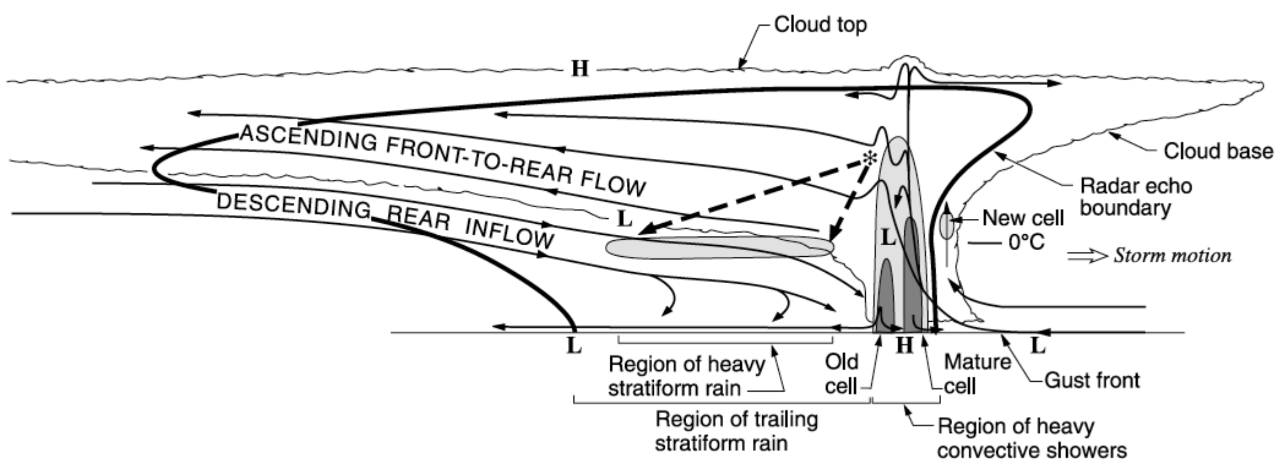
(green = hail)
(blue = svr winds)
(red = tornadoes)

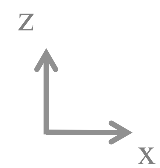


Conceptual Model





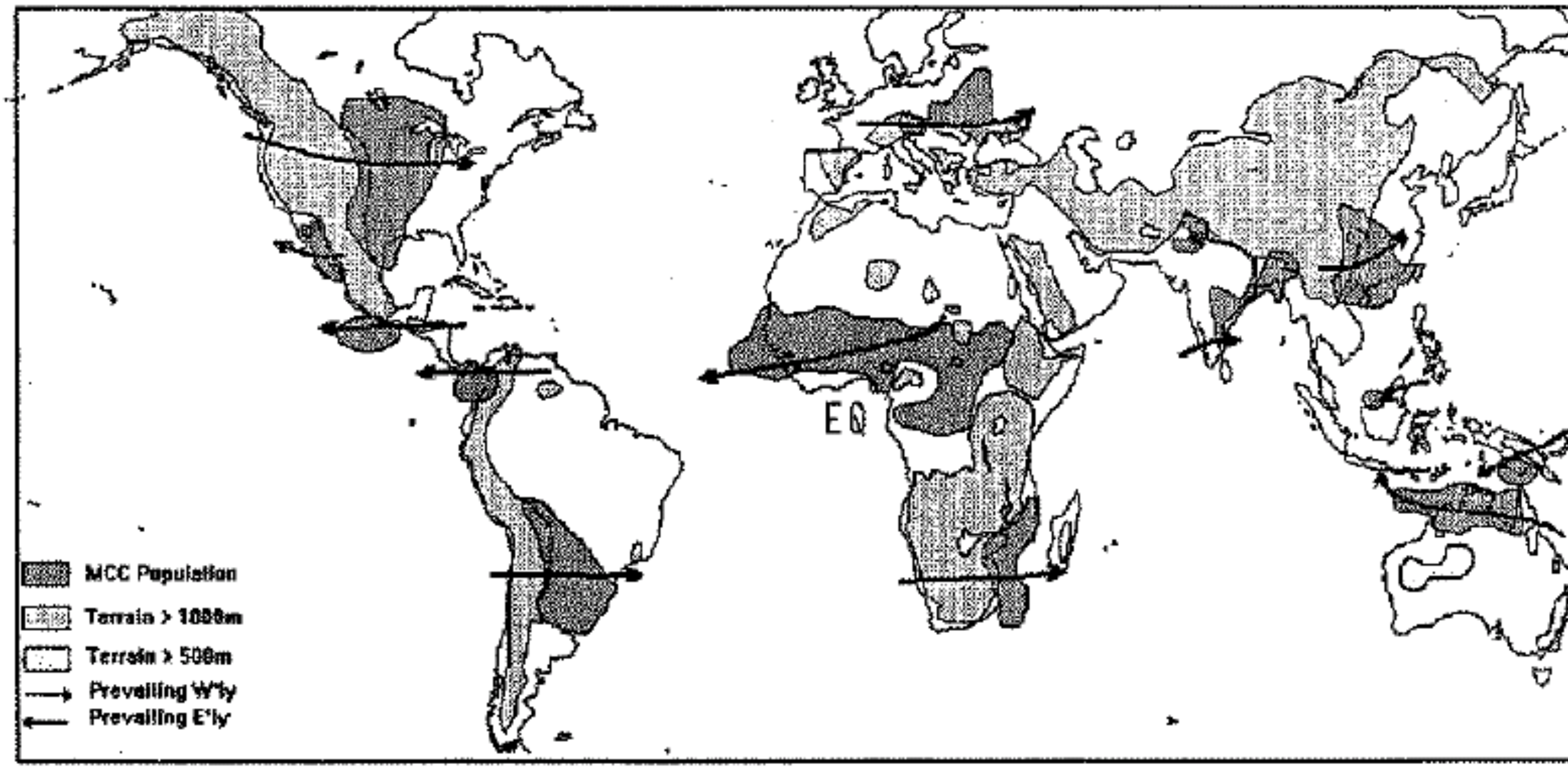




Houze (2004, *Reviews of Geophysics*)

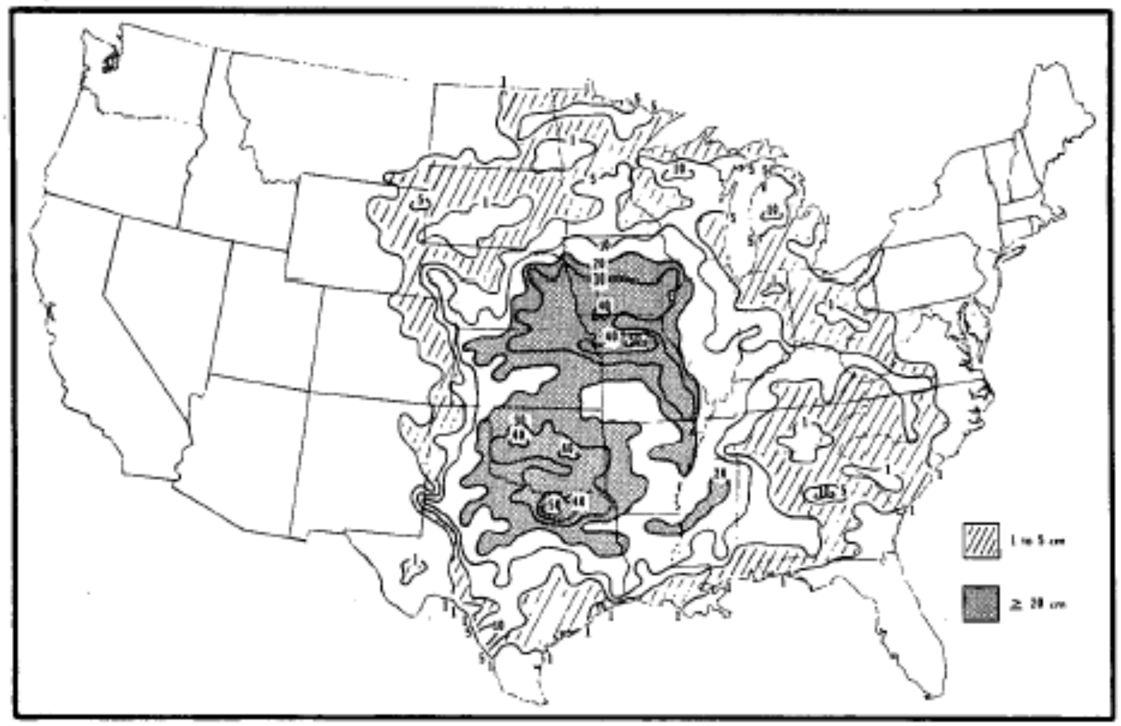
Global Population of MCCs (MCSs with circular IR satellite signatures)

Dark shading: frequent MCCs
Light shading: high terrain



Laing and Fritsch (1997)

Effects of several MCSs:
accumulated precipitation (cm) from 60 MCSs in 1982

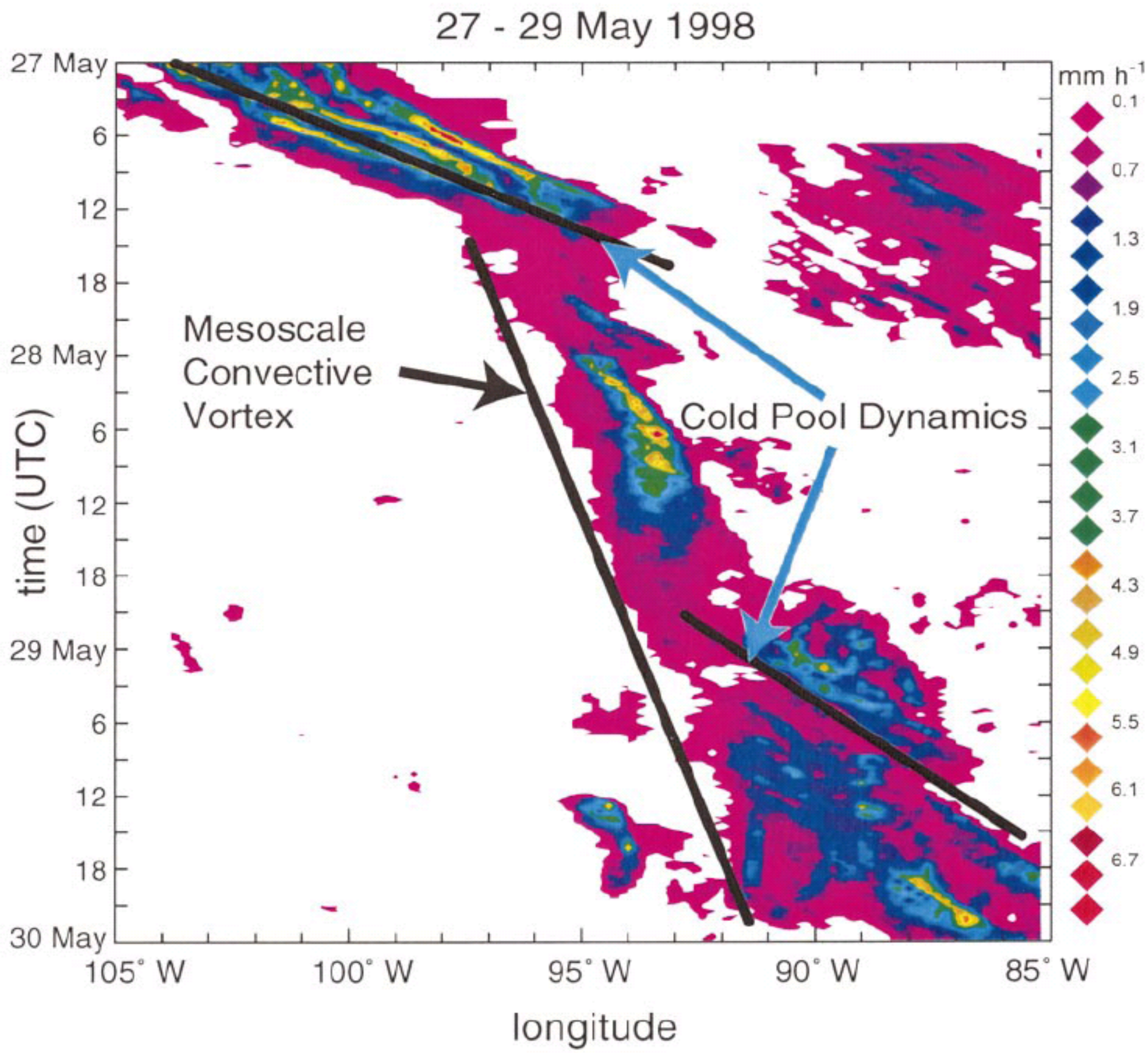


dark shading:
≥ 20 cm

Fritsch et al. (1986)

- Fritsch et al. (1986): MCSs account for 30-70% of warm-season precipitation in the central United States
- Carbone and Tuttle (2008): about 60% of warm-season precipitation occurs from propagating, nocturnal MCSs

Rainfall Rate: (latitudinal-average)

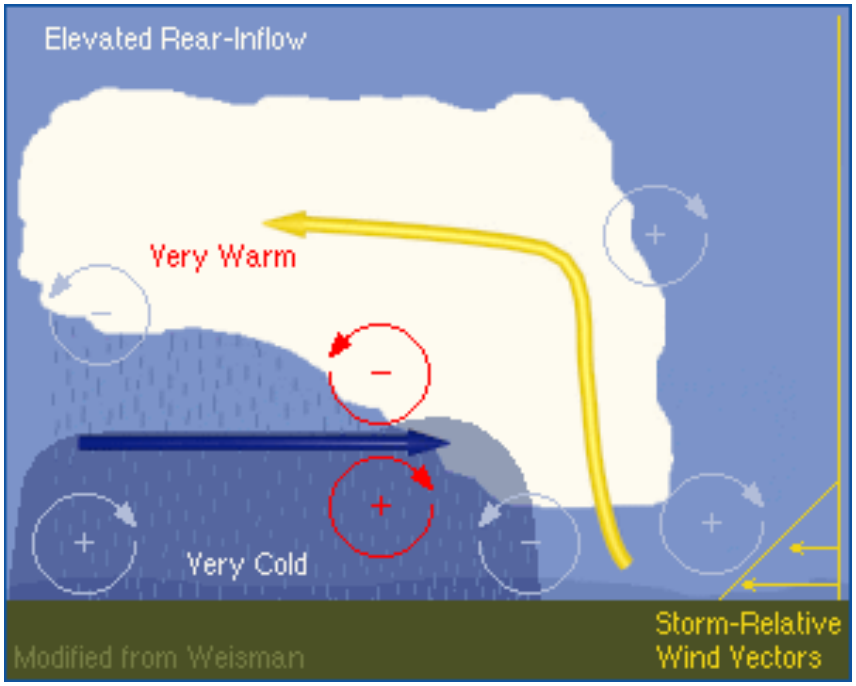


Carbone et al. (2002)

MCS vertical structure

MCSs typically have layers of relatively cold air near the surface: cold pools

~15 km



100s of km

(from COMET, www.meted.ucar.edu)

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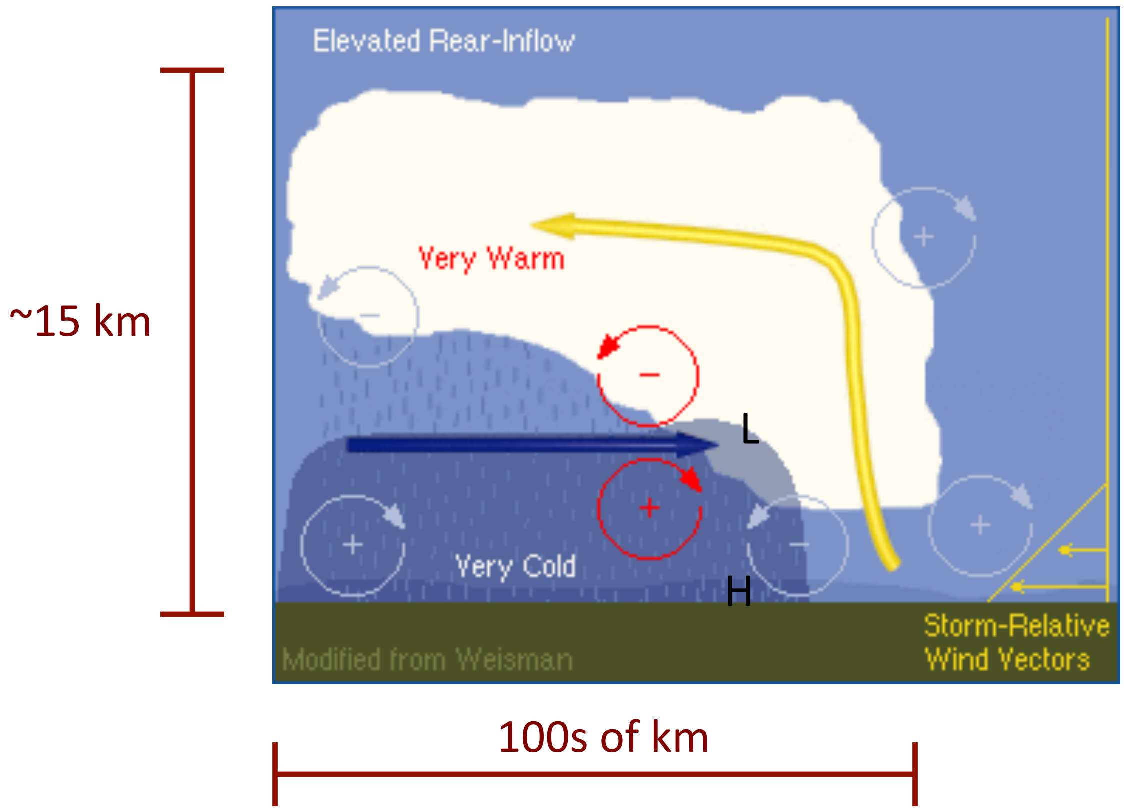
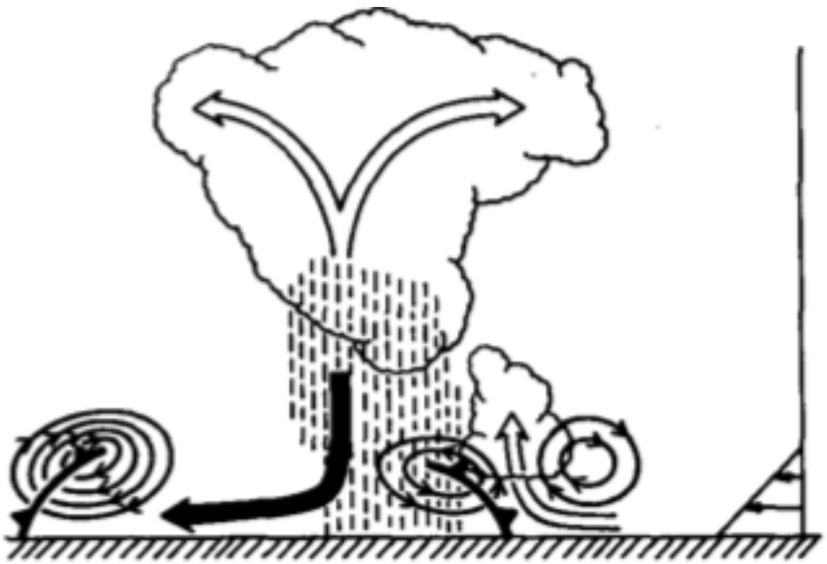


(from COMET, www.meted.ucar.edu)

Dynamic effects of cold pools:

- Relatively high pressure at surface, low pressure at top
- Accelerates mesoscale flow ---> severe winds, propagation

MCS processes



shear vector: →

- MCSs are composed of ordinary convective cells (*)
- New convective cells are continuously generated at edges of cold pools (and, at times, other processes … e.g., gravity waves)
- We know that <u>cold pools</u> and <u>vertical wind shear</u> are important for MCSs

Rotunno et al (1988; RKW)

Relative intensity of cold pool and shear

Intensity of cold pool is usually quantified by $\underline{C}$:

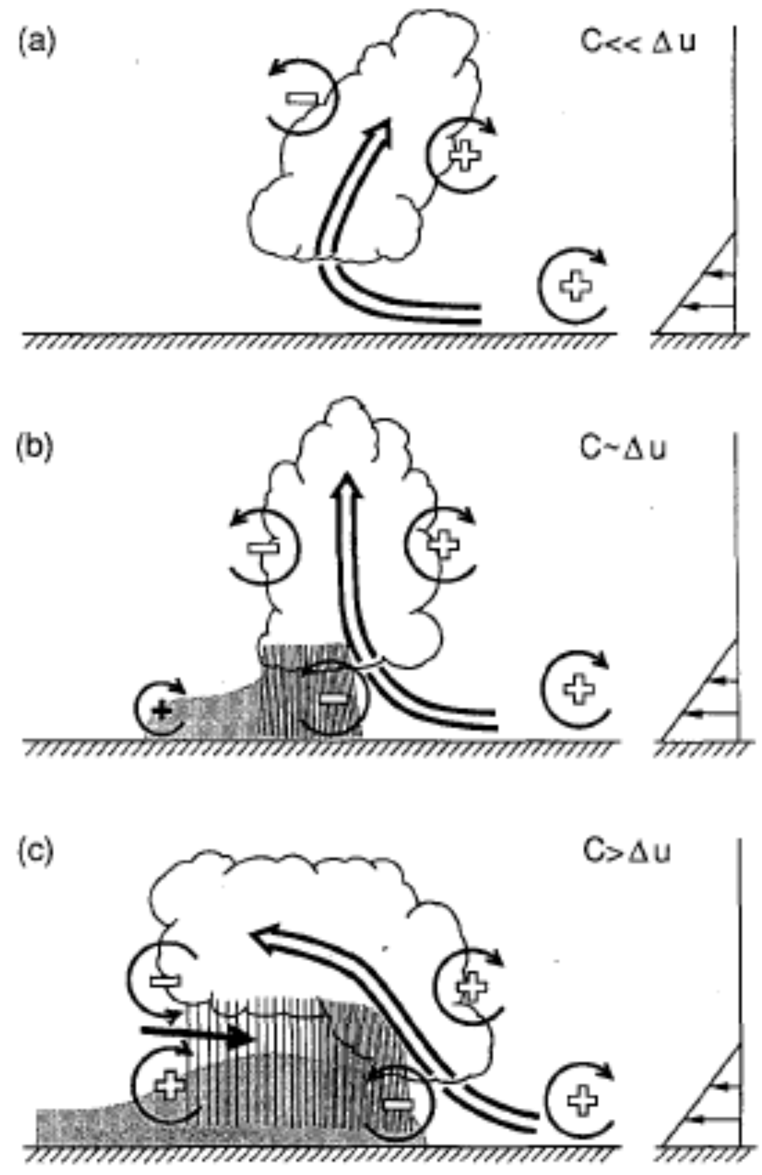
$$C^2 = -2\int_0^h B\,dz$$

where

$$B = g\frac{(\theta-\theta_0)}{\theta_0} + 0.61g(q_v - q_{v0})$$

Intensity of environmental shear can be quantified by $\underline{\Delta u}$:

(the change in wind speed between two levels)

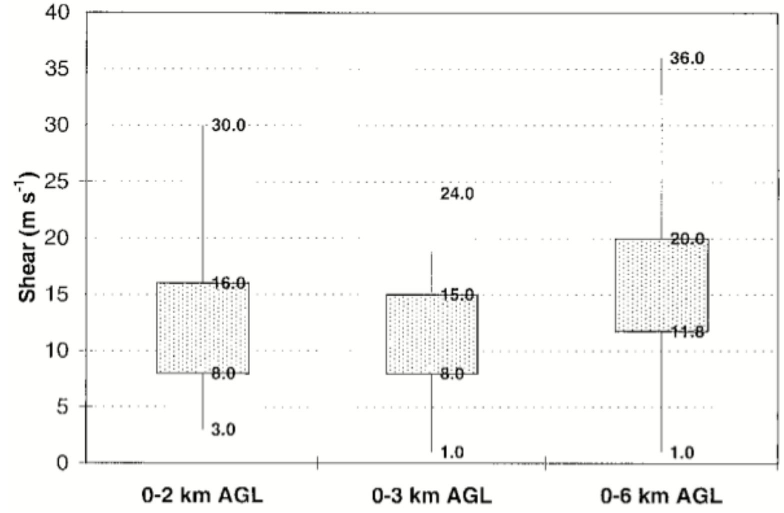


Weisman (1992)

Measurements of C and Δu

- Much is known about Δu
  - e.g., Evans and Doswell (2001):

Δu in severe MCS environment



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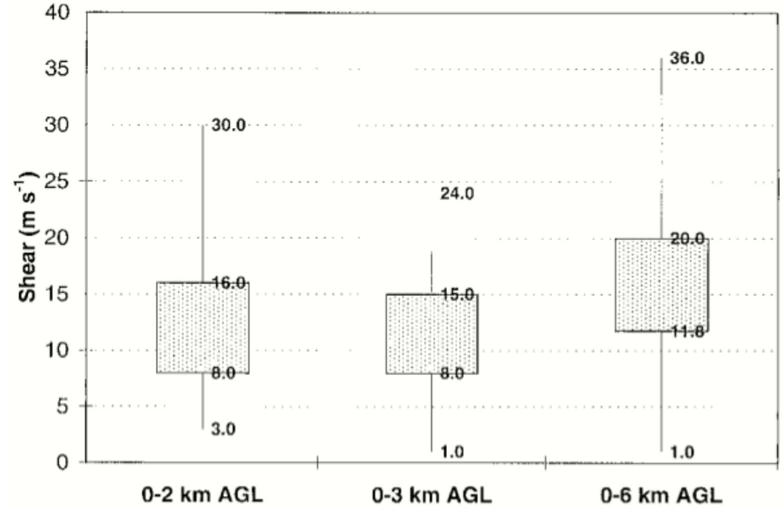
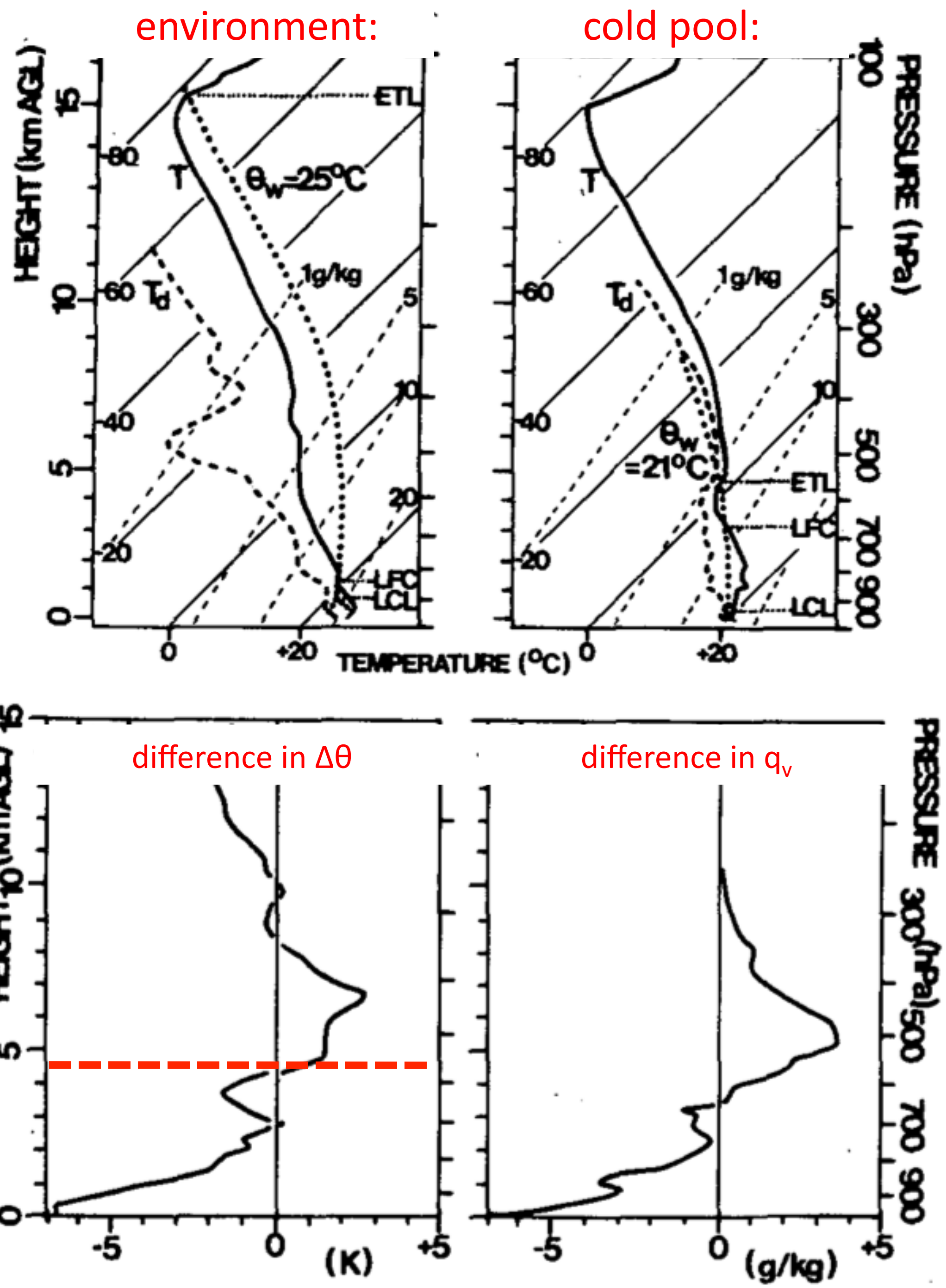


- Little is known about cold pools (C)
  - Engerer et al (2008): "knowledge of their typical characteristics is largely anecdotal"
  - Depth (h) and integrated intensity (C)
  - Requires two soundings:
    - A reference (environmental) sounding
    - A "cold pool" sounding (hazardous conditions: rain, wind)



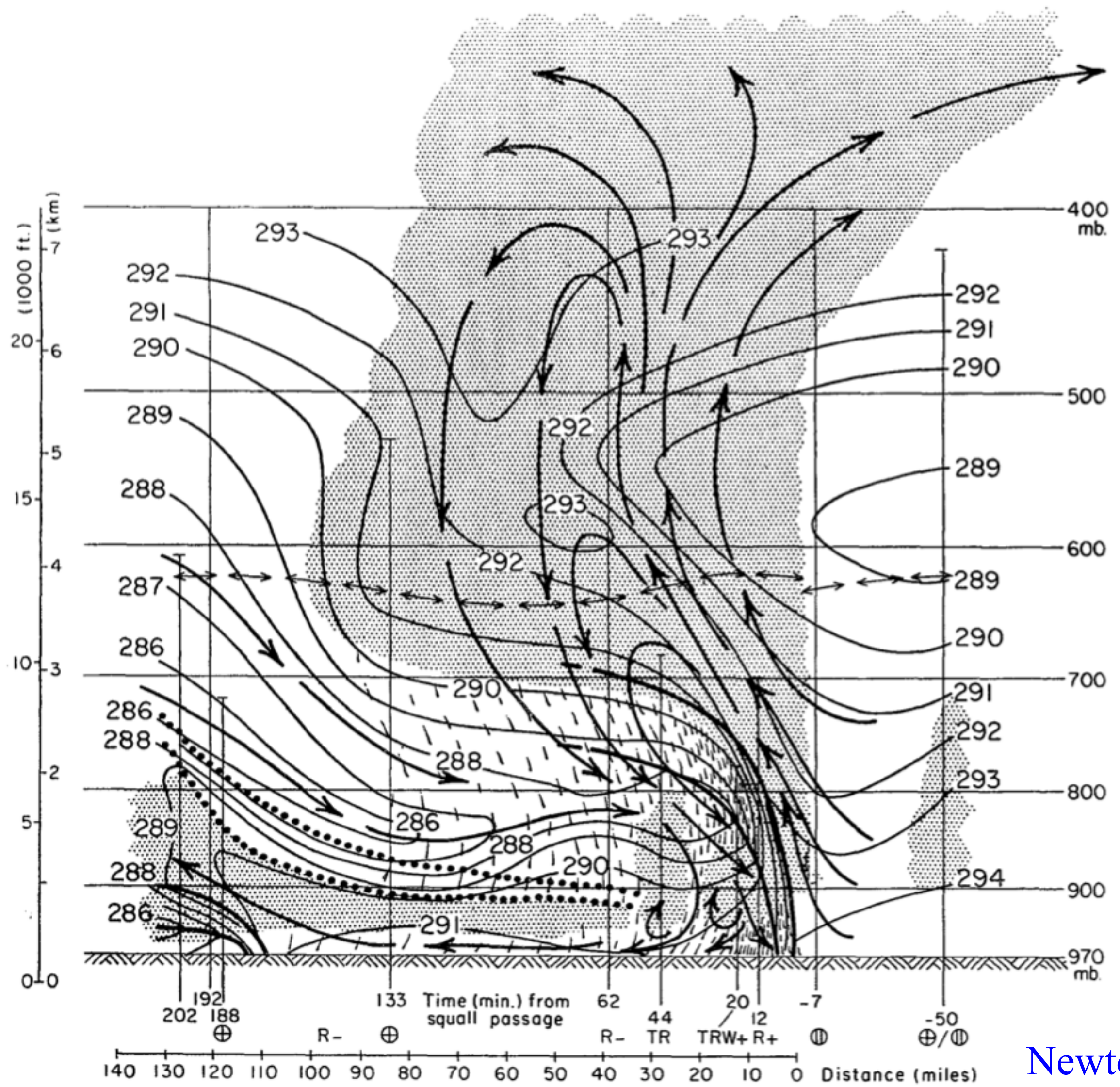
Depth of relatively
cold air: 4.5 km

Roux (1988)

Analysis of rawinsonde data (1947 Thunderstorm Project)

10 soundings in 3.4 hrs

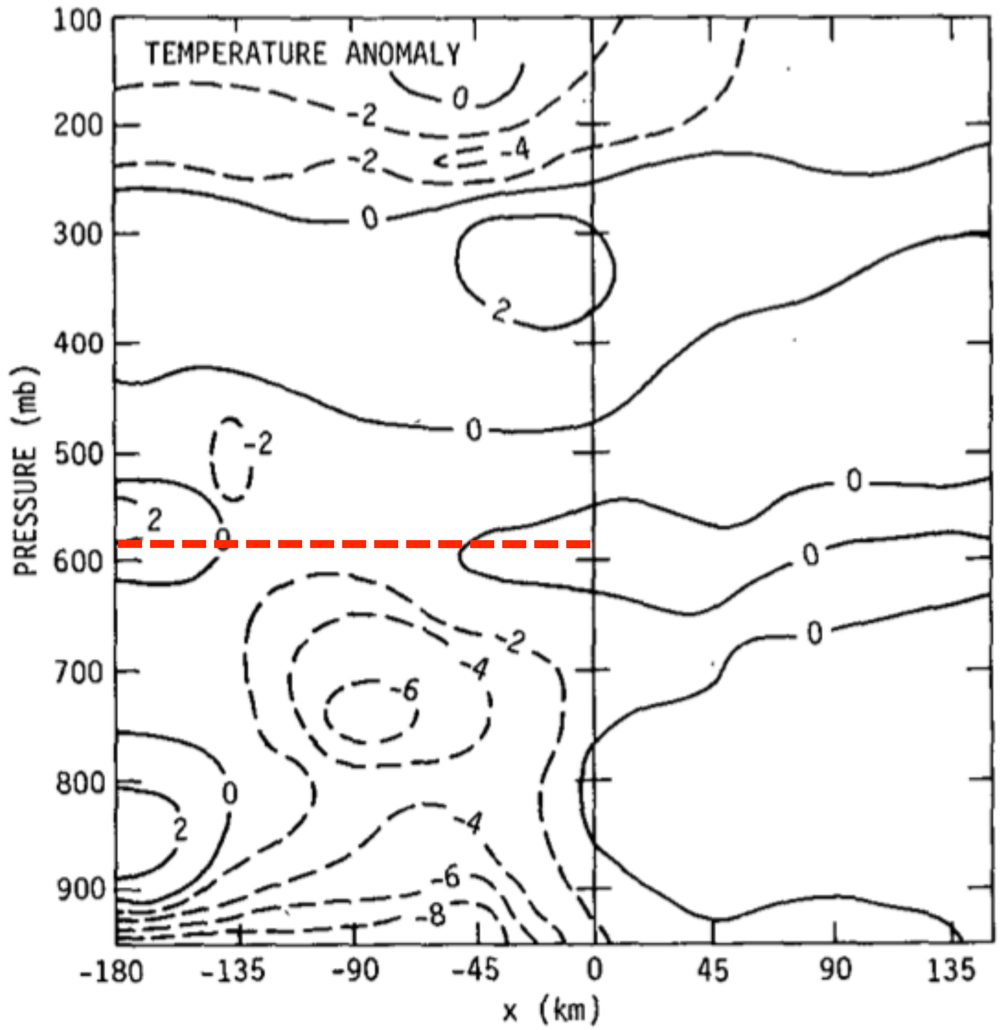
Solid contours: θ_w (wet-bulb potential temperature)



Newton and Newton (1959)

A mesoscale analysis using NSSL mesonetwork of soundings (1976)

Depth of cold air:
~4 km



Ogura and Liou (1980)

A literature review by Weisman and Rotunno (2005)

average potential temp. perturbation

depth

integrated intensity

Case study	$\overline{\Delta\Theta}$ (K)	H (km)	C (m s^{-1})
Miller and Betts (1977, their Table 2)	1.4–5.2	0.8–2.4	8.1–26.3
Ogura and Liou (1981, their Fig. 21@$x = -45$ km)	4.8	2.5	28
Smull and Houze (1987, their Figs. 6–7)	5.5	2.5	30
Roux (1988, his Fig. 1c)	3.5	2.5	24
Heymsfield and Schotz (1985, their Fig. 4)	4.1	2.5	25.8
Carbone (1982, his Fig. 17)	2.3	2.1	17.8
Fankhauser et al. (1992, their Fig. 17)	3.0	1.2	12.2

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A more thorough (and more modern) analysis is needed .....

- To better quantify the magnitude of cold pools (midlats. vs tropics)
- To evaluate/validate numerical models

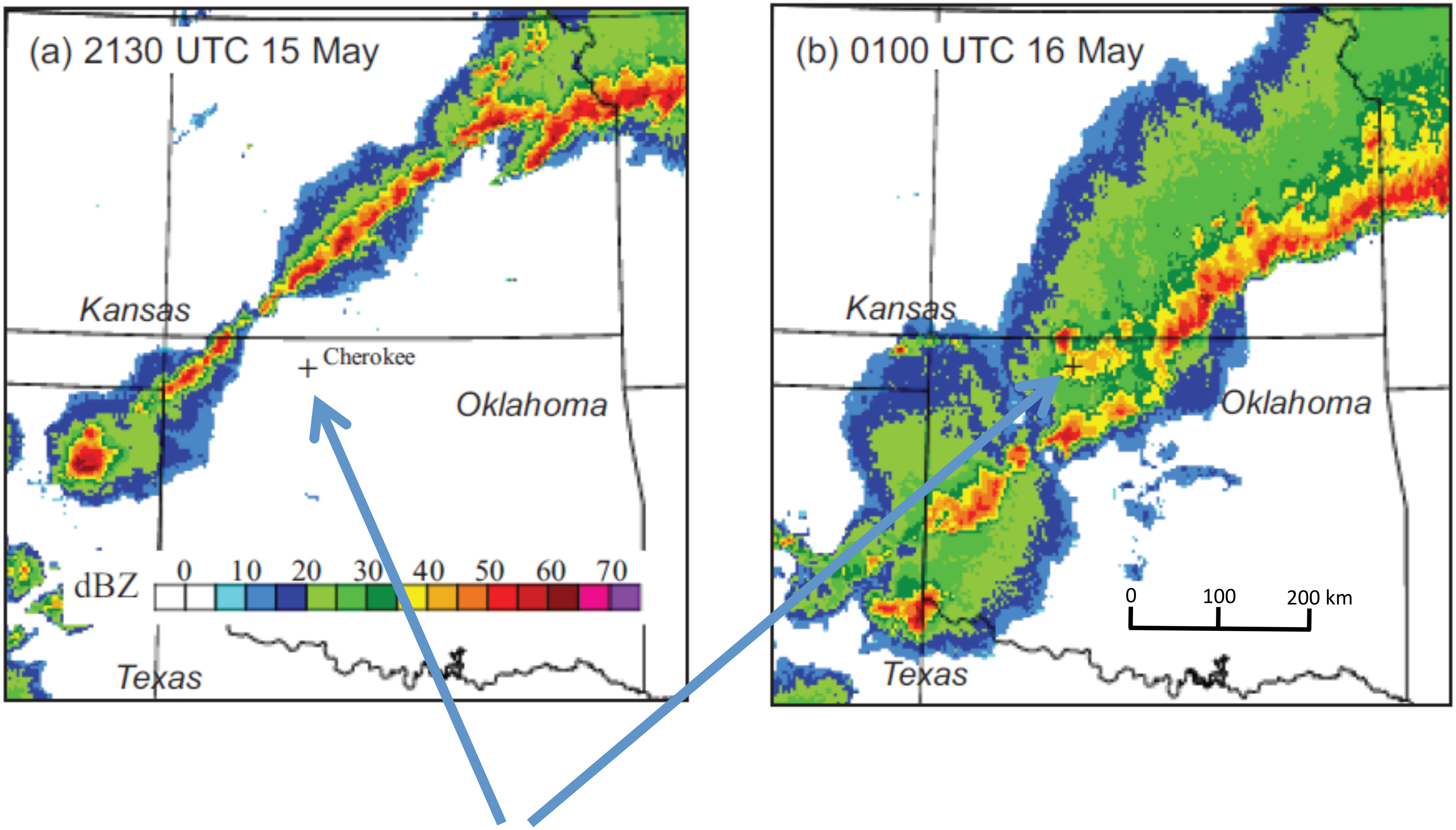
Recent Work

- BAMEX (2003): focus on MCSs and mesoscale vortices

- VORTEX2 (2009 and 2010): focus on tornadoes

Regional Reflectivity Composite

at beginning of data collection: at end of data collection:



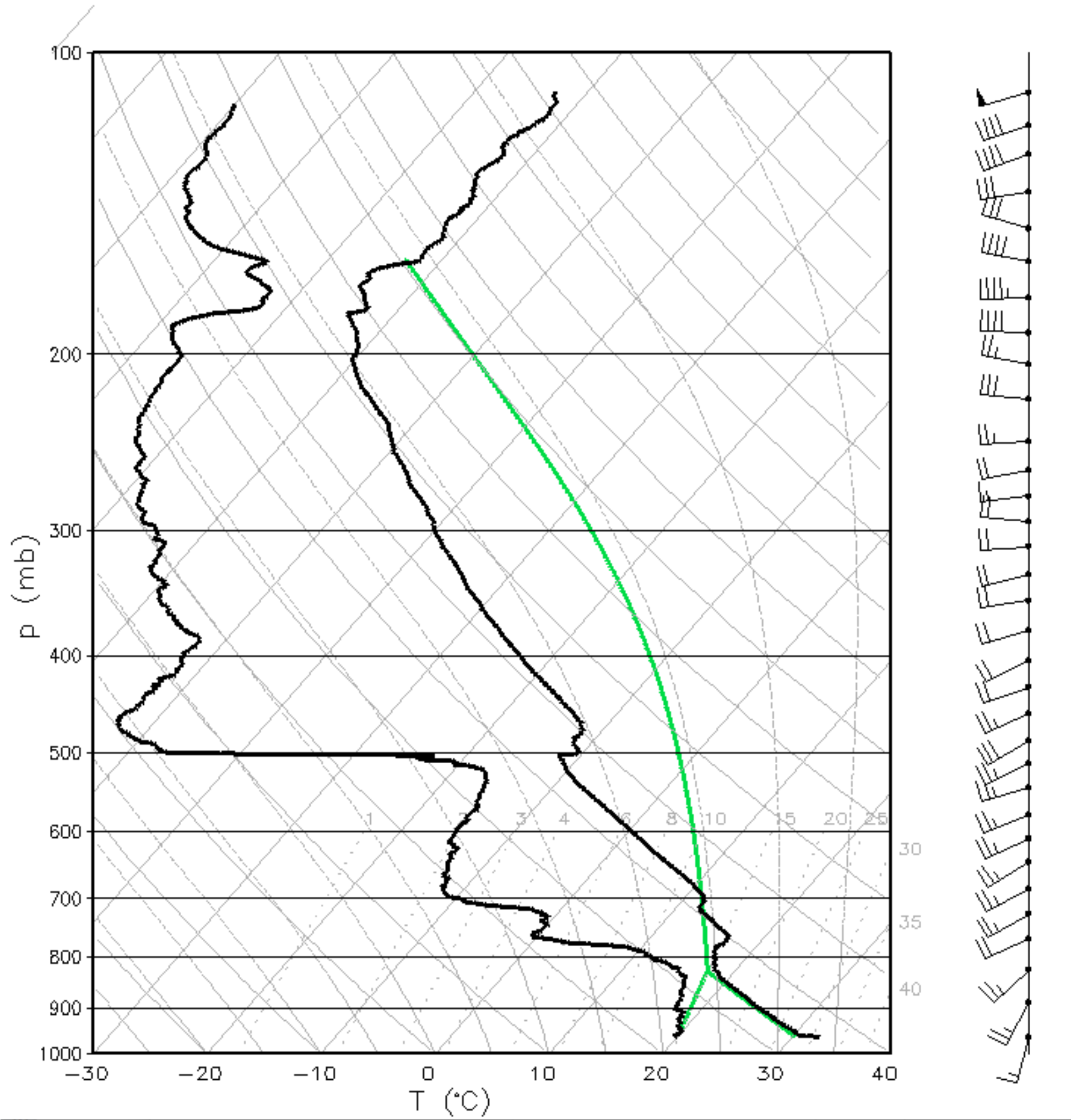
location of data collection (Cherokee, OK)

Summary of Sounding Data

- 9 soundings in 3 hours
  - 8 from Cherokee, OK (serial launches)
  - 30 minute frequency before squall line
  - 15 minute frequency after squall line
- First sounding:
  - about 106 km ahead of gust front (x_c = +106 km)
- Final sounding:
  - about 74 km behind gust front (x_c = -74 km)
- Details:
  - Vaisala RS92 (GPS winds)
  - Nominal balloon ascent rate: 5 m s^{-1}

for more details: Bryan and Parker (2010, MWR)

S1 (first sounding): x_c = +106 km



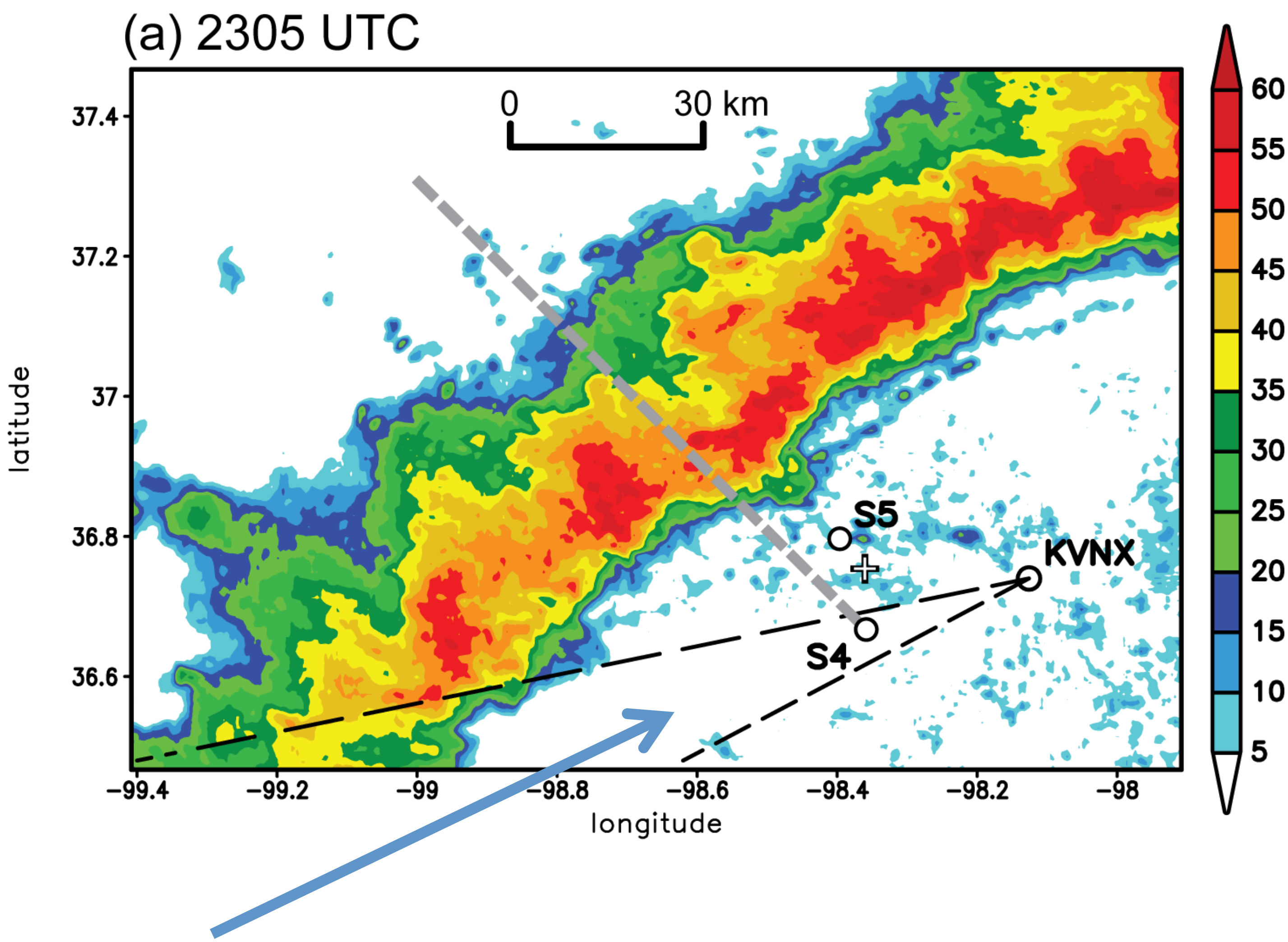
CAPE = 4200 J kg^{-1}

CIN = 8 J kg^{-1}

Δu (0.5 – 2 km) = 10 m s^{-1}

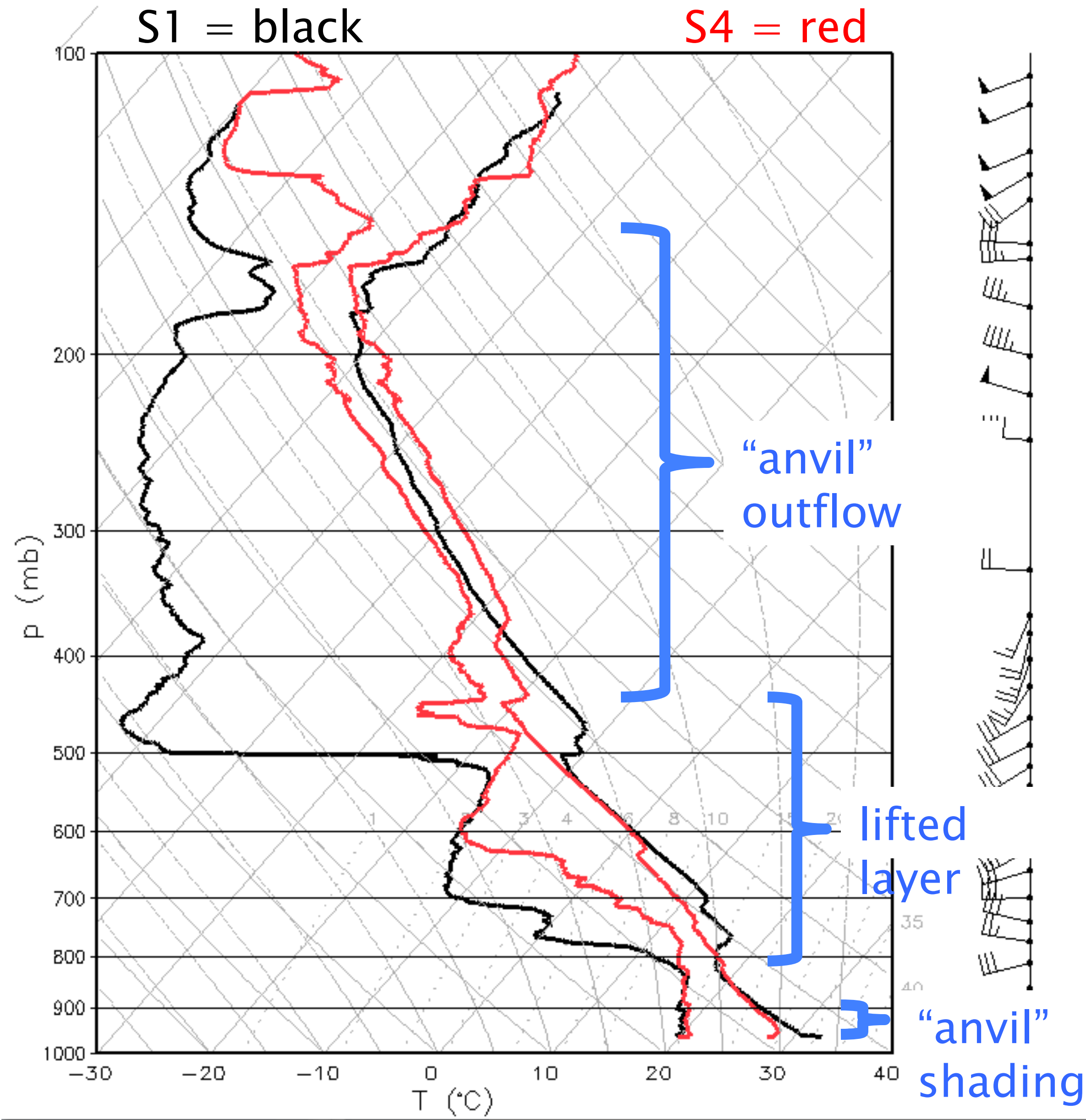
Δu (0.5 – 10 km) = 10 m s^{-1}

KVNX, lowest elevation (0.5°)

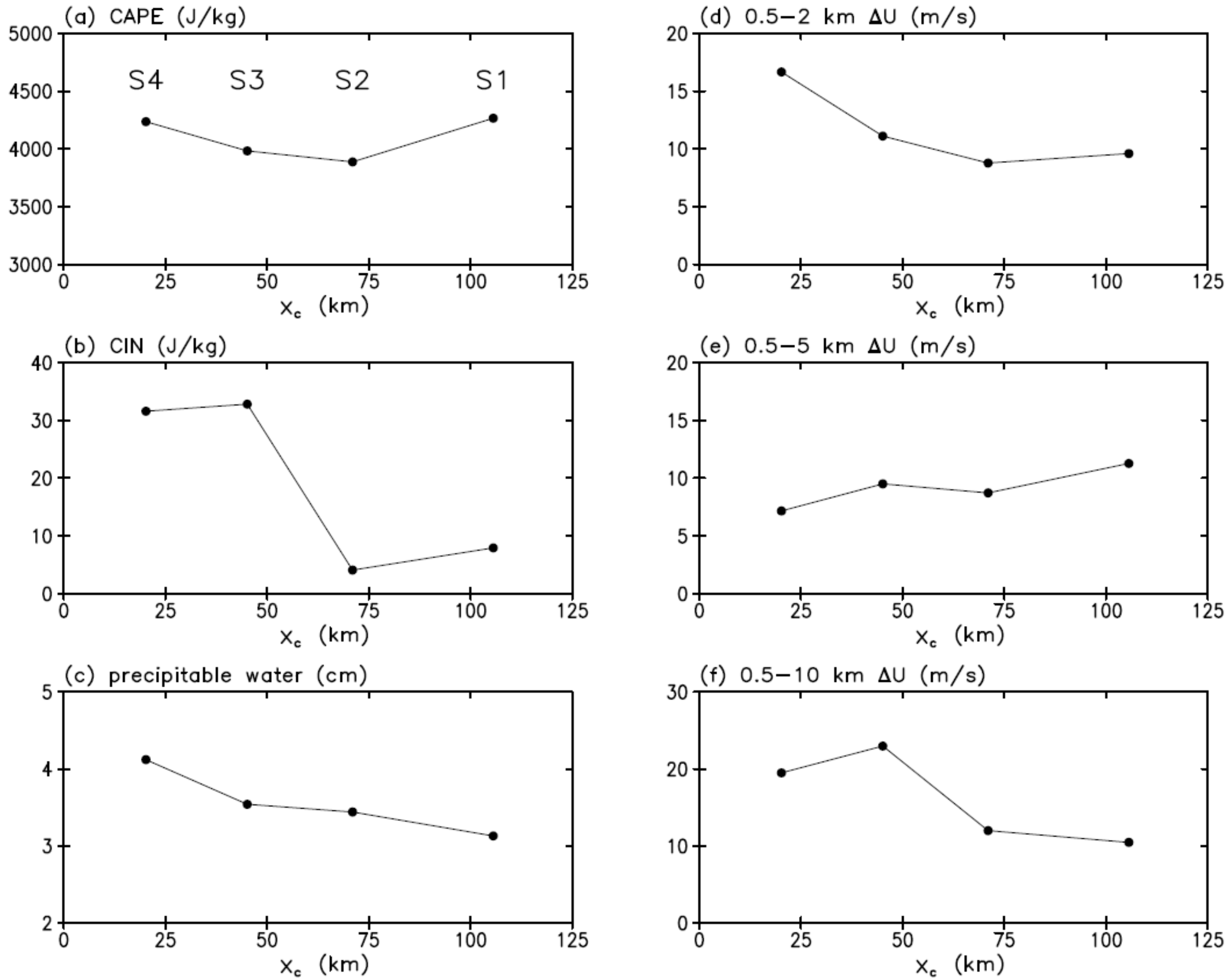


(region of partial beam blockage)

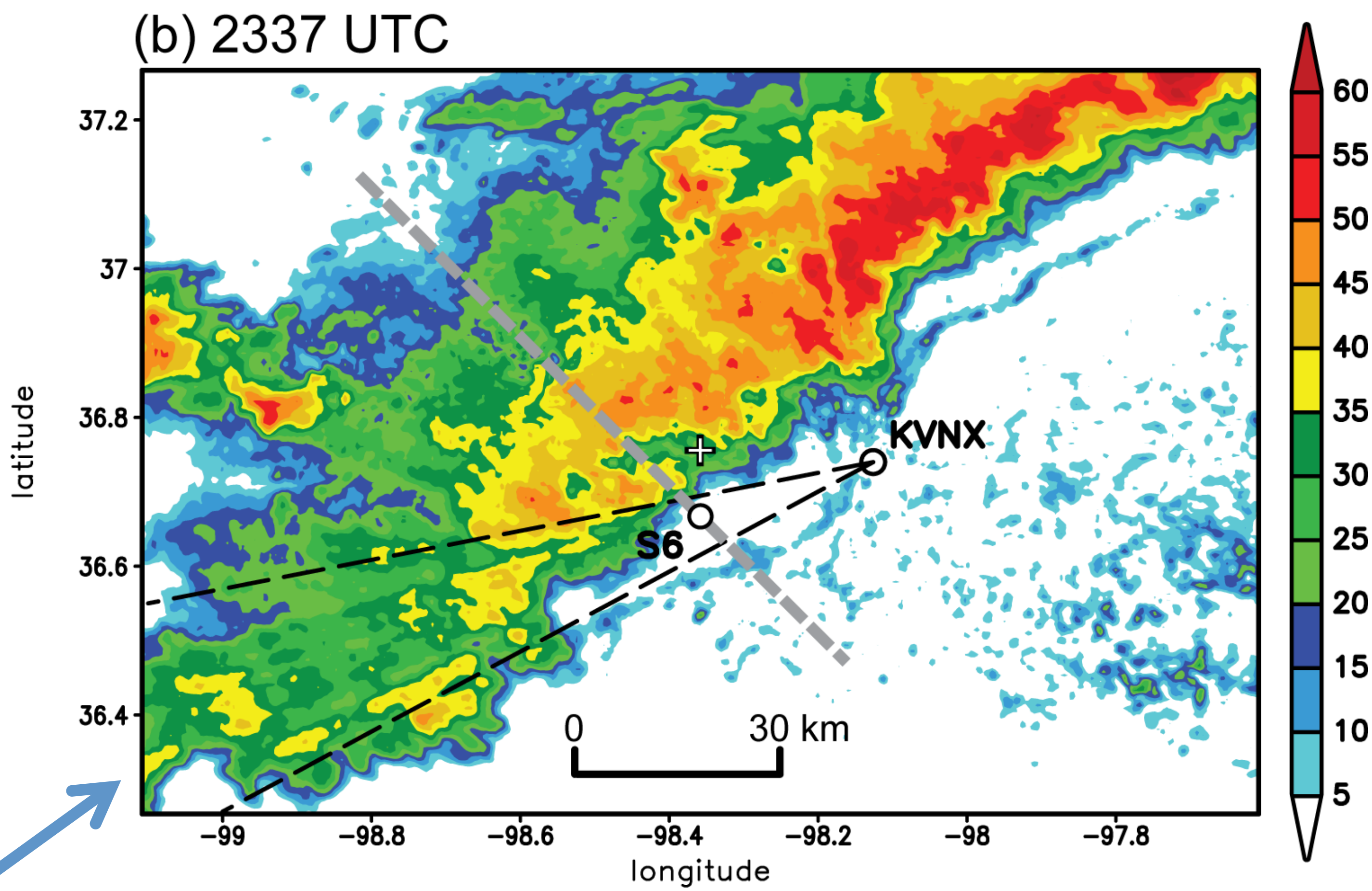
S1 (+106 km) and S4 (+20 km)



Evolution of pre-storm environment



KVNX, lowest elevation (0.5°)

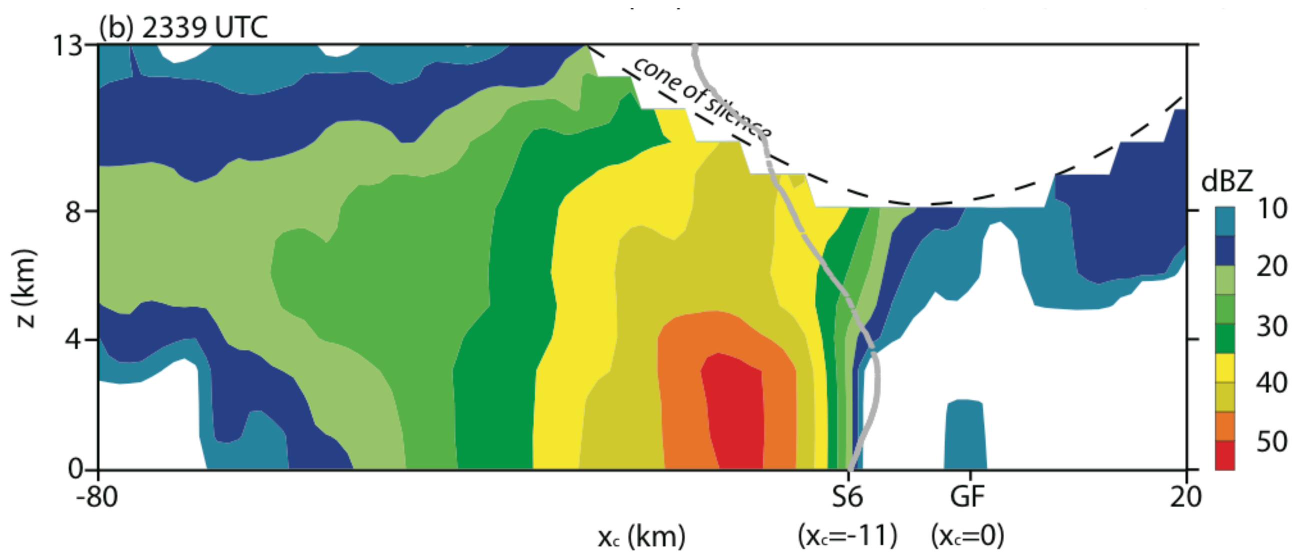


(region of partial beam blockage)

S6: “cold pool” sounding

Radar analysis (normal to line)

Gray line is sounding trajectory



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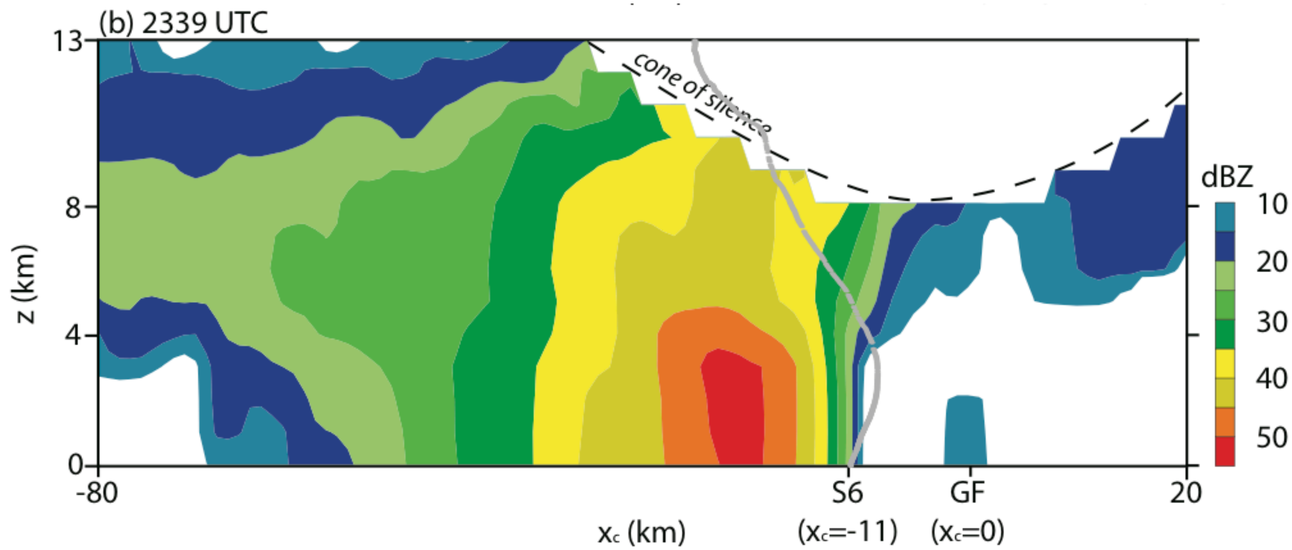
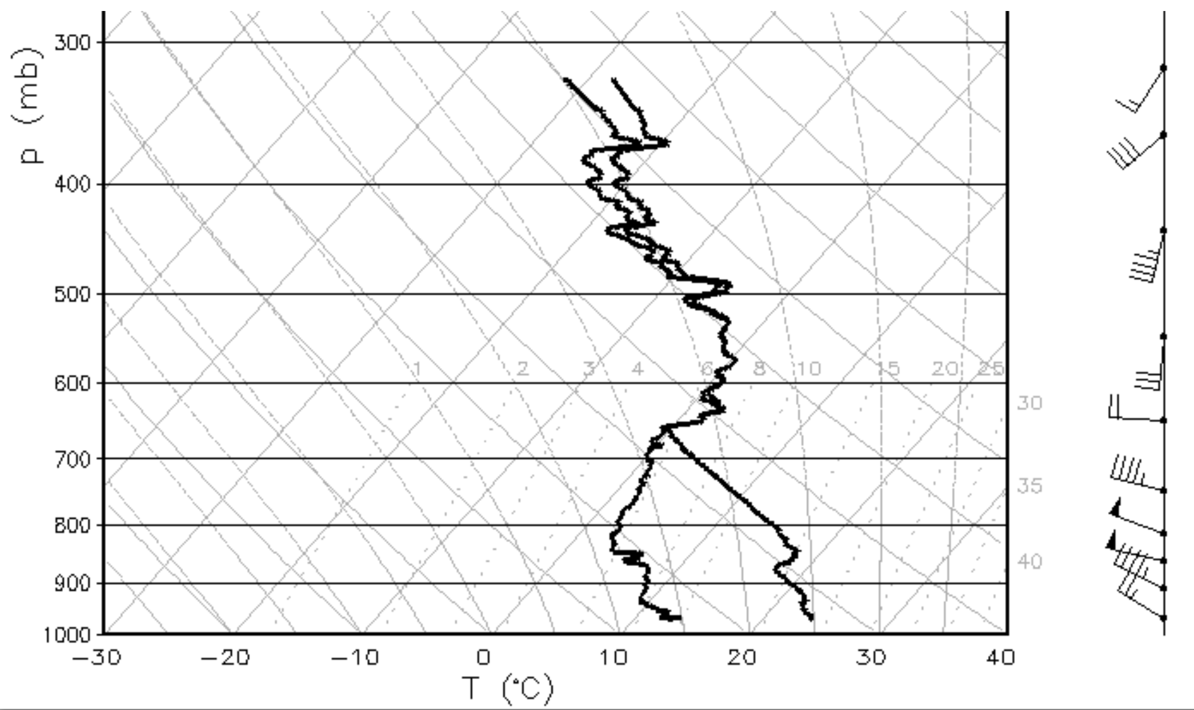
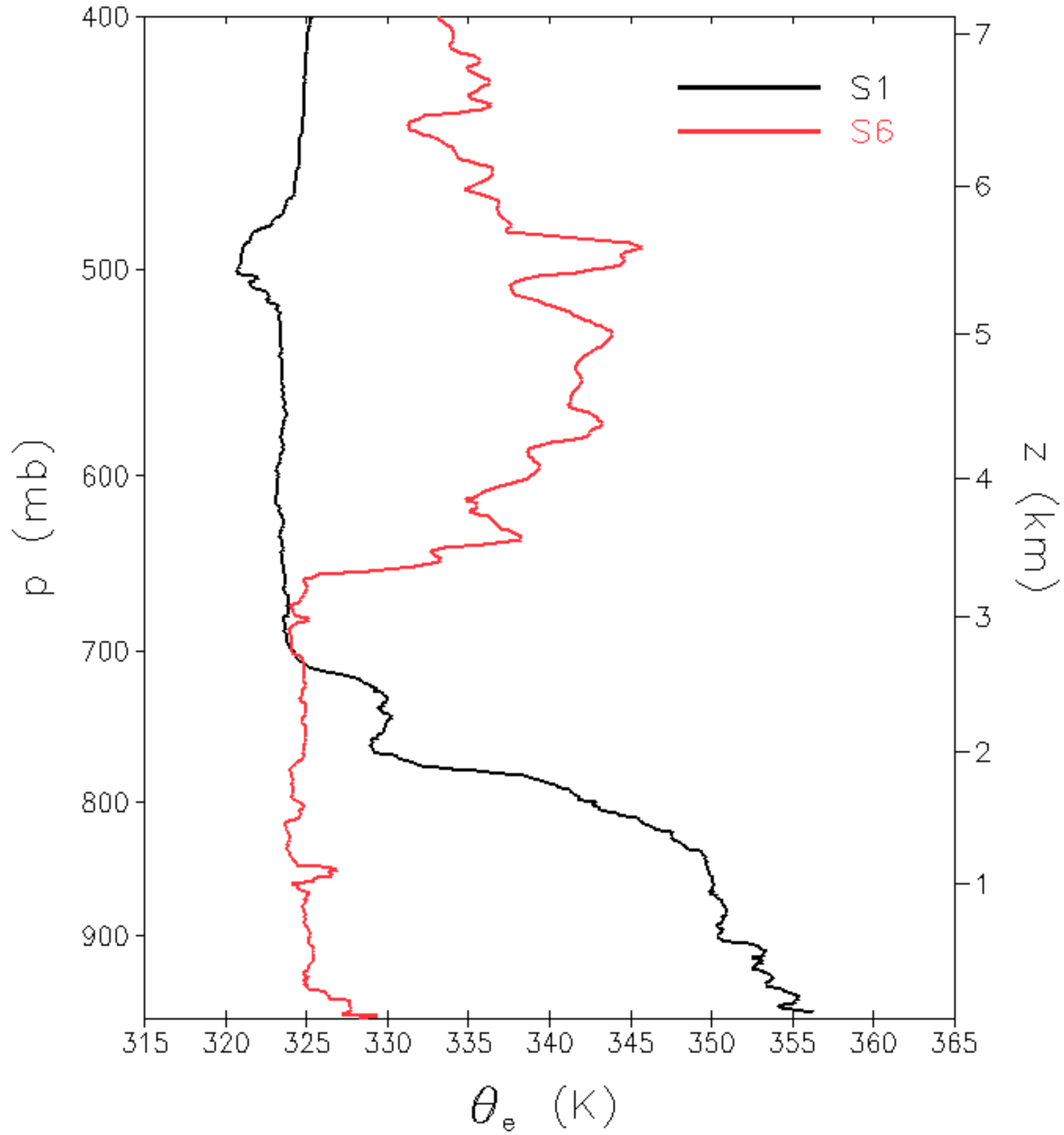


S6 data on skew-T diagram:



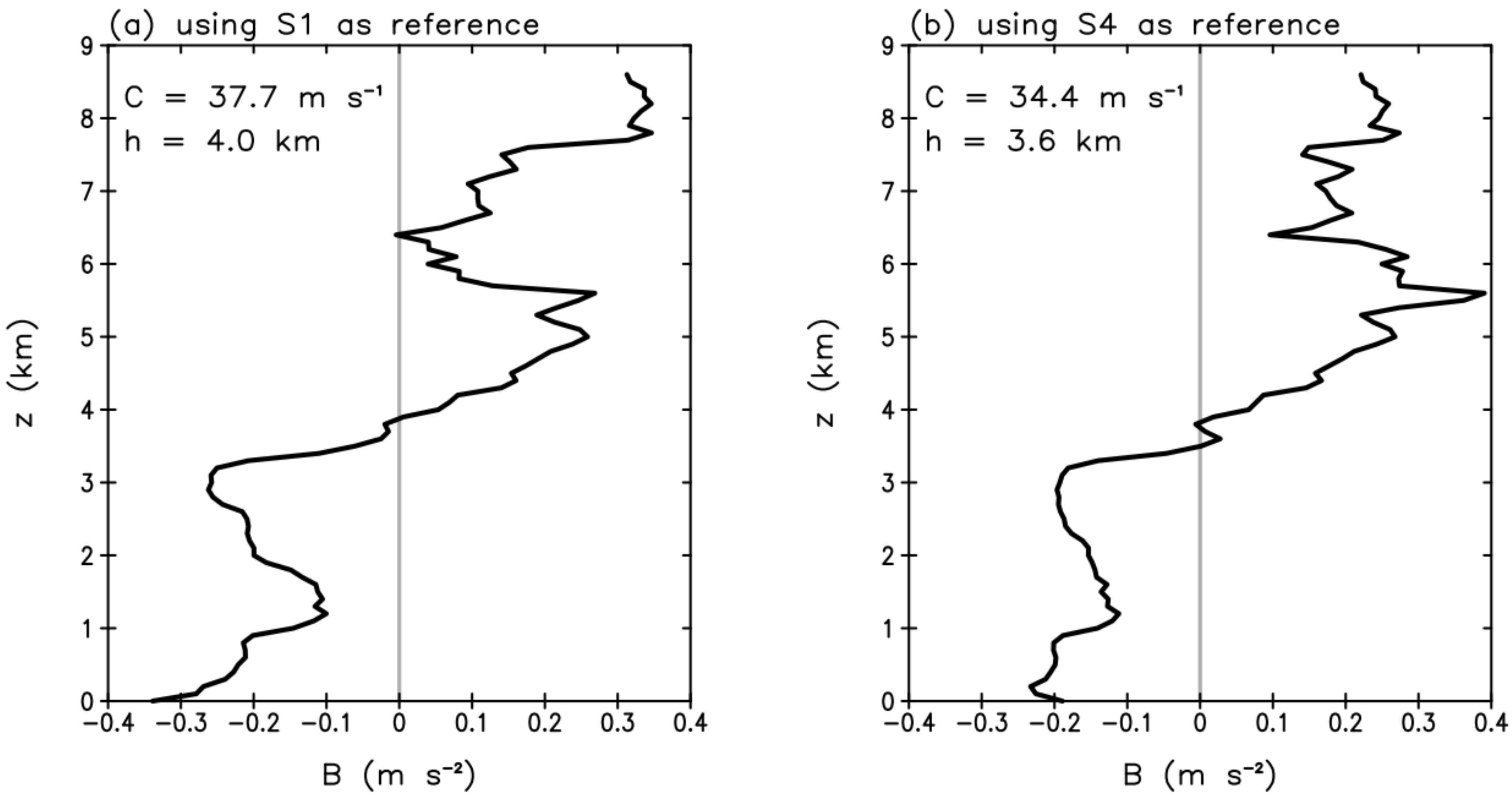
Vertical profiles of equivalent potential temperature (θ_e)



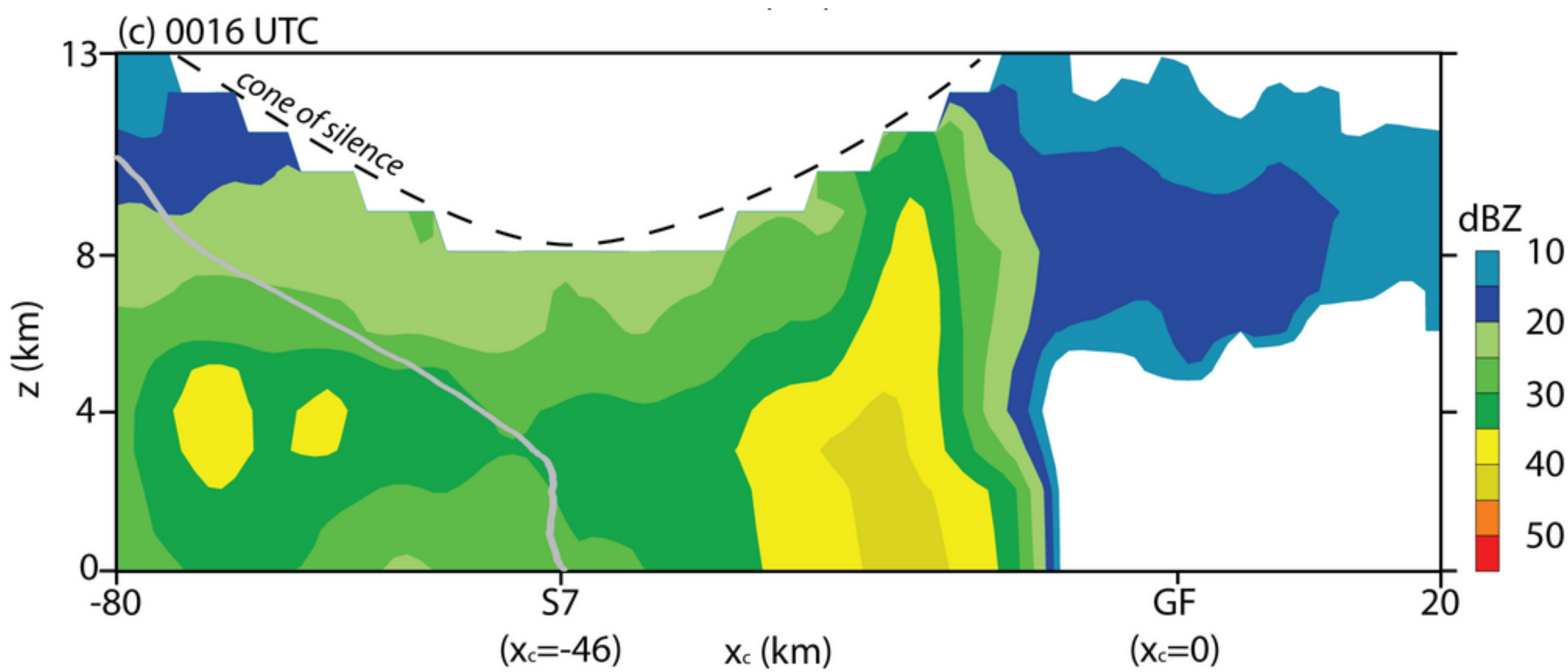
Vertical profiles of buoyancy (B) from S6:

$$B = g\frac{(\theta - \theta_0)}{\theta_0} + 0.61g(q_v - q_{v0})$$

$$C^2 = -2\int_0^h B\, dz$$



Radar analysis: trailing stratiform region

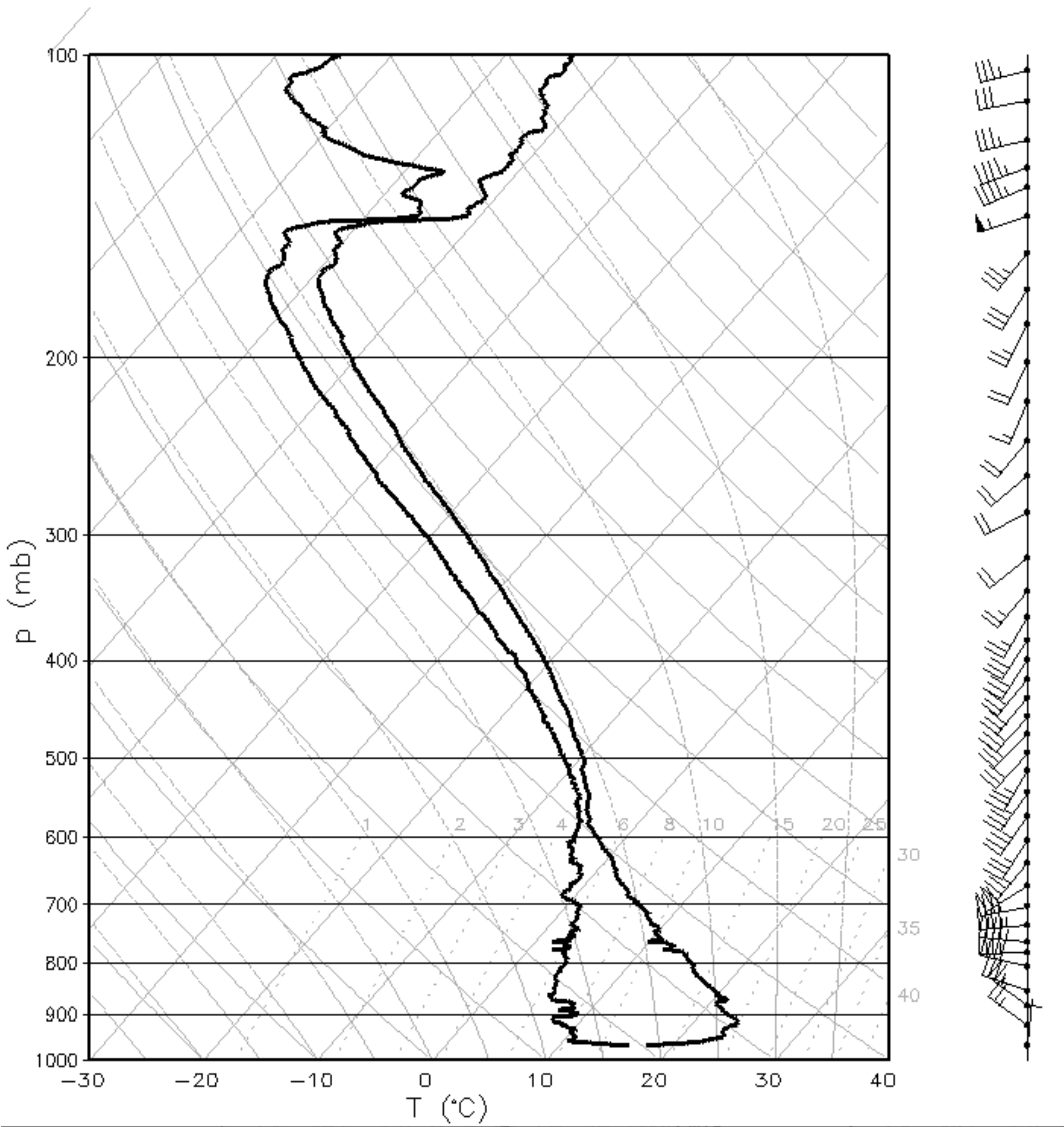


stratiform region

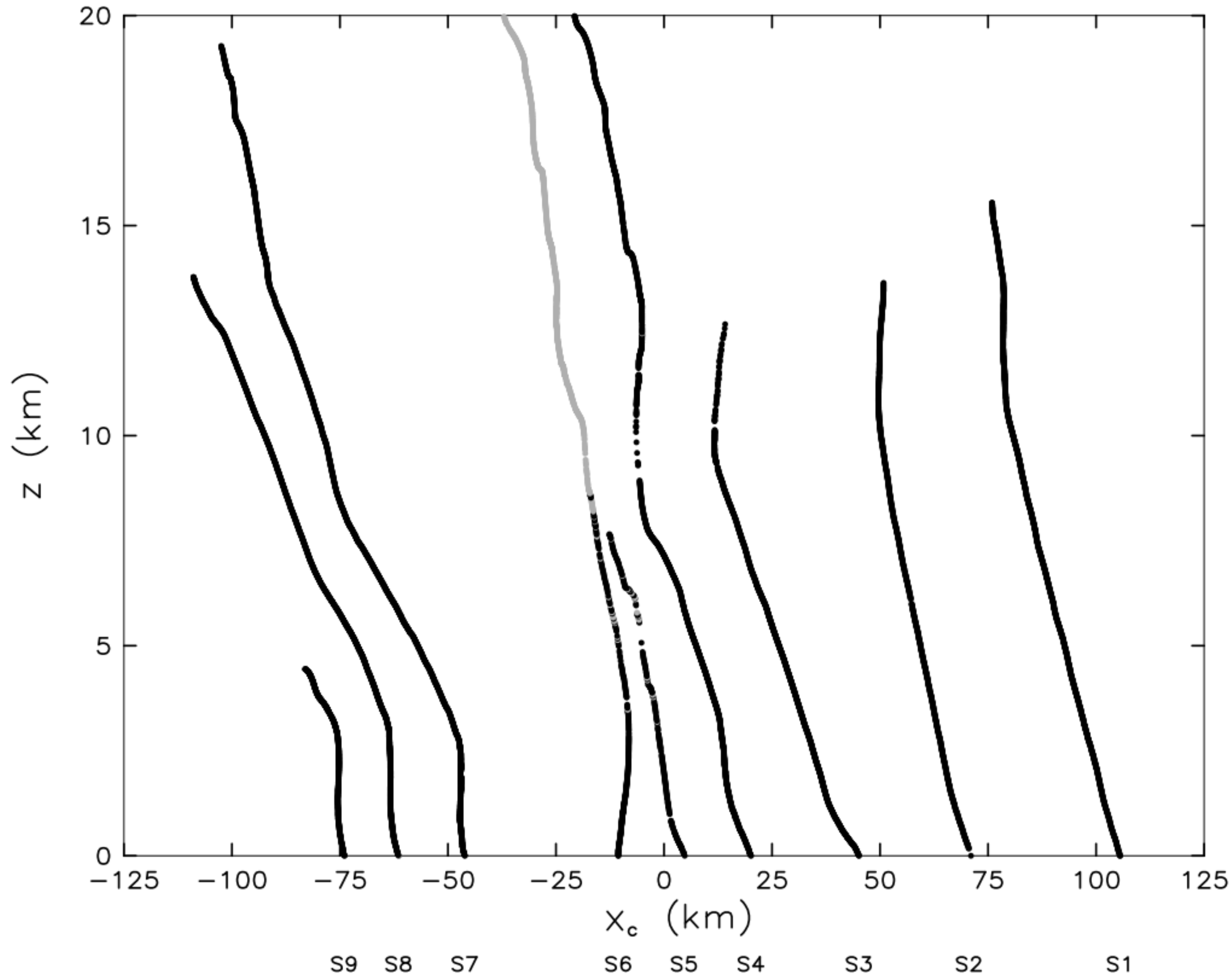
convective region

S7 (x_c = -46 km)

(trailing stratiform region)

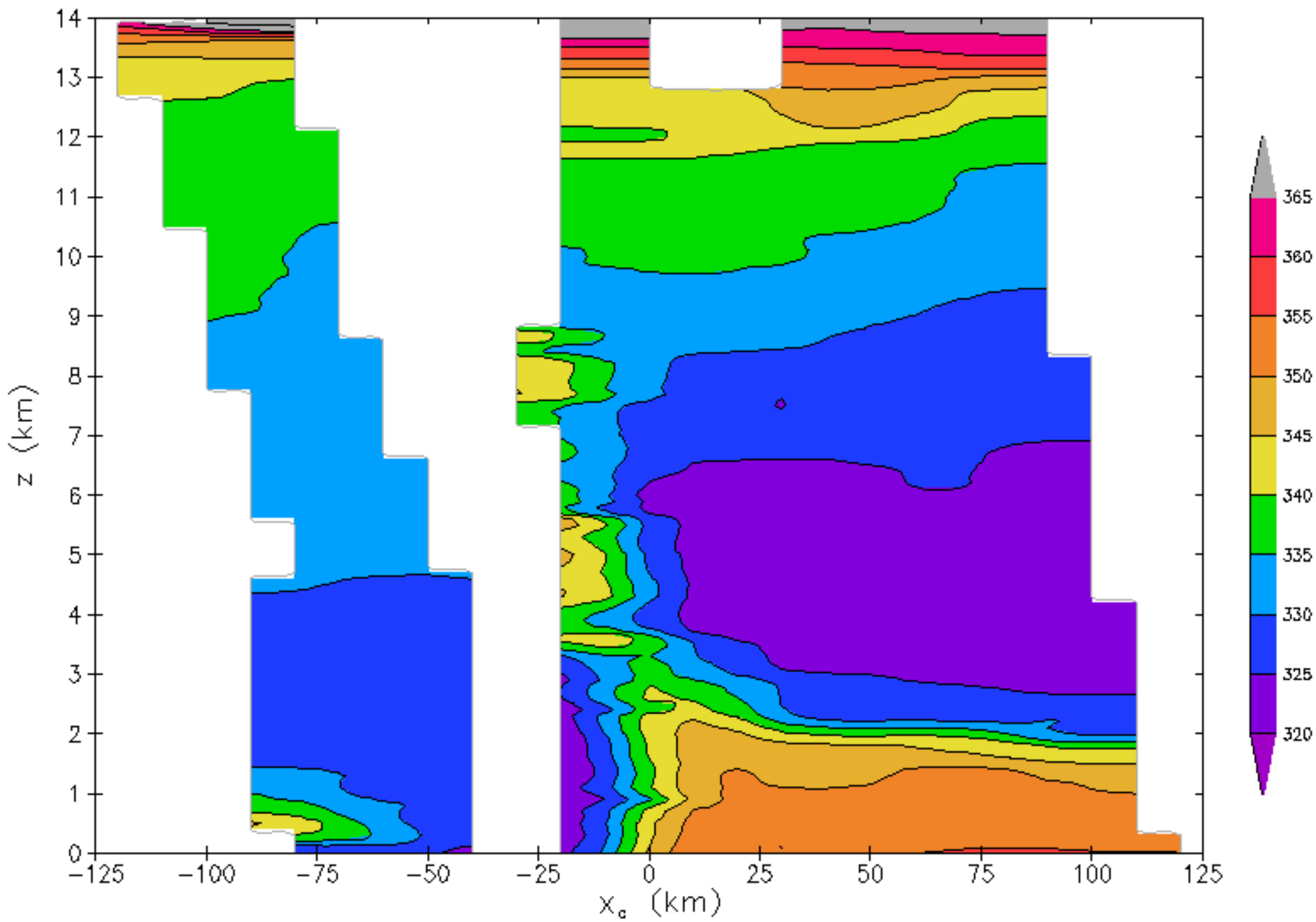


System-relative location of *all* sounding data

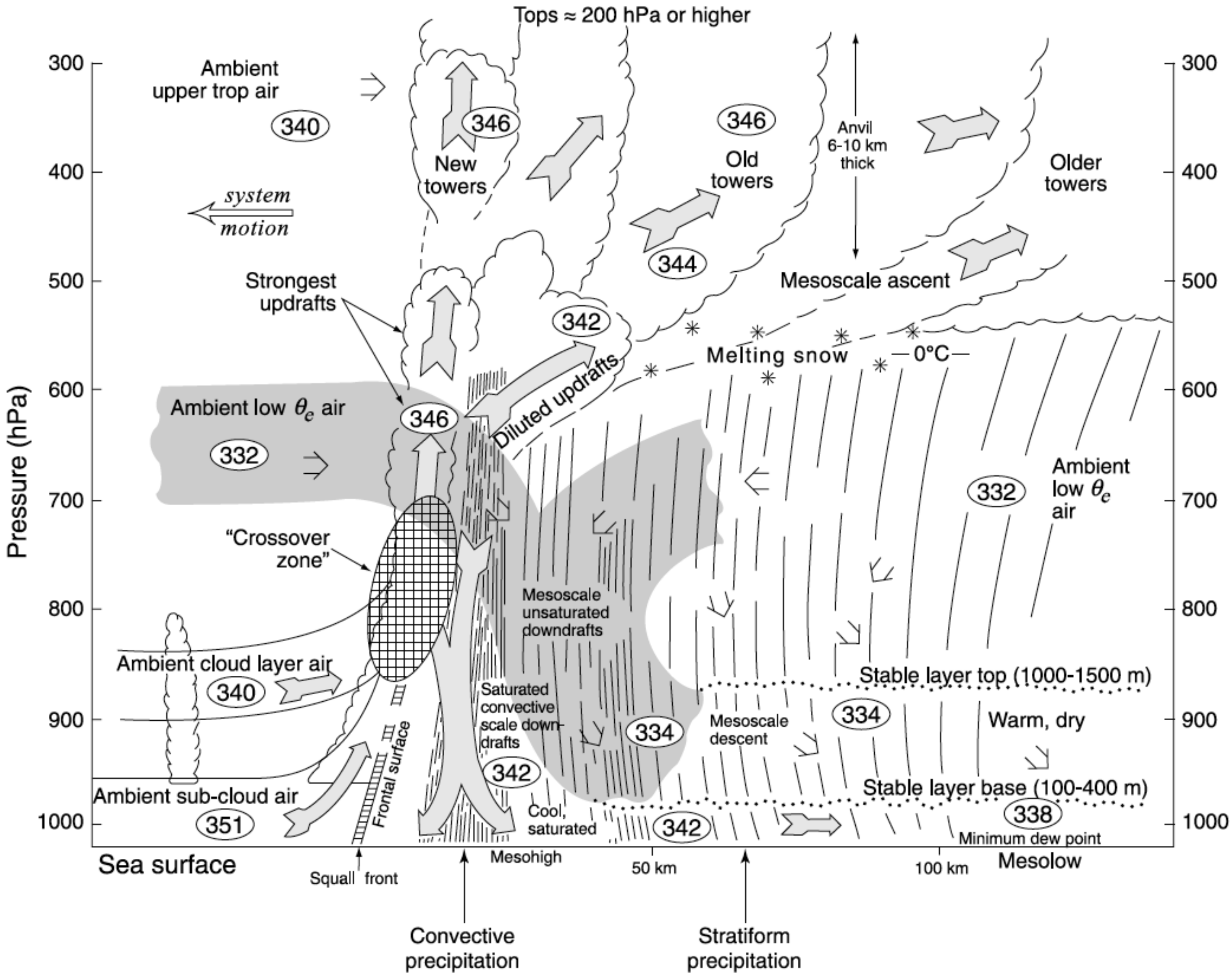


Mesoscale analysis: 2-pass Barnes method with $\Delta x = 10$ km, $\Delta z = 100$ m

Analysis of equivalent potential temperature θ_e (K)

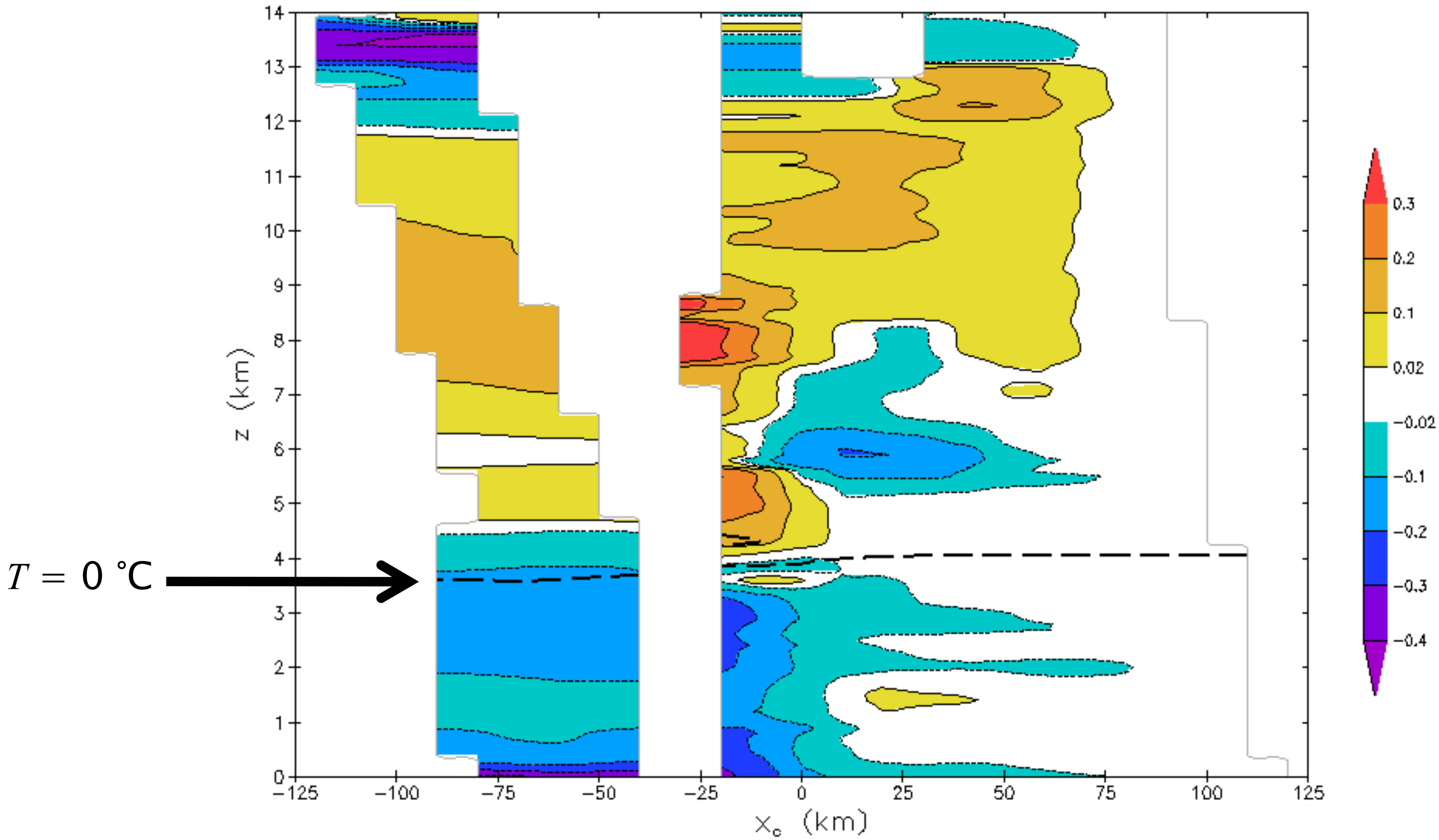


Conceptual model of tropical MCSs



Zipser (1977), adapted by Houze (2004)

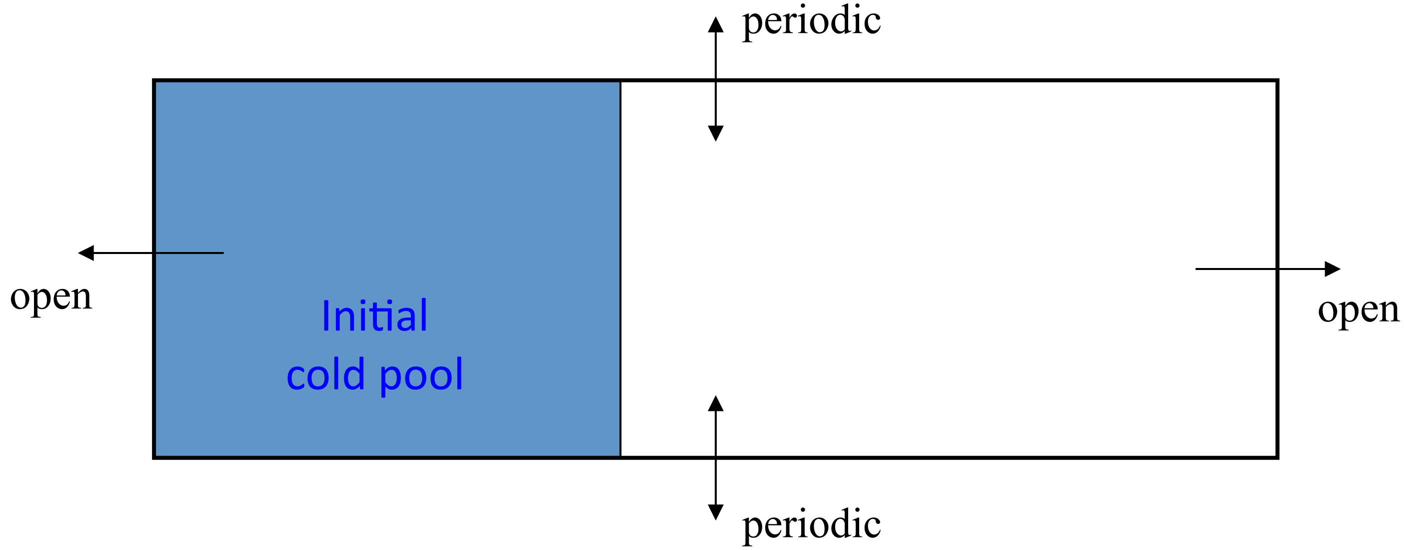
Analysis of buoyancy B (m s^{-2})



Numerical Simulations

- Numerical model: CM1 (nonhydrostatic, same numerics as WRF)
  http://www.mmm.ucar.edu/people/bryan/cm1/
- Horizontal grid spacing (Δx): 4 km, 1 km, or 0.25 km
- Vertical grid spacing (Δz): varies from 100 m at z=0 to 400 m at z=25km
- Initialized using environment of the 15 May 2009 MCS

Domain: 576 km x 144 km

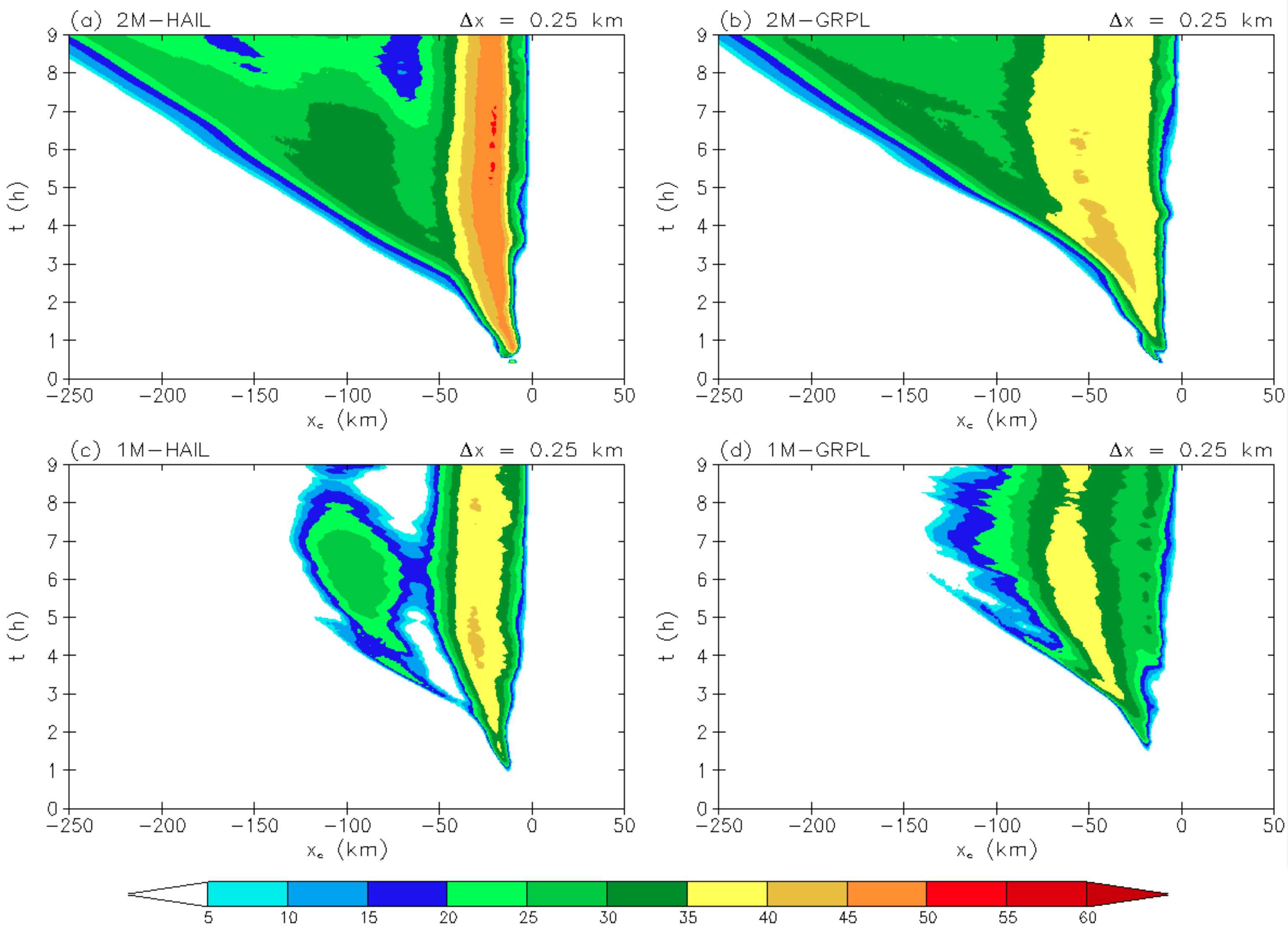


Numerical Simulations

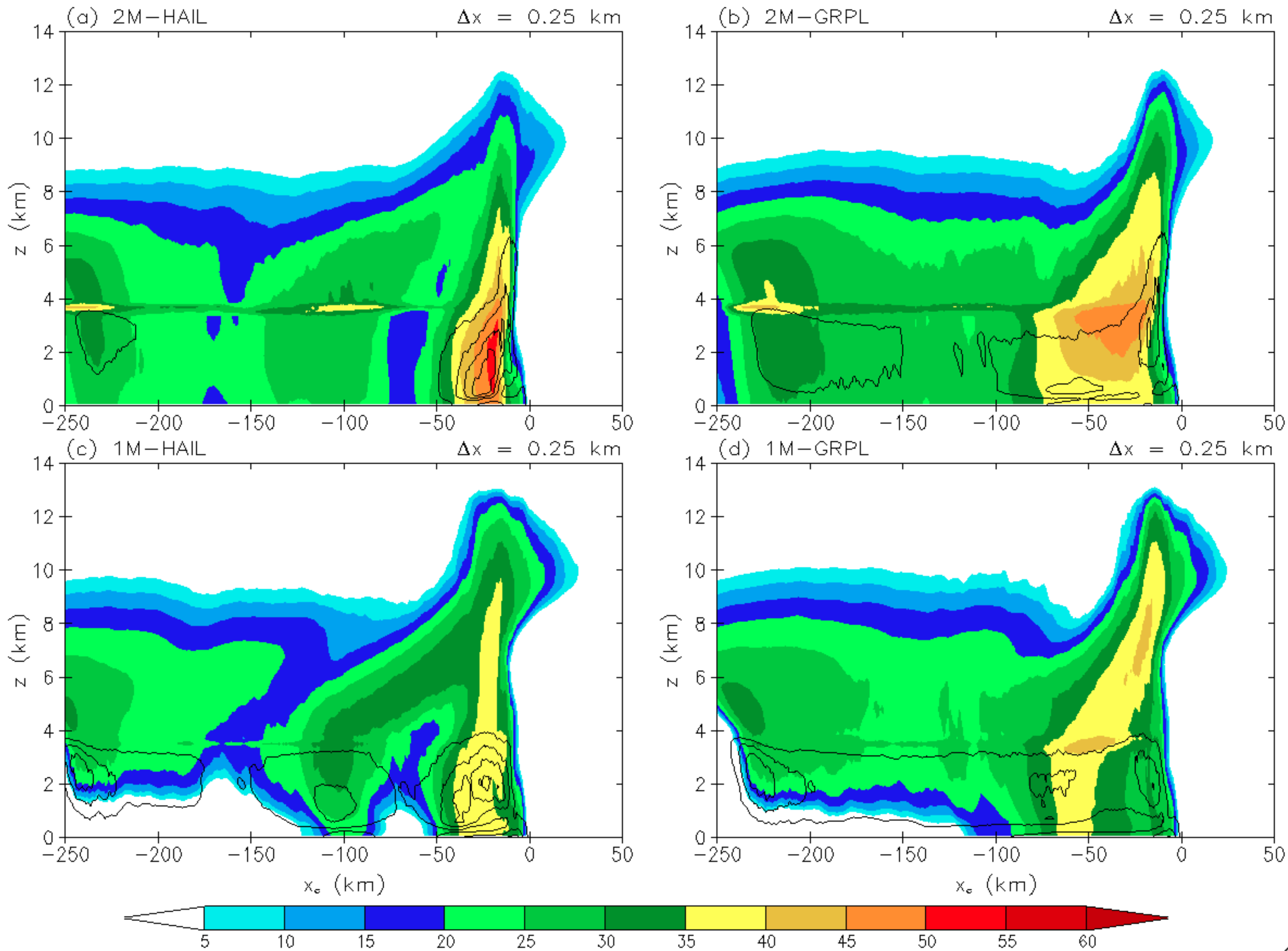
- Microphysics parameterization: Morrison et al. (2009)
  - Species: cloud water, rain water, ice crystals, snow, and graupel/hail
    - GRPL = graupel, HAIL = hail
  - Single-moment scheme (1M):
    - Only total mass is predicted
    - Total number and size distribution are *specified*
  - Double-moment scheme (2M):
    - Predicts total mass *and* total number of each microphysical species
    - (size distribution is still parameterized)
  - Estimated reflectivity is obtained by integration of drop size distributions, assuming 10-cm wavelength radar

for more details: Bryan and Morrison (2011, MWR, in press)

Hovmoller diagrams: reflectivity at surface

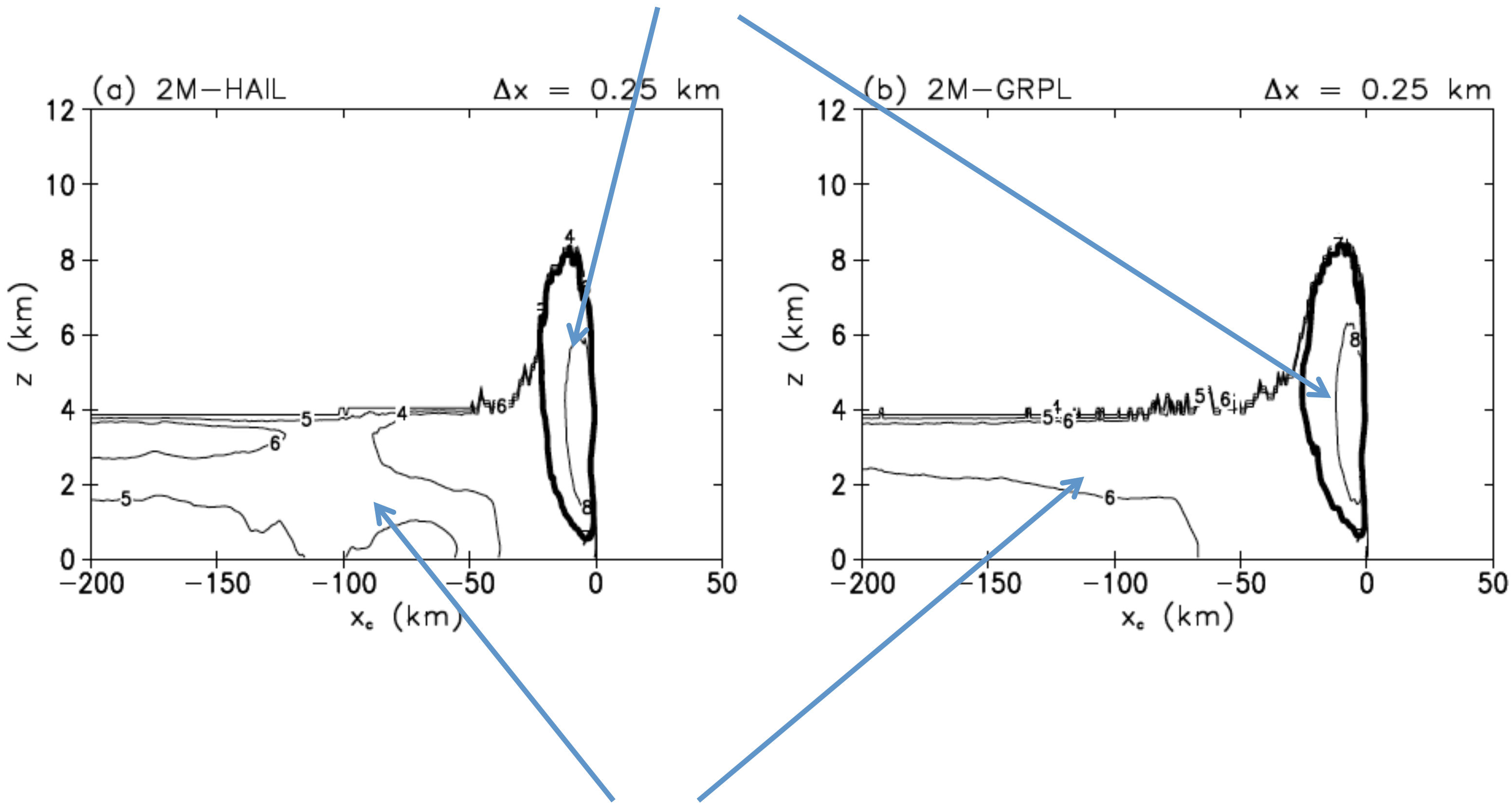


Vertical cross sections: reflectivity (shaded) and evaporation rate (contour)



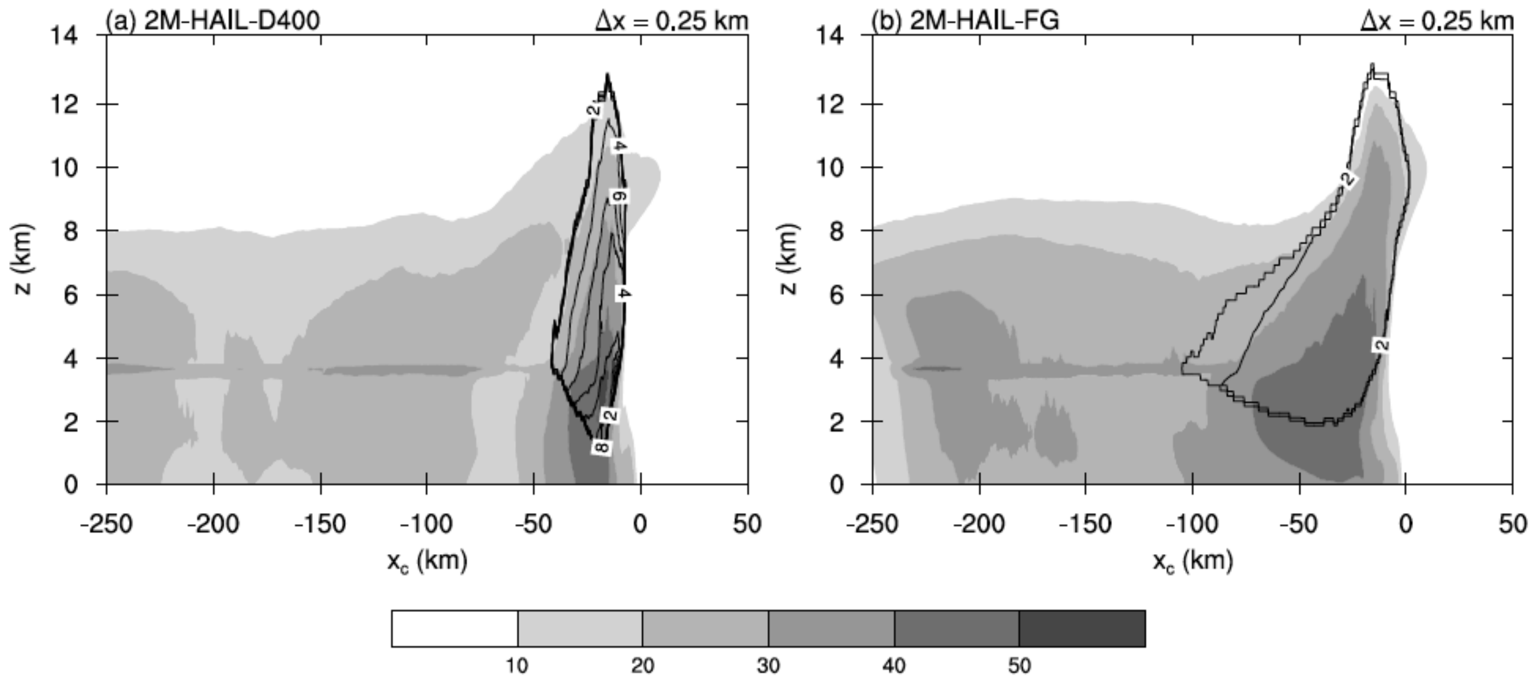
N_{0r} ($\log_{10}$ scale): intercept parameter for rain

small drops in trailing convective region



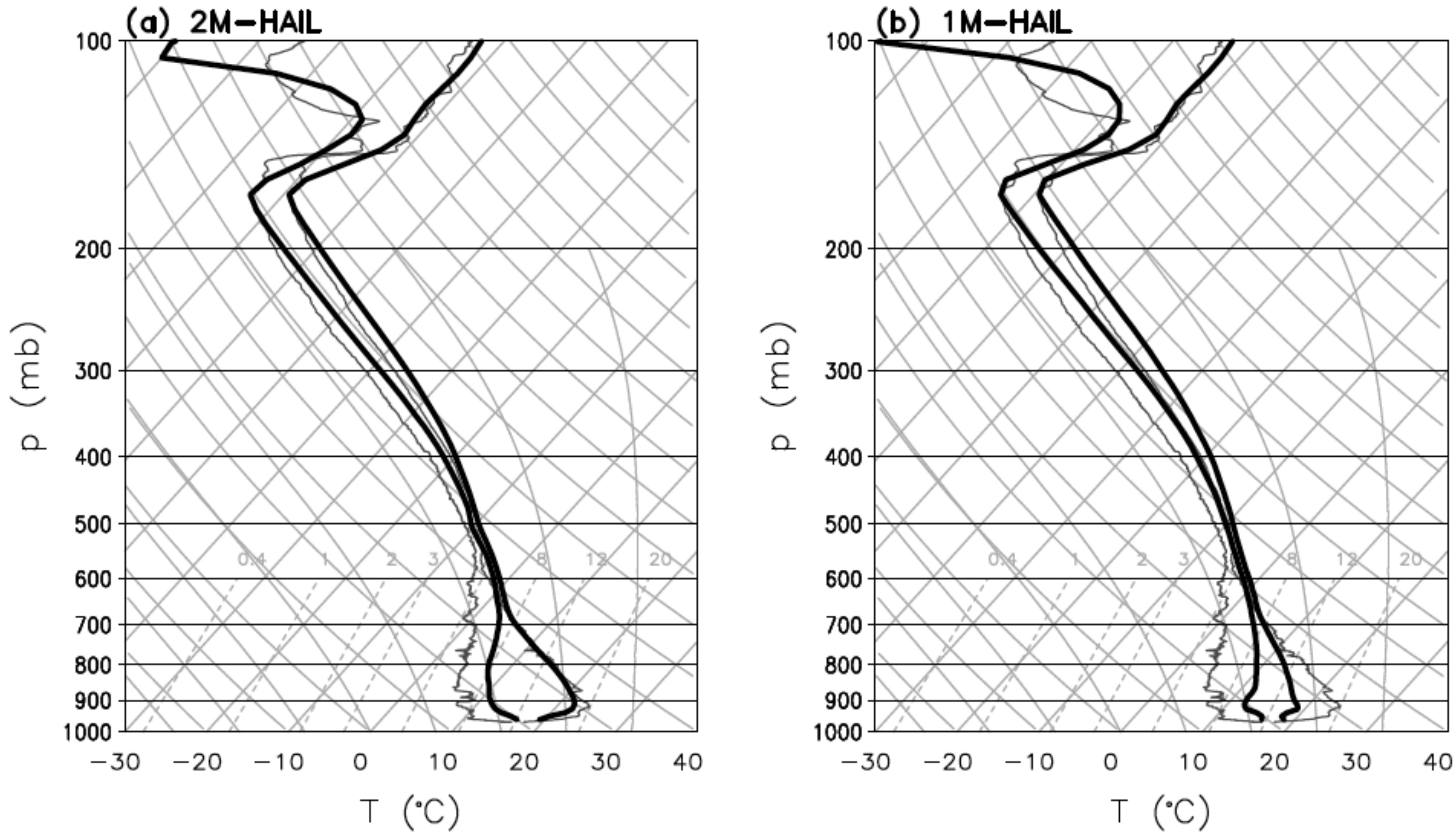
large drops in trailing stratiform region

Fall velocity (m s^{-1}) of large (rimed) ice

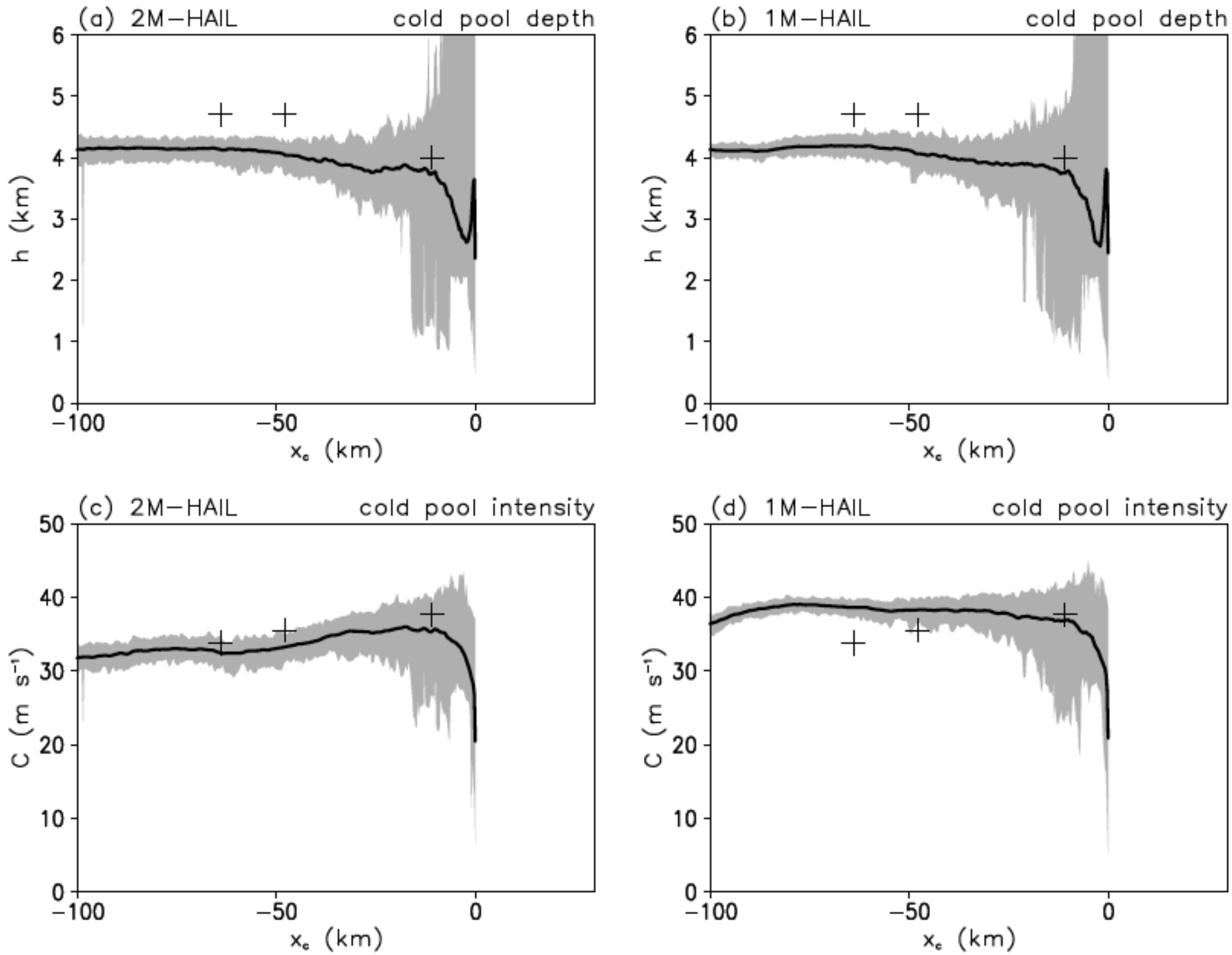


Soundings in trailing stratiform region

(thick = simulation,   thin = observed)

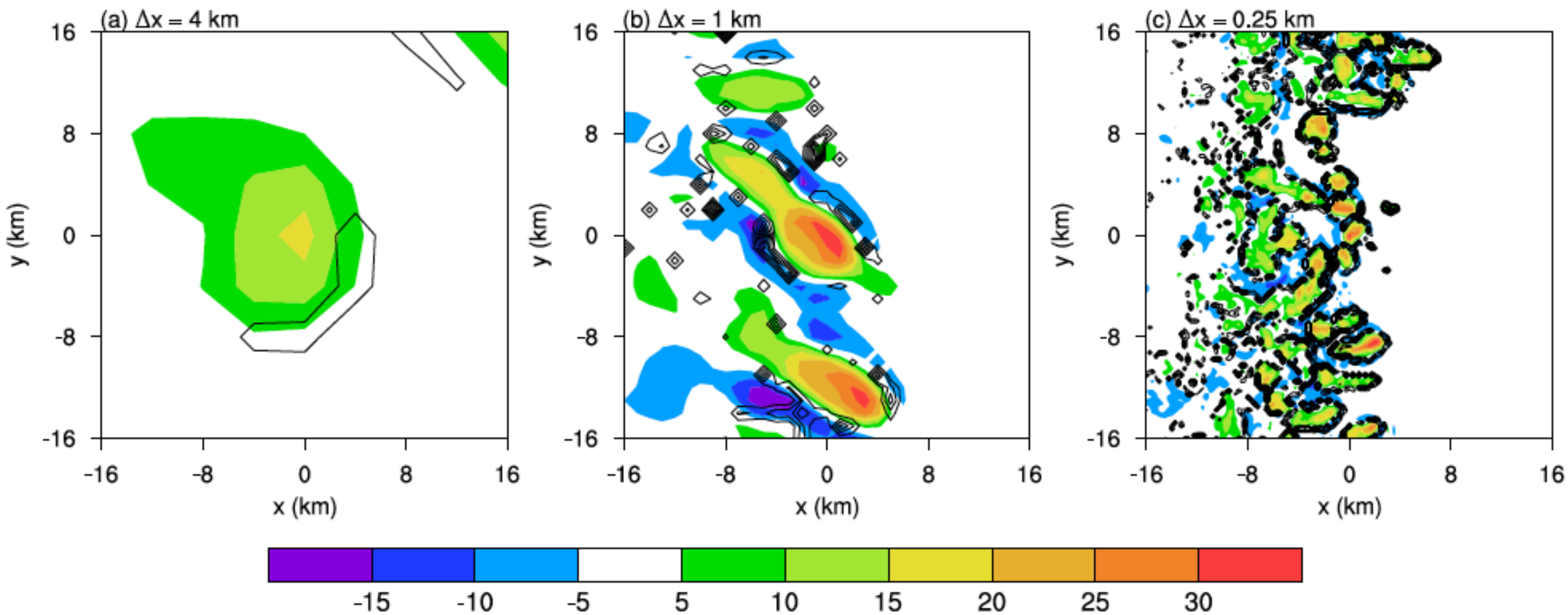


Impacts on cold-pool depth (*h*, top) and intensity (*C*, bottom)



Sensitivity to Δx

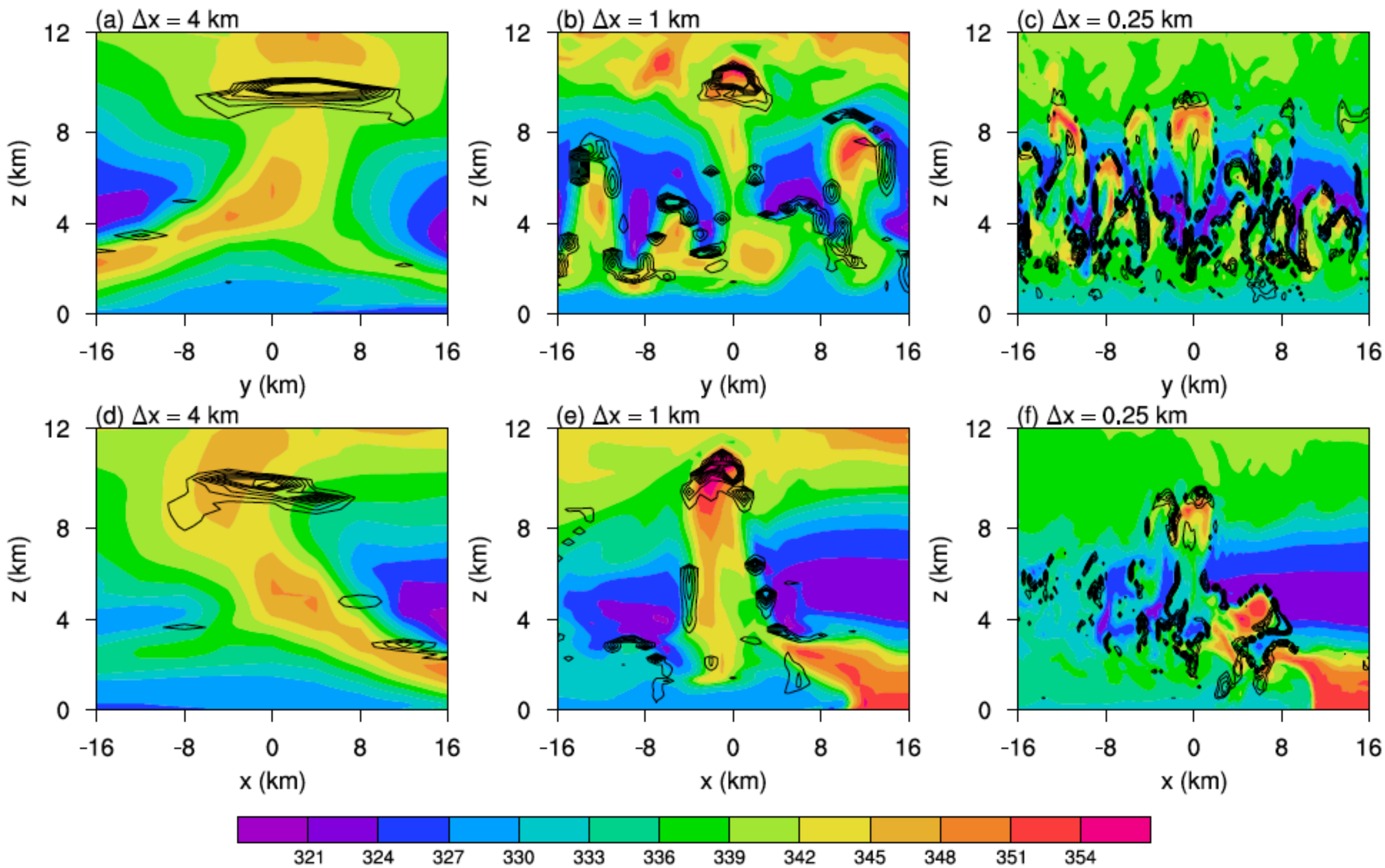
(*w*, m s^{-1}, at 5 km AGL)



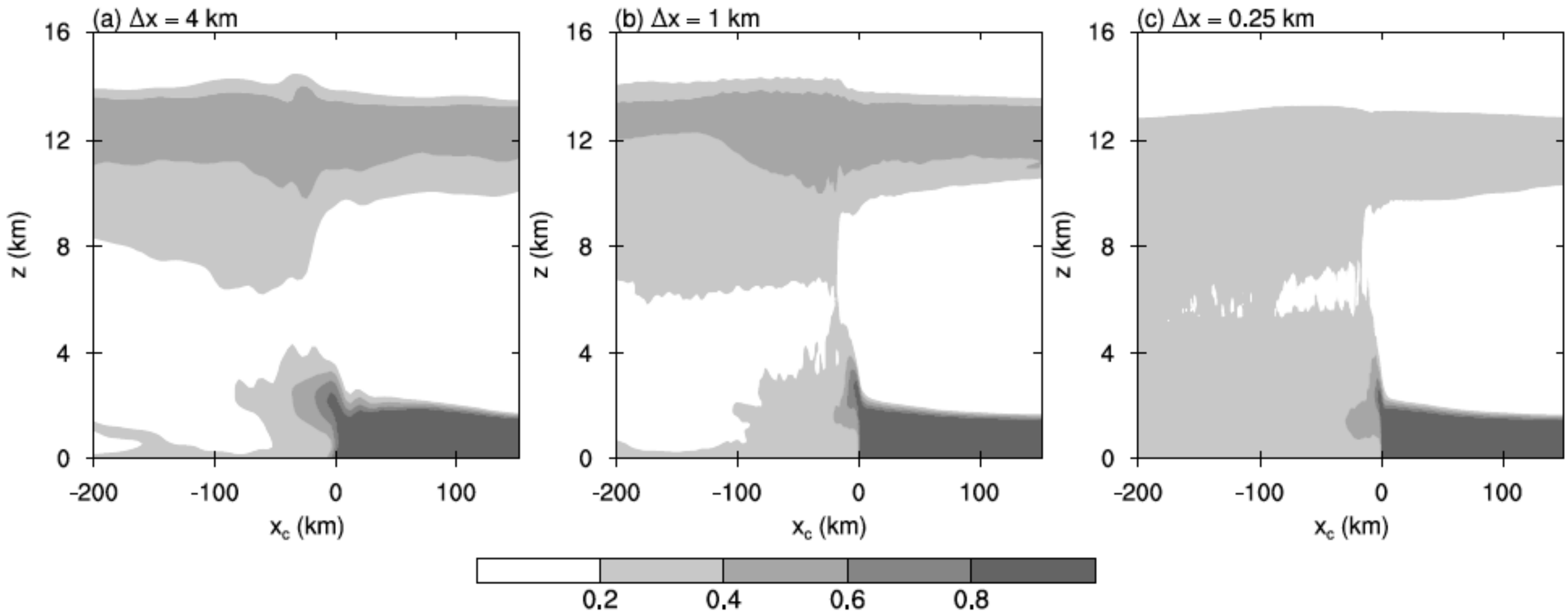
Sensitivity to Δx: equivalent potential temperature (shading)

Top: along-line cross sections

Bottom: across-line cross sections



Sensitivity to Δx: passive fluid tracer (g kg^{-1})



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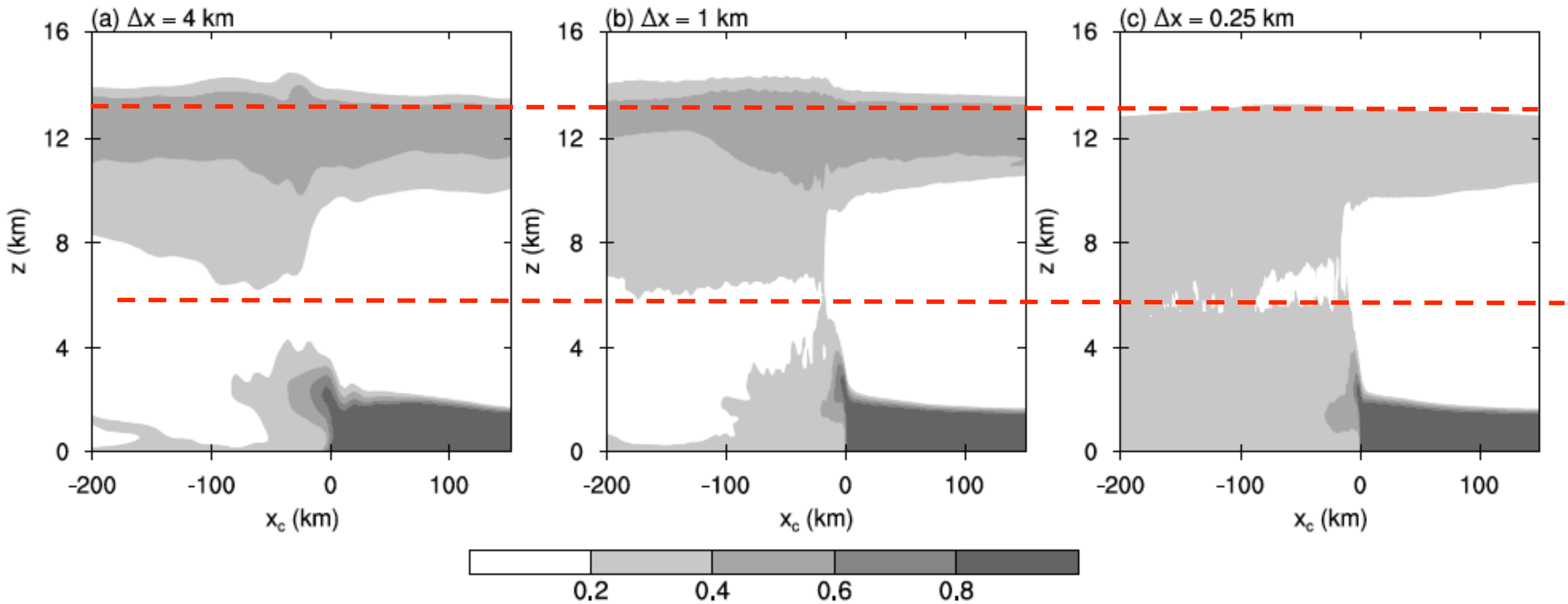

Summary

- Cold pools can be deeper than expected
  - $h \approx 4$ km (instead of 2 km)
  - perhaps only for mid-latitude continental regions
- Cold pools can be stronger than expected
  - $C \approx 35$ m s^{-1} (instead of 25 m s^{-1})
  - [James et al (2005,2009): only idealized modeling study with $C > 35$ m s^{-1}]
- Numerical simulations best match observations when:
  - using double-moment rain (predicts mass and number of raindrops)
  - having large, dense ice (hail) (perhaps midlats. only)
  - using $\Delta x \approx 250$ m (or less) (turbulent entrainment!)
- Needed: measurements of C and h in tropical MCSs
  - targeted field project? - or - serendipitous data collection?