# A Primer on Cloud-Resolving Modeling

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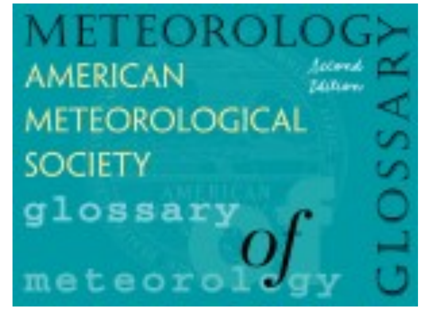
Merriam-Webster

m-w.com

- from Merriam-Webster Dictionary:
  - \\`pri-mer, ***chiefly British*** \`prī-mer\\

1. : a small book for teaching children to read
2. : a small introductory book on a subject
3. : a short informative piece of writing

From the AMS Glossary of Meteorology:




- cloud model—A physical or numerical framework for the prediction of cloud behavior.

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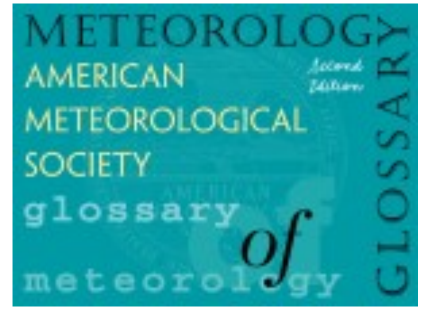


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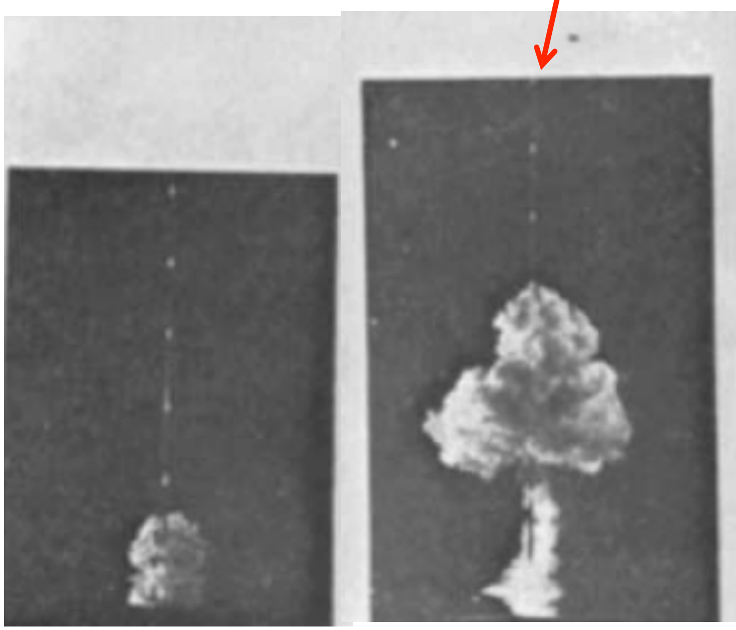
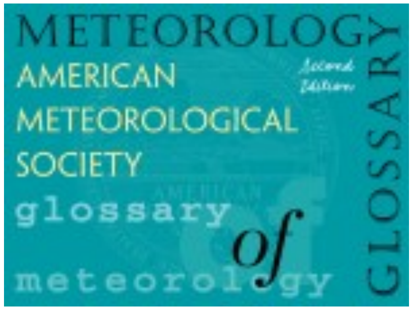


(Scorer 1957)

From the AMS Glossary of Meteorology:

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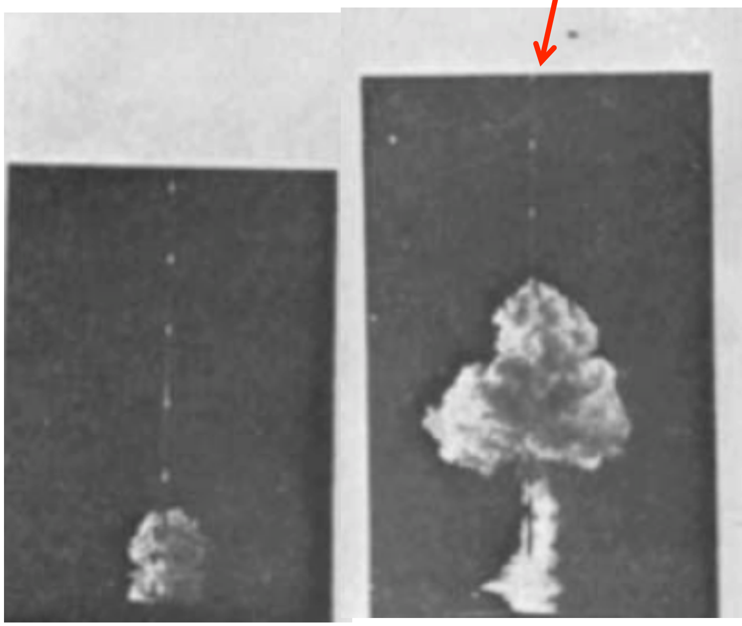
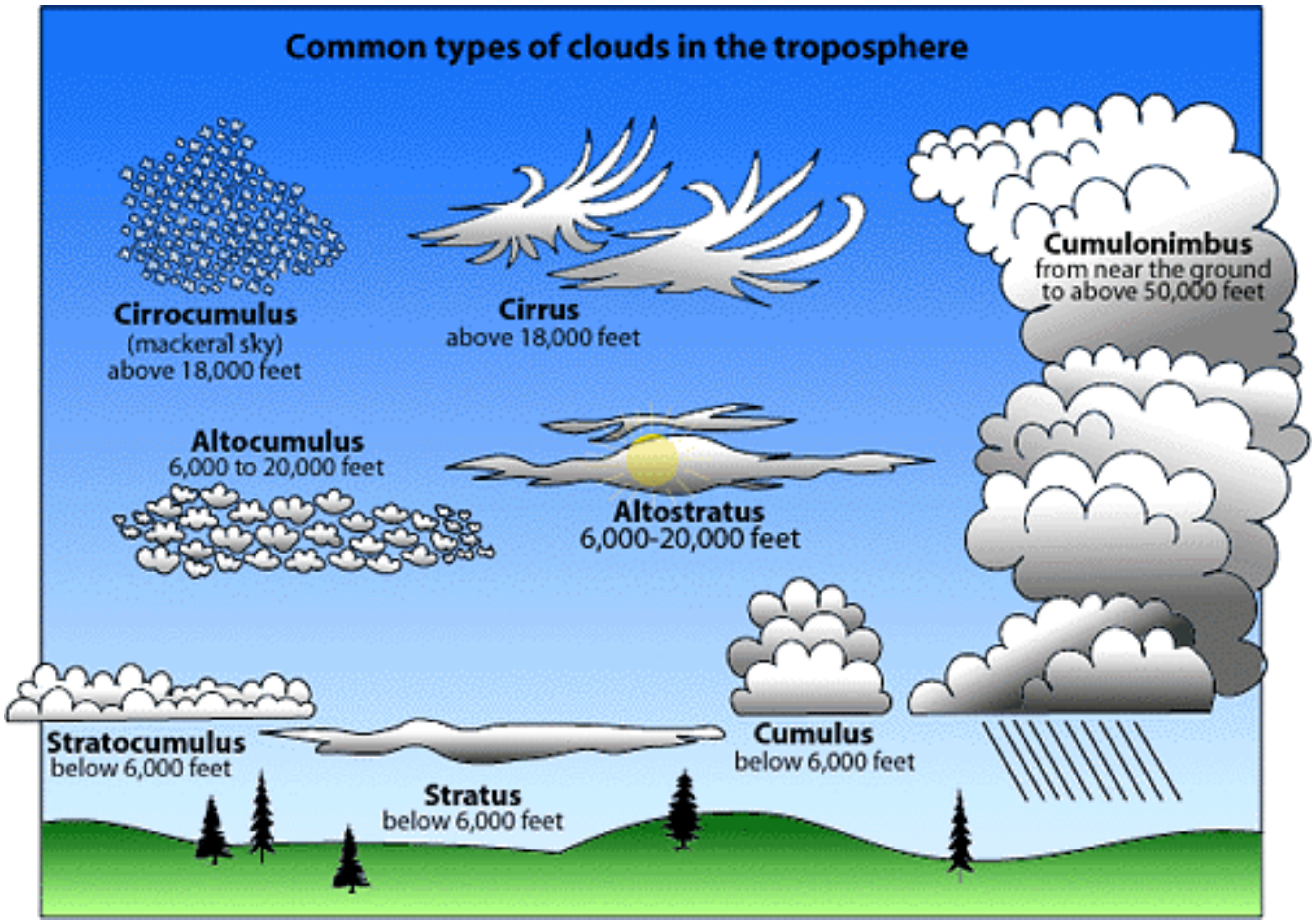


(Scorer 1957)


(bluefire;  http://www2.cisl.ucar.edu)

# Why use models?

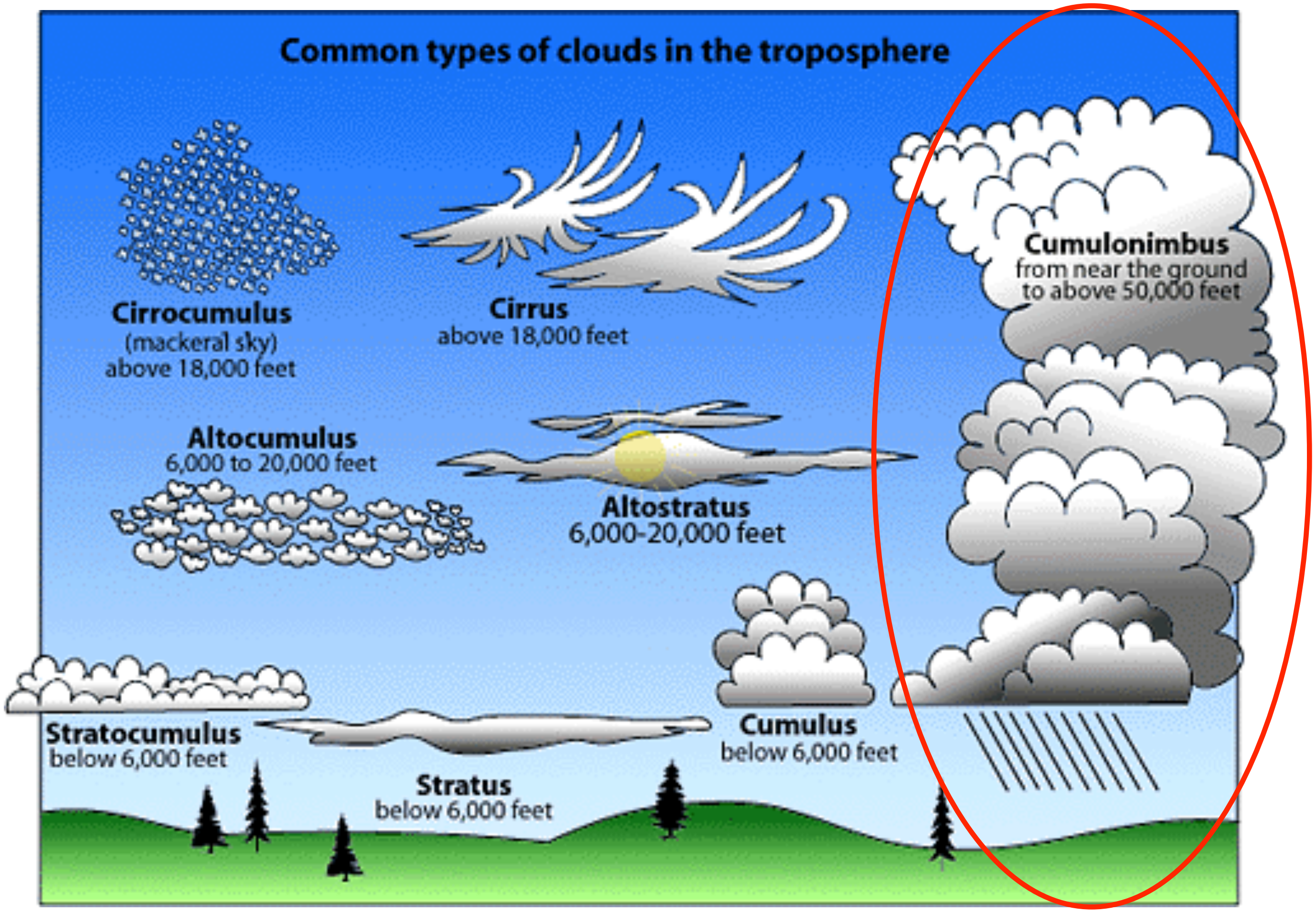
- Observational data are always incomplete
- Theory is always simplified
- Forecasting  (weather *and* climate)
- It's a challenge!




UCAR E&O  (http://eo.ucar.edu/webweather)

# Why use models?

It depends on what you're working on …



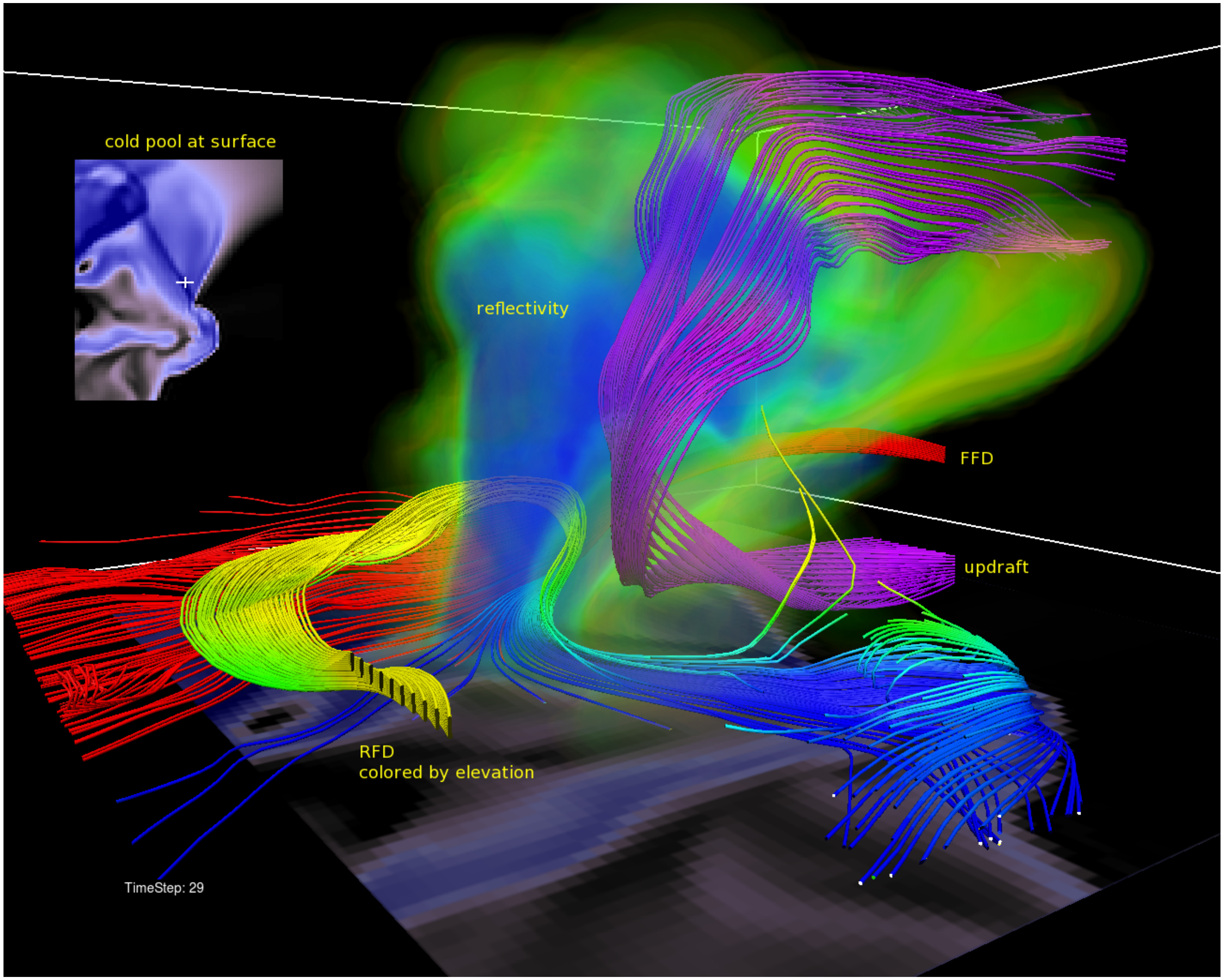

UCAR E&O (http://eo.ucar.edu/webweather)

# A tornadic supercell thunderstorm

La Plata, Maryland, USA:  28 April 2002

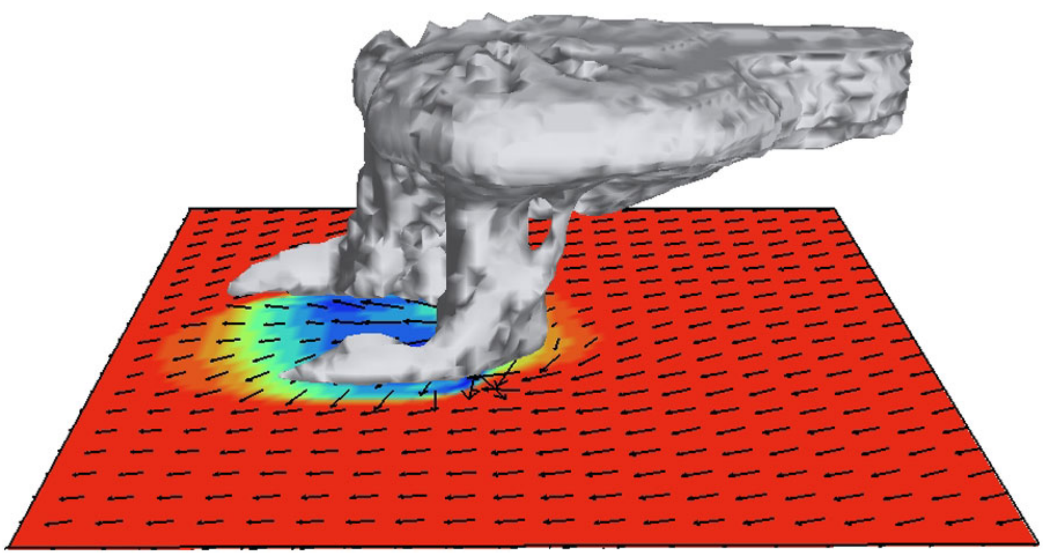
photo by Steven Maciejewski

# A numerical simulation of a supercell thunderstorm




Simulation and visualization by Leigh Orf, Central Michigan University

- Definition for this talk: *<u>cloud-resolving modeling</u>* refers to the simulation of deep precipitating clouds (i.e., thunderstorms) <u>explicitly</u> on the model grid; in other words, without a convective parameterization scheme



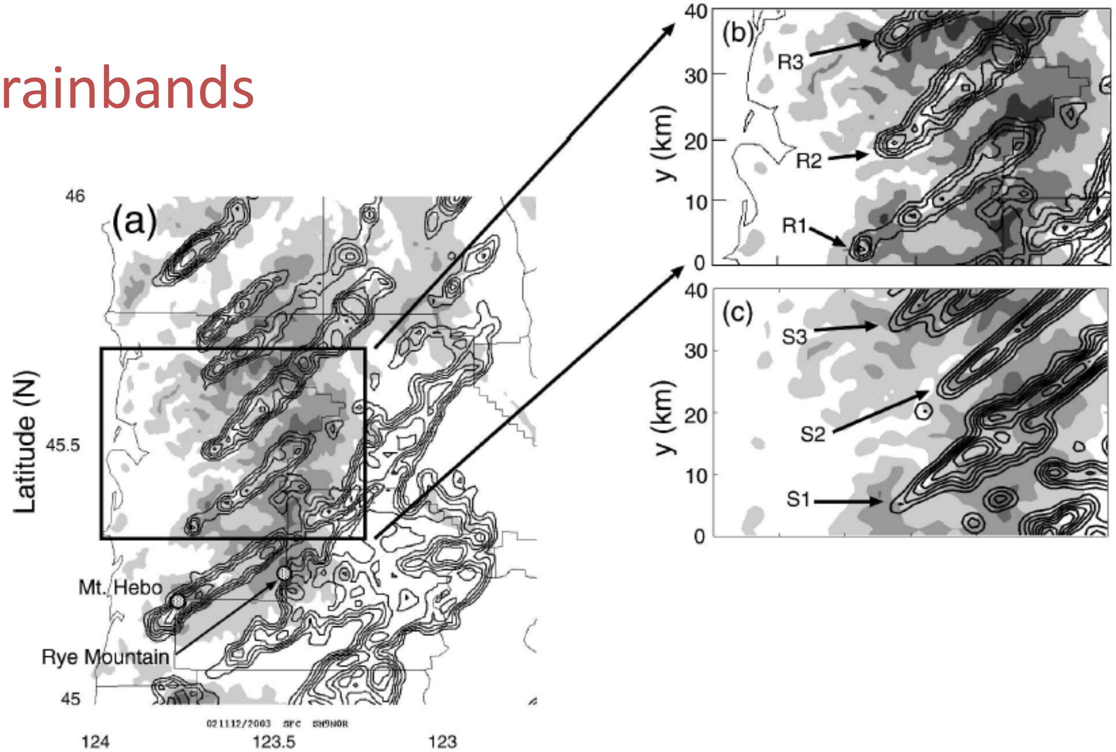
Klemp et al. (2007)

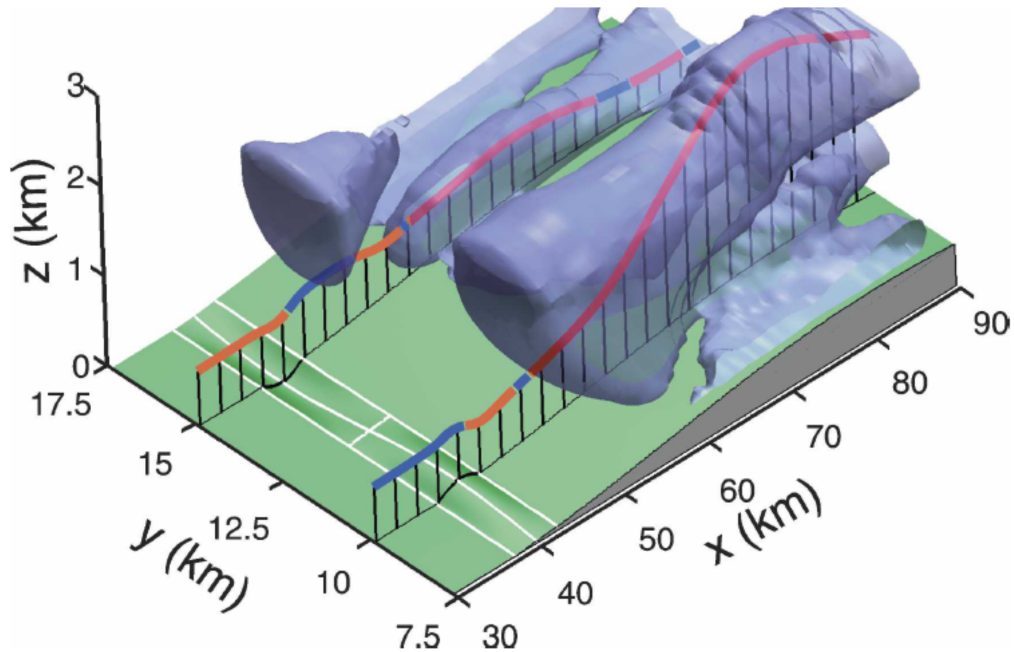
Equivalent terms:

"cloud-system-resolving modeling" (CSRM)

"cloud-permitting model"

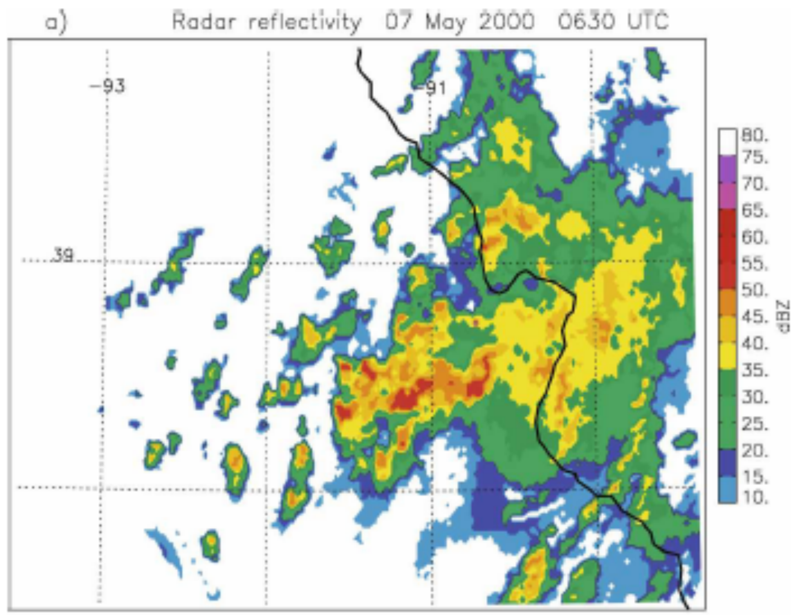
## Orographic rainbands

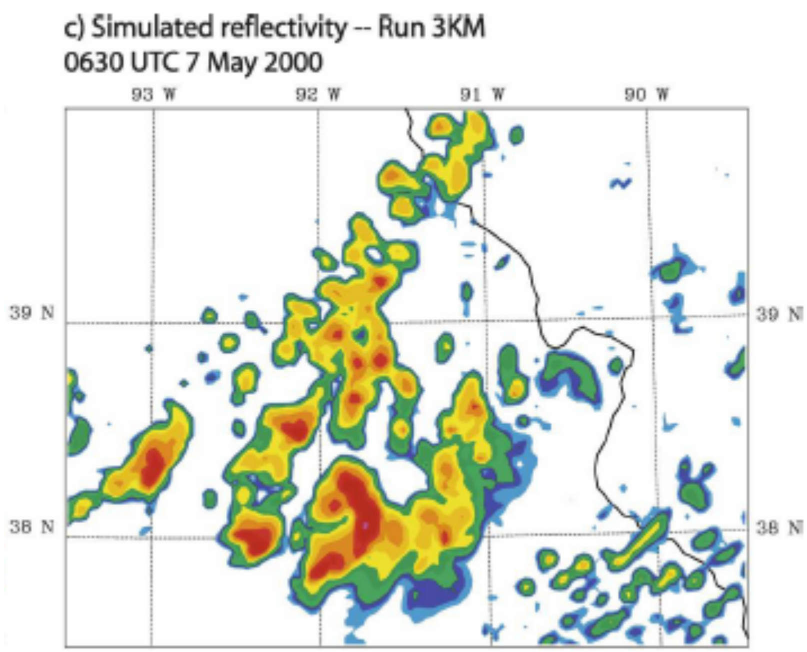


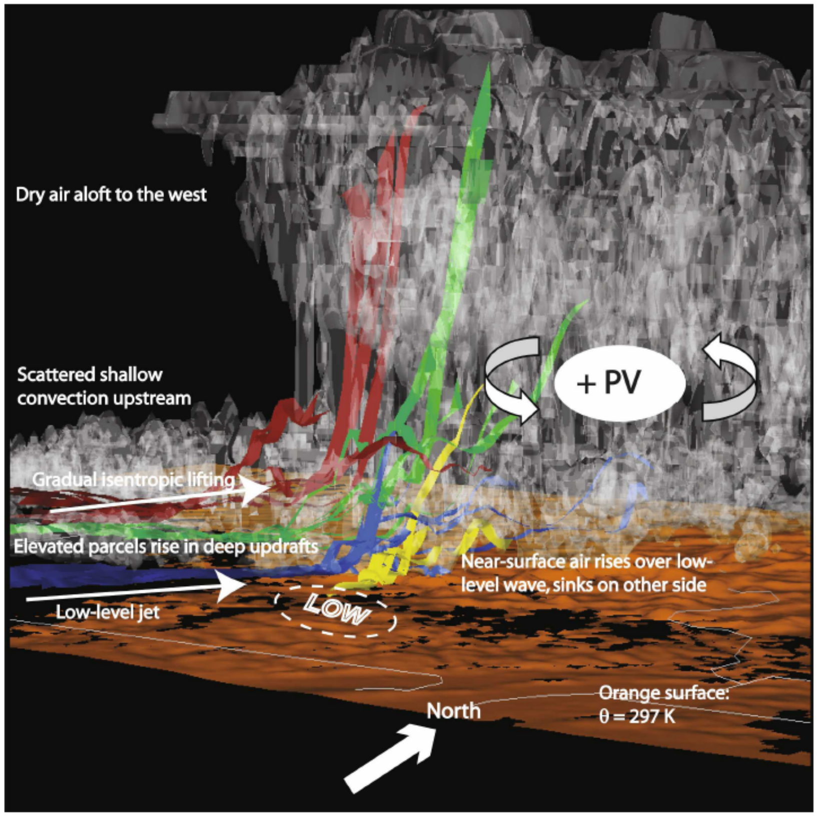




Kirshbaum et al. (2007)

# Mesoscale Convective System (MCS)



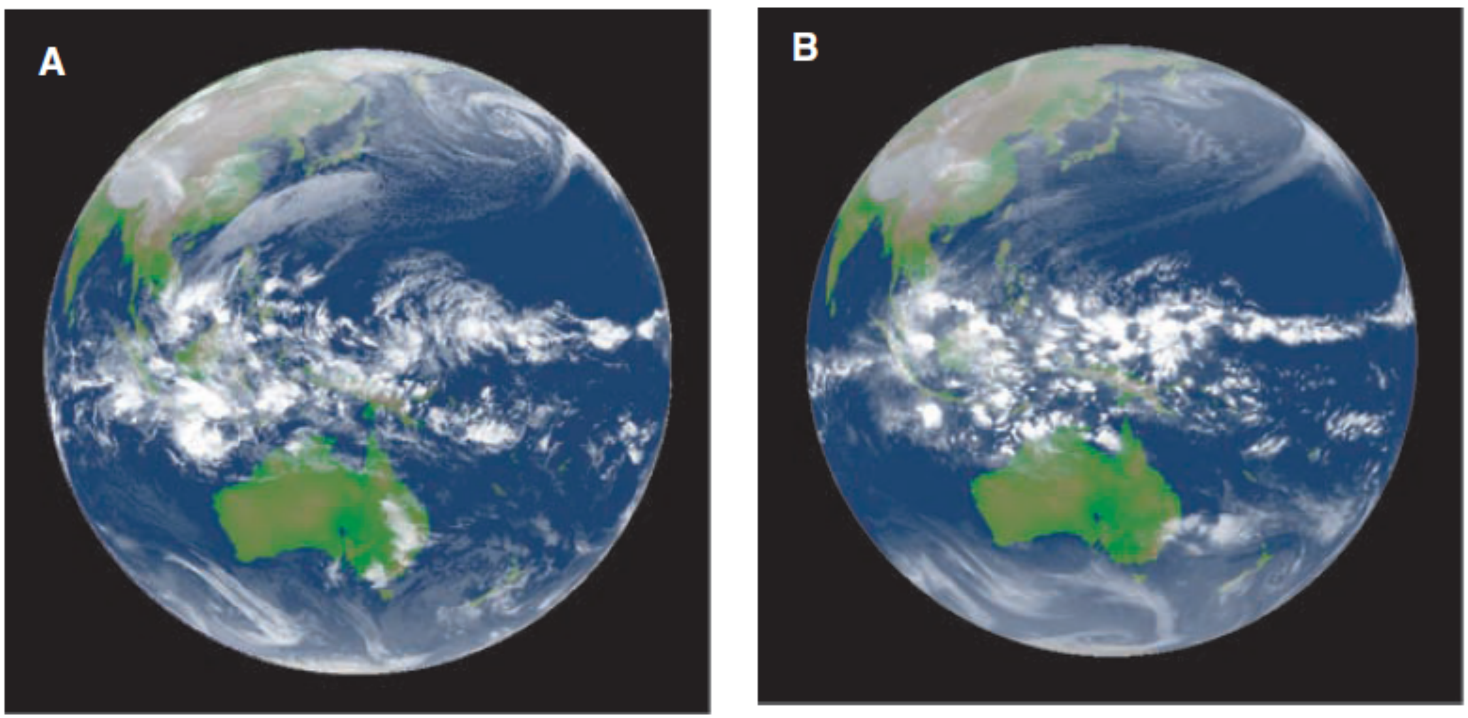

Schumacher and Johnson (2008)

# A Global Cloud-Resolving Simulation

Outgoing longwave radiation (OLR)

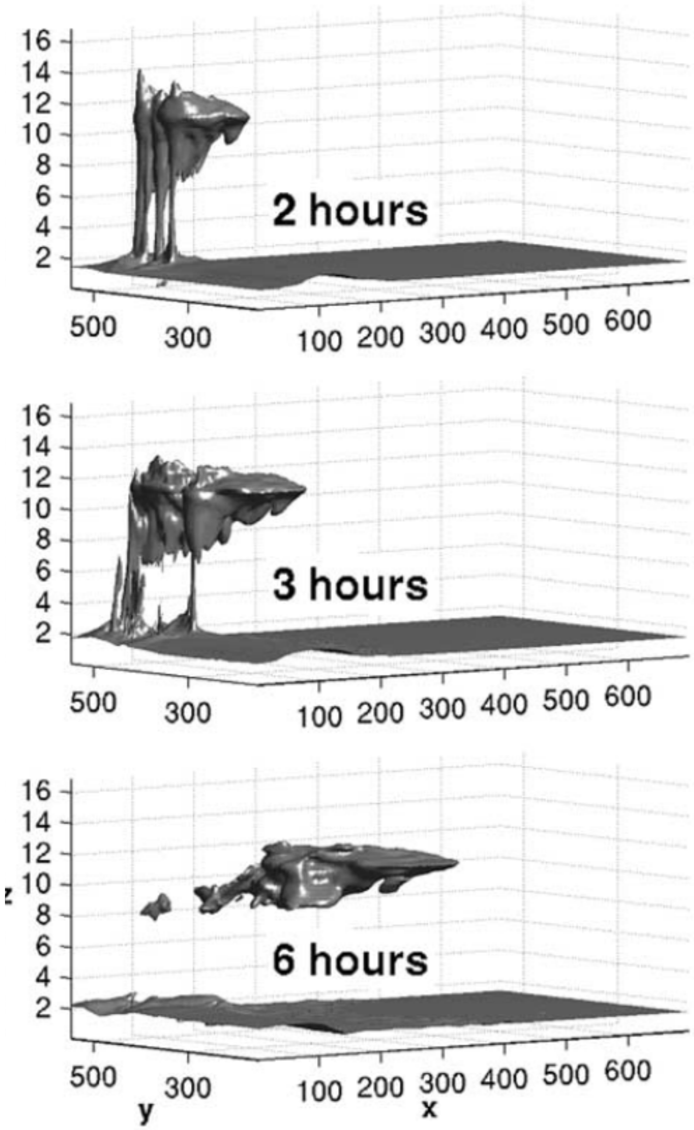
Observation (MTSAT-1R)

Simulation

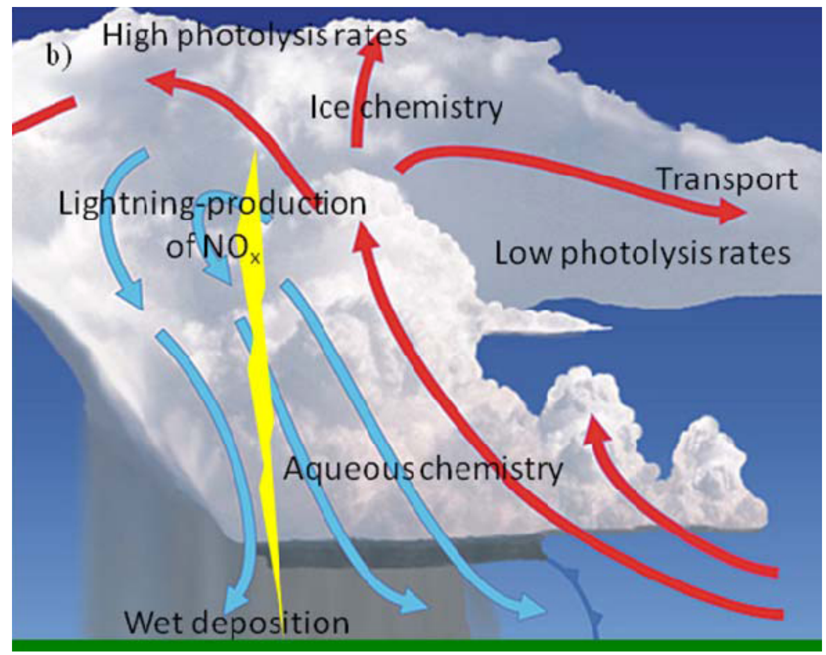



Miura et al. (2007)

# Transport/Chemistry




Mullendore et al. (2005)

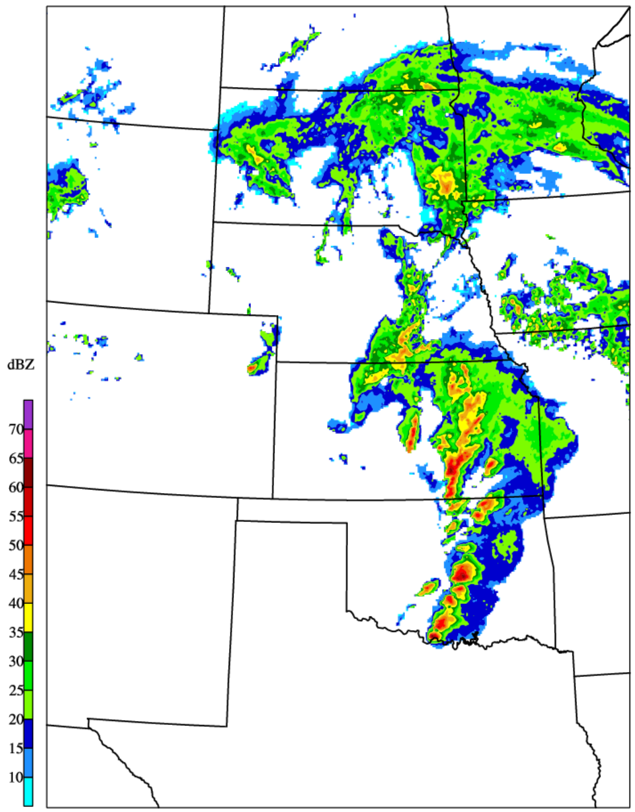



DC3 webpage (www2.acd.ucar.edu/dc3)

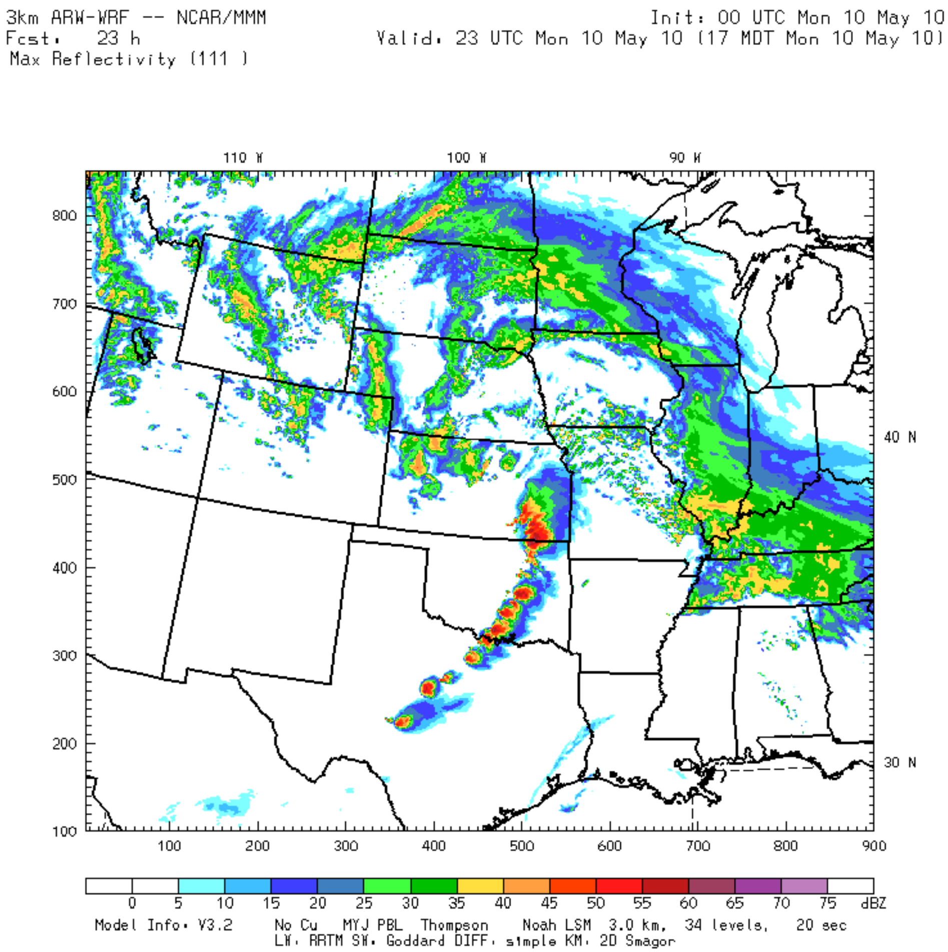
# Real-time forecasting

<u>observation</u>

NSSL Q2 Composite Reflectivity valid 2300 UTC 05/10/2010




<u>23-h forecast</u>



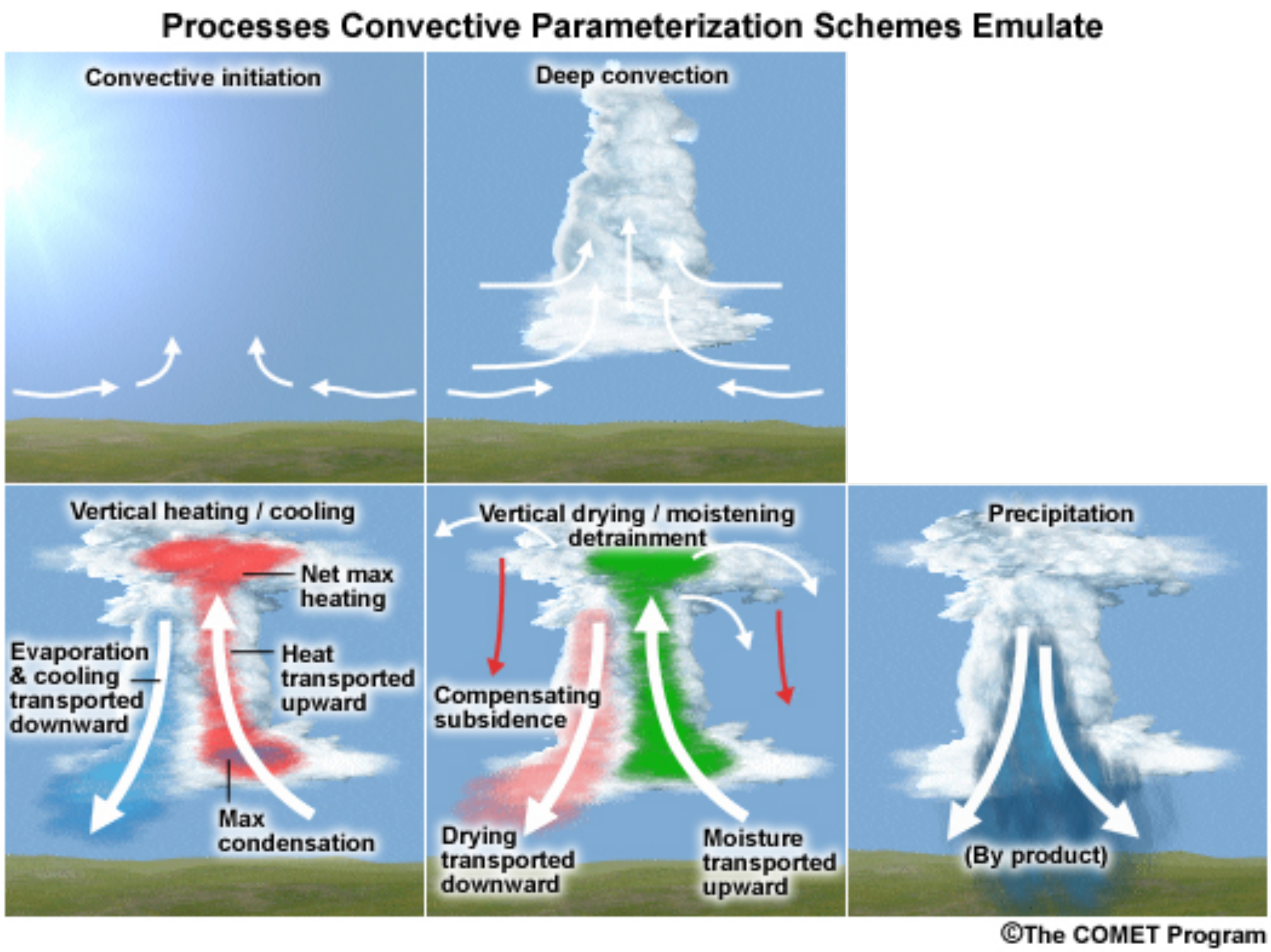
# What is a cloud-resolving model?

- It’s computer code!
  (10,000+ lines of computer code)

- Components of a cloud-resolving model:
  - Dynamical solver:
    - Solves governing equations for the atmosphere (momentum equations, first law of thermodynamics, equation of state, etc)
    - Nonhydrostatic! (e.g., MM5, WRF, MPAS)
    - Numerical methods (grid structure, advection/transport scheme, time integration method, etc)
  - Data assimilation scheme (initial conditions, boundary conditions)
  - A set of physical parameterization schemes
    - a.k.a. “physics”
    - Atmospheric radiation (IR,UV); microphysics (cloud drops, rain drops, snow, hail, etc); small-scale turbulence (PBL)
  - Sufficient resolution
    - Horizontal grid spacing ($\Delta x$) must be of-order 1 km
    - Must have of-order 50 vertical levels

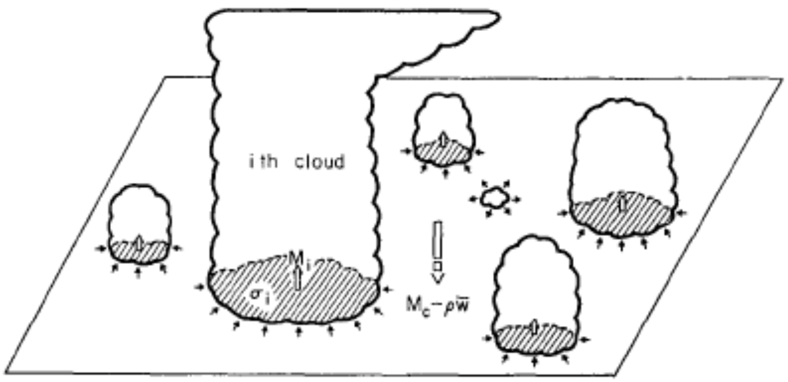
From AMS Glossary:

> Subgrid-scale process: Atmospheric processes that cannot be adequately resolved within a numerical simulation. Examples can include turbulent fluxes, phase changes of water, chemical reactions, and radiative flux divergence. Such processes are often *parameterized* in numerical integrations …

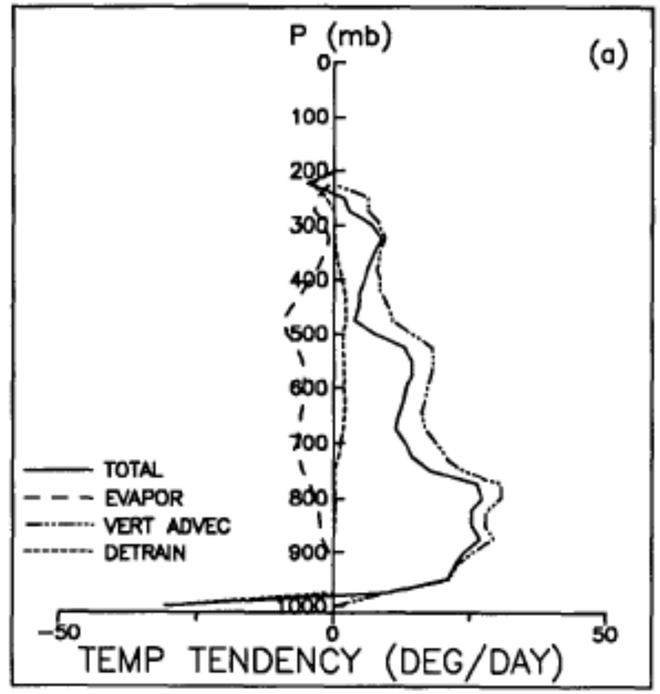



COMET: http://www.meted.ucar.edu

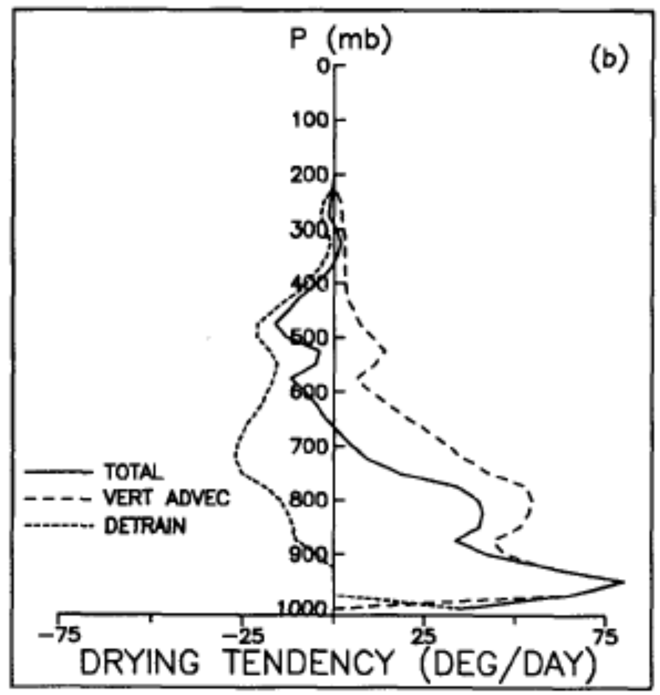
Conceptual model:



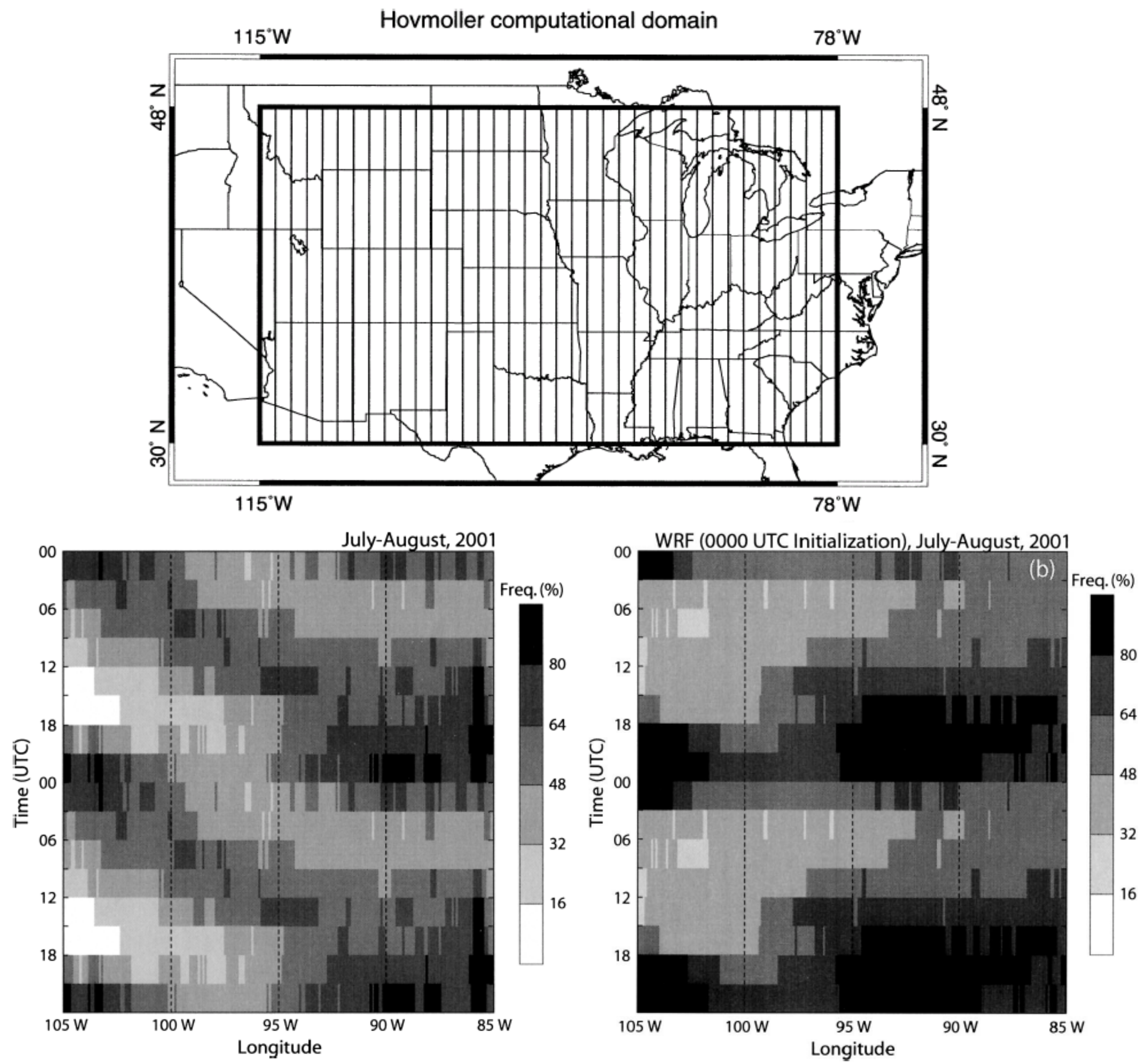

Arakawa and Schubert (1974)




This is what comes out of the subroutine:
heating (top) and drying (bottom) tendencies:




Kain and Fritsch (1990)



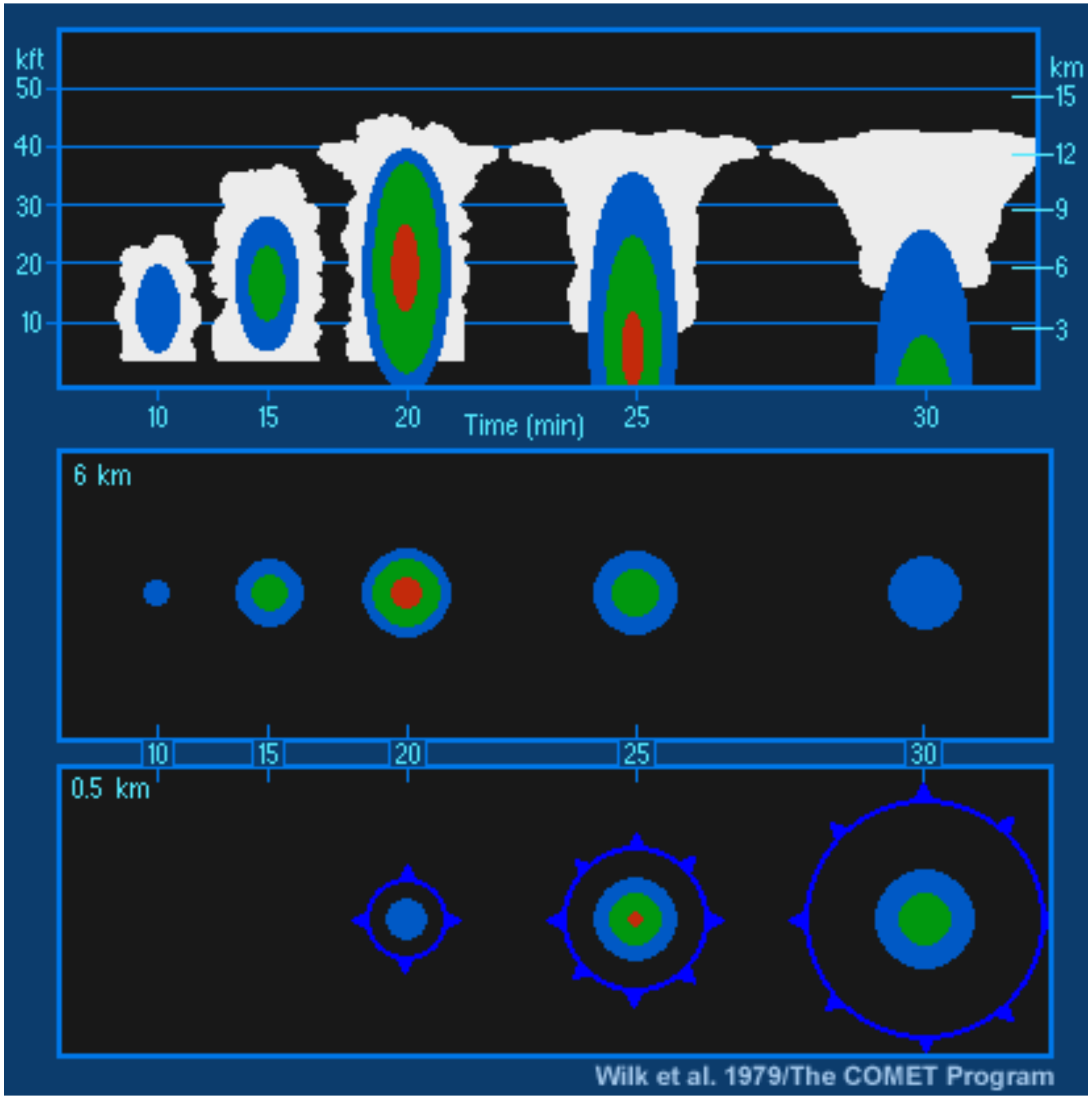

Davis et al. (2003)

# Convection (i.e., cloud) parameterization

- Common shortcomings:
  - Convection happens too often (especially over warm oceans)
  - Convection happens too early
  - Convective systems do not propagate correctly

- Randall et al, 2003, *Bull. Amer. Meteor. Soc.*, "Breaking the Cloud Parameterization Deadlock"
  - "cloud parameterization deficiencies will continue to plague us for many more decades into the future."
  - "our rate of progress is unacceptably slow."

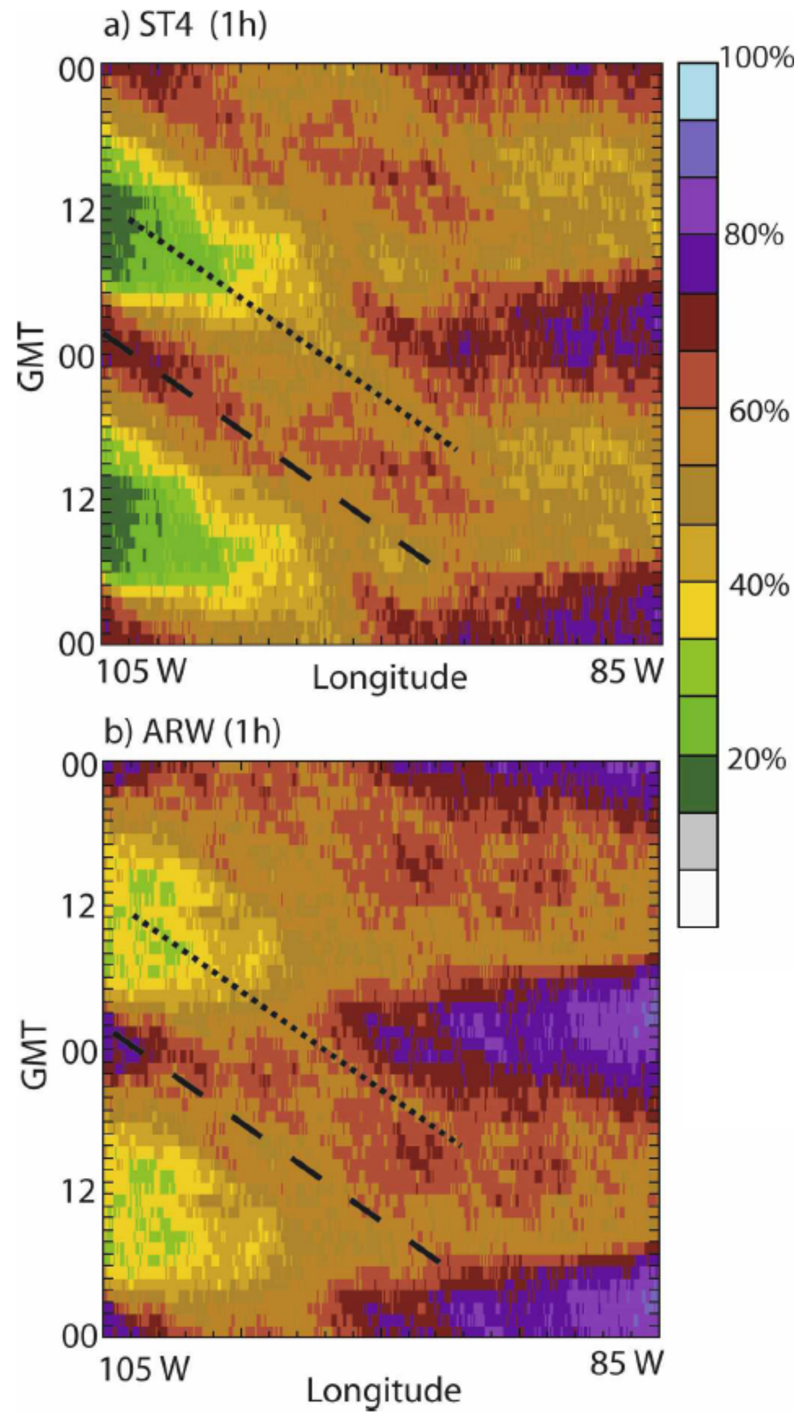
# Single cell:  lifecycle




COMET:  http://www.meted.ucar.edu

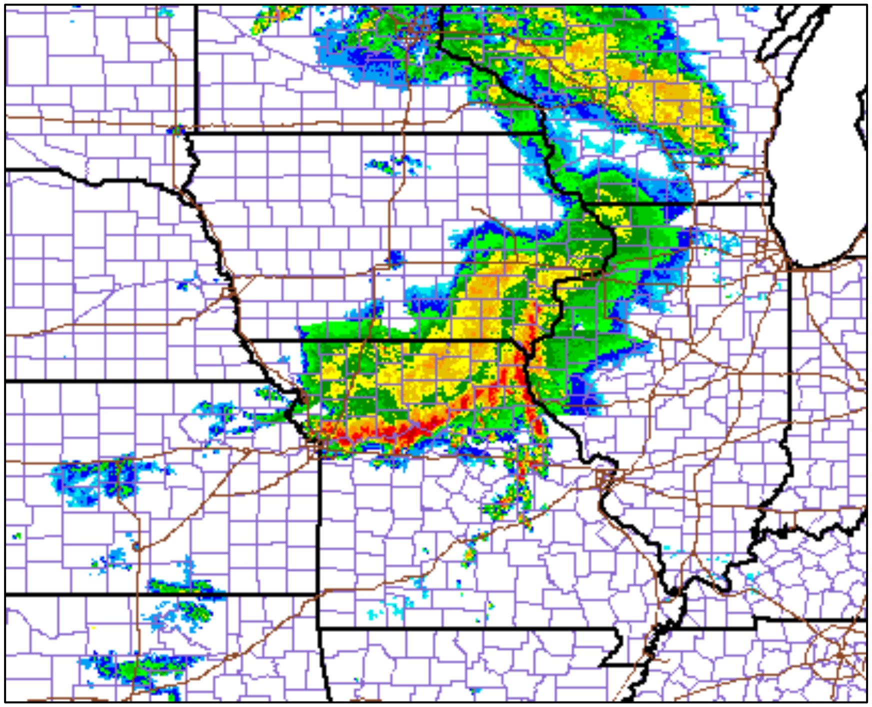
Observations

Simulations
(cloud-resolving)



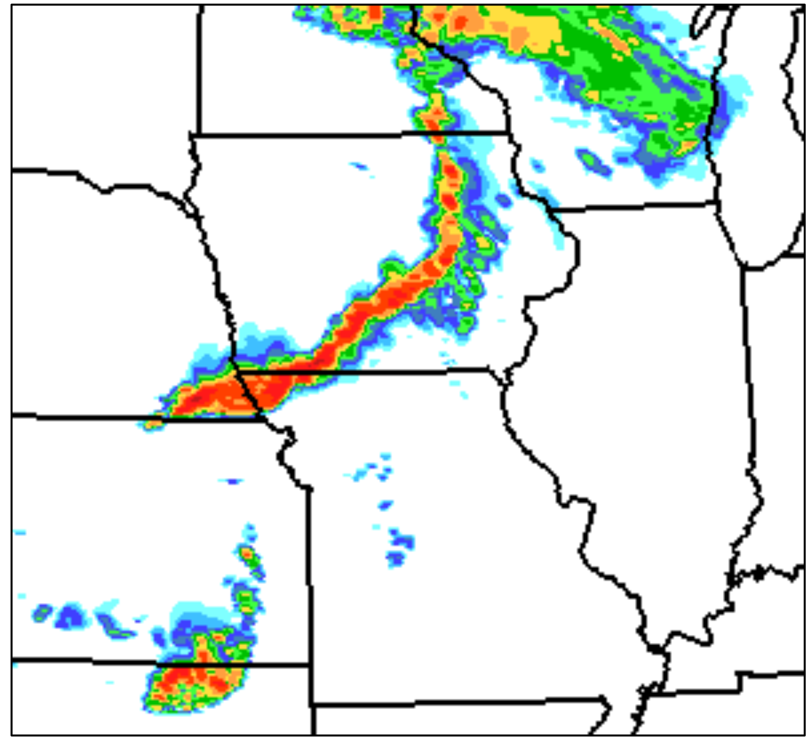

Weisman et al (2008)

## WRF Model forecast: 10 June 2003



Observed radar image

**<u>09 UTC</u>**



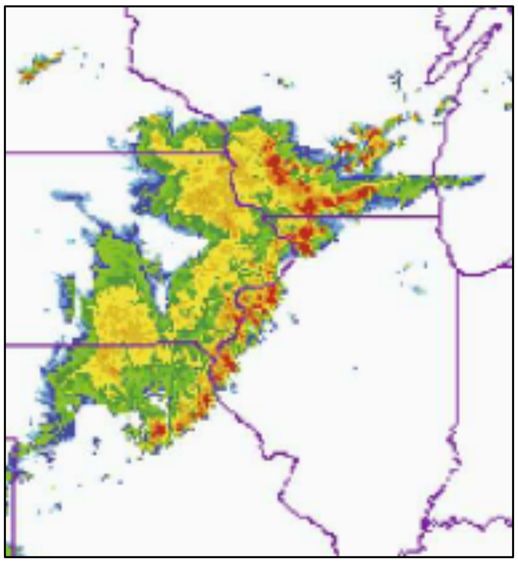
**WRF forecast ($\Delta x$ = 4 km)**

**9 h forecast valid <u>09 UTC</u>**

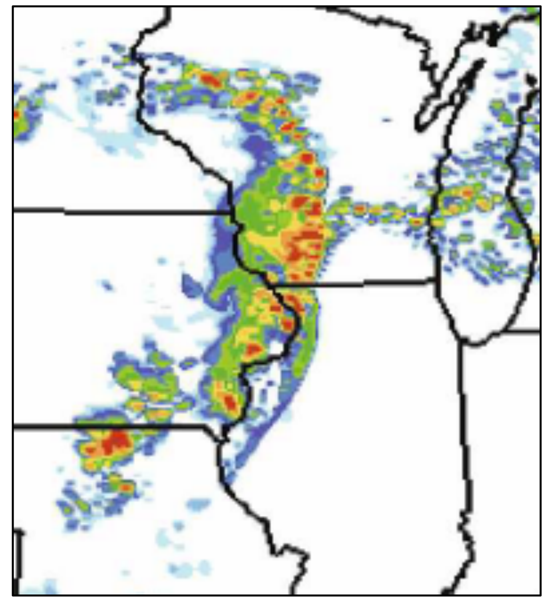
from M. Weisman

# WRF model forecast: 5 June 2005

observation



forecast

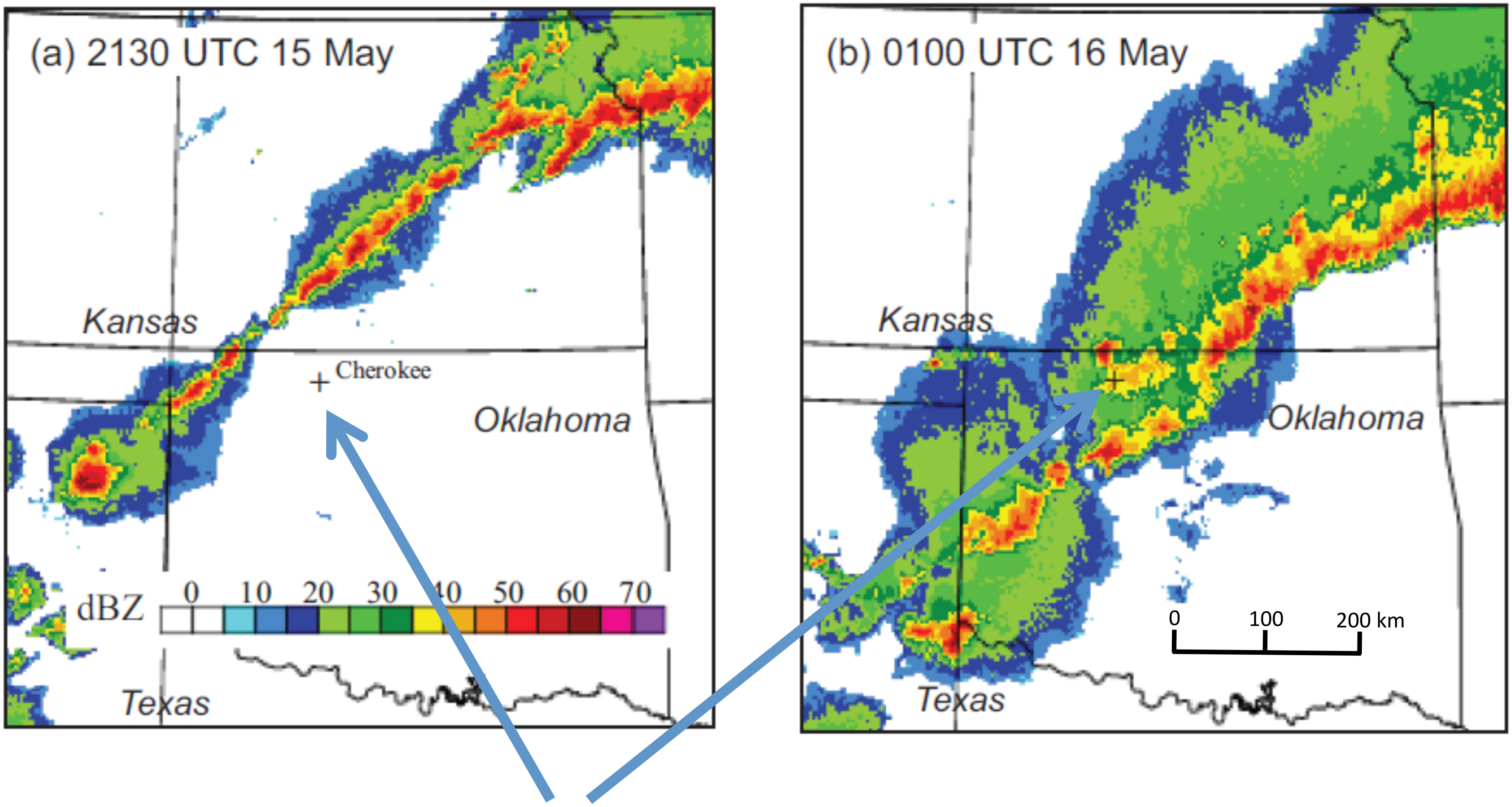


Weisman et al (2008)

# Case study: 15 May 2009 (during VORTEX2)

## regional reflectivity composite:

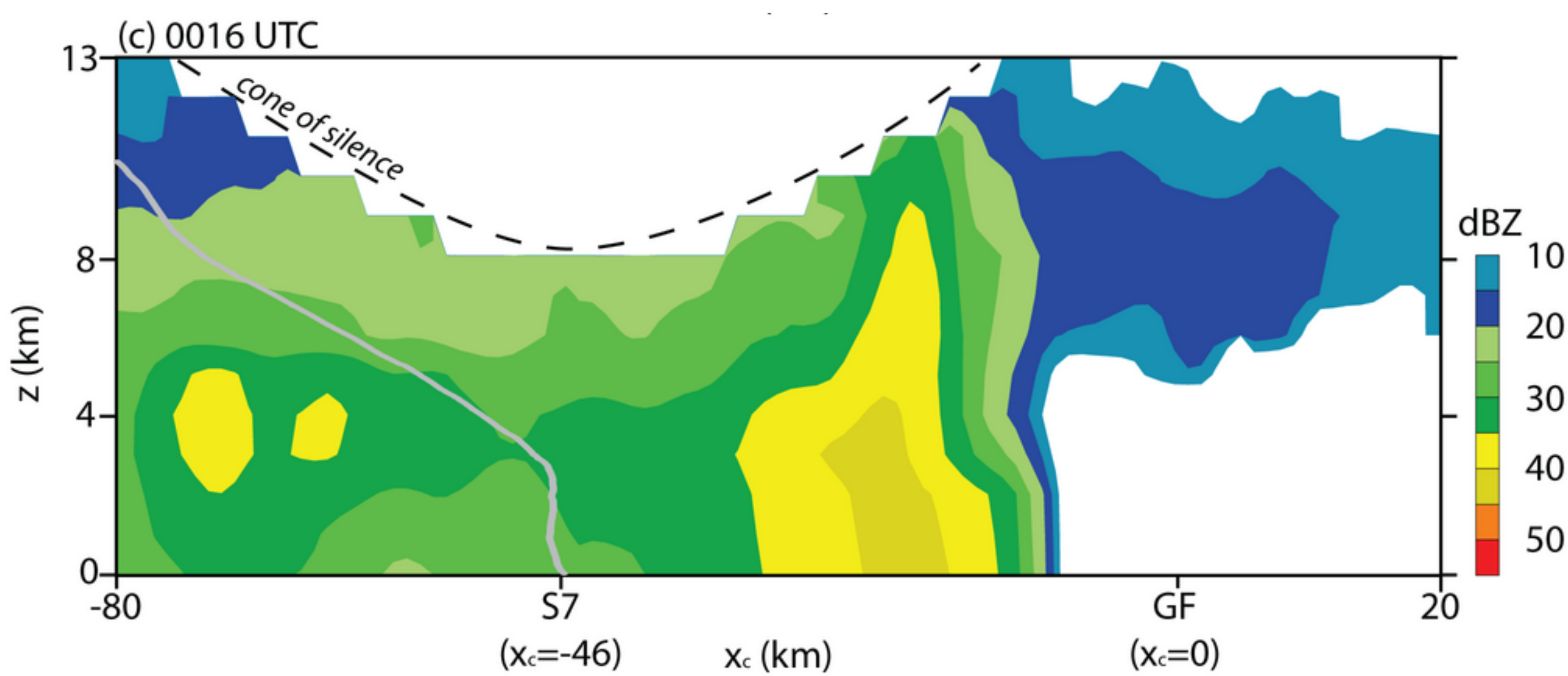
at beginning of data collection: at end of data collection:




location of data collection (Cherokee, OK)

Bryan and Parker (2010)

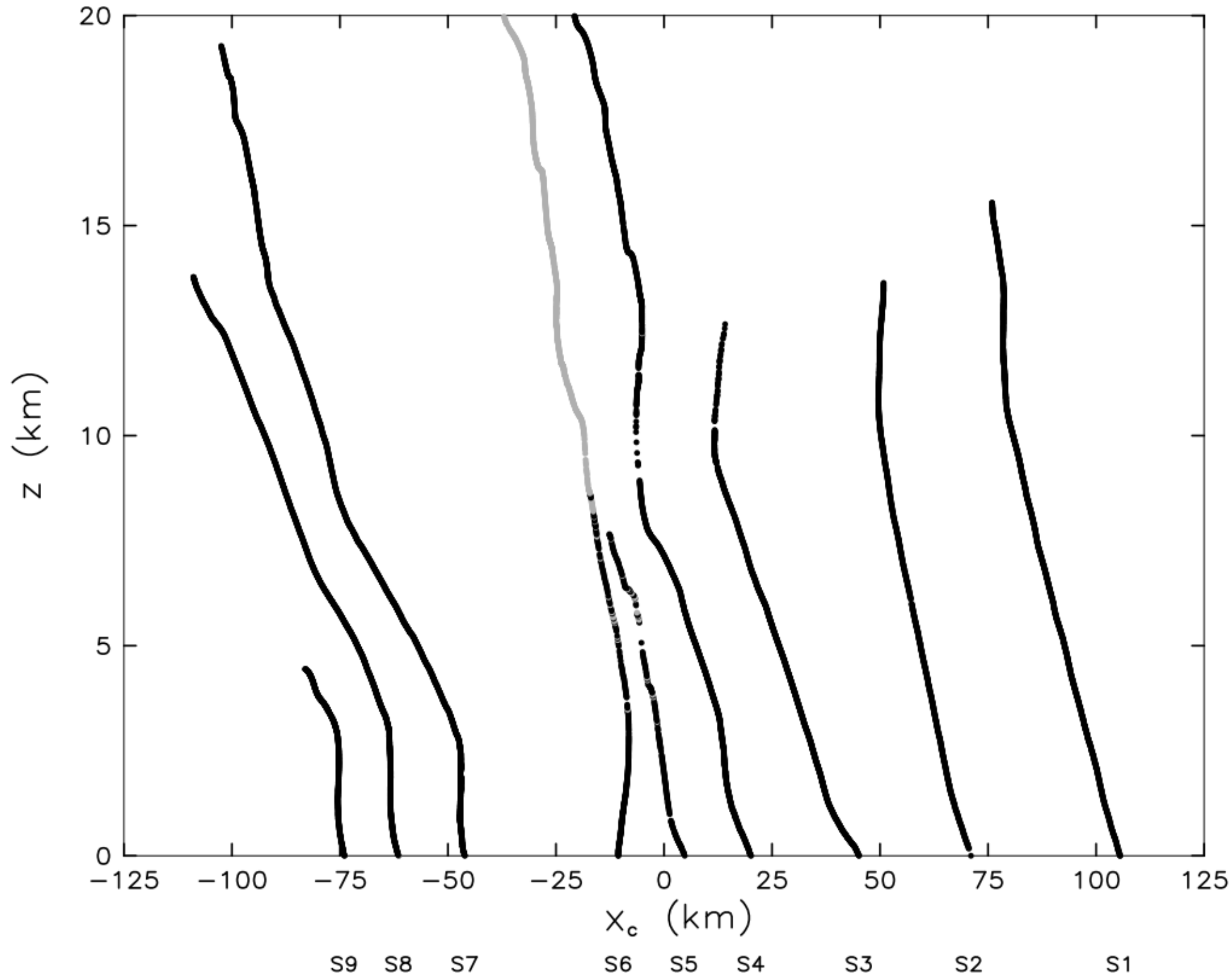
# Radar analysis:  trailing stratiform region




stratiform region

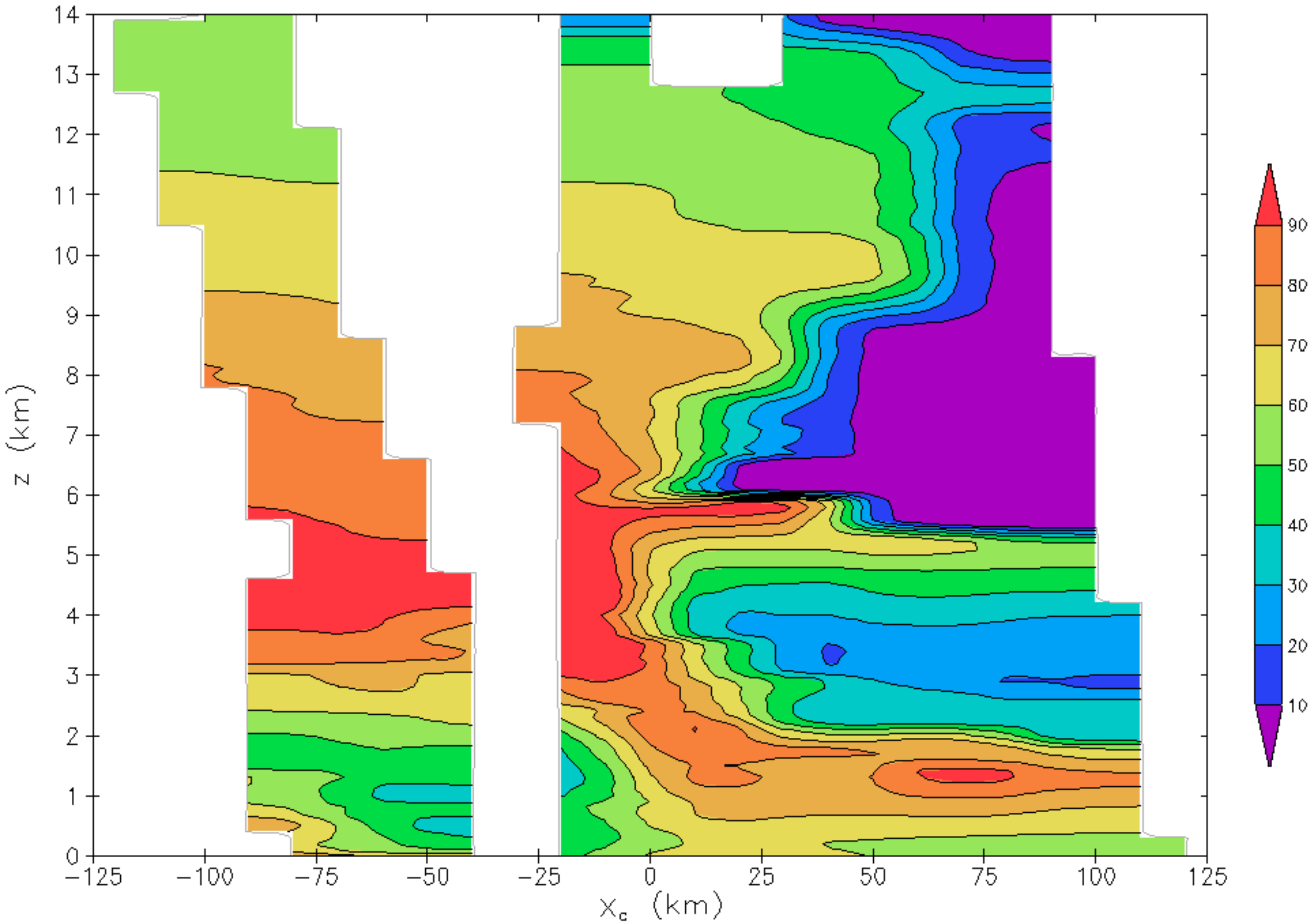
convective region

# System-relative location of all sounding data

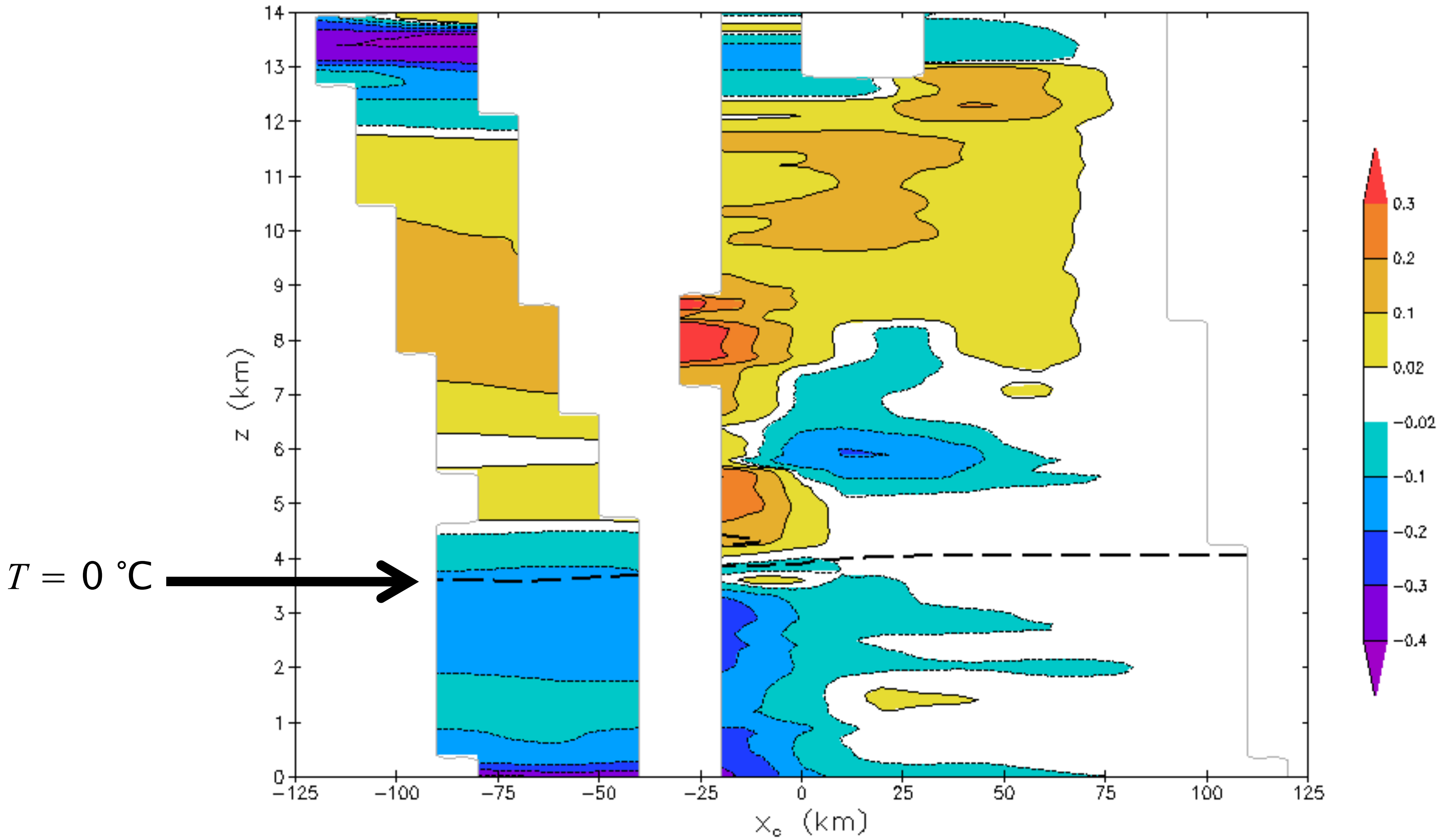



Mesoscale analysis: 2-pass Barnes method with $\Delta x = 10$ km, $\Delta z = 100$ m

# Analysis of relative humidity (wrt water) (%)



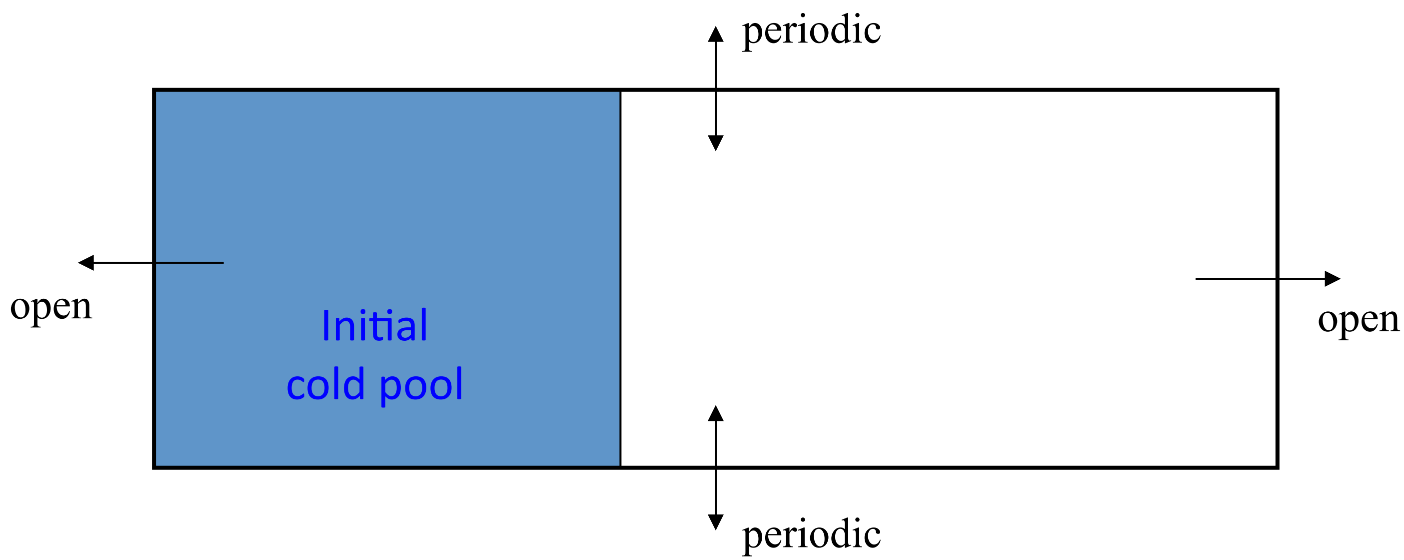
# Analysis of buoyancy $B$ (m s$^{-2}$)



# Numerical Simulations

- Numerical model:  CM1  (similar numerics as WRF)
- Horizontal grid spacing ($\Delta x$):  4 km, 1 km, or 0.25 km
- Vertical grid spacing ($\Delta z$):  varies from 100 m at $z$=0 to 400 m at $z$=25km
- Initialized using environment of the 15 May 2009 MCS
- Neglected radiation and surface fluxes  (to keep environment the same)

Domain:  576 km x 144 km

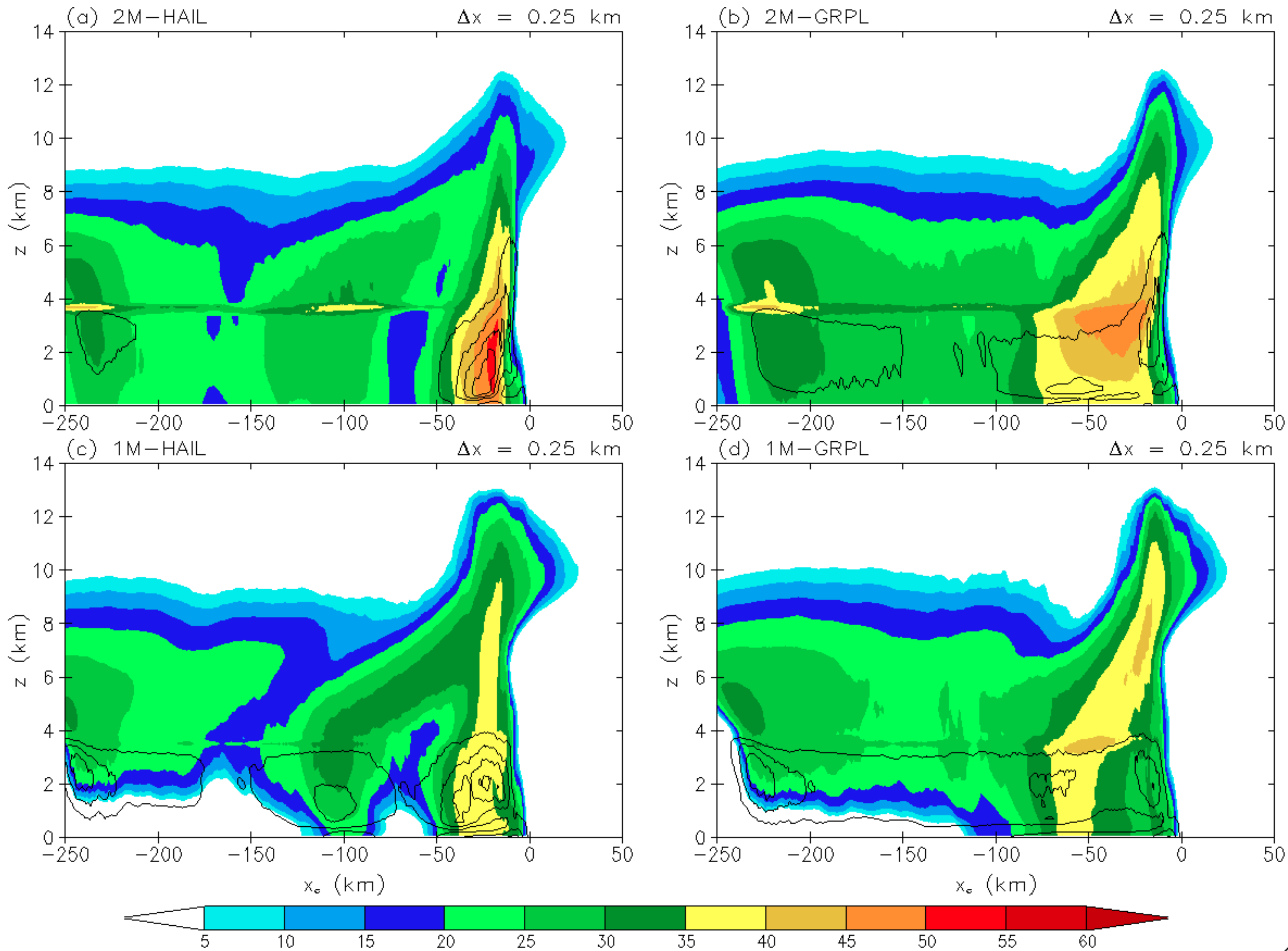


# Numerical Simulations

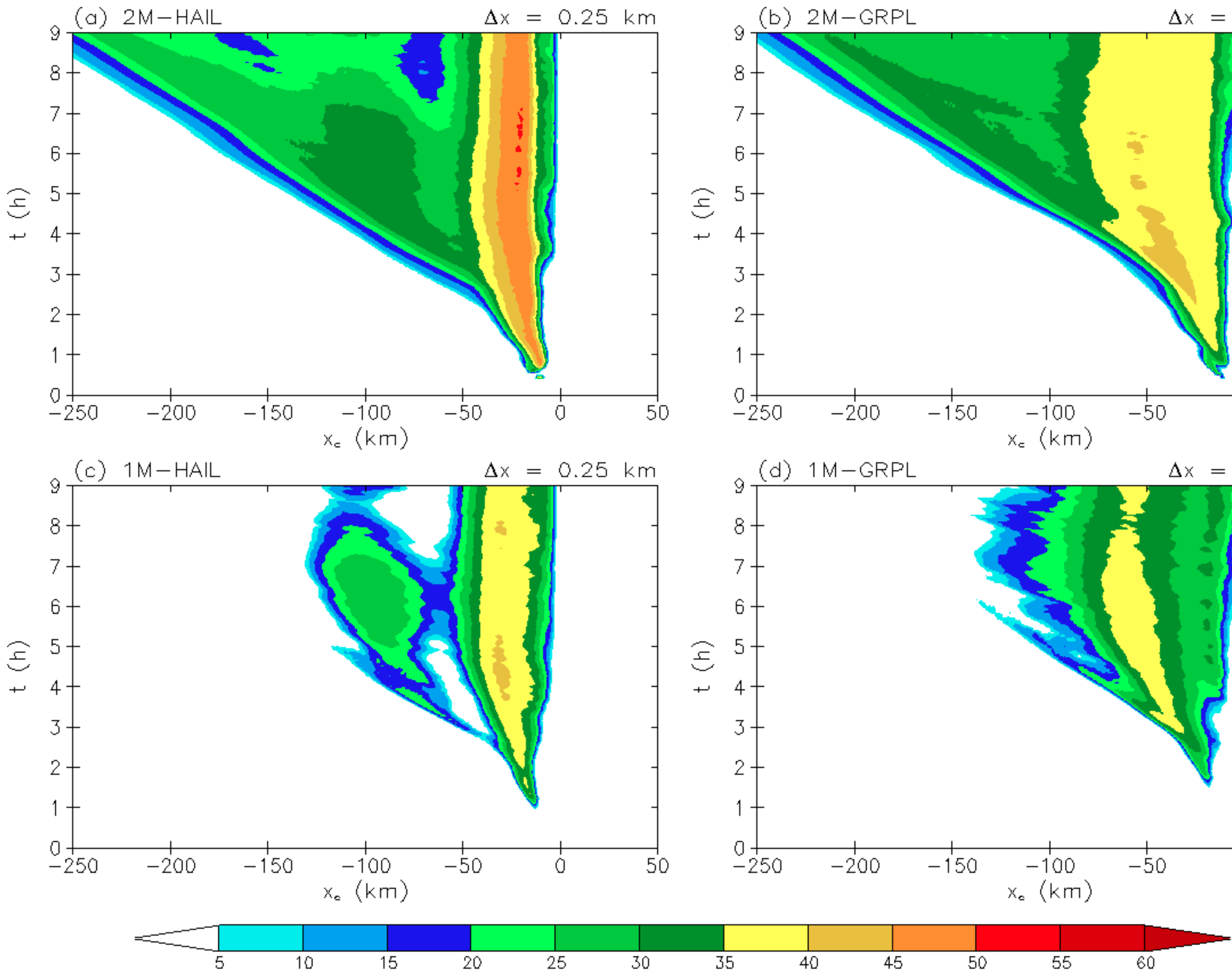
- Microphysics parameterization: Morrison et al. (2009)
  - Species: cloud water, rain water, ice crystals, snow, and graupel/hail
    - GRPL = graupel, HAIL = hail
  - Single-moment scheme (1M):
    - Only total mass is predicted
    - Total number, and size distributions, are *specified*
  - Double-moment scheme (2M):
    - Predicts total mass *and* total number of each microphysical species
    - (size distributions are 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)

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

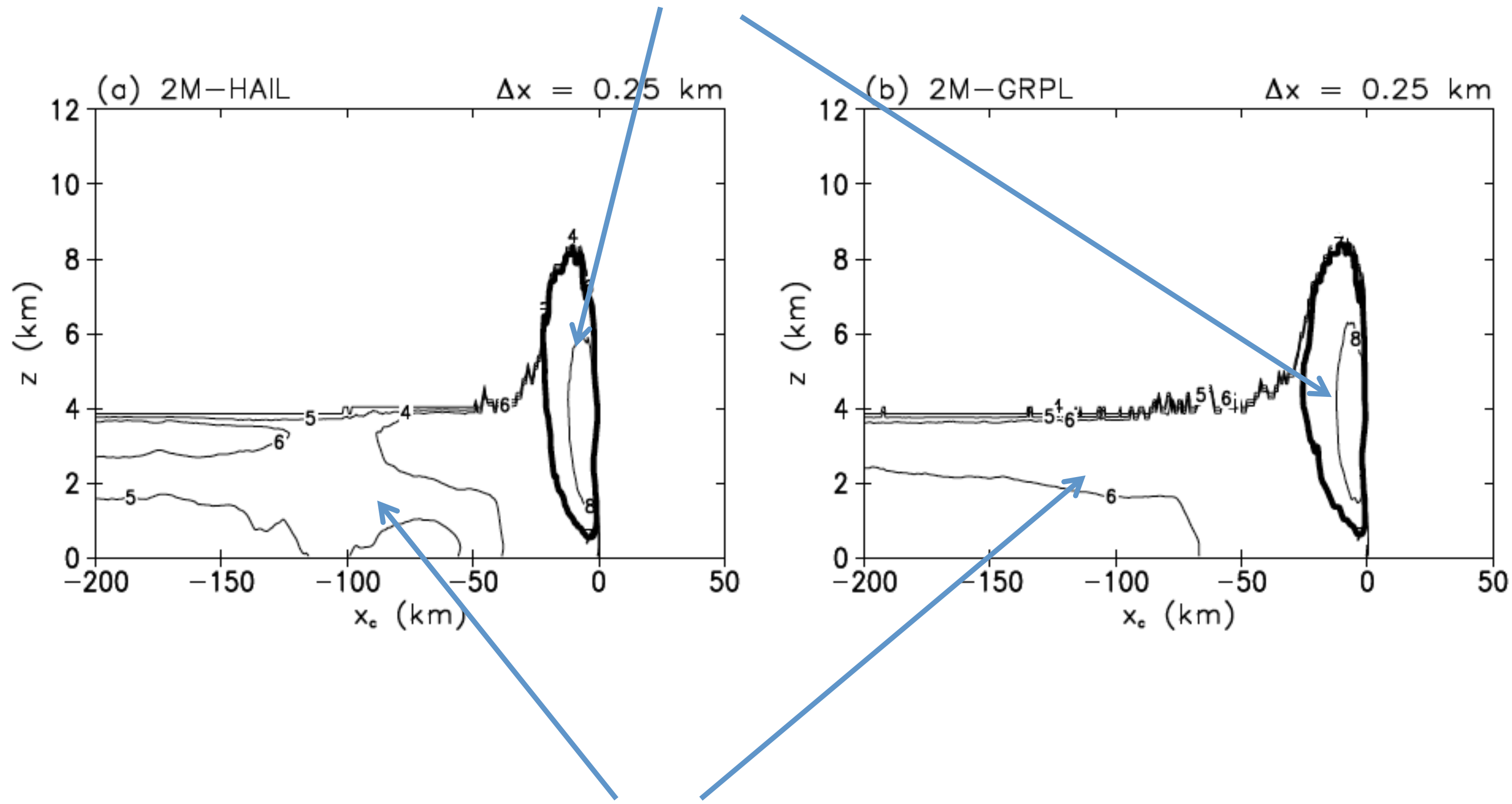


# Hovmoller diagrams:  reflectivity at surface



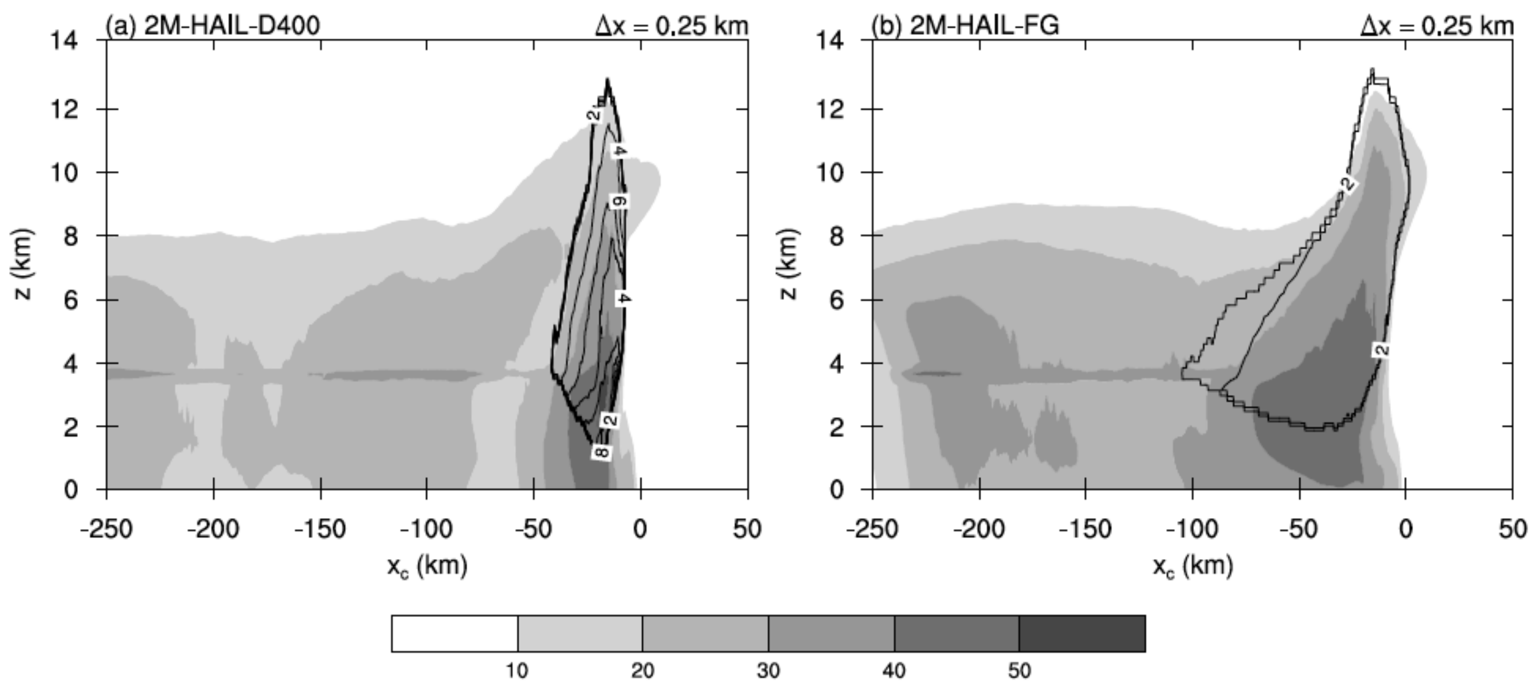
$N_{0r}$ ($\log_{10}$ scale): intercept parameter for rain

small drops in trailing convective region

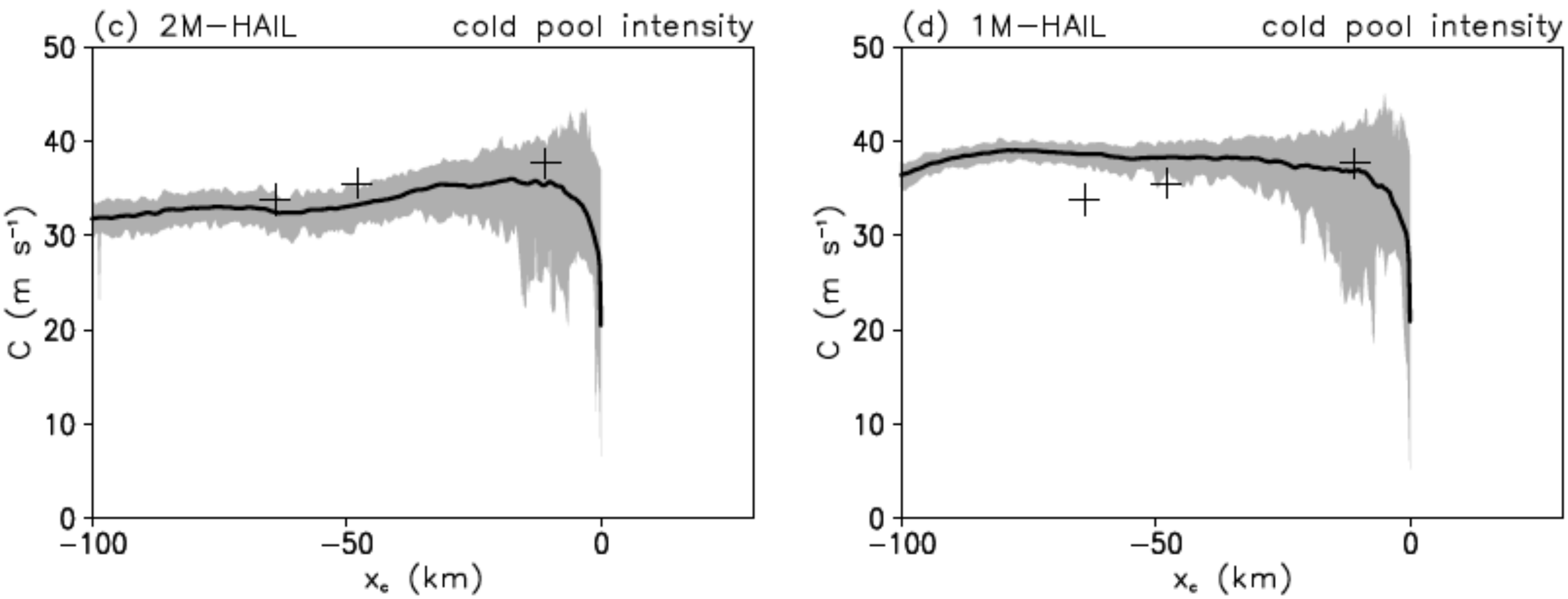



large drops in trailing stratiform region

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



# Cold-pool intensity ($C$)

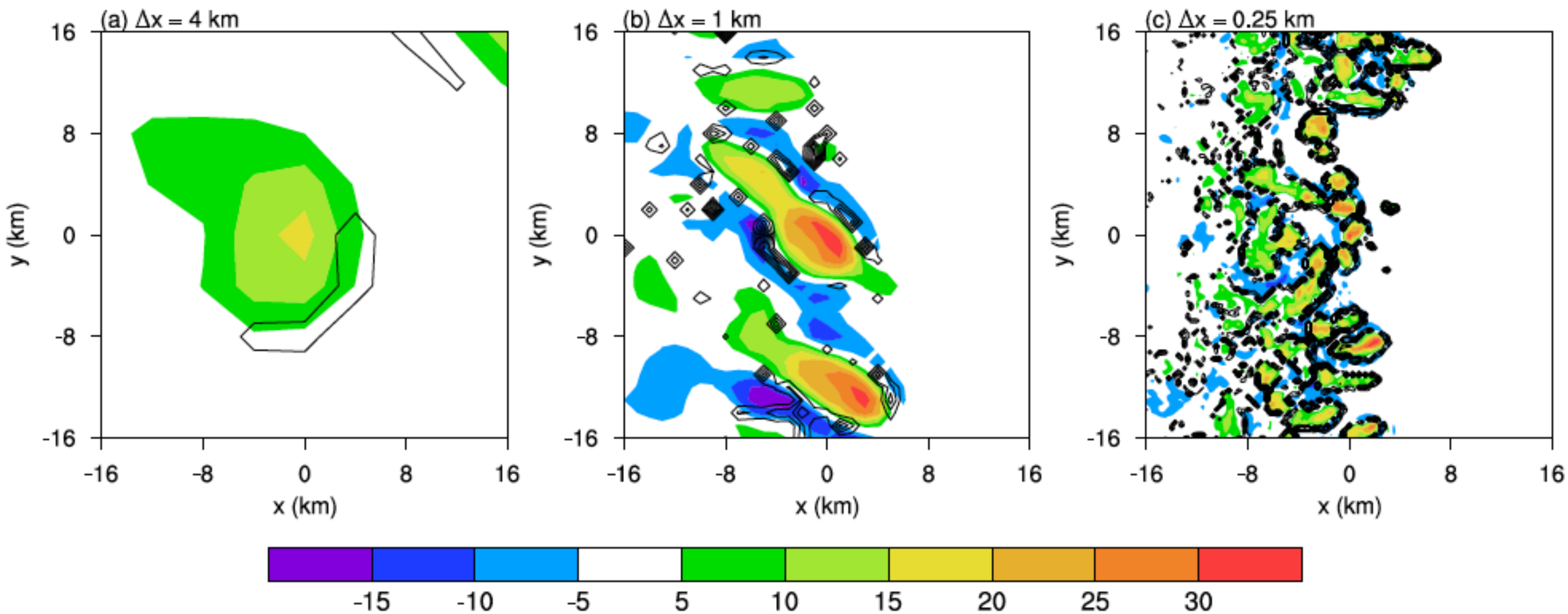



$$C^2 = -2\int_0^h B\, dz$$

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

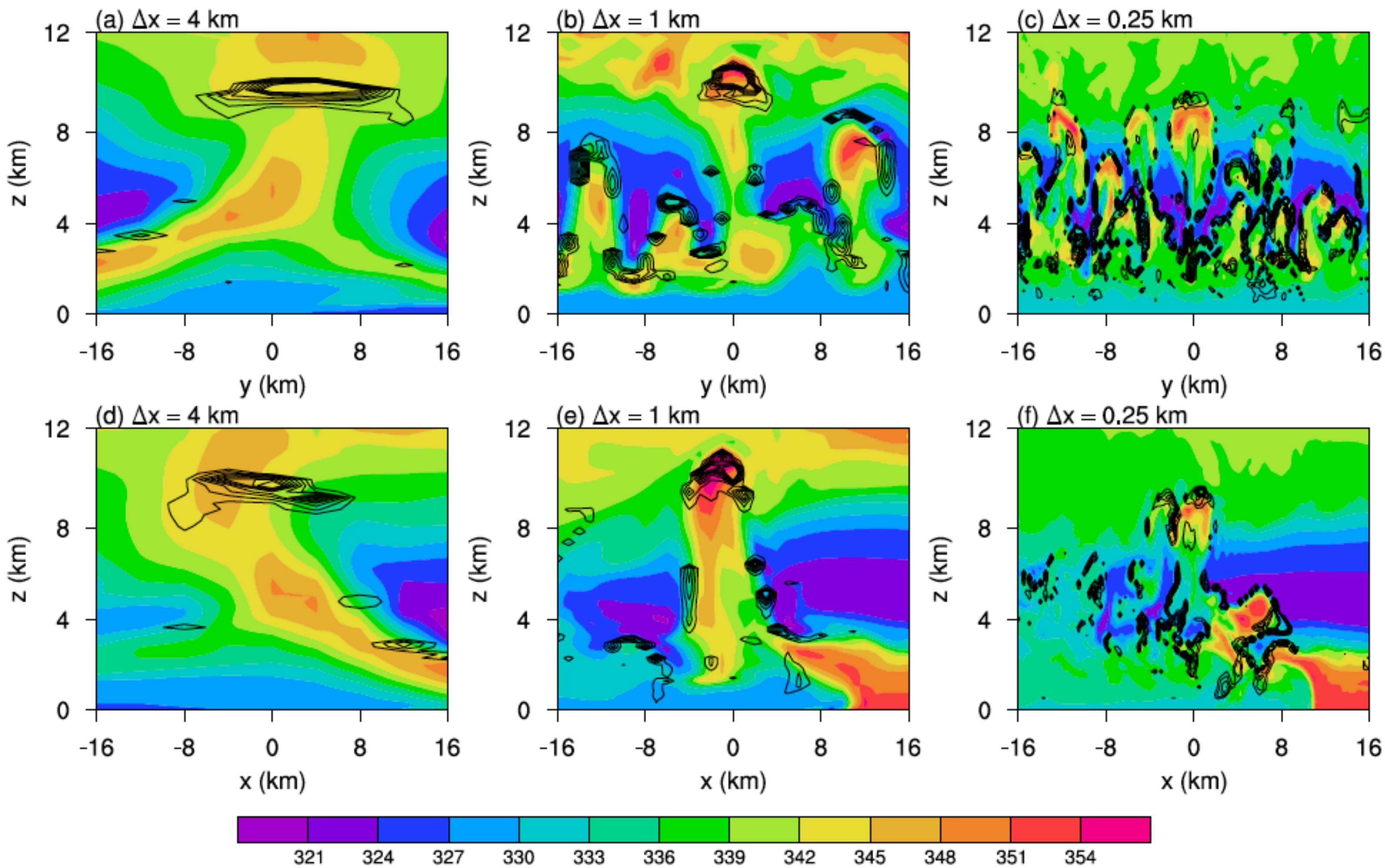
# Sensitivity to Δx: Vertical velocity in mid-levels

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

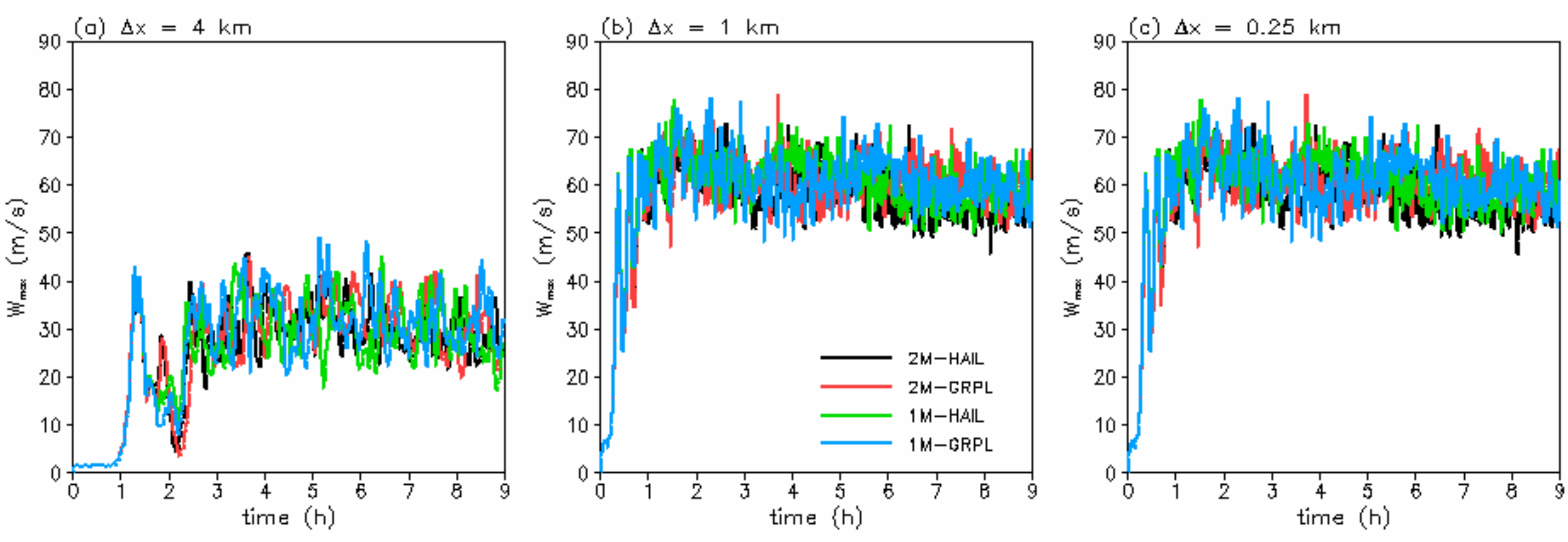


# Sensitivity to Δx:  equivalent potential temperature (shading)

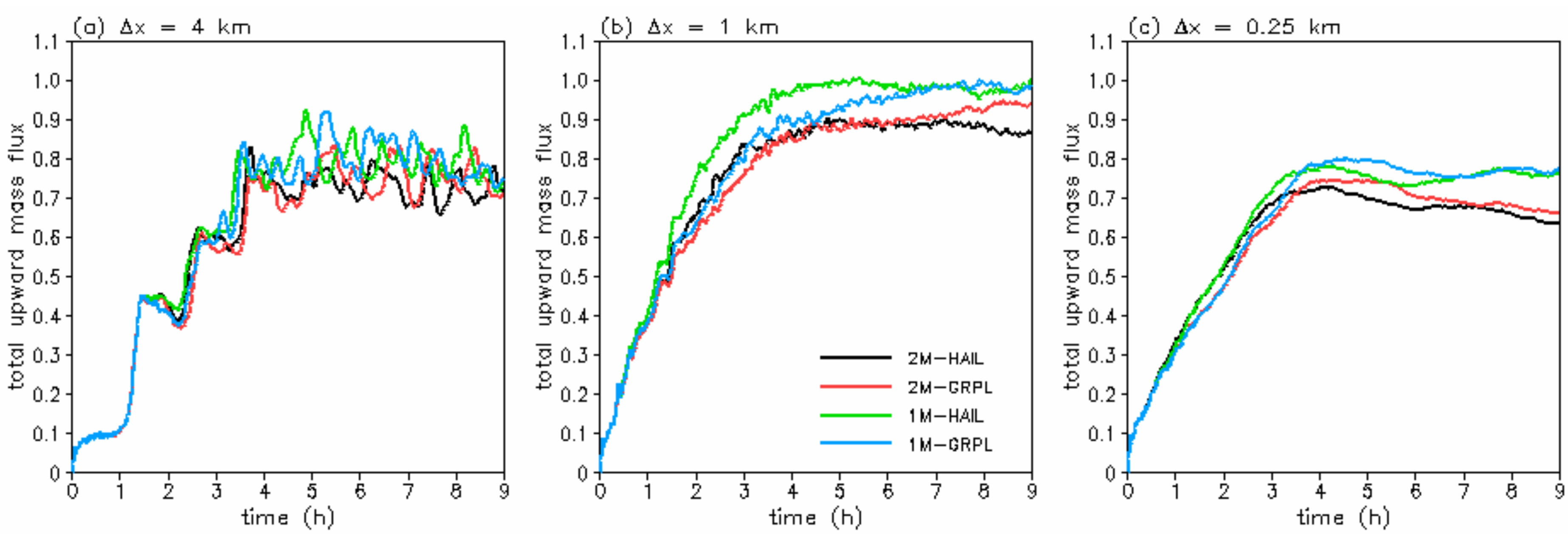
Top:  along-line cross sections
Bottom:  across-line cross sections



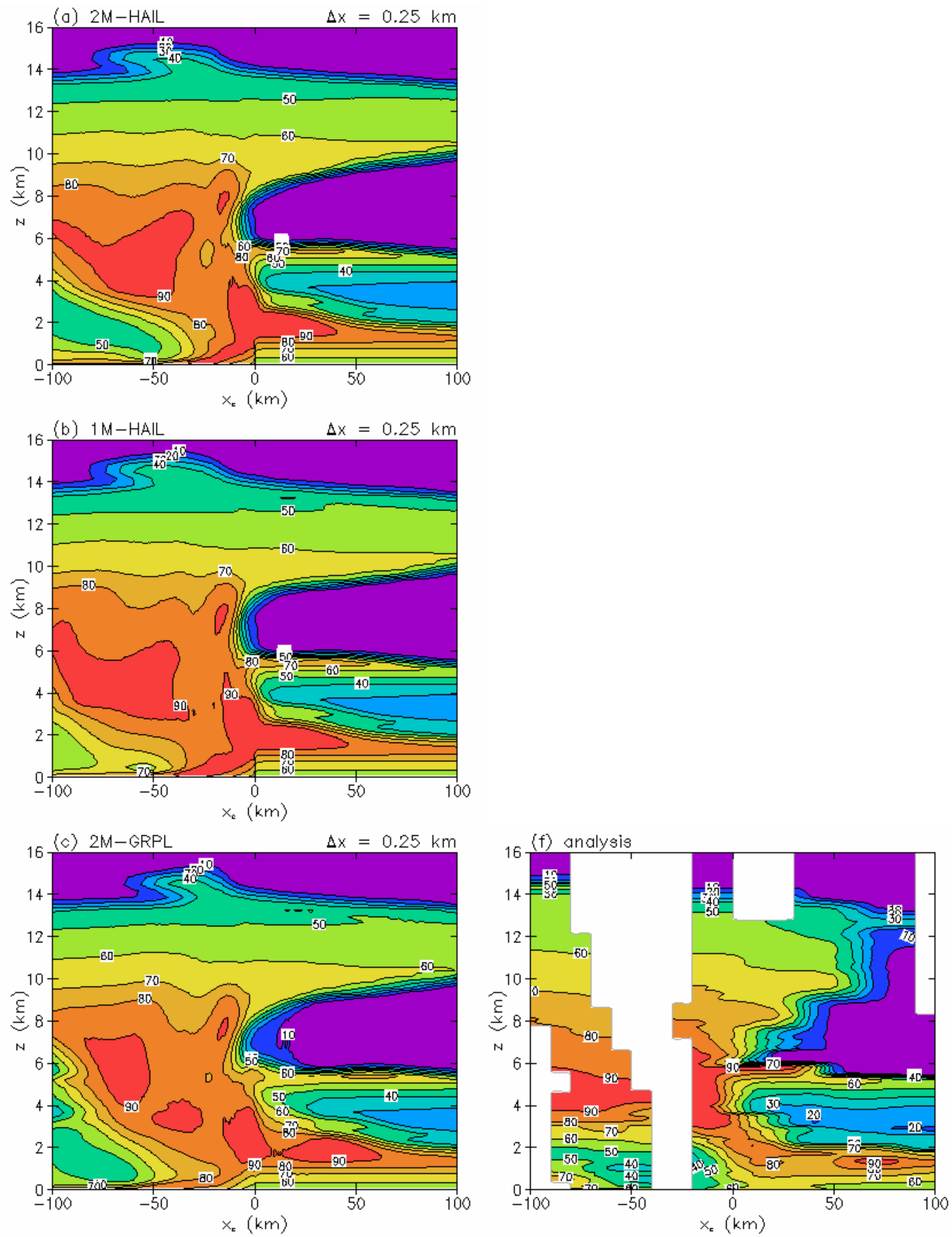
Maximum vertical velocity ($w_{max}$, m $s^{-1}$)



# Total upward mass flux (kg s$^{-1}$)



Relative humidity
(wrt water)  (%)



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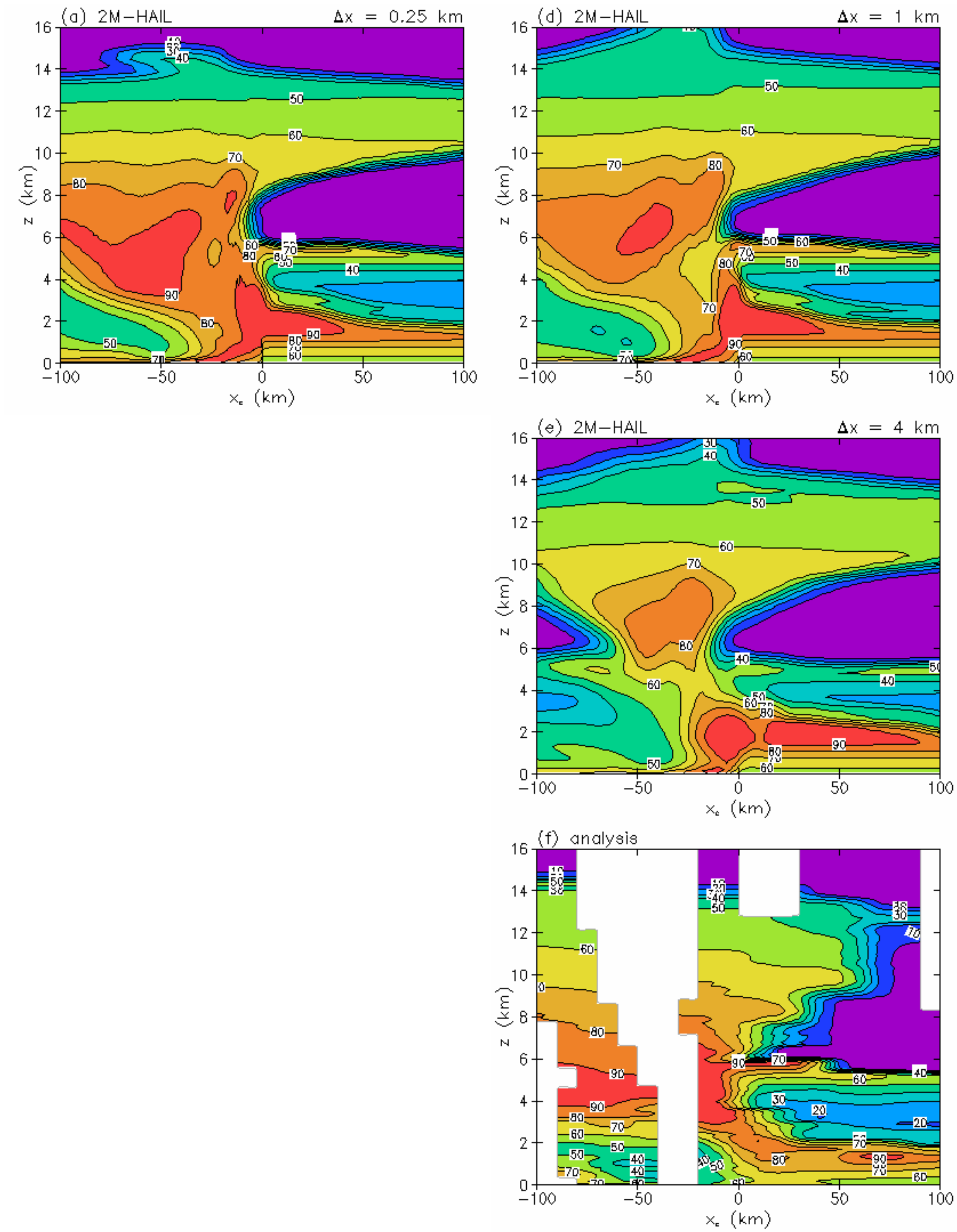
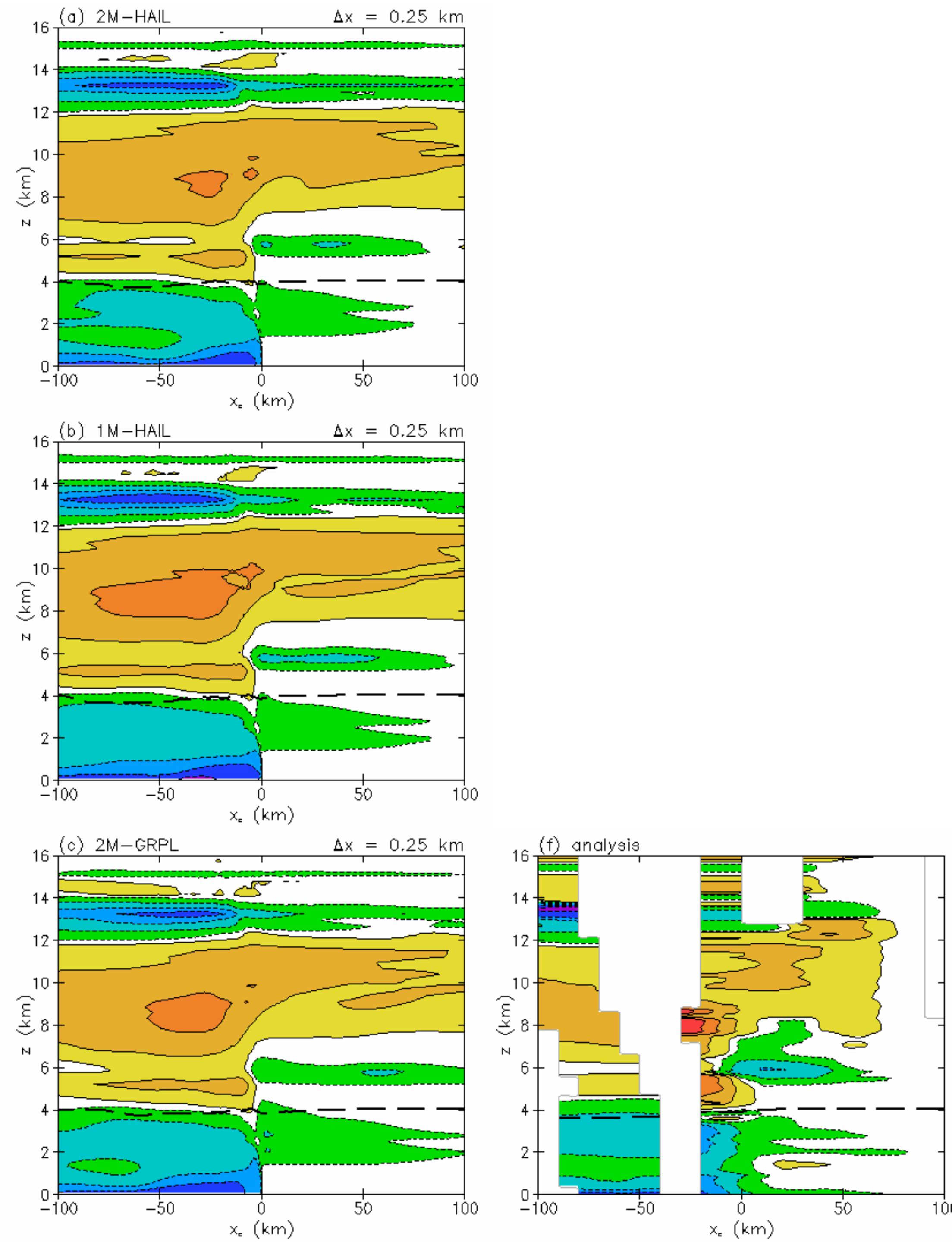


Buoyancy (m s$^{-2}$)
(wrt initial sounding)



Buoyancy (m $s^{-2}$)
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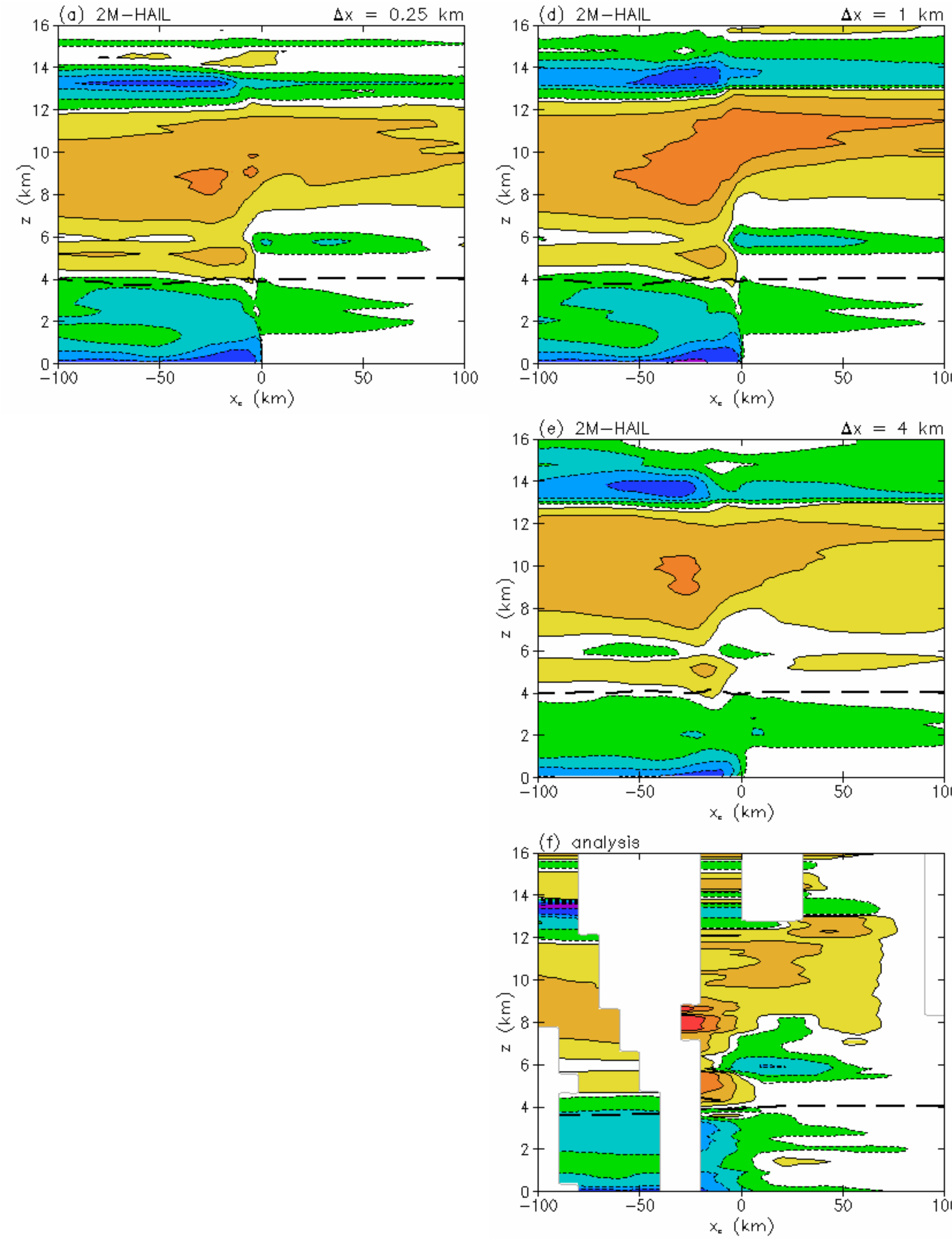
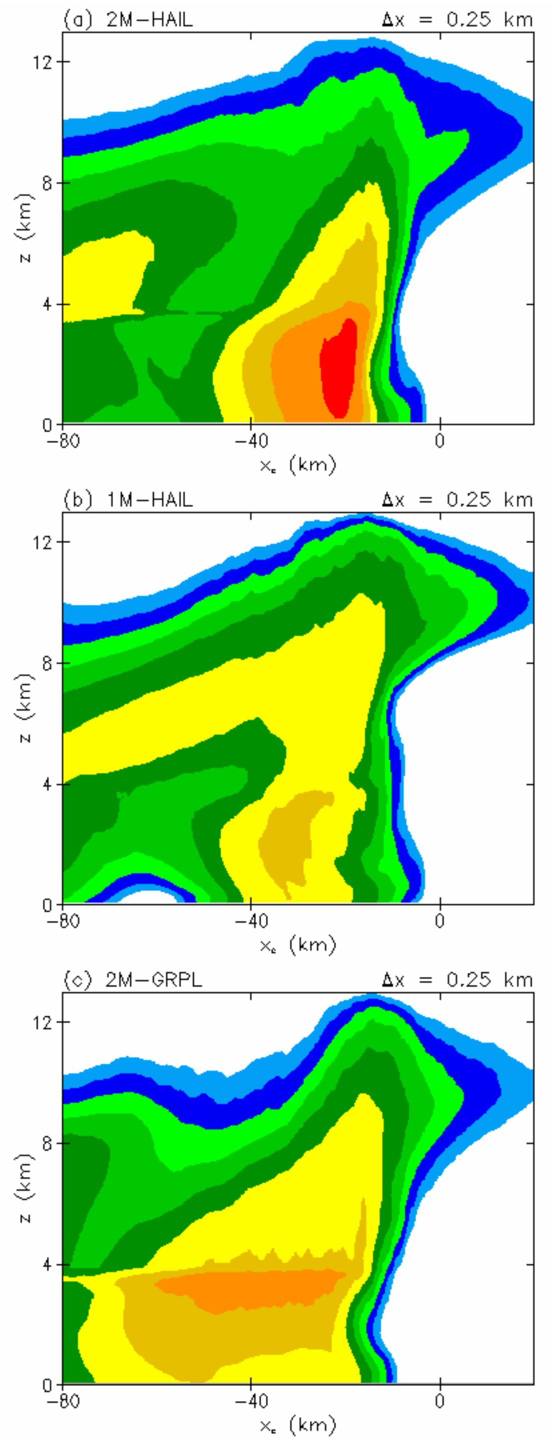
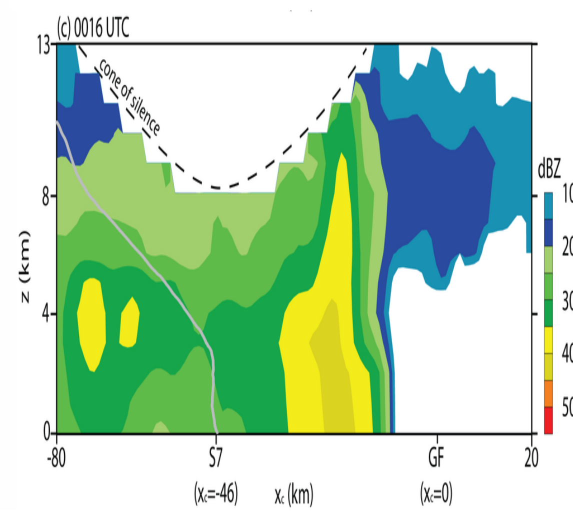


radar reflectivity
(dBZ) (10-cm)



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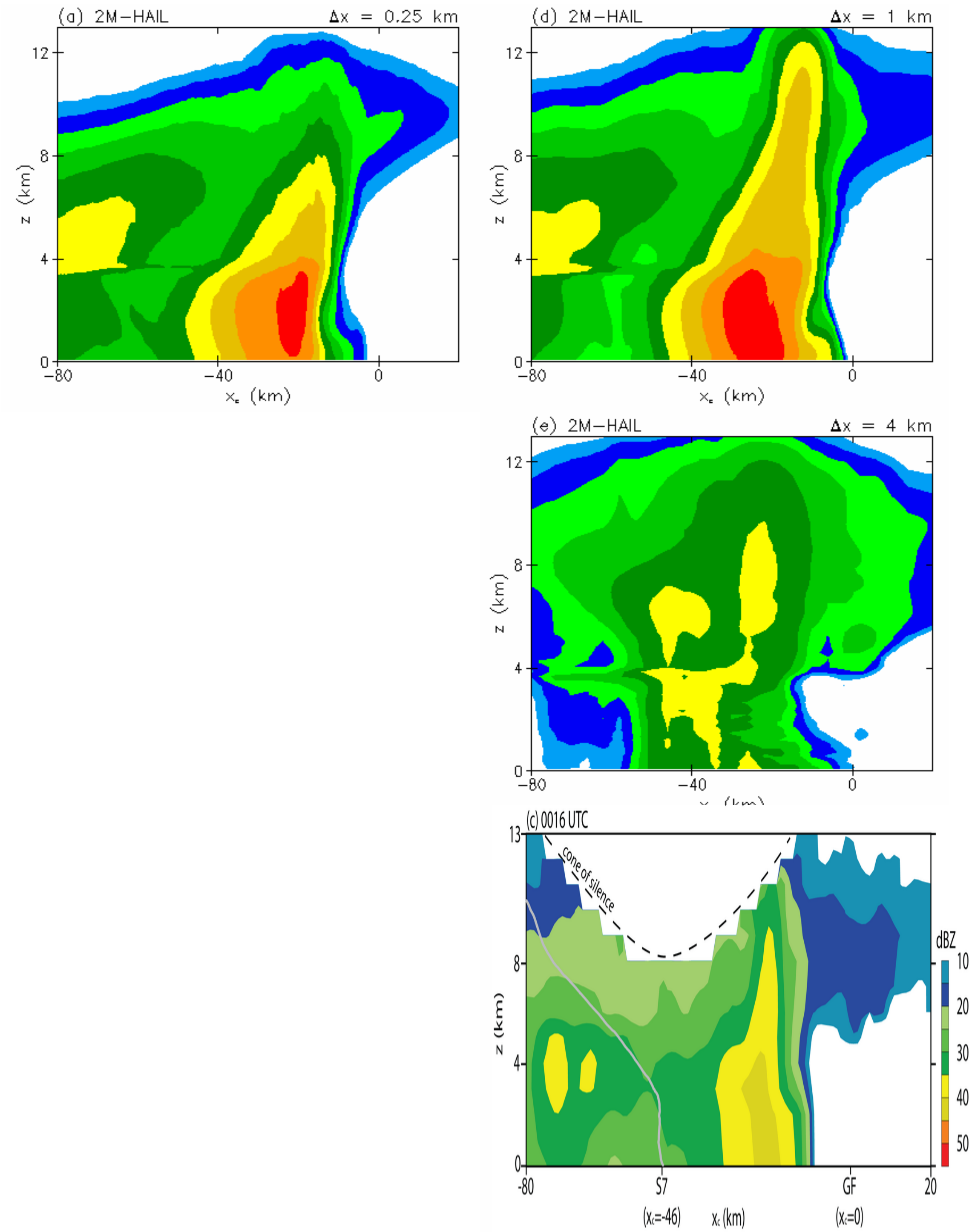
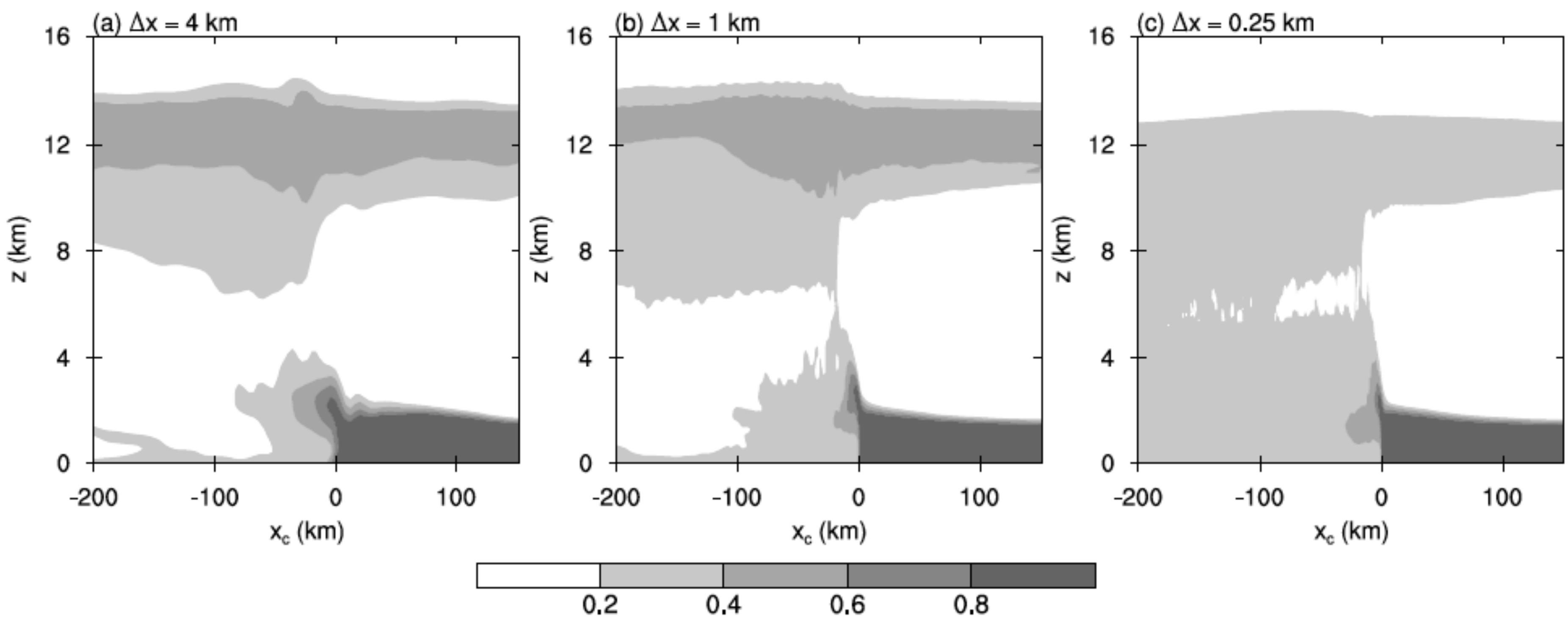
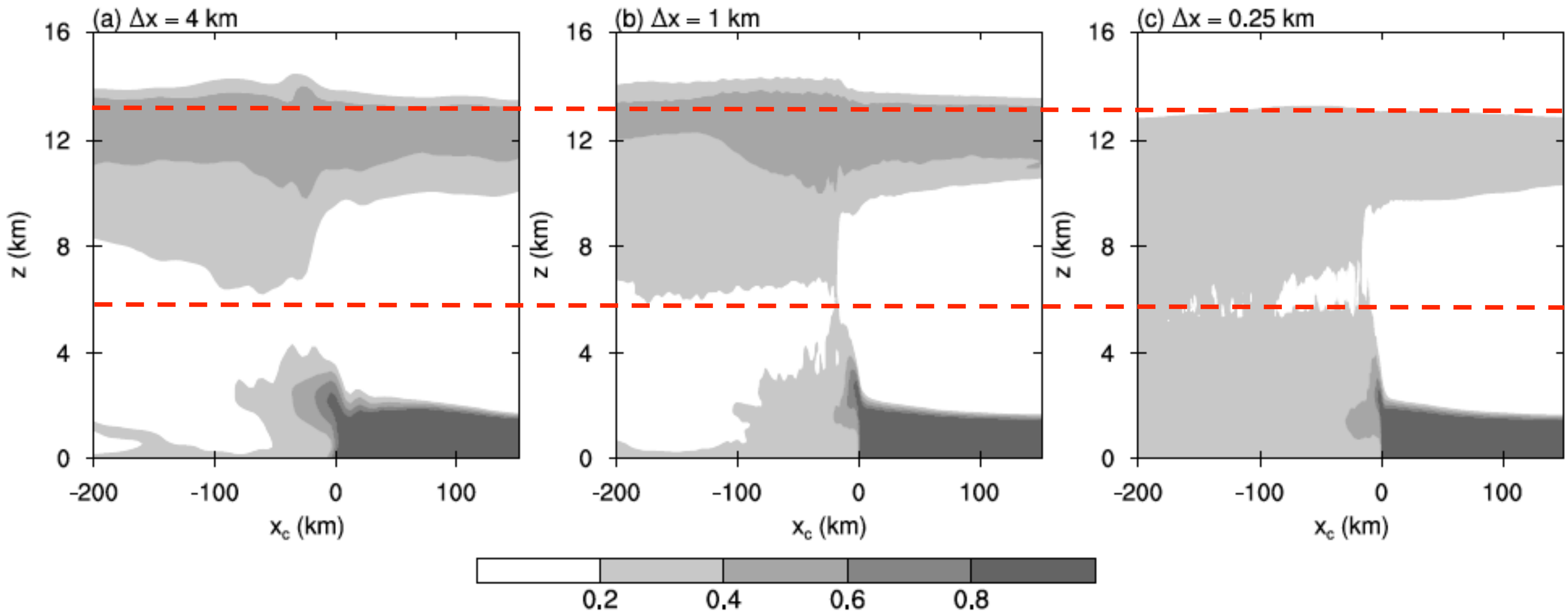


Sensitivity to Δx: passive fluid tracer (g kg$^{-1}$)



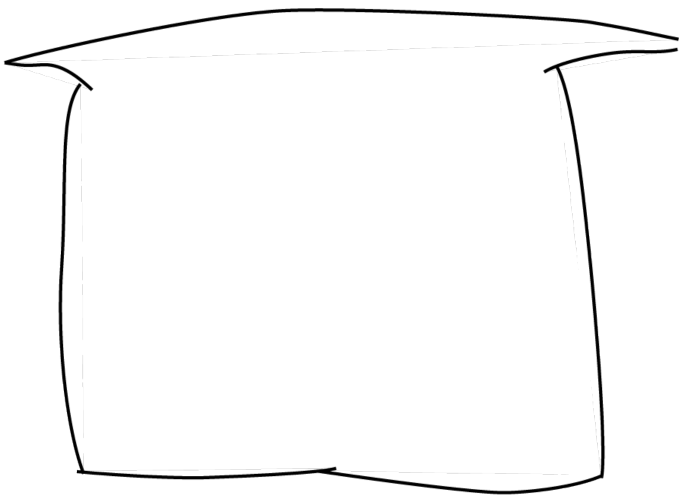
# Sensitivity to Δx: passive fluid tracer (g kg$^{-1}$)



# Conceptual Model of Resolution Dependence

$\Delta \approx 4$ km

(too wide, laminar)

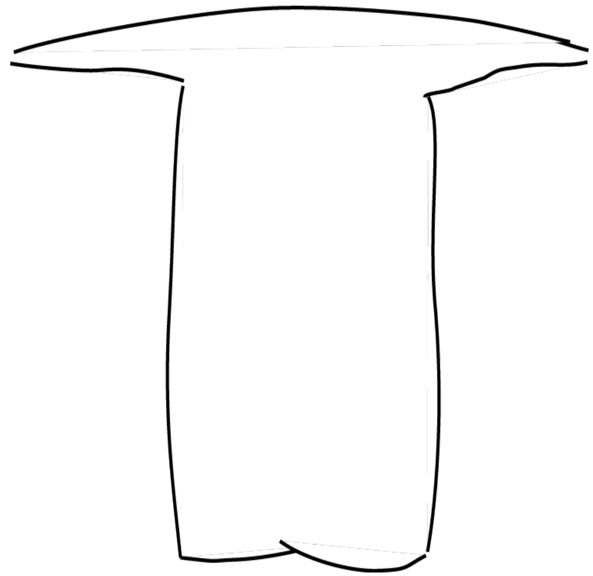


**Consequences:**

→ too slow

$\Delta \approx 1$ km

(correct width, but laminar)



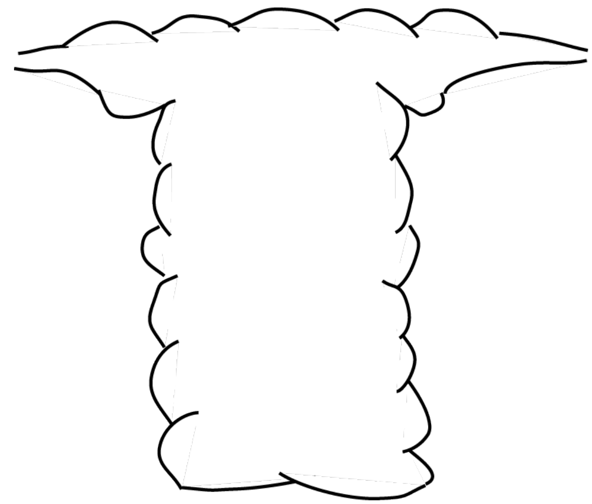
**Consequences:**

→ too intense

→ over-stabilizes

$\Delta \approx 0.1$ km

(turbulent, entraining)



**Consequences:**

→ very expensive