A Review on the Uses of Cloud-(System)-Resolving Models

Jeff Duda

What is a Cloud-Resolving-Model (CRM)?

- General definition: A model with the following properties…
  - Resolution high enough to be able to explicitly resolve individual clouds
    - How high is "high enough"?
      - 4 km grid spacing (Cheng and Cotton 2004)
      - O(1 km) (Guichard et al. 2004)
  - Domain large enough to include a cloud system (ensemble of clouds)
  - Simulation run long enough to cover many cloud lifecycles

Uses Highlighted in this Literature Review

- Dimensionality
- Cloud Resolving Convection Parameterization (CRCP)
- Shallow convection
- Shallow-to-deep convection transition
- Weather forecasting (sensitivity of convection to moisture)

Dimensionality

- 2D vs. 3D – which is best?
  - First point: take the extra resources saved from not using three dimensions and use them for higher resolution
    - Higher resolution → higher resolved vertical motion
      - Higher cloud mass flux values for 2D simulations (Grabowski and Wu 1998)
- Little in the way of significant differences between 2D and 3D CRMs
  - Some additional exceptions are notable, however

Dimensionality

- Other notable exceptions:
  - 2D CRMs warmer and drier (Tompkins 2000; Khairoutdinov and Randall 2003)
  - 2D CRMs prefer to simulate two-dimensional convection (e.g., squall lines)
    - 3D CRMs tend to outperform when simulating three-dimensional convection (random, scattered convecton, mesoscale convective complexes, isolated cellular thunderstorms) (Tompkins 2000)
  - 2D CRMs too fast in the shallow-to-deep convection transition (compared to 3D CRMs) (Xu et al. 2002; Grabowski et al. 2006)
  - Petch (2006): "minimum benchmark simulation" – use 3D
    - 2D CRMs suppressed convection more than 3D CRMs

Dimensionality

- Seems like 3D is the way to go…
- But wait!
  - Grabowski et al. (2006): “it is difficult to separate the statistics and physics of 2D and 3D CRM simulations for a given case, so expect some differences regardless”
  - Xu et al. (2002): despite the early transition in 2D CRMs, behavior of deep convection simulated very similarly to that of 3D CRMs.

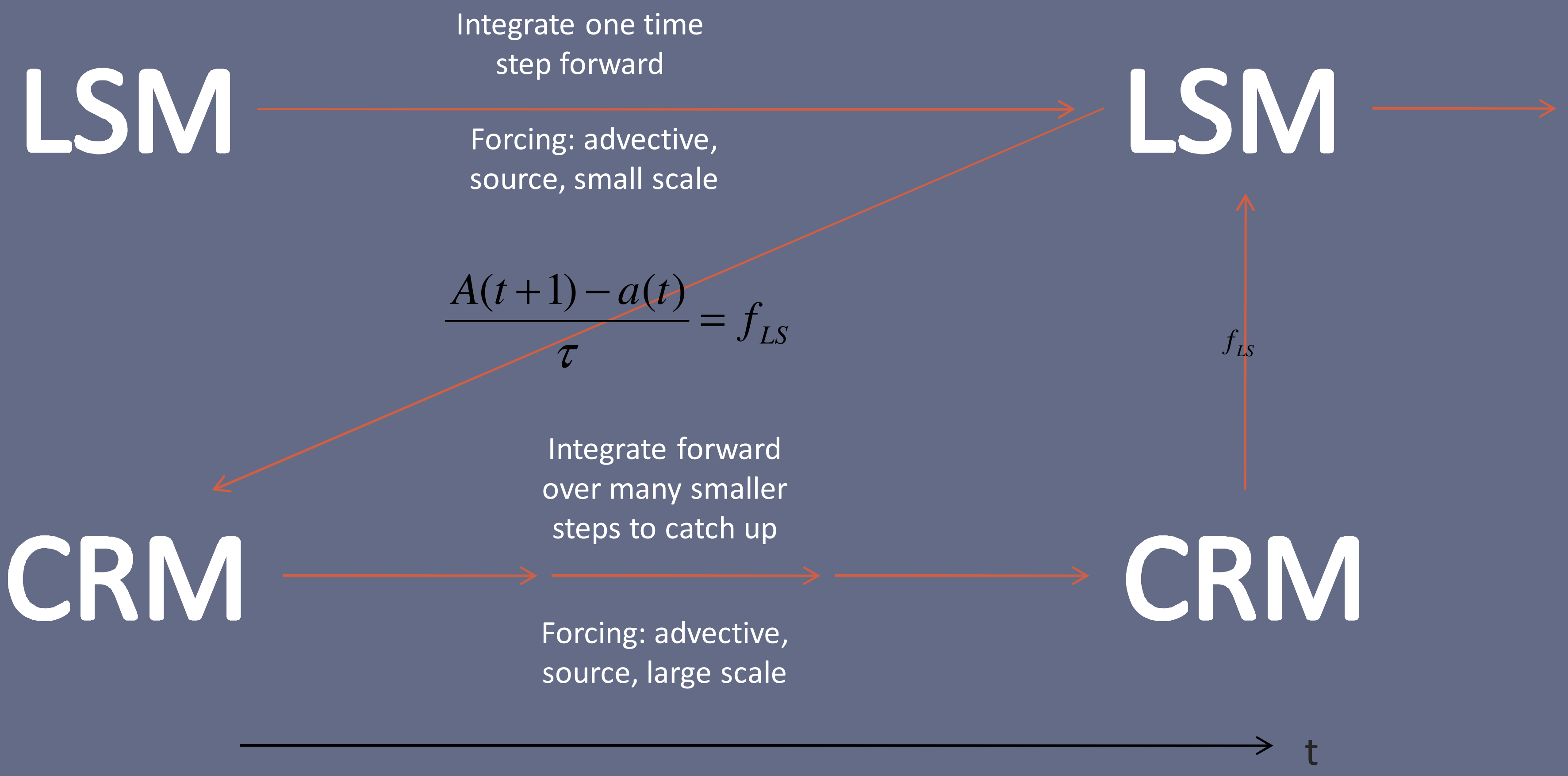
Cloud Resolving Convection Parameterization (CRCP)

“Superparameterization”

- Grabowski and Smolarkiewicz (1999): let’s insert a 2D CRM into the individual grid columns of a GCM (or other large scale model)!
  - Hence born was CRCP
- Enables explicit simulation of convection, better climate studies
- Uses less resources than running a GCM at CRM-resolution
  - About 10^3 to 10^4 fewer computations (Randall et al. 2003)

How does it work?

Grabowski (2004)



LSM

Integrate one time step forward

Forcing: advective, source, small scale

LSM

$$\frac{A(t+1)-a(t)}{\tau}=f_{LS}$$

CRM

Integrate forward over many smaller steps to catch up

Forcing: advective, source, large scale

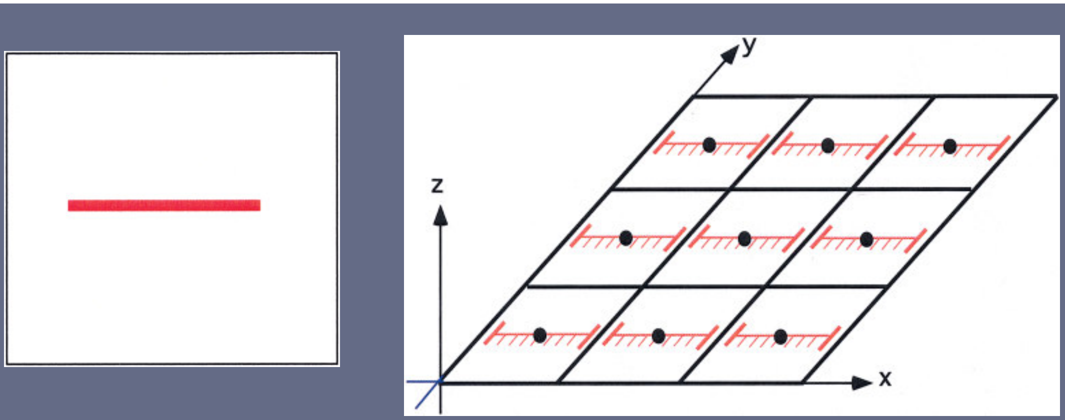
CRM

Coupling requirement: $\langle a(x,y,z,t)\rangle_{X,Y}=A(X,Y,Z,t)$

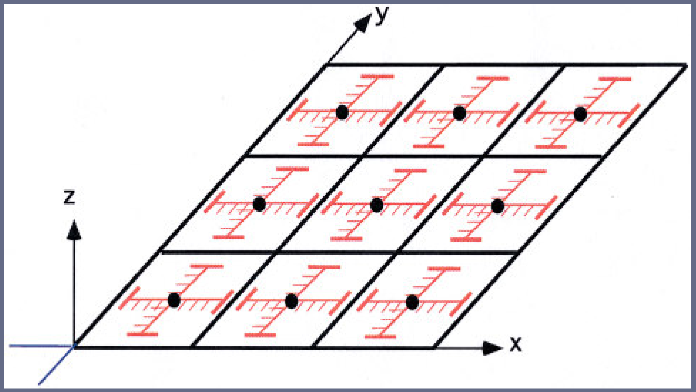
CRCP

- Problem: the CRMs don’t “talk” to each other
- Problems getting MCSs to propagate between LSM grid columns (Grabowski 2001)
  - Cold pools not propagating
- What about orientation?
  - West-east vs. along the lower troposphere mean wind vector
  - Weaker westerly winds in MJO for the latter (Grabowski 2004)
  - Little differences otherwise
- Arakawa in Randall et al. (2003): let’s just bypass this

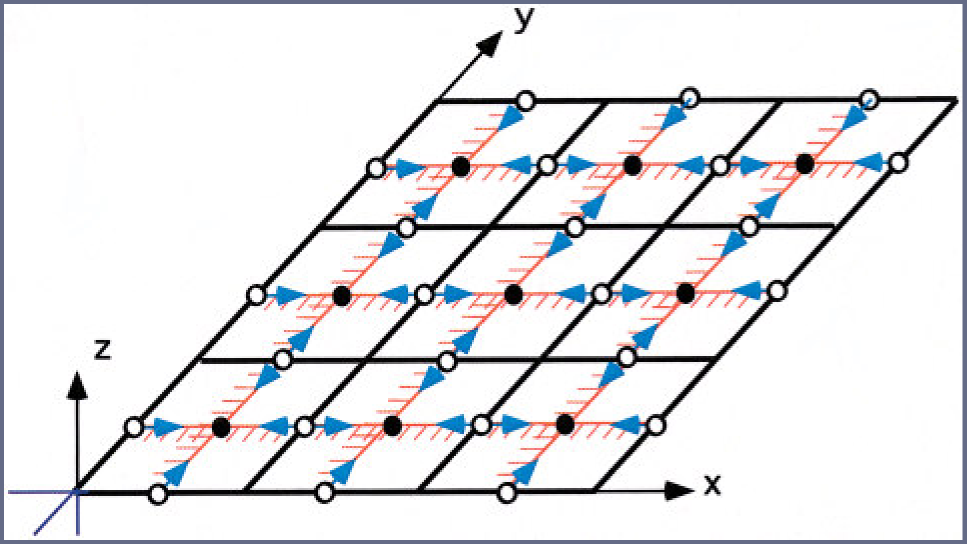
Single LSM grid column
with embedded 2D CRM



Add in second set of 2D CRMs
oriented perpendicular to the
first set



Extend 2D CRMs to
edges of LSM grid
columns



Shallow convection

- Model intercomparison studies
  - Do compare CRMs with single-column models (SCMs), but not meant to compare individual CRMs
- Resolution requirements
  - 2 km (horizontal) and 100 m (vertical) not good enough (Guichard et al. 2004)
  - 500 m (horizontal) is good enough (Grabowski et al. 2006)
  - O(100 m) (Bryan et al. 2003)

Shallow convection

- HIGH resolution!

Reference	Horizontal grid spacing	Vertical grid spacing
Stevens et al. (2001)	100 m	20 m
Brown et al. (2002)	66.7 m, 100 m	40 m
Siebesma et al. (2003)	100 m	40 m
Guichard et al. (2004)	250 m	47 m, 75 m, 102 m
Grabowski et al. (2006)	50 – 400 m	25 – 100 m
Kuang and Bretherton (2006)	100 m	50 m (below 12 km)

  - Don’t need all that extra space
  - Sufficient or in the ballpark

Shallow convection

- Entrainment rate: 2.0 km^{-1} at cloud base and decreasing with height (Stevens et al. 2001; Siebesma et al. 2002; Kuang and Bretherton 2006)
- Similar vertical profiles of cloud mass flux (above + Brown et al. 2002 and –KB06)
  - Only differences seem to be a scalar
  - Oh yeah, and 50% of cloud was “core”

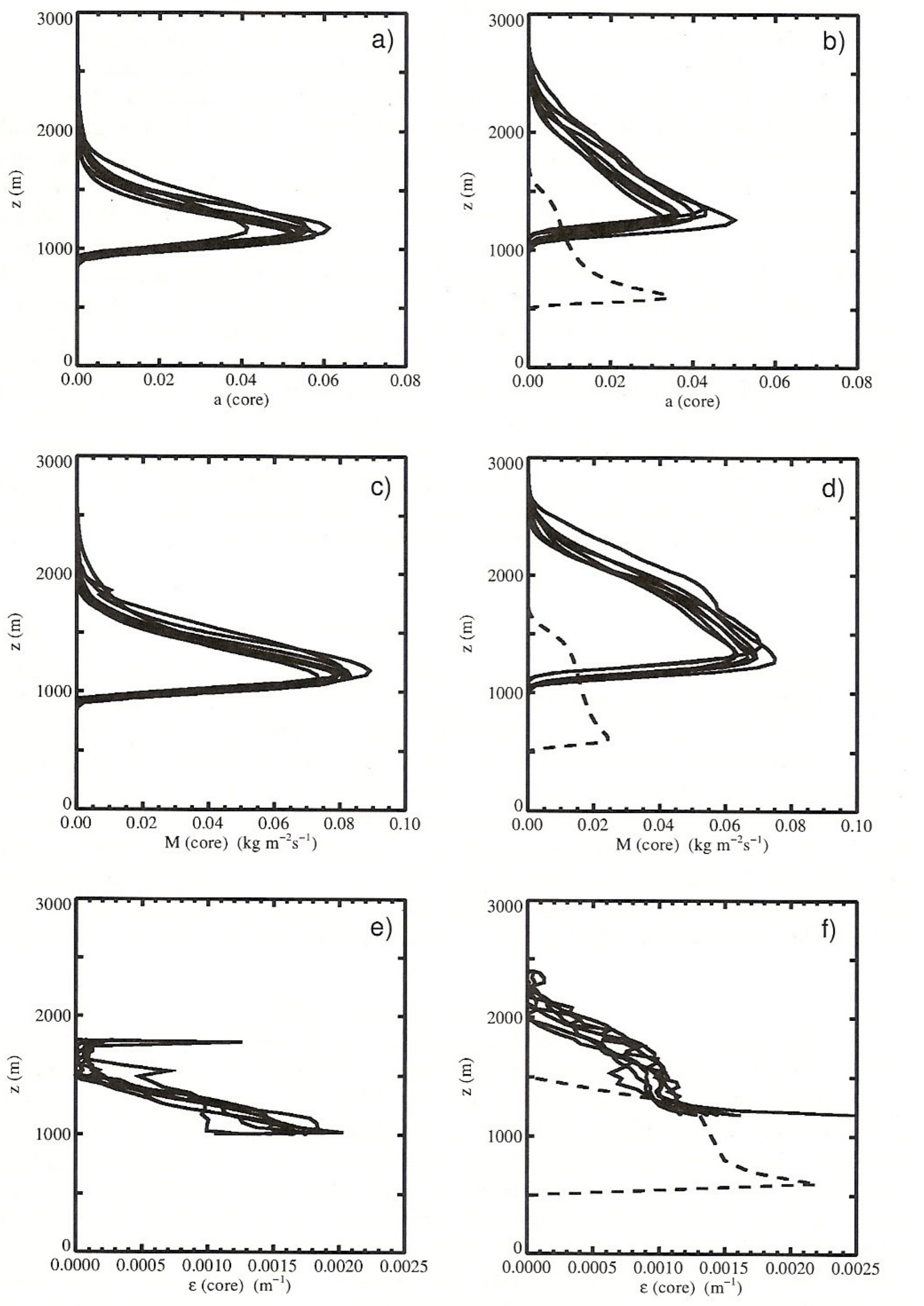
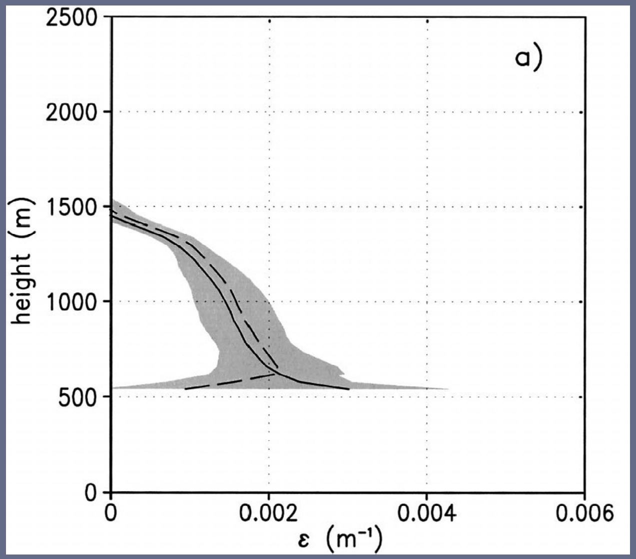
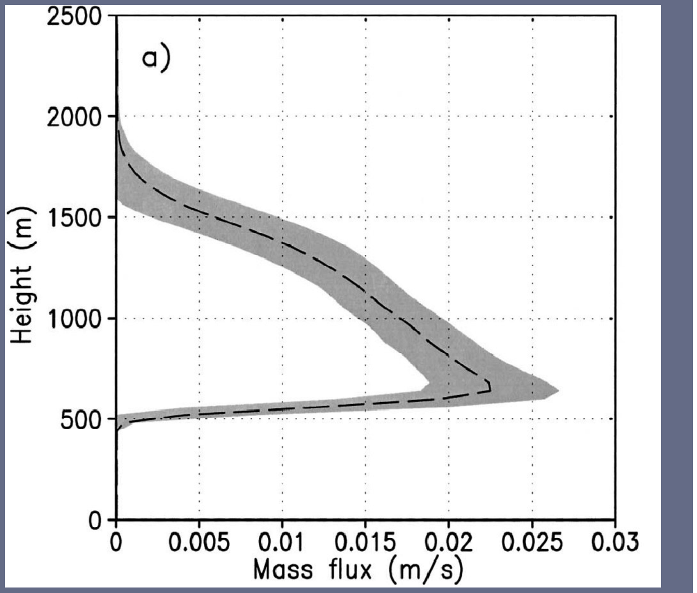


Figure 8. Profiles from the eight models at 1830 UTC (left column) and 2030 UTC (right column). (a)–(b) core fraction, (c)–(d) core mass flux and (e)–(f) core fractional entrainment rate. In the right column the dotted lines show the BOMEX results (simulation HR-CONV) from Brown (1999a).



Siebesma et al. (2003)



Brown et al. (2002)

Shallow-to-deep convection transition

- Usually marked by increase in cloud mass flux above cloud base, increase in liquid and ice water path, precipitation rate, widening of clouds, and increase of center of mass of clouds and maximum cloud top height (Grabowski et al. 2006; Khairoutdinov and Randall 2006)
- Subtle moistening of boundary layer noted just before transition (Guichard et al. 2004; G06; Khairoutdinov and Randall 2006)

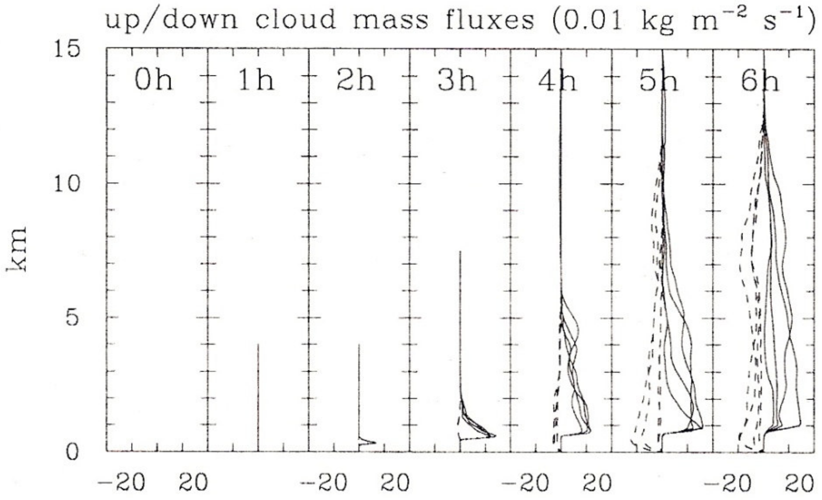


Figure 9. Evolution of the updraught (solid lines) and downdraught (dashed lines) cloud mass-flux profiles averaged over the four benchmark simulations.

Grabowski et al. (2006)

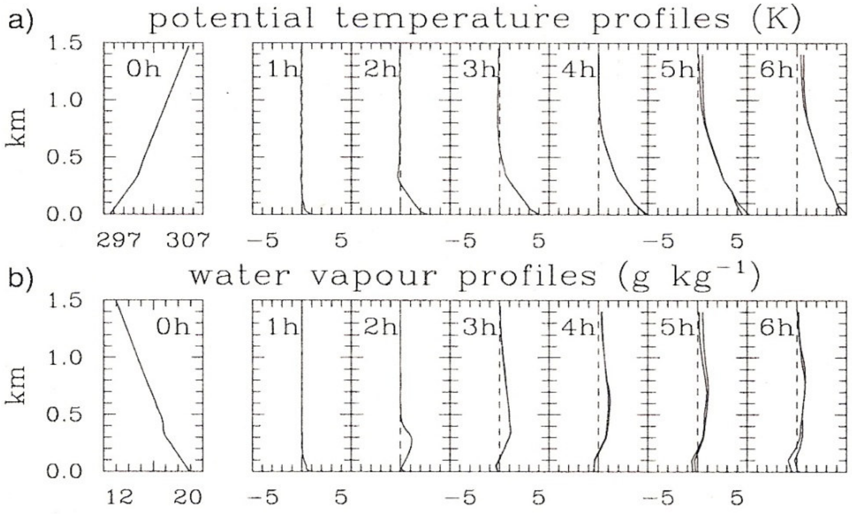
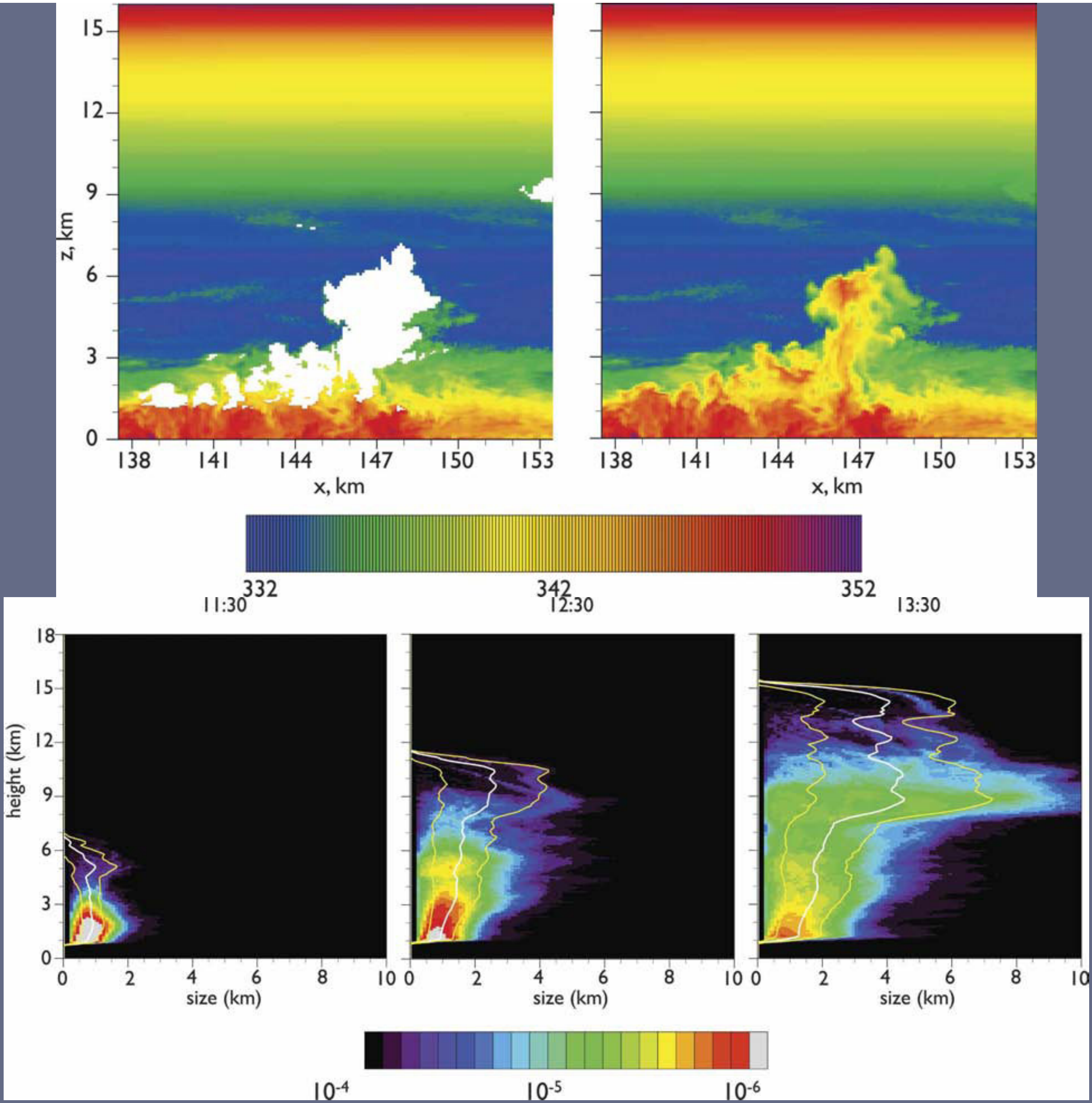


Figure 4. Evolution of the lower-tropospheric (a) potential-temperature and (b) water-vapour mixing-ratio profiles for four benchmark simulations. The profiles are plotted as deviations from the initial profiles to better expose the changes due to boundary-layer and cloud processes.



Khairoutdinov and Randall (2006)

Shallow-to-deep convection transition

- Kuang and Bretherton (2006): truly undiluted parcels rare – don’t contribute much
- Khairoutdinov and Randall (2006): least diluted parcels had entrainment rate of 0.1 km^{-1}
- Despite favorable thermodynamic profiles, deep convection occurs late. Why?
  - Entrainment and dynamics (cold pool really spurs development)

Weather forecasting

- CRMs used to investigate the effects of moisture on deep, moist convection (Texas and Oklahoma panhandles)
  - High soil moisture suppresses convection, NCMC along boundary enhances convection (Cheng and Cotton 2004)
    - Convection preferred over areas of high sensible heat flux
  - Problem: other studies have said just the opposite…
  - Solution: Findell and Eltahir (2003a): climatology

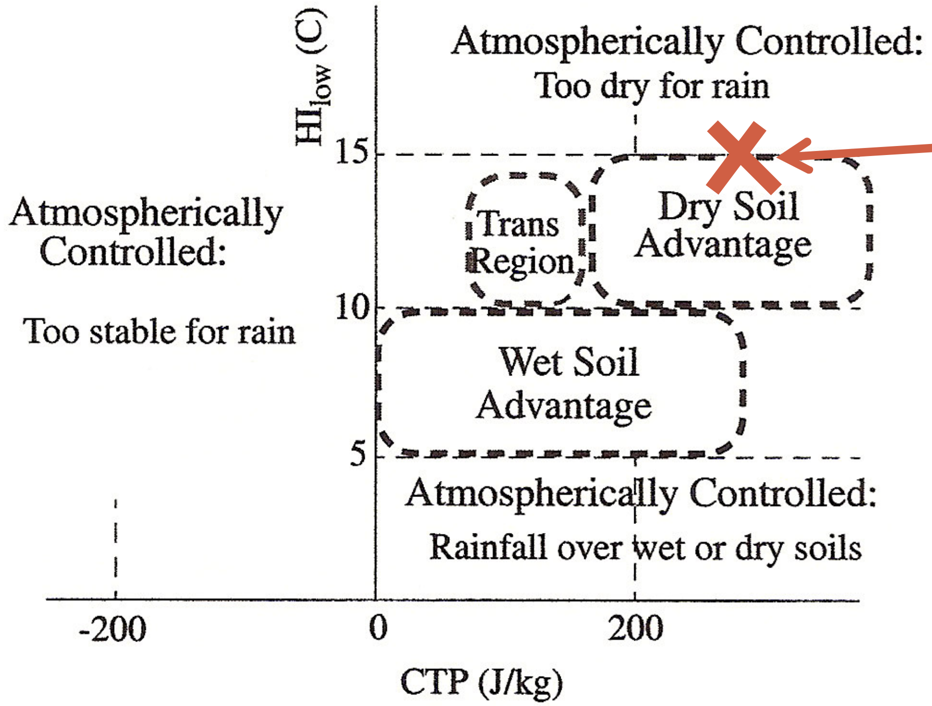


FIG. 20. The CTP–HI$_{low}$ framework for describing atmospheric conditions in soil moisture–rainfall feedback [taken from Fig. 15 of Findell and Eltahir (2003a)].

Texas and Oklahoma panhandle region here

Cheng and Cotton (2004)

Weather forecasting

- Deep moist convection VERY sensitive to tropospheric RH (Derbyshire et al. 2004)
    - Difference between RH = 25%, 50%, 70%, 90% results in a difference between deep convection and shallow convection only

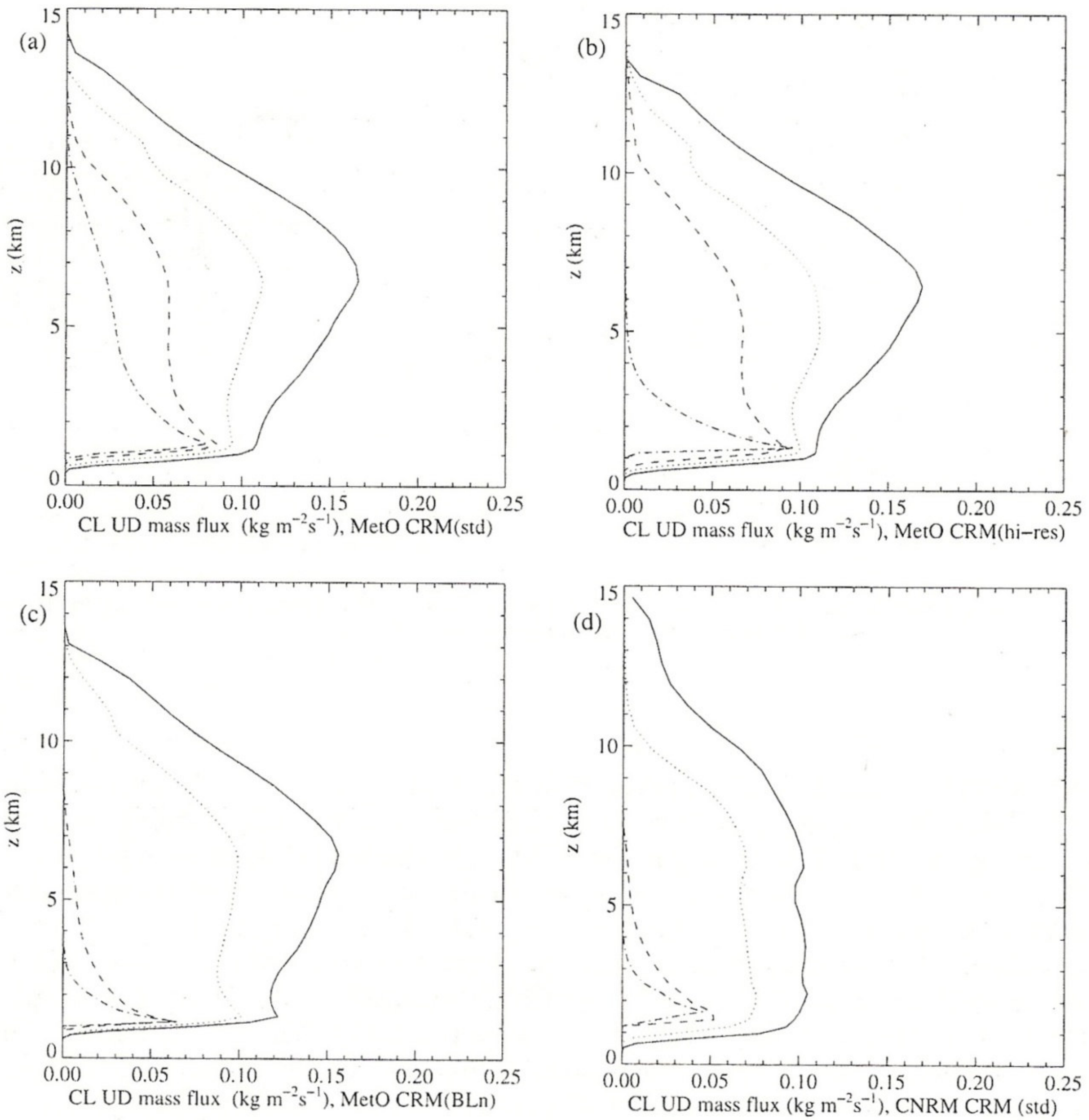


Figure 4. Cloudy updraught mass flux profiles for the four RH_t values in the cloud-resolving models (CRMs): the Met Office CRM at (a) 500 m, (b) 250 m, (c) 500 m with boundary-layer nudging (see text), and (d) the CNRM–GAME CRM at the standard 500 m horizontal resolution (line definitions as in Fig. 1). Note that all four plots are on the same scales.

Solid – 90%
Dotted – 70%
Dashed – 50%
Dashed-dotted – 25%

Derbyshire et al. (2004)

Summary

- CRMs used heavily in research for their high resolution
    - Dimensionality (2D vs. 3D)
    - CRCP
    - Otherwise modeling shallow and deep convection
    - Operational weather forecasting models will soon be in the CRM resolution range

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