An Overview of Convection Parameterization

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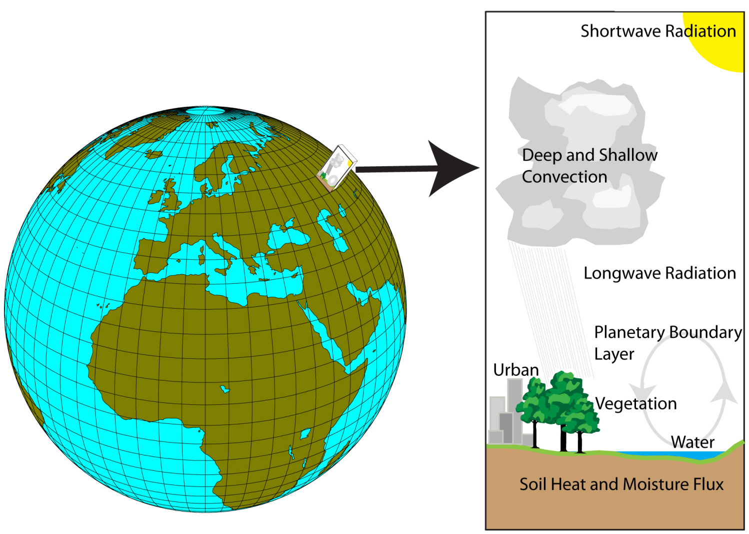
Convection...

...acts to redistribute heat and moisture vertically and produce rainfall.

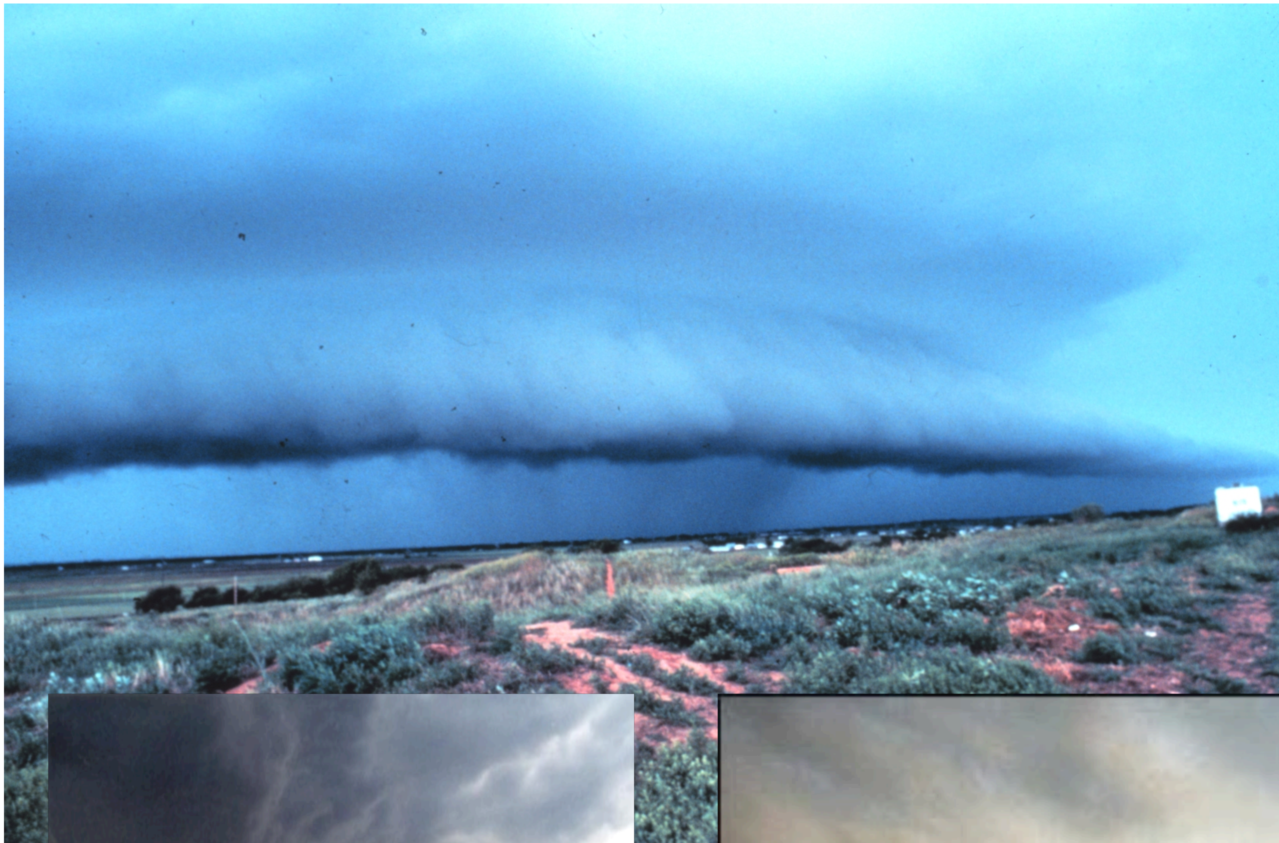
- Convective parameterization is a technique used in NWP to predict the collective effects of (many) convective clouds that may exist within a single grid element … *as a function of known model variables.*

  – Needed to produce effects of convection prior to grid-scale saturation.



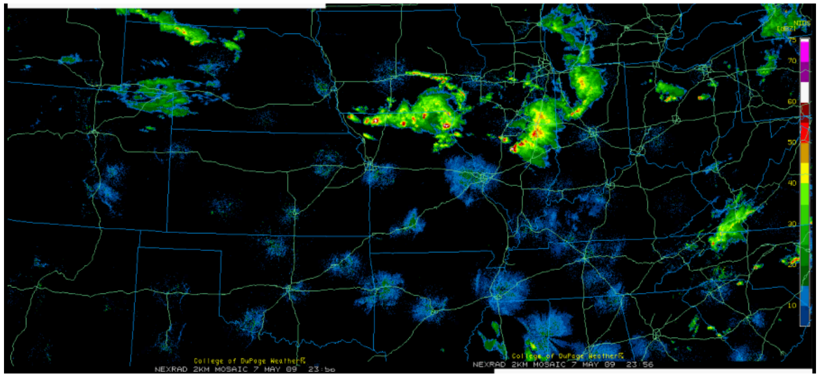
Rich History

- *Manabe et al. (1965)*
- *Kuo (1965), Kuo and Raymond (1980)*
- *Arakawa and Schubert (1974), Pan and Wu (1995), Han and Pan (2011)*
- *Kreitzberg and Perkey (1976)*
- *Fritsch and Chappell (1980)*
- *Bougeault (1985)*
- *Betts and Miller (1986), Janjic (1994)*
- *Frank and Cohen (1987)*
- *Tiedtke (1989)*
- *Gregory and Rowntree (1990)*
- *Kain and Fritsch (1990), Kain (2004)*
- *Grell et al. (1991)*
- *Emanuel (1991)*
- *Lindstrom and Nordeng (1992)*
- *Donner (1993), Donner et al. (2001)*
- *Hack (1994)*
- *Zhang and McFarlane (1995)*
- *Grell and Devenyi (2002)*
- *Bechtold et al. (2004, 2008)*
- *Wagner and Graf (2010)*



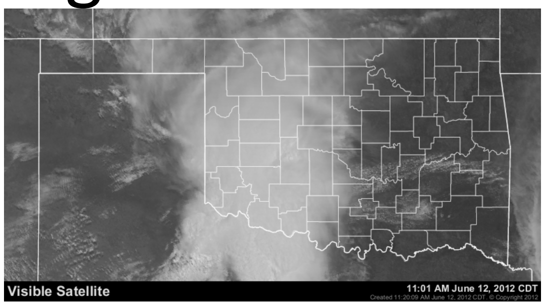
Convection

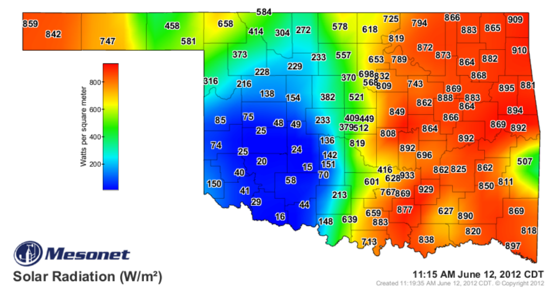
- Convection is widely varying in shape, size, and duration.
  - Isolated
  - Organized into groups of cells
  - Weak or intense
  - Deep or shallow



- Convection produces
  - Beneficial rainfall and snowfall
  - Clouds and changes vertical stability
  - Devastating floods
  - Ice storms and blizzards
  - Damaging winds, hail, lightning, tornadoes, hurricanes

- Gradients in convective heating helps to drive the Hadley and Walker circulations
- Convection shades the ground from sunlight and has large effect on radiation budget of the Earth

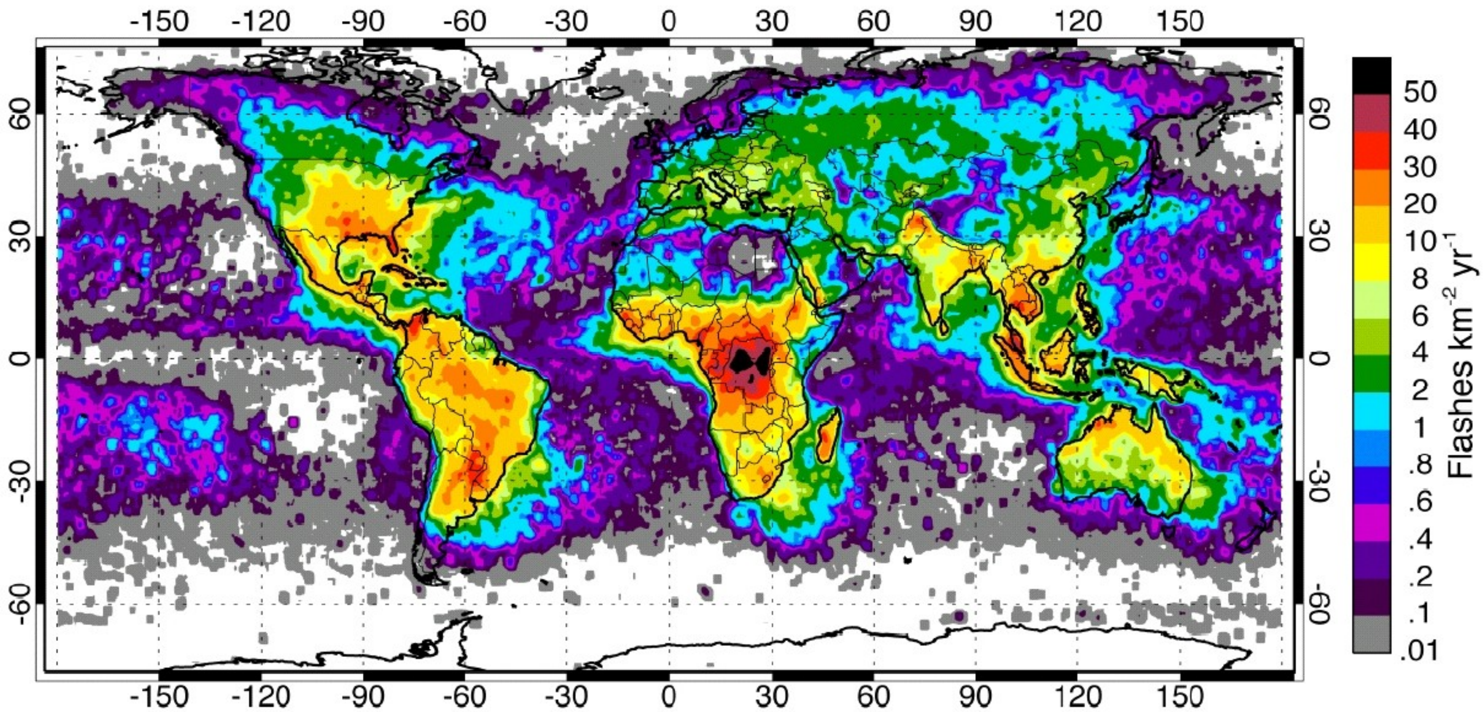




- Convection produces feedbacks that influence large-scale flow patterns

  – Long-lived organized convective systems alter upper-level winds

  – Convection during ENSO an important component in producing the global response to SST change



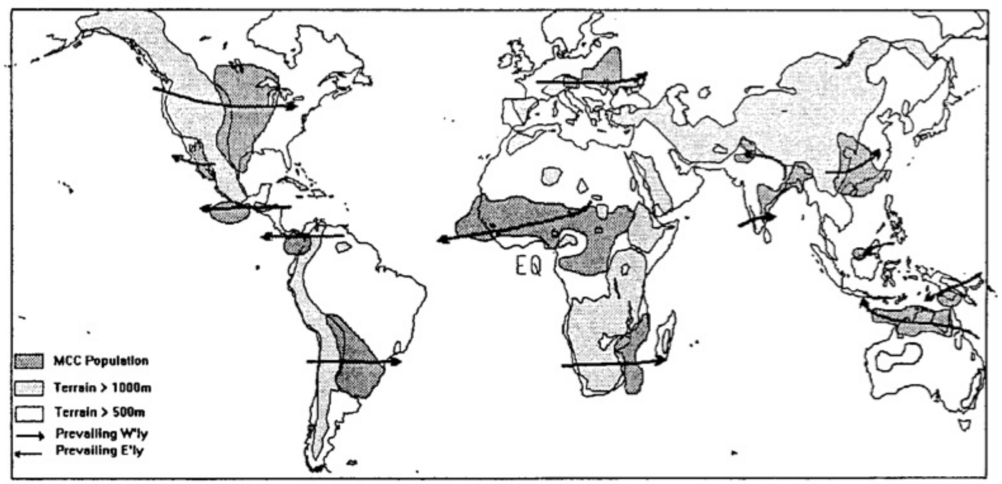
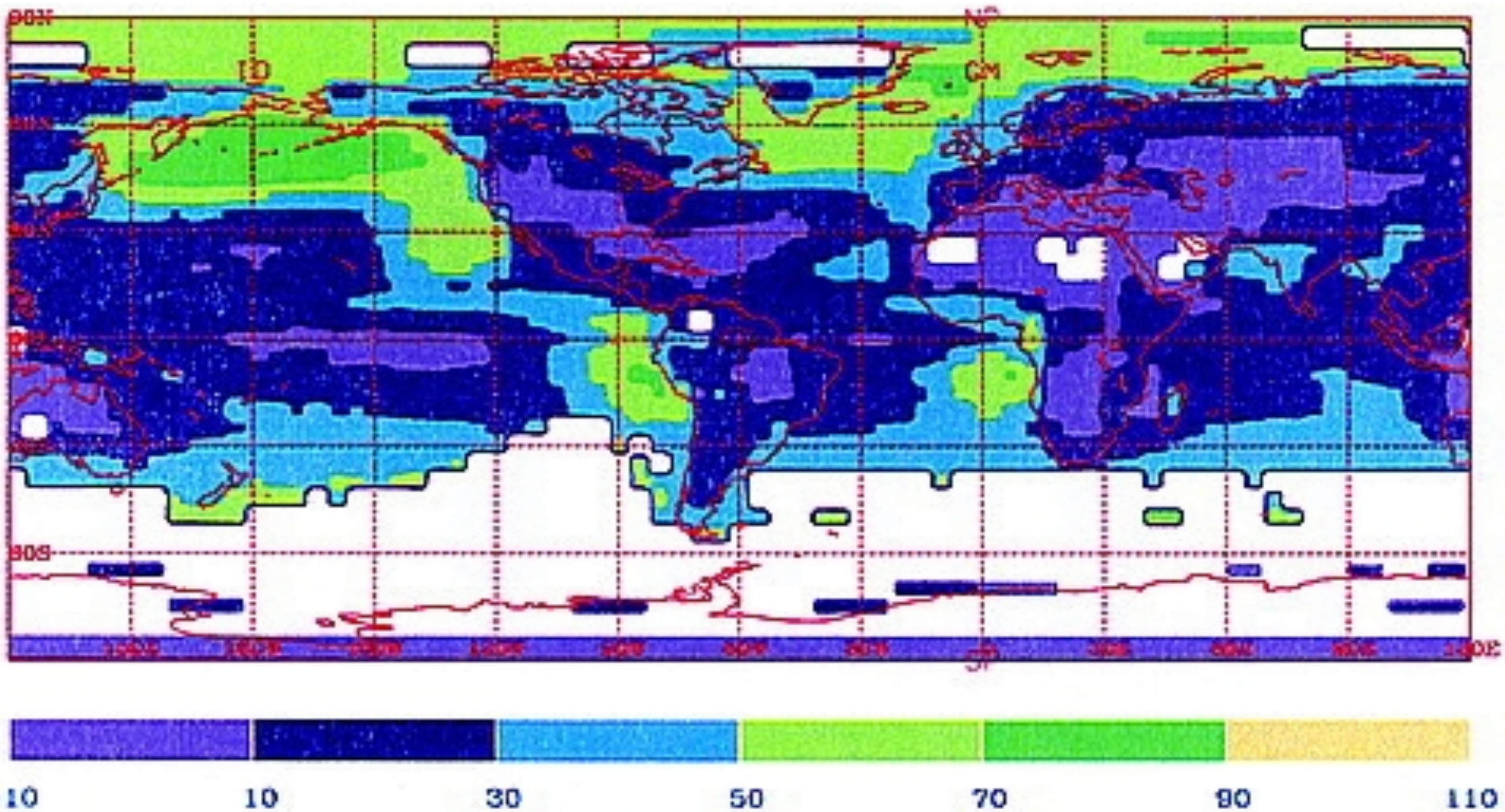


Figure 4. Relationship among mesoscale convective complex (MCC) population centres, elevated terrain, and prevailing mid-level flow.

Global lightning map from NASA matches well with MCC population centers from Laing and Fritsch (1997)



(a)

Global frequency of low-level clouds during JJA from Warren et al. (1988).

We love convection for its beauty and rainfall, yet worry about convection due to the hazards it can produce

Correctly predicting convection is often the most difficult forecast aspect…

…as is requires all other parameterizations of the numerical model to be correct.

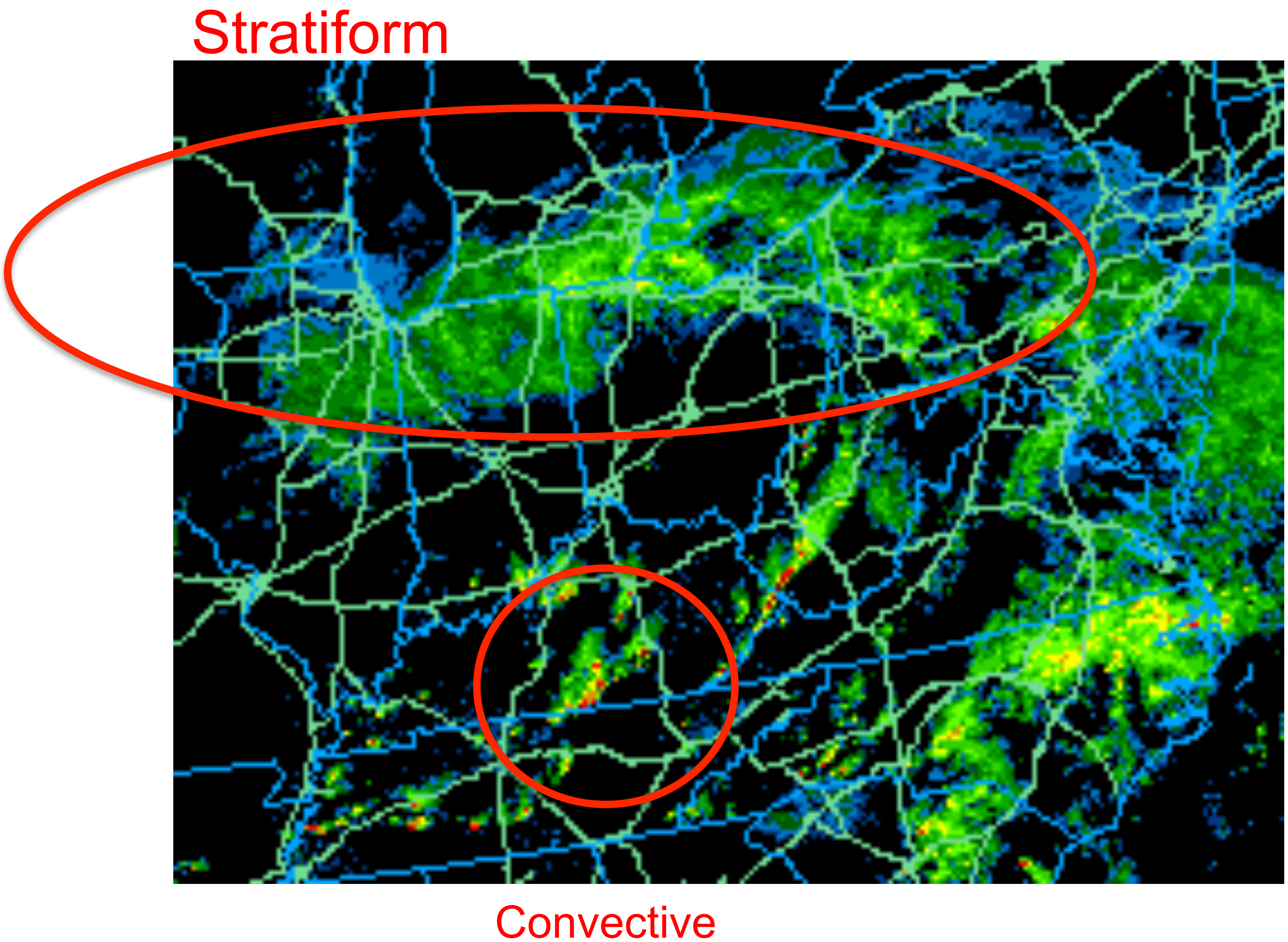
Two major categories

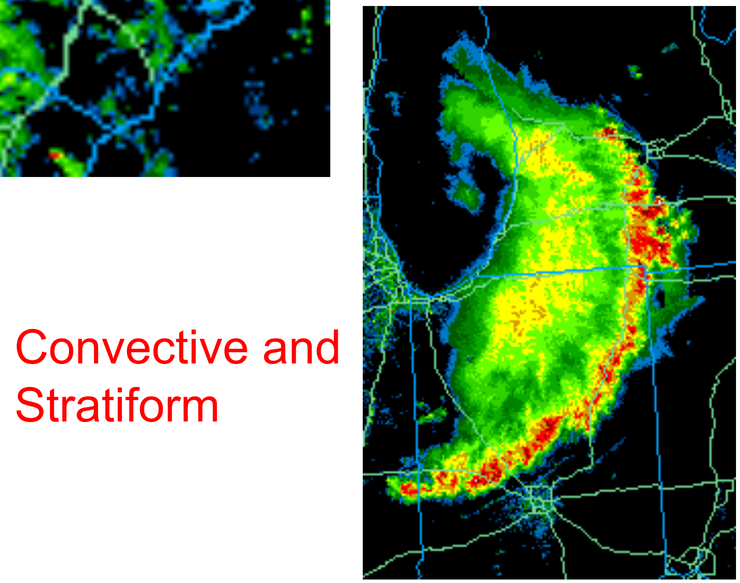
- Deep convection
  - Spans much of the troposphere
  - Produces rainfall
  - Acts to warm and dry the environment

- Shallow convection
  - Spans small portion of the troposphere
  - Produces no precipitation
  - Acts to cool and moisten upper half of cloud and warm and dry lower half of cloud

More sub-categories possible

- Convective
  - Individual cells that have horizontally small regions of intense updrafts and downdrafts
- Stratiform
  - Older regions of convection covering broader areas often with updrafts of less than 1 m/s


Stratiform
Convective


Convective and
Stratiform

Convective Parameterization

- Needed to parameterize convection in numerical models when grid spacing greater than ~5 km
- When grid spacing < 5 km, then we can parameterize microphysical processes only and convective processes are resolved by the model (to some extent)
- When grid spacing between 5 and 40 km, one can use both convective parameterization and include microphysical processes. Stick around for next talk by Georg Grell!

Decisions

- A convective scheme must determine three things
  - Activation? - Trigger Function
  - Intensity? - Closure Assumptions
  - Vertical distribution? - Specified profile or cloud model

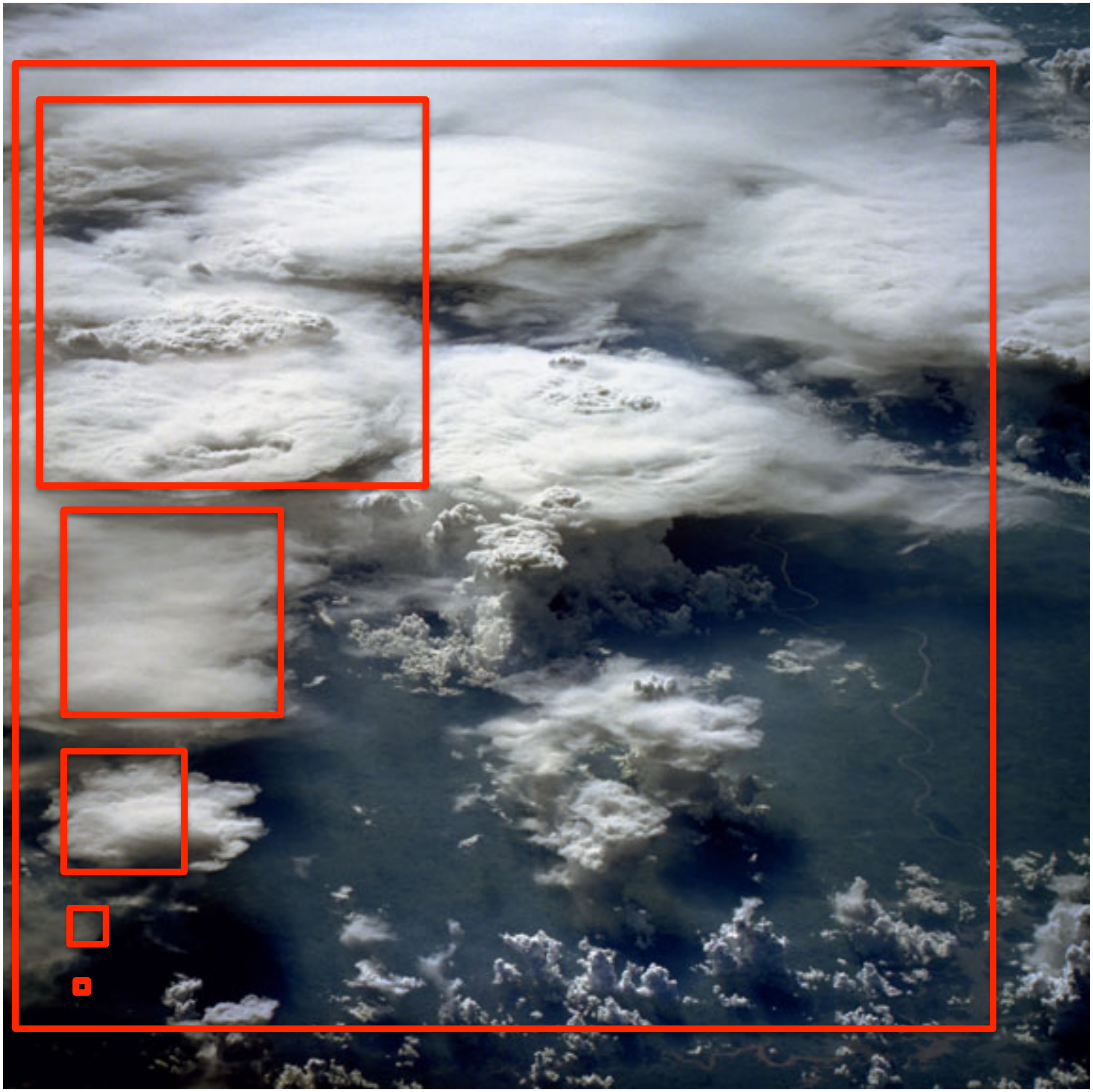
What controls convection?

Local buoyancy?

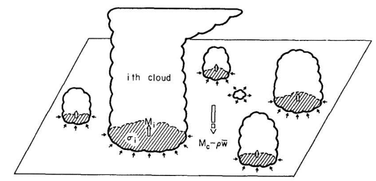
Moisture content?

Large-scale forcing?

Small-scale activation?



Represent a single cloud or an ensemble of clouds?



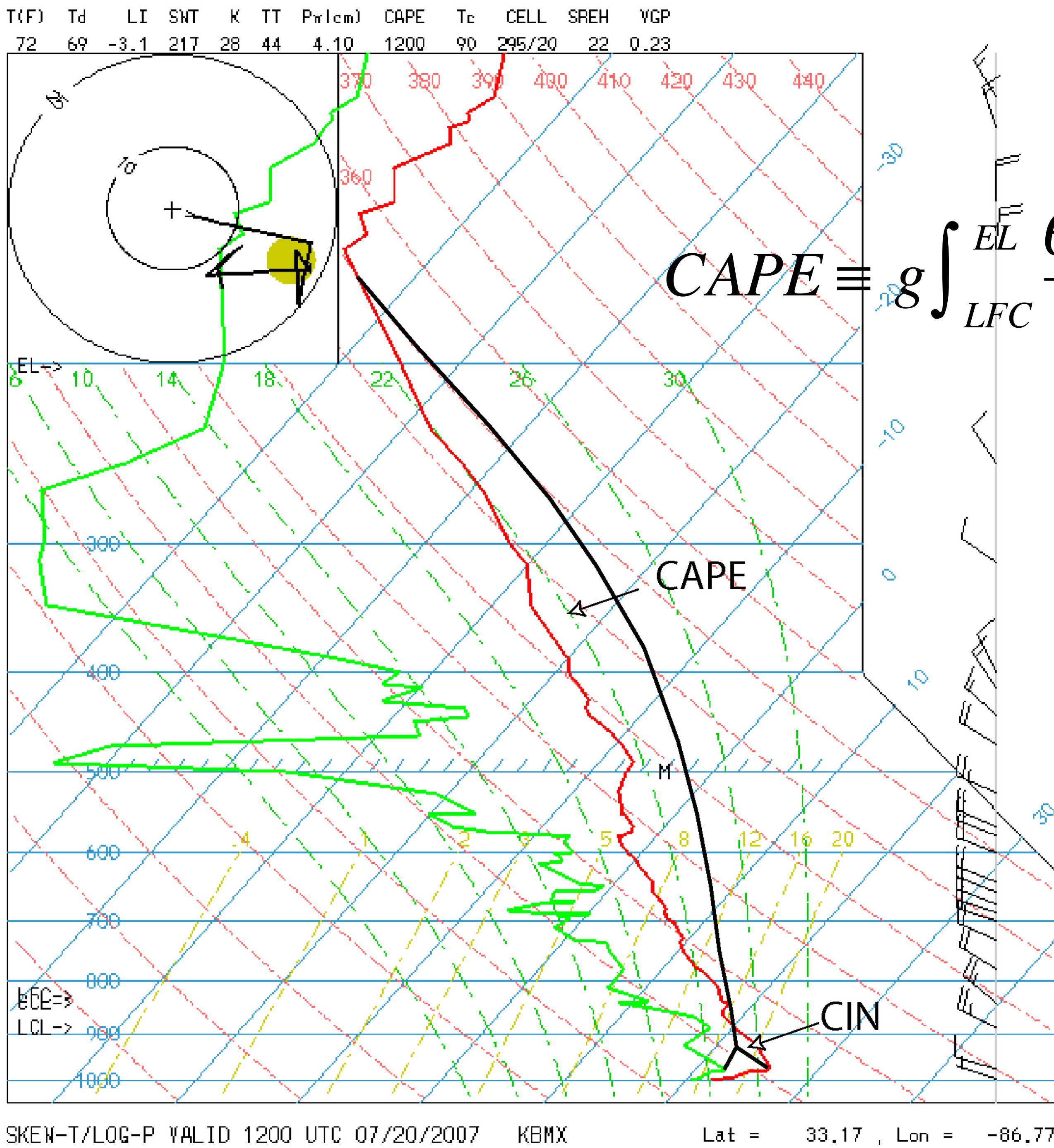
From Arakawa and Schubert (1974)

Represent total effect of all convective elements (convective and stratiform) or just convective portion?

Common Traits

- Convective parameterization schemes tend to evaluate the convective available potential energy (CAPE) of the environment - the maximum energy available to an ascending parcel as determined from simple parcel theory

- Deep convection cannot occur unless CAPE > 0



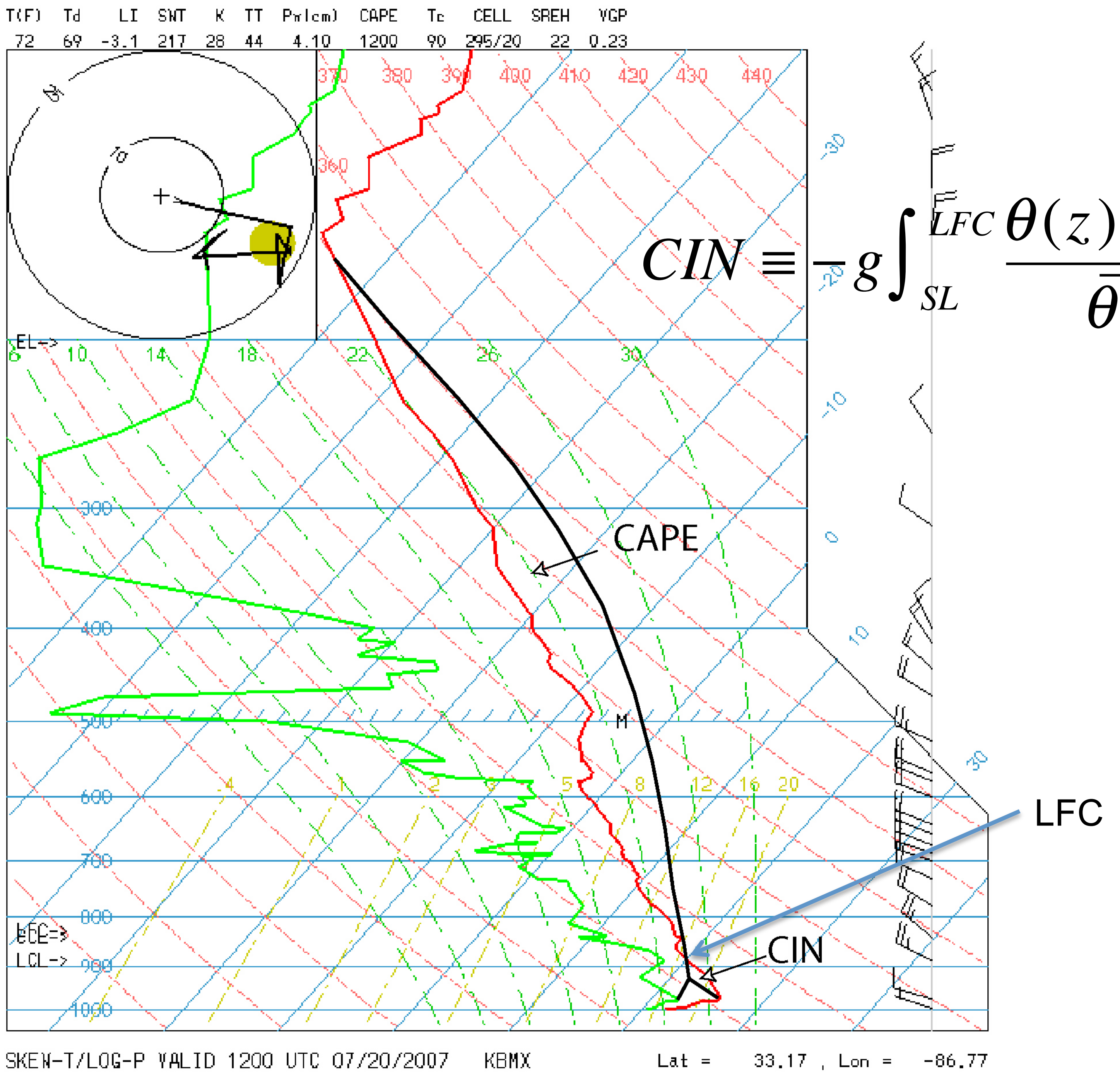
$$CAPE \equiv g\int_{LFC}^{EL} \frac{\theta(z)-\bar{\theta}(z)}{\bar{\theta}(z)}dz$$

Common Traits

- A second term common in discussions of convection and its parameterization is convective inhibition (CIN).

- The CIN of a parcel is defined as the energy needed to lift the parcel vertically and pseudoadiabatically from its starting level to its Level of Free Convection (LFC).

$$CIN \equiv -g\int_{SL}^{LFC} \frac{\theta(z)-\bar{\theta}(z)}{\bar{\theta}(z)}\,dz$$



Two Main Approaches

- Deep-layer control schemes
  - tie the creation of CAPE by large-scale processes to the development and intensity of convection.
  - Mapes (1997) suggests that these schemes could be termed "supply-side" approaches, as it often is assumed that convection consumes the CAPE that is created.
  - Kuo, Betts-Miller-Janjic, Arakawa-Schubert schemes are all deep-layer control schemes

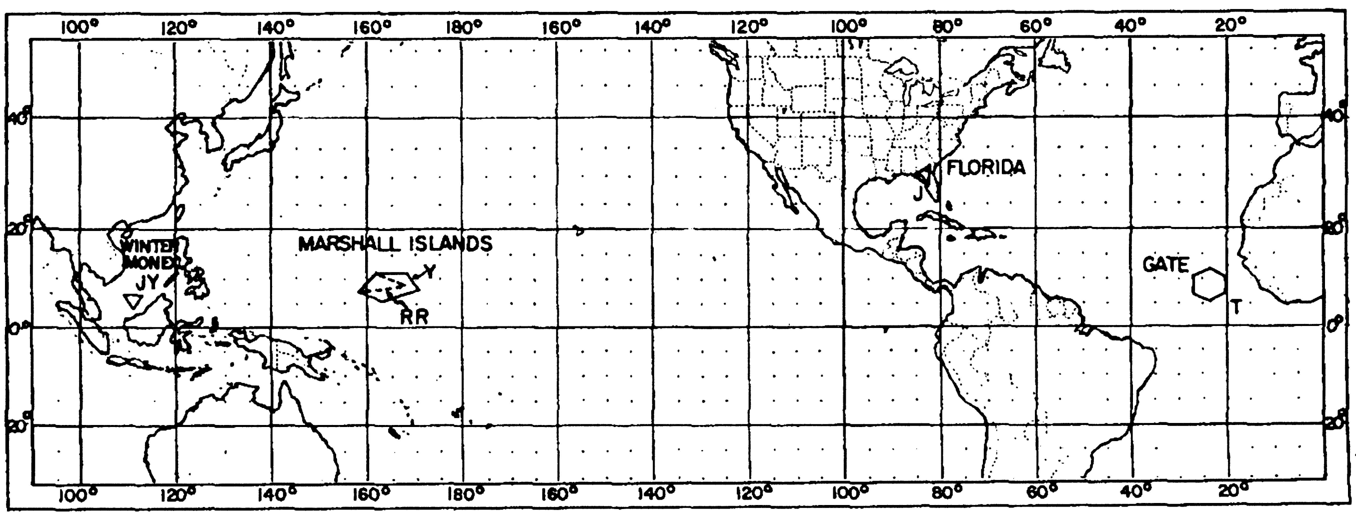
Two Main Approaches

- Low-level control schemes
  - Tie the development of convection to the initiation processes by which CIN is removed.
  - CAPE can be generated and stored for long periods before it is consumed by the scheme.
  - Examples include Fritsch-Chappell, Kain-Fritsch, Emanuel, Tiedtke, and Gregory-Rowntree schemes

- Many schemes have properties of both approaches

How does convection influence the environment?

- Large-scale heat and moisture budgets have been used to determine the influence of convection on the environment
- These budgets are calculated from data collected during special field programs

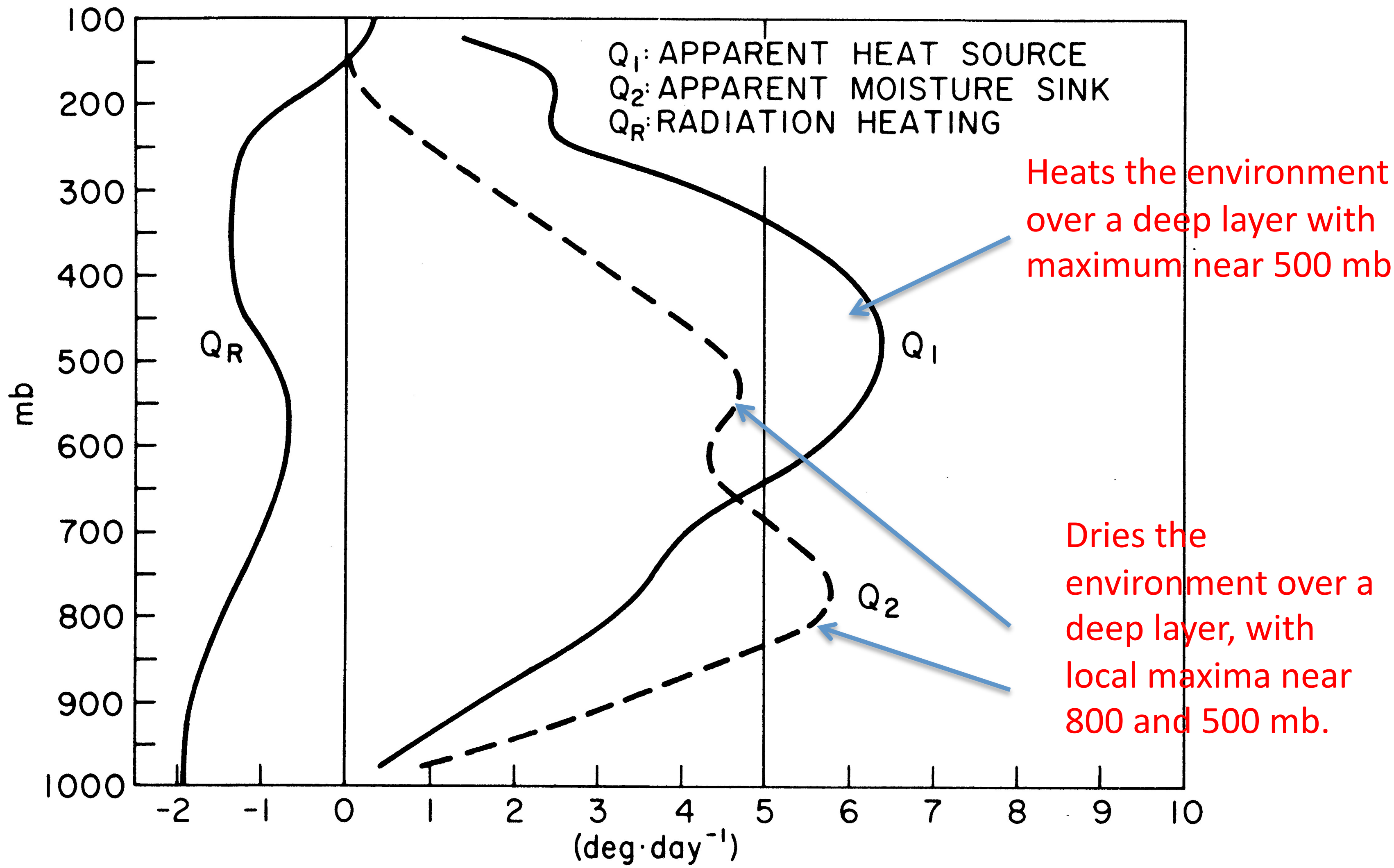


From Johnson (1984)

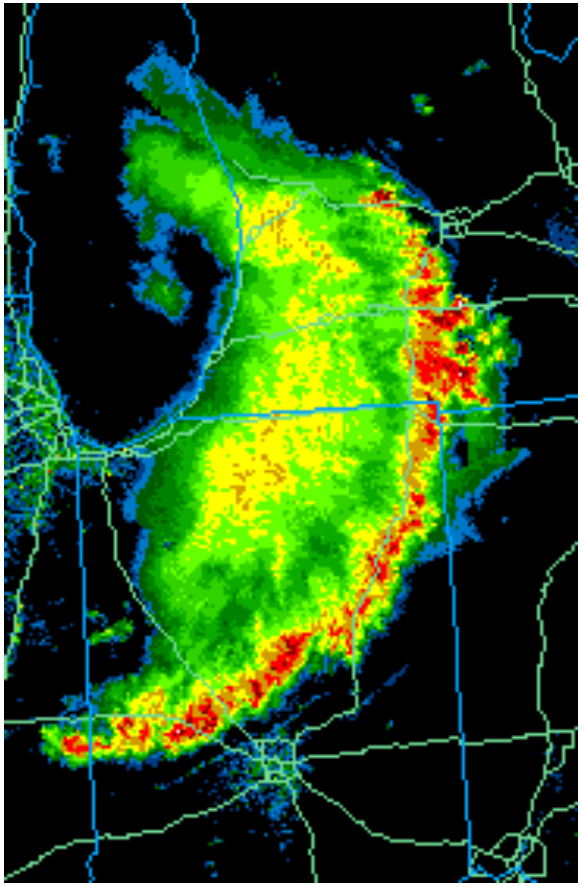
Heat and Moisture Budgets

- Q_1 represents the effects of convection on the heat budget (temperature). Typically this includes both convective and stratiform components. Positive Q_1 implies warming.

- Q_2 represents the effects of convection on the moisture budget. Positive Q_2 implies drying.

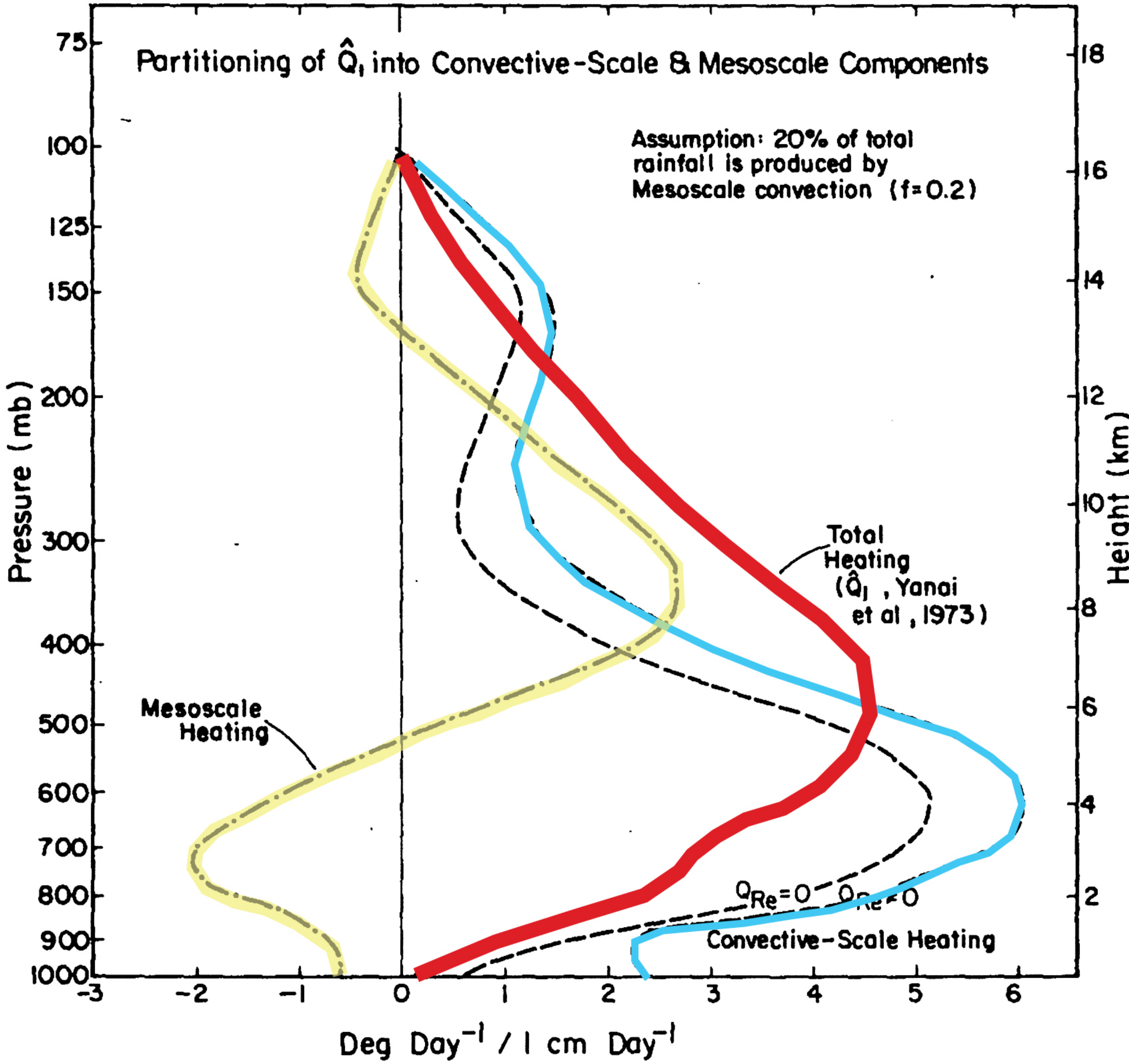


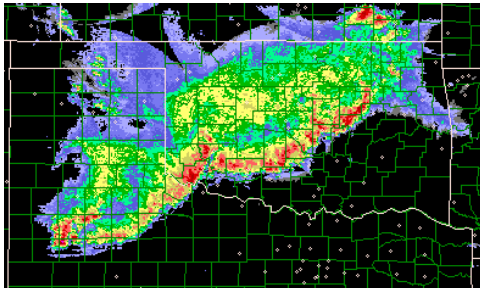
From Yanai (1973)



Can we separate contributions from the convective and stratiform components of the convective systems to see their individual contributions to the total heating and drying?

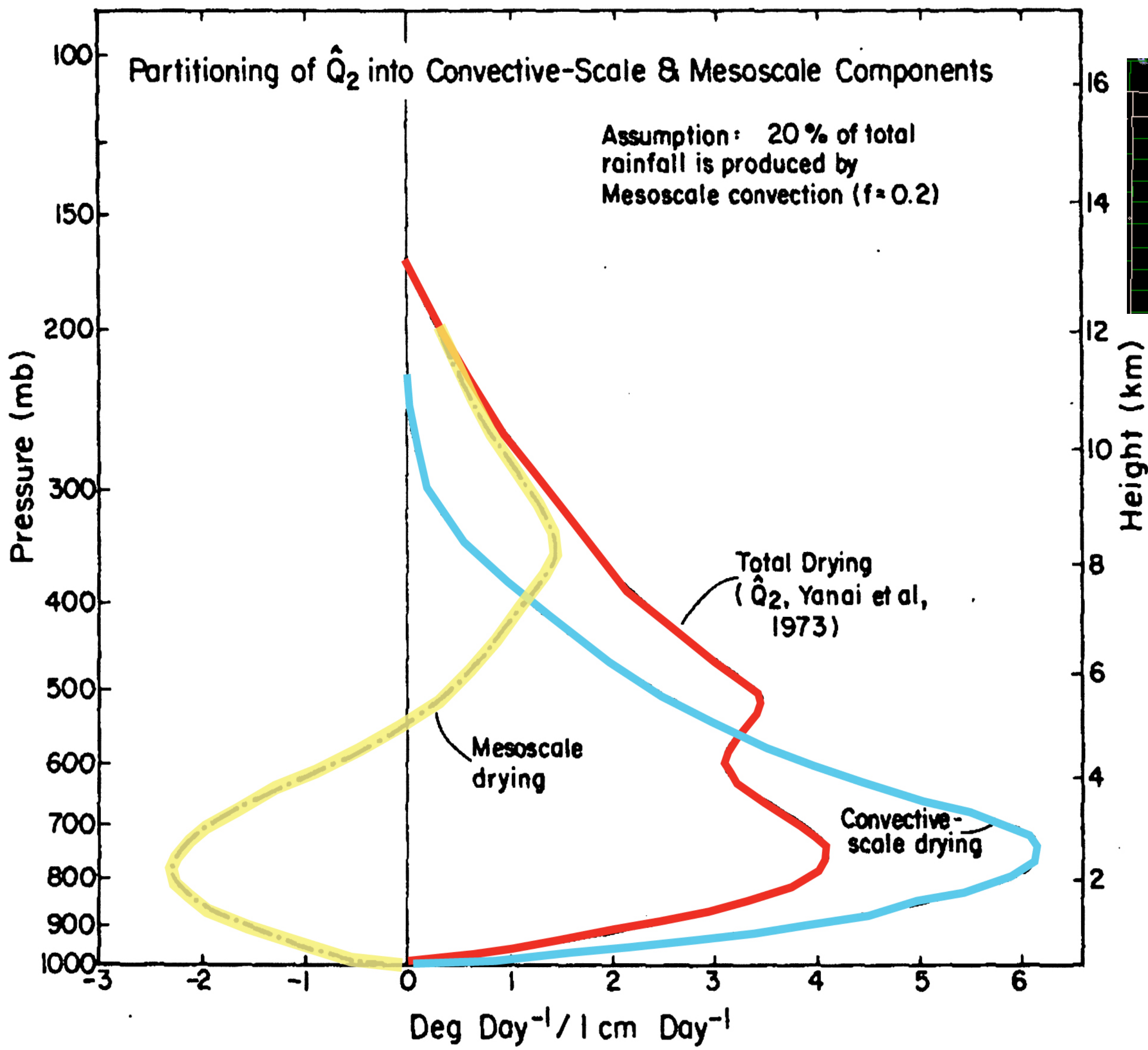
Yes, as shown by Johnson and Young (1983).

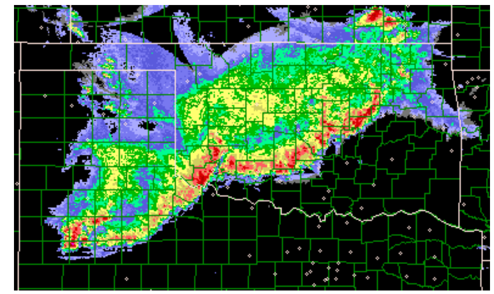




Apparent Heat Source

From Johnson (1984)





Apparent Moisture Sink

From Johnson (1984)

Importance of Budget Studies

- These studies tell us how modeled convection should influence the environment
  - Allows for comparison of end results from convective parameterization to make sure it mimics what occurs in the atmosphere

- Most convective parameterization schemes only modify environmental T and q.
  - a very few also alter the winds (e.g., Fritsch and Chappell 1980, Donner et al 2001).

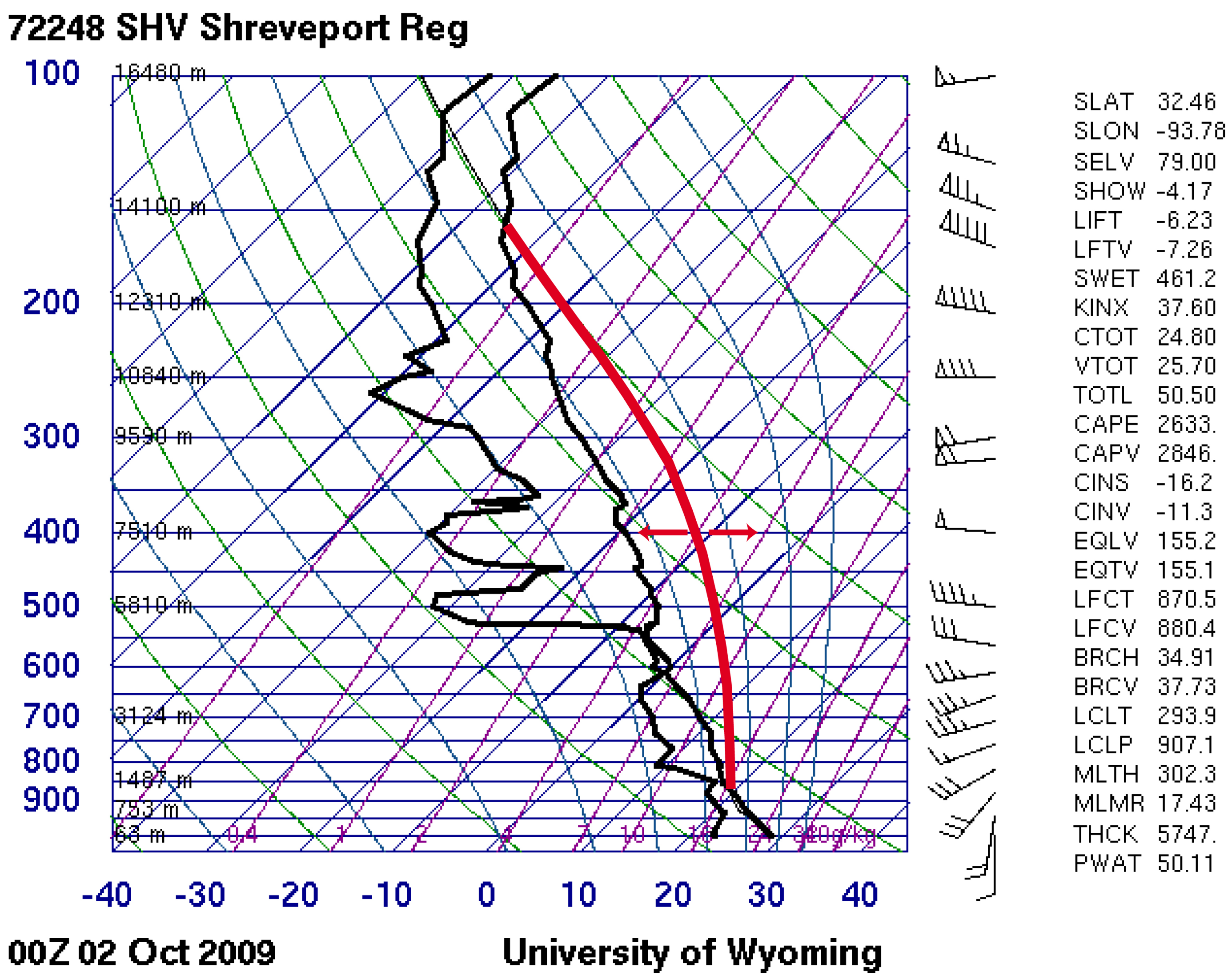
Deep-Layer Control Schemes

- Kuo scheme (1965)
  - Enduringly popular scheme
  - Easy to code and conceptualize
  - Relates moisture convergence (instead of CAPE) to convective activity [precipitation rate (PR)]

$$PR = (1-b)\left[-\frac{1}{g}\int_{0}^{p_{sfc}} \nabla \bullet (\overline{\vec{V}}\,\overline{q})\,dp + \frac{1}{L_v} Q_E\right] = (1-b)M_t$$

Total column moisture convergence

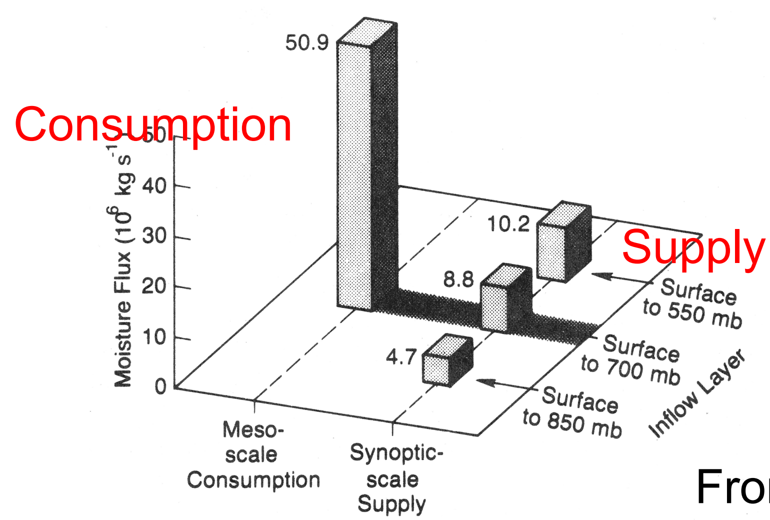
"*b*" defines the fraction of total moisture convergence that is stored in the atmosphere, and (1-*b*) defines the fraction that is precipitated and used to heat the atmosphere



Kuo scheme relaxes the temperature profile towards a moist adiabat chosen to produce the needed amount of heating.

Concerns

- Convection is assumed to consume water (not energy) at the rate at which water is supplied by the atmosphere
  - Problem is that this assumption is not true – "convection is not caused by the macroscale water supply." (Raymond and Emanuel 1993)



From Fritsch et al. (1976)

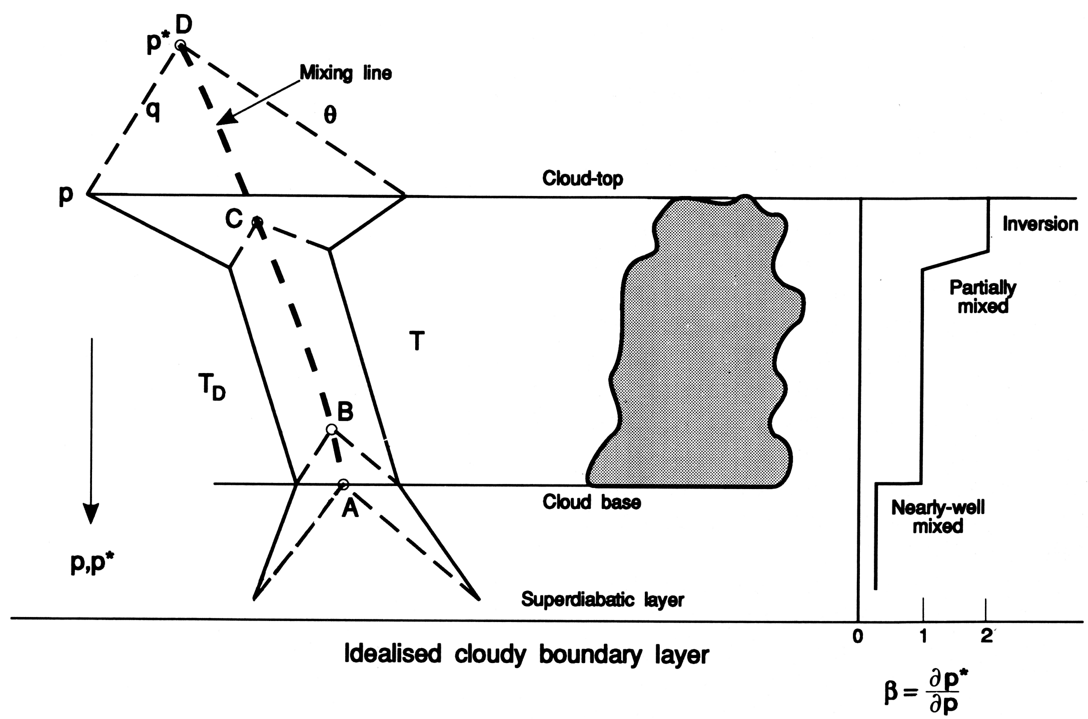
Deep-Layer Control Scheme

- Betts-Miller-Janjic convective scheme
  - Based upon similar sounding structures taken in regions of tropical convection
  - Designed to represent the quasi-equilibrium state established by deep convection => thus deep convection consumes CAPE as fast as large-scale processes create CAPE
  - Includes both deep and shallow convection
  - Arguably represents total response due to both convective and stratiform portions

Saturation Points (SPs)

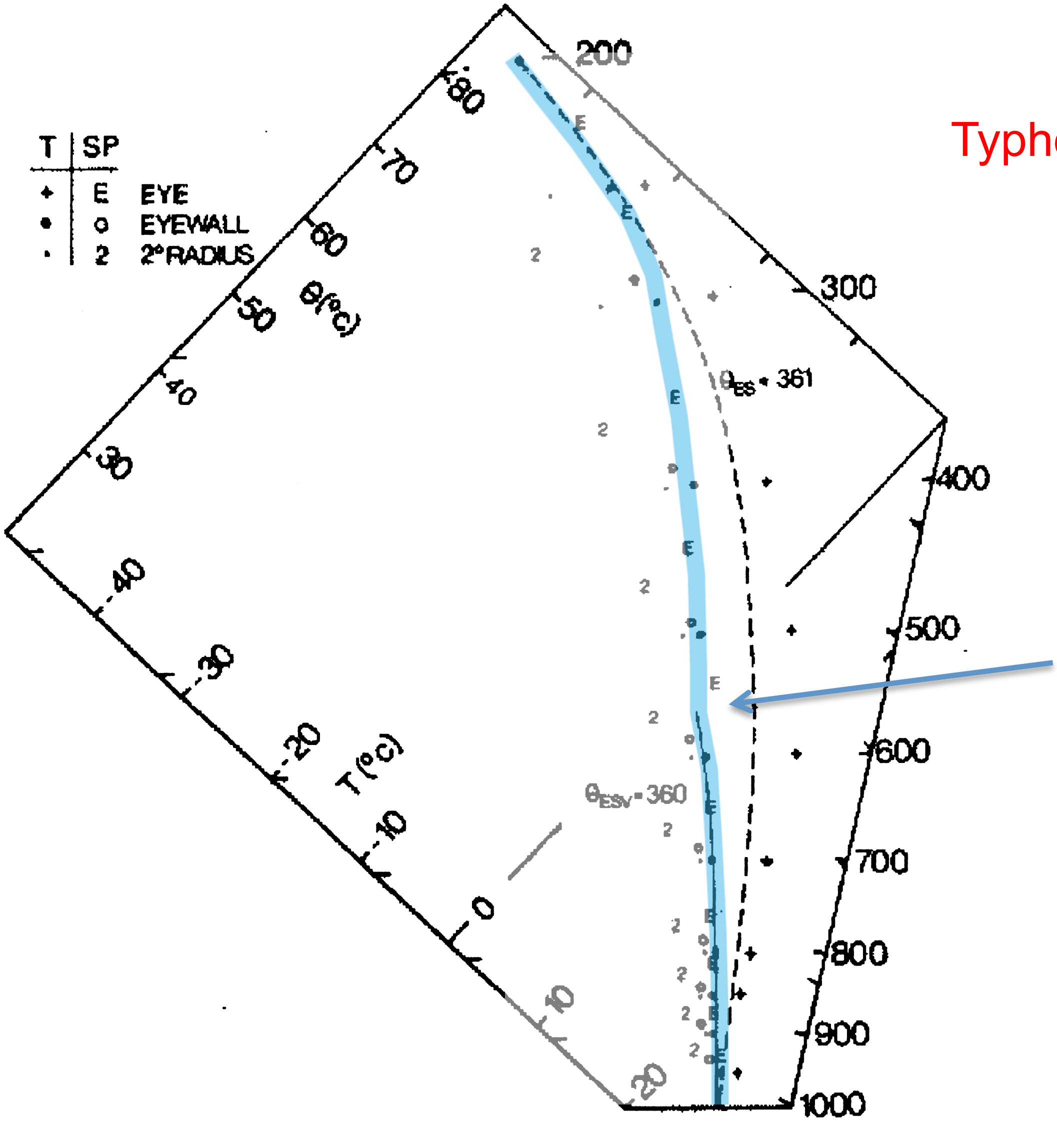
- Instead of working in T and q, the Betts-Miller scheme uses saturation points (SPs)
  - SPs are defined at the lifting condensation level (LCL) of a parcel. Indicated by a *.
  - Location of parcel on a thermodynamic diagram usually requires knowledge of (T,q,p).
  - With SPs, you only need to know two variables (T^*, q^*), (T^*,p^*), (q^*,p^*) to uniquely define the parcel

- SPs are very useful for diagnosing mixing.
  - If mixing occurs, SPs will occur along a straight line called a "mixing line"
  - T and q profiles may have a great deal of structure, but mixing lines tend to be smooth.



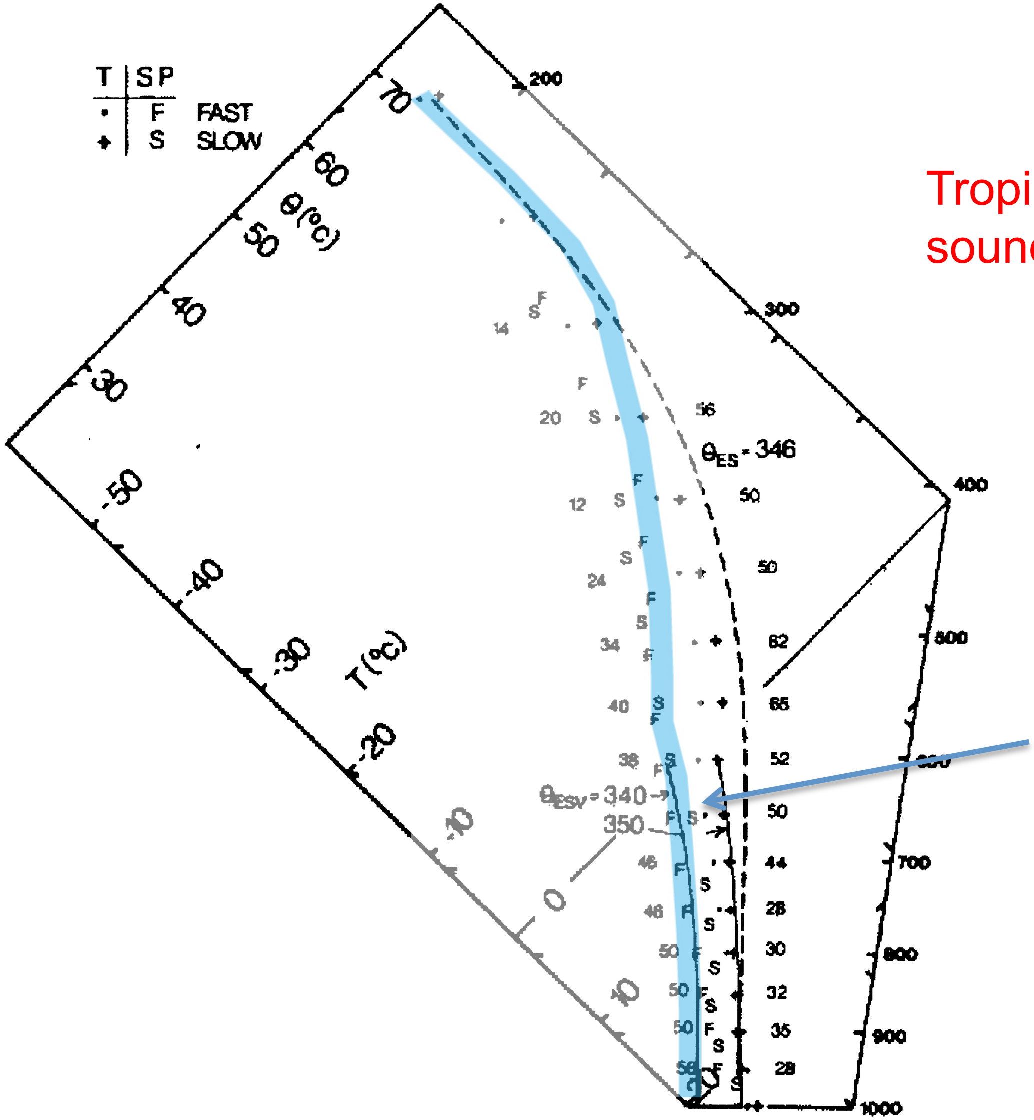
From Betts (1986)

Typhoon soundings



Saturation points follow a moist virtual adiabat from the surface to the freezing level and then asymptote to a moist adiabat at cloud top

From Betts (1986)



Tropical convective system soundings

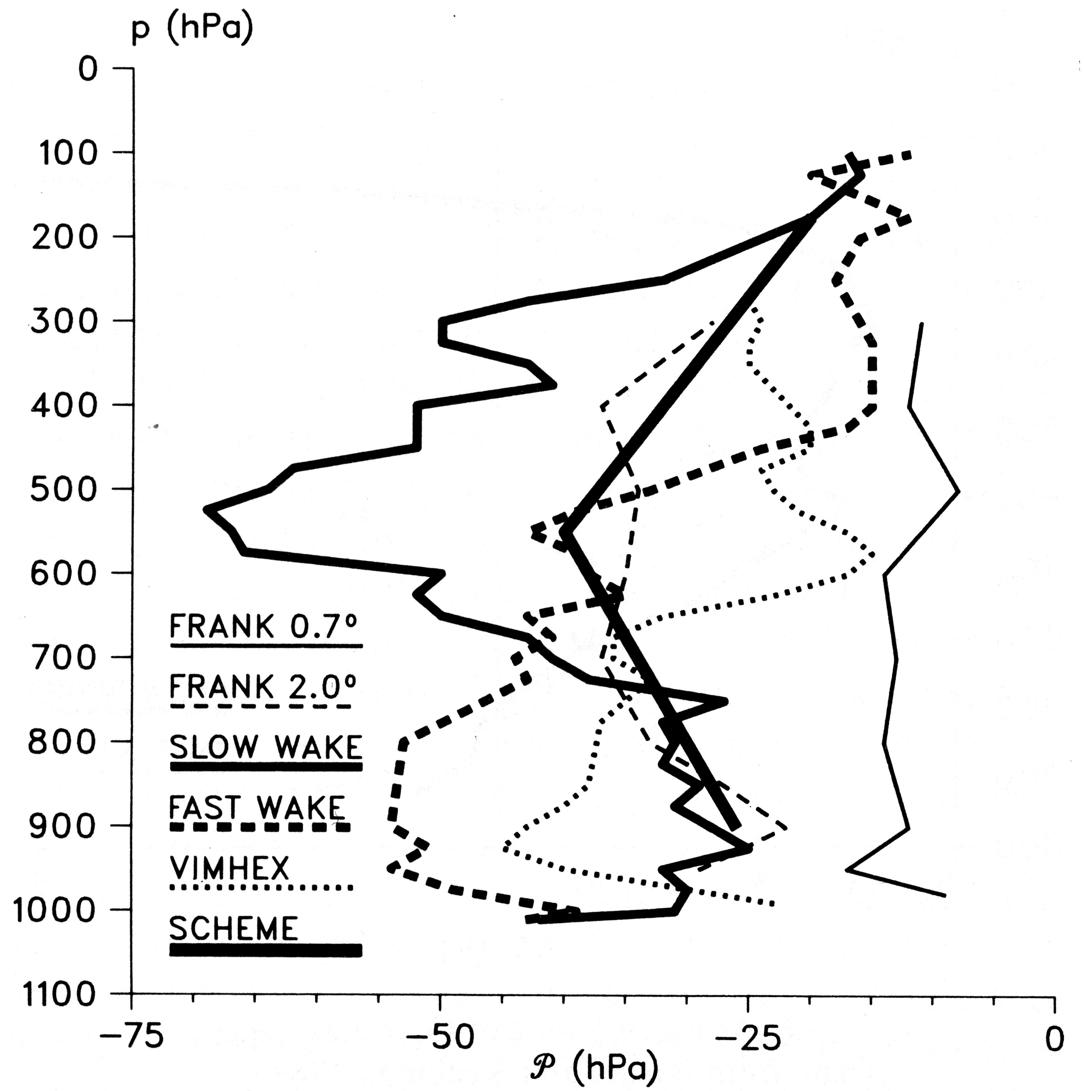
Same SP structure is seen in tropical convective system soundings as found in typhoons.

Empirical results drive convective scheme behavior.

From Betts (1986)

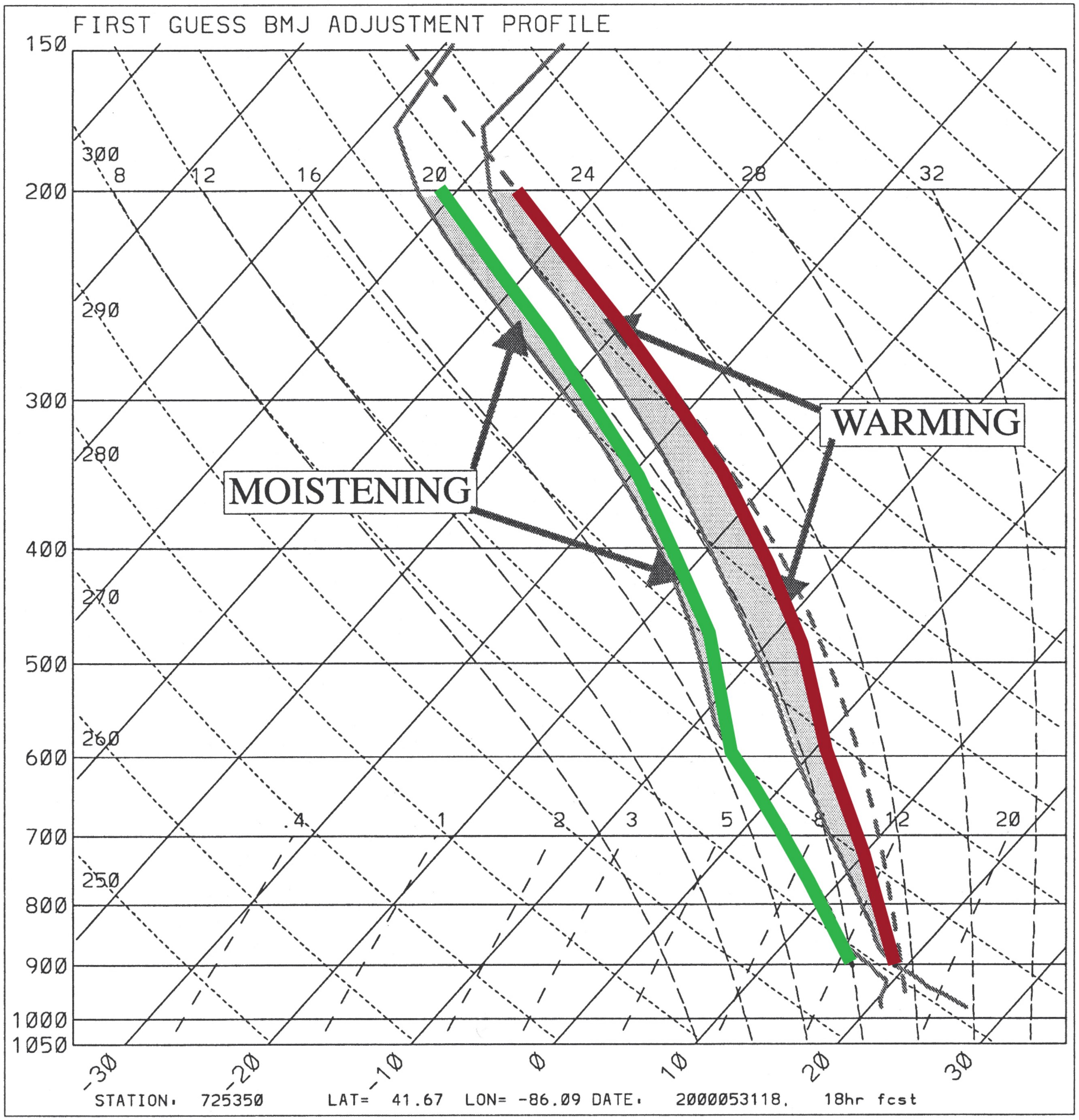
Betts-Miller-Janjic Scheme Details

- Determine if CAPE > 0
- Find cloud base and cloud top from most unstable parcel in lowest 200 mb
- Construct reference SP profile based upon cloud base and cloud top
- Convert reference SP profile to actual T and q profiles using an assumed "saturation pressure departure"

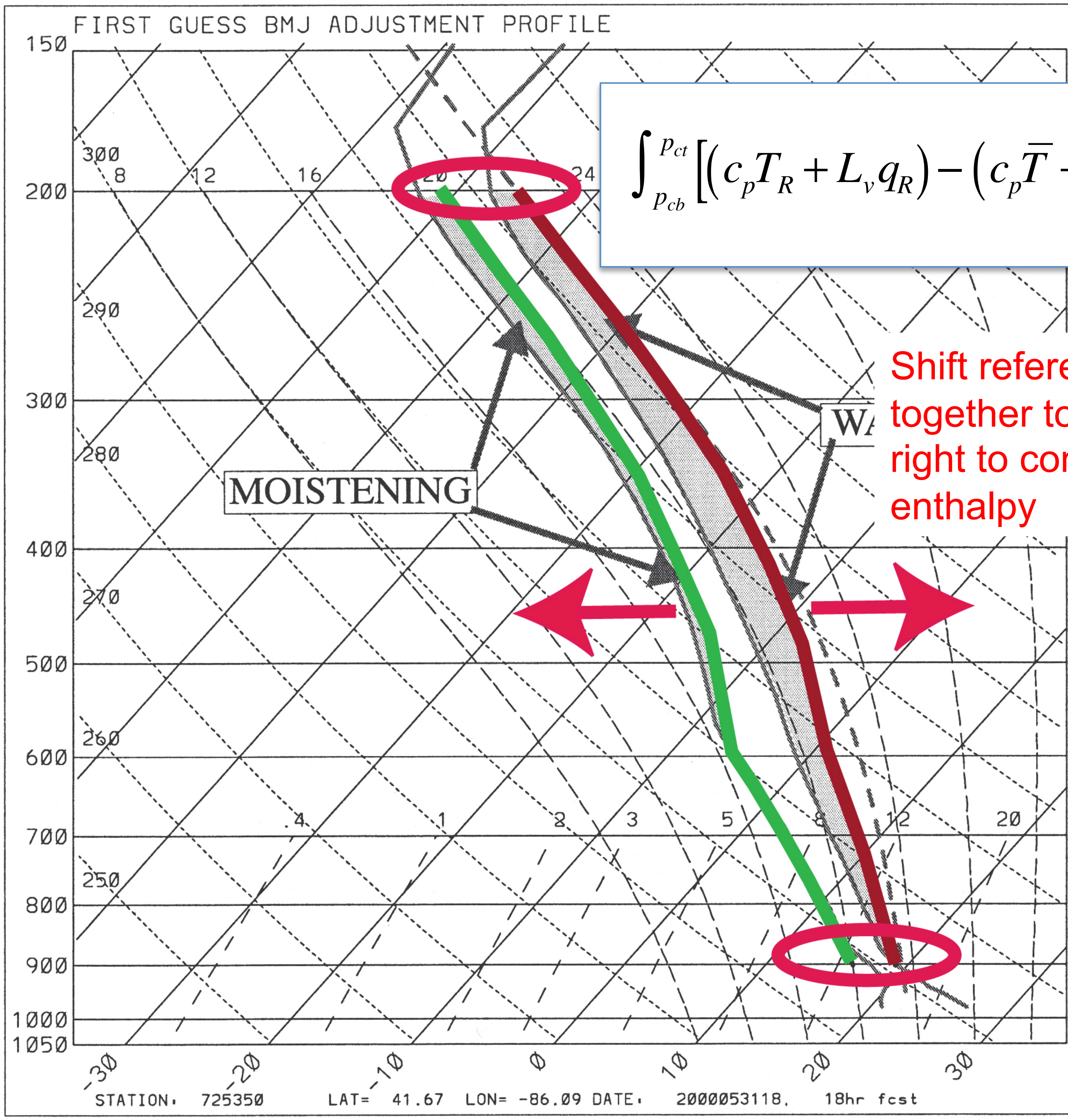


Saturation pressure departure used by scheme

From Betts and Miller (1993)



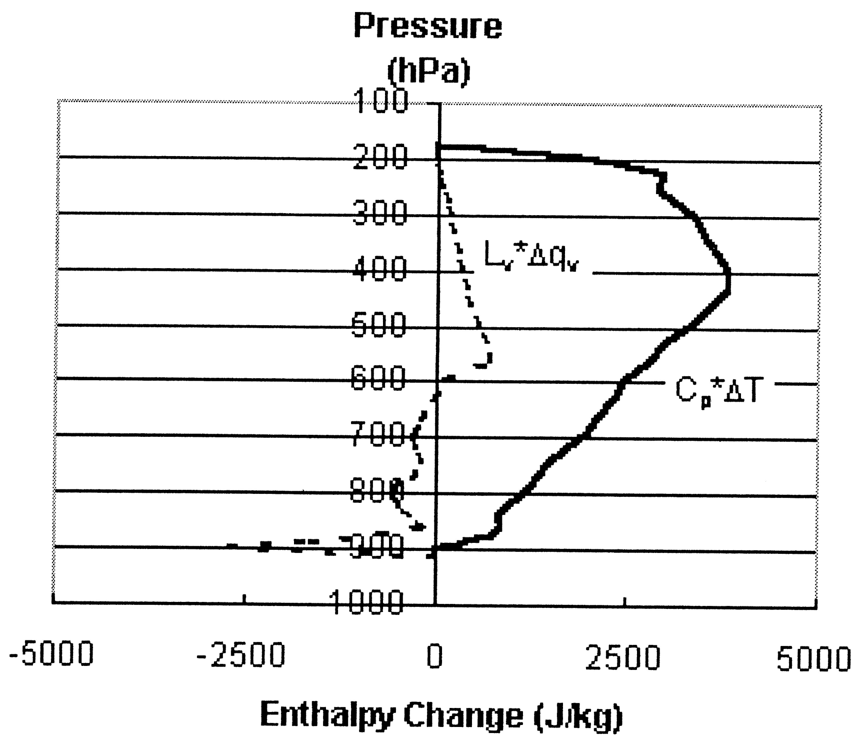
From Baldwin et al. (2002)



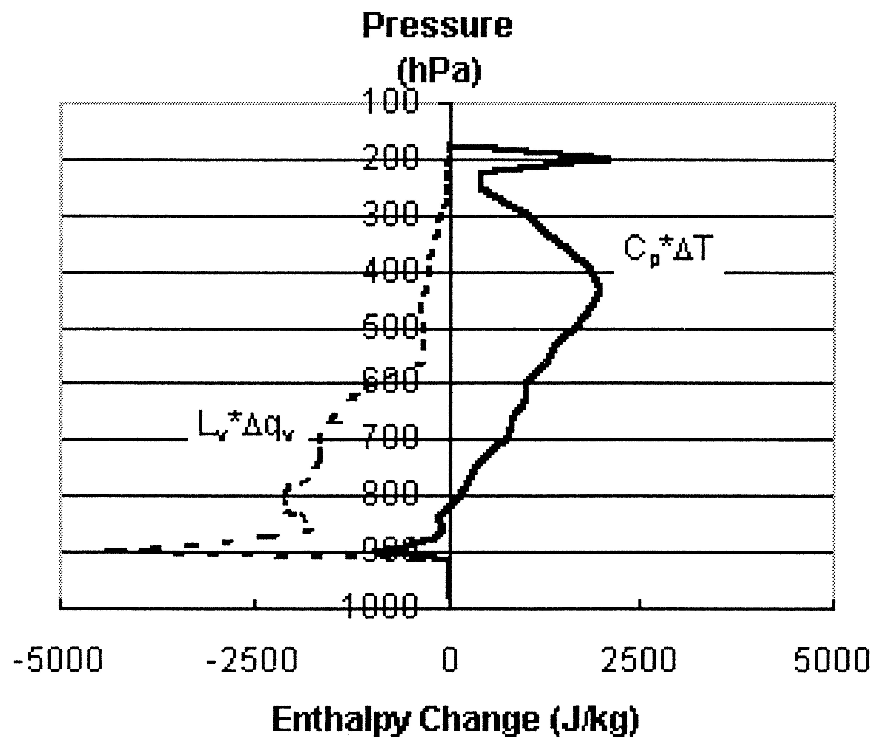
$$\int_{p_{cb}}^{p_{ct}} \left[\left(c_p T_R + L_v q_R \right) - \left(c_p \overline{T} + L_v \overline{q} \right) \right] dp = 0$$

Shift reference profiles together to the left or right to conserve total enthalpy

From Baldwin et al. (2002)



First-guess

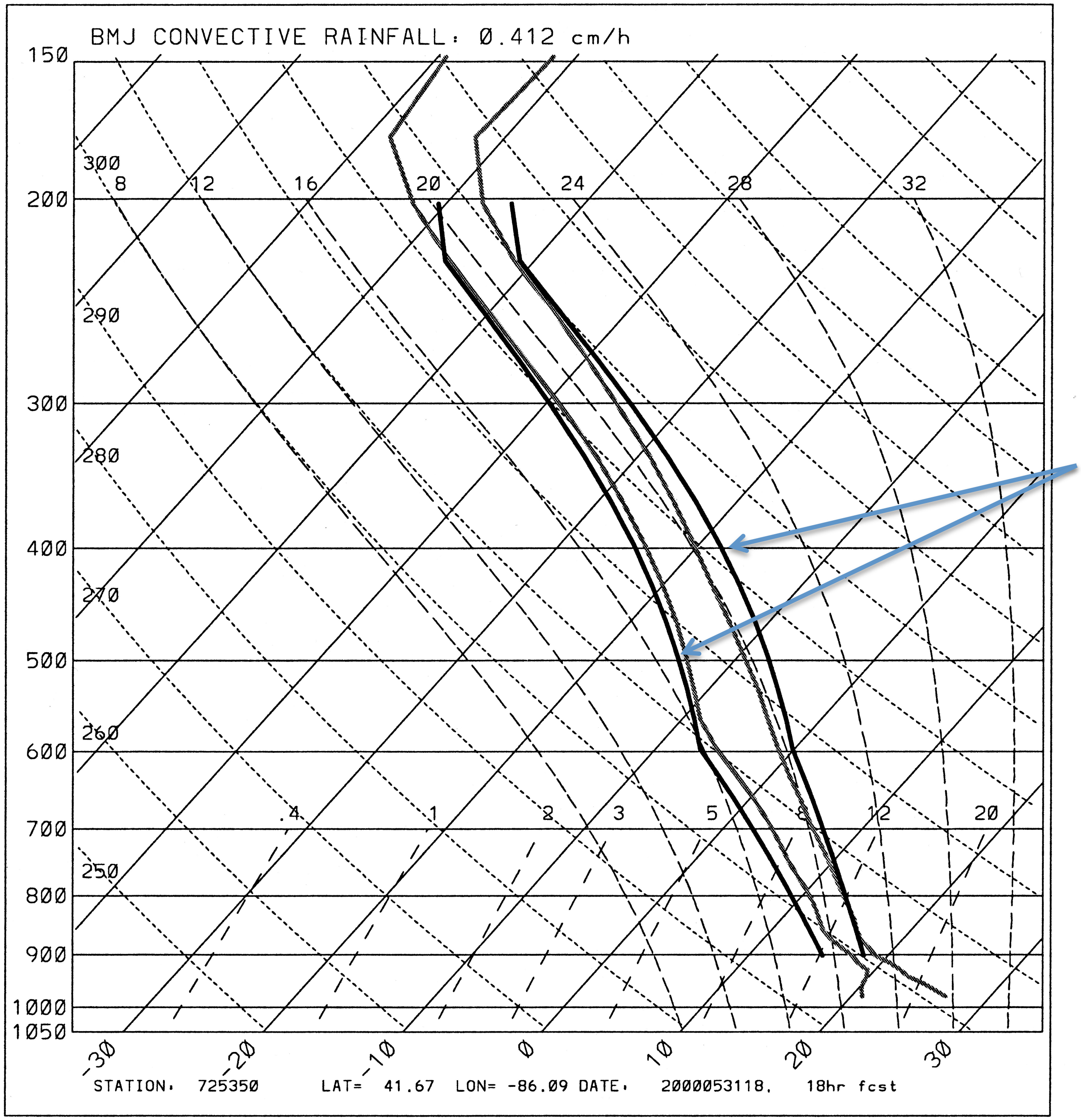


After Enthalpy Conservation

From Baldwin
et al. (2002)

- Once the reference profiles conserve enthalpy, determine if rainfall is produced
  - If rainfall, then activate scheme and relax towards reference profiles over ~ 1 hour
  - If no rainfall, then do not activate scheme (scheme must act to dry atmosphere or does not activate)

$$PR = \int_{p_{cb}}^{p_{ct}} \left(\frac{q_R - \overline{q}}{\tau} \right) \frac{dp}{g} = -\frac{c_p}{L_v} \int_{p_{cb}}^{p_{ct}} \left(\frac{T_R - \overline{T}}{\tau} \right) \frac{dp}{g}$$



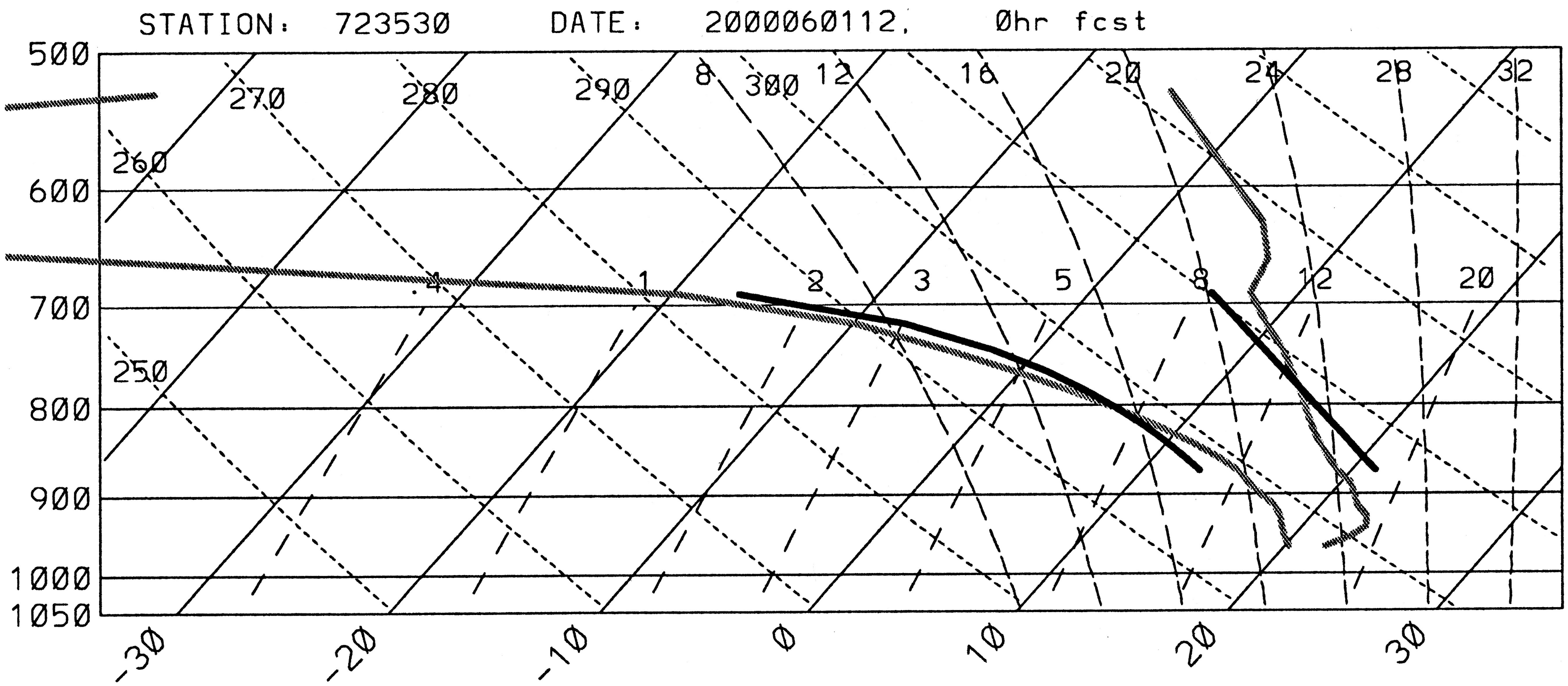
Reference profiles are darker black lines.

Slight mid-level warming and drying. Rainfall produced!

From Baldwin et al. (2002)

Shallow Convection

- If cloud depth < 200 mb, or scheme fails to produce rainfall then adjust according to shallow convection
- Uses typical mixing line to determine reference profiles for shallow convection
- Adjusts profiles to conserve enthalpy
- Acts to warm and dry lower half of cloud and cool and moisten upper half of cloud

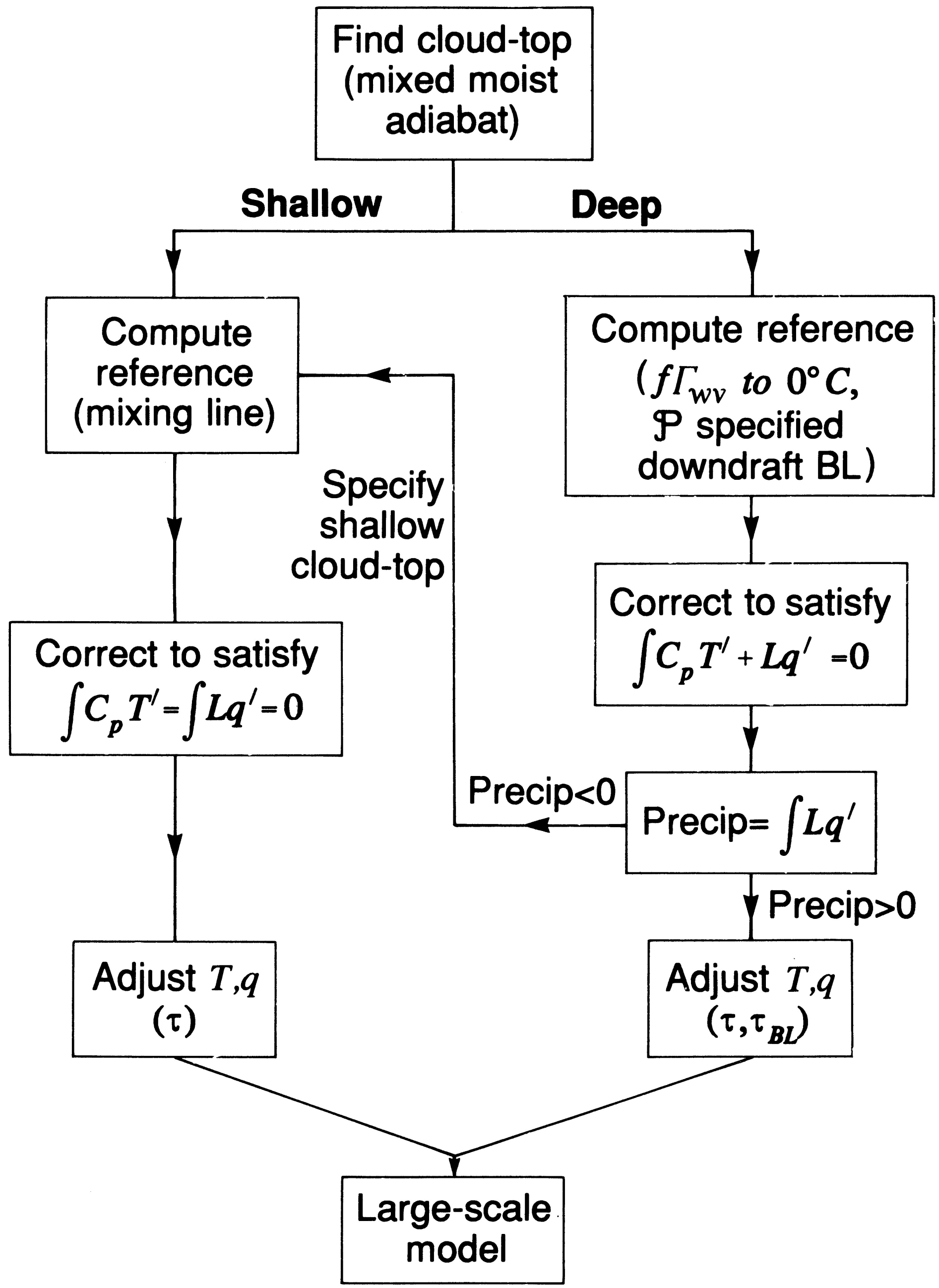


$$\int_{p_{cb}}^{p_{ct}} c_p(T_R - \overline{T})dp = 0$$

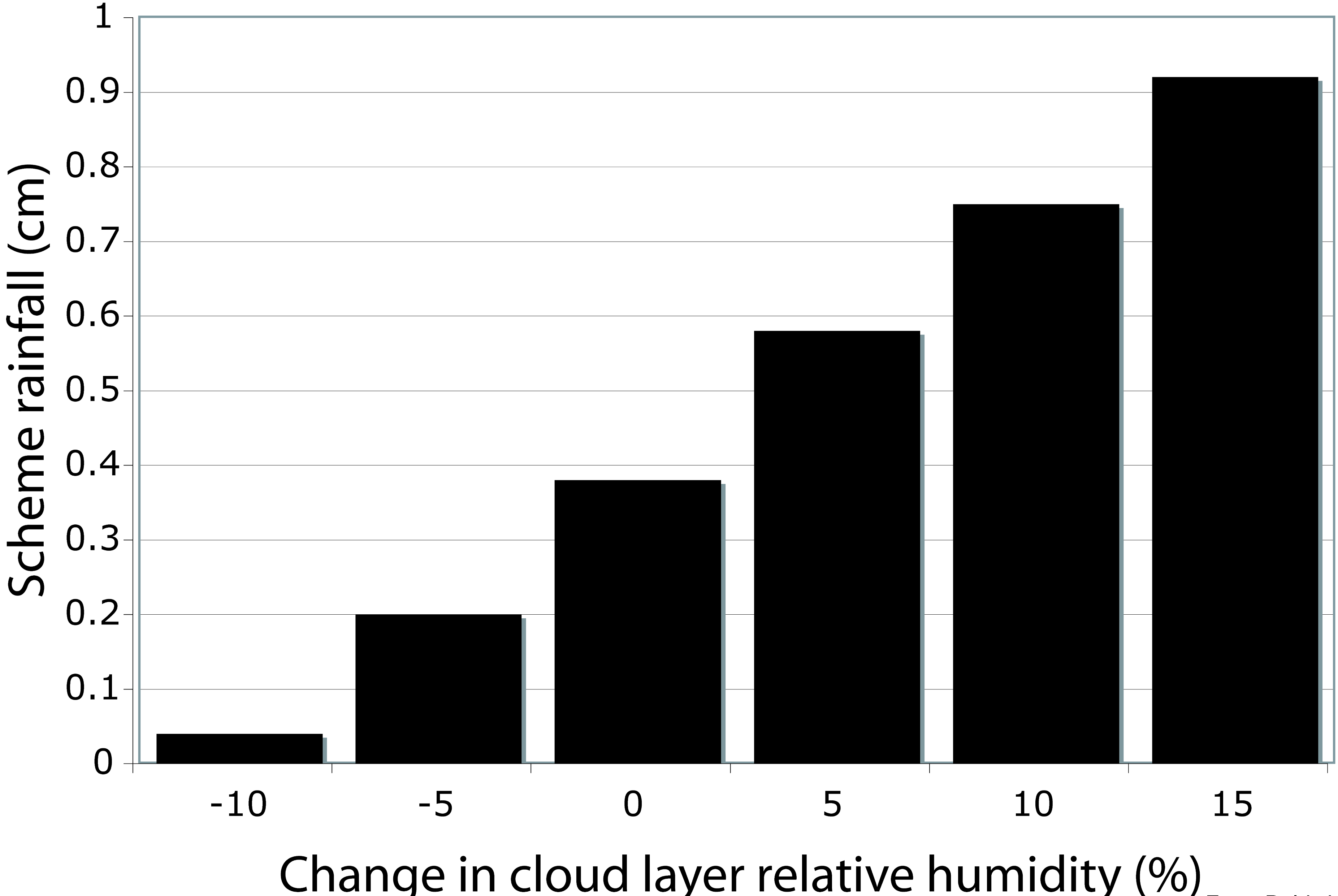
$$\int_{p_{cb}}^{p_{ct}} L_v(q_R - \overline{q})dp = 0$$

Constraints applied independently to T and q profiles over cloud depth

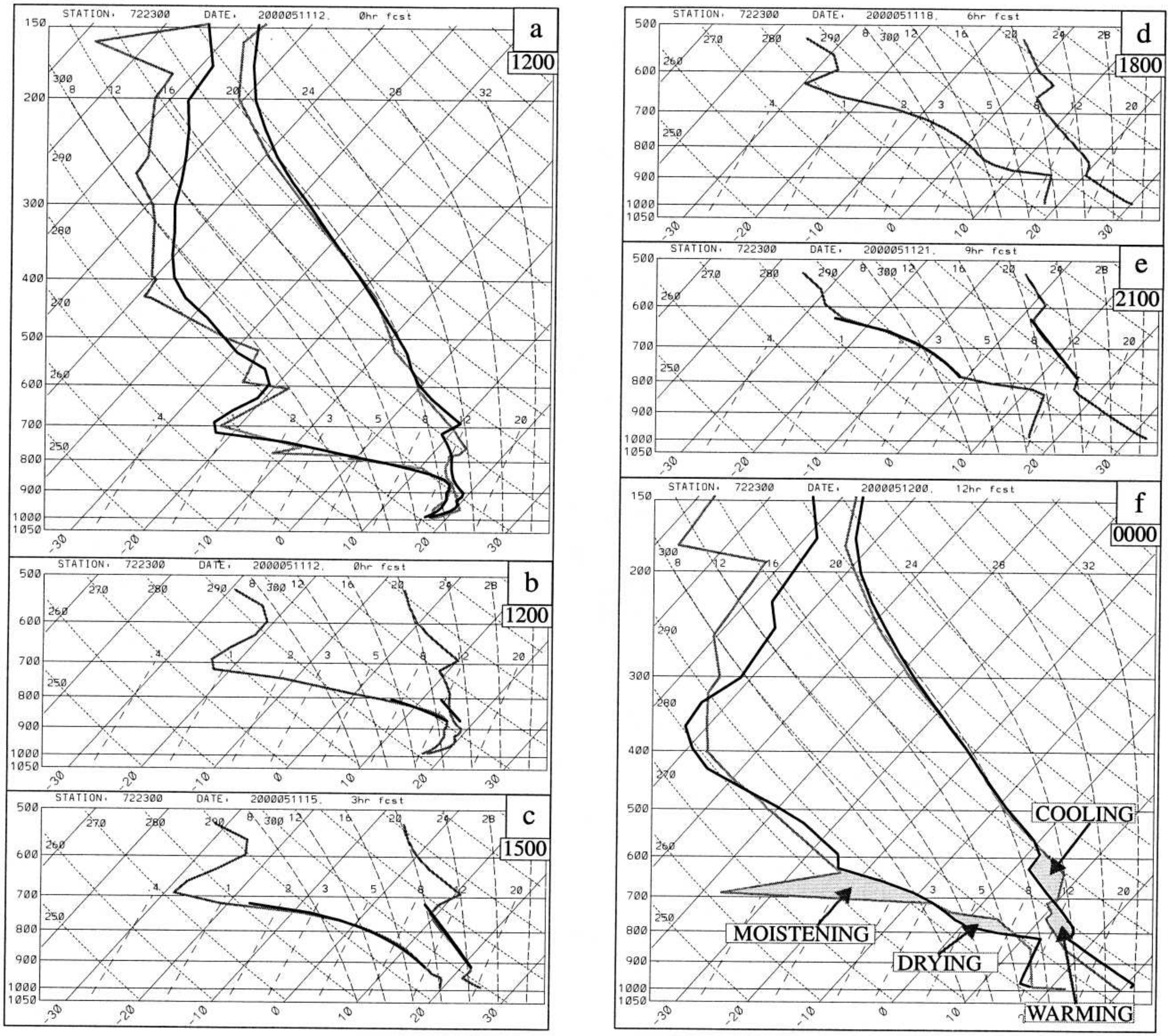
From Baldwin et al. (2002)



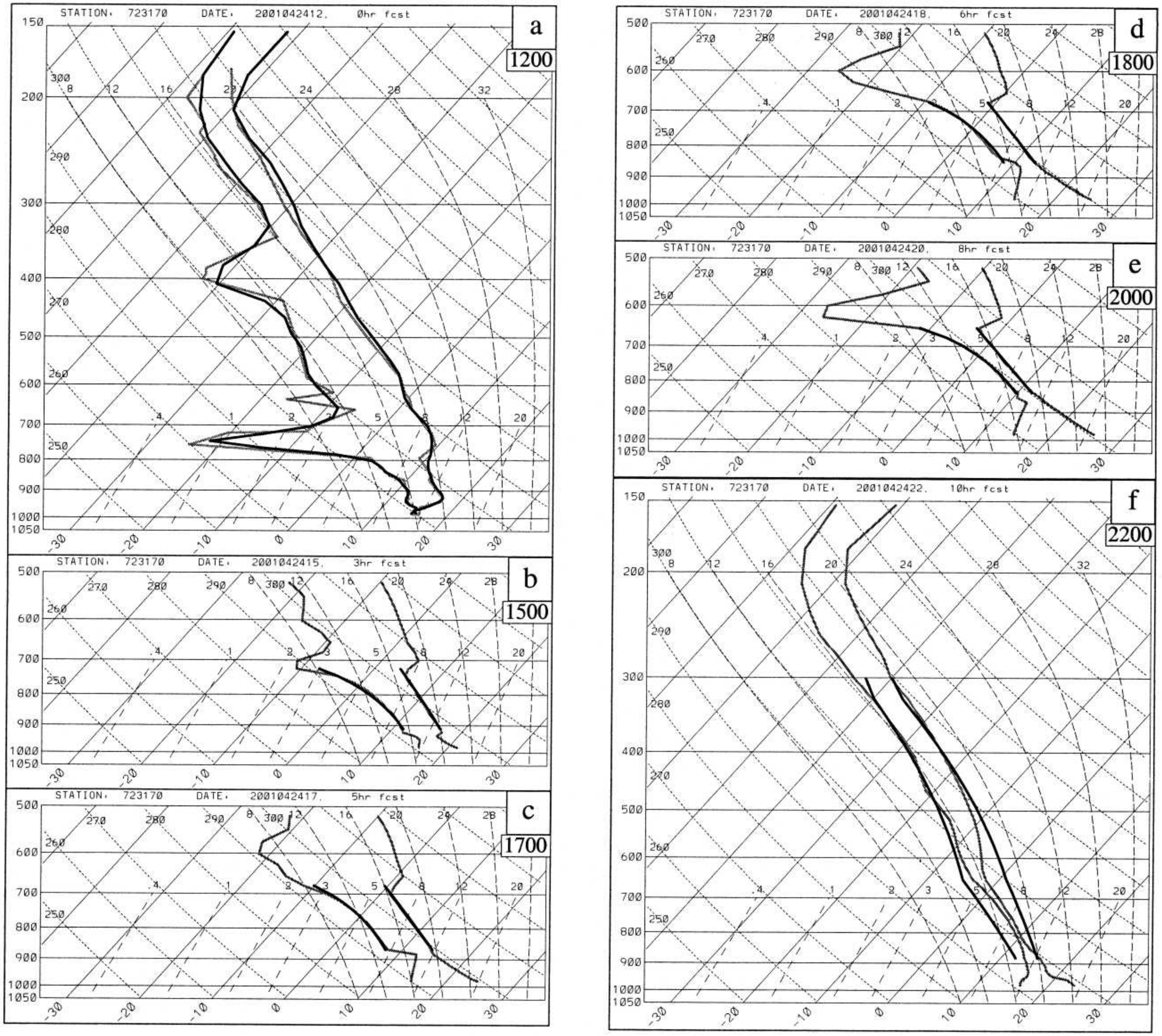
From Betts and Miller (1993)



From Baldwin et al. (2002)

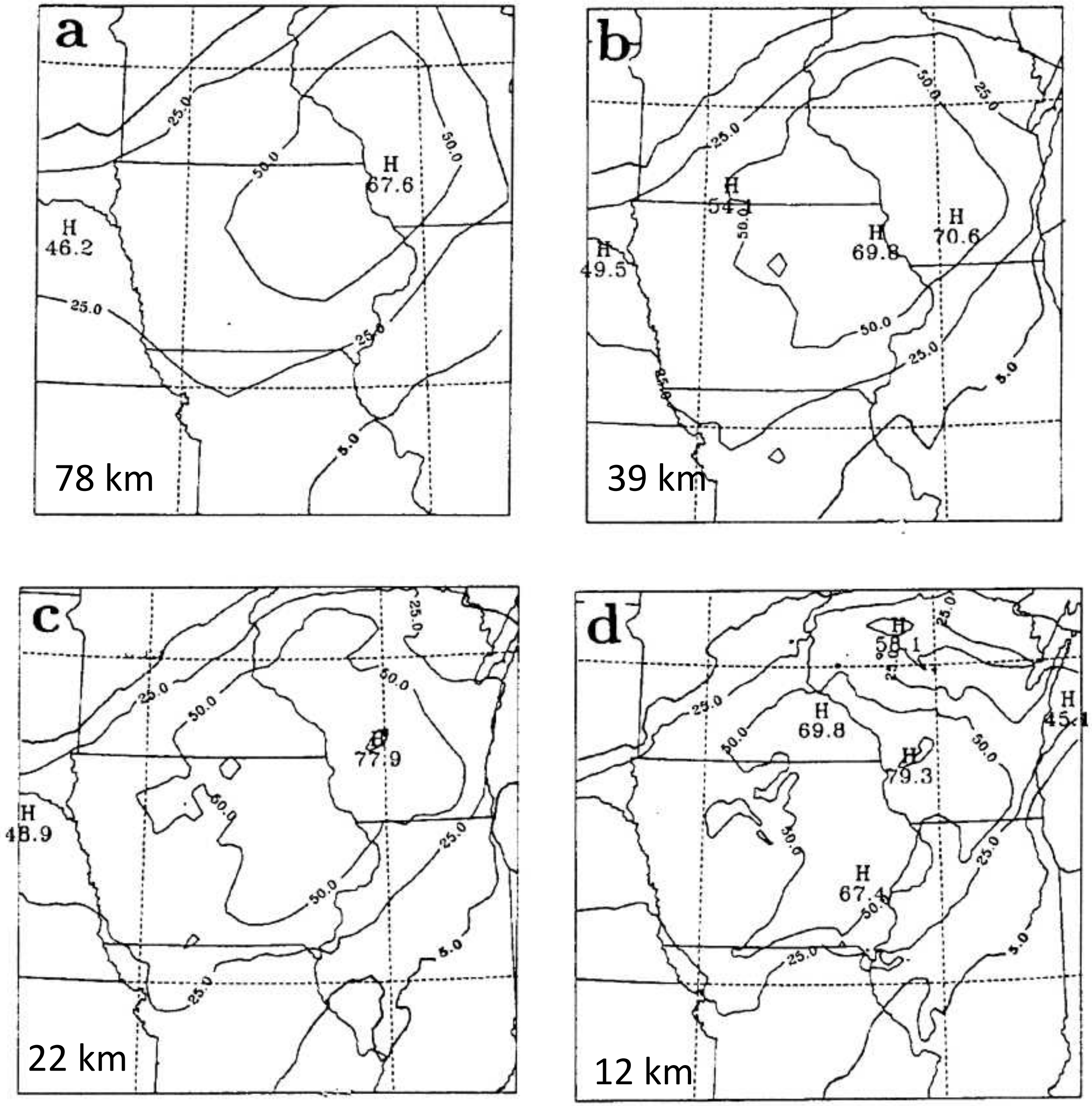


From Baldwin et al. (2002)



From Baldwin et al. (2002)

BMJ

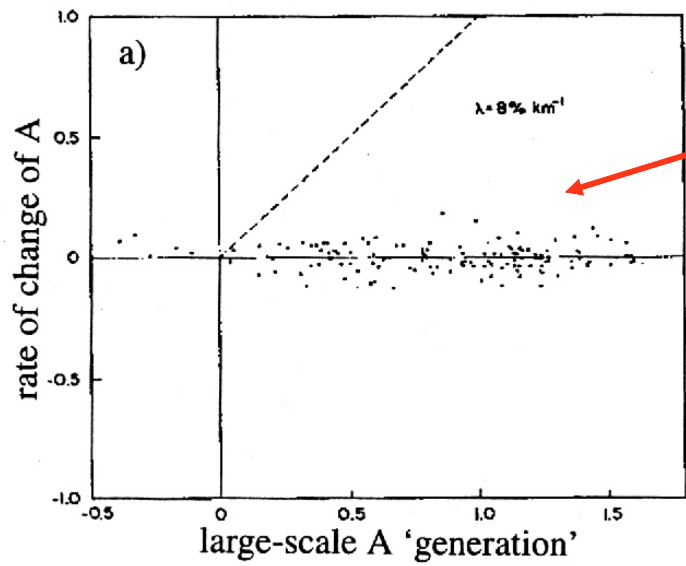


From Gallus (1999)

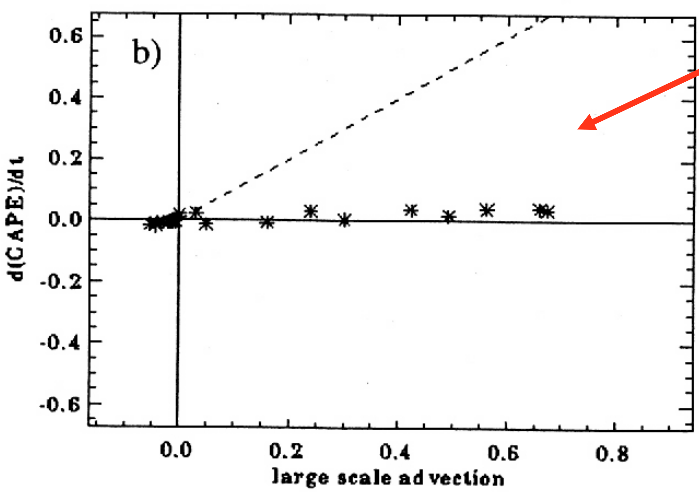
Betts-Miller-Janjic Scheme

- Deep-layer control scheme with shallow component
- Very sensitive to cloud-layer moisture – moisture control scheme
- Static scheme (relaxes to specified profile)
- Conceptually simple
- Has led to forecast improvements
- Not responsive to changes in grid spacing
- Represents total effects of convective system?

Quasi-equilibrium

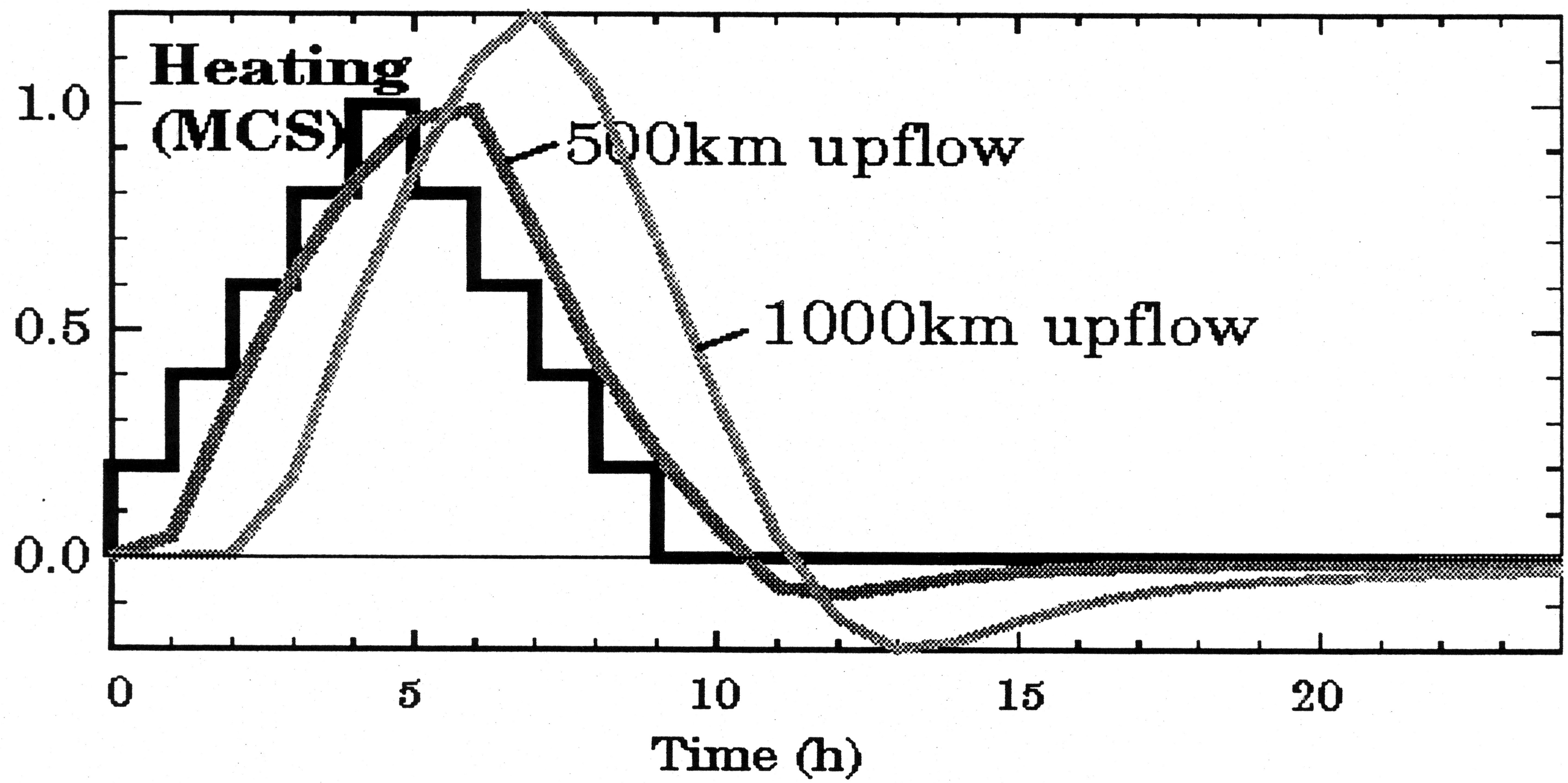


Observations show that large-scale generation of CAPE occurs, but locally the CAPE is not changed. This is the motivation for many deep-layer control schemes.

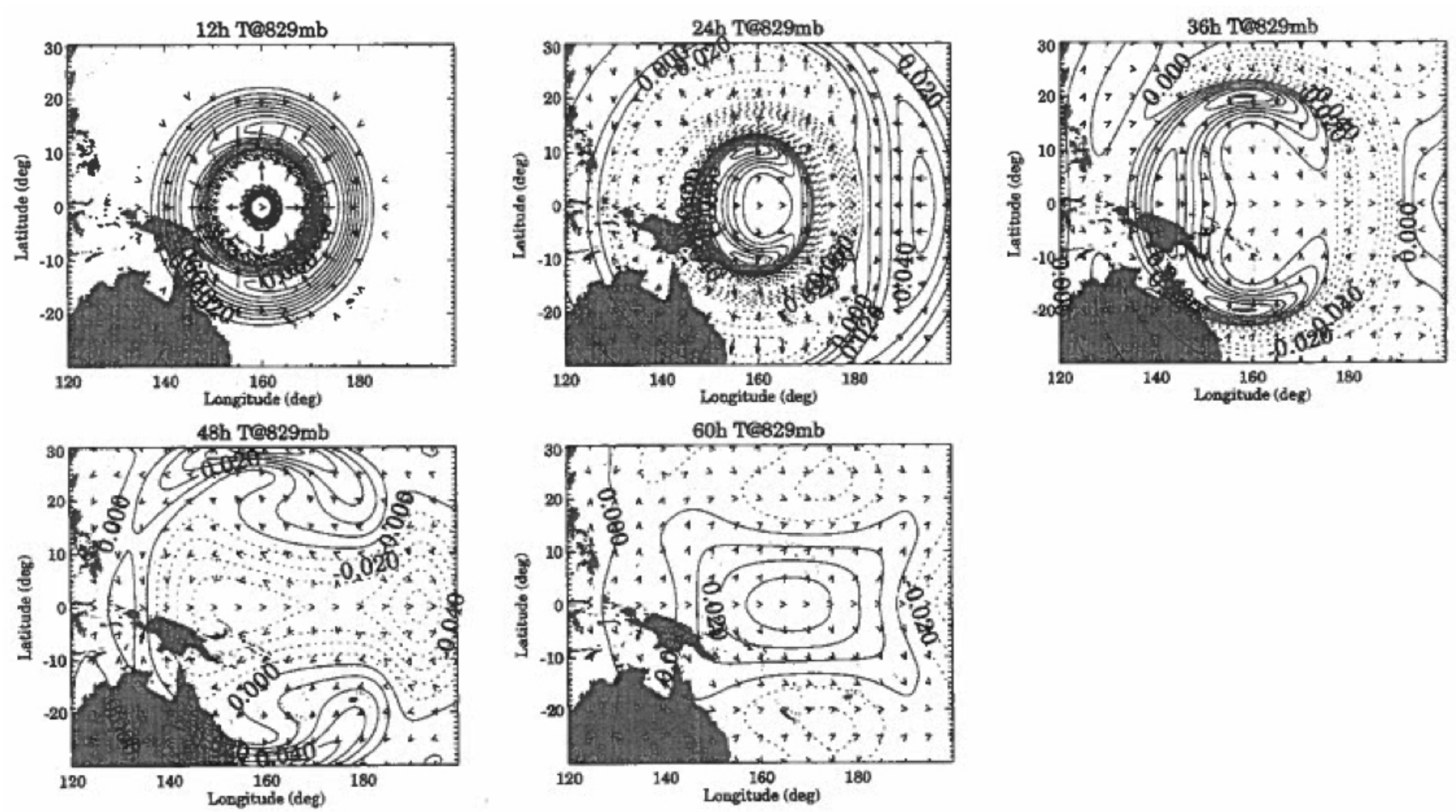


However, same result occurs if convection responds randomly to the large-scale creation of CAPE. This occurs because gravity waves redistribute heating quickly over large areas.

From Mapes (1997)



Time series of imposed MCS-like heating from a linear model, along with area-averaged values of upward motion as sampled by a rawinsonde array with 500 km and 1000 km diameters. Heating produces an upward motion response owing to fast-moving gravity waves. “Quasi-equilibrium holds trivially at the scales represented by rawinsonde networks, because gravity wave processes are efficient at redistributing convective heating, and not necessarily because convection is obedient to large-scale forcing.” - Mapes (1997).



Temperature and wind perturbations at 829 hPa after MCS heating profile applied. From Mapes (1998). Note how quickly gravity waves influence environment over a large area.

Concerns

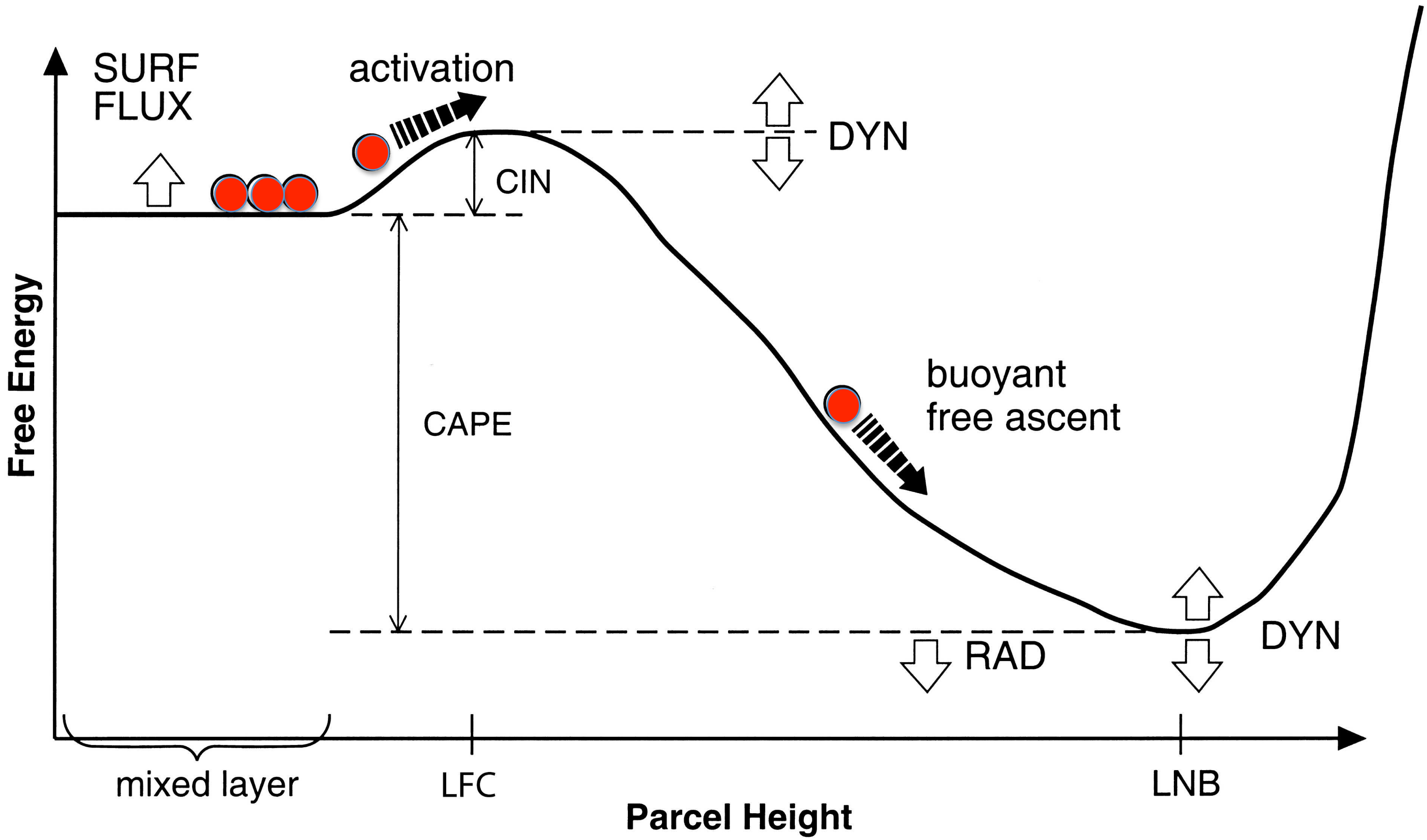
- The work by Brian Mapes and others raise questions about the validity of the quasi-equilibrium assumption that often goes into developing deep-layer control schemes
  – Assumed scale separation is not so clear cut.

- However, they have been successful in improving numerical forecast skill

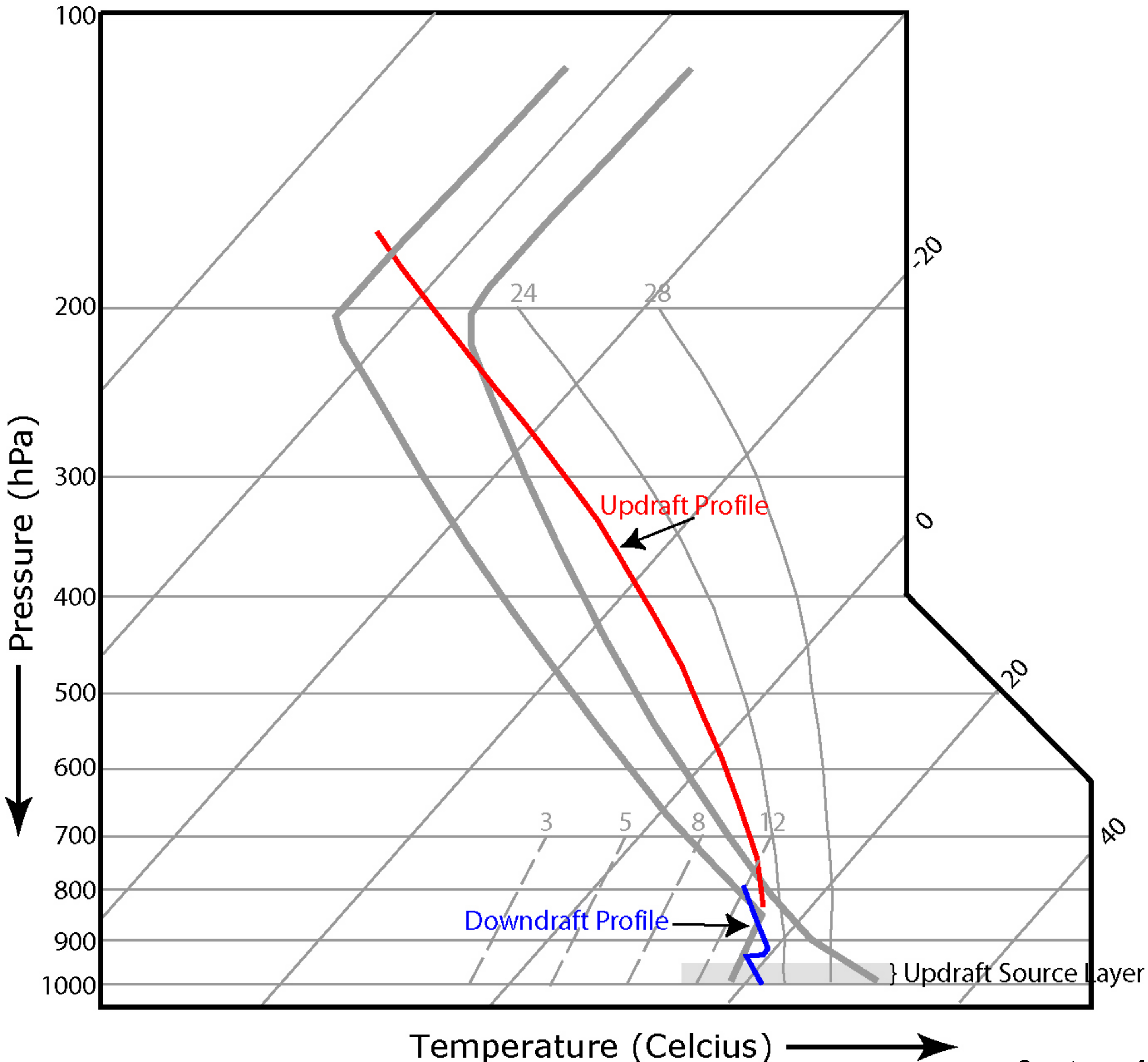
Low-level Control Schemes

- Kain-Fritsch convective scheme
  - 1-d cloud model that includes *updrafts and downdrafts* in formulation
  - Updrafts and downdrafts entrain and detrain according to buoyancy sorting of sub-parcels
  - Equations for rate of change for potential temperature, water vapor mixing ratio and cloud water mixing ratio due to convective effects
    - Conserves mass, thermal energy and total moisture
    - Simple treatment of hydrometeors

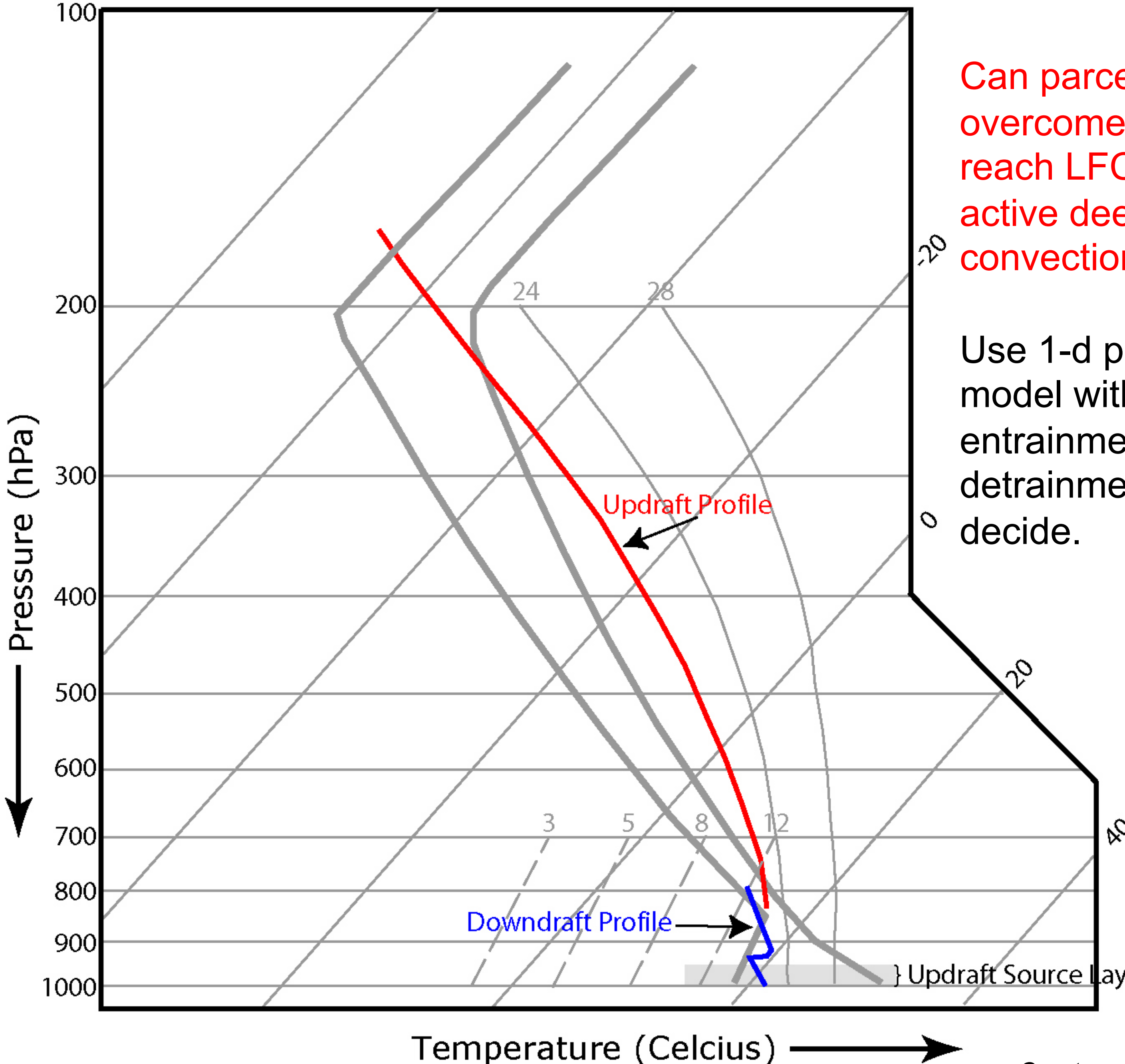
- Responds to grid spacing via the advective time scale. This aspect is unique for convective schemes. (dx/v)
- Net effect of scheme is to remove CAPE.
- Designed to represent effects of convective line and *work in conjunction* with microphysics scheme that handles the stratiform portion
- Can output rain water, ice and snow to resolved scales if desired (hybrid approach)



From Mapes (1997)



Courtesy of Jack Kain



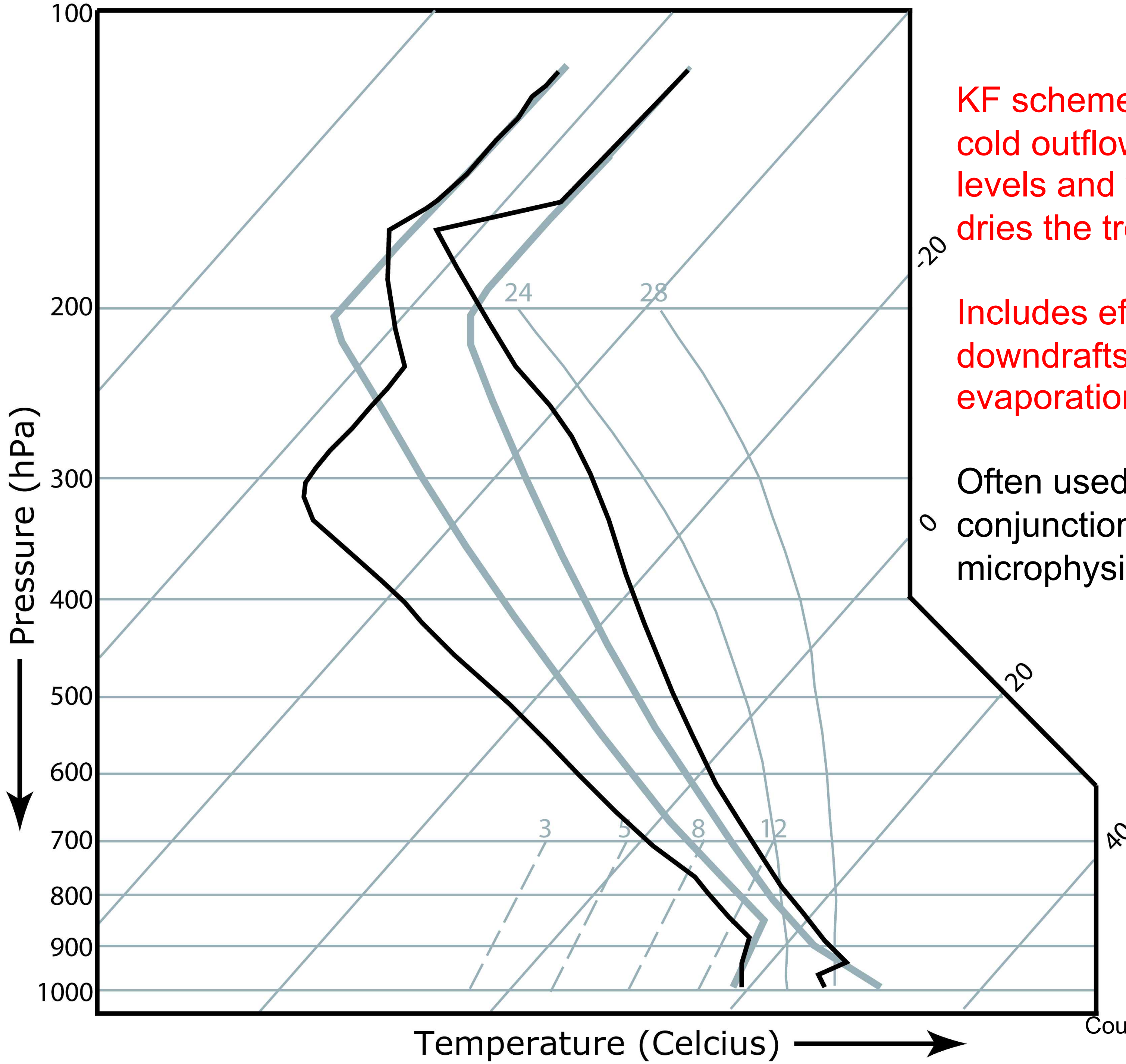
Can parcel overcome CIN to reach LFC and active deep convection?

Use 1-d plume model with entrainment/ detrainment to decide.

Courtesy of Jack Kain

Kain-Fritsch Details

- Once updraft and downdraft profiles are known
  - For a given updraft mass flux, determine how much downdraft mass flux can be produced via evaporation
  - Close scheme by assuming that 90% of CAPE is removed. This is done by increasing updraft mass flux (which then increases downdraft mass flux) until reduction in CAPE is met.



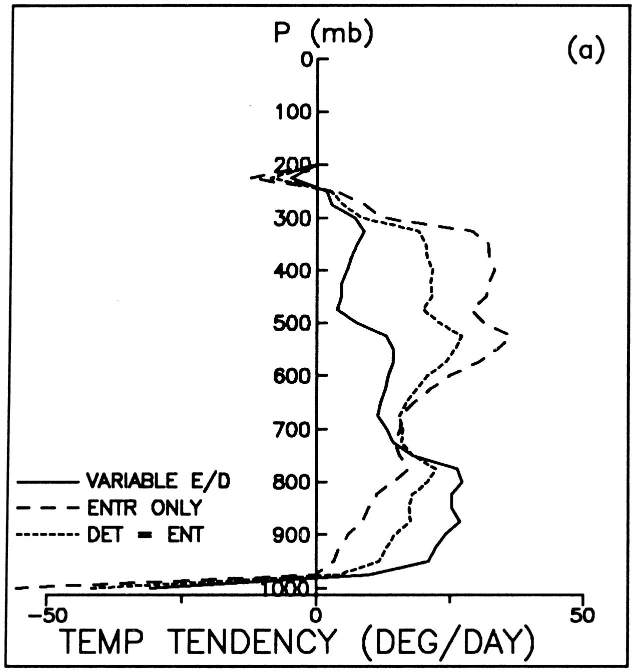
KF scheme develops cold outflow at low-levels and warms and dries the troposphere.

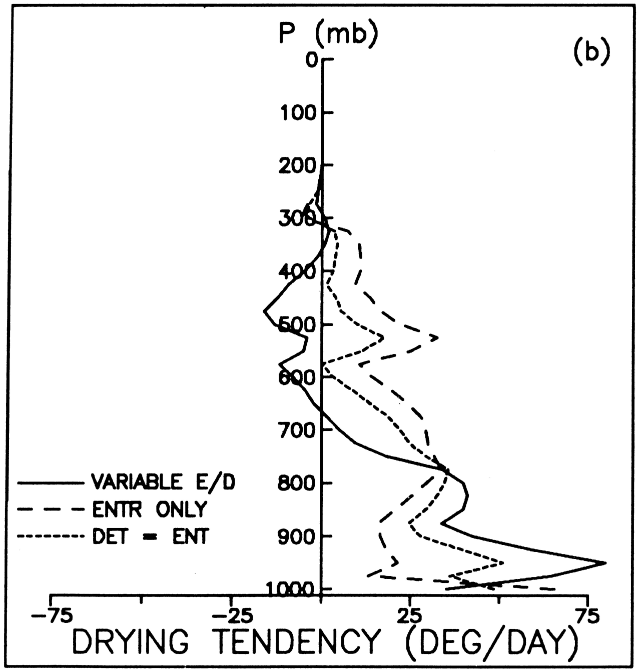
Includes effects of downdrafts driven by evaporation.

Often used in conjunction with microphysics scheme.

$$t_c = \frac{\Delta x}{V_{clayer}}$$

Courtesy of Jack Kain

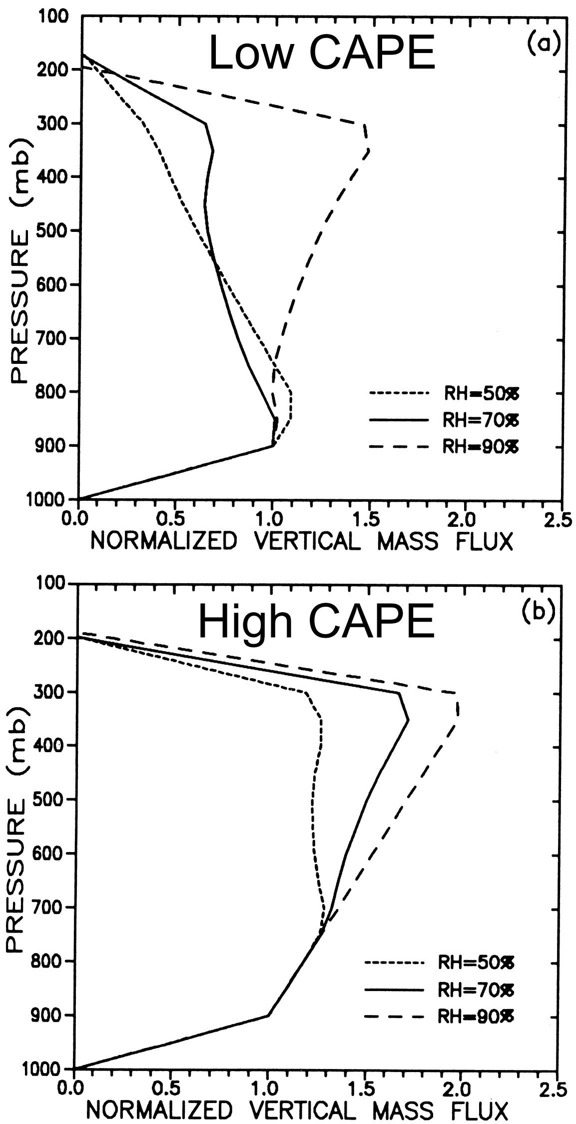




Sensitivity tests show that the heating and drying profiles are sensitive to the way entrainment and detrainment is handled.

Variable entrainment and detrainment appears to produce more reasonable profiles.

From Kain and Fritsch (1990)



From Kain and Fritsch (1990)

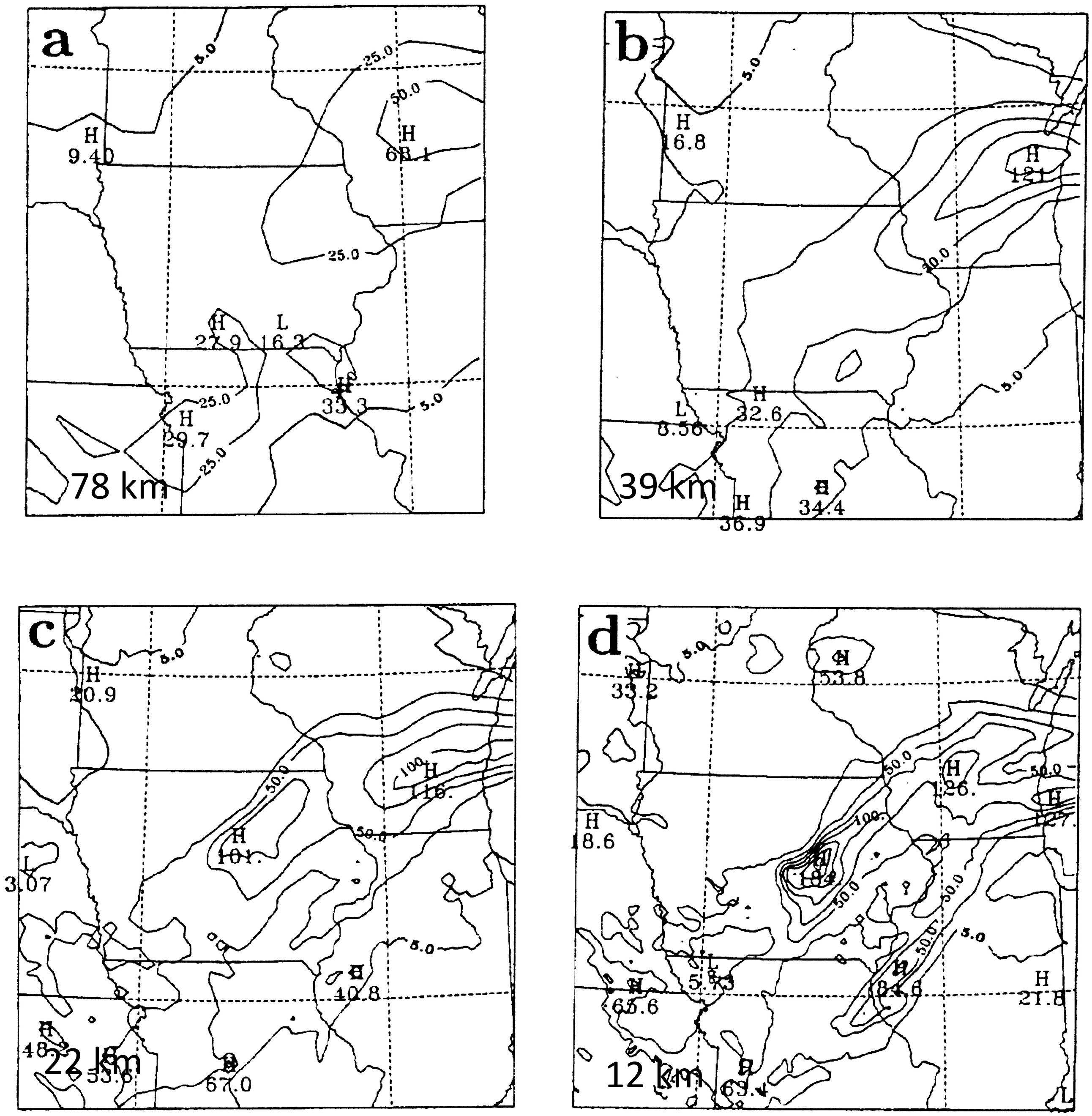
Even though the KF scheme is a low-level control scheme, the vertical mass flux is very sensitive to the environmental relative humidity.

Thus, scheme reproduces some of the behavior of the Betts-Miller-Janjic scheme without the direct importance of cloud-layer moisture in scheme construction.

Shallow Convection

- Activated when all criteria for deep convection are satisfied except for minimum cloud depth (2000 to 4000 m depending upon T)
- Deepest shallow cloud layer is used
- Same 1-d cloud model with entrainment/ detrainment used to determine cloud properties
- Any precipitation generated by scheme is fed back to resolvable scales as moisture source
- Mass flux at cloud base related to TKE

KF



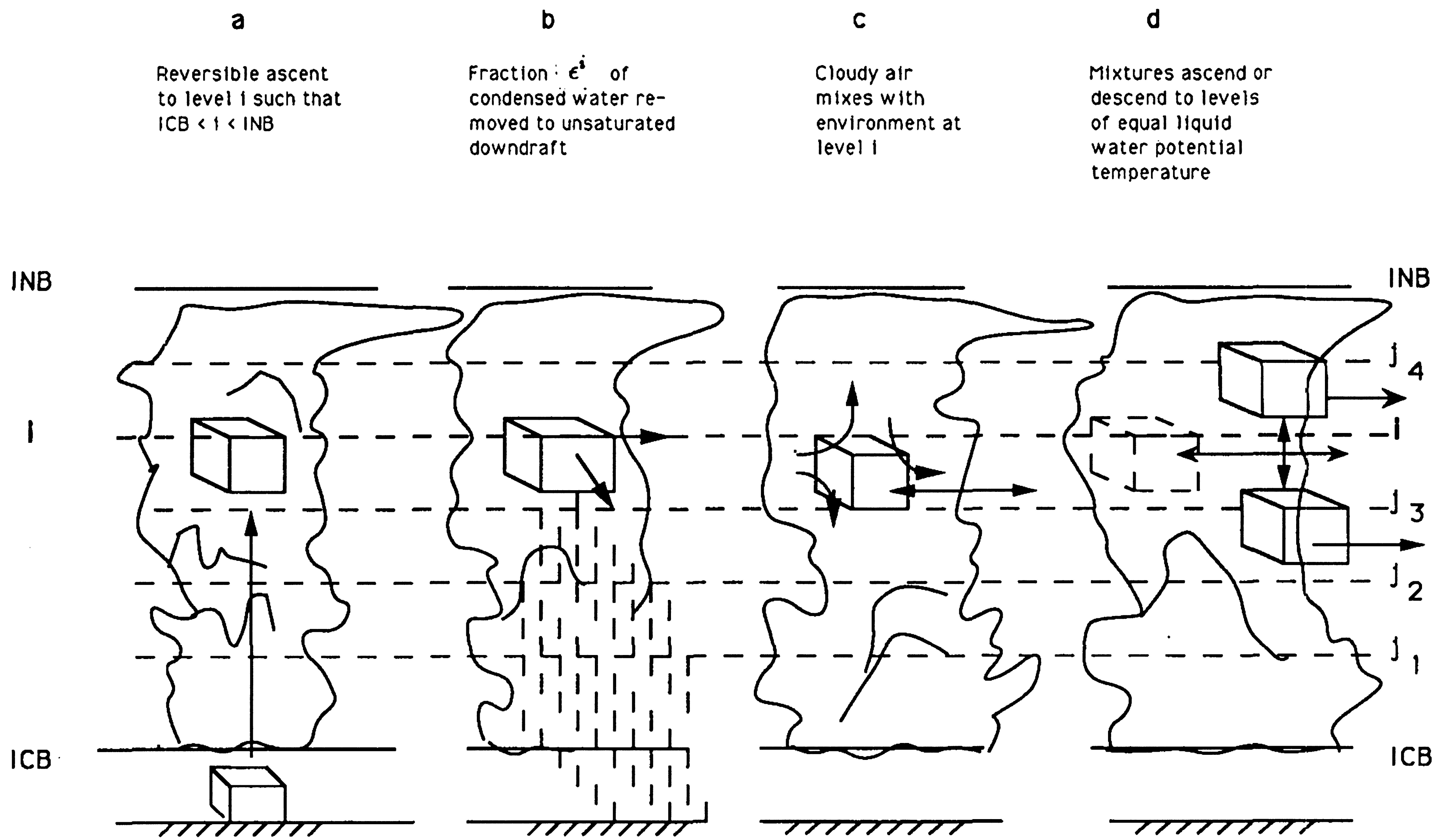
From Gallus (1999)

Kain-Fritsch Scheme

- Low-level control scheme with shallow component
- Dynamic scheme (profile changes as environment changes)
- Response changes with grid spacing
- More physically-based approach
- Rainfall amounts often reasonable, but location may be incorrect as initiation depends on local features that are not always correctly forecast

Emanuel Convective Scheme

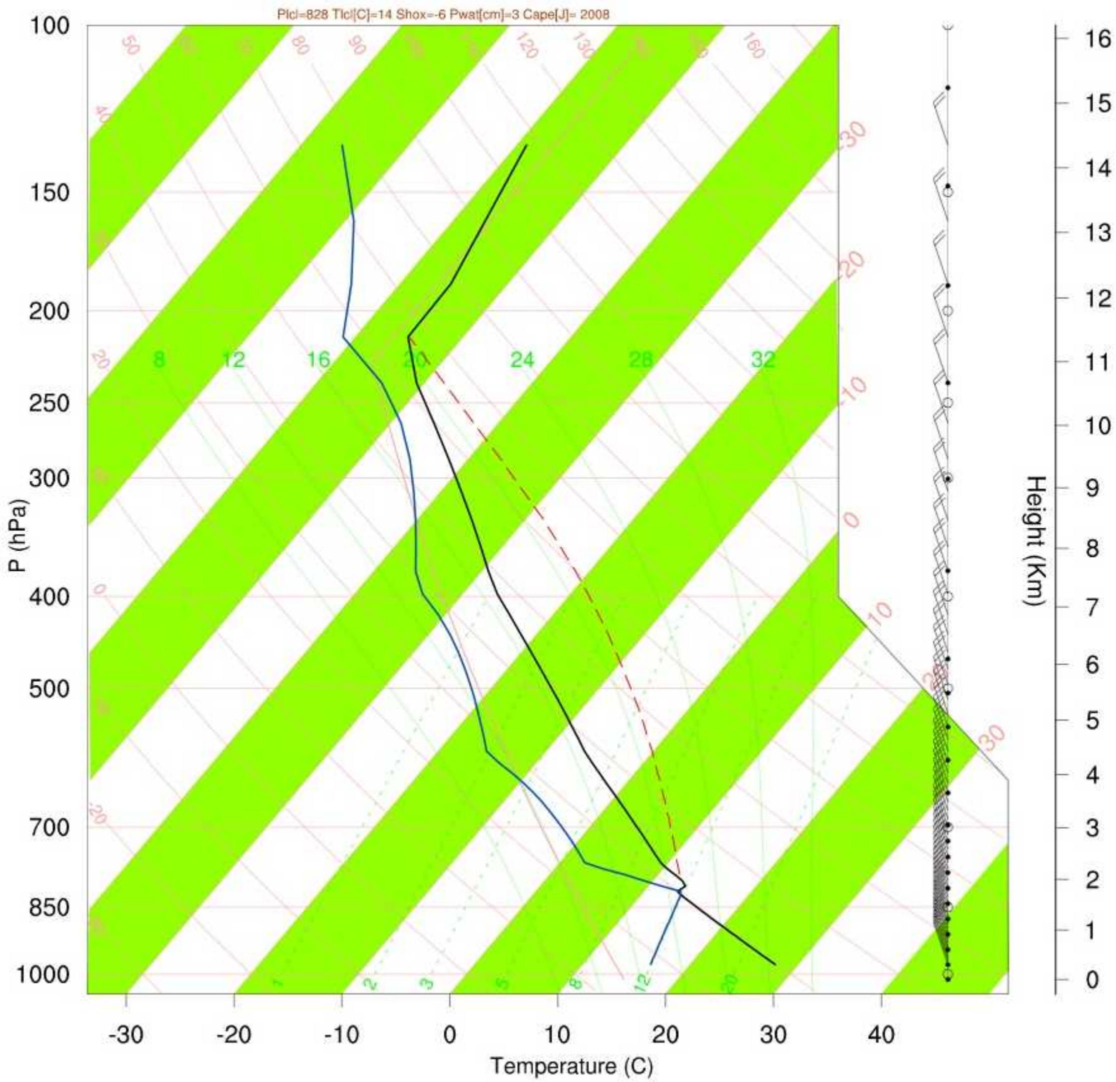
- Mass flux scheme like Kain-Fritsch
- Uses idealized model of buoyancy sorting for updraft parcel
- Mixing in clouds occurs episodically instead of continuously as occurs in entraining plume models
- Interesting approach, but not used in many studies



From Emanuel (1991)

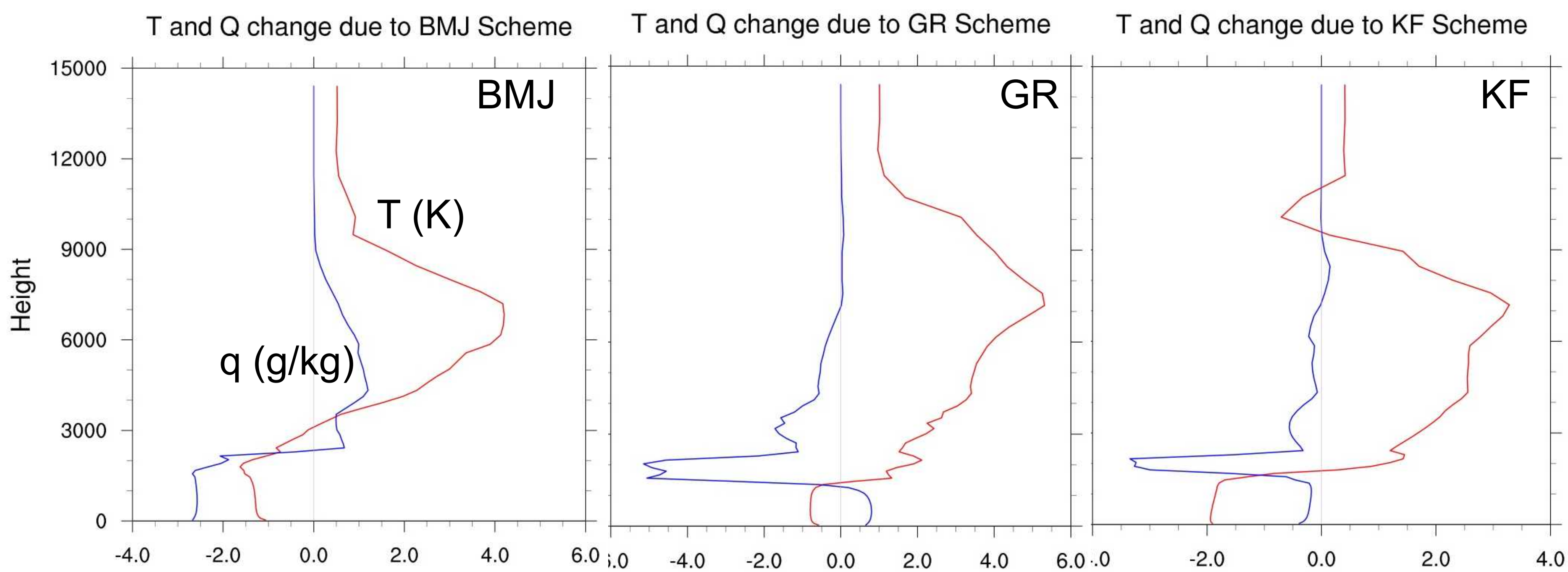
Simple SCM Comparison

- 1-d version of ARW
- Input single sounding
- Short and longwave radiation, YSU PBL and LSM turned on
- Starts at noon local time and runs for 4 hours
- Compare changes in vertical profile due to using BMJ, Grell and KF schemes (not all changes due to just convective scheme)



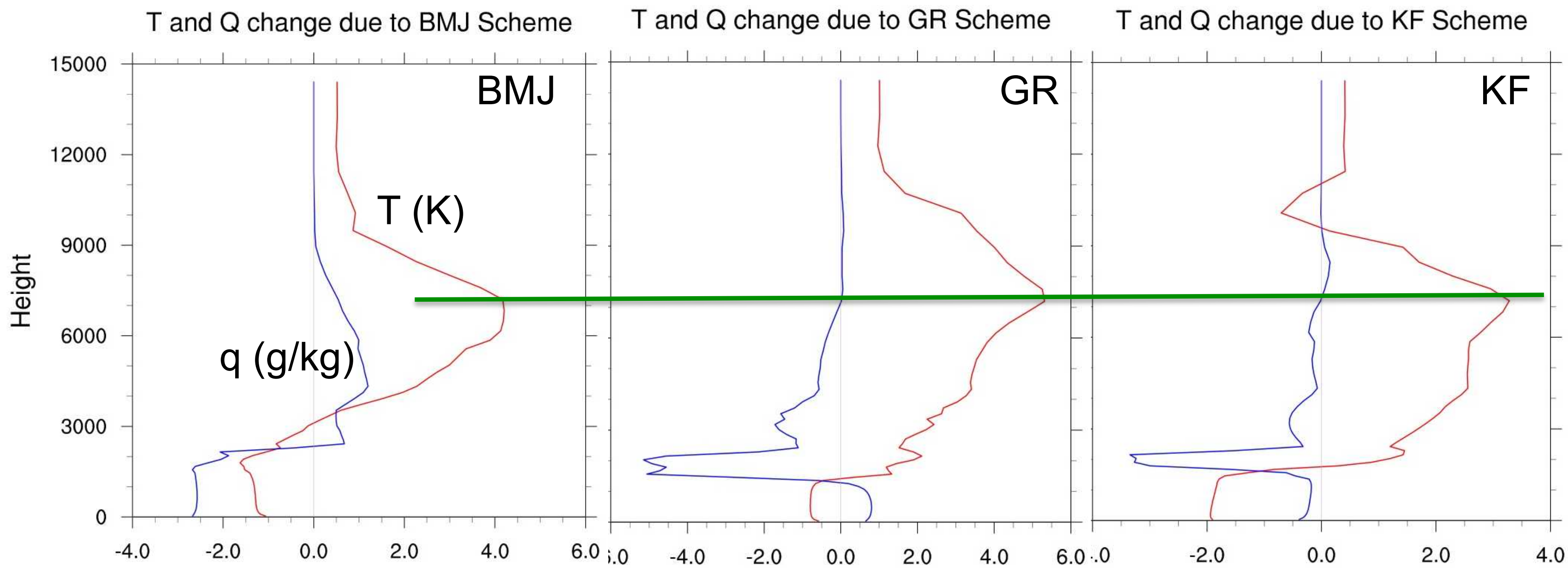
Plcl=828 Tlcl[C]=14 Shox=-6 Pwat[cm]=3 Cape[J]= 2008
P (hPa)
Temperature (C)
Height (Km)

SCM Results



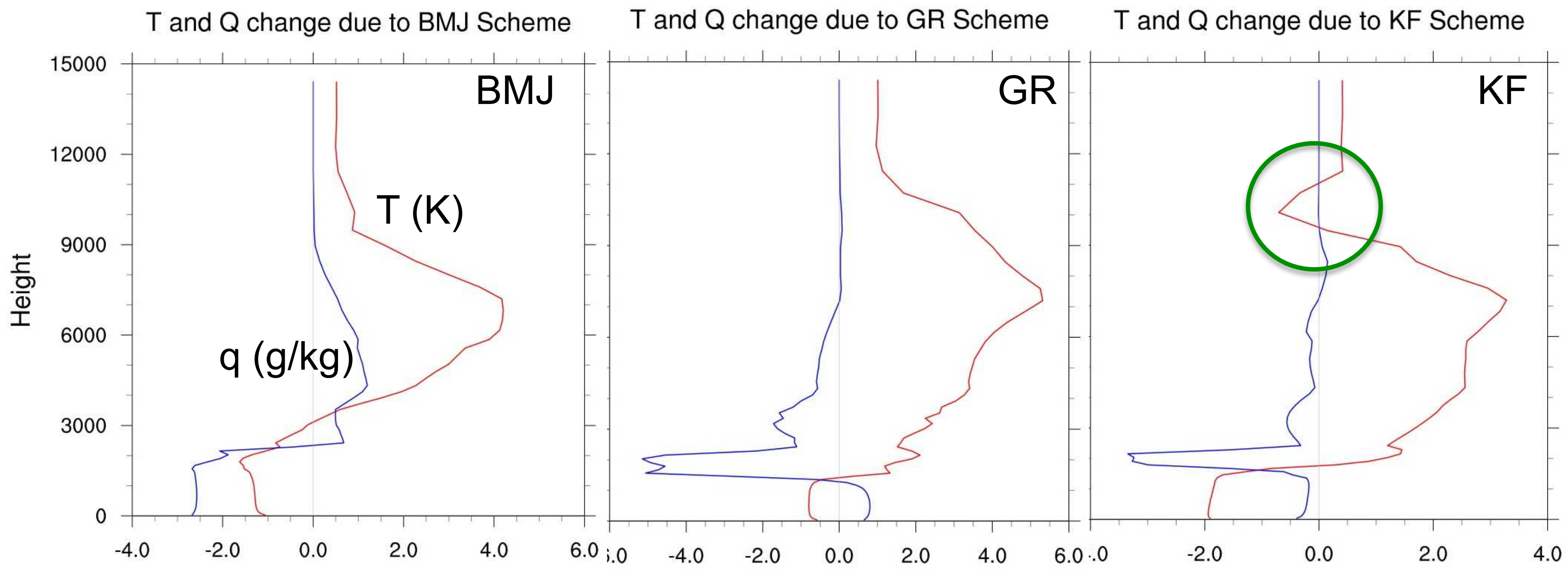
T and Q change due to BMJ Scheme
T and Q change due to GR Scheme
T and Q change due to KF Scheme
BMJ
GR
KF
T (K)
q (g/kg)
Height
15000
12000
9000
6000
3000
0
-4.0
-2.0
0.0
2.0
4.0
6.0

SCM Results



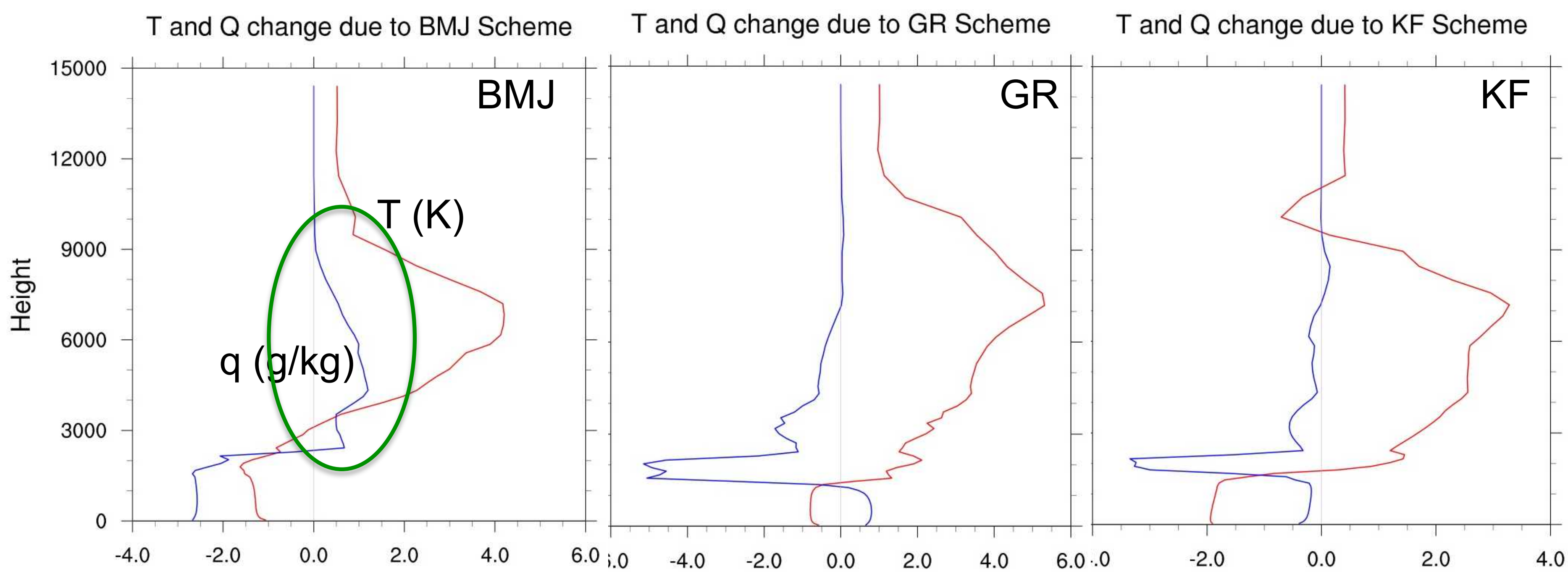
Heating in column at roughly the same height, with BMJ maximum a little lower. Note smooth structure of BMJ heating compared to structure in GR and KF heating profiles.

SCM Results



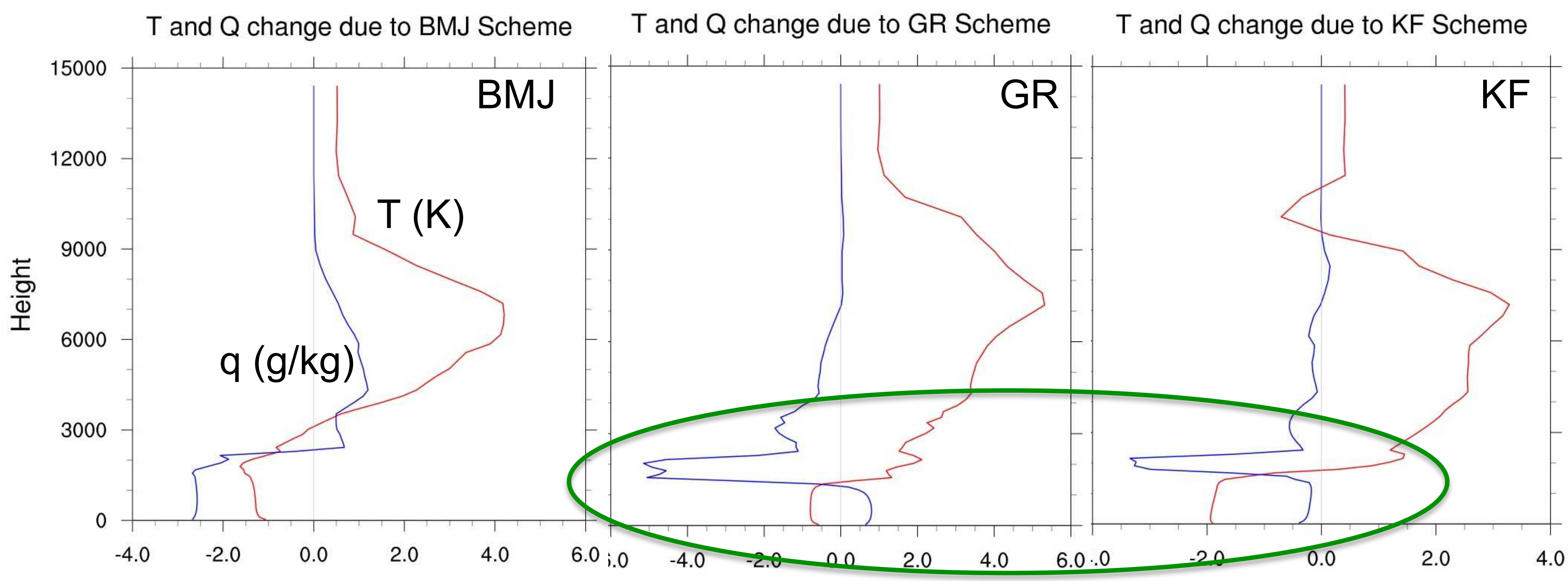
KF scheme includes overshooting tops, so produces cooling aloft not seen in BMJ or GR schemes.

SCM Results



BMJ scheme for this sounding actually moistens cloud layer slightly, while removing moisture from bottom of cloud layer. Deeper layer of low-level cooling in BMJ due to interplay between shallow scheme and PBL scheme that yields deeper PBL.

SCM Results

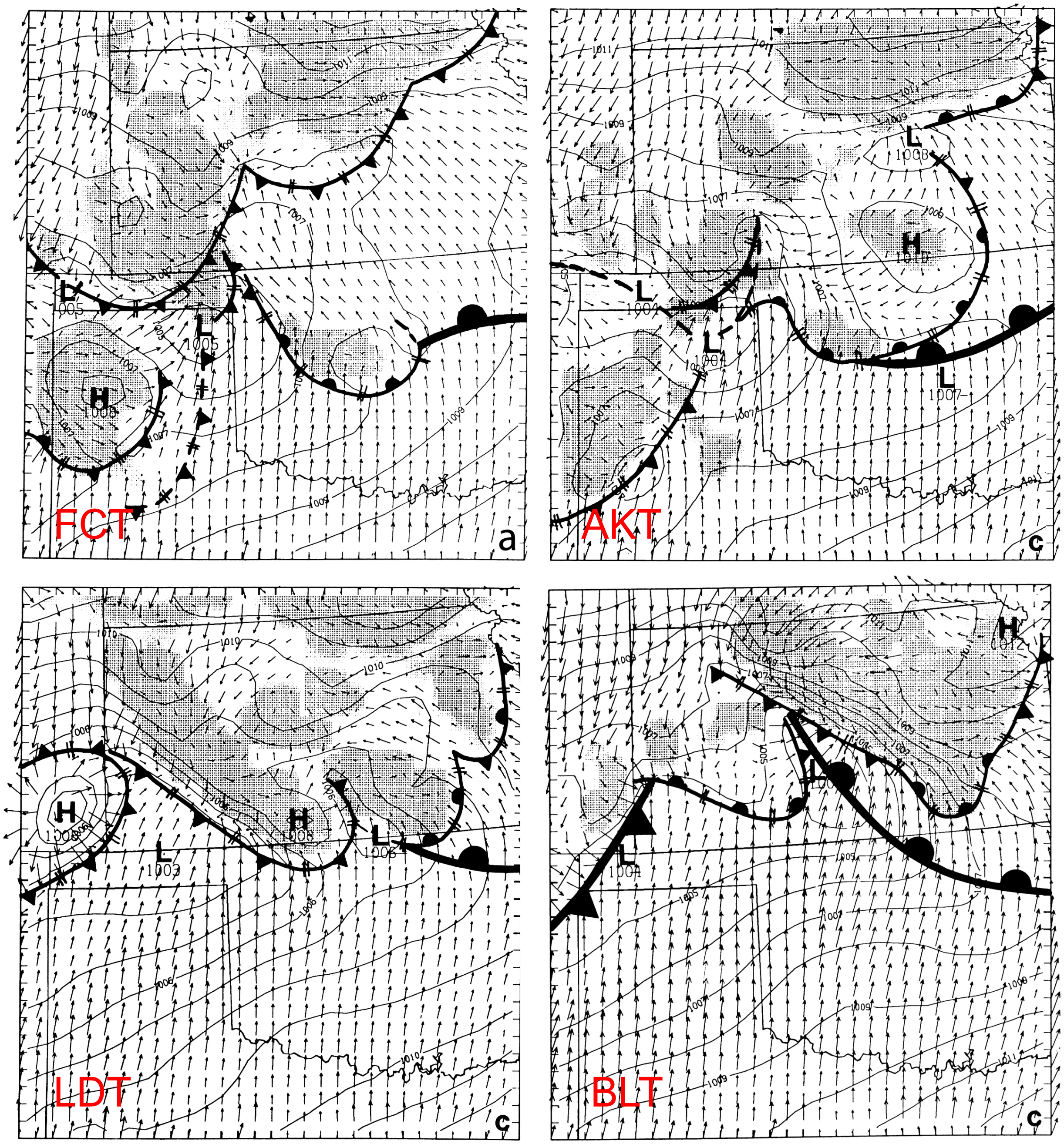


Similarity in drying at top of PBL from GR and KF schemes. Both remove moisture from cloud layer and increase moisture in lowest levels due to evaporation within downdraft.

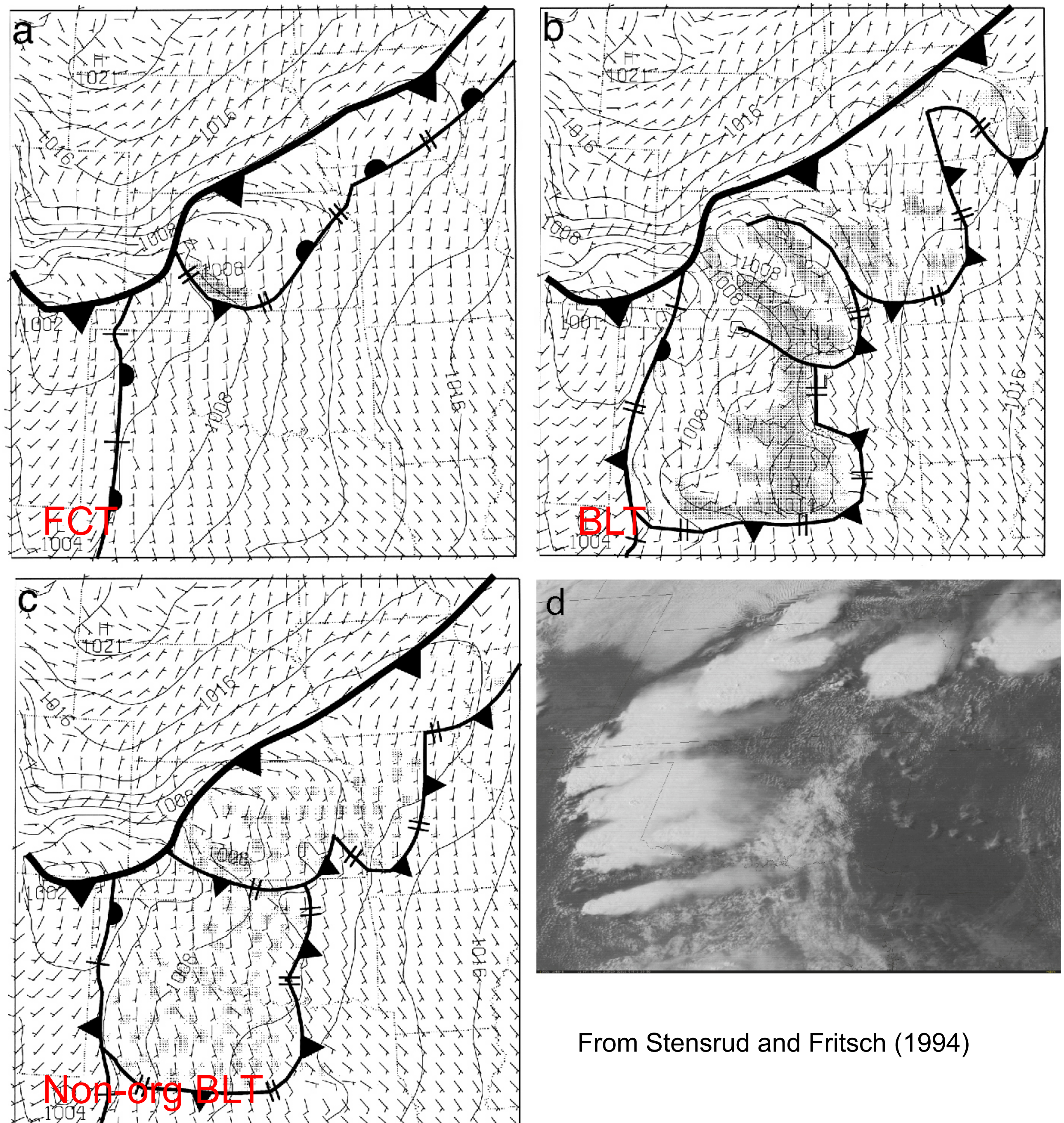
Do these differences matter to an actual forecast?

Trigger functions

- Criteria that determine when and where convection is activated
  - All schemes have them
  - Very important to scheme behavior, but not always clearly defined
  - Betts-Miller trigger function is tied to cloud-layer moisture
  - Kain-Fritsch trigger function is tied to grid-scale vertical motion and parcel reaching it's LFC



From Kain and Fritsch (1992)



From Stensrud and Fritsch (1994)

Trigger Functions (from talk by Kain and Baldwin)							
	CAPE	Cloud Depth	CIN	Moist. Conv.	Sub-cloud Mass conv.	Cloud-layer Moisture	∂(CAPE)/∂t
BMJ (Eta)	🌧	🌧				🌧	
Grell (RUC, AVN)	🌧	🌧	🌧				🌧
KF (Research)	🌧	🌧	🌧		🌧		
Bougeault (Meteo FR)	🌧			🌧			
Tiedtke (ECMWF)	🌧	🌧		🌧			
Bechtold (Research)	🌧	🌧	🌧		🌧		
Emanuel (Research)	🌧		🌧				

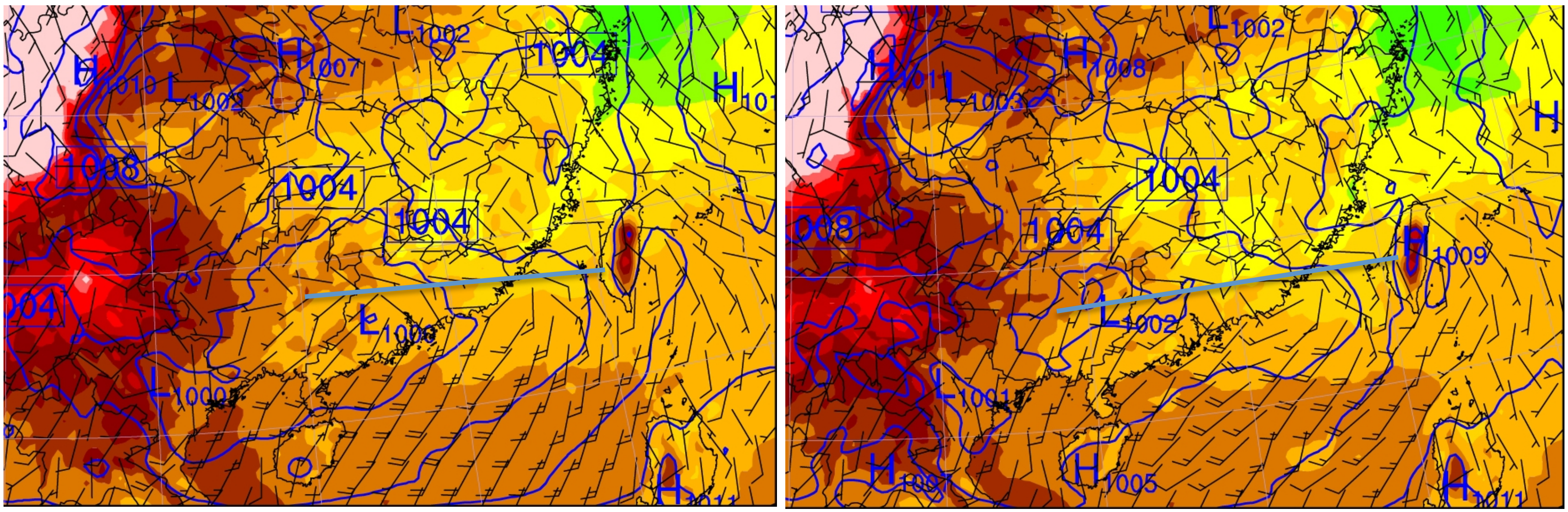
Does the Choice of Scheme Matter?

WRF Simulation Comparison

- ARW with 15-km grid spacing and 35 levels
- Same initial and boundary conditions
- Same physics, except for convective scheme. One run with KF and one run with BMJ.
- Look at differences in sea level pressure, 2-m temperature and low-level winds
- 6 June 2003 Mei-Yu event over southeastern China

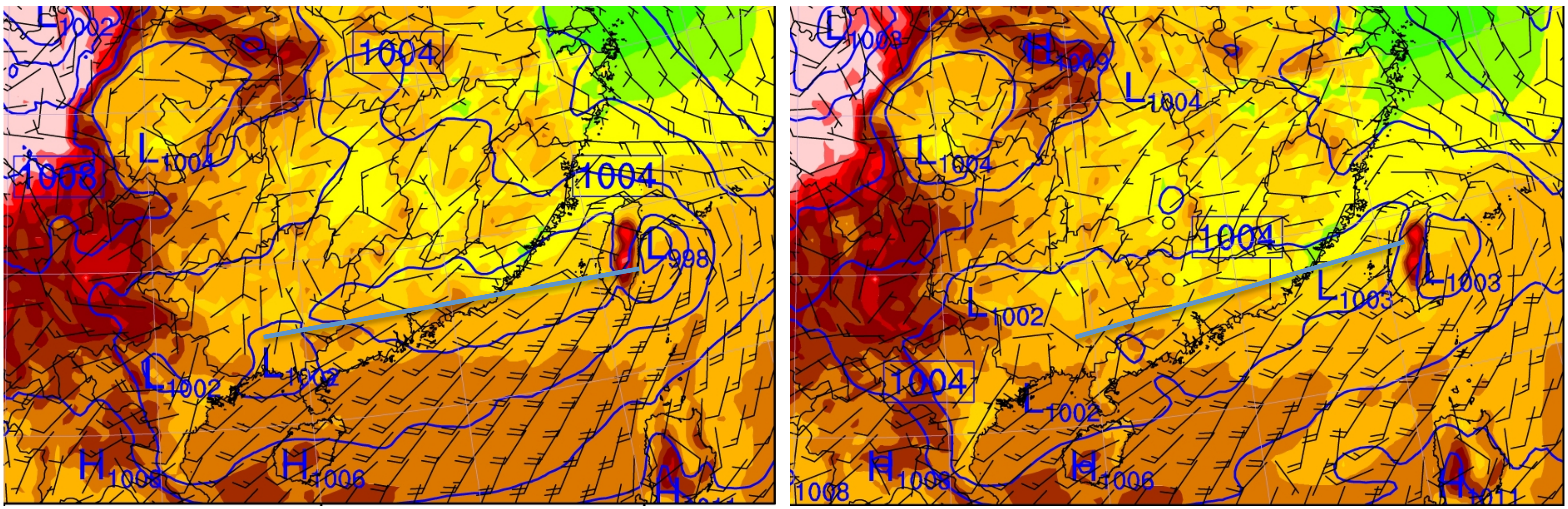
Kain-Fritsch

BMJ



12 h simulation 1200 UTC 6 June 2003

Kain-Fritsch BMJ



24 h simulation 0000 UTC 7 June 2003

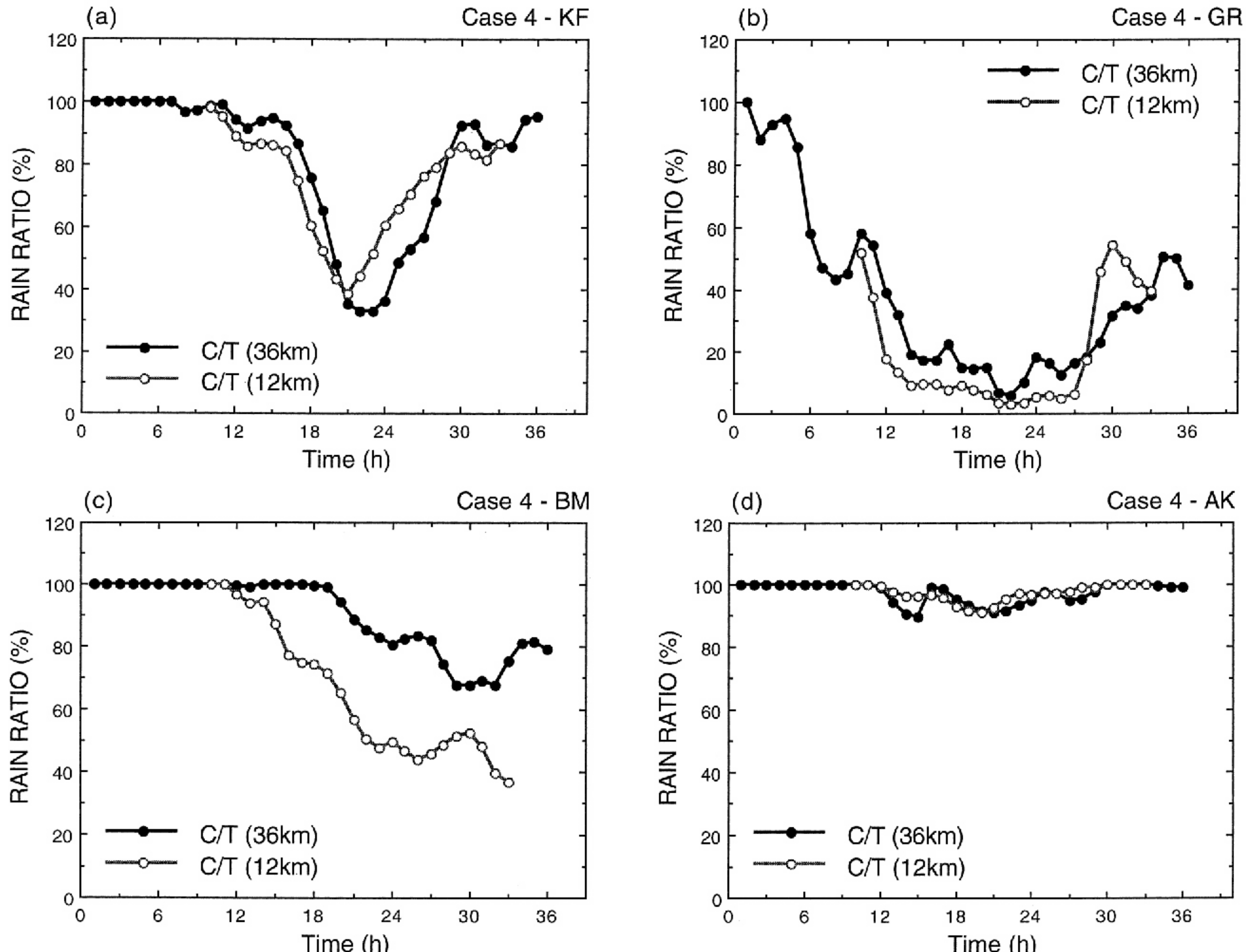
WRF Comparison

- Both schemes put convection in roughly the same locations
  - Different rainfall totals, rainfall evolution
  - Different partitioning of rainfall from convective scheme and rainfall from microphysical schemes
  - Different Mei-Yu front locations
  - Different CAPE distributions

Discussion

- Convective parameterization is needed for grid spacings > ~ 5 km.
    - Gray zone between 5 and 20 km

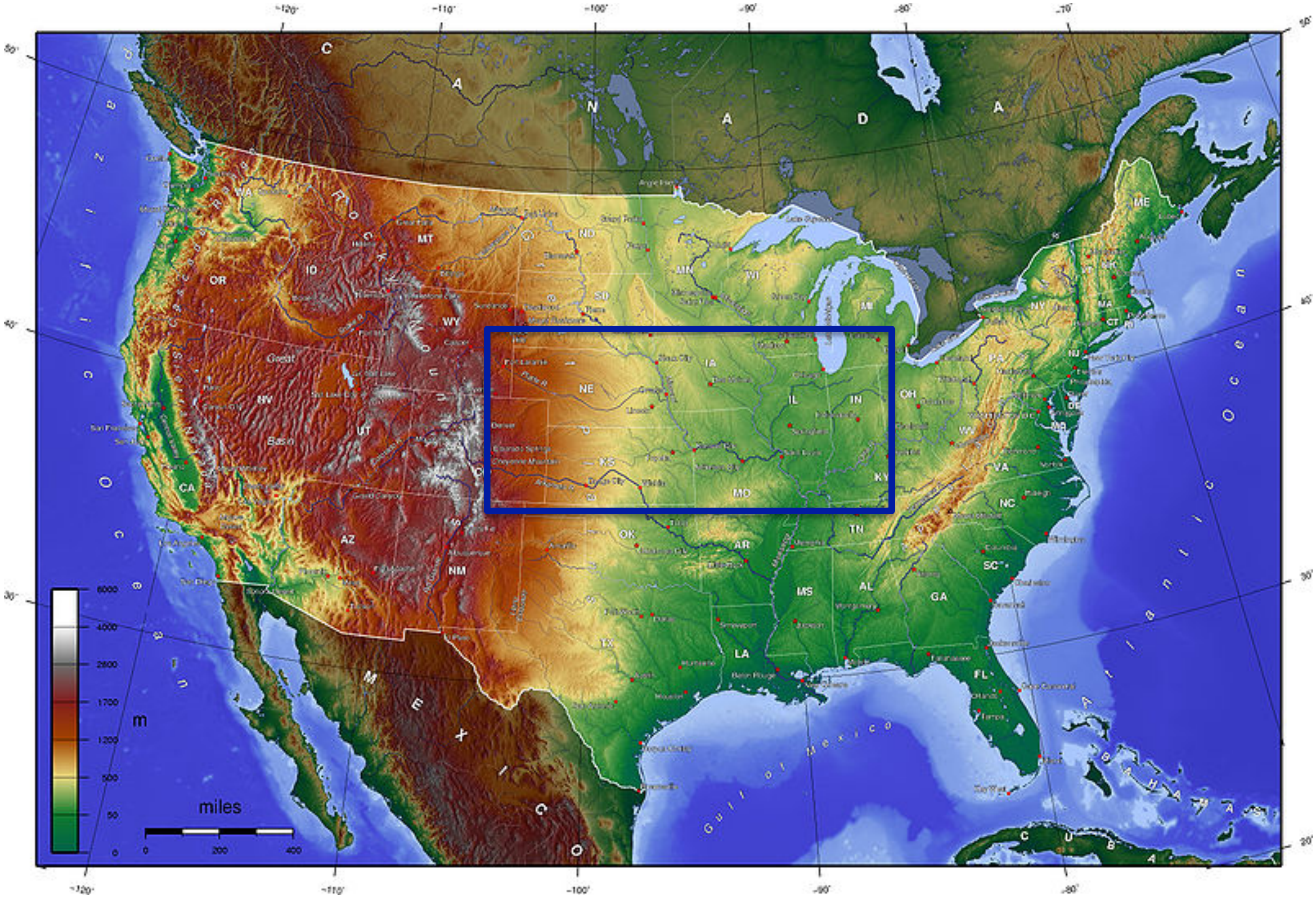
- Schemes use very different assumptions and can be categorized in several ways
    - Deep-layer or low-level control?
    - Moisture or instability or forcing?
    - Mass flux or profile?
    - Single cloud or ensemble of clouds?
    - Represent all convective elements (including stratiform) or just convective line?
    - Simple adjustment profile or detailed cloud model?



Wang and Seaman (1997)

Ratios of convective/total precipitation show very different behaviors among schemes

(C/T = convective divided by total rainfall).



C A N A D A
M E X I C O
Gulf of Mexico
Great Basin
WA
OR
ID
MT
WY
ND
SD
MN
WI
MI
NY
ME
NH
VT
MA
CT
RI
PA
NJ
NE
IA
IL
IN
OH
NV
UT
CA
CO
KS
MO
KY
WV
VA
MD
DE
NC
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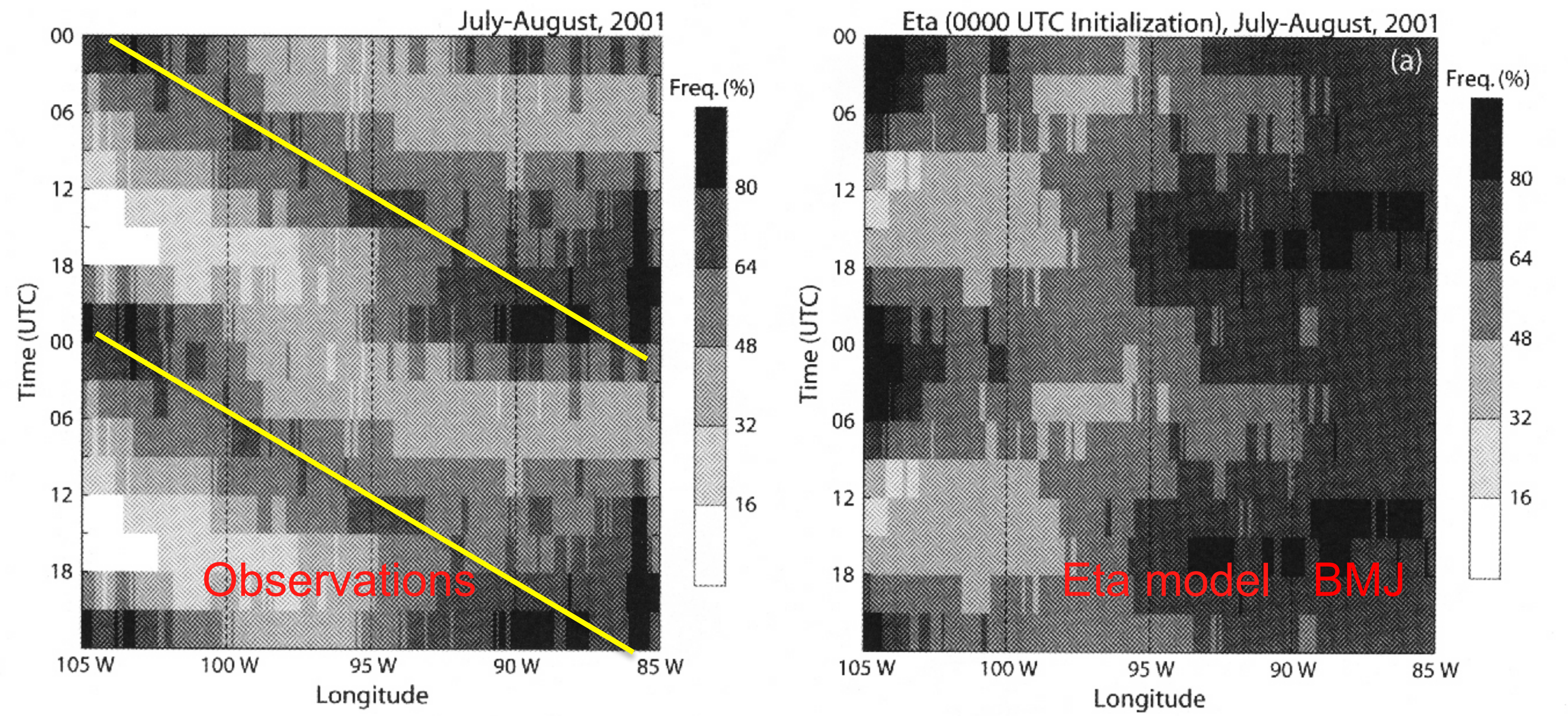
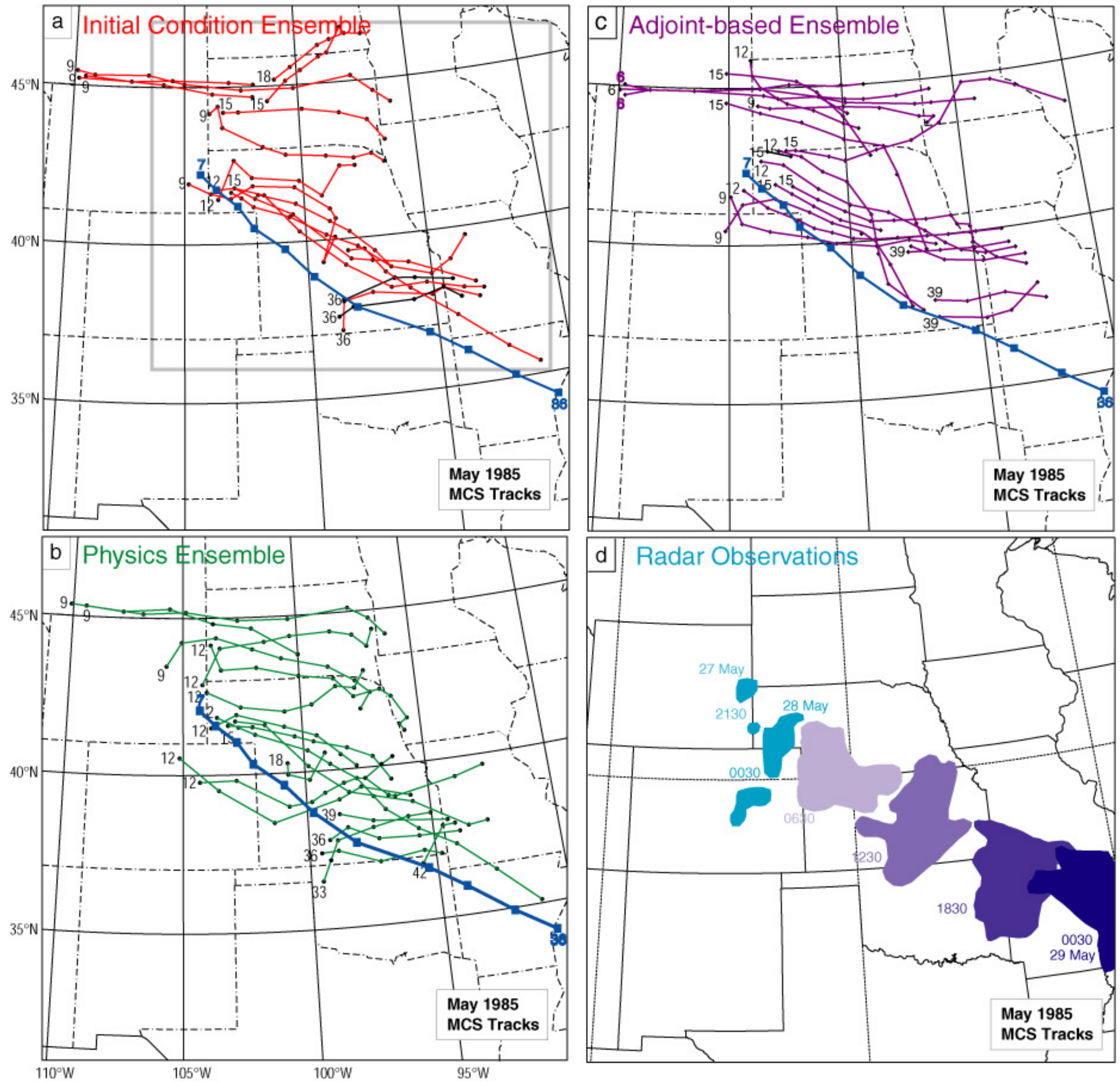
200
400



From Davis et al. (2003)

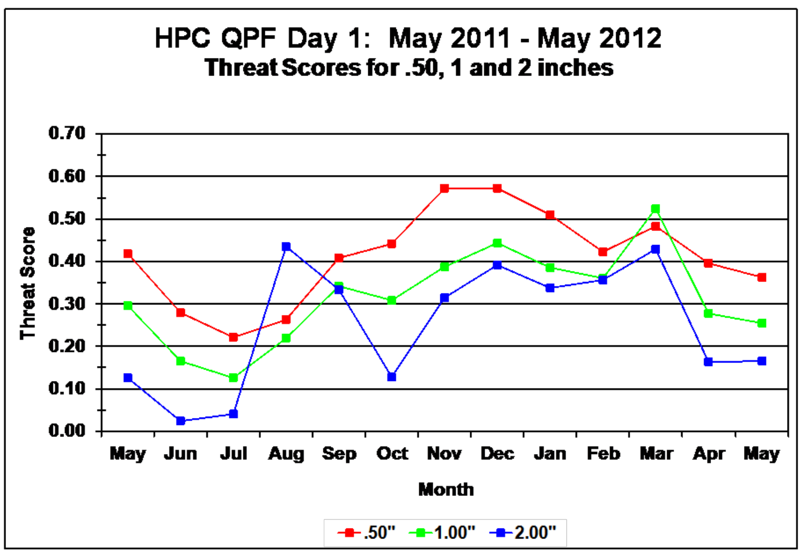
- Hovmoller diagram shows that convection forms along mountains and moves east overnight, whereas model does not reproduce this behavior consistently. Why does this happen?

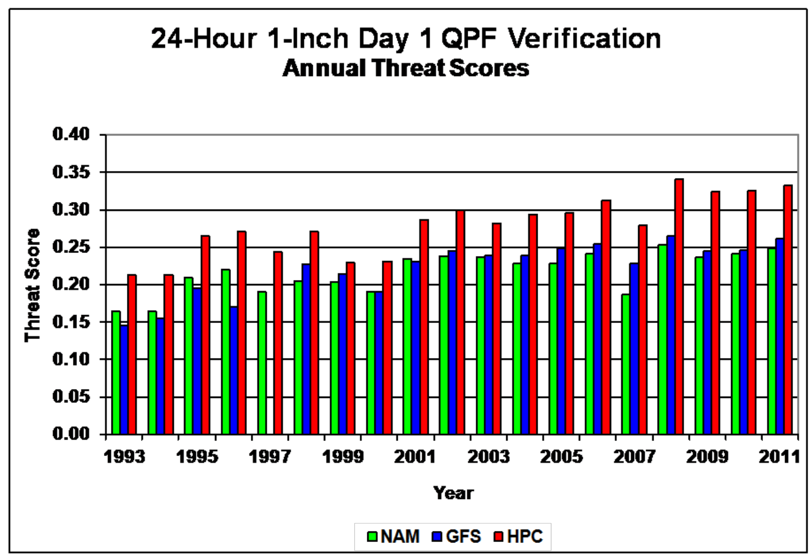


From Xu et al. (2001)

Yet case studies show that propagating MCSs are possible with parameterized convection. What limits this propagation from happening more routinely?

- Is there a convection parameterization deadlock as suggested by Randall et al. (2003)?
- It is well known that convection parameterization is a significant source of uncertainty in climate change studies.





Scale Separation?

- On global scales, we find a state of near radiative-convective equilibrium
- On mesoscales, the organization of convection clearly related to existence of gust fronts, sea breeze fronts, etc, that initiate convection
- *Somewhere in between there is a transition from deep-layer to low-level control*

- Assumptions are important to understand if you want to understand model behavior and improve model forecasts
- Schemes often created and tested to address a specific problem, then applied globally!
- Parameterization is a reductionist approach
  - Assume sum of the parts equals the whole but is this true?

- Assumptions can be violated, yet model still will run and produce forecasts!

- Open questions
  - Aerosol effects
  - Obtaining maximum precipitation intensities
  - Gray zone in horizontal grid spacing
  - Interactions with radiation, cloud cover, boundary layer and other parameterization schemes
  - Lack of convective system propagation
  - Difficulties in simulating MJO
  - Trigger function
  - Tendency for overproduction of light precipitation
  - Including momentum transport by convection
- *We need to recognize that how we frame our questions is important to making progress*

Questions?