Convective vs anvil heating structures and their impact on the large-scale circulation

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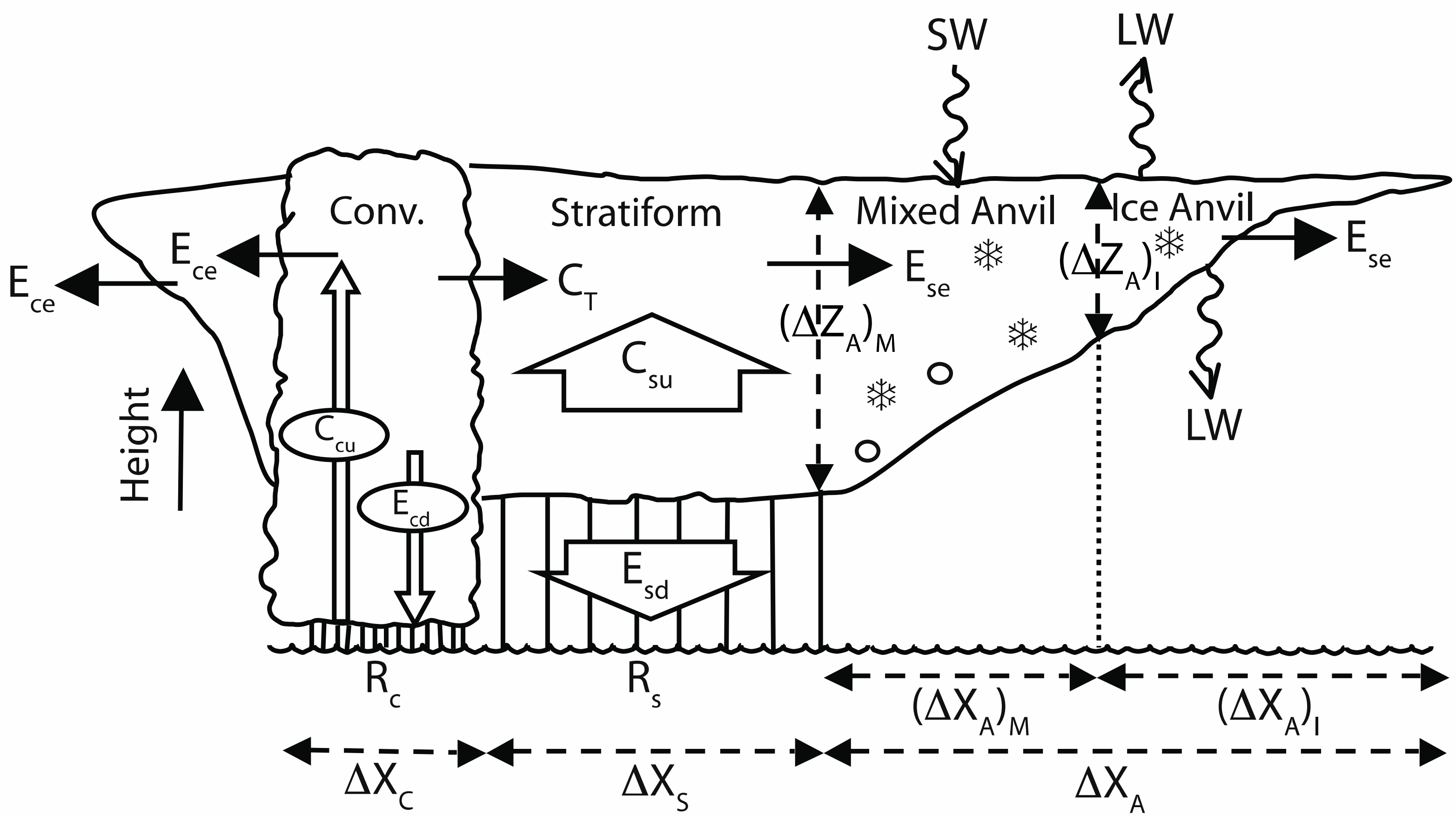
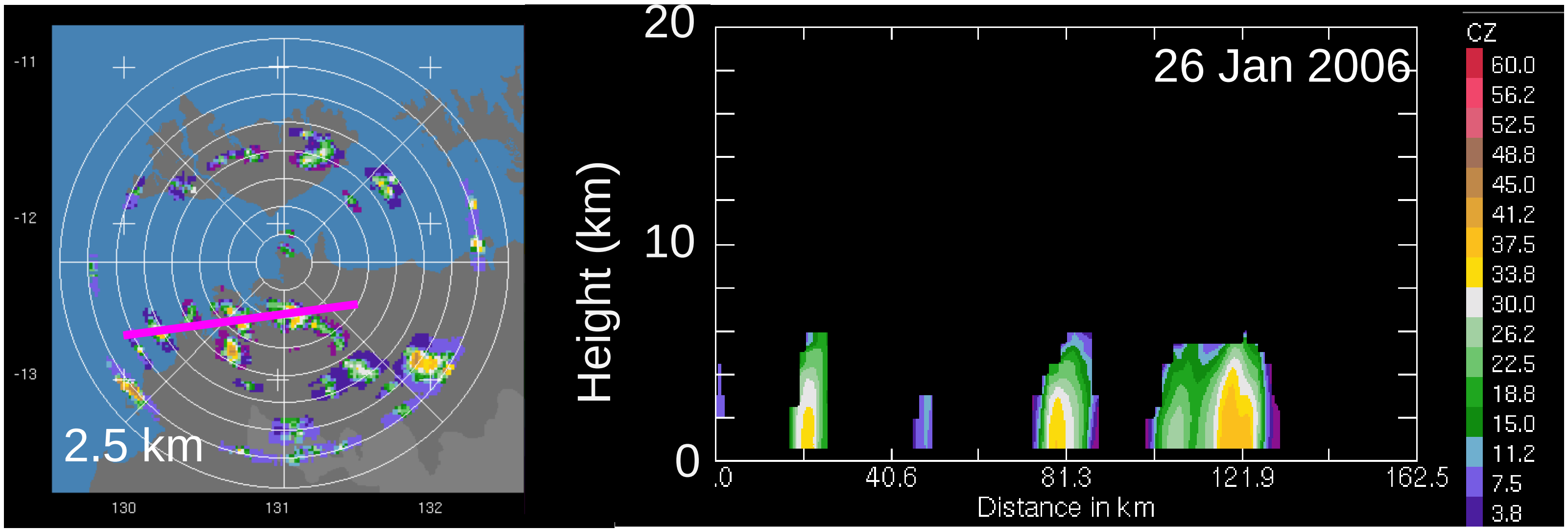
MCS energy budget



Houze et al. (1980), Frederick and Schumacher (2008)

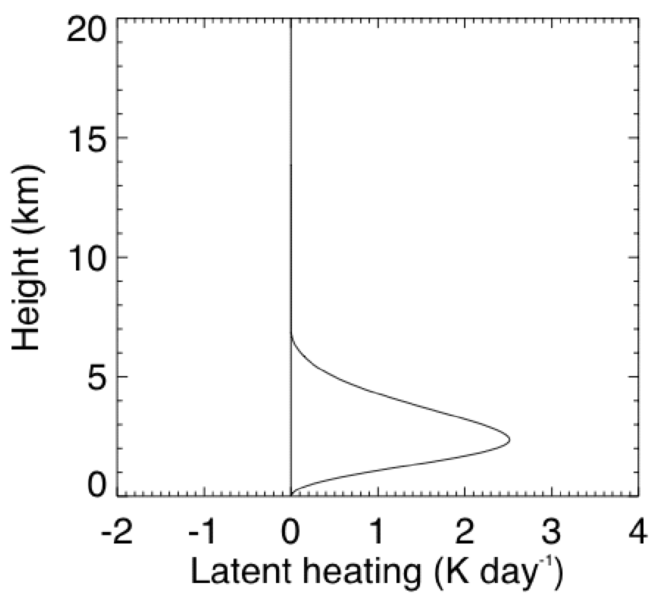
Latent heating processes dominate in the precipitating regions while radiative processes dominate in the non-precipitating anvil.

TWP-ICE (Darwin, Australia) C-Pol

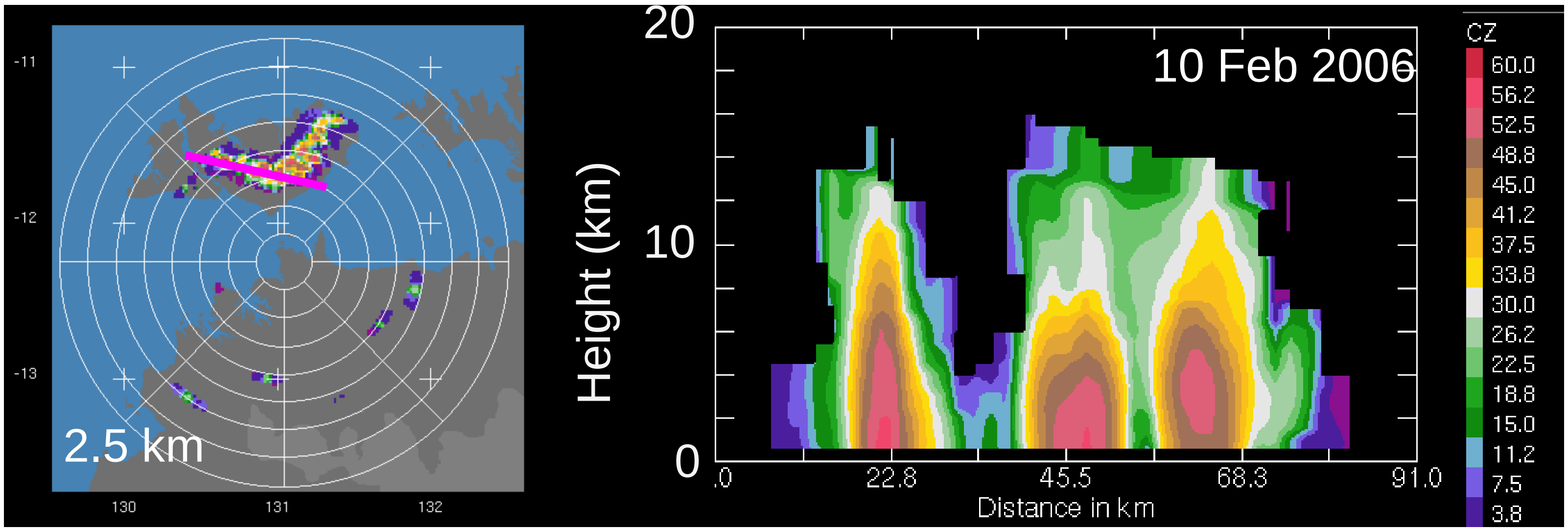


Suppressed monsoon

Shallow-to-moderate convection

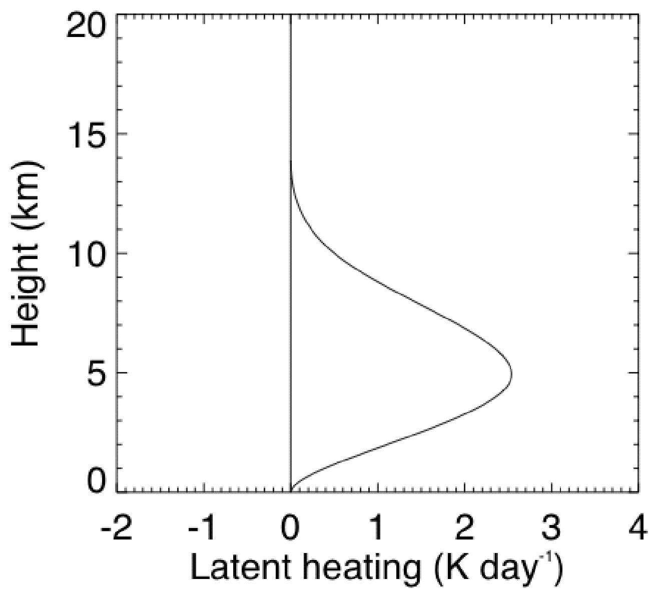


TWP-ICE (Darwin, Australia) C-Pol

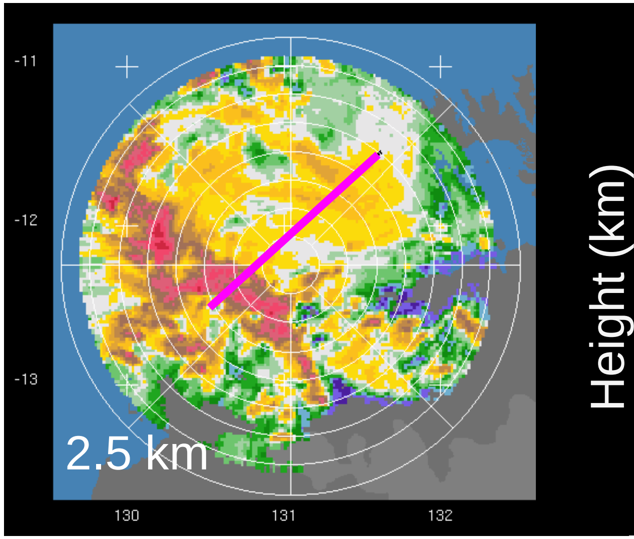


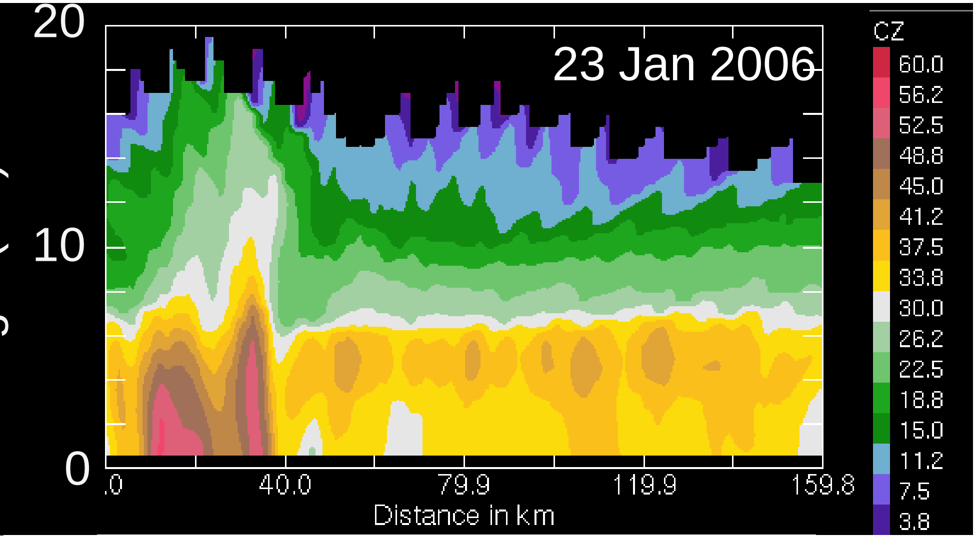
Break period

Deep convection



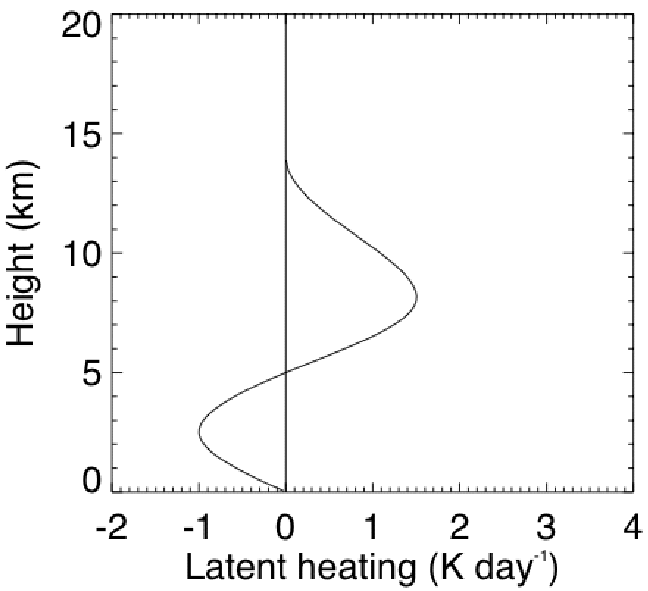
TWP-ICE (Darwin, Australia) C-Pol





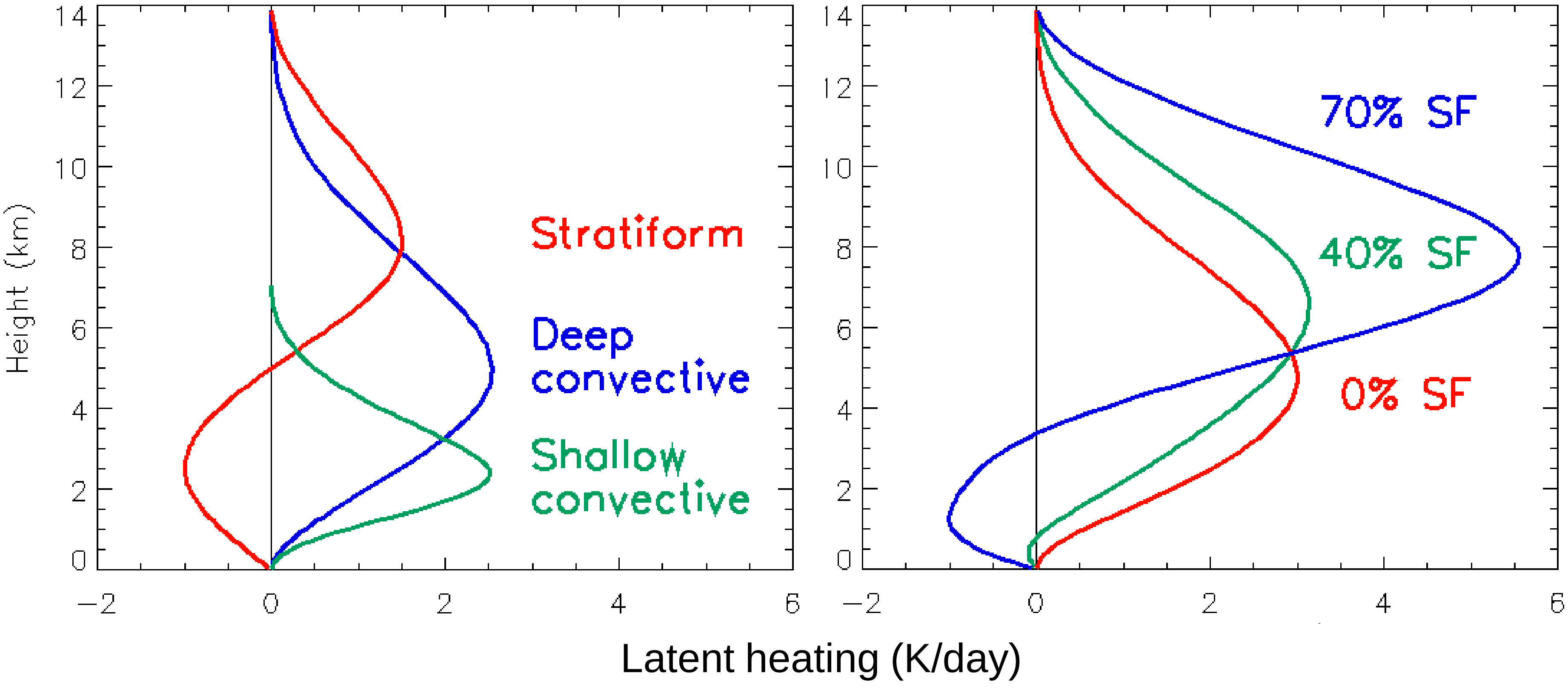
Active monsoon

Robust stratiform regions in MCSs



Simplified latent heating retrieval

Precipitation = column-integrated latent heating and is distributed in vertical based on cloud type

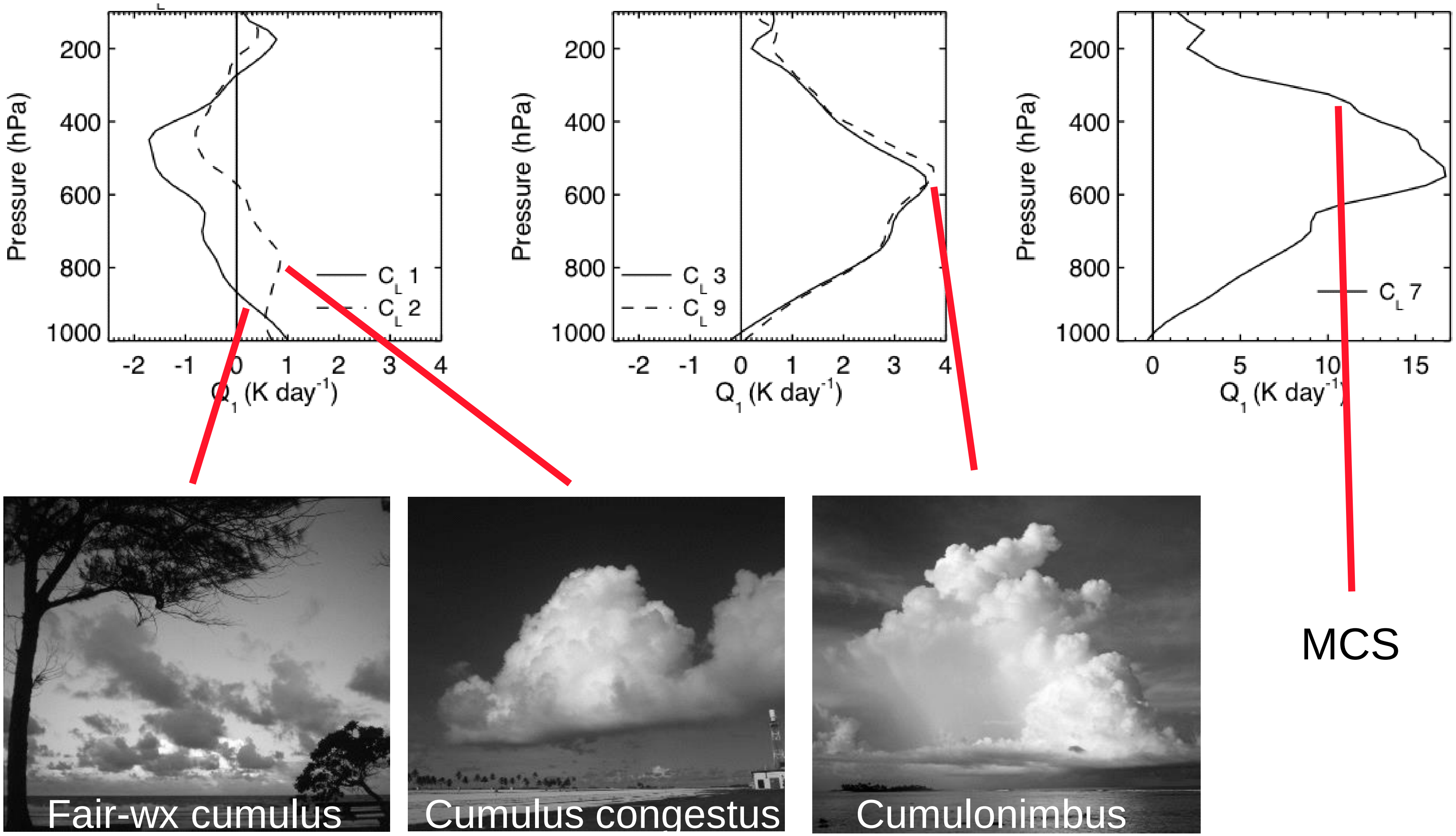


In the tropics, more stratiform rain leads to higher peaks in heating; convective heating is more variable in height.

Schumacher et al. (2004)

Convective cloud heating (Q_1) during KWAJEX

$$Q_1 = \frac{\partial \bar{s}}{\partial t} + \overline{\nabla \cdot sV} + \frac{\partial \bar{s}\bar{\omega}}{\partial p} = \bar{Q}_R + L(c-e) - \frac{\partial \overline{s'\omega'}}{\partial p}$$



22%, < 1 mm/d

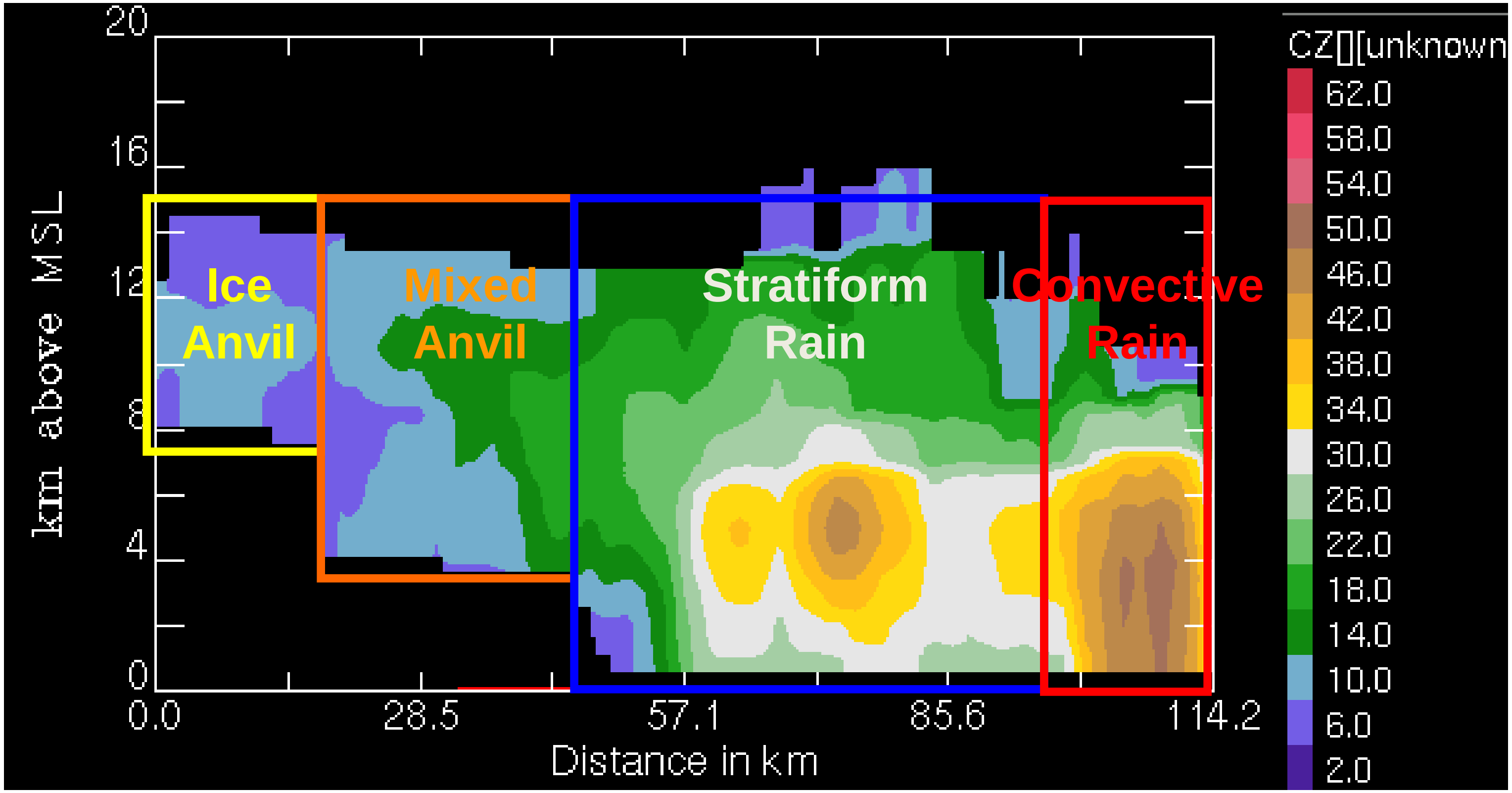
31%, 3 mm/d

39%, 8 mm/d

7%, 28 mm/d

Schumacher et al. (2008), photos from Rangno and Hobbs (2005)

Ice and mixed anvil from Darwin's C-Pol



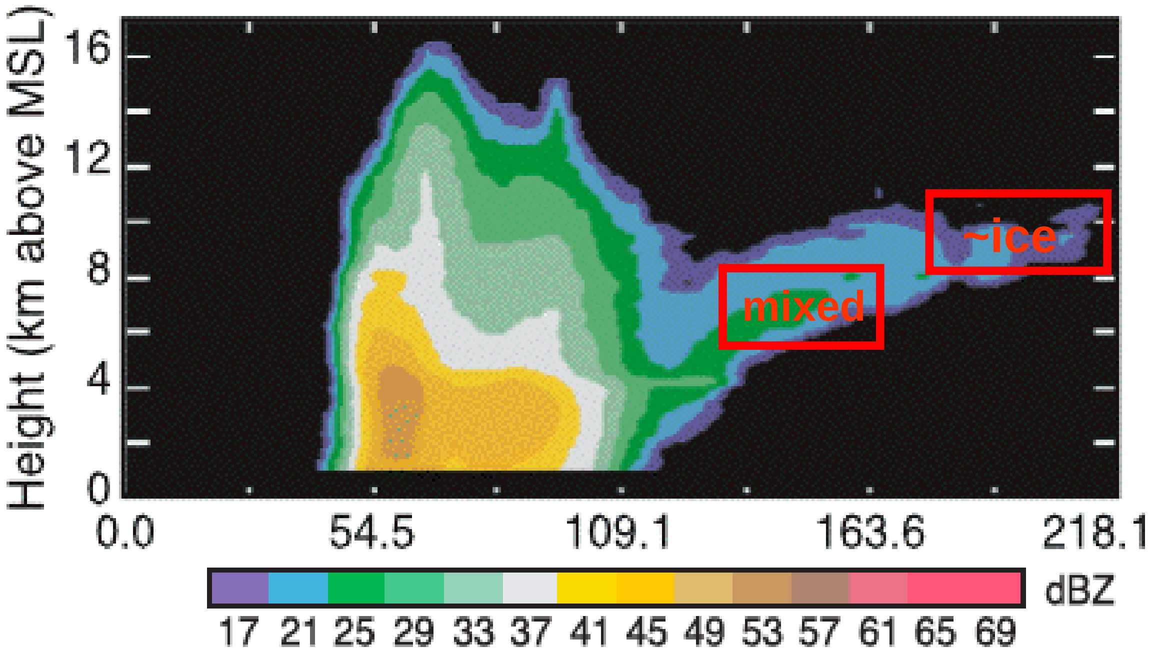
Frederick and Schumacher (2008)

Convective and stratiform rain = reflectivity peakedness at 2.5 km

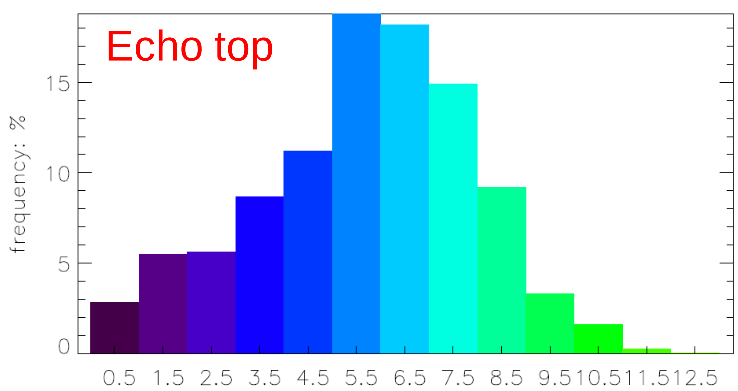
Mixed anvil = echo base ≥ 3 km, echo top ≥ 6 km

Ice anvil = echo base ≥ 6 km (i.e., safely above 0°C level)

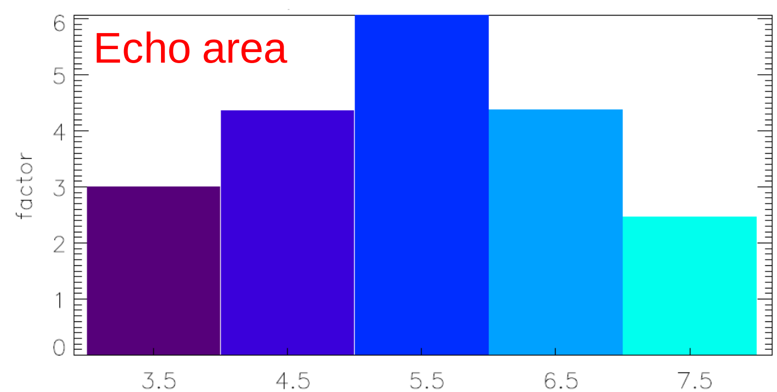
TRMM PR vs CloudSat



- PR misses ~5 km near cloud top and a factor of 5 horizontally



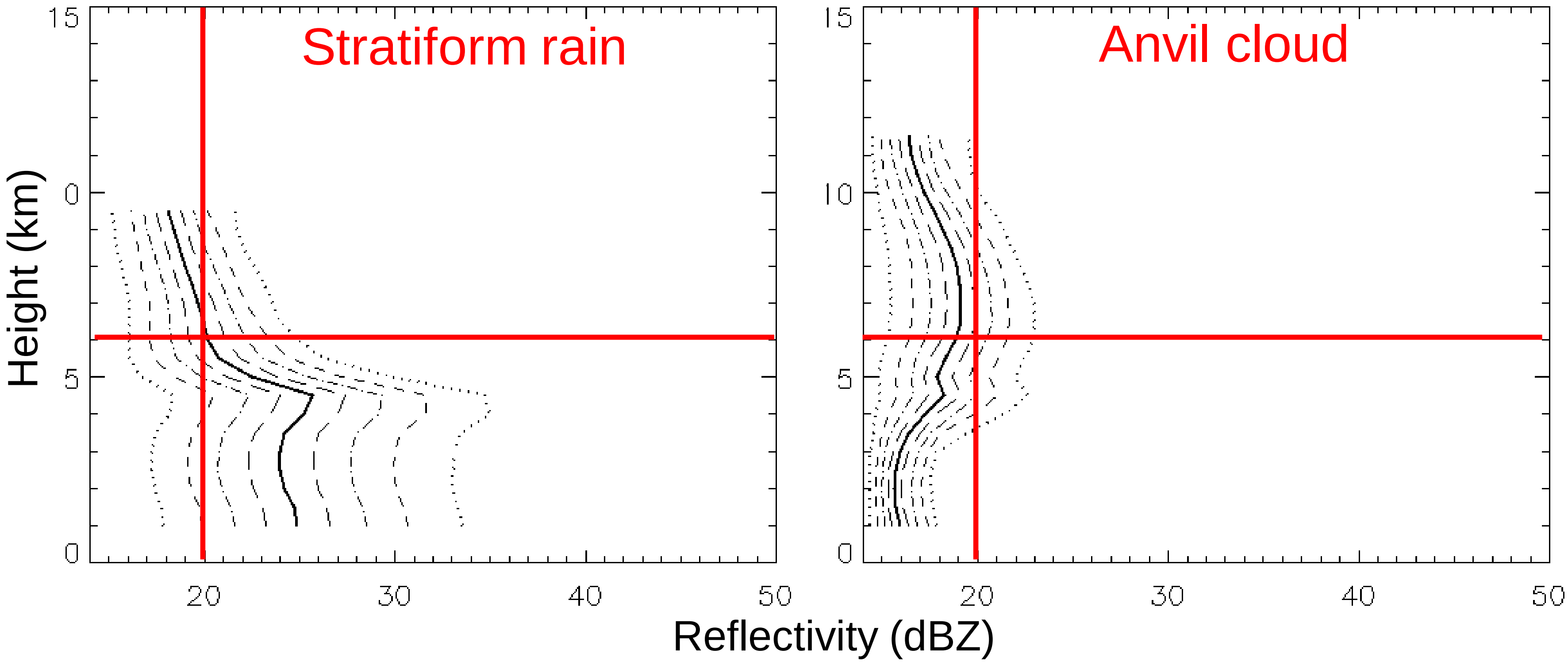
Missed height (km)



Missed area (factor)

Li and Schumacher (2010)

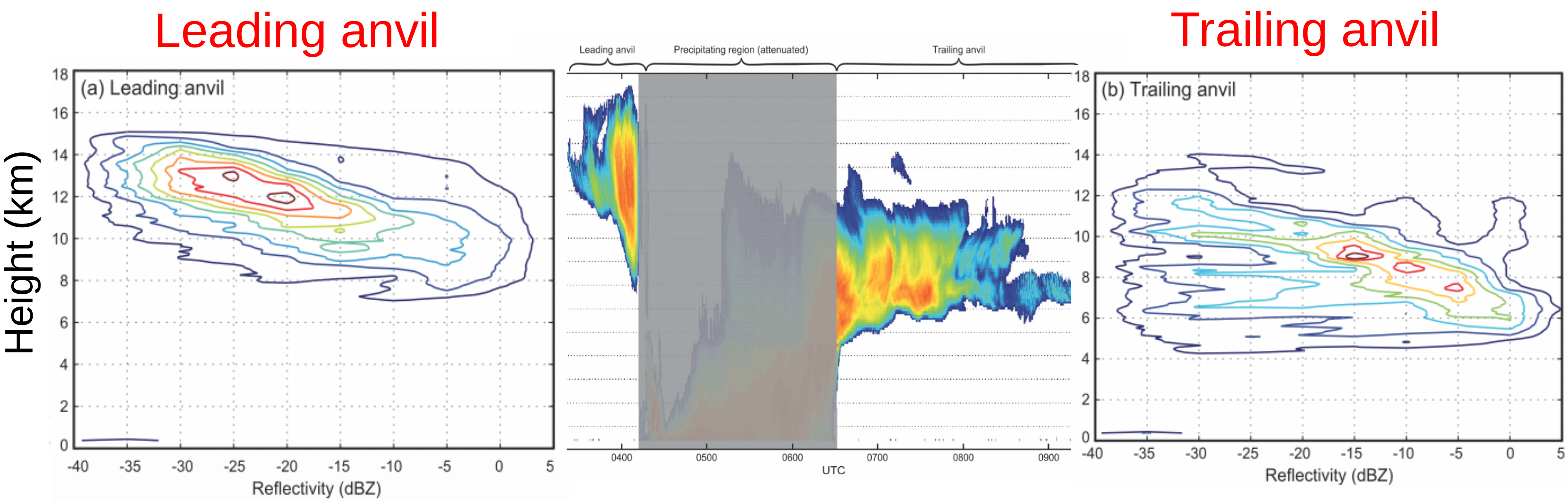
TRMM PR tropics-wide reflectivity distributions



Schumacher and Houze (2006)

While reflectivities are somewhat similar aloft, lower level reflectivities suggest different heating profiles.

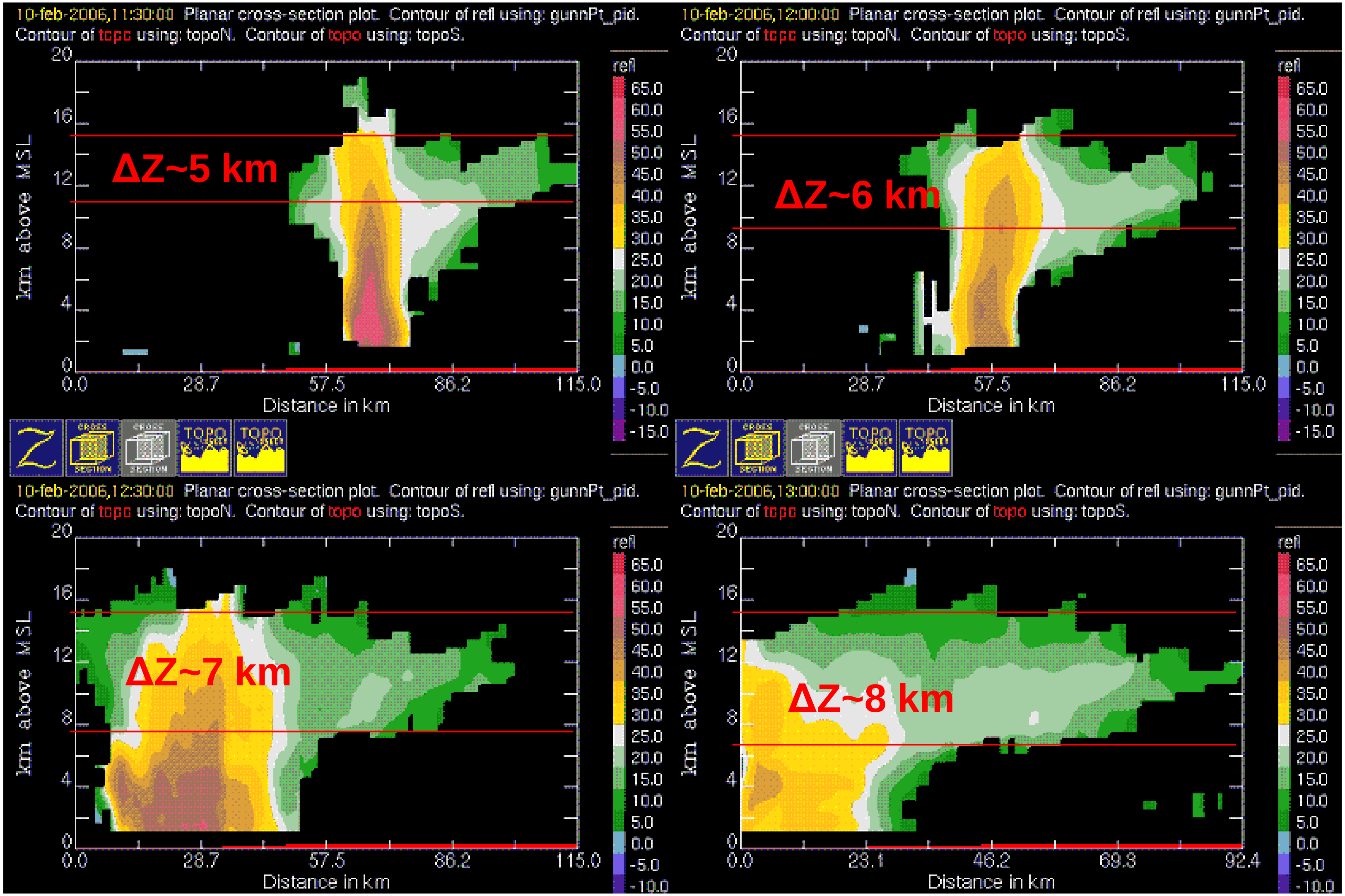
Cloud radar view of anvil in Niamey, Niger



Cetrone and Houze (2011)

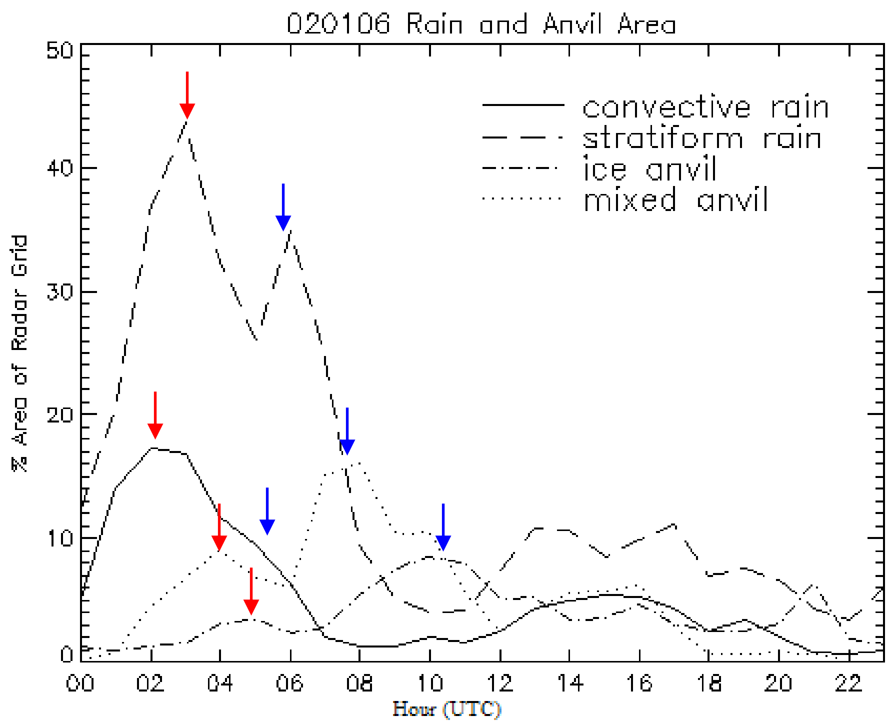
Leading (ice) anvil is more directly linked to convective updrafts, while trailing (mixed) anvil often extends from stratiform rain regions.

TWP-ICE C-band anvil growth every 30 min



Frederick and Schumacher (2008)

TWP-ICE C-Pol MCS evolution



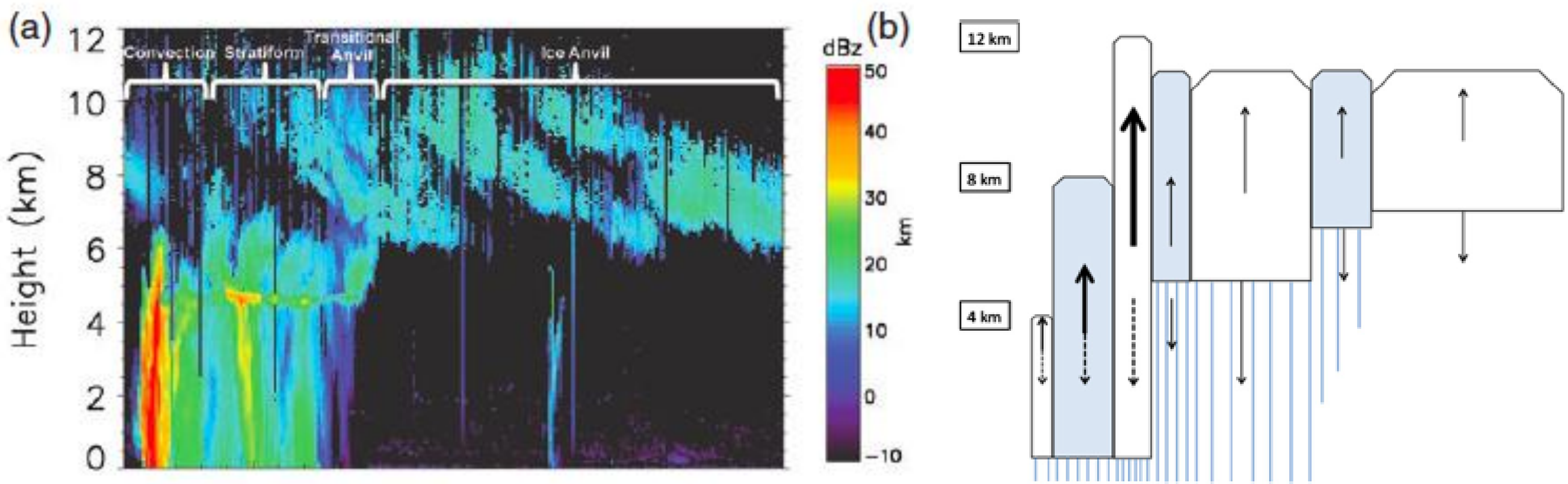
- 8 out of 12 MCSs followed this pattern
- Mixed anvil lags 1-2 hr behind stratiform rain peak, ice anvil lags 1-3 hr behind mixed anvil peak

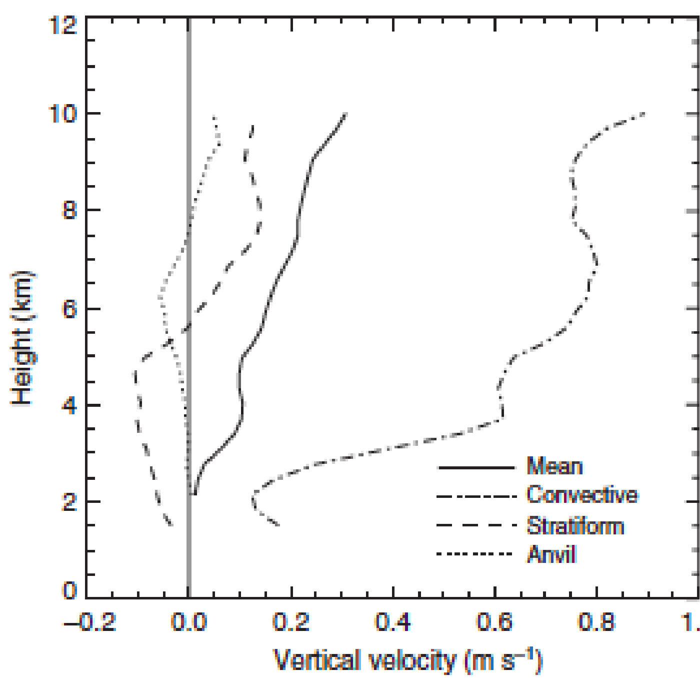
TWP-ICE mean echo coverage

	Ice	Mixed	Convective	Stratiform	Total
Area (%)	4.0	4.8	4.4	14.9	28.2

Frederick and Schumacher (2008)

TWP-ICE profiler vertical velocities

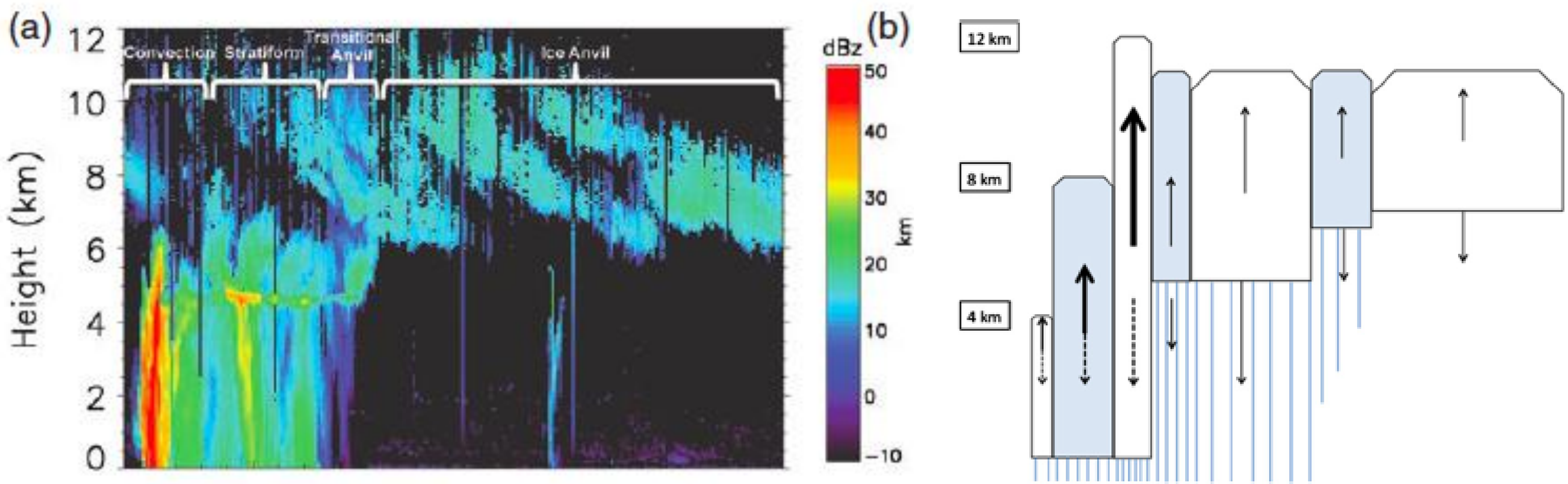


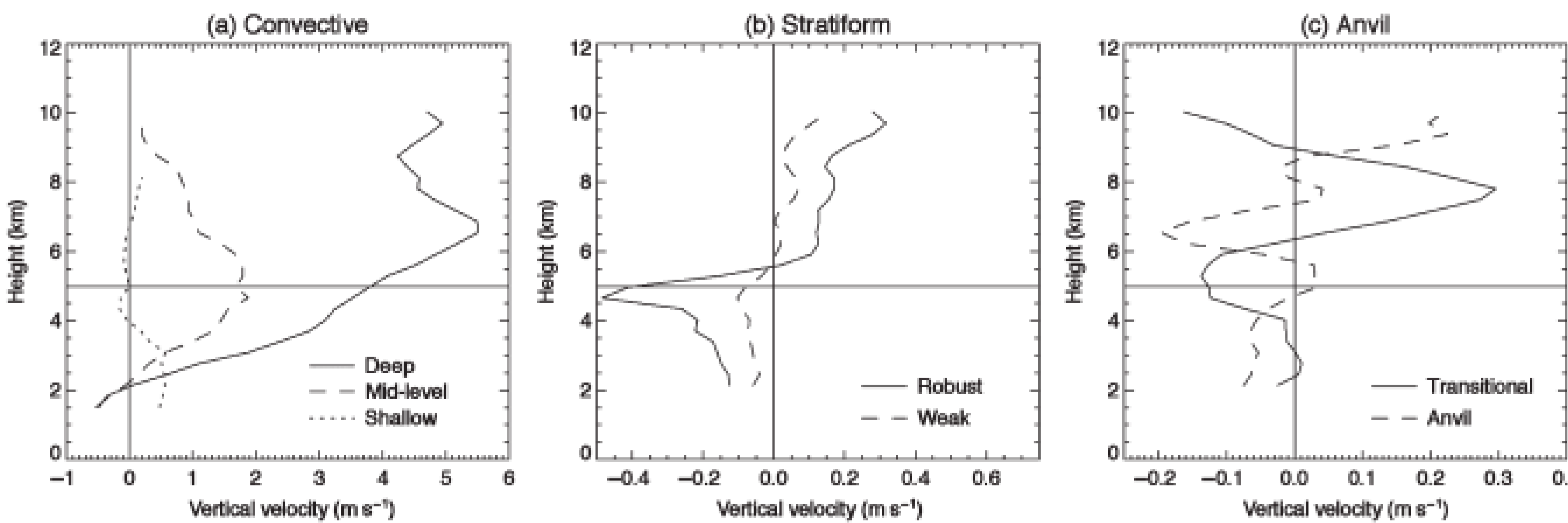


- Multi-month climatology shows that in-cloud vertical motion increases in height and decreases in magnitude as anvil transitions from robust stratiform to ice anvil

Schumacher et al. (2015)

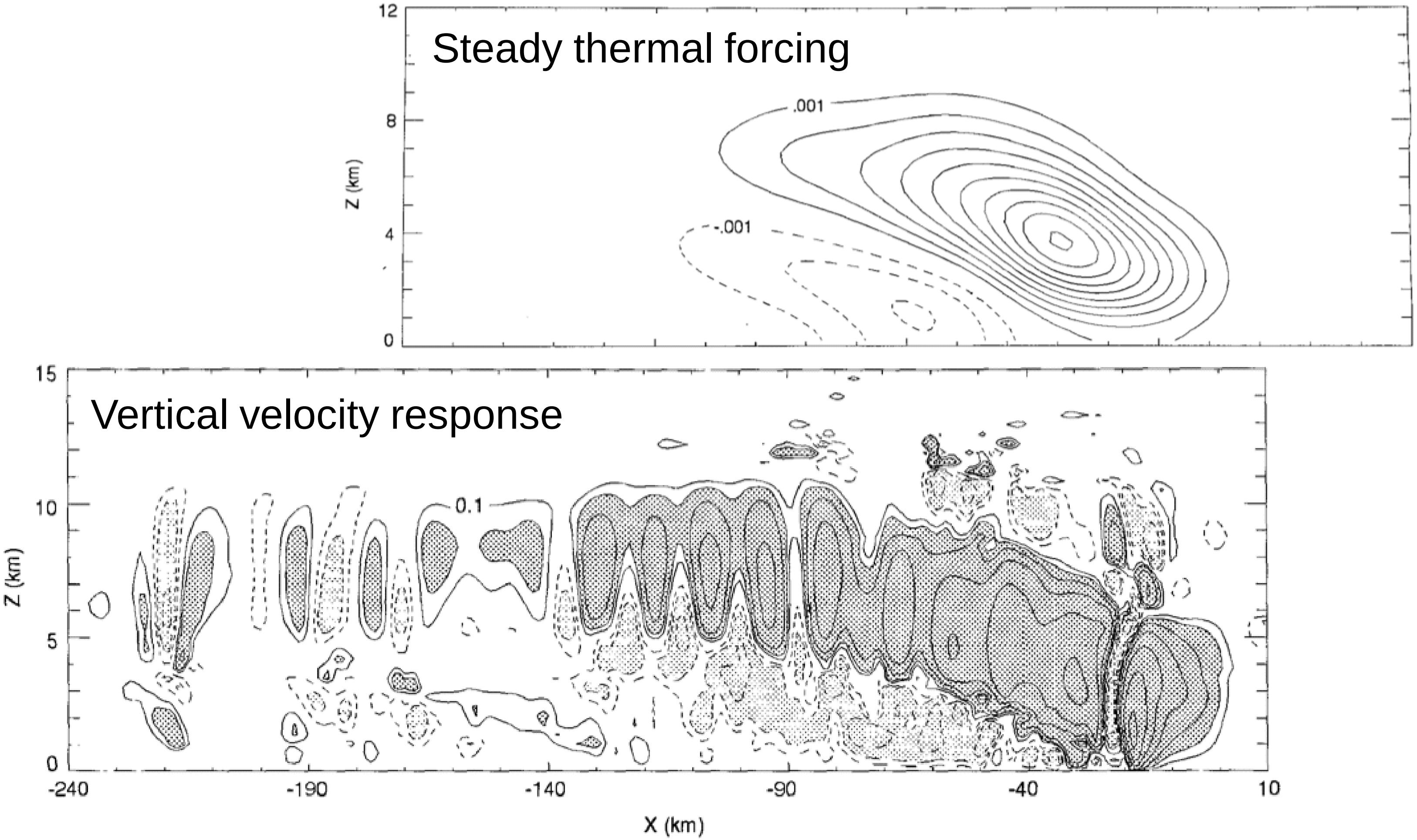
TWP-ICE profiler vertical velocities





Schumacher et al. (2015)

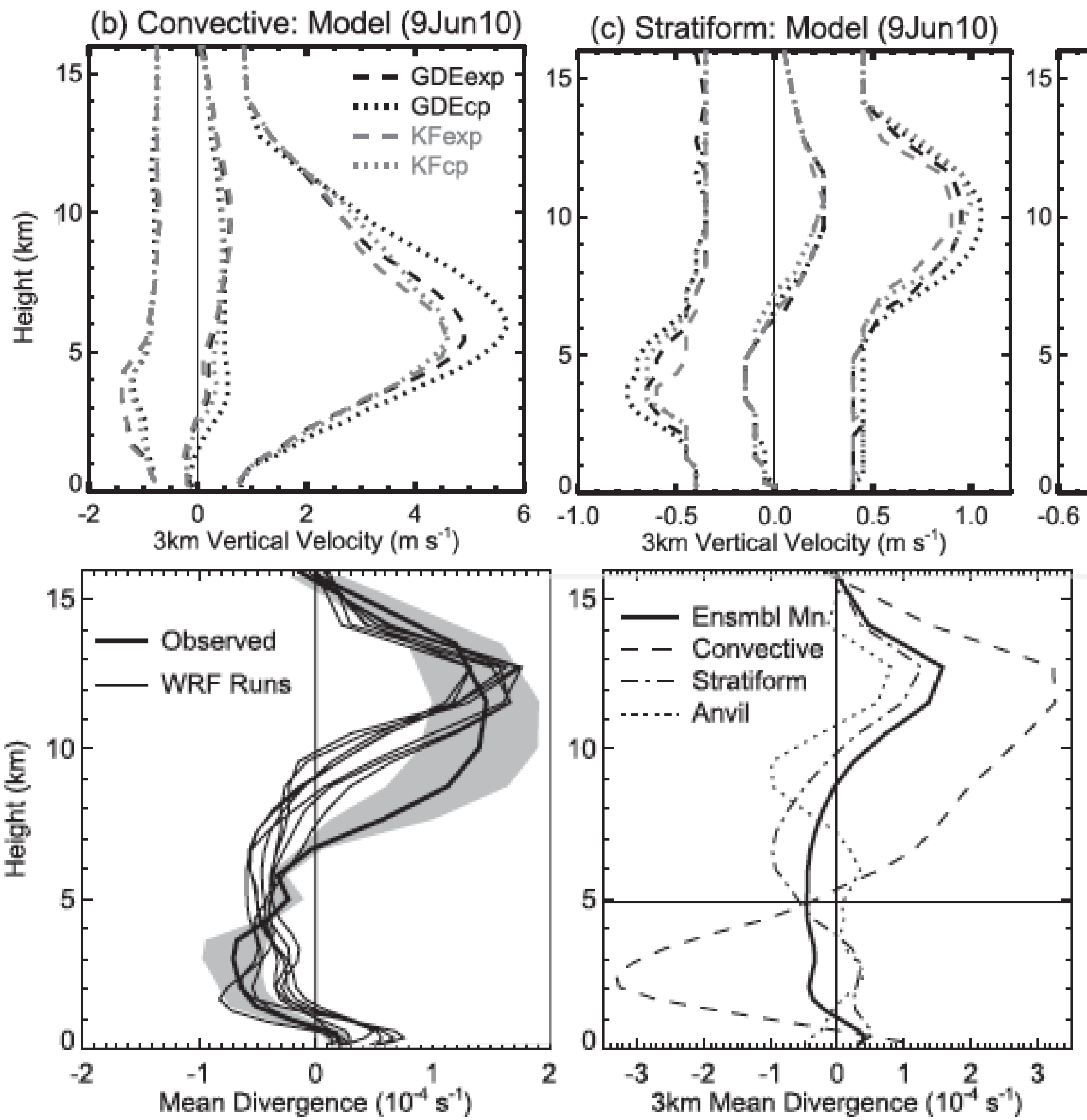
Role of gravity waves



Pandya and Durran (1996)

Thermal forcing in convective region creates a realistic mesoscale circulation and anvil region in non-linear, dry numerical simulations.

Anvil dynamical structure from WRF in Texas

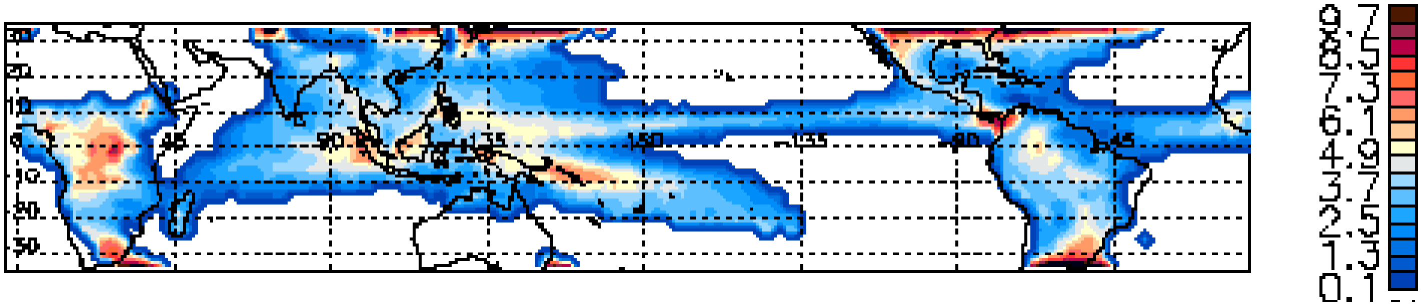


Anvil has elevated convergence and impacts gradient of upper level heating.

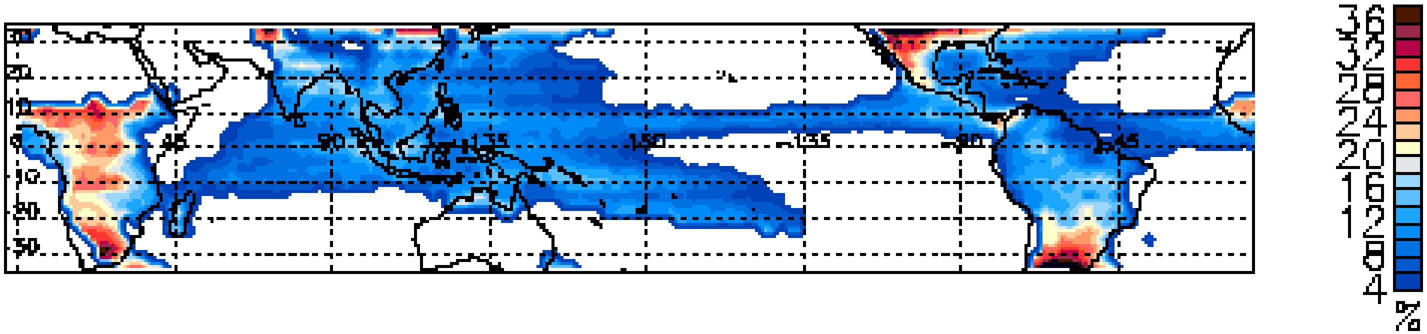
Hopper and Schumacher (2012)

TRMM PR tropics-wide anvil statistics

Anvil occurrence frequency



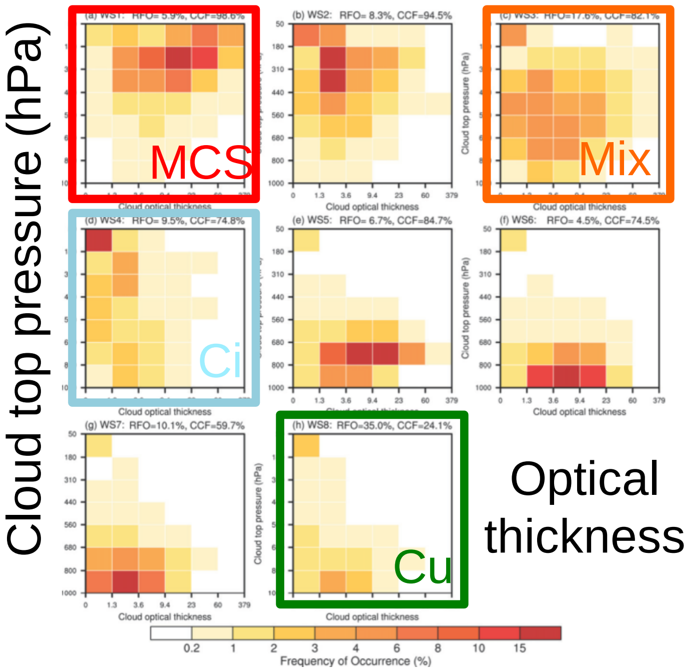
Convection generating anvil frequency

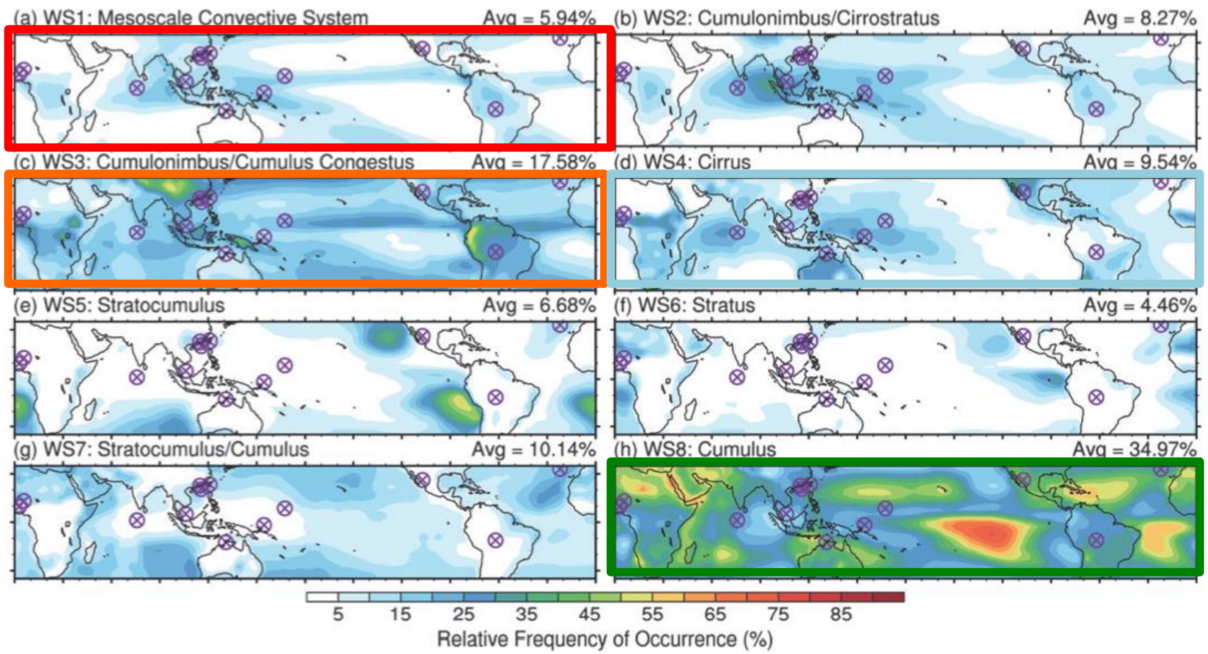


Li and Schumacher (2010)

- Anvil occurs ~5% of the time and convection is more likely to generate anvil over land
- Convective area and echo-top height is best predictor of anvil occurrence (not stratiform rain area or echo-top heights)

ISCCP weather states (WS)

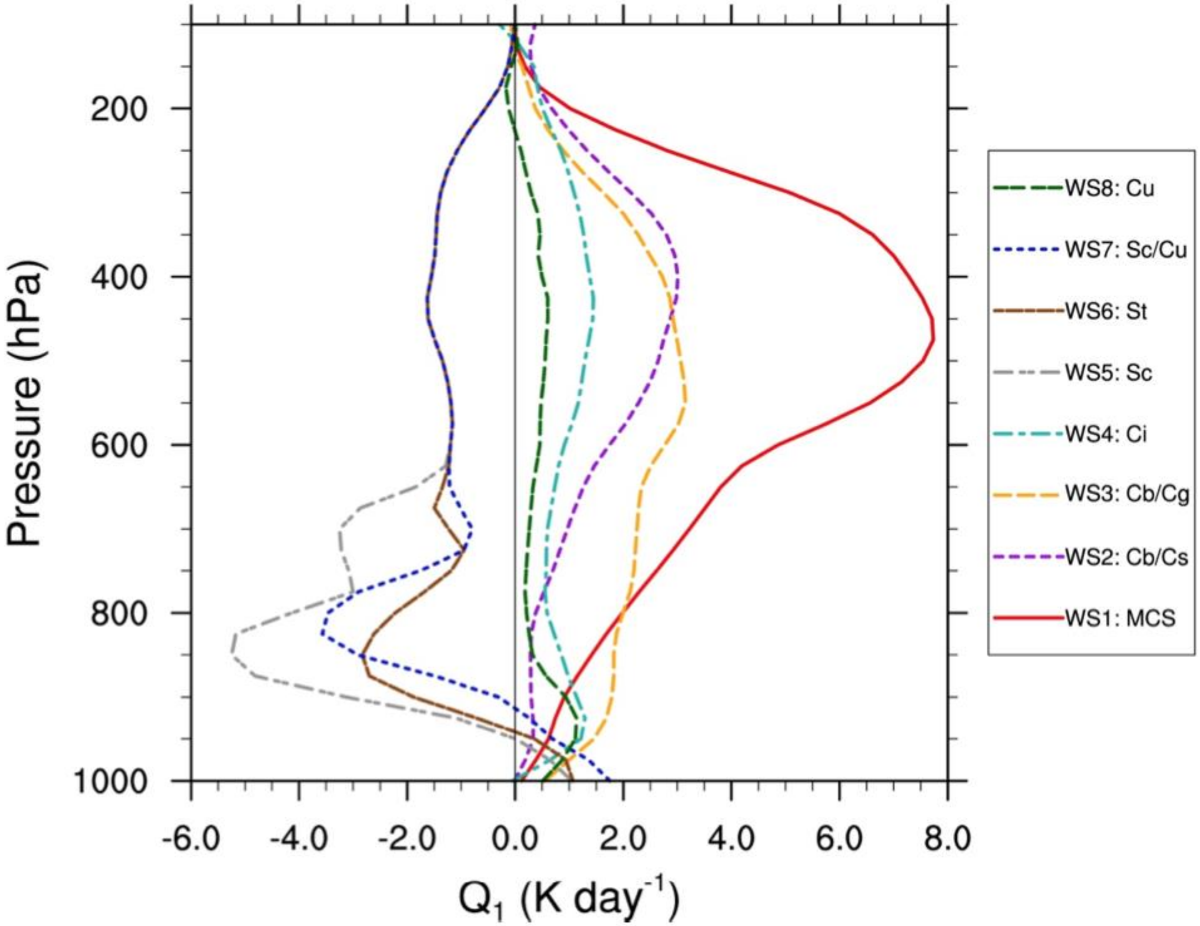




ISCCP optical properties can delineate cloud populations with distinct characteristics and areal distributions. Sounding budgets from across the tropics and subtropics (purple marks) were used to assign heating profiles to each weather state.

Rossow et al. (2005), Stachnik et al. (2013)

ISCCP weather state Q_1 retrievals

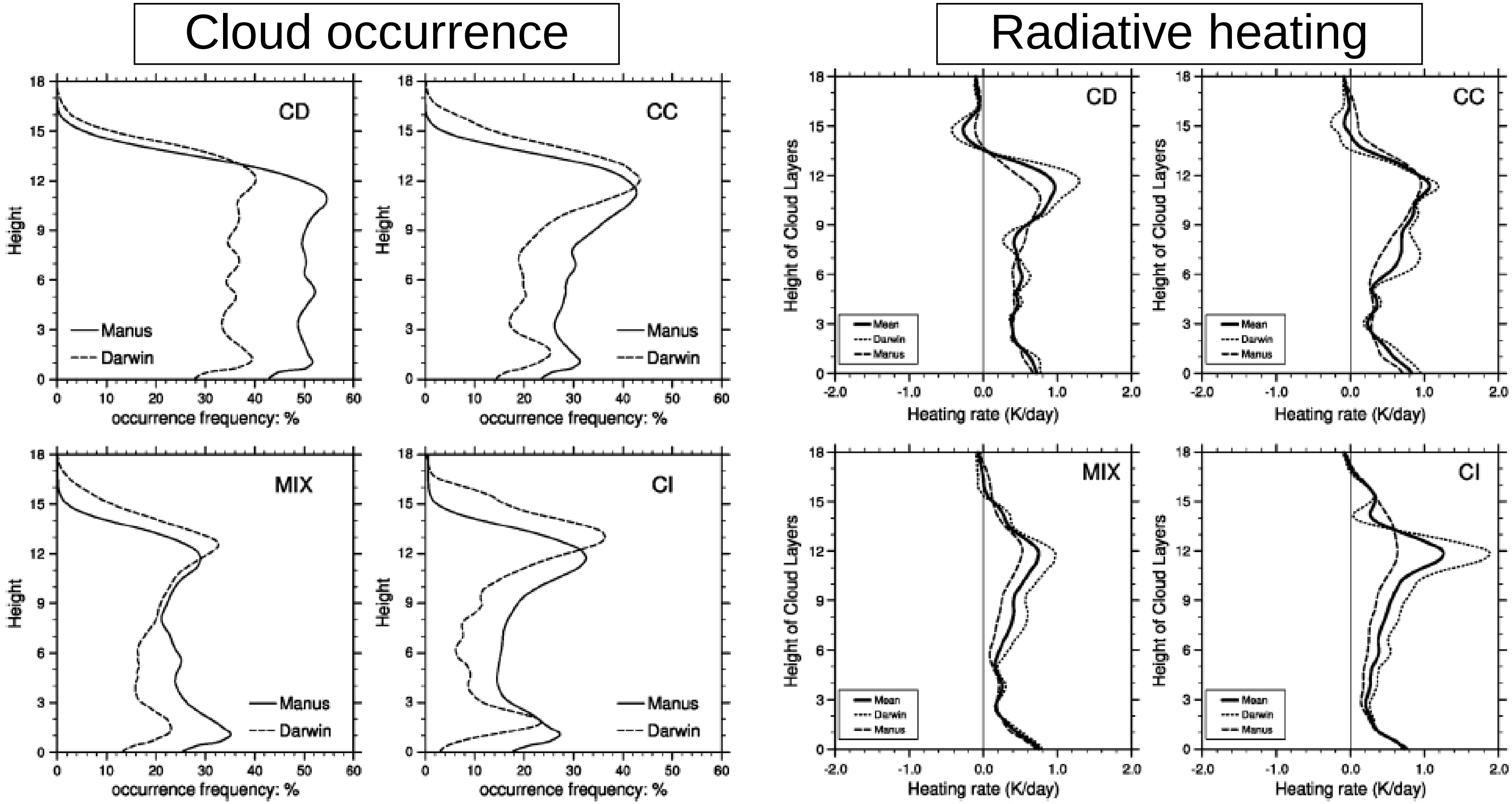


UL heating of 3-8 K/day dominates in convectively active WSs (1-MCSs, 2-Cbs, 3-mix). WS4 (thin cirrus) and WS8 (cumulus) have UL heating of 1 K/day.

Stachnik et al. (2013)

ISCCP WS radiative heating retrievals

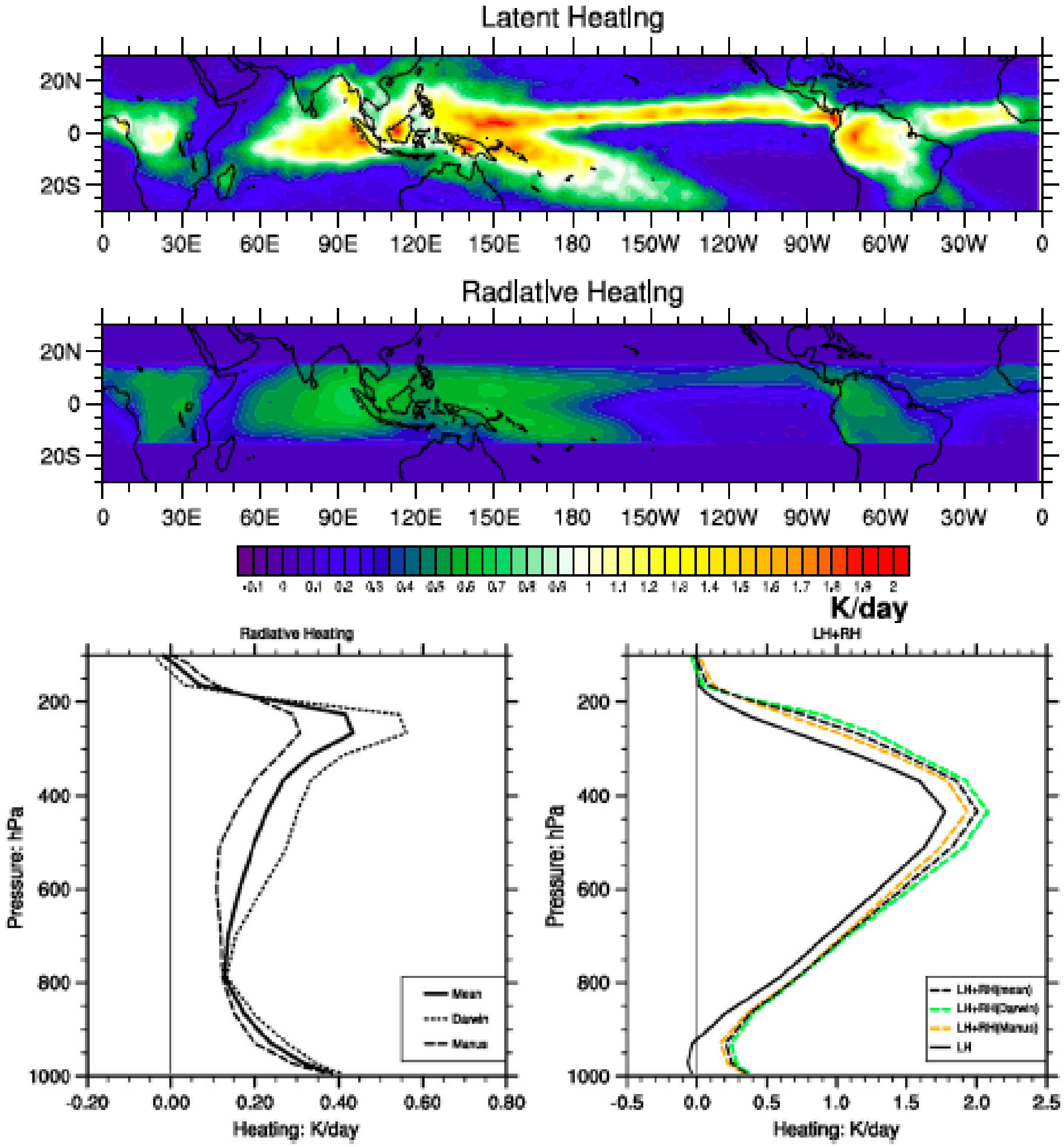
(based on Darwin and Manus cloud radars)



Convectively active WSs have 30-50% cloud cover aloft and ~1 K/day radiative heating. Cirrus WS has pronounced peak at 12 km.

Li et al. (2013)

TRMM LH vs ISCCP RH

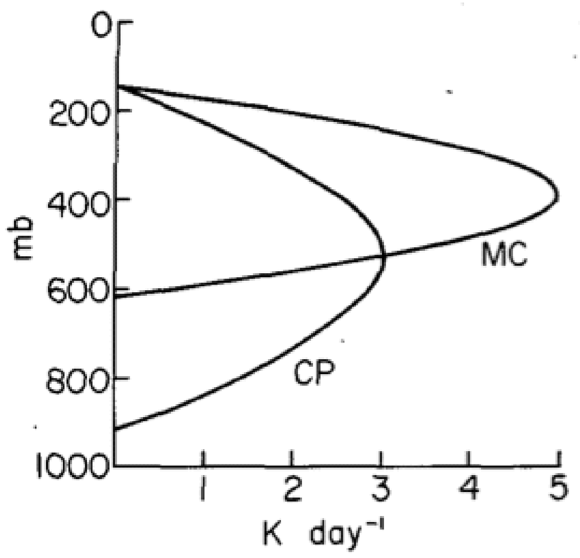


- Total radiative heating enhances gradient of latent heating at upper levels (e.g., 250 mb), esp. over Africa, Maritime Continent and South America and enhances overall LH by ~20%

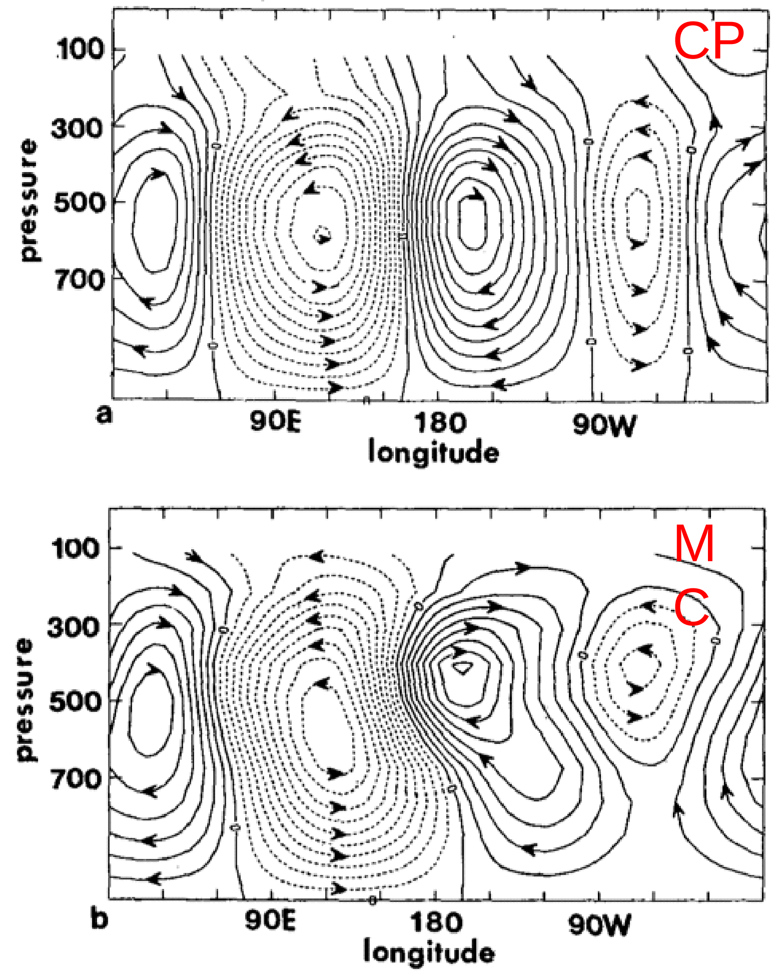
Li et al. (2013)

Idealized experiment from Hartmann et al. (1984)

Input heating

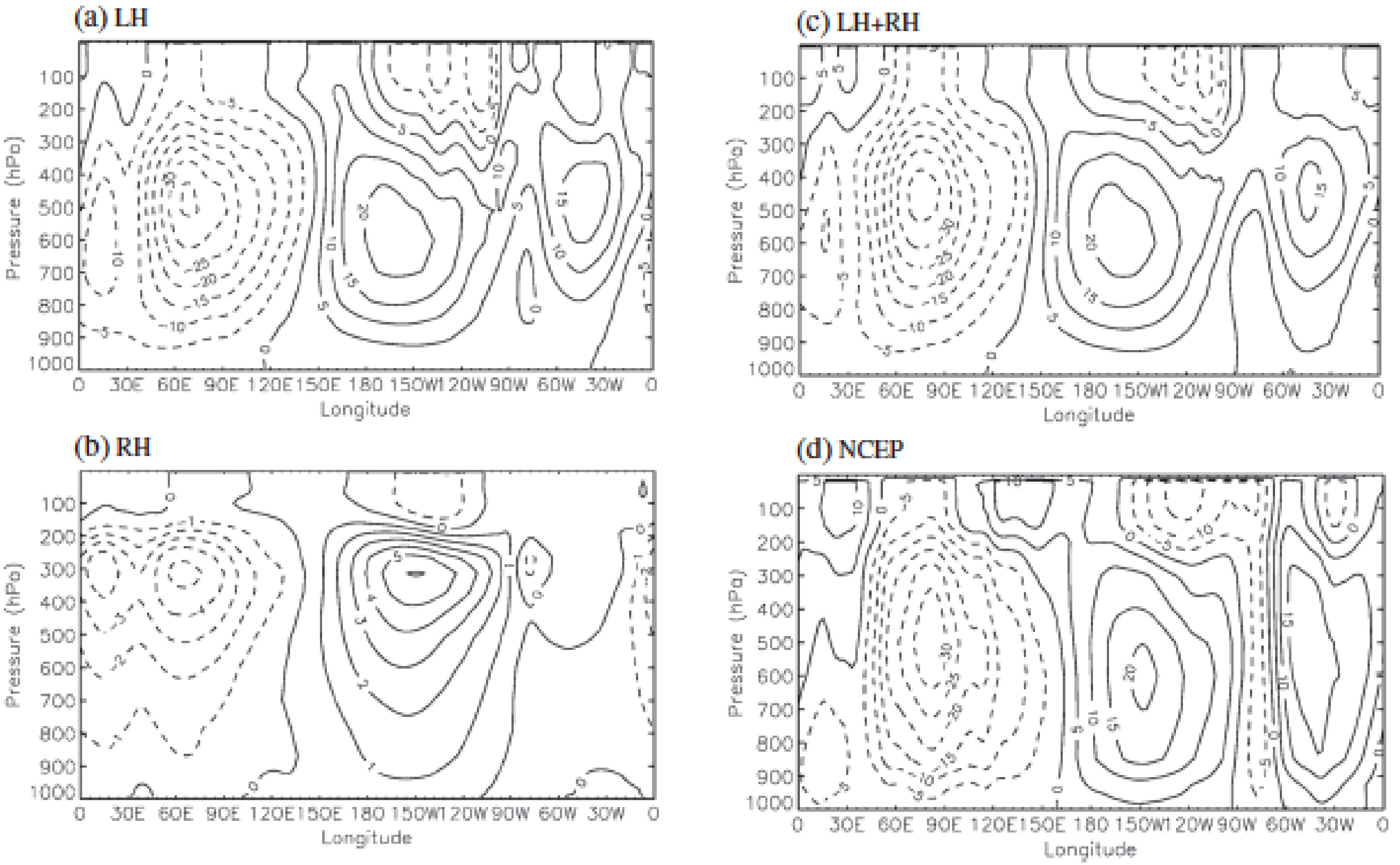


Zonal mass flux



Higher circulation center and westward tilt over the Pacific Ocean resulted from elevated heating profile

Direct radiative impact on zonal mass flux



RH creates weak and elevated circulation centers that only have a minor impact on the steady-state GCM solution.

Li et al. (2013)

Conclusions and next steps

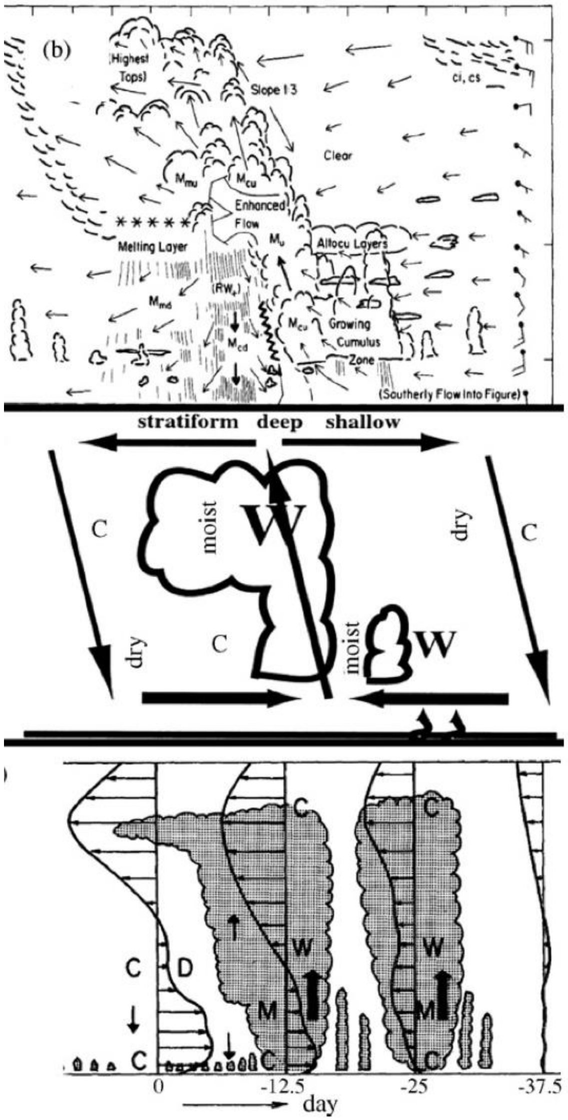
- Anvils are integral to the energy budget of tropical convective systems but there is room to improve retrievals of the heating structures and understanding of the role of gravity waves in anvil cloud
- Large uncertainty exists in modeling anvil’s formation process so we should look more closely at CRMs for accurate depiction of anvil properties (area, height, thickness, ice properties, vertical velocity, divergence, etc.) in relation to convection
- Impact on large-scale circulation through anvil radiative heating is often based on idealized assumptions so one avenue would be to run more realistic (i.e., interactive) GCMs with varying heating structures from anvil/cirrus

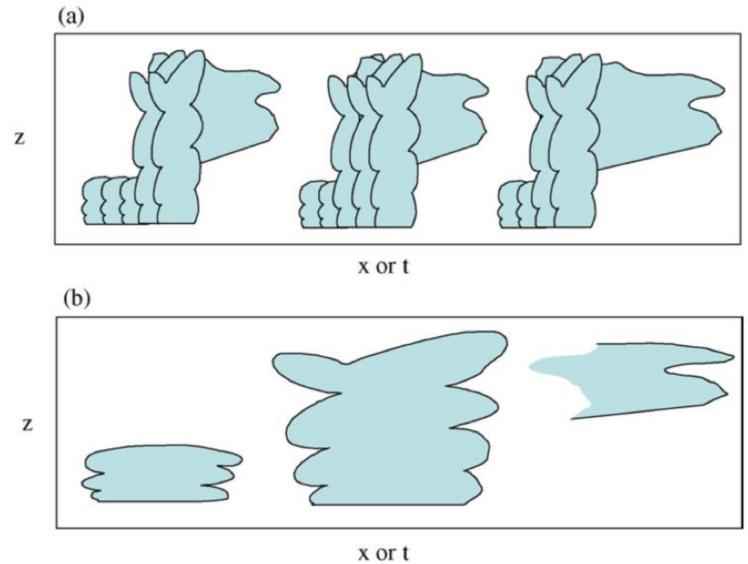
Convective building blocks

MCS

Kelvin wave

MJO





- Convective phenomena at many scales can be described by relative amounts of shallow and deep convection and stratiform rain/anvil cloud

Mapes et al. (2006)