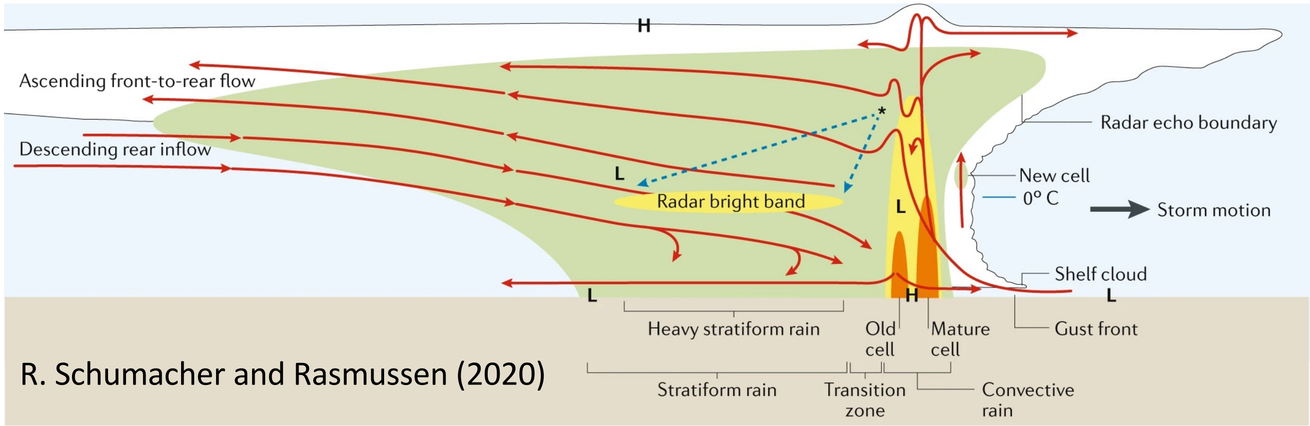
Mesoscale convective systems (MCSs)



R. Schumacher and Rasmussen (2020)

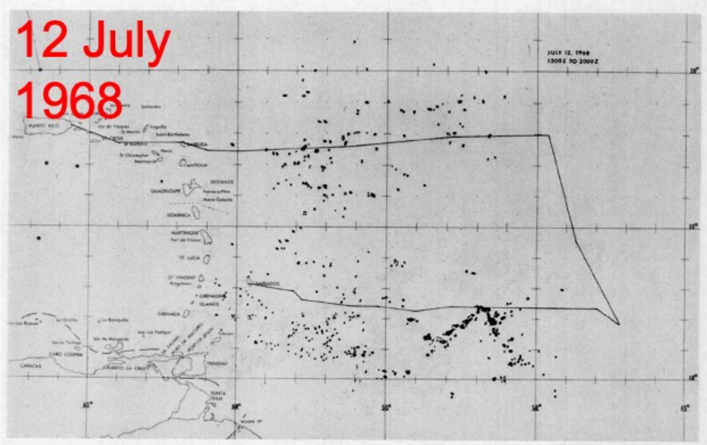
Courtney Schumacher

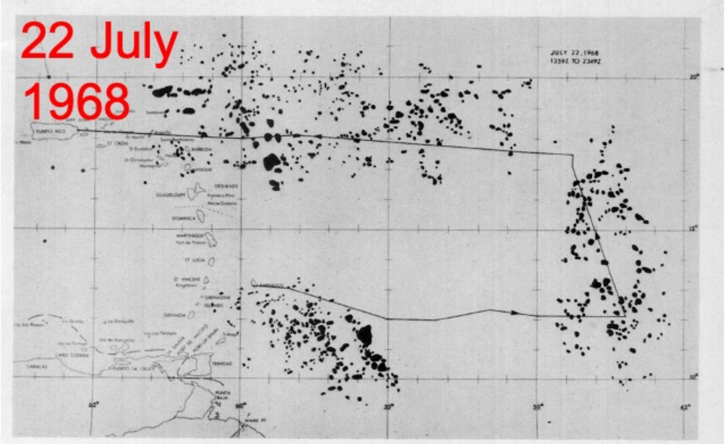
Texas A&M University

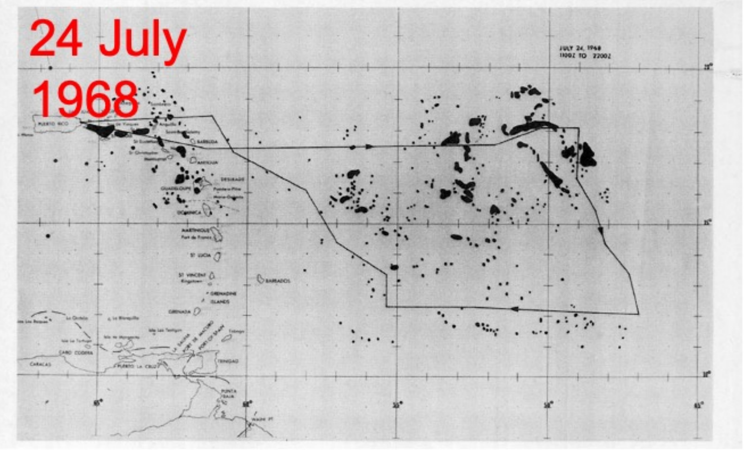
ICTP

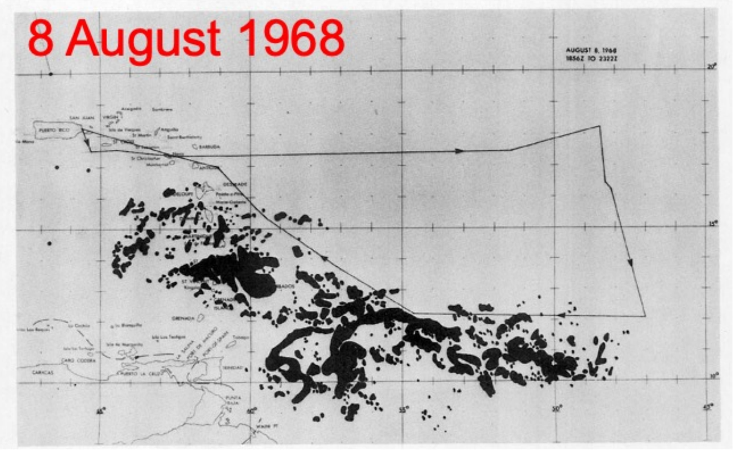
July 5, 2024

Degrees of convective organization









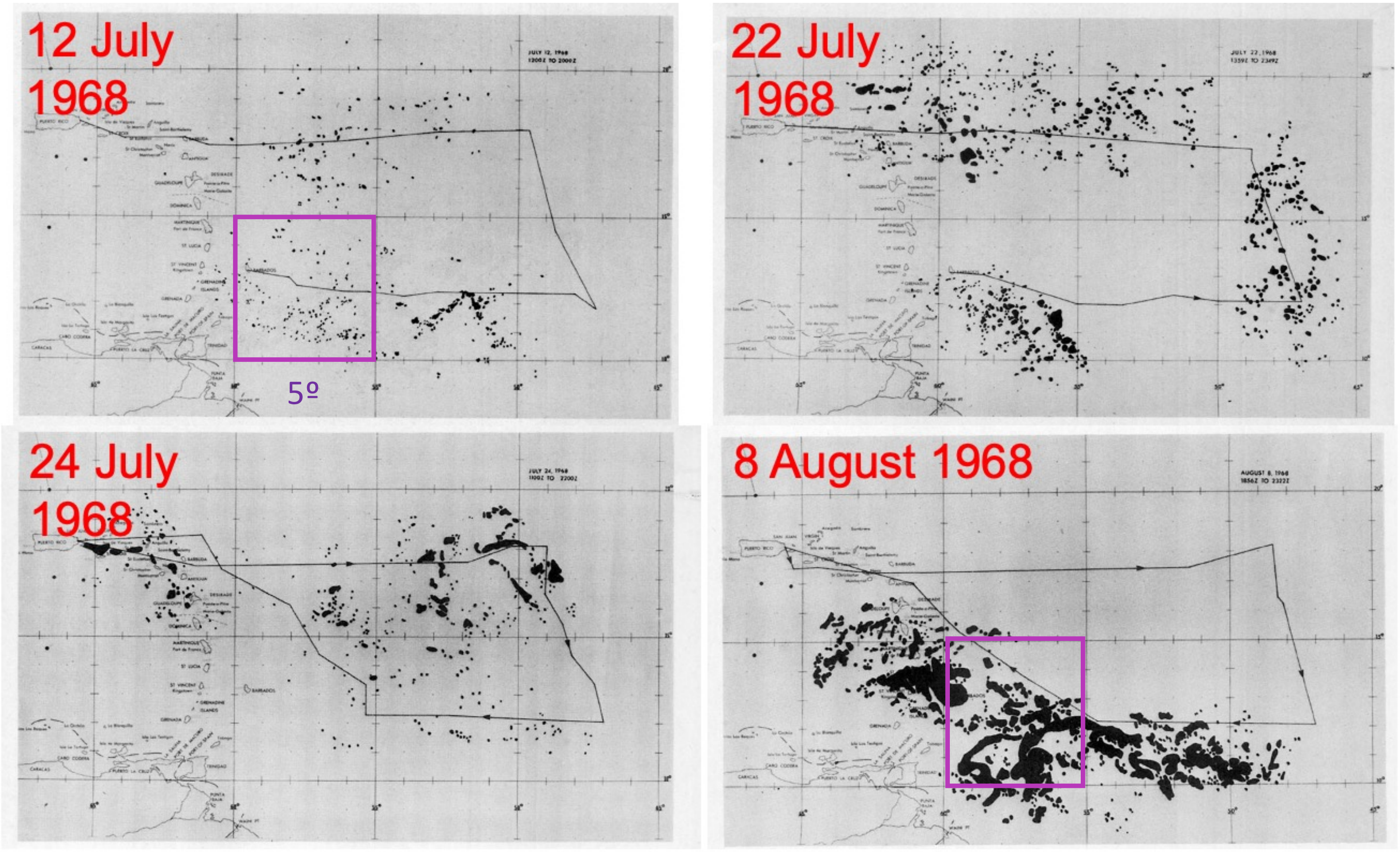
Lopez (1976)

- Radar aircraft observations of raining regions in the Caribbean and West Atlantic
- Lognormal distribution of precipitating cells in both size and occurrence

Definitions of convective organization

- Mesoscale convective system (i.e., size > 100 km of precipitation in horizontal extent, Houze 1994)
- Shape (linear)
- Lifetime (> 6 hours)
- Existence of a mesoscale updraft or bright band
- Indices of aggregation over a large grid box: SCAI (Tobin et al. 2012), I_{org} (Tompkins and Semie 2017), etc.

Degrees of convective organization



- I will briefly focus on the diabatic heating expected at each end of the convective spectrum

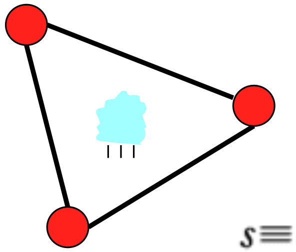
Lopez (1976)

The apparent heat source, Q_1

(i.e., the heating from unresolved diabatic processes in atmosphere)

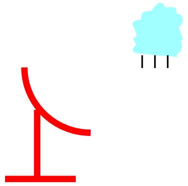
1. Sounding-based budget (environment)

$$Q_1 = \frac{\partial \bar{s}}{\partial t} + \overline{\nabla \cdot sV} + \frac{\partial \bar{s}\bar{\omega}}{\partial p}$$



$s \equiv c_p T + gz$

2. Ground radar, gauge, aircraft, satellite, photography (phenomenon)



$$Q_1 = \bar{Q}_R + L(c - e) - \frac{\partial \overline{s'\omega'}}{\partial p}$$

Radiative

Latent

c = condensation

e = evaporation

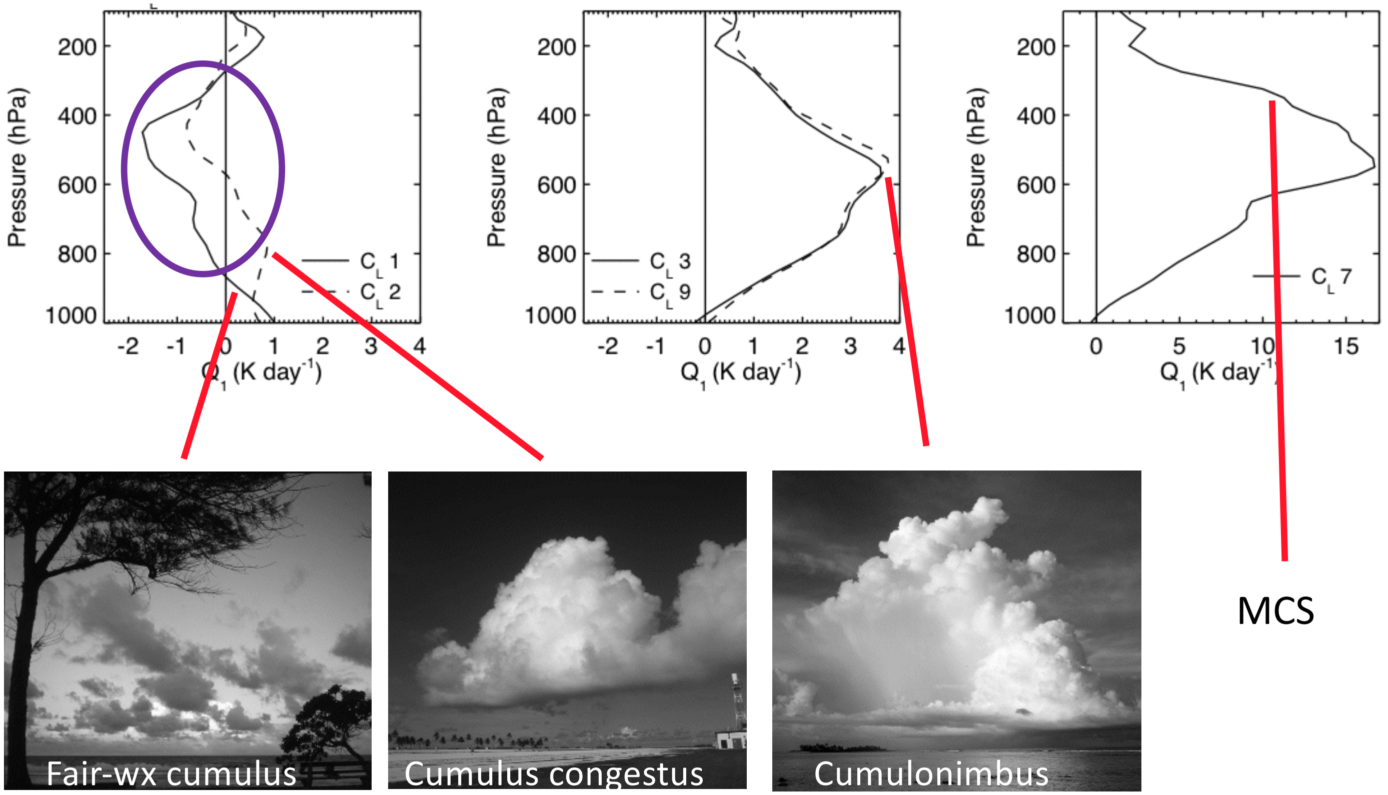
Eddy sensible

Yanai et al. (1973)

Apparent heat source (Q_1) during KWAJEX

$$Q_1 = \frac{\partial \bar{s}}{\partial t} + \overline{\nabla \cdot (s\mathbf{V})} + \frac{\partial(\overline{s\,\omega})}{\partial p}$$

Look, Boualem!



22%, < 1 mm/d

31%, 3 mm/d

39%, 8 mm/d

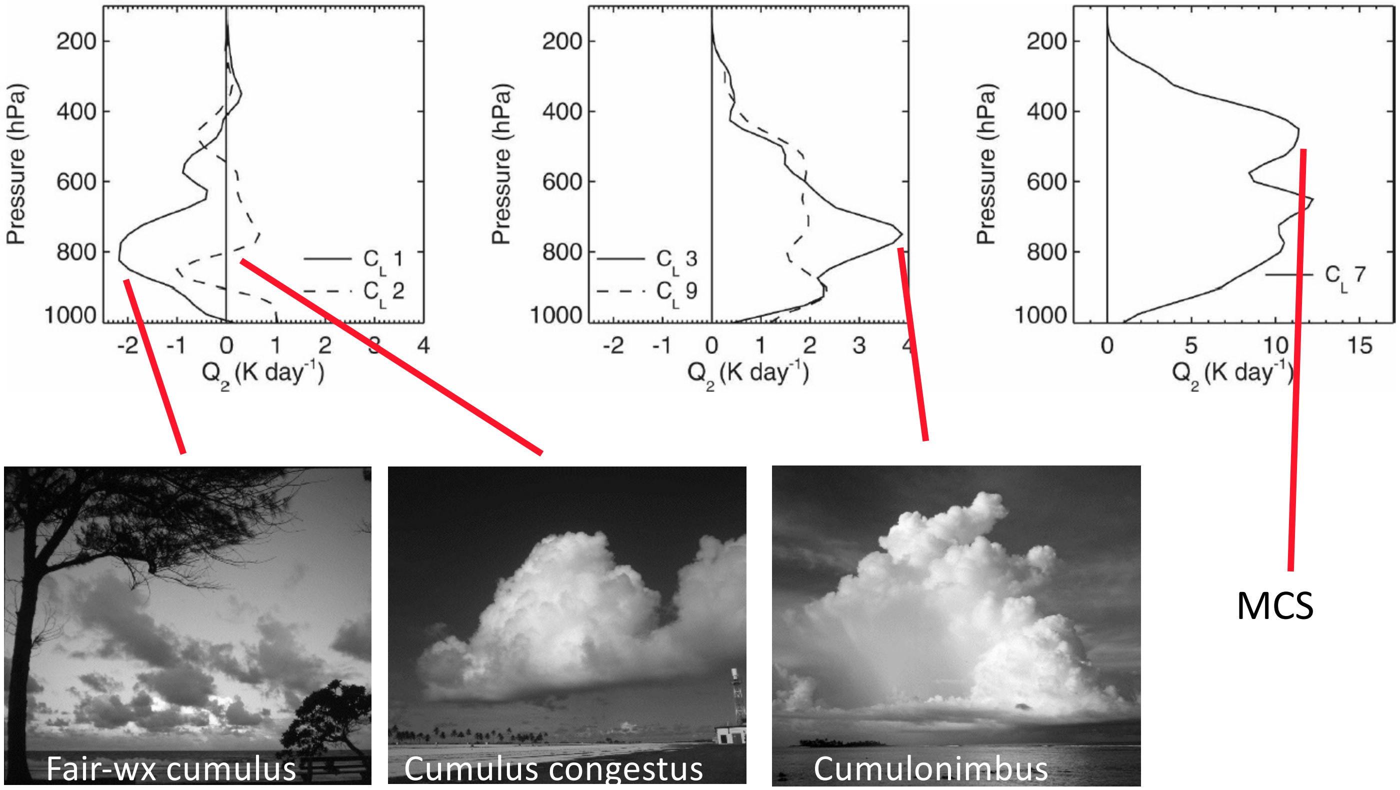
7%, 28 mm/d

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

- Synoptic cloud observations were used to separate budget-based Q1 profiles by low-base cloud types
- The height and magnitude of heating increases from fair weather cumulus to MCSs
- Cooling aloft in fair weather cumulus and congestus

Apparent moisture sink (Q_2) during KWAJEX

$$Q_2 = -L\left(\frac{\partial \overline{q}}{\partial t} + \overline{\nabla \cdot (q\mathbf{V})} + \frac{\partial(\overline{q}\,\overline{\omega})}{\partial p}\right)$$



22%, < 1 mm/d

31%, 3 mm/d

39%, 8 mm/d

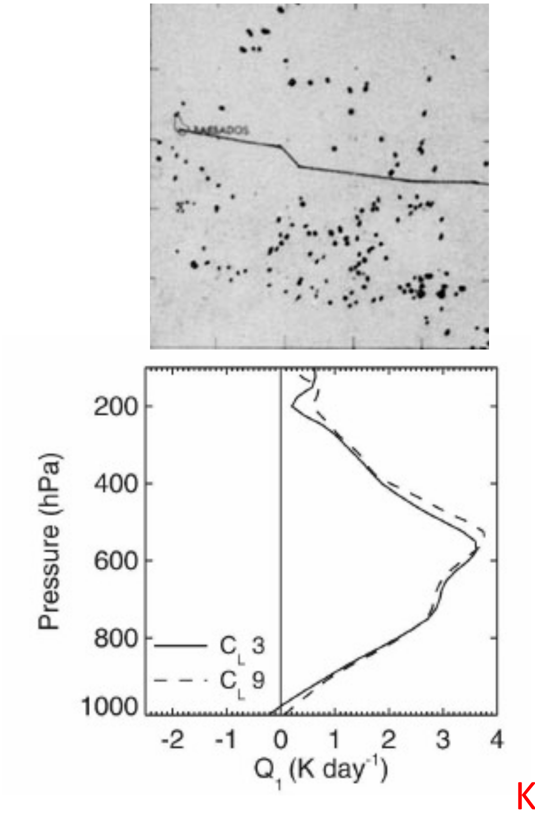
7%, 28 mm/d

- Only significant moistening from fair-wx cumulus (Nitta and Esbensen 1974)
- Congestus has small signal in moistening at cloud top (lower peak likely from fair-wx cumulus)
- Cumulonimbus and MCSs both show strong drying (e.g., Lin and Johnson 1996)

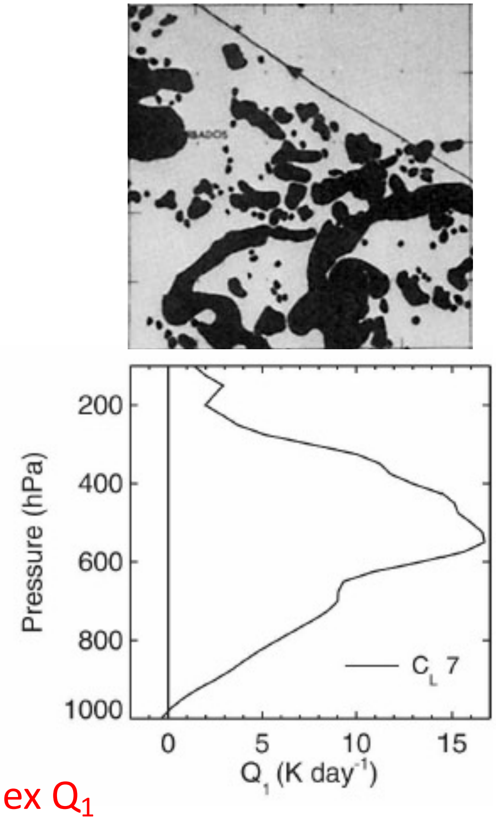
Schumacher et al. (2008), photos from Rangno and Hobbs (2005)

Impact of convective organization on heating

Classic view of convection



Mesoscale view of convection



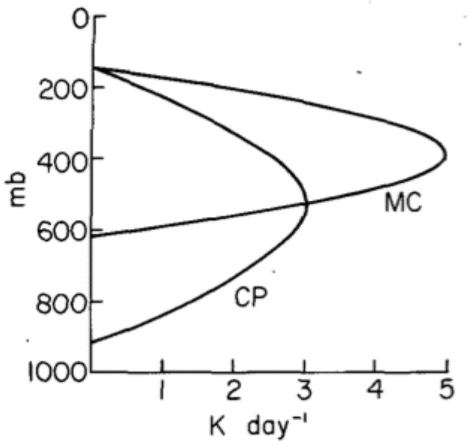
Kwajex Q_1

- Heating is significantly stronger and more elevated during organized convective events
- Heating is stronger because of higher rain amounts, but profile is elevated due to stratiform processes

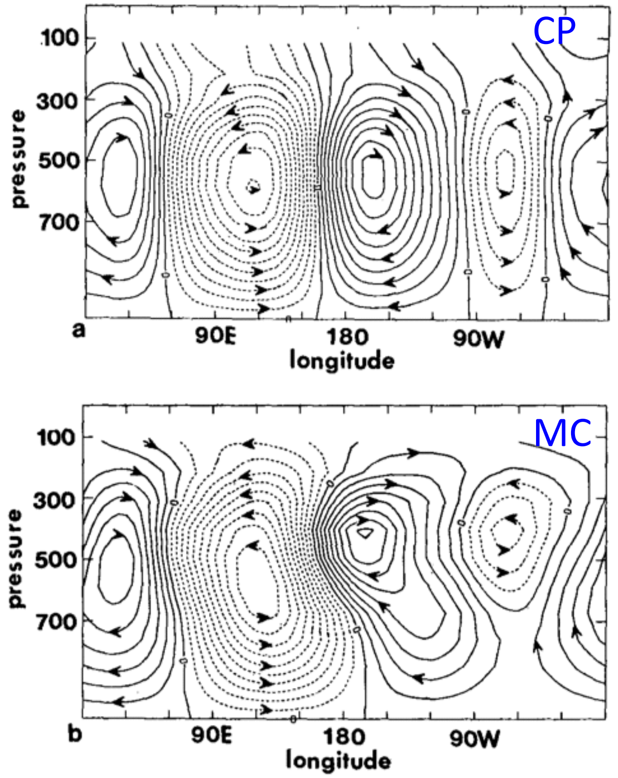
Schumacher et al. (2008)

Implications for the large-scale circulation

Input heating



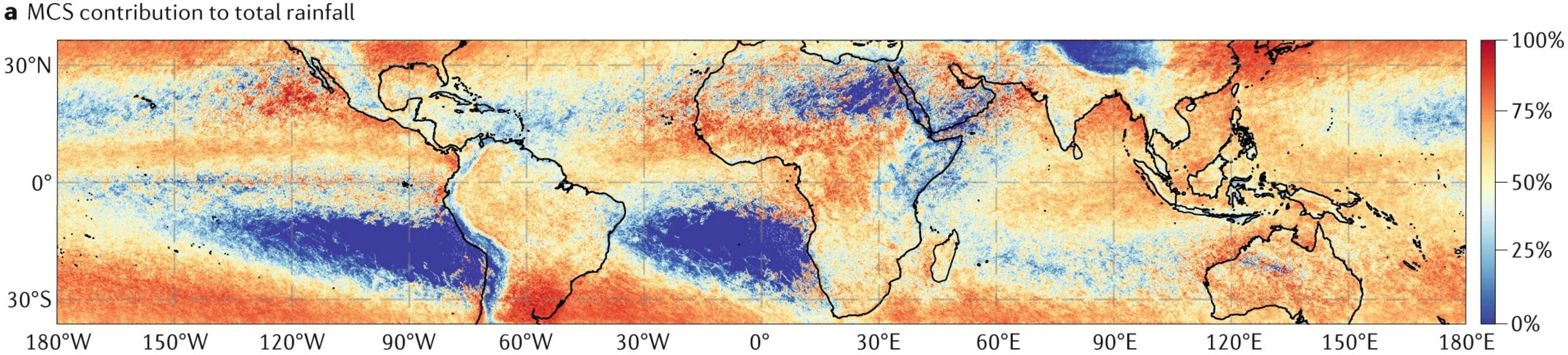
Zonal mass flux



- Elevated heating profile as forcing in dry GCM results in higher circulation center and westward tilt in the Walker circulation over the Pacific Ocean

Hartmann et al. (1984)

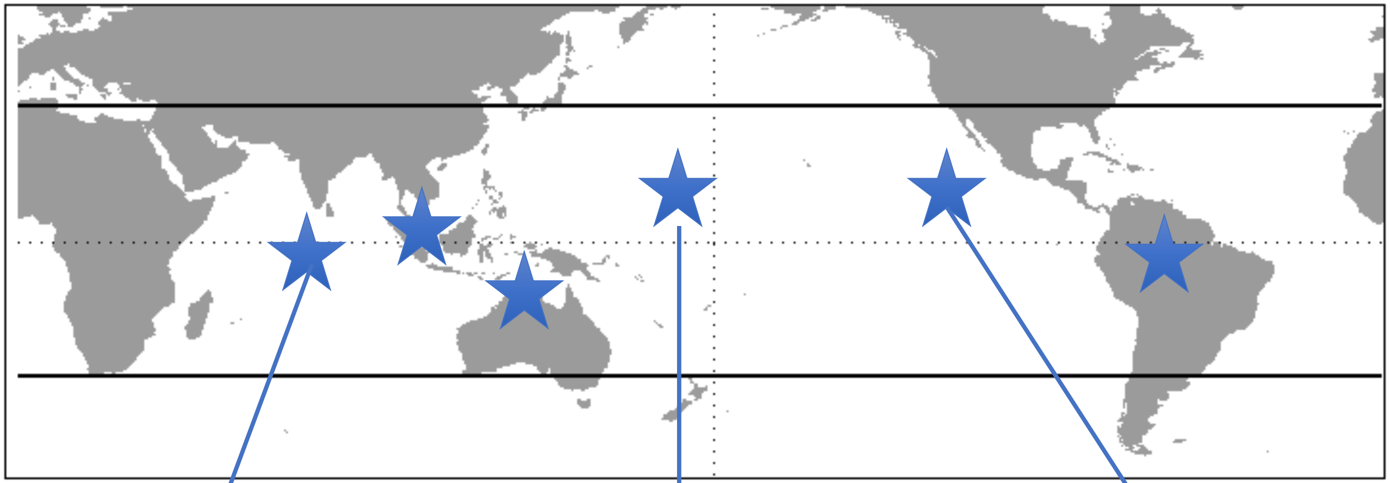
Impact of organized convection on precipitation



TRMM-observed MCSs account for more than 50% of rain in regions with average annual > 3 mm/day.

Nesbitt et al. (2006), R. Schumacher and Rasmussen (2020)

Where I've gone to observe MCSs with radars



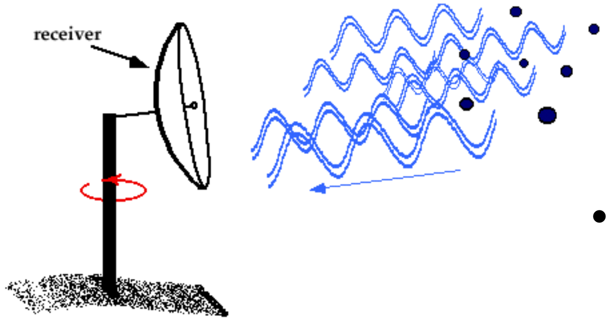
DYNAMO

KWAJEX

TEPPS

Radar = Radio detection and ranging

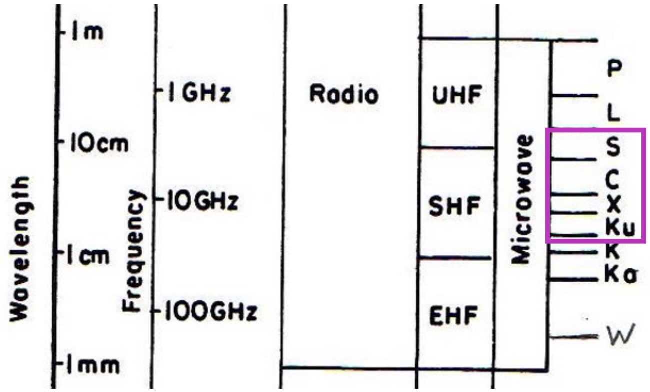
Radar sends out pulse of electromagnetic energy and listens back for scattered energy



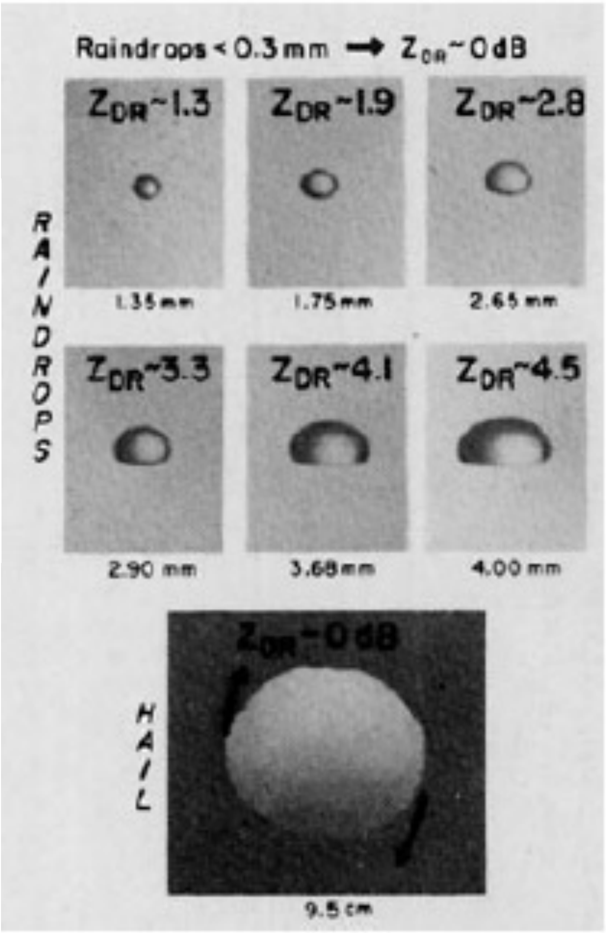
Scattered Energy ~ Number x (Diameter)^6

Received energy converted to REFLECTIVITY (dBZ)

Precipitation radar bands



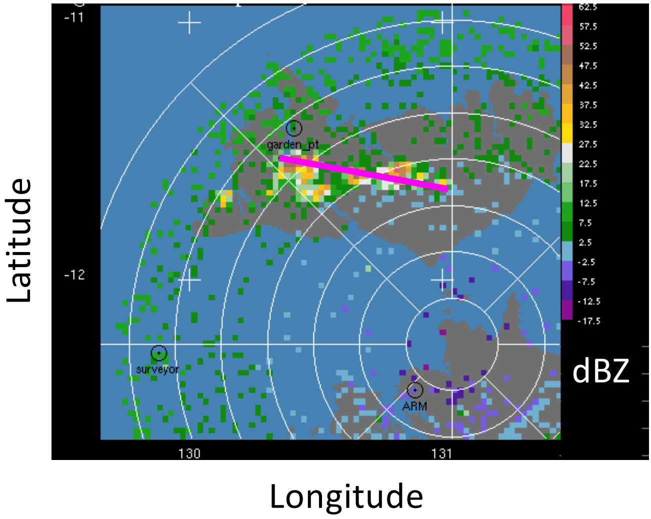
- Want scattering for particles small compared to wavelength



Wakimoto and Bringi (1988)

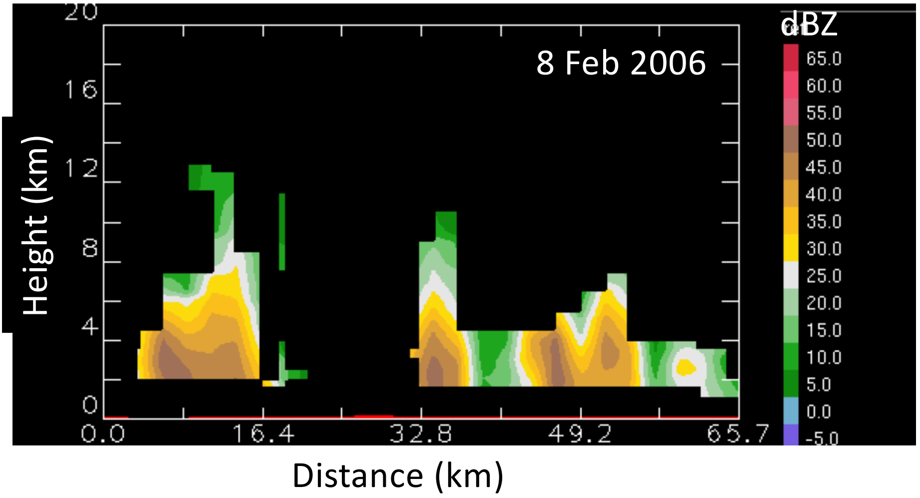
Hector over the Tiwi Islands

Reflectivity at 2.5 km AMSL



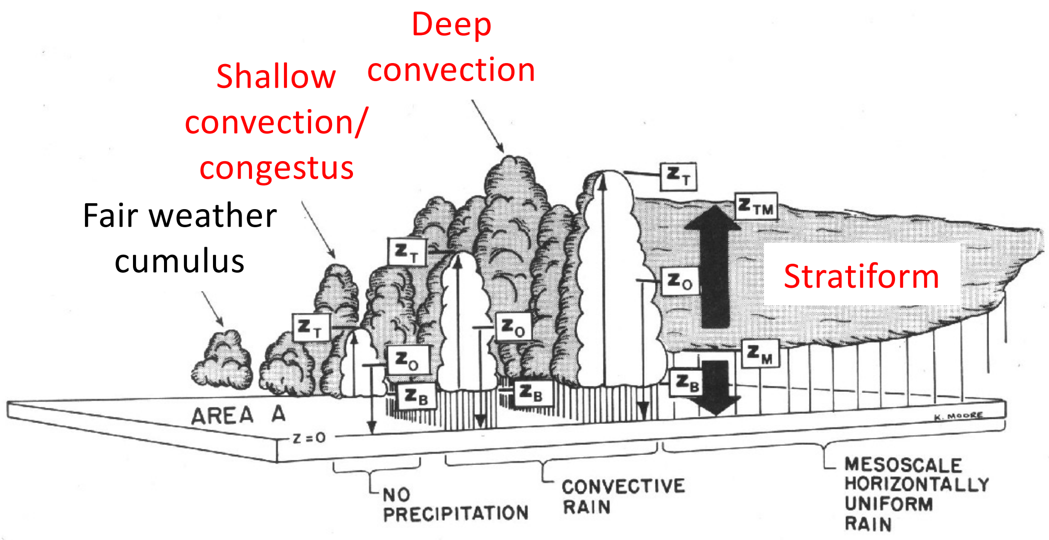
Cumulonimbus clouds at different stages

E. Zipser



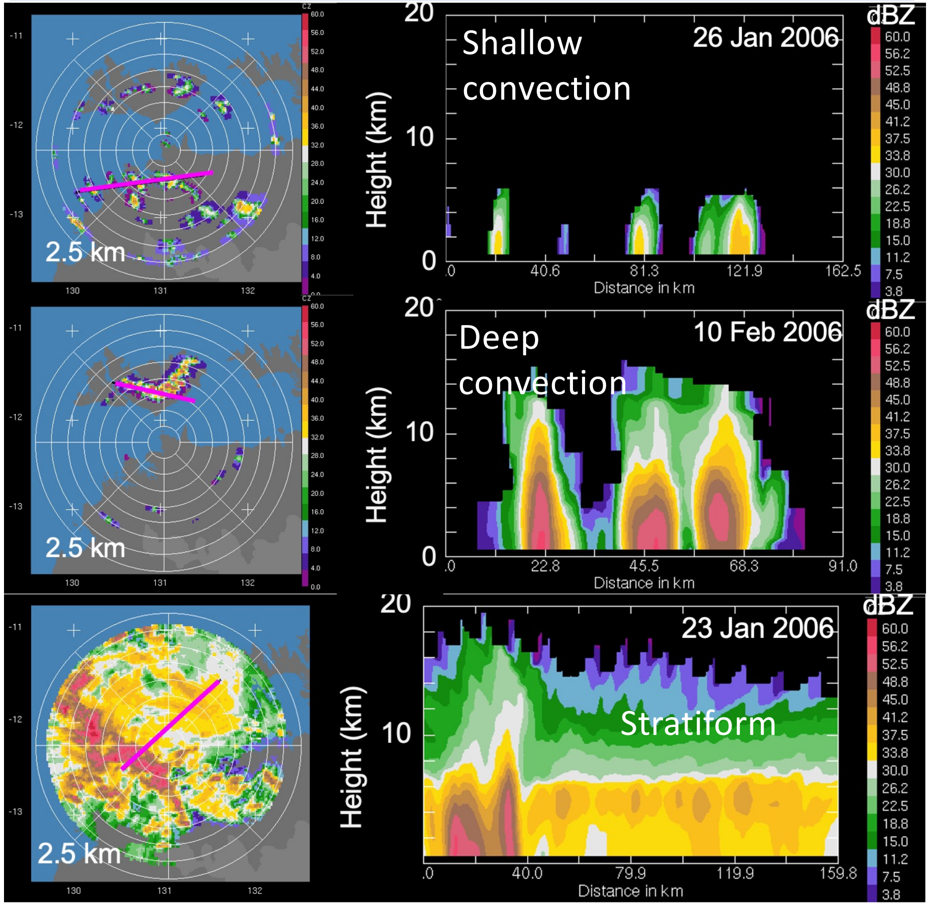
C-Pol (5 cm) radar in Darwin, Australia

Convective cloud population in the tropics



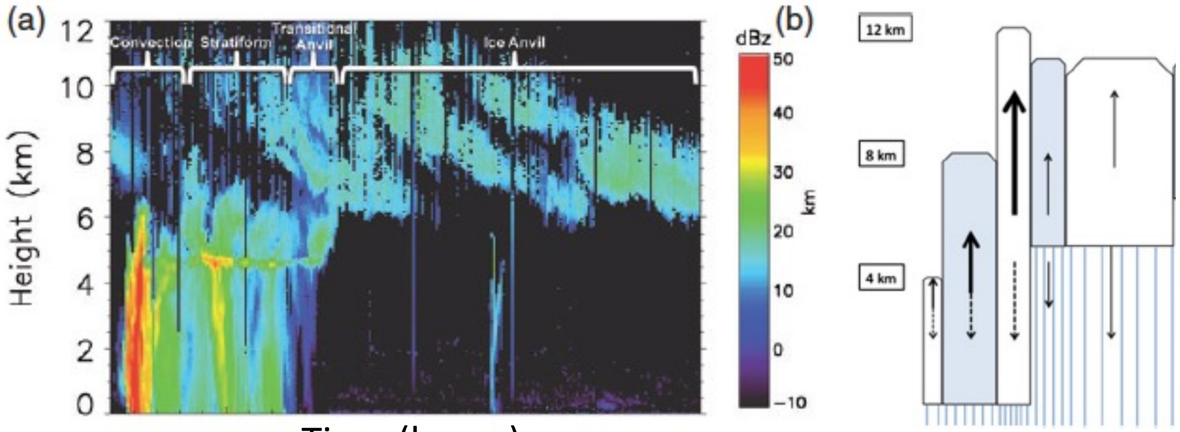
Houze et al. (1980)

Convective rain types observed by radar in Darwin

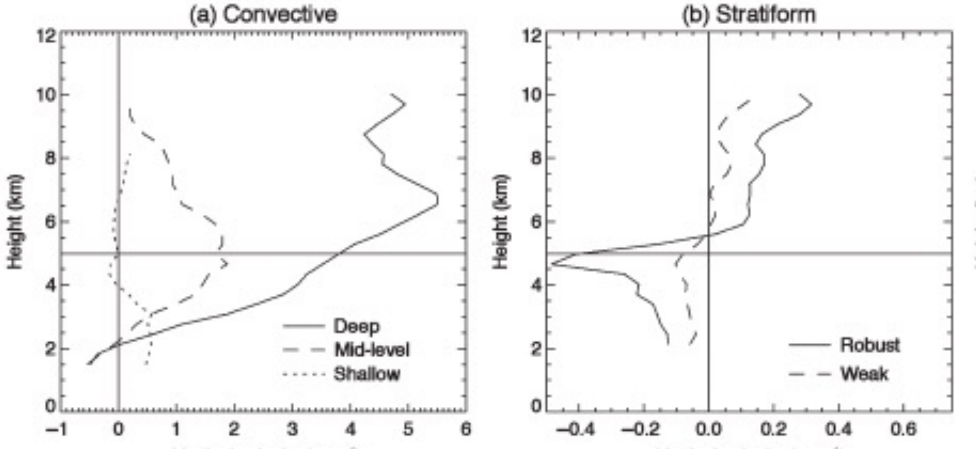


- Shallow (deep) convective rain has echo tops ~0°C (tropopause) and moderate (heavy) rain
- Stratiform is horizontally homogeneous with weak rain, connected to deep convection
- Vertical motions and microphysical growth processes are distinct between rain types, warranting separation

Vertical motion profiles over Darwin



Time (hours)

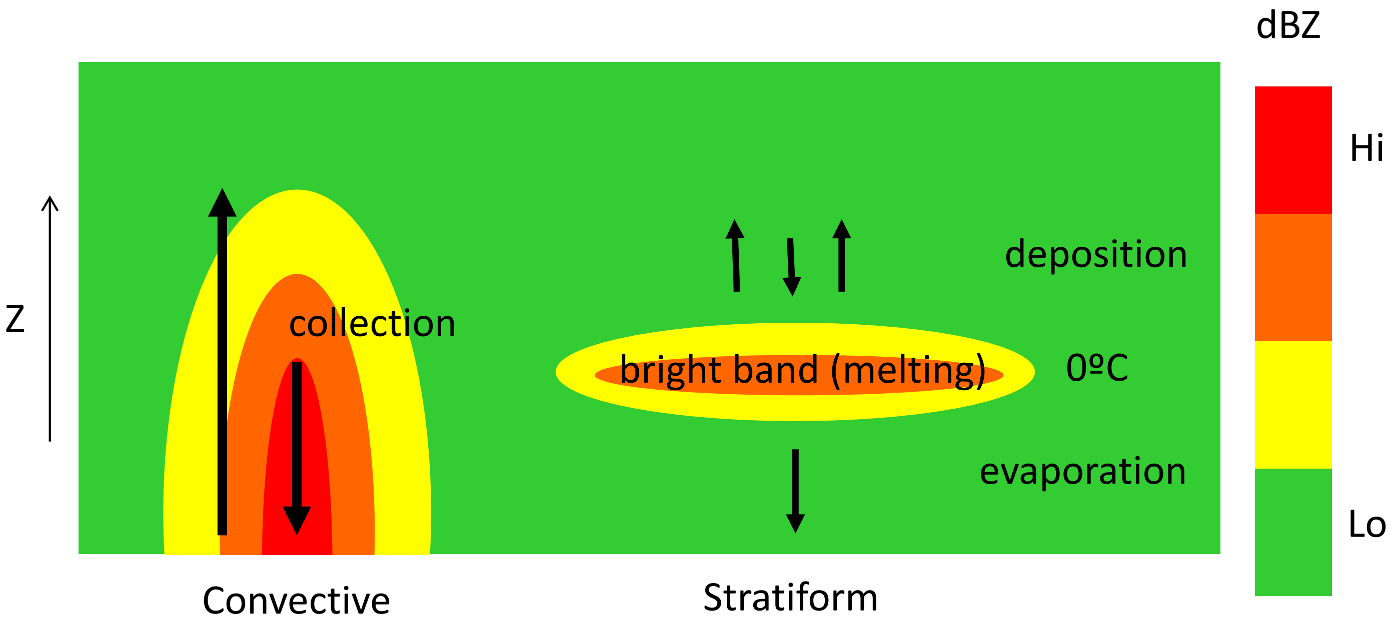


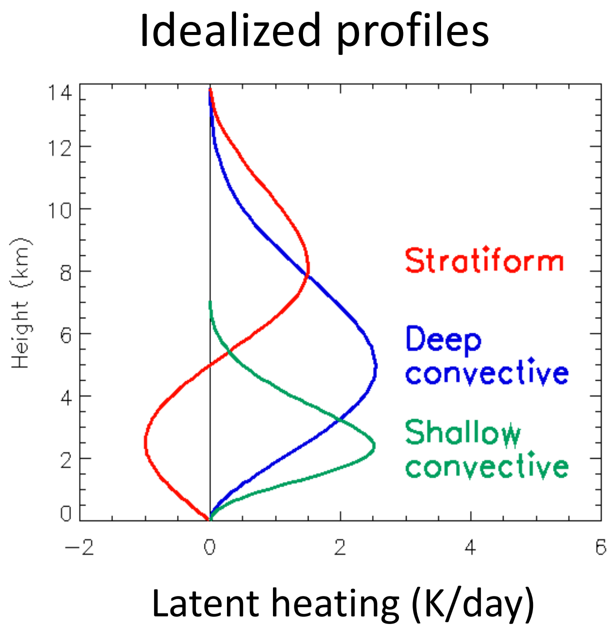
Vertical velocity (m/s)

- Vertical motion profiles retrieved from radar wind profilers show that mean updrafts increase in magnitude from < 1 m/s to > 5 m/s and in height as convection shifts from shallow to mid-level to deep, consistent with Q_1
- Stratiform rain region has weak (< 0.3 m/s) updrafts above 5 km and weak downdrafts below 5 km
- (Will return to anvil)

Schumacher et al. (2015)

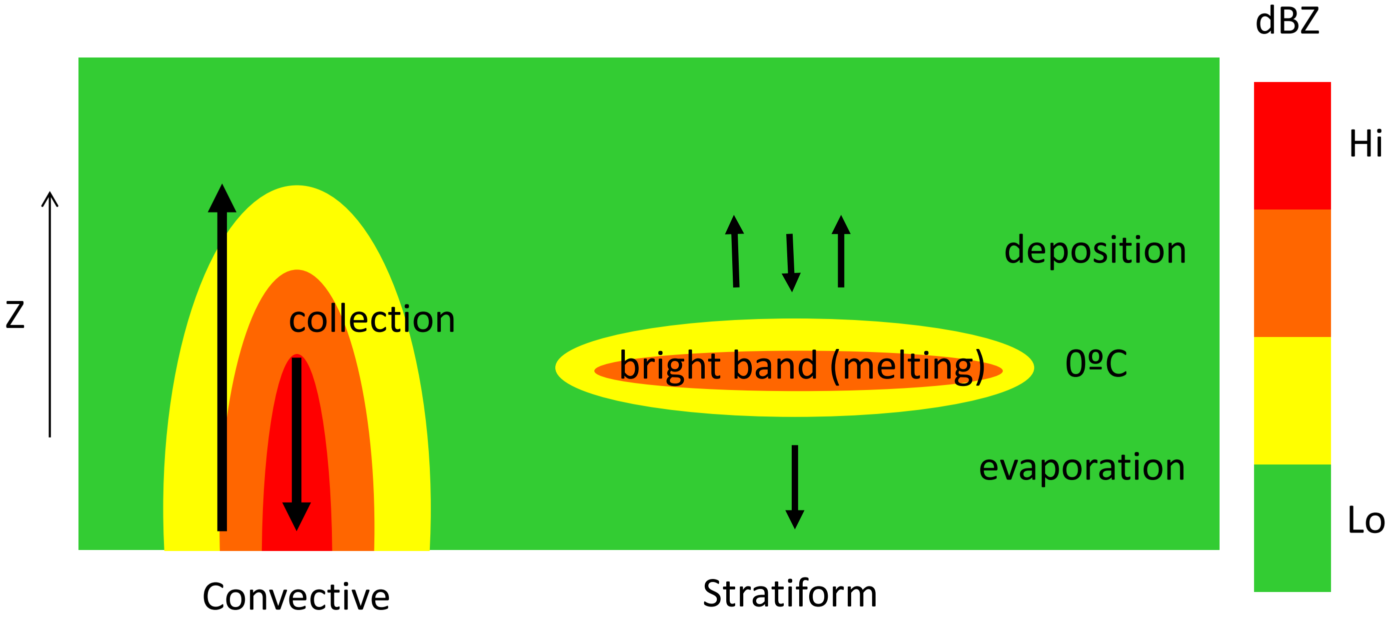
Convective and stratiform kinematics and microphysics



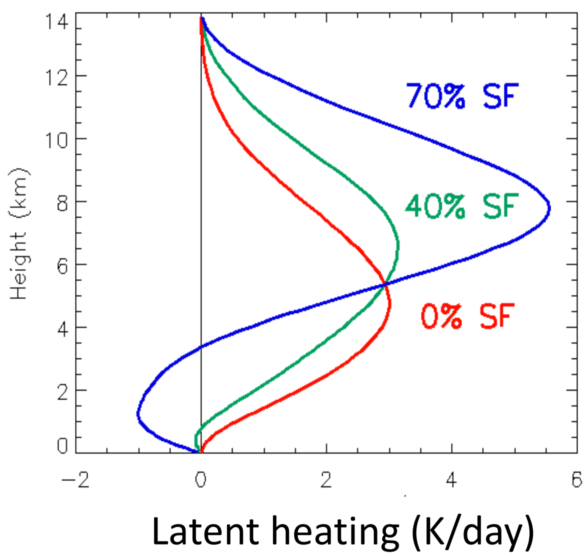


- Mean upward motion through depth of deep convective cloud leads to mid-tropospheric latent heating maximum (shallow convective heating is similar, but limited in height)
- Mean upward motion in stratiform region above 0ºC and evaporation in downdraft below cloud base leads to heating/cooling couplet

Convective and stratiform kinematics and microphysics


dBZ
Hi
Lo
Z
collection
bright band (melting)
deposition
0ºC
evaporation
Convective
Stratiform

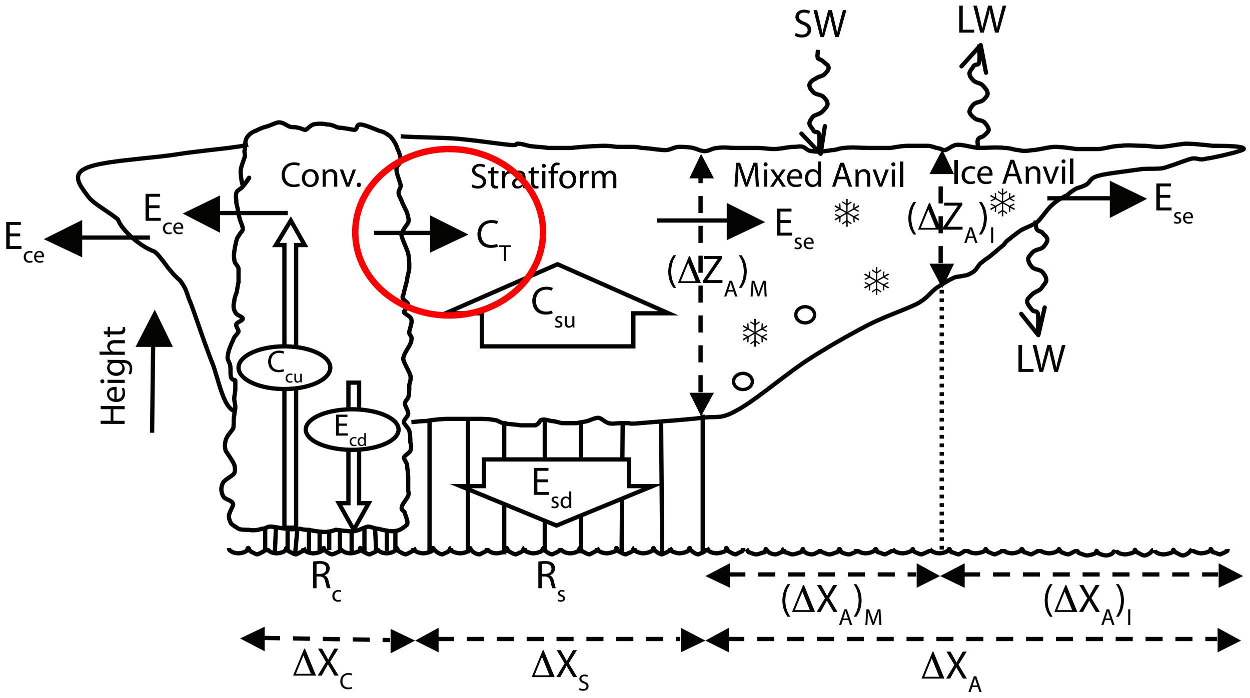
Idealized profiles



- Together, the different vertical wind motions and precipitation growth processes in the stratiform cloud region lead to the elevated latent heating profiles in MCSs

Schumacher et al. (2004)

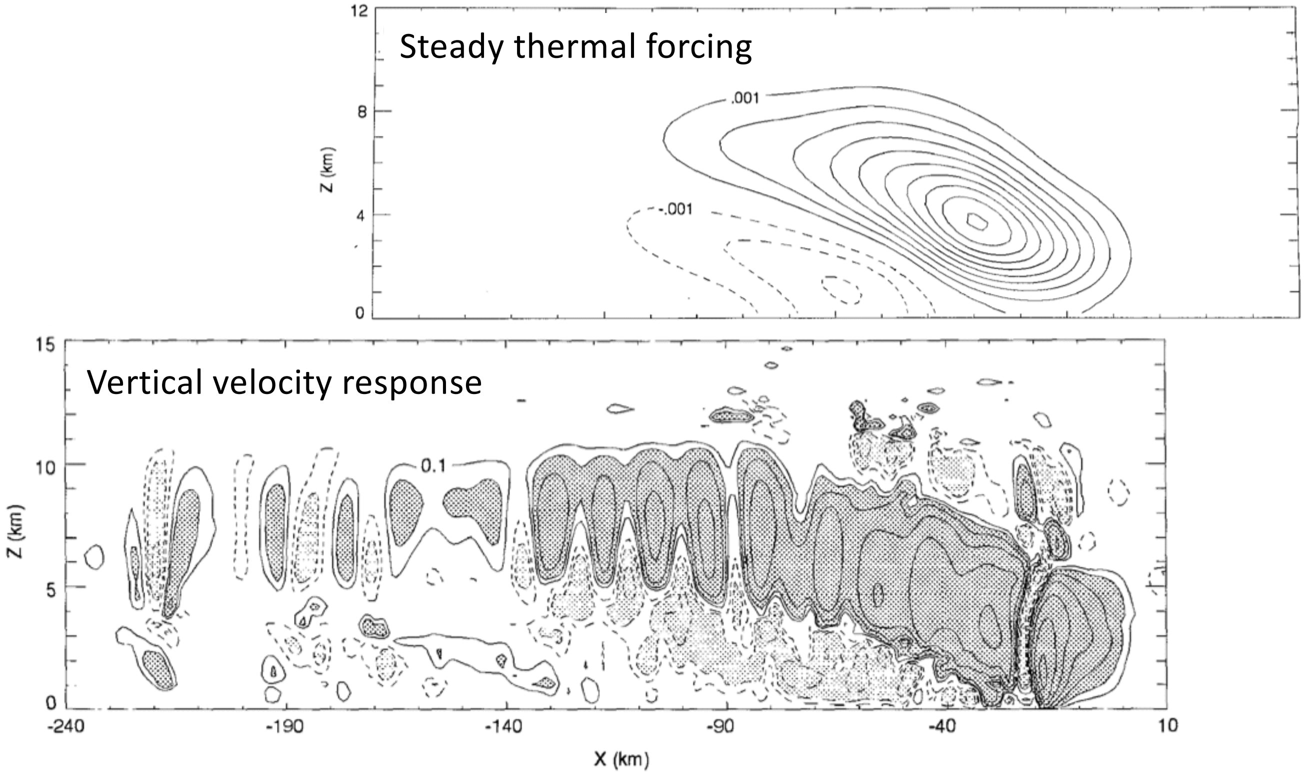
The full MCS energy budget



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

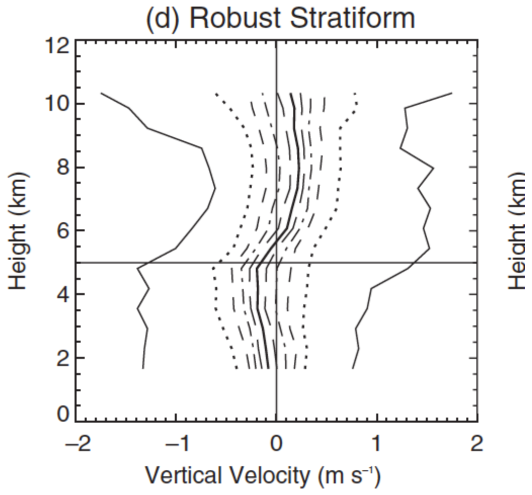
- Latent heating processes dominate in precipitating regions while radiative processes dominate in non-precipitating anvil (~80% LH/20% radiative heating)
- Deep convection feeds the stratiform rain region through hydrometeor transport

Role of gravity waves



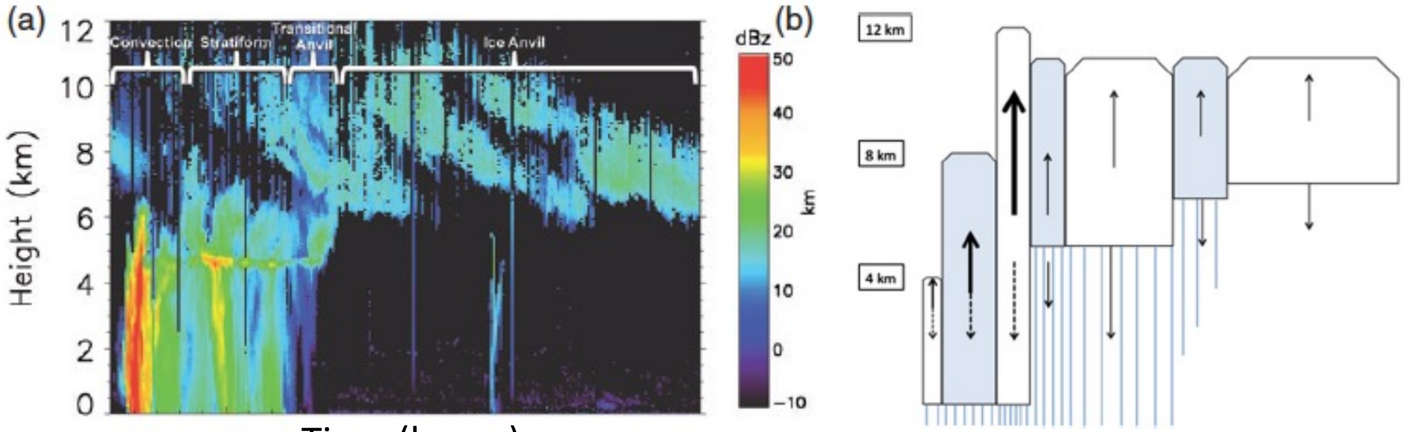
Pandya and Durran (1996)

Darwin profiler

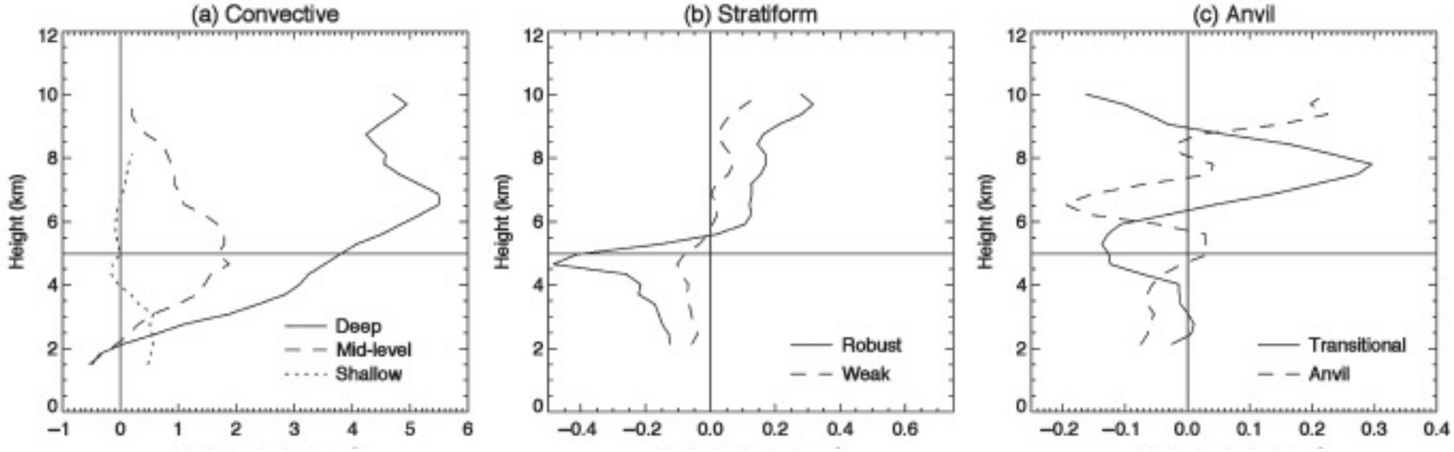


Thermal forcing in convective region creates a realistic mesoscale circulation and anvil region in non-linear, dry numerical simulations.

Vertical motion profiles over Darwin



Time (hours)

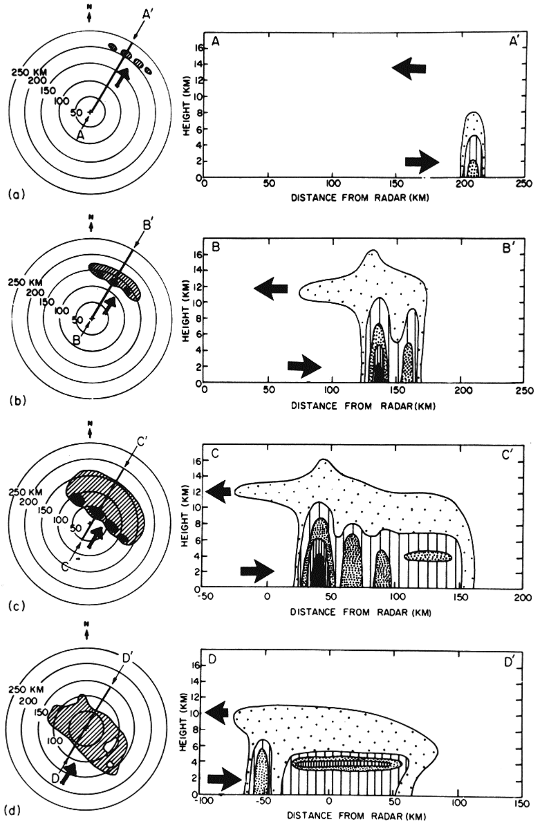


Vertical velocity (m/s)

- Anvil connected to MCSs is also dynamically active, which is likely associated with cloud top radiative processes, but also possibly gravity waves from deep convection

Schumacher et al. (2015)

MCS life cycle



Isolated cells

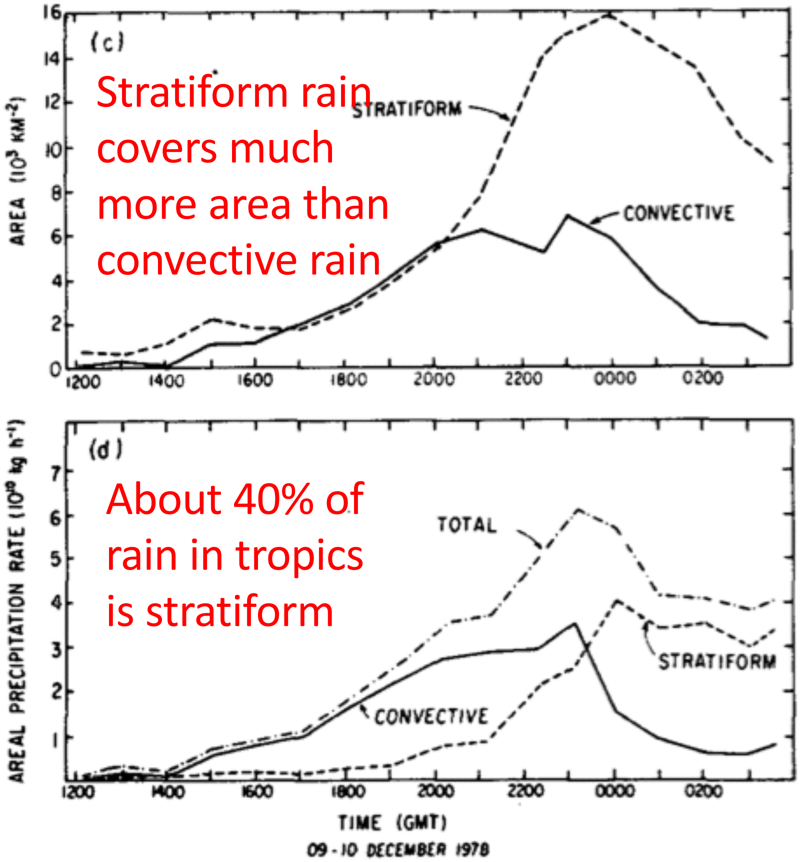
Cells merge

Mesoscale rain region forms

New cells stop forming

Leary and Houze (1979a)

MCS area and rainfall

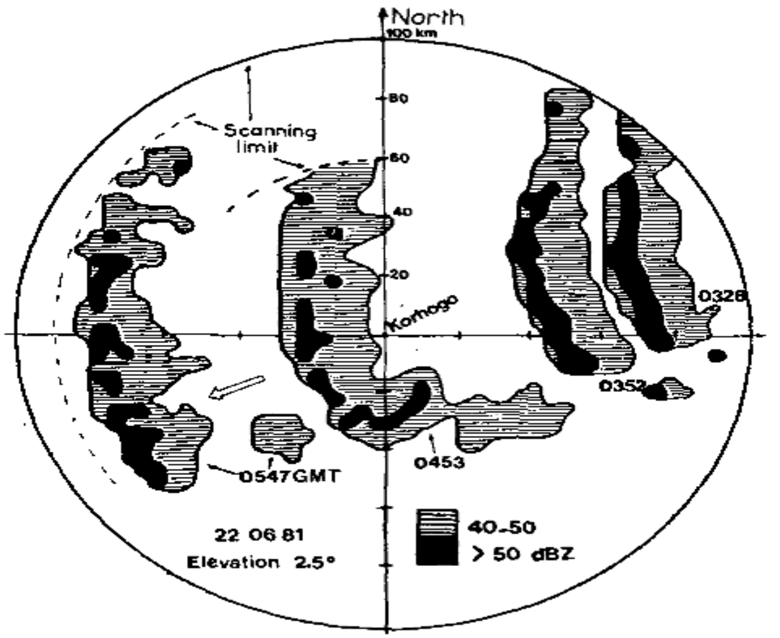


Stratiform rain covers much more area than convective rain

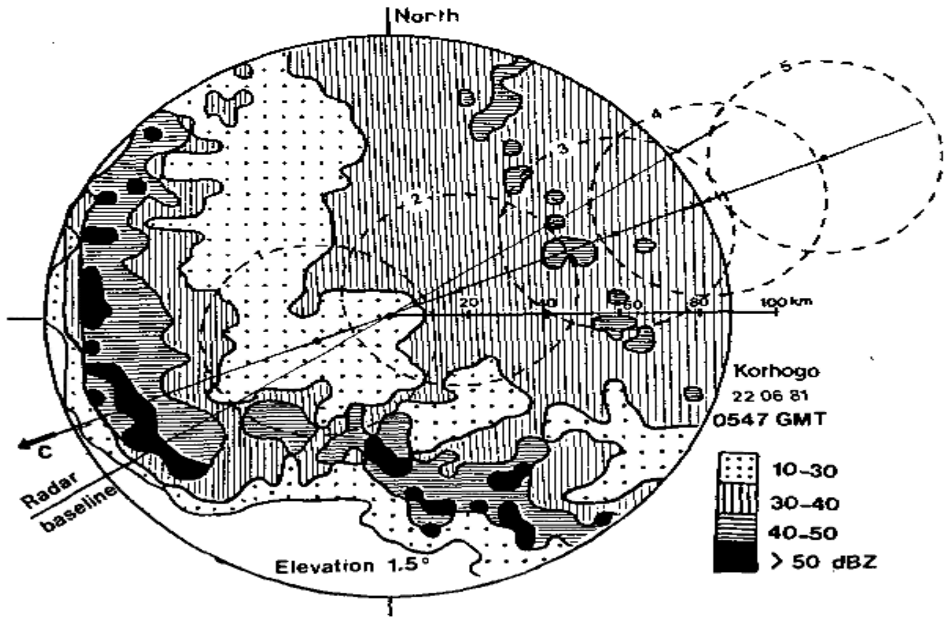
About 40% of rain in tropics is stratiform

Churchill and Houze (1984)

African squall line evolution



Successive locations of high reflectivity cores

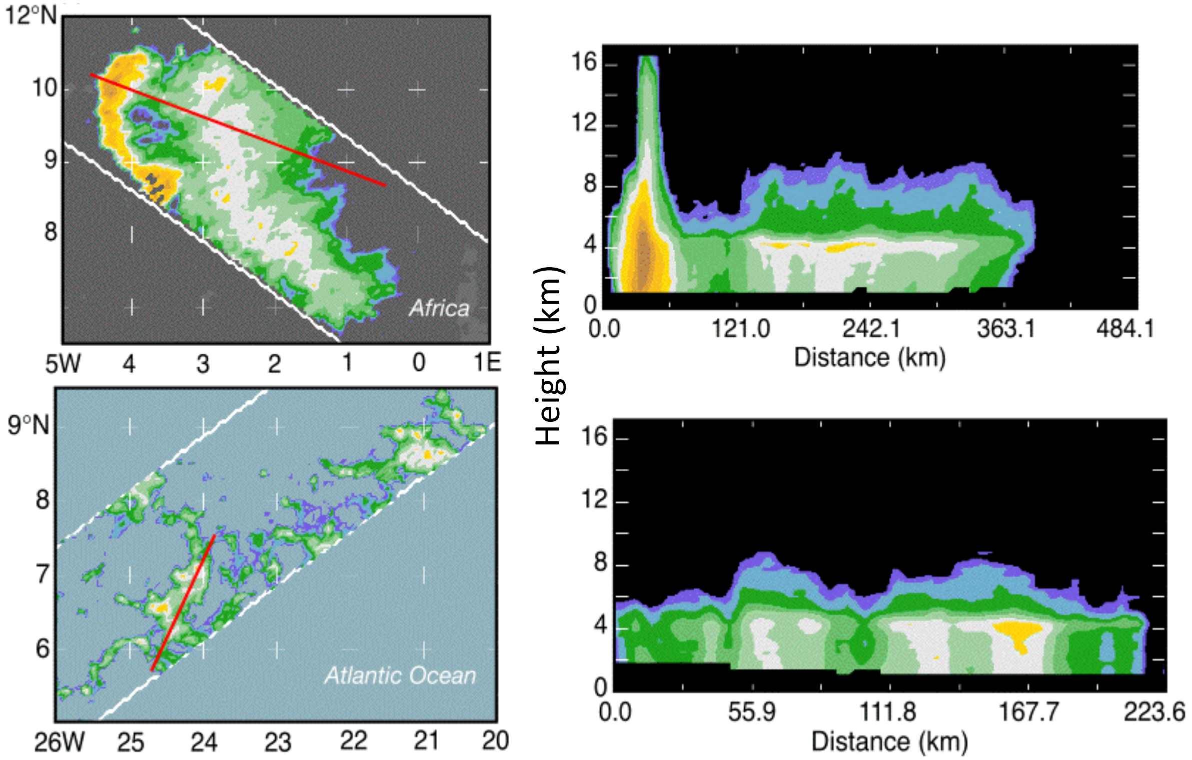


Stratiform rain area at 0547 GMT

Chong et al. (1987)

Classic leading line-trailing stratiform vs messy oceanic system

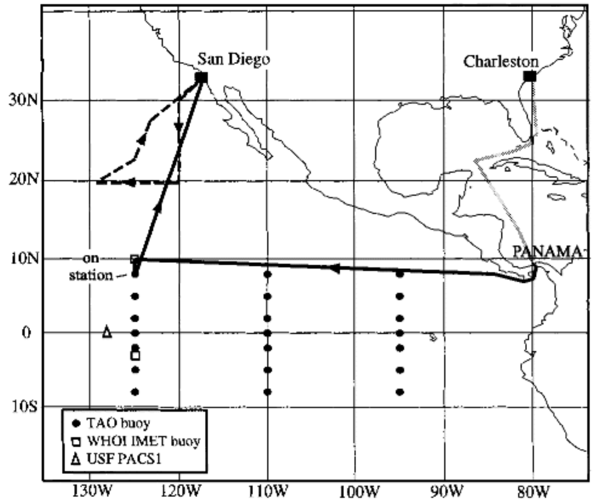
TRMM PR

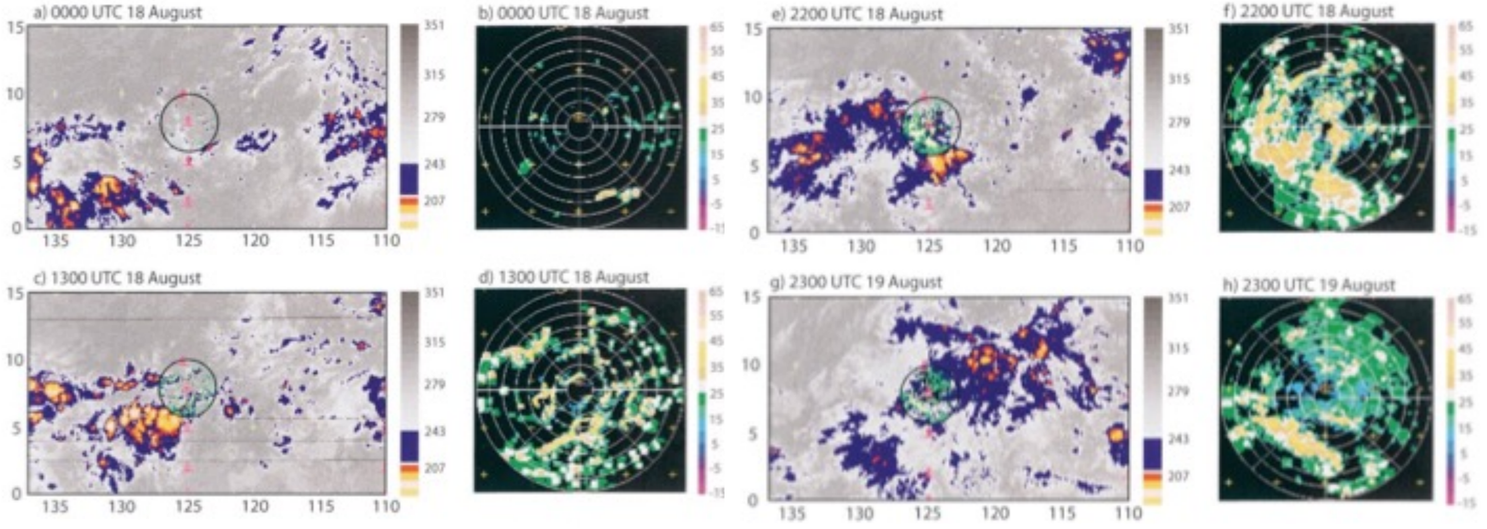


Schumacher and Houze (2006)

TEPPS 1997

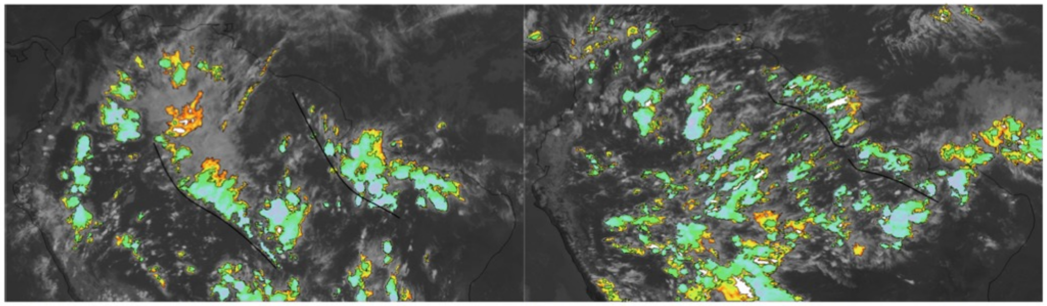
Seven-week cruise of the RH Brown to study convective rain processes in the East Pacific (like the Kelvin wave passage below in the ITCZ)





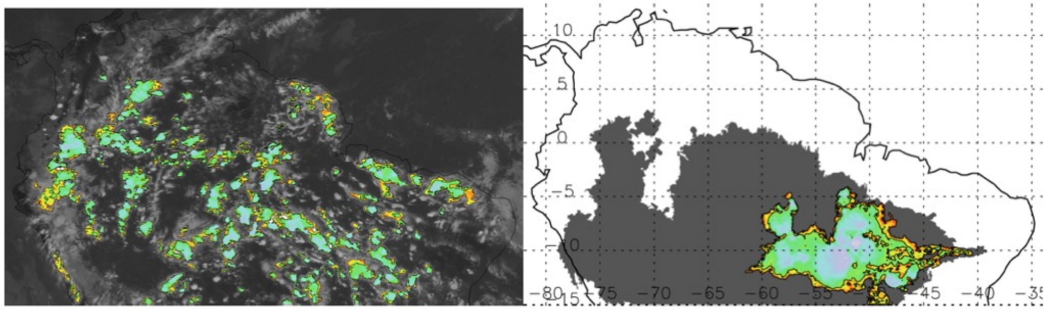
Straub and Kiladis (2002)

MCS types across the Amazon



(a) Large scale SL in sequence at 2014-04-01 22:30.

(b) Coastal systems – SL with some hundread of kilometers of propagation inland – at 2014-04-20 20:30.



(c) Convection spread at 2014-04-05 20:30.

(d) Extreme long-lived with 82h of lifetime at 2014-11-09 02:30

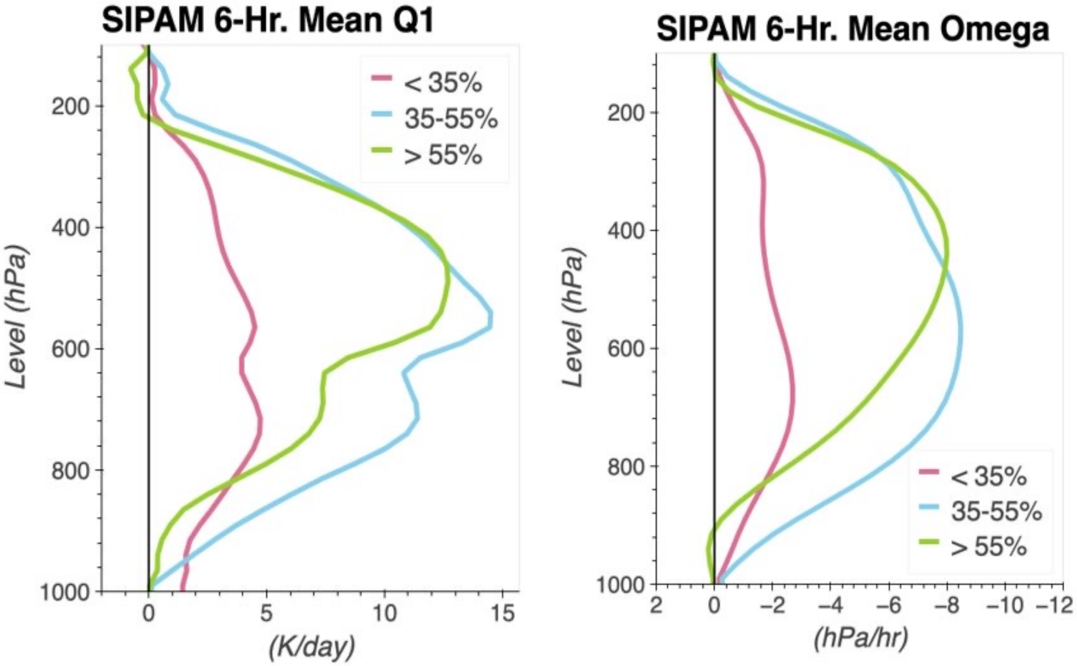
Anselmo et al. (2021)

GOES-13 30-min IR satellite images were used to track cloud clusters $\geq$ 2500 km^2 and with $T_b \leq$ 235 K across the Amazon for 2014-2015

Following work by Machado and Rossow 1993, Mathon and Laurent 2001, etc.

GoAmazon Q_1 vs large-scale omega

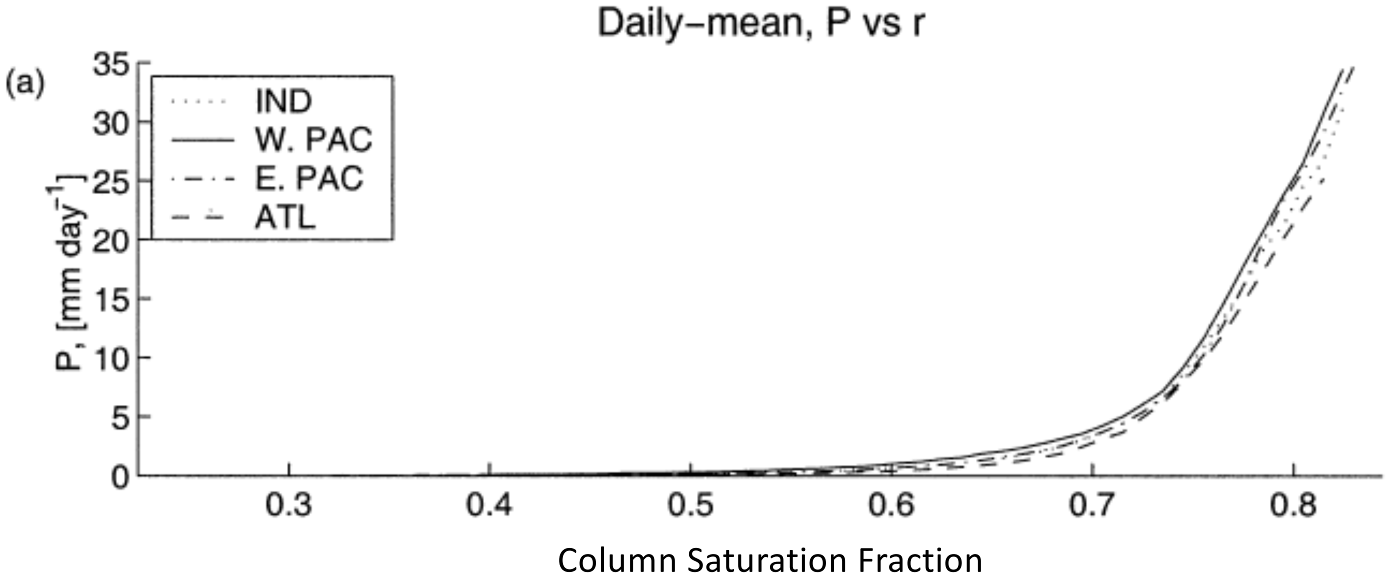
Q1 and Omega from budget-based variational analysis



Percentages represent stratiform rain fraction from the SIPAM S-band (10-cm wavelength) radar

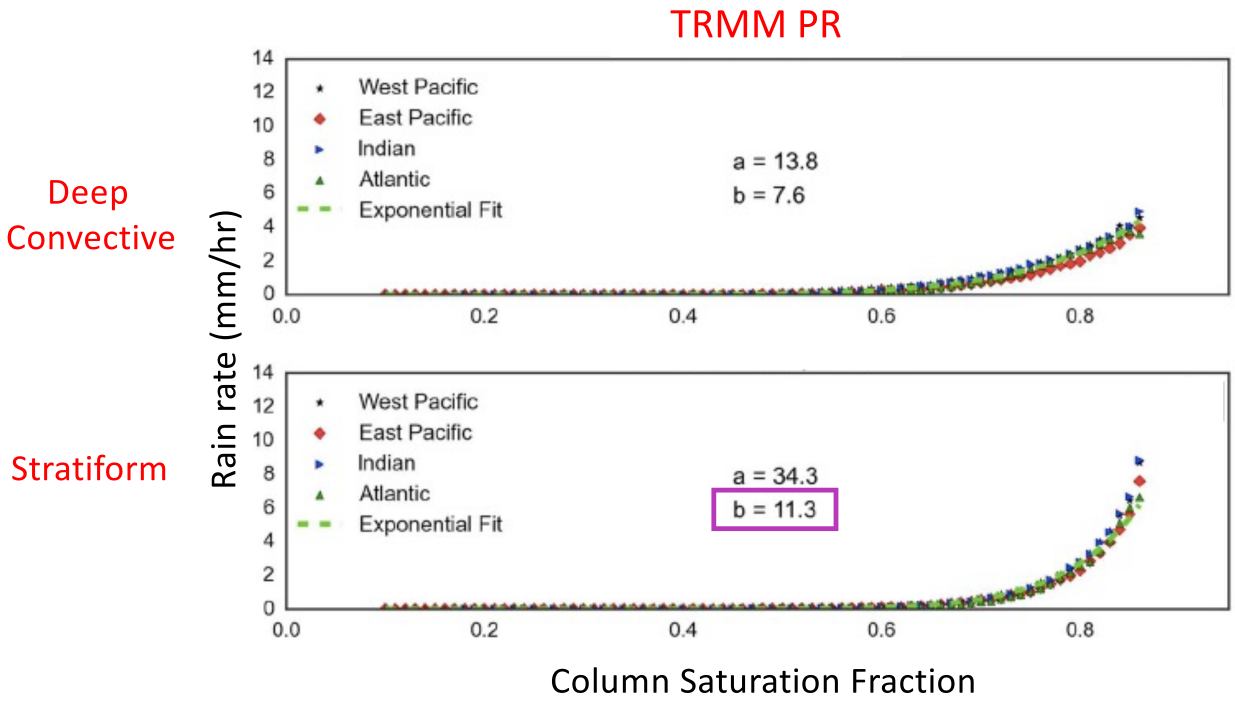
- Q_1 and omega are often used synonymously even though they represent different processes in the atmosphere (although this approximation is better in rainy regions, e.g., Mapes and Houze 1995)
- Because it is easier to measure vertical motion than heating (and with the advent of new measurement technology, especially spaceborne missions like INCUS and AOS), there is motivation to examine omega in this framework as well

What dictates the shape of the precipitation-moisture relationship over tropical oceans?



Bretherton et al. (2004)

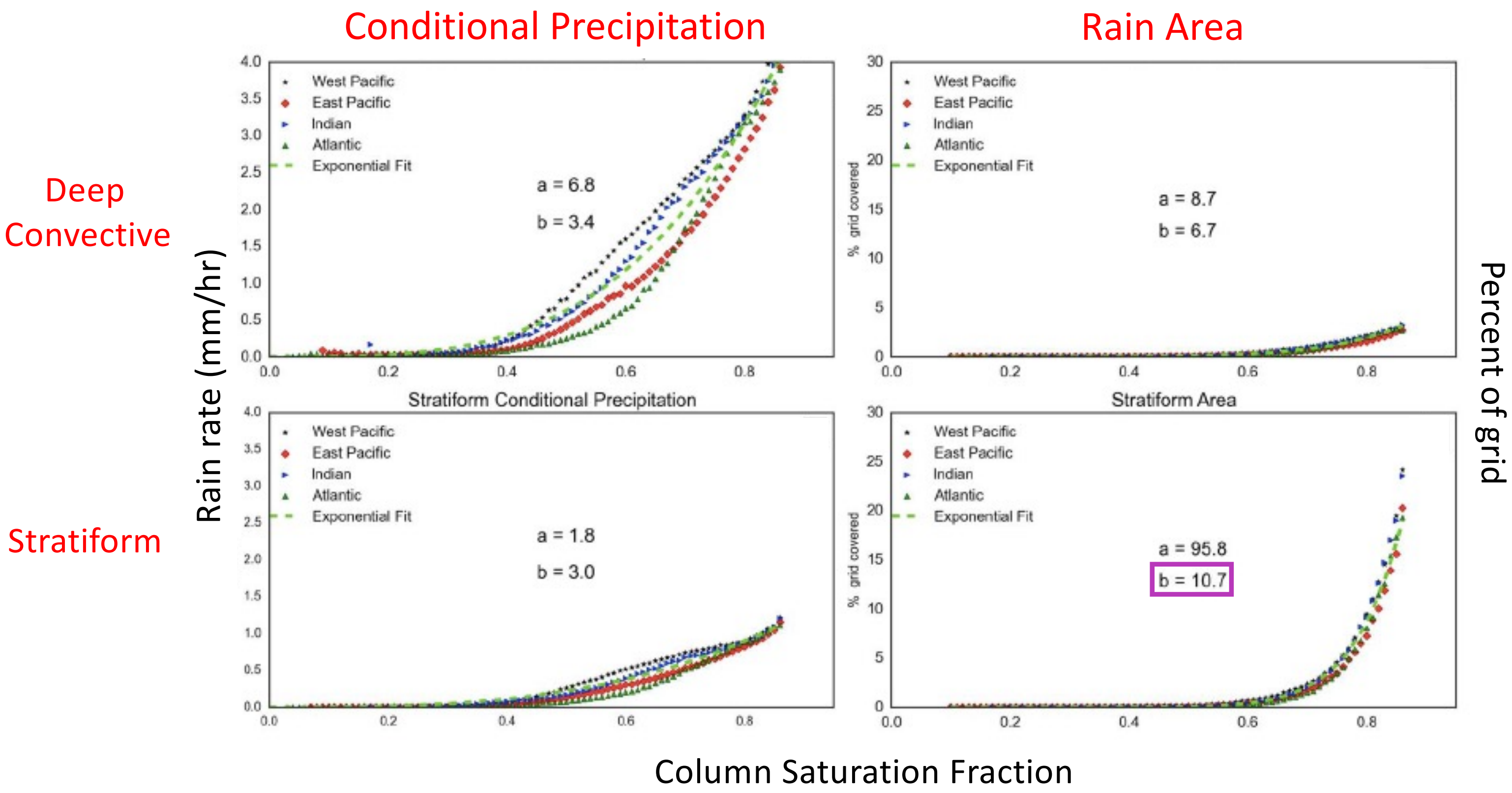
What dictates the shape of the precipitation-moisture relationship over tropical oceans?



- Stratiform precipitation shows a more rapid rise in all ocean basins based on TRMM precipitation radar (PR) observations and MERRA humidity fields

Ahmed and Schumacher (2015)

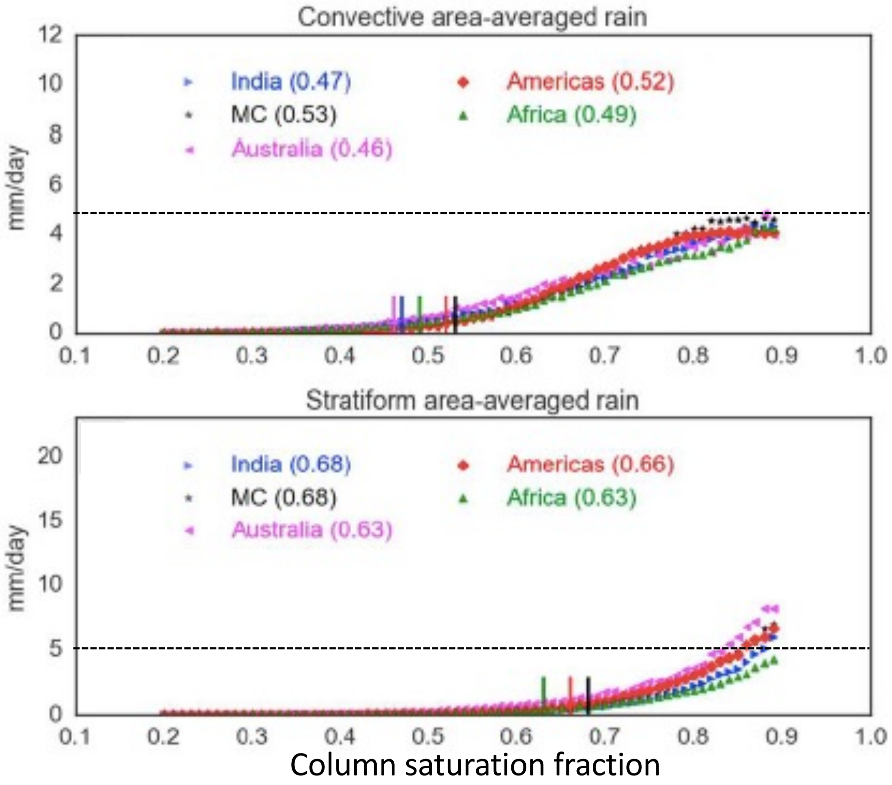
What dictates the shape of the precipitation-moisture relationship over tropical oceans?



- When TRMM PR precipitation is decomposed into conditional rain rate and rain area, stratiform rain area dominates the non-linearity

Ahmed and Schumacher (2015)

What dictates the shape of the precipitation-moisture relationship over tropical land?



Deep Convective

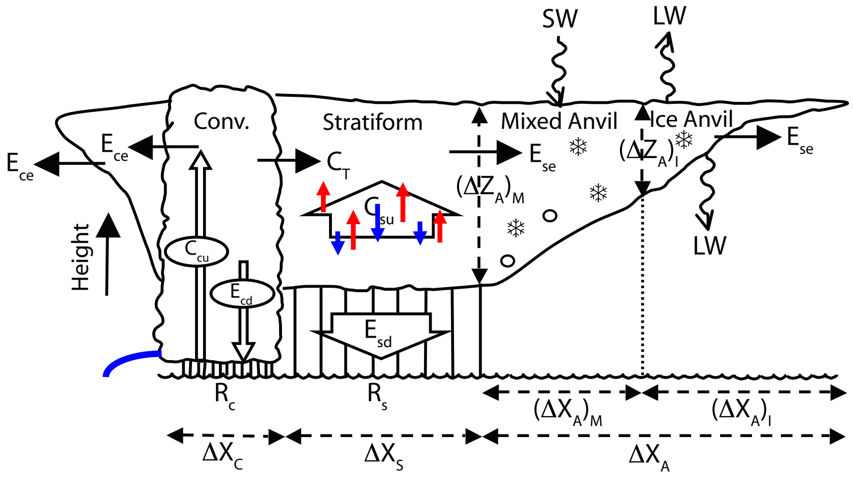
Stratiform

- Over land, the pickup for convective rain occurs before the pickup for stratiform rain and the convective relationship is linear vs. stratiform rain's more exponential curve

Ahmed and Schumacher (2017)

Some things that matter to mesoscale convective organization

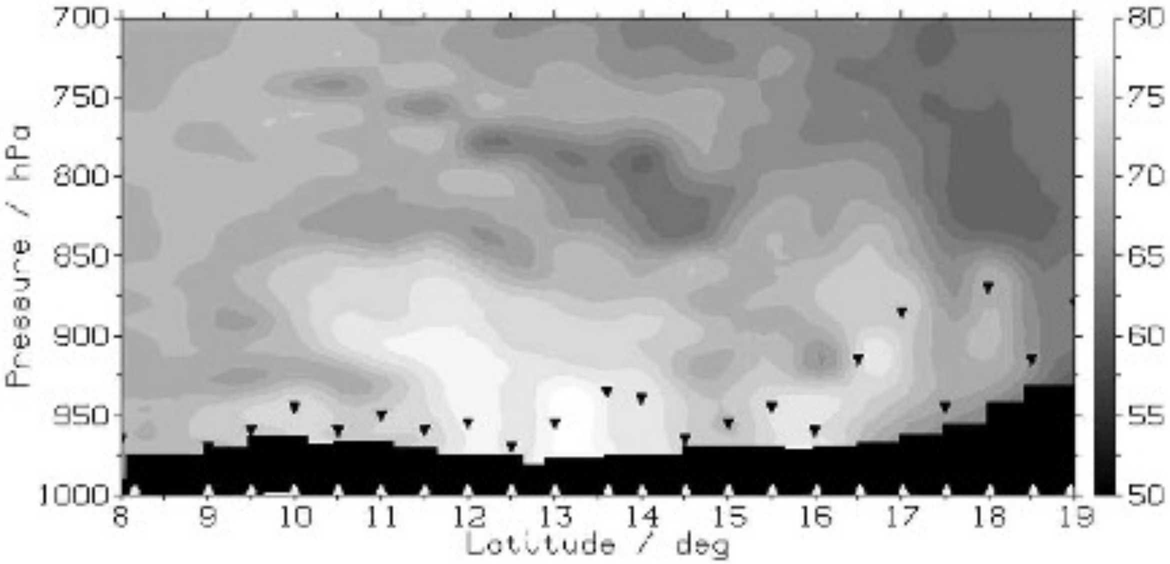
Convective initiation and maintenance	Stratiform rain and anvil production
Warm, moist boundary layer	Mid and upper-level moisture
Low-level shear	Mid- and upper-level shear/hydrometeor advection
Downdraft/cold pools	Gravity waves
Synoptic and mesoscale boundaries	Radiative feedbacks



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

How does convection initiate?

- Warm, moist boundary layer

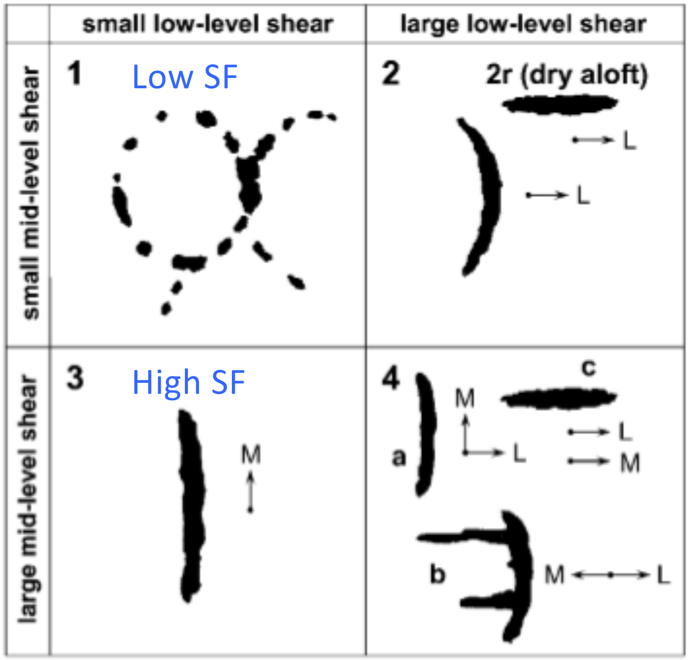


Equivalent potential temperature profiles from dropsondes over the African Sahel show significant PBL variability.

Taylor et al. (2003)

How does convection organize?

- Warm, moist boundary layer
- Low-level/mid-level shear



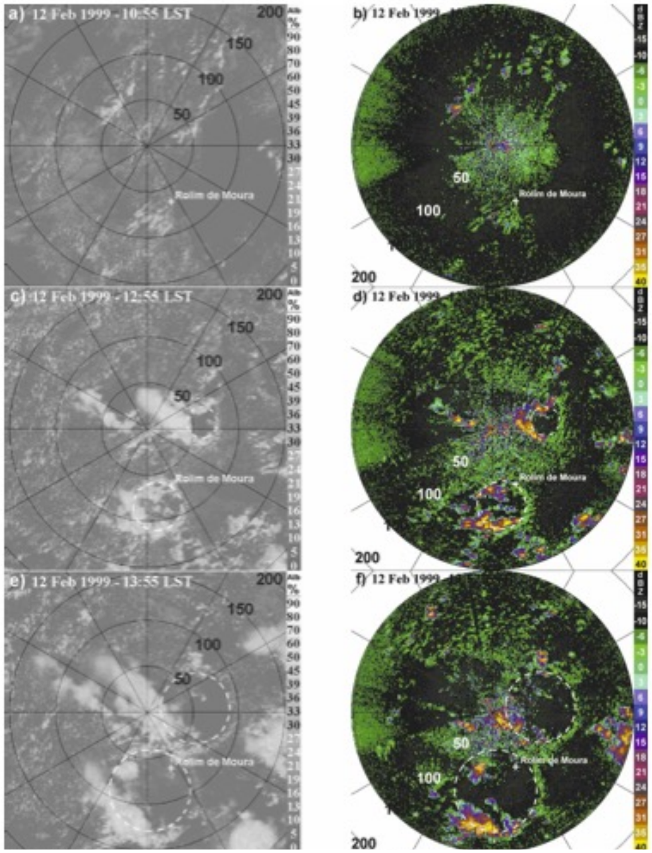
Variations in low (1000-800 hPa) and mid (800-400 hPa) level shear cause convective structures with different orientations and stratiform rain fractions (based on TOGA COARE and SCSMEX data).

Lemone et al. (1998), Johnson et al. (2005)

How does convection organize?

- Warm, moist boundary layer
- Low-level/mid-level shear
- Downdrafts/cold pools

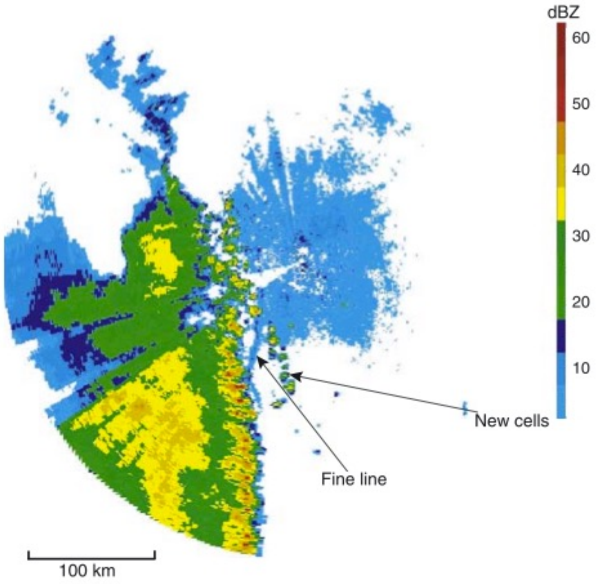
Gust fronts (including colliding gust fronts) caused more than half of the storm cell initiations on a weakly forced day during TRMM-LBA.



Lima and Wilson (2008)

How does convection organize?

- Warm, moist boundary layer
- Low-level/mid-level shear
- Downdrafts/cold pools
- Synoptic and mesoscale boundaries

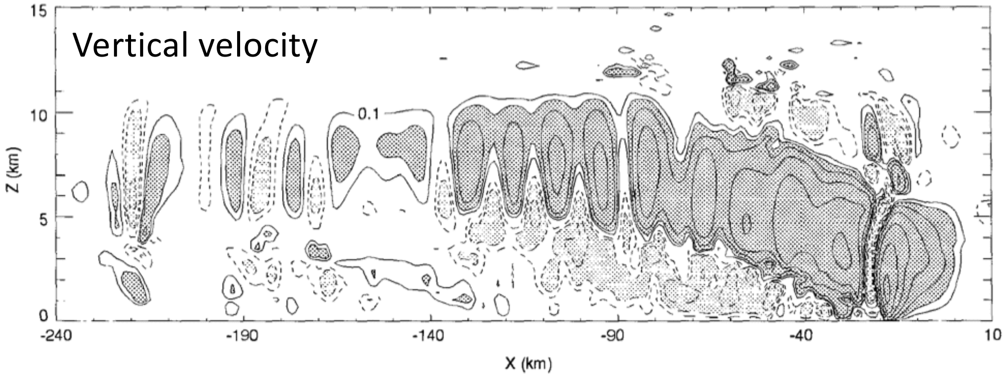


Fronts and discrete propagation provide additional boundaries for convective cells to form upon.

Houze (2004)

How does convection organize?

- Warm, moist boundary layer
- Low-level/mid-level shear
- Downdrafts/cold pools
- Synoptic and mesoscale boundaries
- Gravity waves

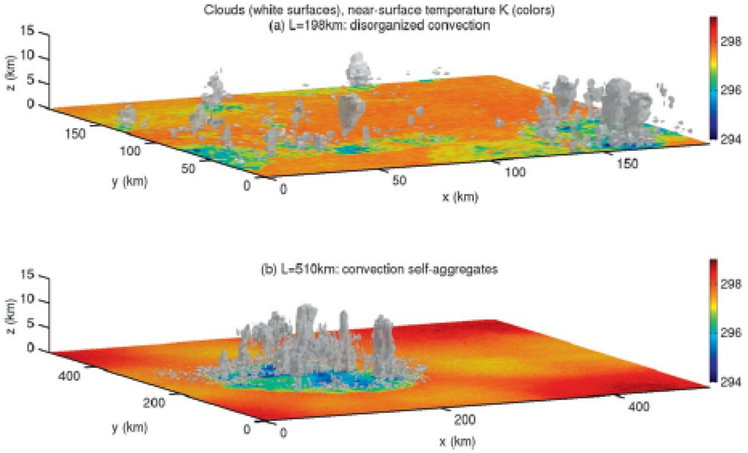


Thermal forcing in convective region creates realistic mesoscale circulation and anvil region in non-linear, dry numerical simulations.

Pandya and Durran (1996)

How does convection organize?

- Warm, moist boundary layer
- Low-level/mid-level shear
- Downdrafts/cold pools
- Synoptic and mesoscale boundaries
- Gravity waves
- Self-aggregation



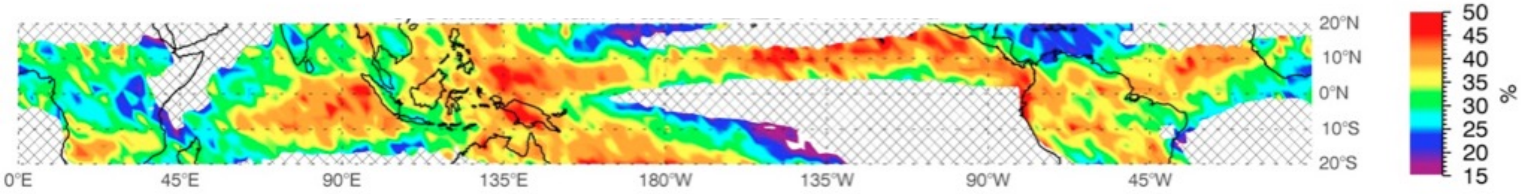
Assuming RCE and a large enough domain, dry regions grow and push convective elements together.

Muller and Held (2012)

How do stratiform rain and anvil regions persist?

- Convective sustainability

Stratiform rain fraction from TRMM PR

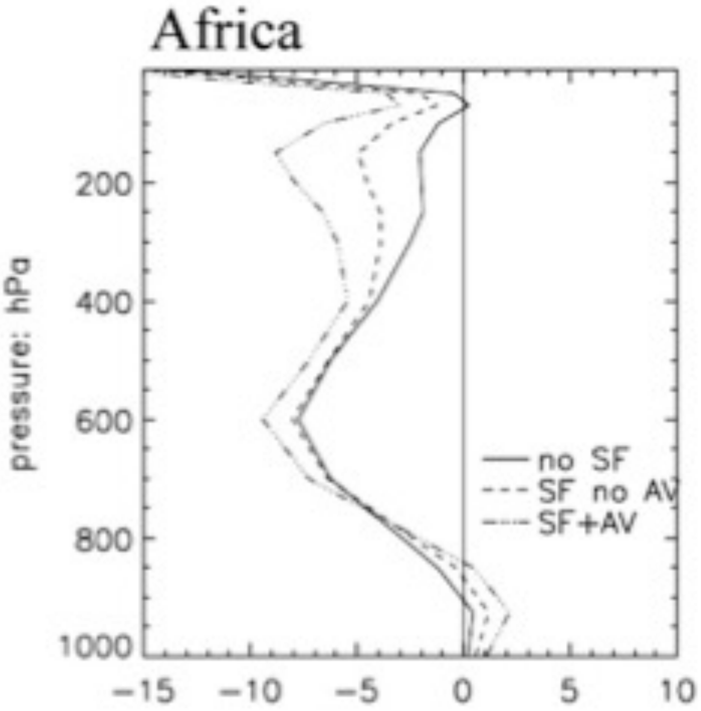


Regions with a warm, moist boundary layer may be more likely to sustain convection throughout the diurnal cycle.

Schumacher and Houze (2006), Funk et al. (2013)

How do stratiform rain and anvil regions persist?

- Convective sustainability
- Upper-level shear/hydrometeor advection



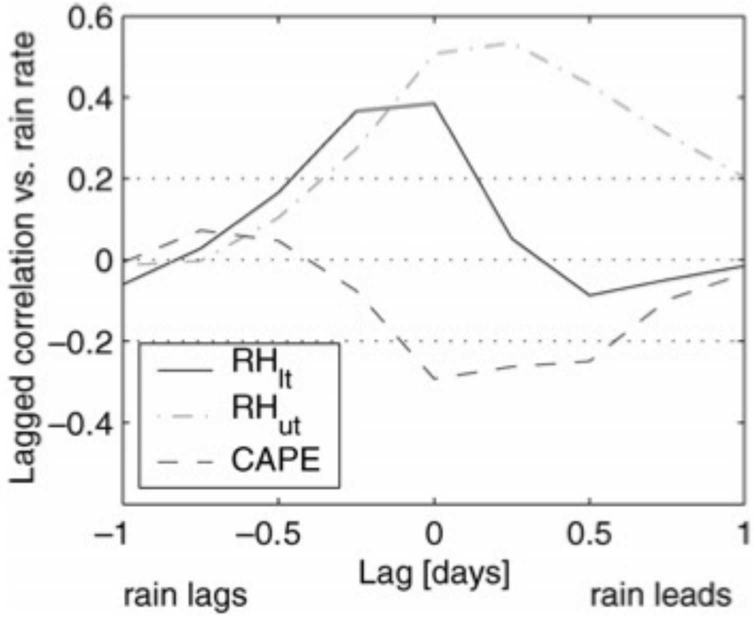
Zonal wind (m/s)

The stronger the upper-level shear, the more likely there is to be stratiform rain and anvil rain regions over Africa as observed by TRMM.

Li and Schumacher (2011)

How do stratiform rain and anvil regions persist?

- Convective sustainability
- Upper-level shear/hydrometeor advection
- Mid- and upper-level moisture

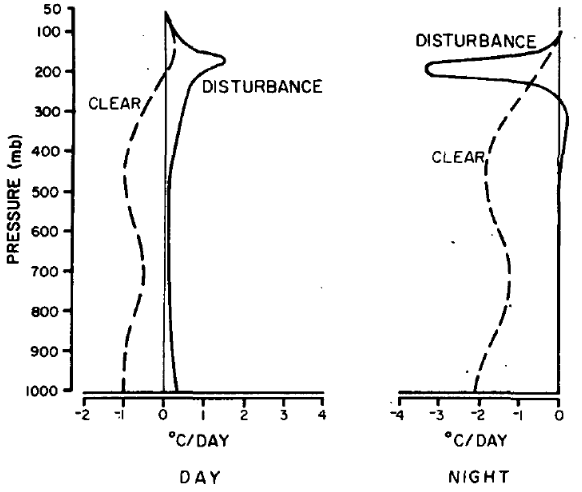


Lower-level RH is high prior to max rainfall, while upper-level RH lags rainfall maximum by ~6 h during KWAJEX.

Sobel et al. (2004)

How do stratiform rain and anvil regions persist?

- Convective sustainability
- Upper-level shear/hydrometeor advection
- Mid- and upper-level moisture
- Radiative feedbacks



For large, opaque disturbances

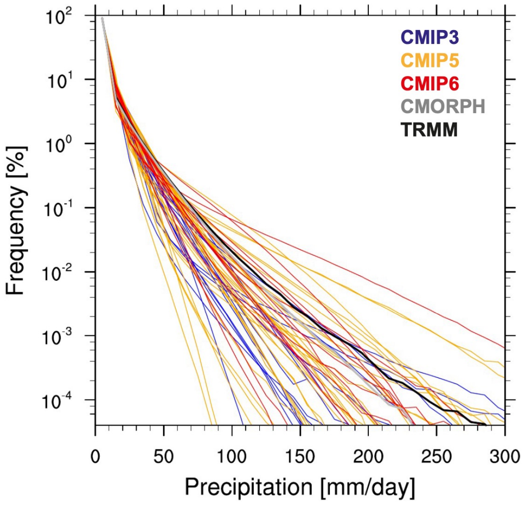
One possible explanation of the diurnal cycle of precipitation over ocean is the large-scale circulation anomaly caused by differential radiative heating between cloudy and cloud-free regions.

Gray and Jacobson (1977)

Global climate model rainfall

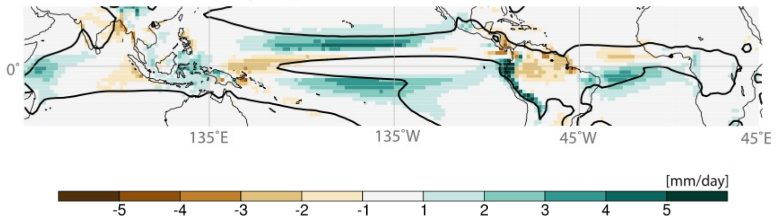
GCM rain biases

Tropical rain PDFs



- Almost all GCMs rain too often at light rain rates (the “drizzle” problem) and not enough at high rain rates from CMIP3 to CMIP6
- Geographical and diurnal biases have also persisted across the last three IPCC reports

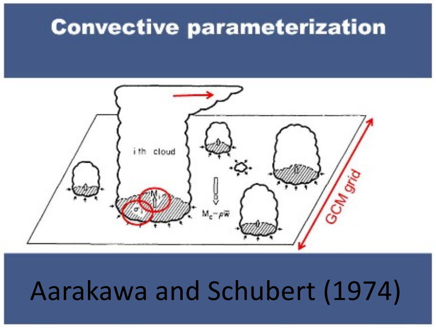
c) CMIP6 - TRMM (tropics)



Fiedler et al. (2020)

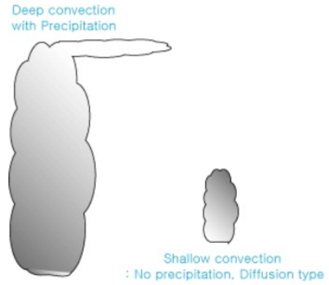
GCM precipitation physics

- GCMs generally have horizontal grids of O(100 km), which is too coarse to resolve convective clouds
- Convective parameterizations relate convective rain to the resolved state of the atmosphere



Convective parameterization

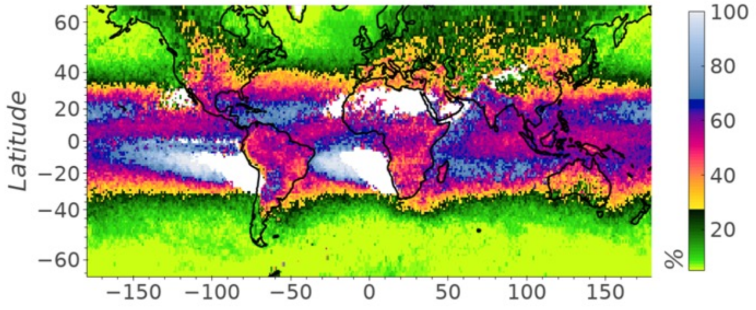
Aarakawa and Schubert (1974)

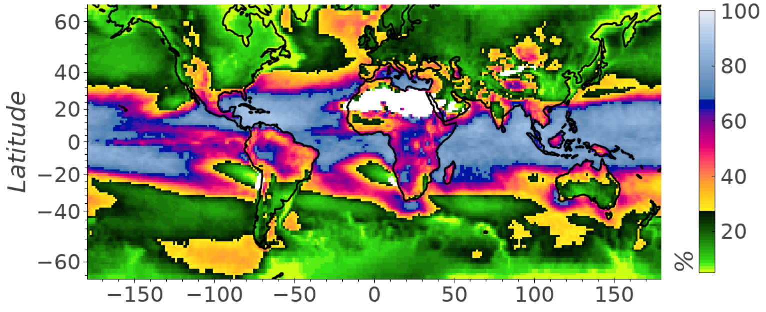


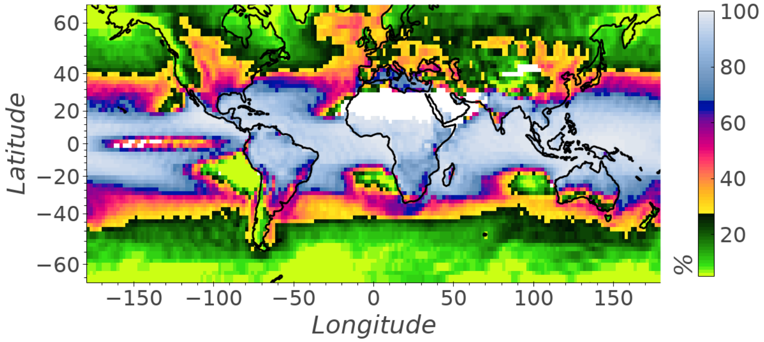
- Note absence of stratiform rain (which is not the same as detrained anvil at cloud top) and non-precipitating shallow cumulus
- The rest of a GCM’s precipitation is diagnosed through large-scale microphysics (again, not the same thing as stratiform rain formed from deep convection)

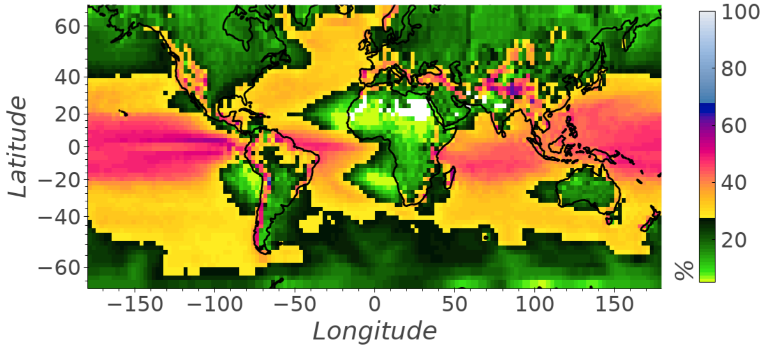
Convective rain fraction in CMIP6

GPM




CMIP6 GFDL Conv. Rainfall Fraction - Annual


CMIP6 MPI Conv. Rainfall Fraction - Annual


CMIP6 NASA Goddard Conv. Rainfall Fraction - Annual

Convection rain fractions can vary widely in GCMs. They generally either don’t “get” stratiform rain or have a different definition (likely a combination of both). But very few GCMs attempt to parameterize mesoscale organization.

Summary

- Mesoscale convective organization can be defined a number of ways, but stratiform rain is often an important contributor
- The impact of organized convective systems on the large scale can be quantified in terms of rain production and heating and moistening
- Multiple physical factors contribute to the organization of convection and maintenance of stratiform rain regions and these mechanisms should be considered in parameterizations of convection and organization