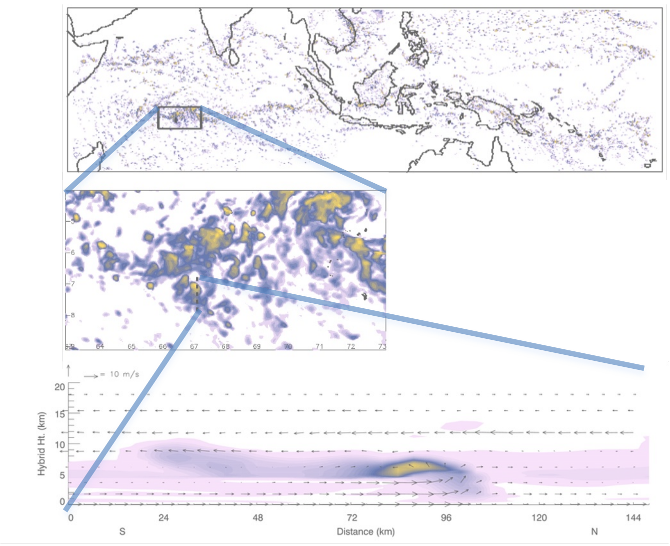

Scale Interactions in the Tropics

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FORTIS : Forecaster Training in Southeast Asia

This material was mostly prepared as part of the UK FORTIS training programme.

Outline

- Introduction (Objectives and Scope)
- Weak Temperature Gradient thinking
- Effects of equatorial waves and rotation
- Moist static energy budget
- Gross moist stability
- Moisture-convection interactions
- MJO and scale interaction (moisture mode theory)
- ITCZ
- ENSO
- Summary

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Learning Objectives

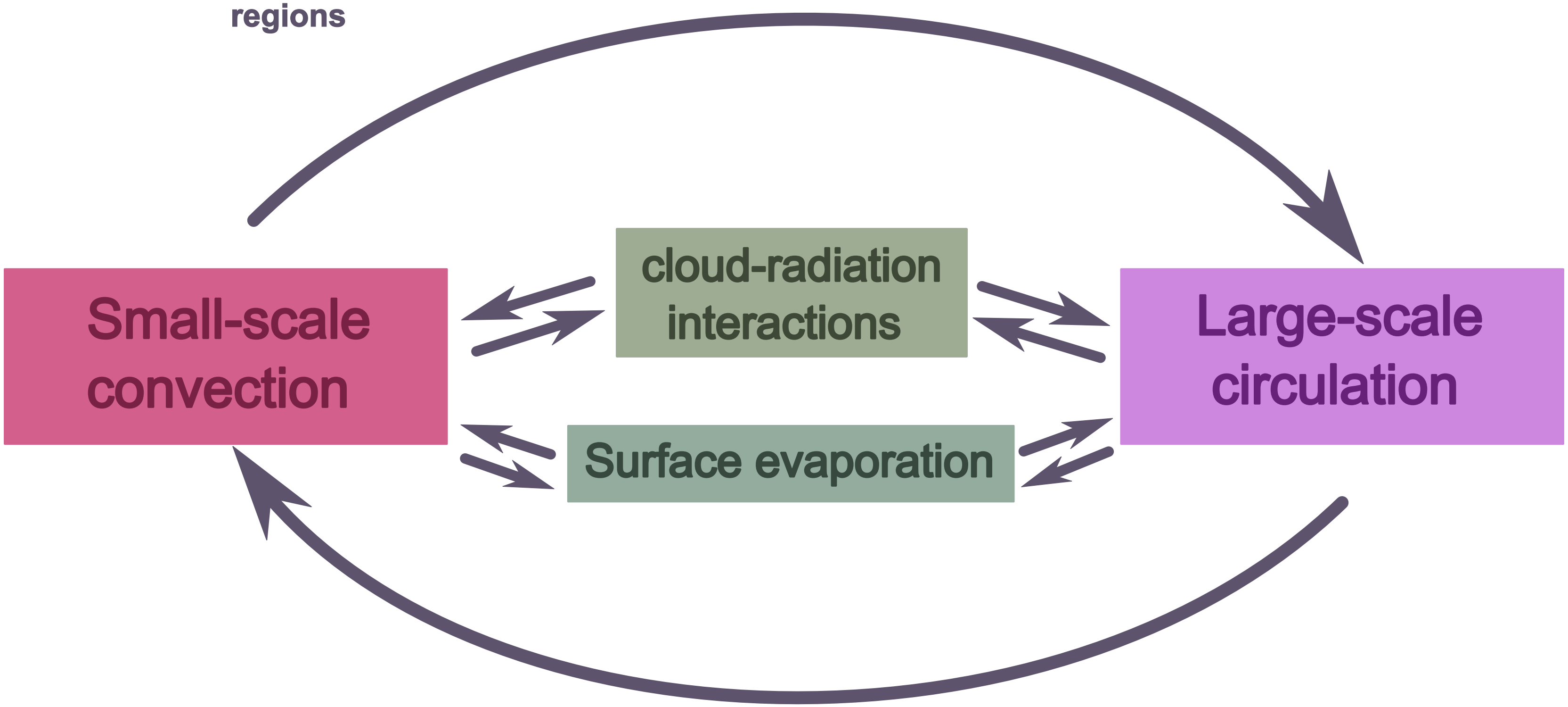
- Understand “weak temperature gradient” thinking and how this links cloud-scale convective heating to large-scale dynamics.
- Link weak temperature gradient thinking to the moist static energy budget as a useful way of investigating interactions between convection and larger scales.
- Apply this to a theory of the Madden-Julian Oscillation (MJO), an eastward-propagating tropical cloud/rain anomaly that is order 10,000 km in horizontal scale and has a period of 30-70 days.

Scope of lecture

- Focus on tropics: largest potential for scale interactions involving convective heating.
- Focus on atmospheric scale interactions: ocean interactions also play a role, but tend to be slower and add additional complexity to the problem.
- Focus on deep convection over oceanic regions: land surface effects, and orography (mountains) add additional scales and complications, though these are also important.

Schematic of scale interactions

Local convective latent heating initiates gravity waves that travel across long distances and warm surrounding regions via subsidence, with low-level convergence, mean ascent, and upper-level divergence centred on convective regions



Subsidence drying and warming can suppress convection in less favourable regions, while moisture advection and low-level convergence can favour convection

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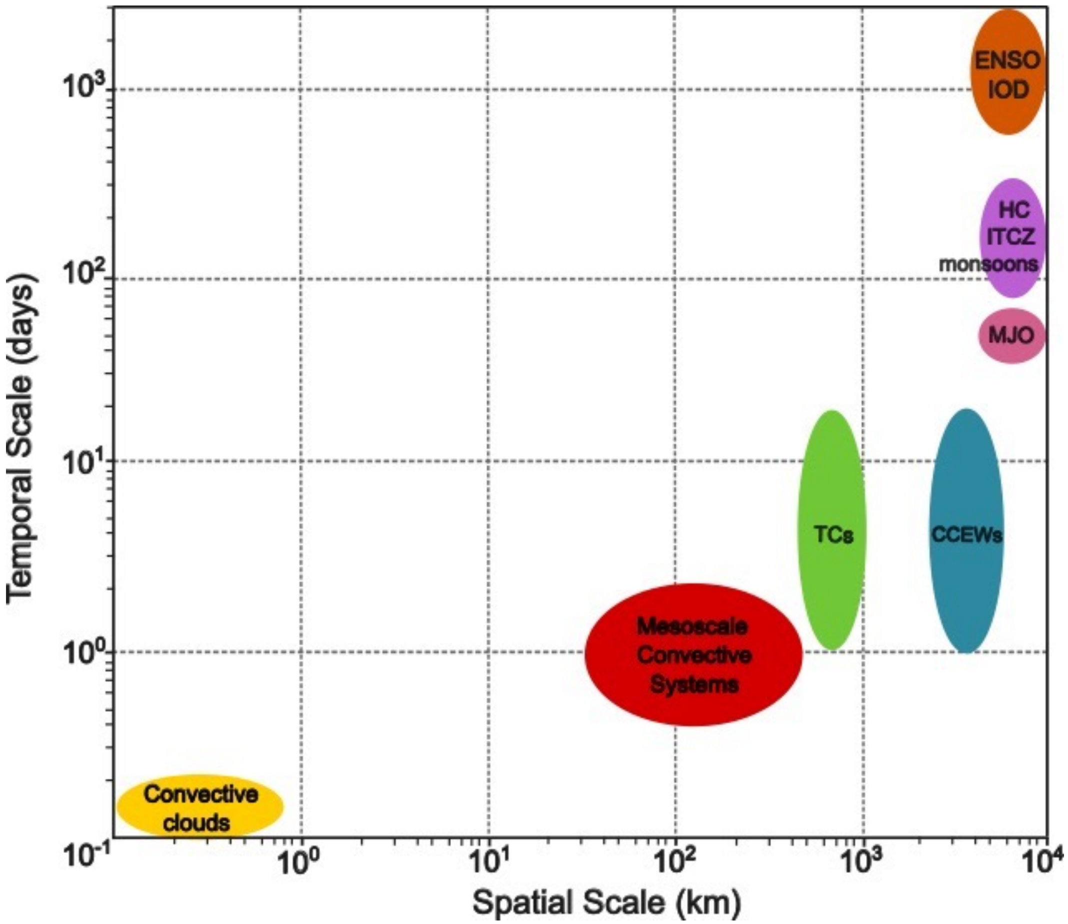
Temporal and Spatial Scales



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Weak Temperature Gradient Thinking

- In the tropics, the Coriolis parameter, f, is small.
- This has implications for the length scale of the region influenced by gravity waves acting to smooth out horizontal density gradients, the Rossby radius of deformation, L_R, defined as the distance at which **inertial flow speeds** equal **gravity wave speeds**:

$$f\, L_R = NH, \qquad L_R \equiv NH/f,$$

  where N is the Brunt Vaisala frequency (vertical dry static stability) and H is the height of the tropopause.
- For typical conditions $N \sim 10^{-2}$ s^{-1} and H ~10 km, then smaller $f \Rightarrow$ larger L_R.
- So in midlatitudes (45° latitude), L_R ~ 1,000 km.
- In the deep tropics (5° latitude), L_R ~ 8,000 km (in zonal direction)
- At the equator (0°), technically L_R becomes infinite in zonal direction, but roughly 3,000 km in meridional direction.

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Weak Temperature Gradient Thinking

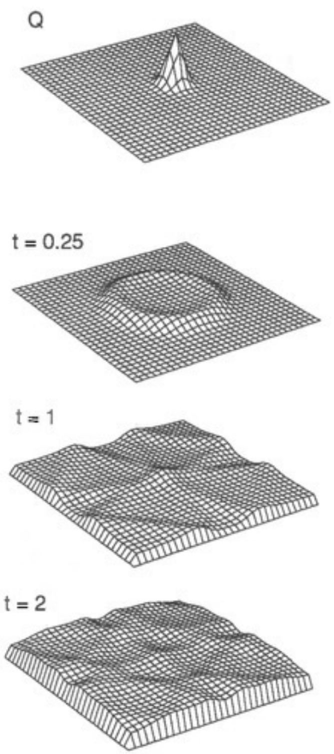

FIG. 5.3. Horizontal section at midheight of the buoyancy perturbation at three times due to a periodic array of heat sources turned on at $t = 0$. The first panel shows the Gaussian heat source; the times are in units of L/c_m.

Bretherton 1993

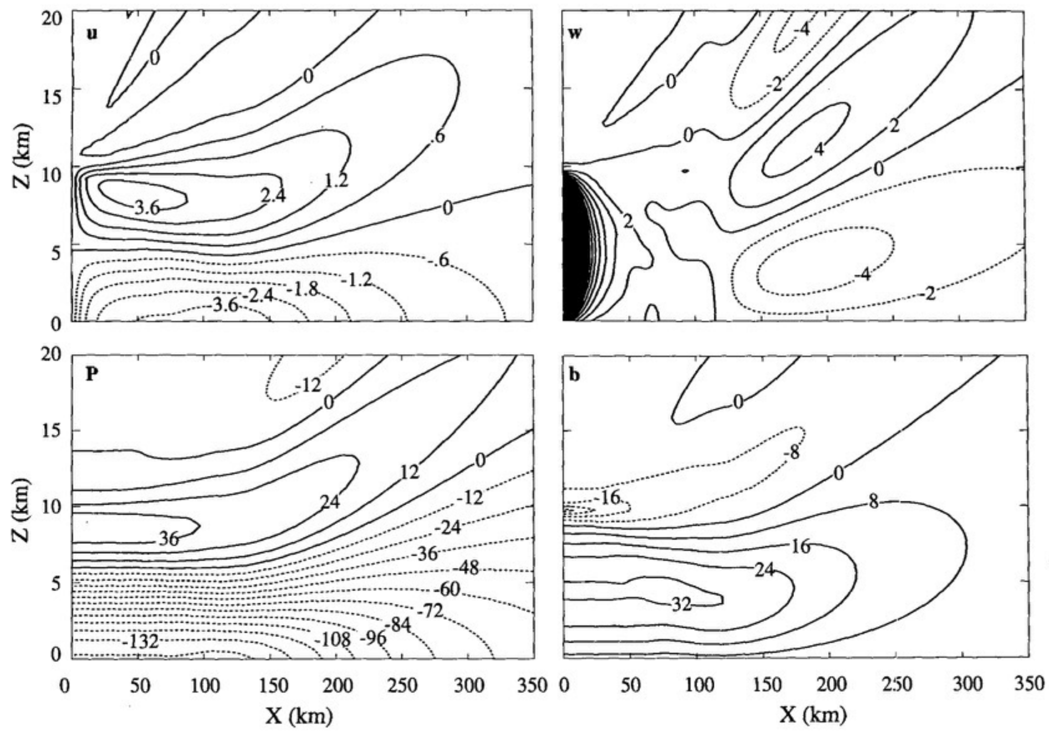

FIG. 1. Solutions for a semi-infinite domain. The contour intervals are 0.60 m s^{-1} for horizontal velocity (u), 0.02 m s^{-1} for vertical velocity (w), 12 Pa for pressure (P), and 0.008 m s^{-2} for the buoyancy field (b).

Pandya et al. 1993

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Weak Temperature Gradient Thinking

- We can write a form of the thermodynamic (potential temperature tendency) equation as follows:

$$\frac{\partial\theta}{\partial t} = -\vec{u}\cdot\nabla_{\mathrm{h}}\theta - w\frac{\partial\theta}{\partial z} + Q$$

  [Local change in θ = – horiz. advec. – vert. advec. + diabatic heating]

  where θ is potential temperature, $\vec{u}$ is the horizontal vector velocity, w is the vertical velocity, and Q is the diabatic heating (mainly from condensation or radiation).

- If we neglect horizontal advection and assume a steady state (completely eliminate temperature gradients altogether), the first two terms become zero and the thermodynamic equation becomes:

$$w\frac{\partial\theta}{\partial z} = Q$$

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Weak Temperature Gradient Thinking

$$w \frac{\partial \theta}{\partial z} = Q,$$ vertical advection = diabatic heating

$$w = Q \left(\frac{\partial \theta}{\partial z} \right)^{-1}$$

- Once we know Q (convective heating plus radiative cooling) and $\frac{\partial \theta}{\partial z}$ (which we assume is constant in the horizontal) we know the whole circulation: upward motion in regions of convection with divergence aloft and convergence below, and subsidence away from convective regions. The vertical profile shape of w tends to be similar to that of Q since $\frac{\partial \theta}{\partial z}$ varies less.
- In practice, convective heating does create temperature anomalies which propagate outward at gravity wave speeds, so it is better to assume a relaxation of horizontal temperature (or pressure) gradients over some finite time scale(s).
- However, we can see how convective heating can interact with the flow even at large distances in the tropics (and this flow in turn will affect the convection and the location of the heating).

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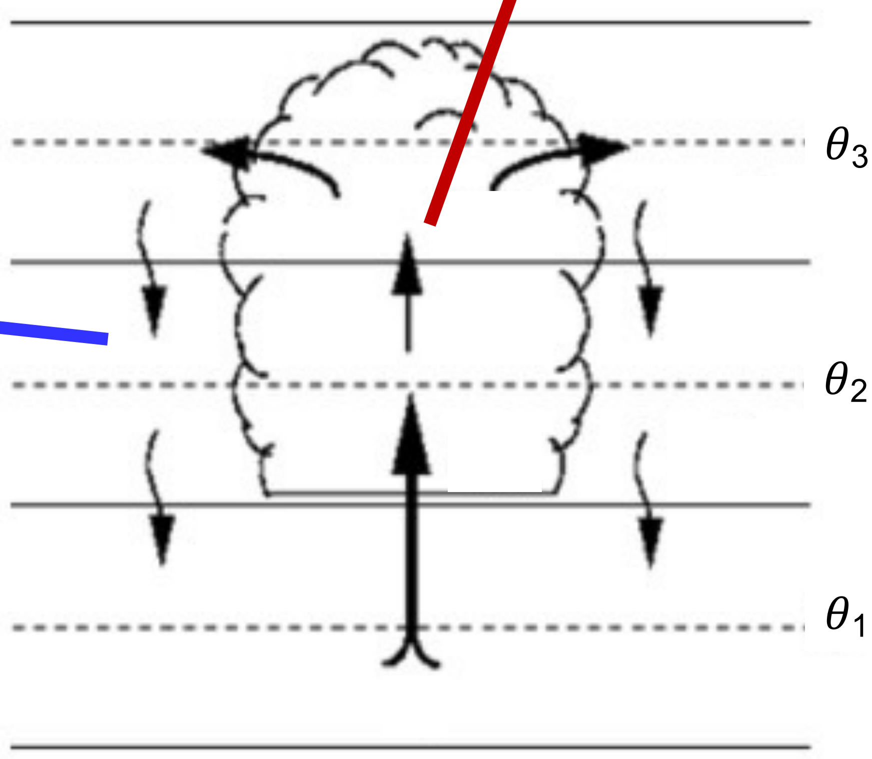
Weak Temperature Gradient Thinking

Inside clouds, latent heating plus smaller radiative cooling balanced by upward motion (cold vertical advection)

Outside clouds, radiative cooling balanced by subsidence (warm vertical advection)



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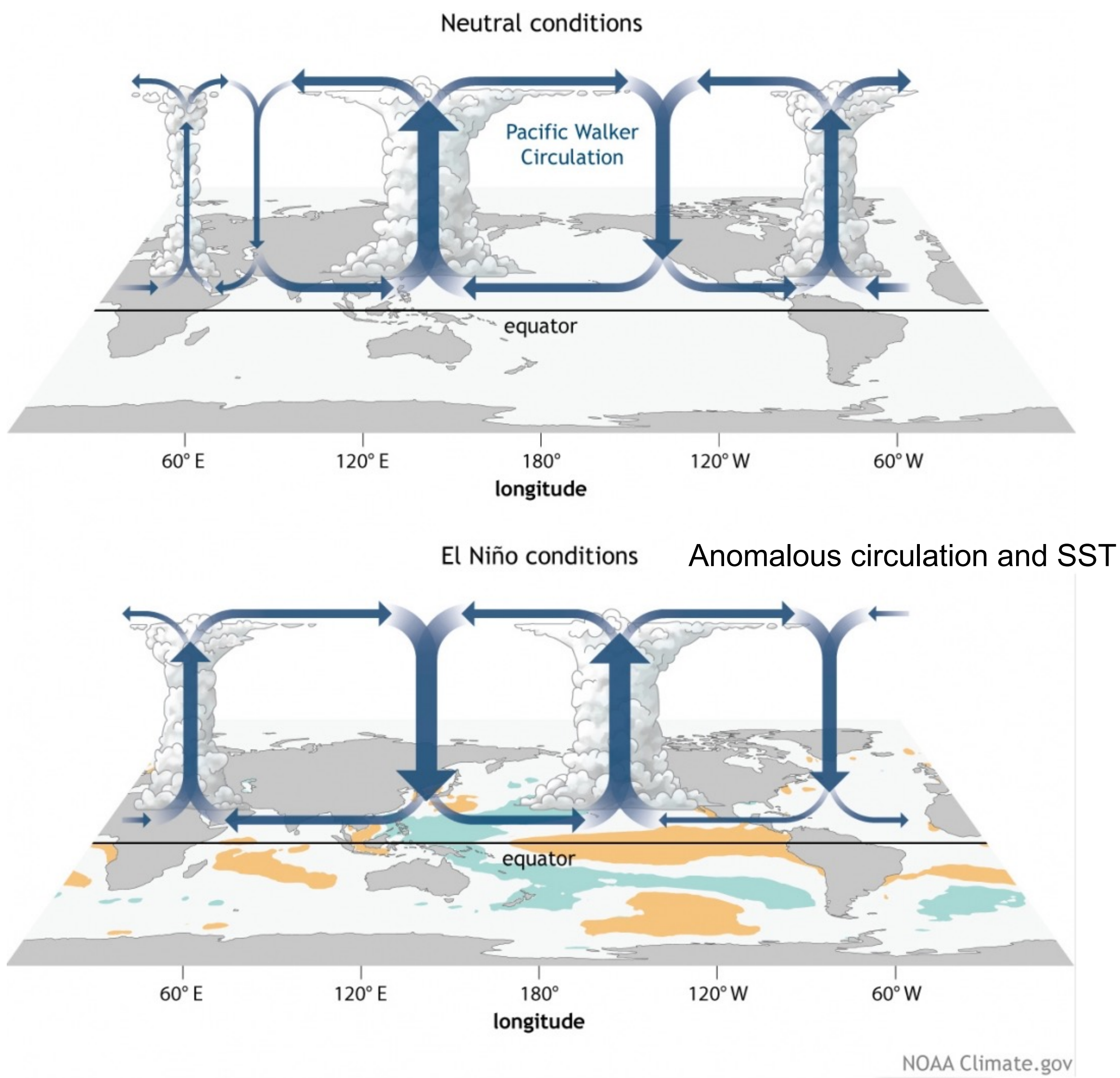
Weak Temperature Gradient Thinking

- Another way to think about convection-circulation interactions is that convection is competing with other convection for scarce resources (ultimately, the scarce resource is convective instability driven by surface solar warming and global atmospheric radiative cooling).
- This means that, across the global tropics, total diabatic heating "Q" is relatively constrained: favourable conditions that increase convection in one location result in less favourable conditions (e.g. by increased subsidence drying or a more stable mean temperature profile) in other locations.
- Weak temperature gradients mean this "competition" takes place over very large horizontal scales.

Weak Temperature Gradient Thinking

Warmer sea surface temperature (SST) in the eastern and central Pacific (El Niño, below) favour convection there, but "competition" helps reduce convection over the West Pacific warm pool.



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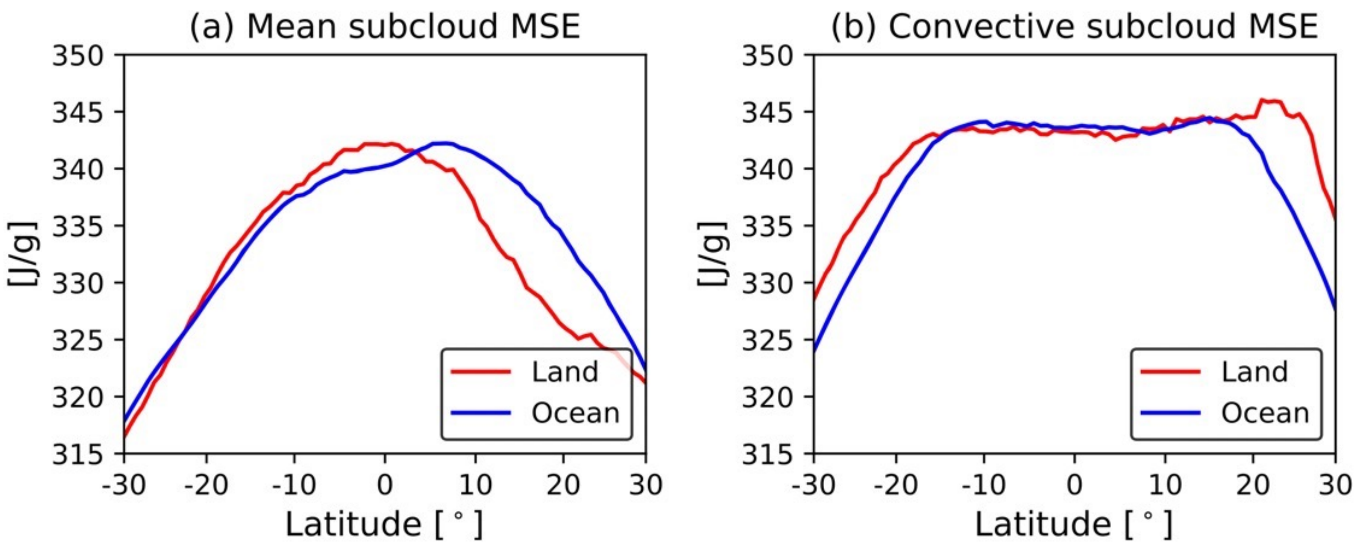
Weak Temperature Gradient Thinking

- Larger subcloud moist static energy (MSE) will provide more buoyancy for convective parcels, and thus convection is favoured in the regions with the highest subcloud MSE; these values then maintain the tropical mean temperature profile close to a moist adiabat tied to them.
- subcloud MSE is very similar across active deep-convective regions over both land and ocean over the whole tropics, even on daily time scales (see below).



Subcloud moist static energy from daily ERA-Interim data over 2001-2014 over land (red) and ocean (blue) for (a) zonal mean of all points, and (b) mean of points weighted by TRMM rainfall. Figure from Zhang and Fueglistaler 2020.

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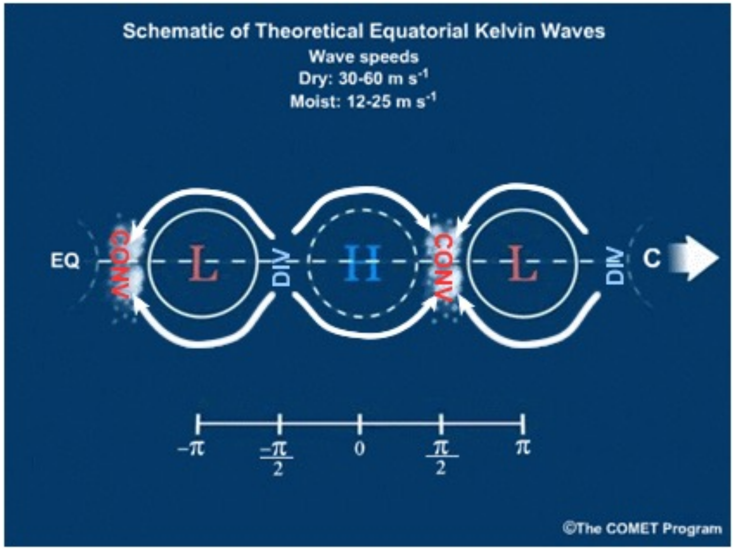
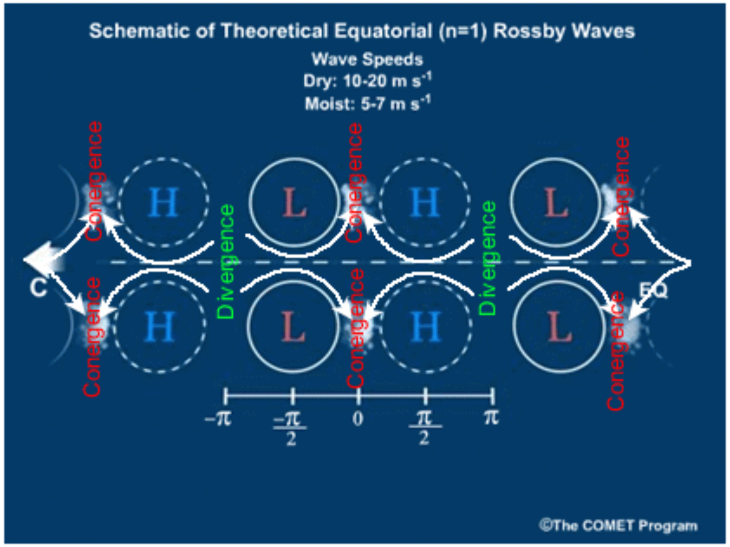
Equatorial waves

- In reality, $f \neq 0$ in general, and increases polewards: this means that diabatic heating actually communicates across the tropics mainly through equatorially trapped waves (e.g. Kelvin waves, Rossby waves).
- These waves still feature convergence and divergence patterns consistent with the heating but also have rotational flow and can lead to additional structures and patterns of convective organisation and propagation.





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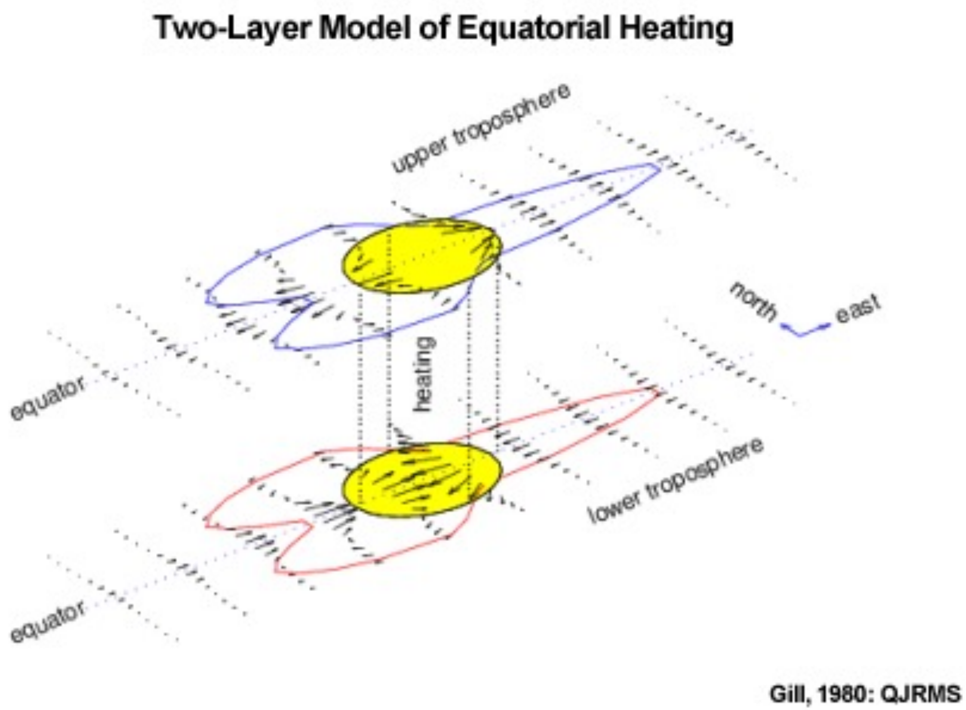
Equatorial waves

- Persistent convective heating in a large region can lead to quasi-stationary circulation patterns as waves interact with surface drag and the mean flow:



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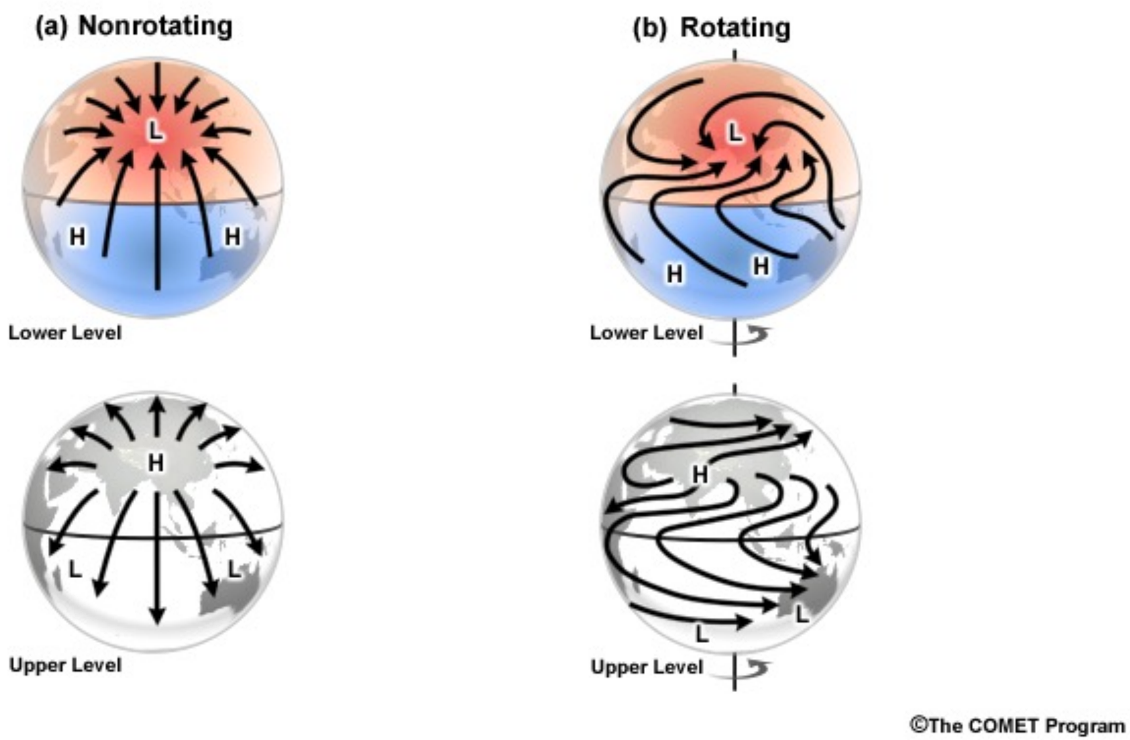
Rotation at large scales

- Earth's rotation has an effect on all large-scale circulations in the tropics. For example, this is a schematic of the Asian monsoon without and with rotation:



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Moist static energy (h) budget

- The moist static energy, h, can be defined as:

$$h \equiv c_p T + gz + L_v q$$

  where c_p is the specific heat of air at constant pressure, T is temperature, g is gravity, L_v is the latent heat of vaporization, and q is the specific humidity. h is approximately conserved for moist adiabatic motion and for condensation or evaporation of condensate.
- In combination with weak temperature gradient thinking, horizontal variations in h in the tropics are mainly related to horizontal variations in moisture (q).
- We are interested in h because, as we will see, large column-integrated h is related to regions of deep convection and rainfall.

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Moist static energy (h) budget

In the $\hat{h}$ budget, where $\hat{h}$ is the column (vertically) integrated moist static energy, warming and moistening a column have the same effect (but drying due to condensation/rainfall and warming due to latent heating cancel out):

$$\frac{\partial \hat{h}}{\partial t} = \mathrm{SEF} + \mathrm{NetSW} + \mathrm{NetLW} - \nabla_h \cdot \widehat{\vec{u}h}$$

where SEF is the total surface enthalpy flux (latent and sensible heat), NetSW and NetLW are the net atmospheric heating from shortwave and longwave radiation, respectively, and $\nabla_h \cdot \widehat{\vec{u}h}$ is the column integrated flux divergence.

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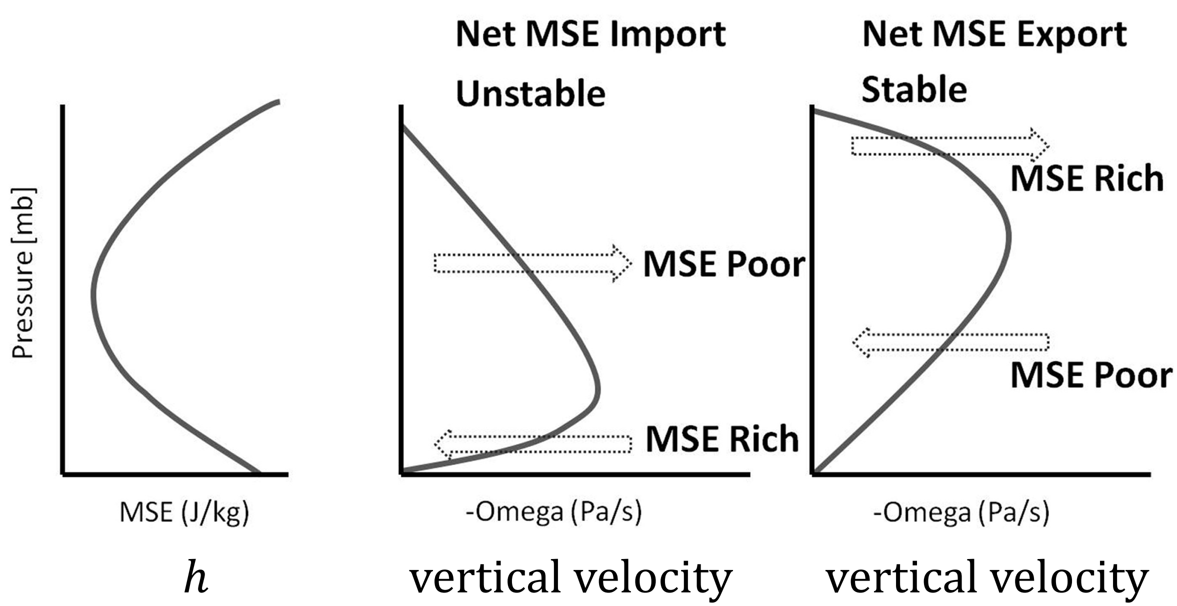
Gross moist stability

- "Gross moist stability" (Neelin and Held, 1987) essentially tells us about the net advective tendency of $\hat{h}$: is advection adding or removing $\hat{h}$ on the whole?
- Sometimes this is simplified to just the vertical advection (the overturning circulation when assuming no horizontal gradients), but horizontal advection can also be important.
- "bottom-heavy" convective heating can lead to low (or even negative) gross moist stability: the vertical structure of both heating (and thus vertical velocity) and h is important.

Inoue and Back 2015



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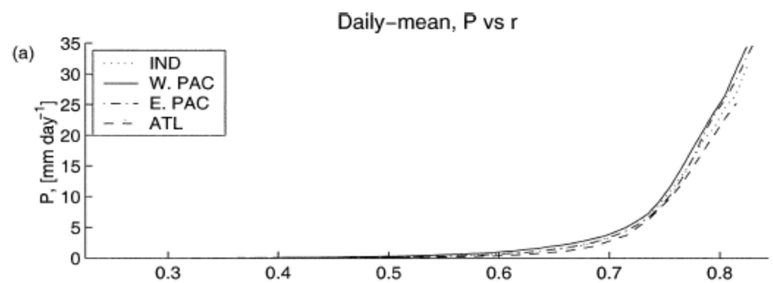
Moisture-convection interactions

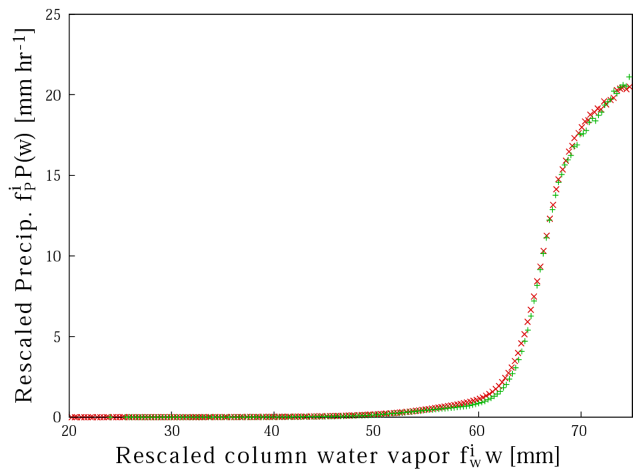
Observations show that large column water vapour, and thus large $\hat{h}$, is associated with convection and high rain rates:

Satellite data:

Bretherton et al. 2004



Peters and Neelin 2006



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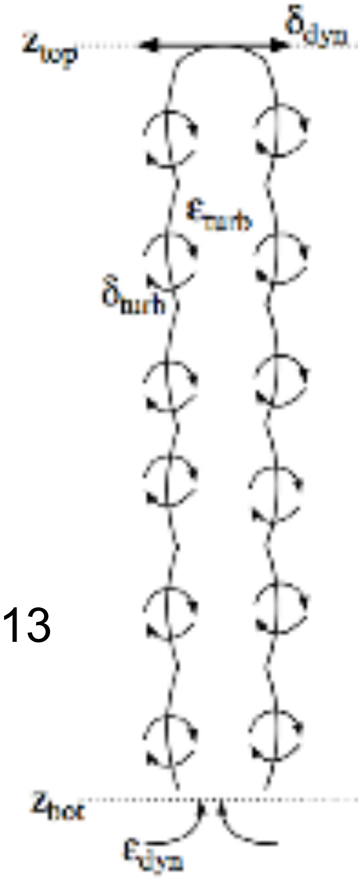
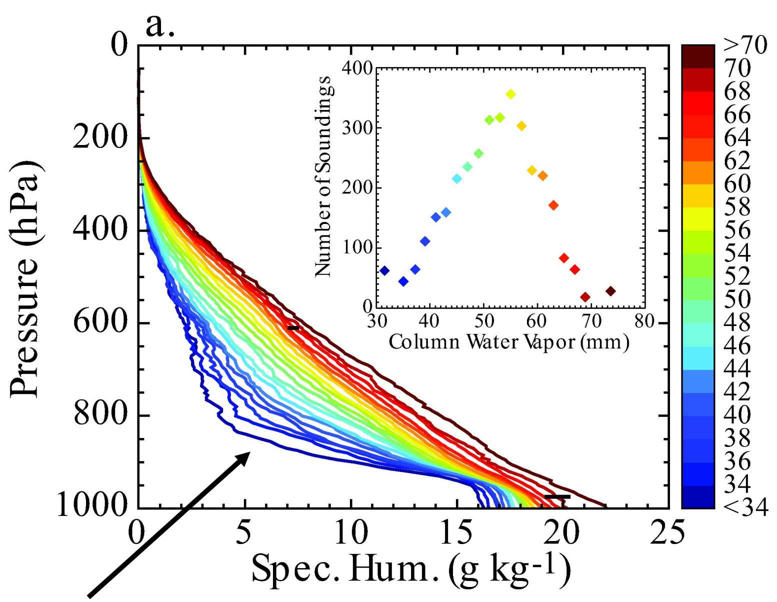
Moisture-convection interactions

Entrainment (mixing between clouds and their environments) means that moist, humid air in the lower-free troposphere favours convection while dry air will reduce buoyancy.



de Rooy et al. 2013



Column water vapor variance is dominated by moisture in the lower-free troposphere

Holloway and Neelin 2009

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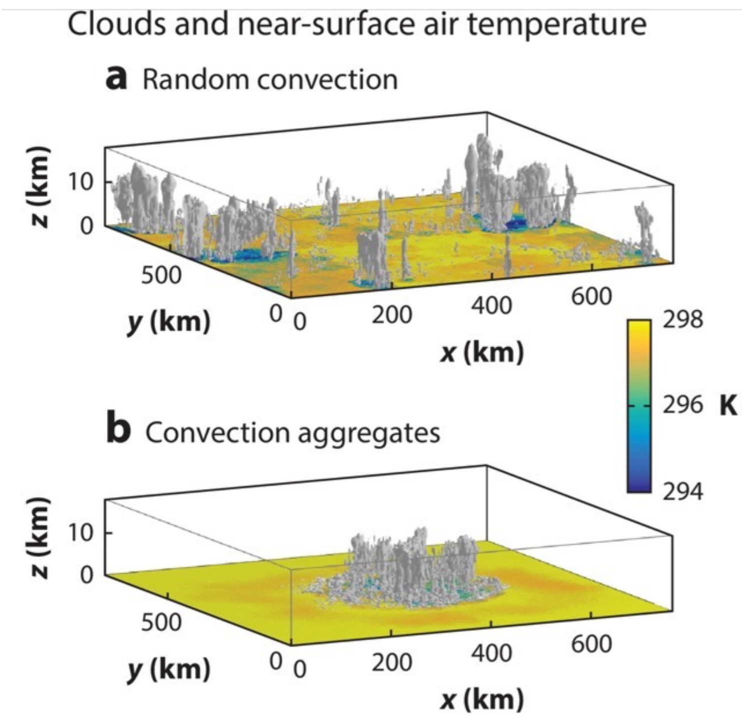
Convective self-aggregation

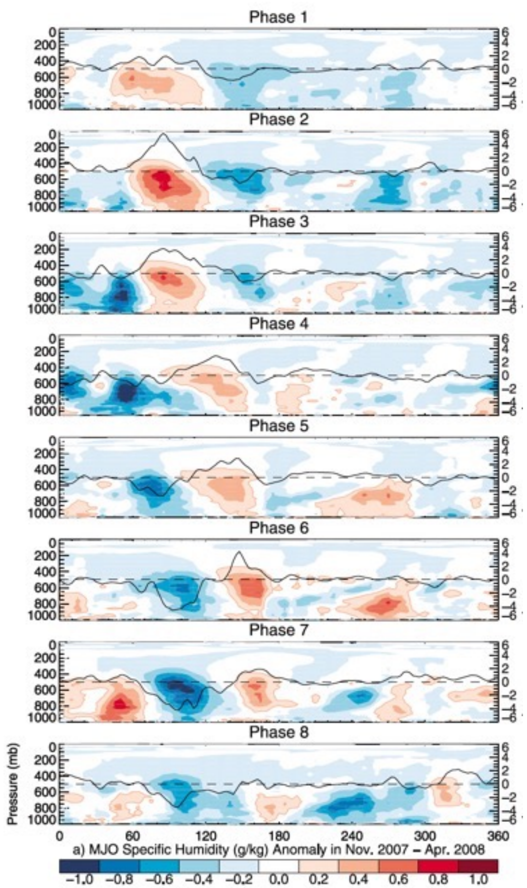
- idealised radiative convective equilibrium (RCE): constant SST, no land, no Coriolis force (no rotation), periodic lateral boundaries, convection permitting (~1-4 km grid)
- initially scattered rainfall becomes aggregated into one region
- linked to feedbacks between convective rainfall, tropospheric water vapor, radiation, and surface fluxes



Muller et al 2022

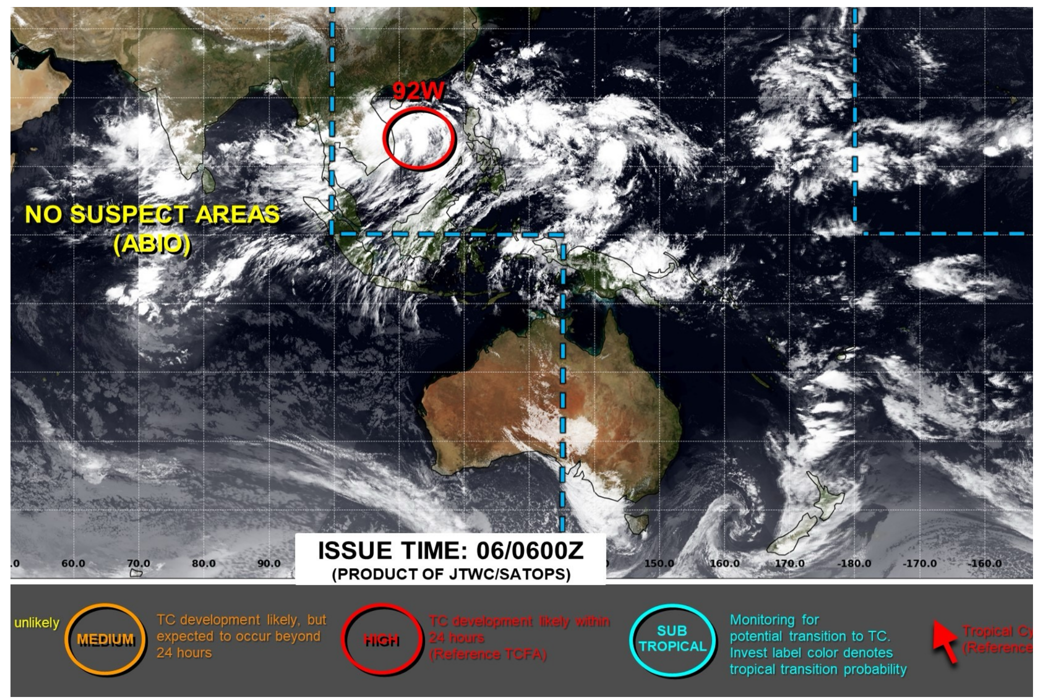
MJO

- According to one theory, the MJO is a large-scale “moisture mode” that propagates eastward along the equator, 30-70 day period (but intermittent):



Zeng et al. 2012

06 October 2021 JTWC satellite / TC risk



cloud cluster shapes and tilts may be important: e.g. vertical heating structures (gross moist stability) or convective momentum transport

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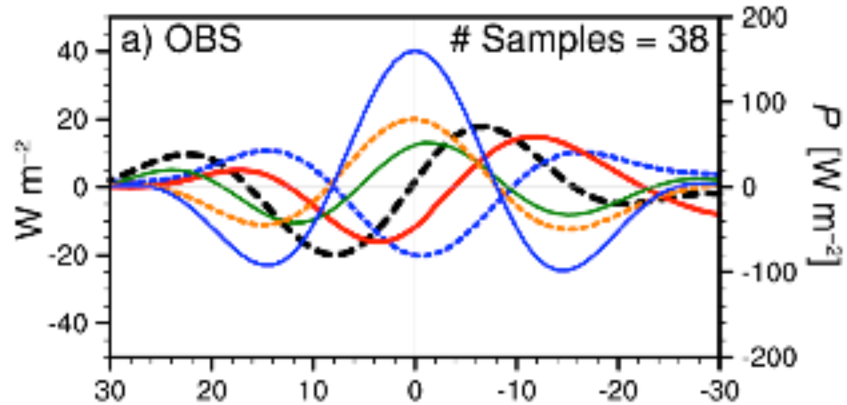
MJO: moisture mode theory

- Moist static energy budget: terms can in some cases cause large-scale growth of $\hat{h}$ (or similarly, of moist entropy), so the MJO is an instability of $\hat{h}$ in this sense.
- As we saw before, small-scale convective processes interact with this large-scale $\hat{h}$ instability.



Precip., moist entropy budget terms

	P	Precip.
	$[\mathrm{LW}]$	Radiation
	$\mathrm{LH} + \mathrm{SH}$	Surface Fluxes
	$-T_R[\mathbf{v} \cdot \nabla s]$	Horiz. transport
	$-T_R[\omega(\partial s / \partial p)]$	Vert. transport
	$T_R[\partial s / \partial t]$	Total change

Benedict et al. 2014

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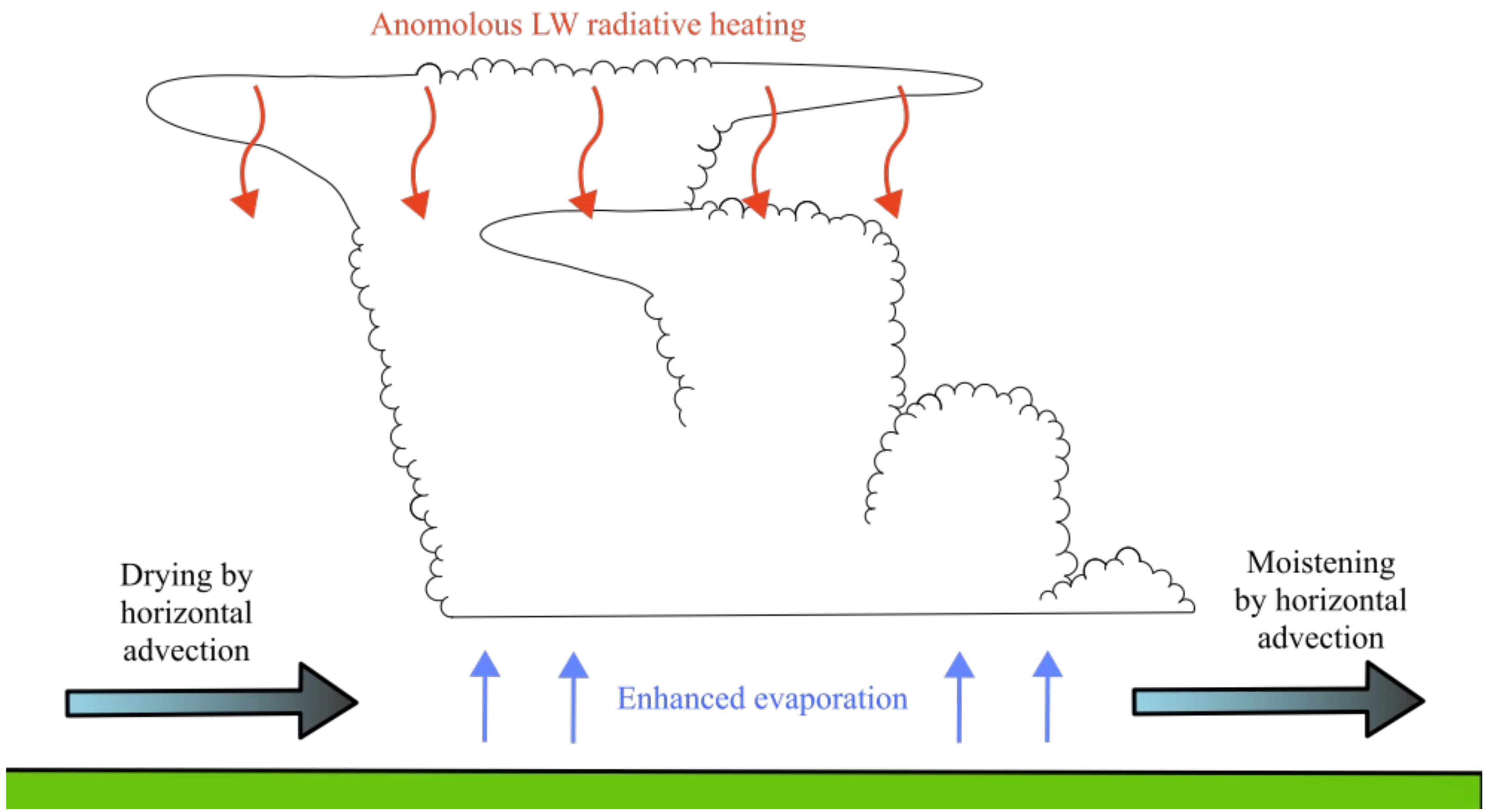
MJO: moisture mode theory



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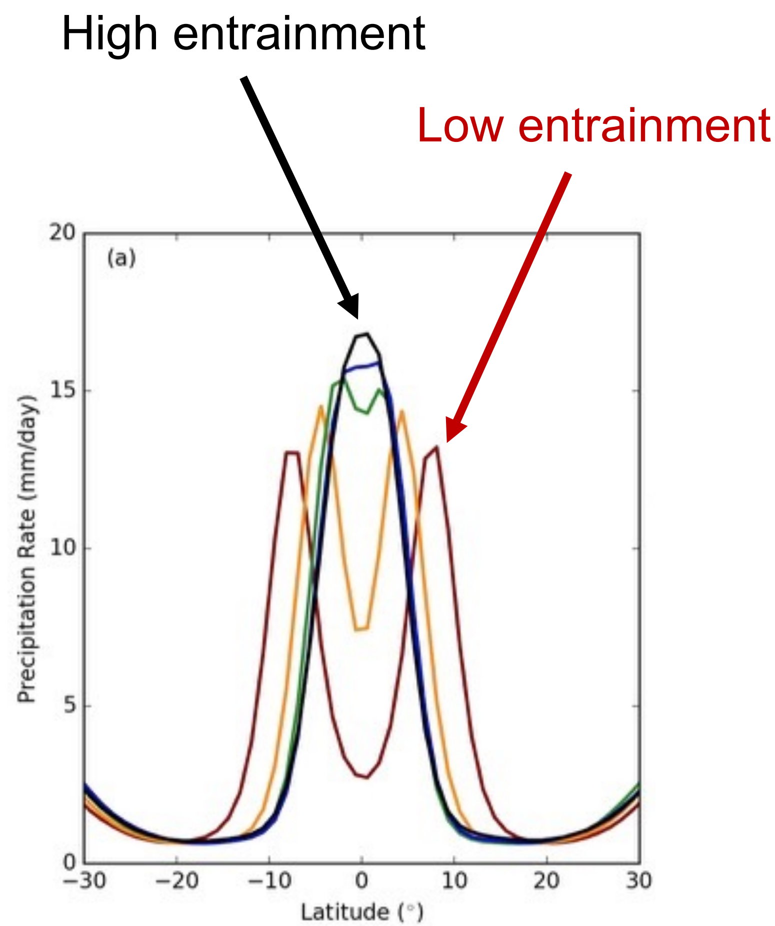
ITCZ: effect of entrainment and clouds

- Cloud radiative effect (mainly anomalous anvil longwave warming) helps maintain the ITCZ closer to the equator and be “sharper” and more intense (Harrop and Hartmann 2016), and the spread in model ITCZ position is related to tropical cloud radiative heating (Voigt et al. 2014).
- In GCMs, higher entrainment also pushes ITCZ closer to equator, and part (but not all) of this sensitivity appears to be due to this cloud radiative effect (Talib et al. 2018).
- Further feedbacks occur with low-level wind and surface evaporation (Möbis and Stevens 2012).



Talib et al. 2018

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ENSO

- Weak temperature gradients allow changes in SSTs to have large remote effects throughout the tropics (as mentioned above).
- Cloud and wind-evaporation feedbacks act to damp El Niño Southern Oscillation (ENSO), and the shortwave cloud effects in particular are a large source of model bias: models with poor ENSO simulation tend to have too-strong positive low-cloud feedbacks in the eastern Pacific (Lloyd et al. 2009, 2011).
- The MJO and other higher-frequency organised tropical convective features appear to be important in modifying ENSO.

Summary

- Small Coriolis force, and thus weak horizontal temperature gradients, allow convective heating to spread out and thereby couple with circulation across large scales in the tropics.
- The column-integrated moist static energy ($\hat{h}$) budget provides one view of how diabatic (evaporation, radiation) and advective processes can favour convection in some areas and consequently suppress convection in other areas: these processes are affected by the large-scale circulation as well as clouds and moisture.
- This, combined with weak temperature gradients and the effects of rotation (including equatorial waves), provides a framework of how convective and diabatic processes and the large-scale circulation interact across scales.
- Examples of these interactions shown in this lecture include the Madden-Julian Oscillation (MJO), the ITCZ, and ENSO.