# Theory-Based MJO Diagnostics[1]

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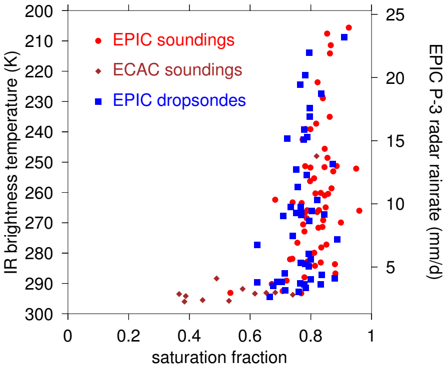
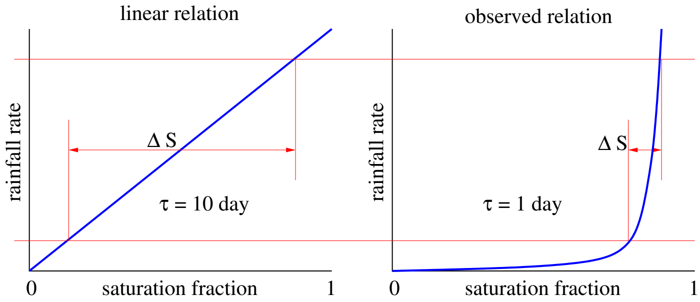
# Precipitation-saturation fraction relationship (Raymond, Sessions, and Fuchs 2007; see also Bretherton et al. 2004, Peters and Neelin 2006)



# Importance of steep dependence



$$S = W/W_{SAT} \qquad \tau = \Delta S W_{SAT}/E \qquad E = \rho C U(r_{SSS} - r_{BL})$$

$W$: precipitable water; $W_{SAT}$: saturated precipitable water; $S$: saturation fraction; $\tau$: moisture adjustment time; $E$: surface evaporation rate (given by bulk flux formula).

# Pressure integrated thermodynamic budgets

$$\frac{\partial [s]}{\partial t} + \nabla \cdot [s\mathbf{v}] = F_s - R$$

$$\frac{\partial [r]}{\partial t} + \nabla \cdot [r\mathbf{v}] = E - P$$

$$[\quad] = \frac{1}{g}\int (\quad)\, dp$$

$s \approx C_p \ln \theta + L r_v / T_R$: specific moist entropy (alternatively, moist static energy)

$r_v, r$: vapor and total cloud water mixing ratio

$F_s, R, E, P$: Surface entropy flux, integrated radiative entropy sink, surface evaporation rate, precipitation rate

# Gross moist stability (Raymond et al. 2009)

Normalized gross moist stability:

$$\begin{aligned}\Gamma &= -\frac{T_R \boldsymbol{\nabla} \cdot [s\mathbf{v}]}{L \boldsymbol{\nabla} \cdot [r\mathbf{v}]} \\ &= -\frac{T_R\left([\mathbf{v} \cdot \boldsymbol{\nabla} s] + [\omega(\partial s/\partial p)]\right)}{L \boldsymbol{\nabla} \cdot [r\mathbf{v}]} \\ &= \Gamma_H + \Gamma_V\end{aligned}$$

- Aside from different normalization, $\Gamma_V$ is closely related to original Neelin and Held (1987) gross moist stability.
- From time-steady ($\partial/\partial t = 0$) governing equations

$$\Gamma_{eq} = \frac{T_R\left(F_s - R\right)}{L\left(P - E\right)}$$

in steady state.

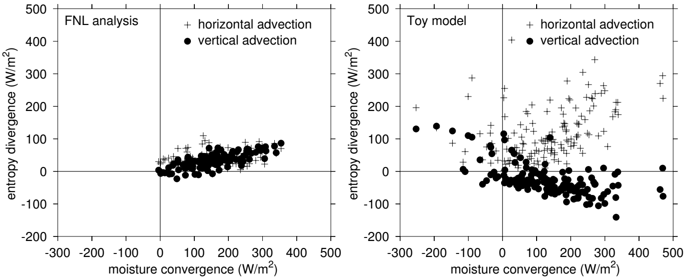
# Reference frame dependence of $\Gamma$

- The normalized gross moist stability $\Gamma$ is not invariant under Galilean transformations, i. e., in general

$$\Gamma(\boldsymbol{v} - \boldsymbol{U}_{trans}) \neq \Gamma(\boldsymbol{v}).$$

- To evaluate the gross moist stability for a geographical region, evaluate in earth-relative reference frame.
- For a moving system (such as a tropical cyclone or an easterly wave) evaluate in the reference frame of the moving system.

# Examples of $\Gamma_H$ and $\Gamma_V$ in west Pacific – slope represents $\Gamma_{H,V}$ in each case (Raymond and Fuchs 2009)

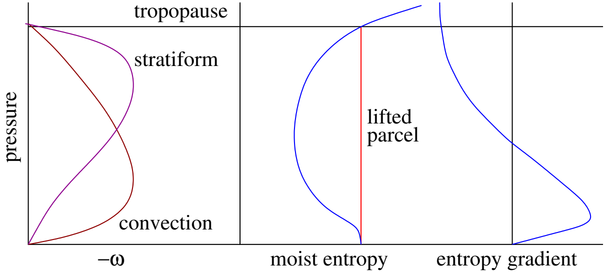


$\Gamma_{H,V}$ is the slope of the fitted line in each case.

# Gross moist stability ($\Gamma_V$) – what determines it?

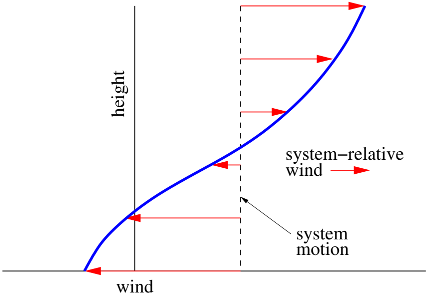
- $\Gamma_V$ is a function of both the environmental profiles of temperature and humidity, radiative cooling profile, and the vertical mass flux profile.
- In addition, $\Gamma_H$ depends on the system-relative winds profile.
- However, the vertical mass flux profile is a function of the environmental profiles and surface heat and moisture fluxes.
- Thus, indirectly, $\Gamma_V$ and $\Gamma_H$ are functions of environmental profiles, radiative cooling profile, and surface fluxes.

# $\Gamma_V$ and the vertical mass flux and environmental profiles (Raymond et al. 2009)



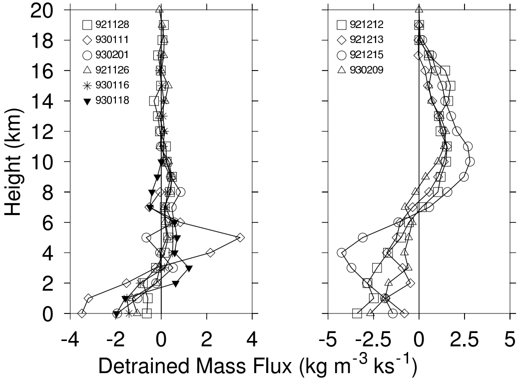
- $[\omega(\partial s/\partial p)]$ for stratiform profile (top-heavy) is greater than for convective profile (bottom-heavy).
- $[\omega(\partial s/\partial p)]$ may even be negative for bottom-heavy profile.

# $\Gamma_H$ and the wind profile



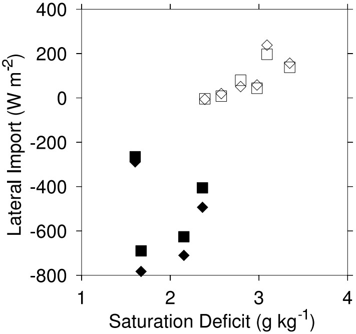
- Wind relative to the system of interest (which may or may not be stationary) can export moist entropy, resulting in $\Gamma_H > 0$.
- Positive $\Gamma_H$ can stabilize a system with negative $\Gamma_V$, since $\Gamma = \Gamma_H + \Gamma_V$ is what counts for rainfall production. (Think of tropical storm in shear.)

# Examples from Western Pacific – weak and strong convection (López Carrillo and Raymond 2005)



Left panel shows cases with low levels of non-divergence; right panel show cases with higher levels.

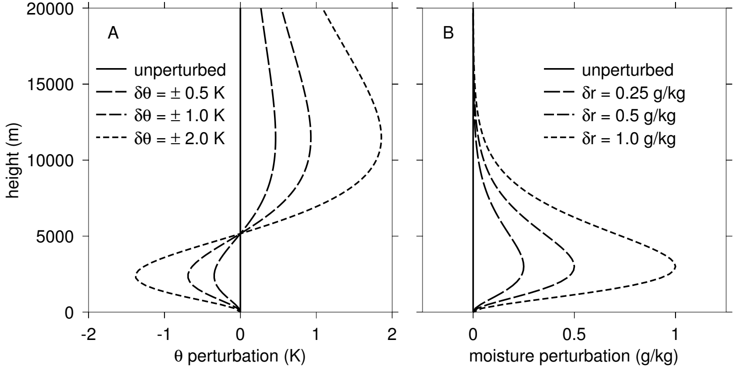
# Lateral entropy (or moist static energy) import



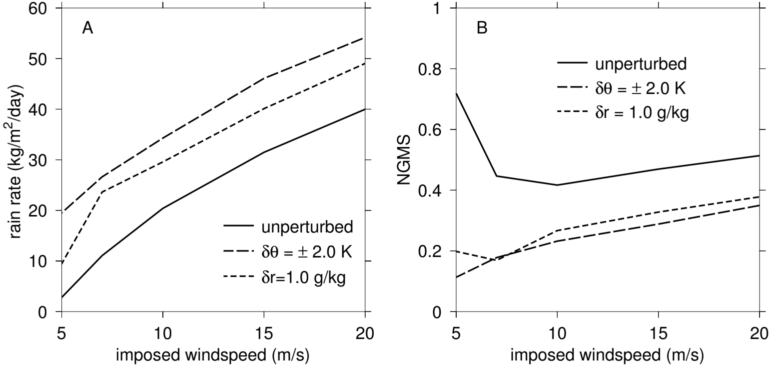
Open symbols correspond to left panel while solid symbols correspond to right panel in previous graphic. Fomer cases exhibit zero or negative $\Gamma_V$.

- Equilibrium is stable if $\Gamma > 0$.
- Equilibrium is unstable if $\Gamma < 0$.
- Negative gross moist stability is necessarily transient.

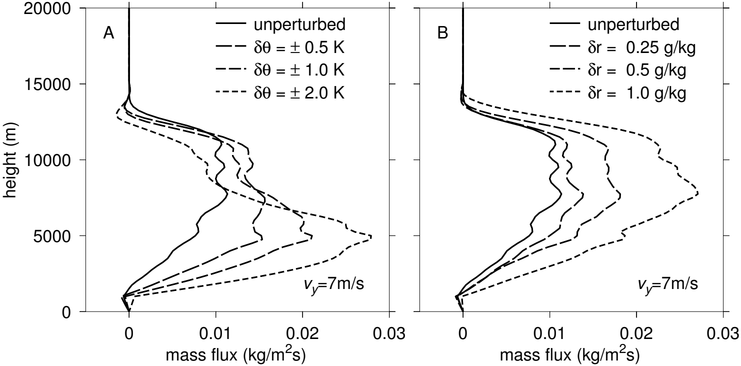
# Equilibrium cloud resolving model results in WTG mode with altered reference profiles (Raymond and Sessions 2007)



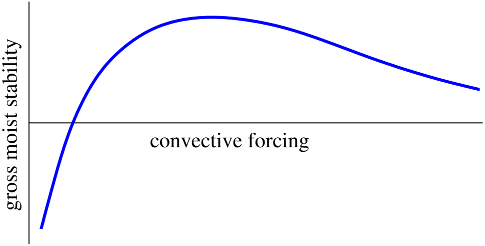
# Moister and more stable environments produce smaller $\Gamma_V$ and more rain



# Increased environmental stability makes convection more "bottom-heavy"



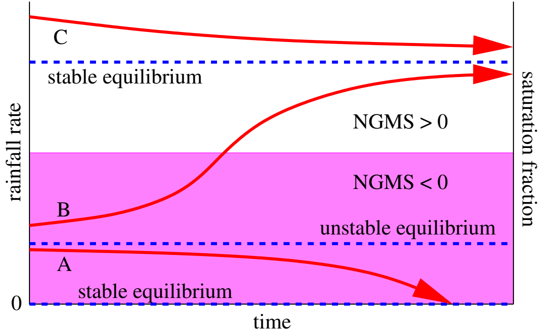
# Tentative summary



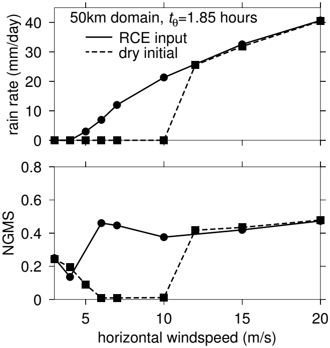
Enhanced convective forcing includes

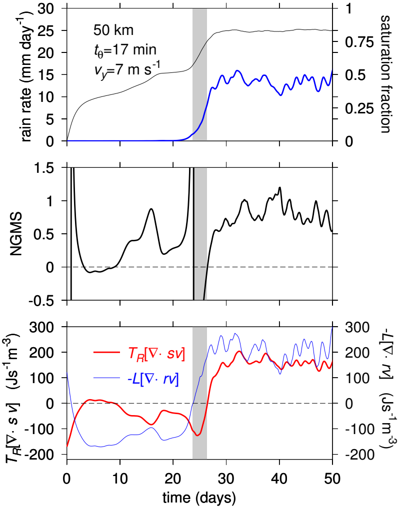
- stronger surface moist entropy flux
- moister environment
- more stable environment (but CAPE still positive).

# Stable and unstable equilibria (Raymond et al. 2009)



# Multiple convective equilibria (Sessions et al. 2010)





# Recommendations

- Tropical oceanic precipitation in global models should exhibit a steep dependence of precipitation on saturation fraction – needed to get correct convective adjustment time scale.
- Models also need to get right the dependence of gross moist stability on environmental conditions.
- More cloud-resolving modeling and observational work is needed to pin down this dependence.
- Model reanalysis schemes are not to be trusted to reproduce correctly the gross moist stability (especially $\Gamma_V$) since this quantity is strongly affected by model biases.