Theory-Based MJO Diagnostics[1]

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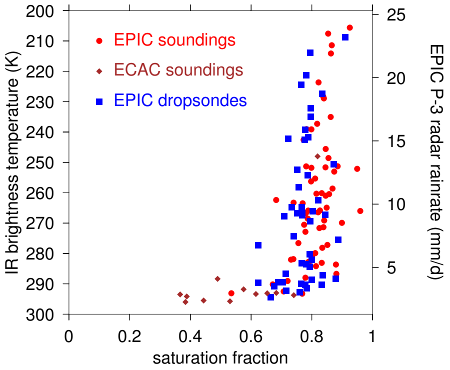
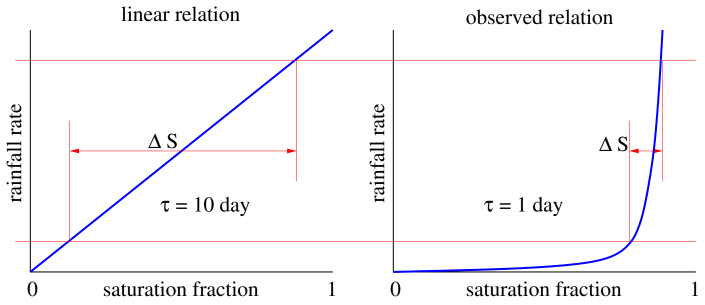
Precipitation-saturation fraction relationship (Raymond, Sessions, and Fuchs 2007; see also Bretherton et al. 2004, Peters and Neelin 2006)



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; τ: moisture adjustment time; E: surface evaporation rate (given by bulk flux formula).

Pressure integrated thermodynamic budgets

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

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

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

$s \approx C_p \ln \theta + L r_v / T_R$: 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:

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

- Aside from different normalization, Γ_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.

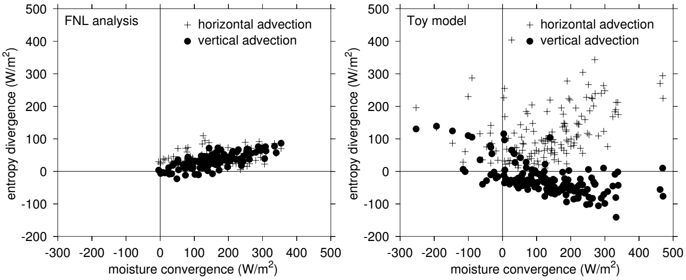
Reference frame dependence of Γ

- The normalized gross moist stability Γ 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 Γ_H and Γ_V in west Pacific – slope represents $\Gamma_{H,V}$ in each case (Raymond and Fuchs 2009)

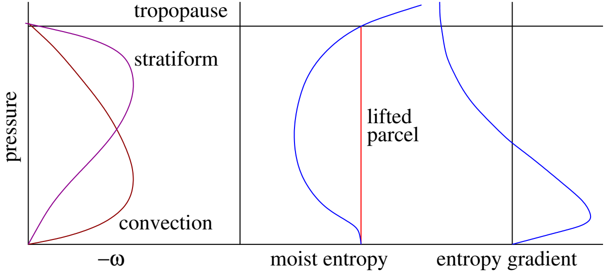


$\Gamma_{H,V}$ is the slope of the fitted line in each case.

Gross moist stability (Γ_V) – what determines it?

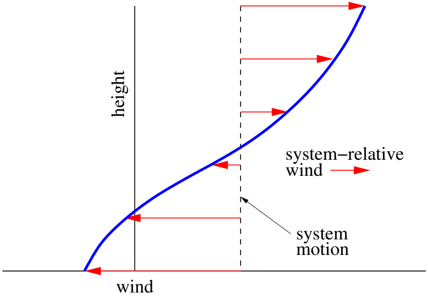
- Γ_V is a function of both the environmental profiles of temperature and humidity, radiative cooling profile, and the vertical mass flux profile.
- In addition, Γ_H depends on the system-relative winds profile.
- However, the vertical mass flux profile is a function of the environmental profiles and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

Γ_V and the vertical mass flux and environmental profiles (Raymond et al. 2009)



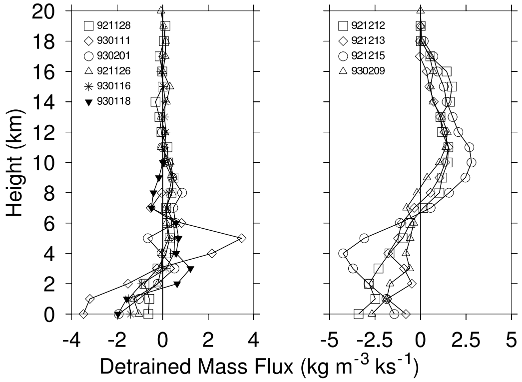
- $[\omega(\partial s/\partial p)]$ for stratiform profile (top-heavy) is greater than for convective profile (bottom-heavy).
- $[\omega(\partial s/\partial p)]$ may even be negative for bottom-heavy profile.

Γ_H and the wind profile



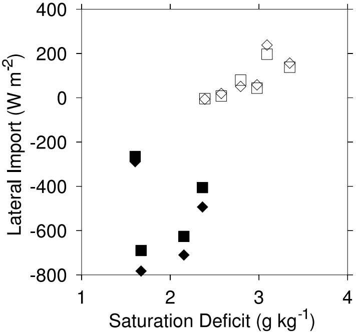
- Wind relative to the system of interest (which may or may not be stationary) can export moist entropy, resulting in $\Gamma_H > 0$.
- Positive Γ_H can stabilize a system with negative Γ_V, since $\Gamma = \Gamma_H + \Gamma_V$ is what counts for rainfall production. (Think of tropical storm in shear.)

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.

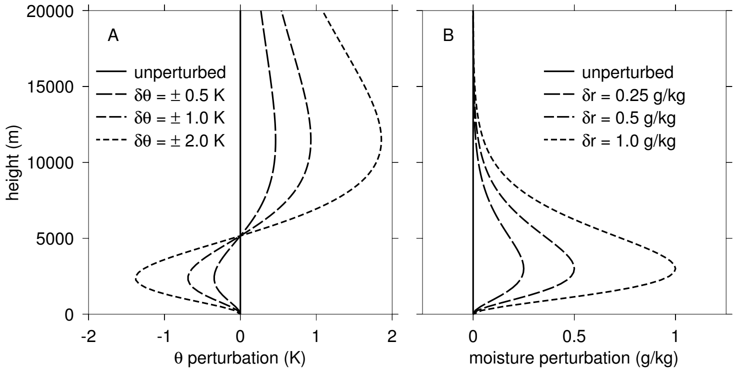
Lateral entropy (or moist static energy) import



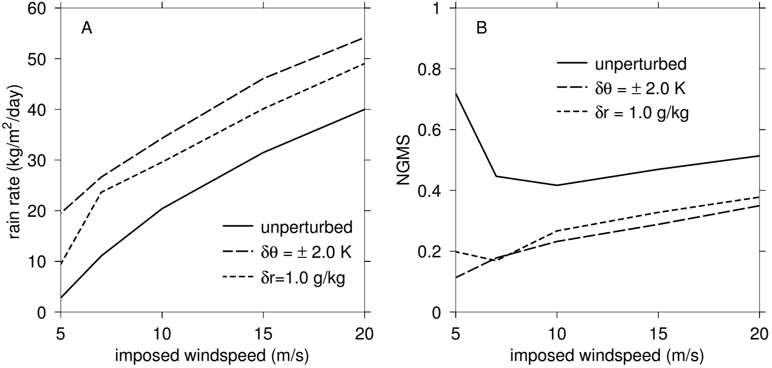
Open symbols correspond to left panel while solid symbols correspond to right panel in previous graphic. Fomer cases exhibit zero or negative Γ_V.

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

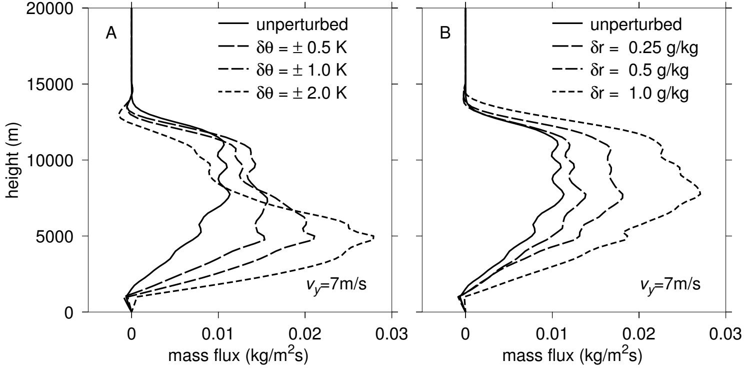
Equilibrium cloud resolving model results in WTG mode with altered reference profiles (Raymond and Sessions 2007)



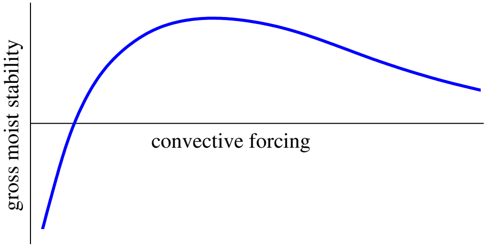
Moister and more stable environments produce smaller Γ_V and more rain



Increased environmental stability makes convection more "bottom-heavy"



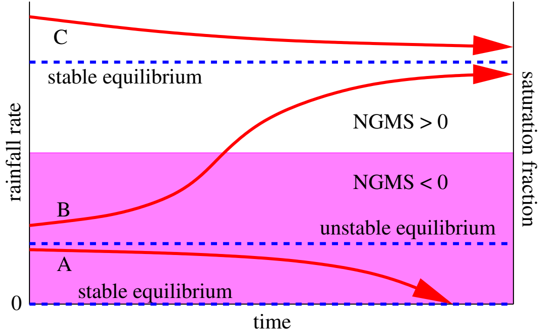
Tentative summary



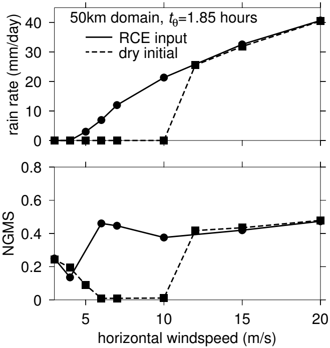
Enhanced convective forcing includes

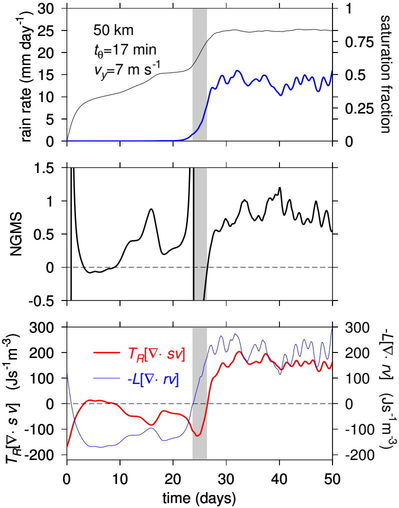
- stronger surface moist entropy flux
- moister environment
- more stable environment (but CAPE still positive).

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 Γ_V) since this quantity is strongly affected by model biases.