Thermodynamics of Tropical Cyclogenesis[1]

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Collaborators

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Flux Form of Vorticity Equation (Haynes and McIntyre 1987)

Vertical component of absolute vorticity:

$$\frac{\partial \zeta_z}{\partial t} + \nabla_h \cdot \boldsymbol{Z} + \hat{\boldsymbol{k}} \cdot \nabla_h \theta \times \nabla_h \Pi = 0$$

Horizontal flux of vertical vorticity:

$$\boldsymbol{Z} = \boldsymbol{Z}_1 + \boldsymbol{Z}_2 + \boldsymbol{Z}_f = \boldsymbol{v}_h \zeta_z - \boldsymbol{\zeta}_h v_z + \hat{\boldsymbol{k}} \times \boldsymbol{F}$$

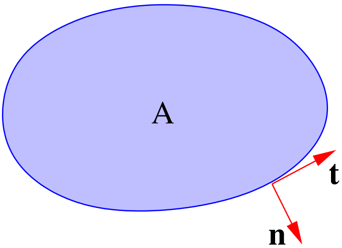
Vertical component of baroclinic generation (ignore):

$$\hat{\boldsymbol{k}} \cdot \nabla_h \theta \times \nabla_h \Pi \approx 0$$

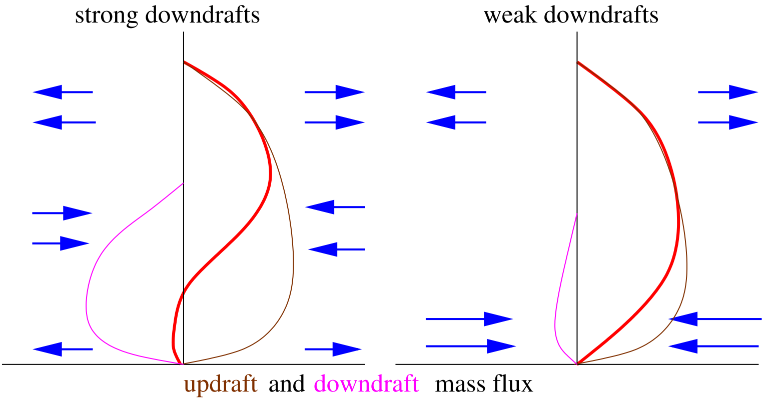
Circulation Tendency Equation

$$\frac{d\Gamma}{dt} = -\oint v_n \zeta_z dl + \oint \zeta_n v_z dl + \oint F_t dl$$

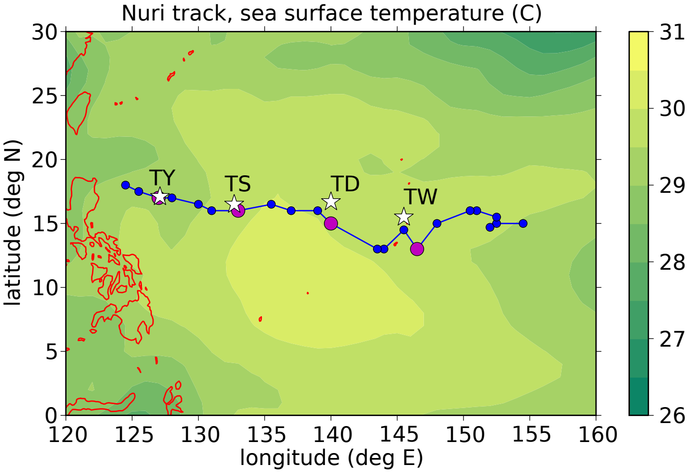
$$\Gamma = \int \zeta_z dA$$



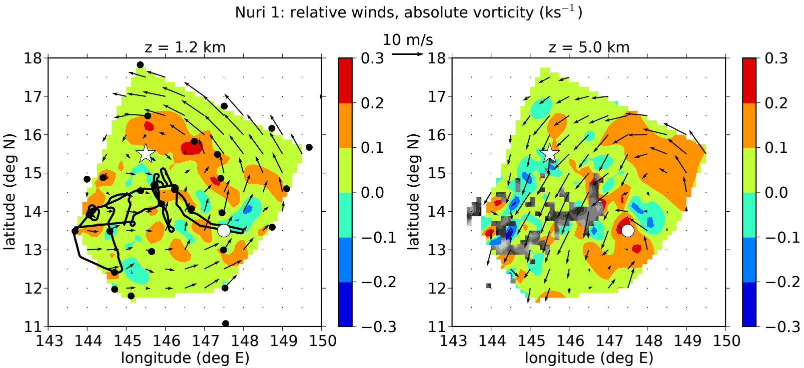
Top and bottom-heavy mass flux profiles



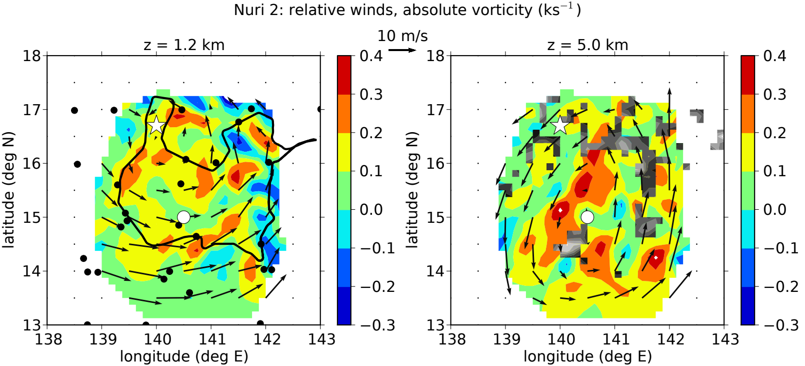
Typhoon Nuri overview



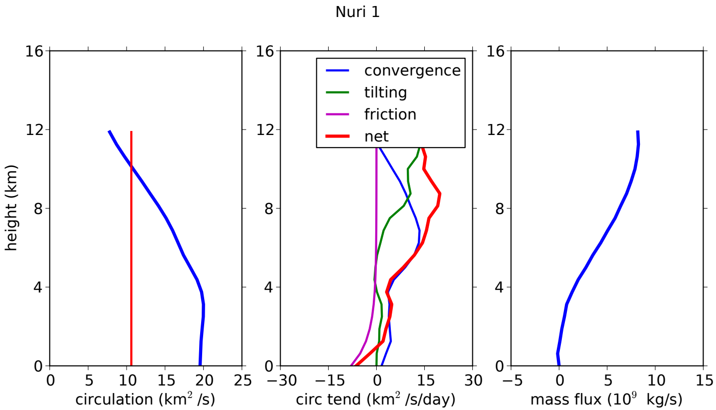
Nuri 1 (tropical wave)



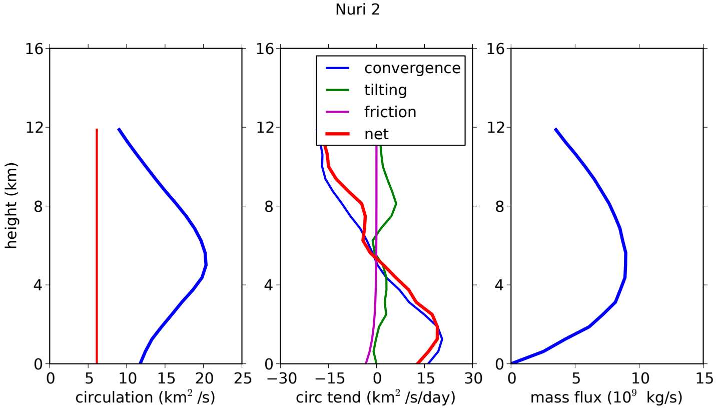
Nuri 2 (tropical depression)



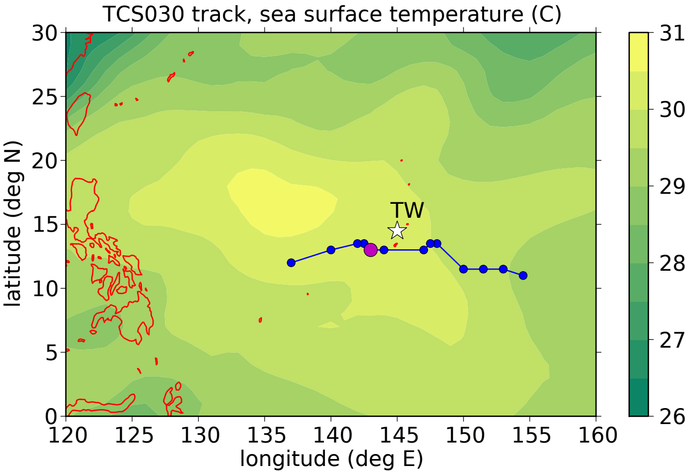
Nuri 1 vorticity budget



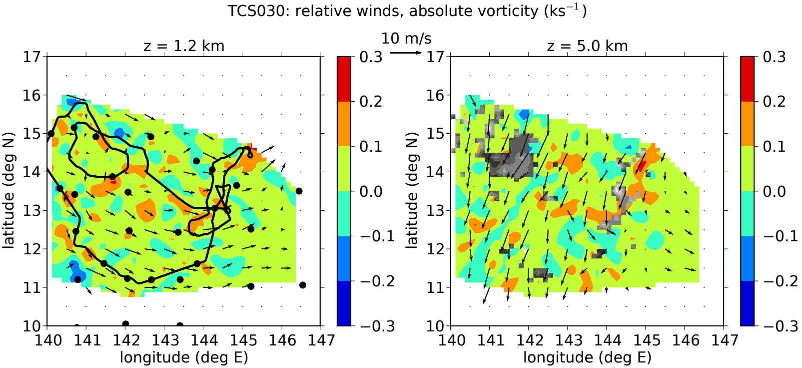
Nuri 2 vorticity budget



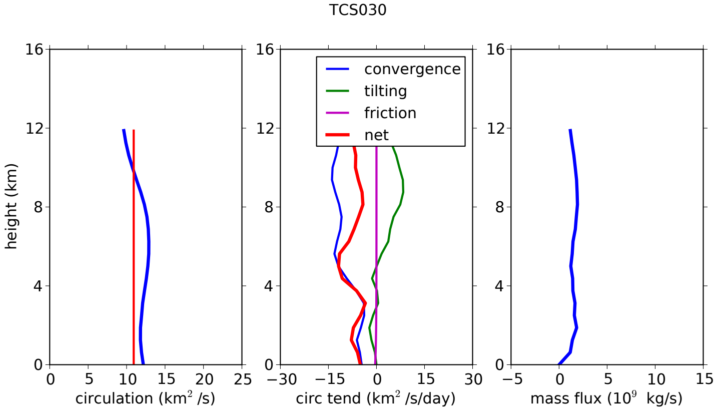
Tropical wave TCS030 overview



TCS030 (Weak tropical wave)



TCS030 vorticity budget



Summary 1

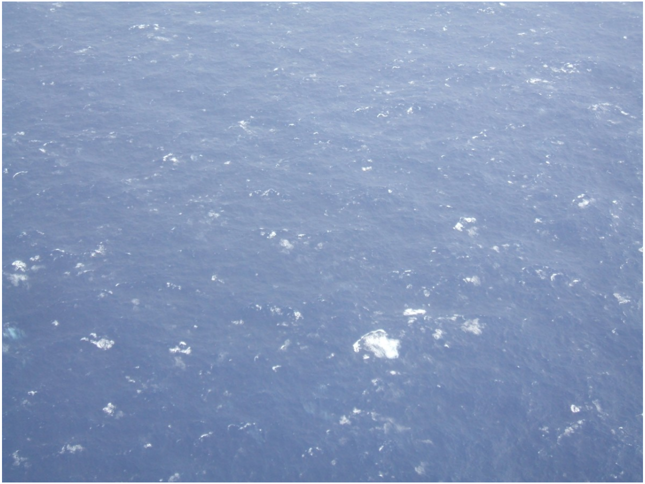
- Circulations spin up when the positive circulation tendency due to the convergence of vorticity exceeds the negative tendency due to friction.
- Top-heavy convective mass flux profiles generate mid-level spinup.
- Bottom-heavy mass flux profiles generate low-level spinup.

Question: What controls the magnitude and shape of mass flux profiles?

Over the Pacific at dawn

Nice clouds

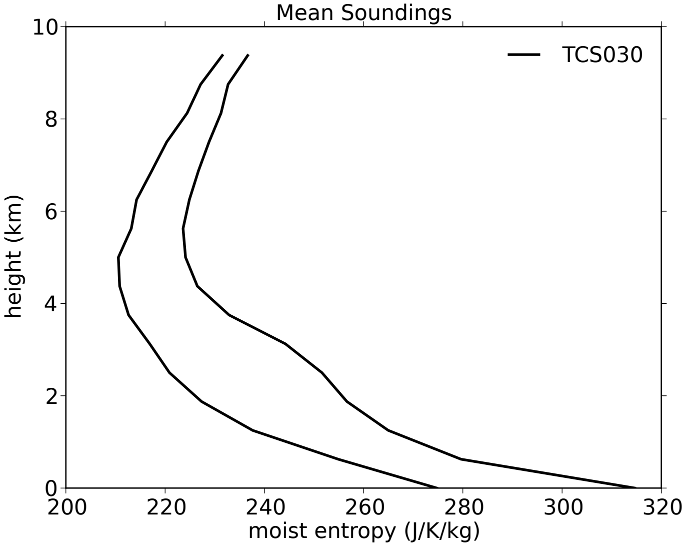
Rough ocean



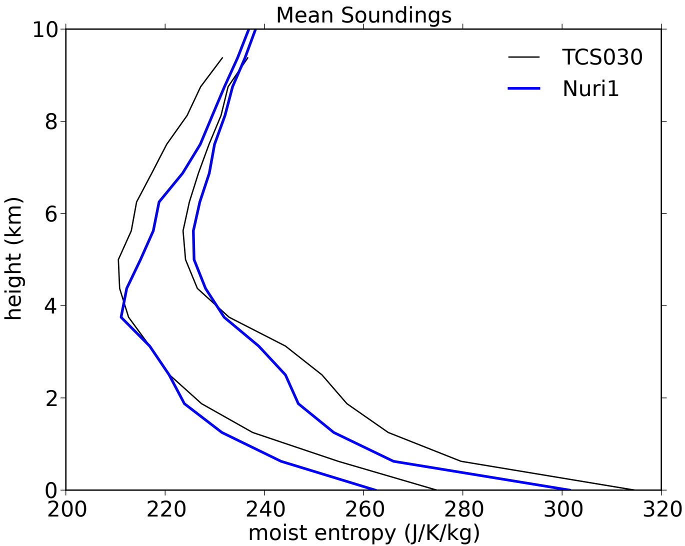
Thermodynamic study of 5 Pacific systems

- Nuri (1 and 2) developing typhoon
- TCS025 (1 and 2) strong wave
- TCS030 weak wave
- TCS037 developing midget tropical cyclone
- Hagupit developing typhoon (very early stage)

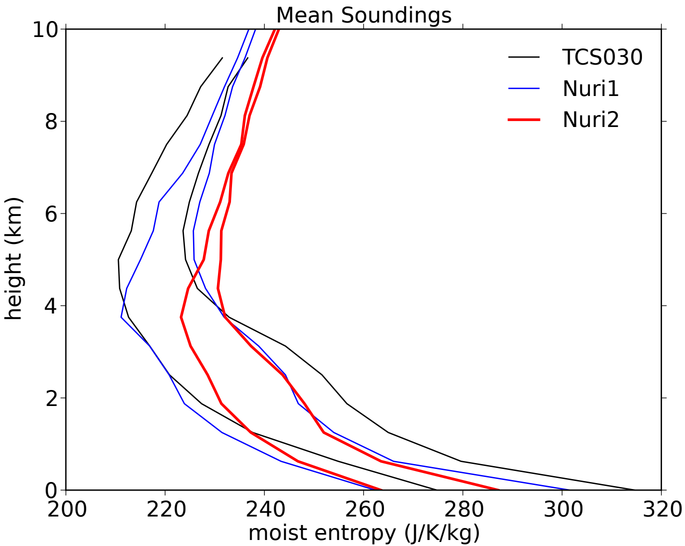
Soundings in moist entropy form – TCS030



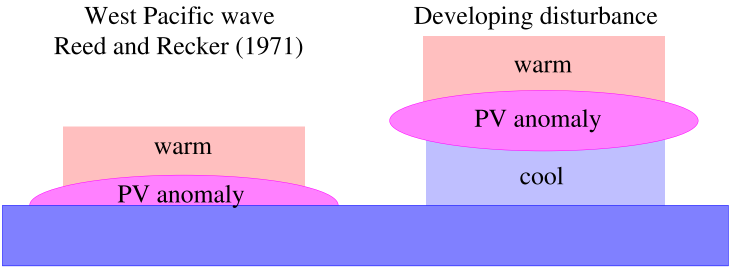
Soundings in moist entropy form – Nuri1



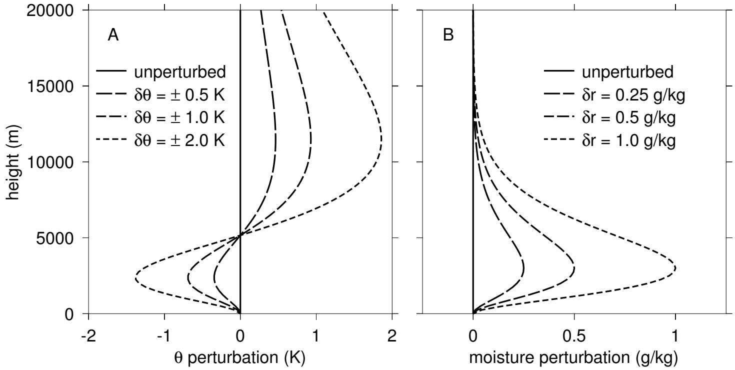
Soundings in moist entropy form – Nuri2



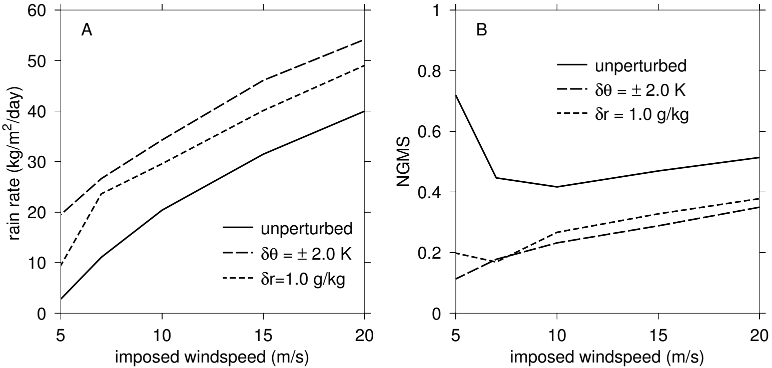
Thermodynamic Effect of Vortices



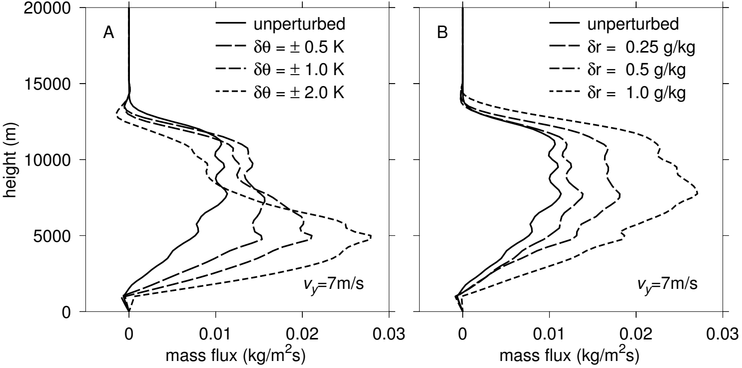
Rain and Mass Flux Profiles (Raymond and Sessions 2007)



Rain and Mass Flux Profiles (cont...)



Rain and Mass Flux Profiles (cont...)



Rain and vorticity convergence

Water budget in a control volume:

$$\frac{d\,[r]}{dt} = -\,[\boldsymbol{\nabla}_h \cdot (\boldsymbol{v}_h r)] - g(\overline{R} - \overline{F}_{rs})$$

Mixing ratio: r; Rainfall rate: $\overline{R}$; Surface evaporation rate: $\overline{F}_{rs}$; Area average: $\overline{X}$; Area average and pressure integral: $[X]$;

Use to estimate rainfall rate (steady state):

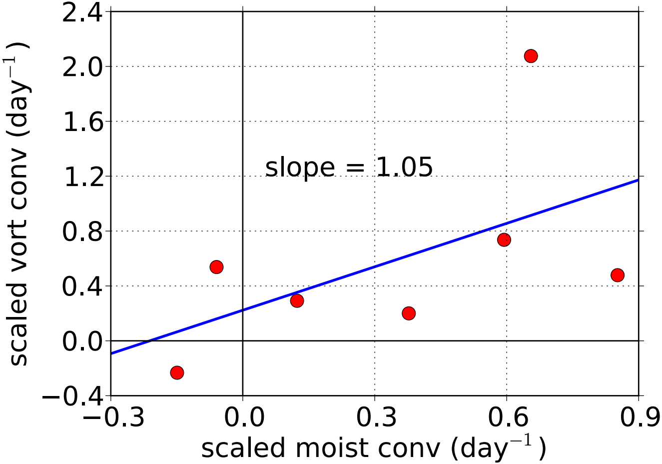
$$\overline{R} \approx \overline{F}_{rs} - [\boldsymbol{\nabla}_h \cdot (\boldsymbol{v}_h r)]$$

Boundary layer vorticity convergence and rainfall rate:

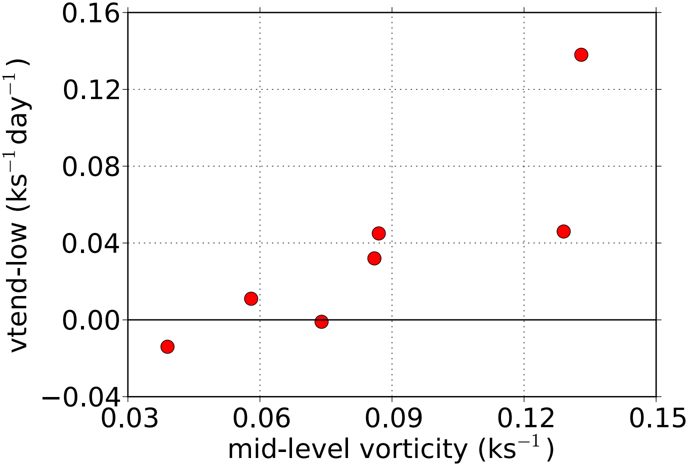
$$-\frac{\overline{\boldsymbol{\nabla}_h \cdot (\boldsymbol{v}_h \zeta_z)}_{bl}}{\overline{\zeta}_z} = -C\frac{[\boldsymbol{\nabla}_h \cdot (\boldsymbol{v}_h r)]}{\overline{W}}$$

Precipitable water: W

Rain and vorticity convergence observed



Mid-level vortex and low-level spinup



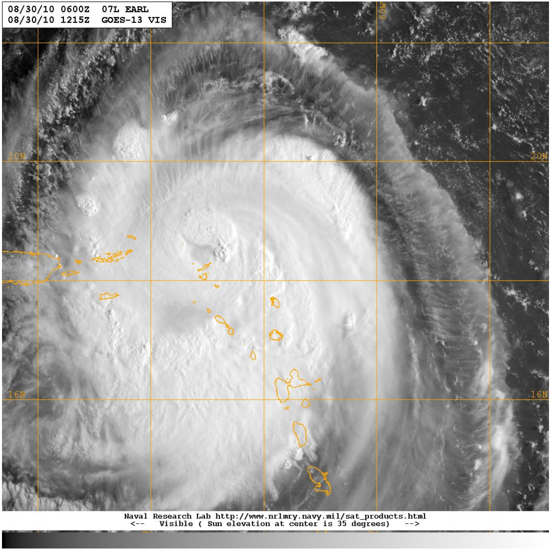
Summary 2

- A mid-level circulation provides a thermodynamic environment which promotes bottom-heavy convective mass flux profiles and more intense rain.
- Intense rain is correlated with strong vorticity convergence.
- These factors promote low-level spinup and consequent formation of a warm-core cyclone.

Question: What limits mid-level vortices?

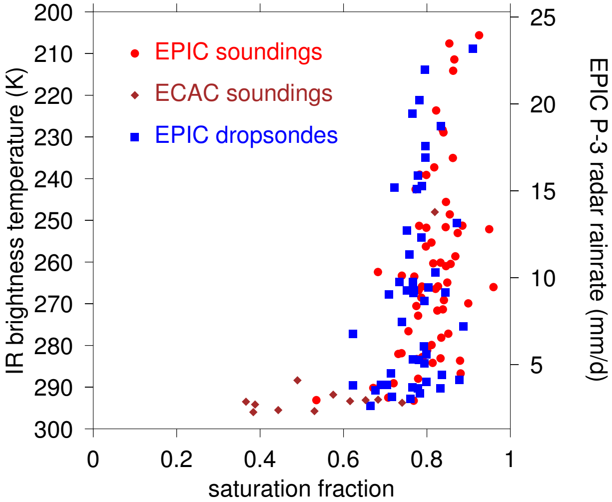
Clouds from G-V over Atlantic

Visible image of Hurricane Earl (2010)



View from the hotel

Rain and Saturation Fraction (Raymond, Sessions, and Fuchs 2007)



Saturation Fraction and Moist Entropy

Saturation fraction (S):

$$S = \frac{[r]}{[r^*]} = \frac{[s - s_D]}{[s^* - s_D]}$$

Approximate moist entropy (s) and saturated moist entropy (s^*):

$$s = C_P \ln(T/T_F) - R \ln(p/p_R) + Lr/T_F = s_D + Lr/T_F$$

$$s^* = s_D + Lr^*(s_D, p)/T_F$$

Moist entropy budget in a control volume:

$$\frac{d\,[s]}{dt} = -\left[\nabla_h \cdot (\boldsymbol{v}_h s)\right] + [G] + g\left(\overline{F}_{es} - \overline{F}_{et}\right)$$

Area average: $\overline{X}$; Area average and pressure integral: $[X]$;
Irreversible generation: $[G]$; Upward fluxes: $\overline{F}_{es} - \overline{F}_{et}$

Environmental injection of dry air

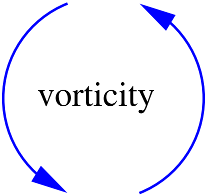
Normalized Okubo-Weiss parameter (measure of rotation vs. horizontal strain; Dunkerton et al. 2009):

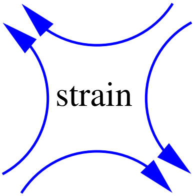
$$\mathcal{N} = \frac{\zeta_r^2 - \sigma_1^2 - \sigma_2^2}{\zeta_r^2 + \sigma_1^2 + \sigma_2^2}$$

where

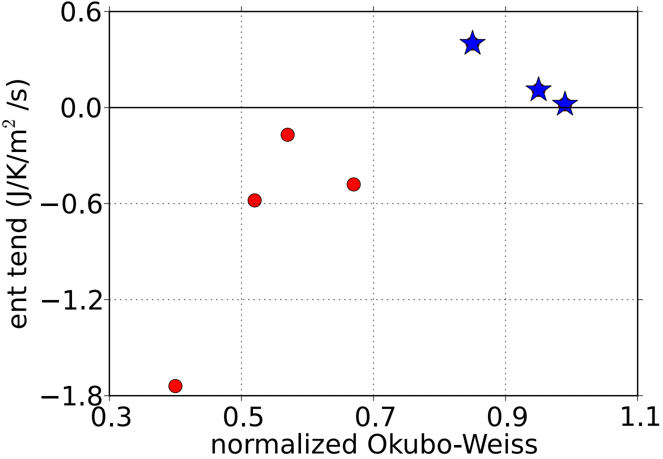
$$\zeta_r = \overline{\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}} \quad \sigma_1 = \overline{\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}} \quad \sigma_2 = \overline{\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}}$$

Averaged over middle levels (3-5 km).





Entropy tendency and Okubo-Weiss



Summary 3

- The entropy tendency should be a measure of future intensification, since this tendency is related to the saturation fraction tendency, and hence the prospects for future rainfall.
- A small value of the normalized Okubo-Weiss parameter is likely to be correlated with the import of dry air via strain flow, and hence a negative entropy tendency.
- Entropy tendency and normalized Okubo-Weiss are well correlated and the three systems undergoing intensification had positive entropy tendency and $\mathcal{N} > 0.8$.

The NCAR Gulfstream-V aircraft in St. Croix