The Formation of Tropical Cyclones [1]

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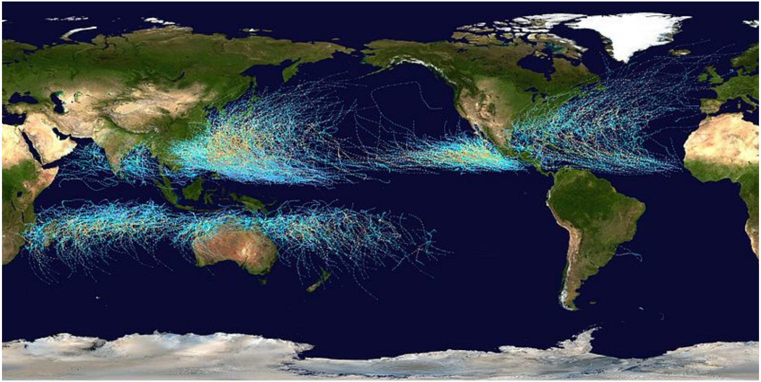
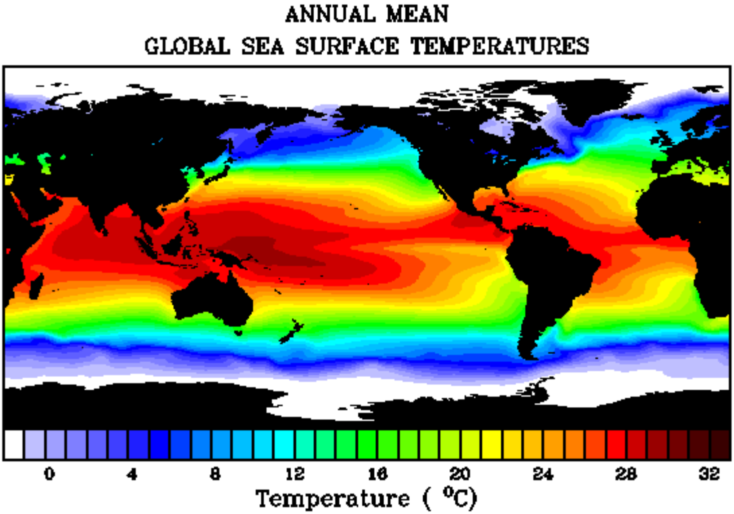
What is a tropical cyclone?

- Closed circulation at all levels
- Warm core
- Maximum wind near surface
- Strong meridional secondary circulation with convection and rain

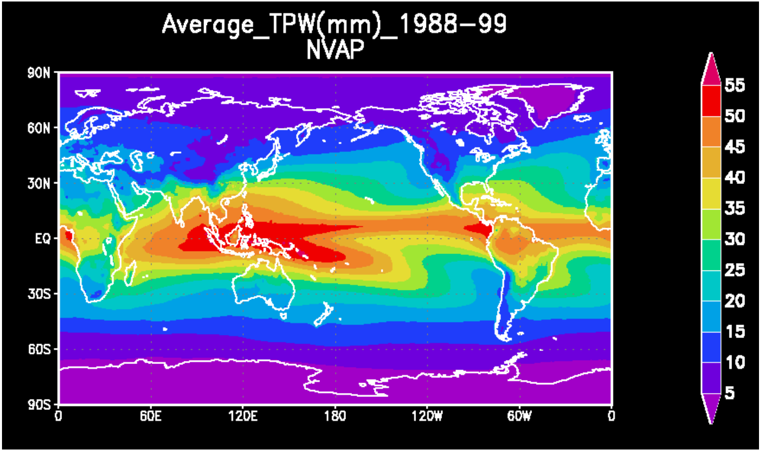
Tropical cyclone tracks 1985-2005 (Wikipedia)



Annual average sea surface temperatures (NOAA)



Annual average atmospheric precipitable water (NASA)



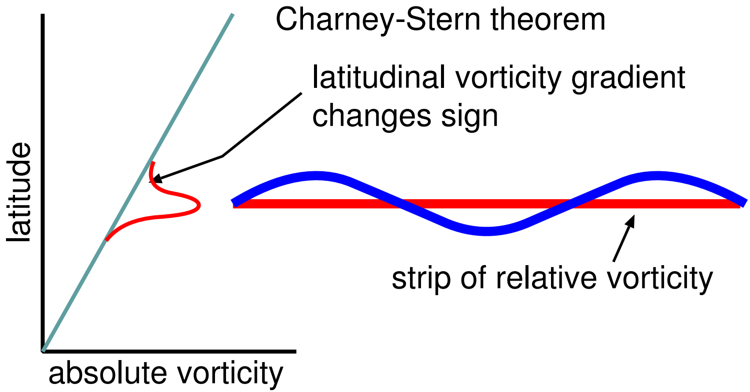
Spontaneous formation of TCs (RCE modeling) [2]

"In some cases, tropical cyclones are found to form spontaneously from random convection. This formation is due to a cooperative interaction between large-scale moisture, long-wave radiation, and locally enhanced sea-surface fluxes, similar to the aggregation of convection found in previous studies."

But it takes about two weeks ... occurs more rapidly from pre-existing disturbance

[2] Nolan, Rappin, and Emanuel (2007)

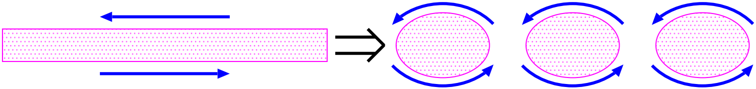
Barotropic instability



$$\frac{d\zeta_a}{dt} = 0; \quad \zeta_a = \frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y} + f$$

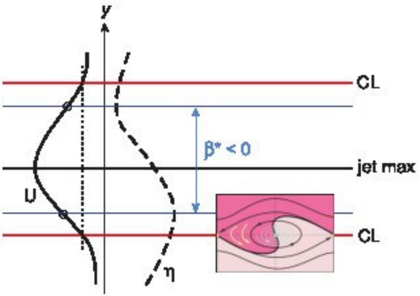
Conclusion...

- Barotropic instability is a key mechanism for generating tropical storms.
- But, why???
- Barotropic instability rearranges pattern of absolute vorticity, but does not increase it.



- The vorticity disturbances produced by baroclinic instability generally result in regions with closed circulations (in the moving reference frame of the disturbance).

Protective "pouch" in a wave[3]



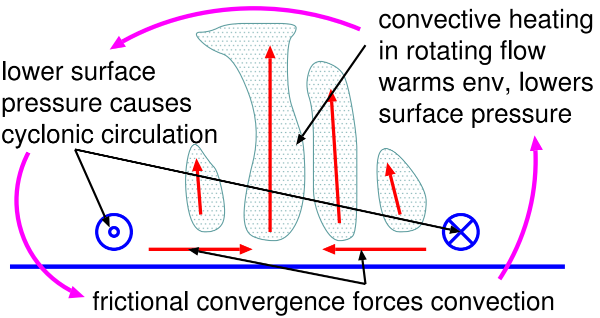
- The closed circulation in a pouch prevents the ingestion of dry air, allowing convection to moisten the pouch.
- This is only effective if pouches at different levels are vertically aligned ⇒ low wind shear.

[3] Dunkerton, Montgomery, and Wang (2009)

Where do tropical cyclones form?

- Moist tropical regions with sea surface temperatures in excess of 26°C.
- Away from equator – need non-zero Coriolis parameter.
- Develop out of pre-existing tropical weather disturbances, often produced by barotropic instability.
- Low wind shear.

Convective Instability of the Second Kind (CISK) [4]



[4] Charney and Eliassen (1964)

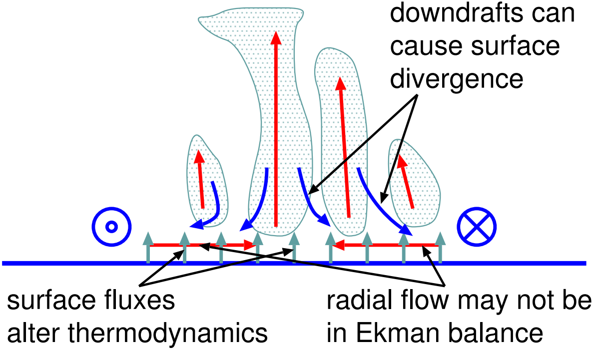
Critique of CISK [5]

"... [T]he existence of a linear instability of the type envisioned by Charney and Eliassen (1964) would imply that weak tropical cyclones should be ubiquitous and not confined to maritime environments."

"All numerical simulations of tropical cyclones reveal the essential importance of latent (and perhaps sensible) heat flux from the sea surface, as proposed originally by Riehl (1954)."

[5] Emanuel (1986)

Actual dynamics of spin up



Flux form of vorticity equation:

$$\frac{\partial \zeta_a}{\partial t} = -\nabla_h \cdot \left(\boldsymbol{v}_h \zeta_a - \boldsymbol{\zeta}_h v_z + \widehat{\boldsymbol{k}} \times \boldsymbol{F} \right) = \textit{vort conv} + \textit{tilting} + \textit{frict}$$

Ekman (im)balance

- Ekman balance in boundary layer (tilting not important there):

$$\textit{vort conv} + \textit{frict} = 0$$

- Spin up cannot occur when Ekman balance holds!
- Understanding of spin up requires independent determination of vorticity convergence and hence mass convergence:

$$\textit{vort conv} \approx \textit{vorticity} \times \textit{mass conv}$$

Observations of tropical cyclone formation [6]

- Proto-cyclones first develop a vortex at middle levels in the troposphere.
- Only then does a smaller surface vortex form beneath the mid-level vortex.

[6] Ritchie and Holland (1993, 1997); Harr et al. (1996a,b); Simpson et al. (1997); Bister and Emanuel (1997); Raymond, López, and López, 1998)

Examples from recent field programs [7]

- TCS-08: August-September 2008, Guam, West Pacific
- PREDICT: August-September 2010, St. Croix, Western Atlantic, Caribbean
- Dense array of dropsondes deployed into candidates for tropical cyclogenesis
- Area-average vorticity tendency obtained from 3-D Var analysis for:
  - Hagupit2: Non-developing wave (developed into typhoon one week later)
  - Nuri1: Intensifying tropical wave.
  - Nuri2: Rapidly developing tropical depression (typhoon two days later)

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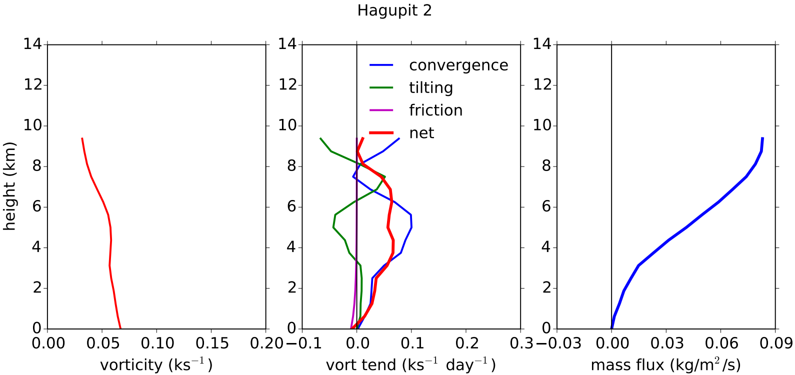
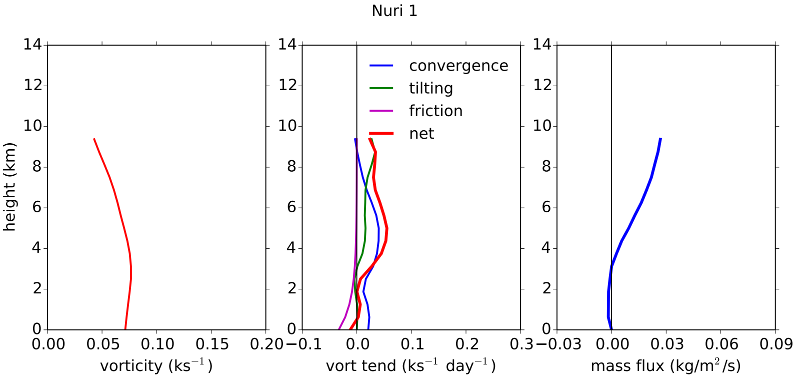
[7] Raymond, Sessions, and López (2011); Gjorgjievska and Raymond (2014)

Hagupit2: Not intensifying at this time



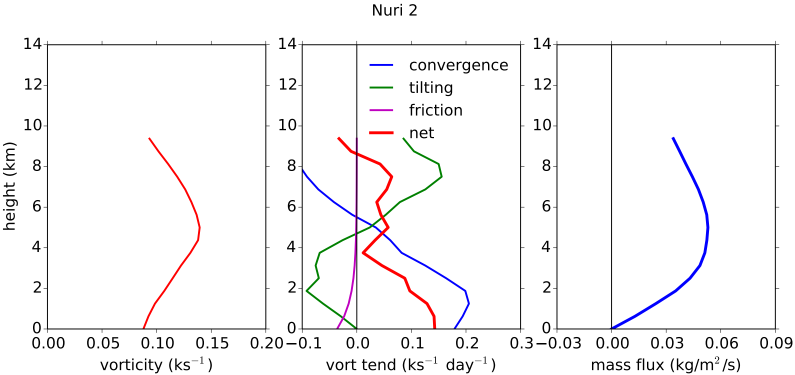
Both convergence and frictional tendencies are negative, resulting in spin-down.

Nuri1: Intensifying wave



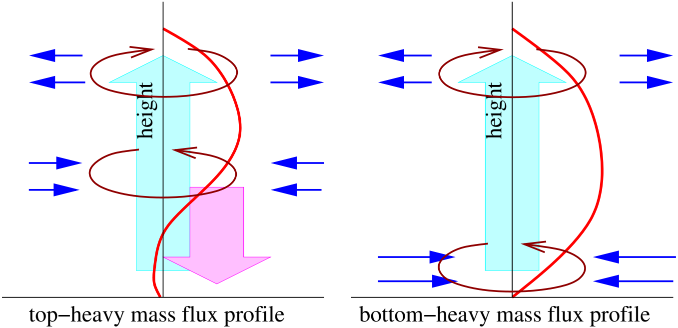
Spin up tendency from convergence strongest at mid-levels.

Nuri2: 24 hr later, rapidly intensifying depression



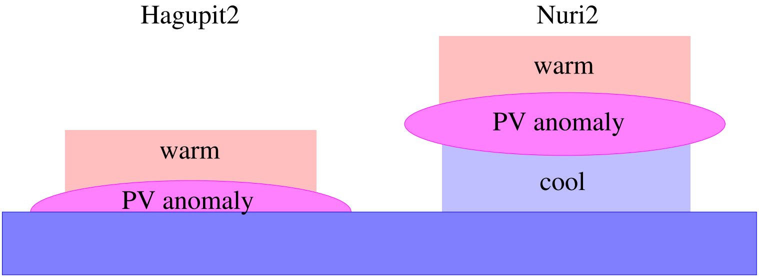
Spin up tendency at surface far exceeds frictional spin-down tendency.

Mass flux profile and vorticity tendency

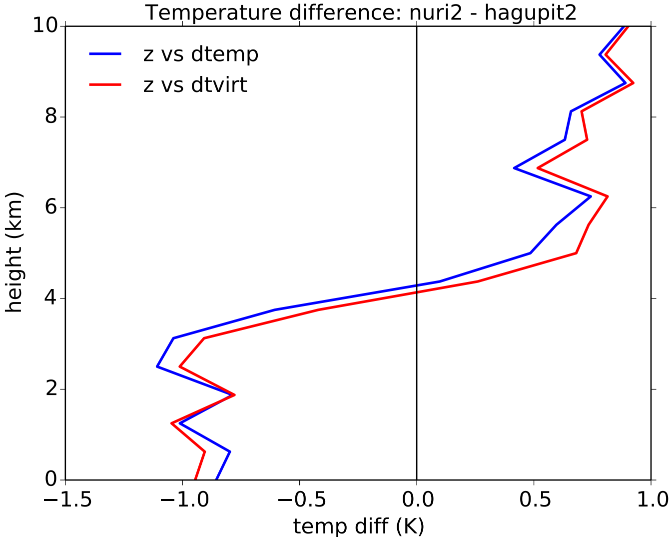


But what controls mass flux profile???

Thermodynamic effect of a vortex



Nuri2 vs. Hagupit2



Two key indices

Saturation fraction:

$$SF = \int_{surf}^{trop} r dp \Big/ \int_{surf}^{trop} r^* dp$$

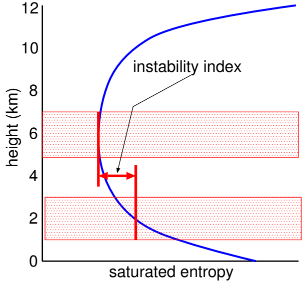
Instability index:

$$II = \Delta s^* = s^*_{1-3km} - s^*_{5-7km}$$

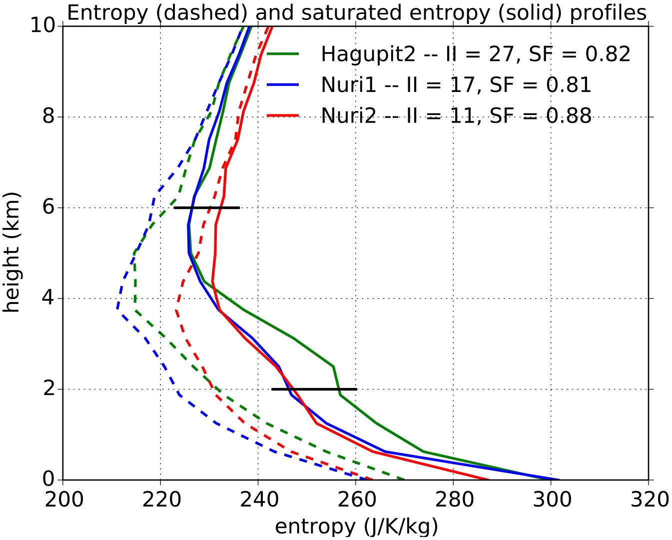
Saturated moist entropy:

$$s^* = C_p \ln \theta_e^*$$

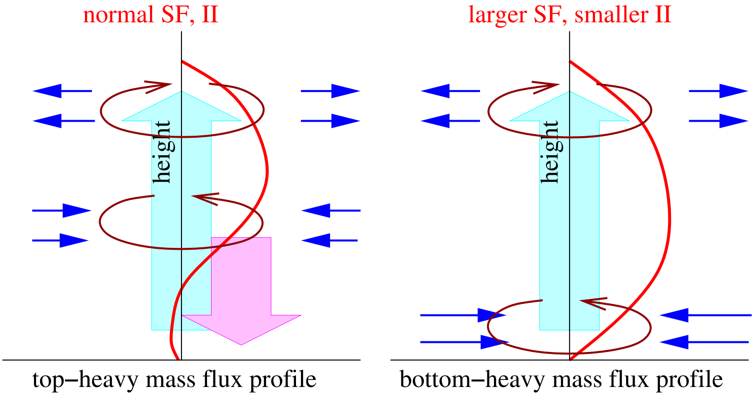
Schematic of instability index



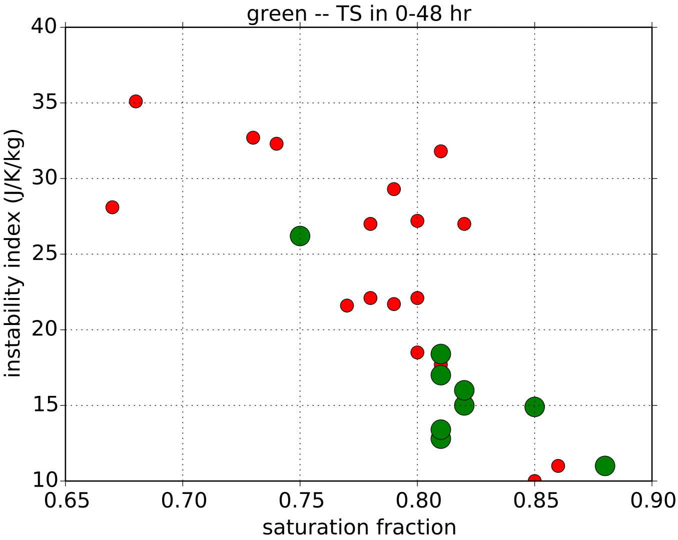
Instability index for Nuri and Hagupit



Mass flux profile and vorticity tendency

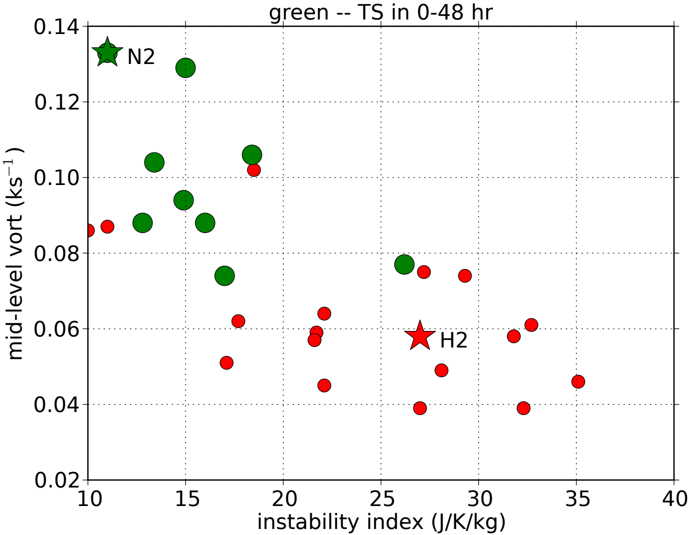


Instability index vs. saturation fraction[8]

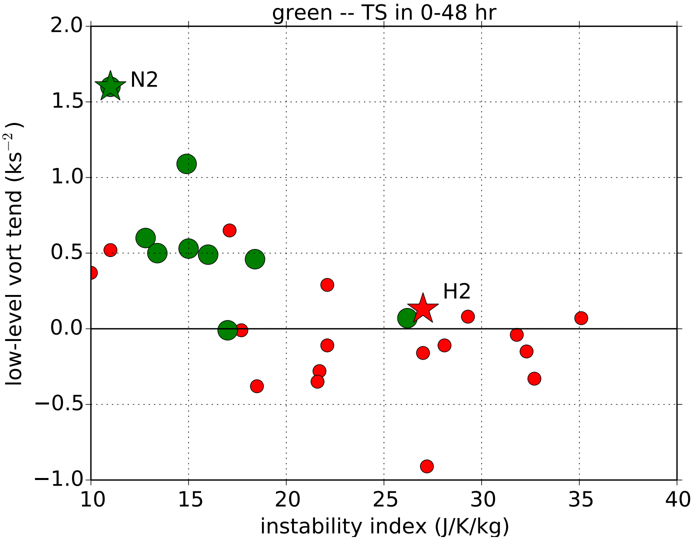


[8] Raymond, Sessions, and López (2011); Gjorgjievska and Raymond (2014)

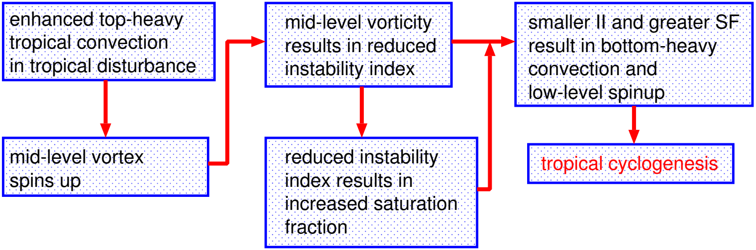
Mid-level vorticity vs. instability index



Low-level vorticity tendency vs. instability index



Pathway to cyclogenesis



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Origin of African easterly waves ...

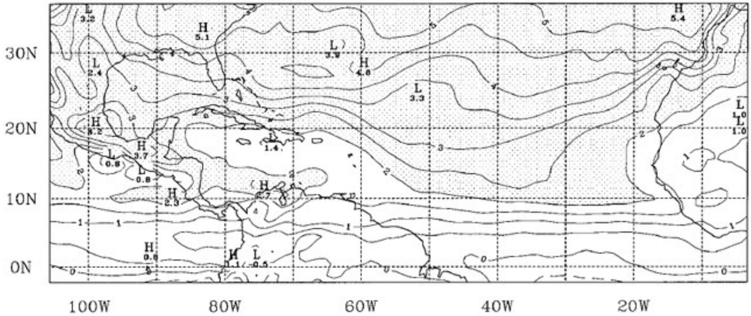
“This study shows that the African waves are directly related to the mid-tropospheric easterly jet that is found within the baroclinic zone to the south of the Sahara. During the same season that the waves are observed, the gradient of the monthly mean potential vorticity vanishes along the isentropic surfaces. Charney and Stern have shown that this is a necessary condition for instability of the jet provided that the amplitude of the waves is negligible at the ground. Results show that the horizontal [south] and vertical [north] shear of the mean zonal wind are acting as nearly equal sources of energy for the perturbations. The role of convection in the origin of these waves has not yet been determined.”

… and their role in TC formation [9]

"From June to early October these waves propagate across the Atlantic and occasionally reach the eastern Pacific. Although only a few of these disturbances actually intensify after reaching the Atlantic, they account for approximately half of the tropical cyclones that form in the Atlantic."

[9] Burpee (1972)

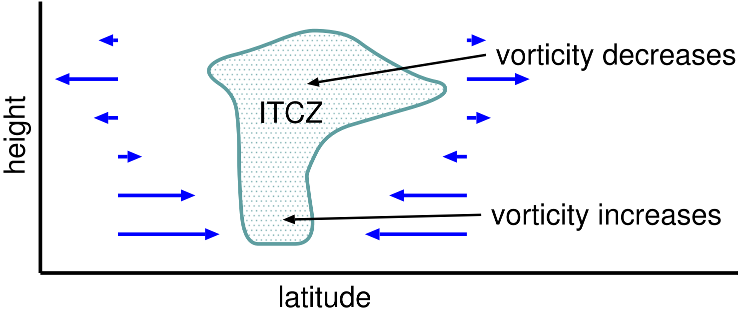
Barotropic instability in SW Caribbean and E Pacific [10]



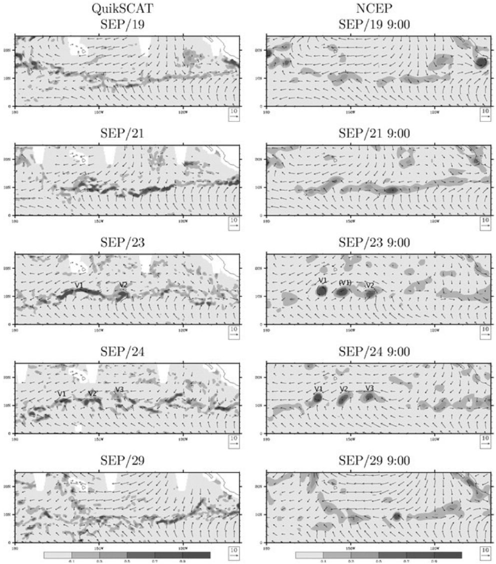
Potential vorticity (0.1 PVU) on 310 K isentropic surface, 15 June through 30 September, 1991.

[10] Molinari et al. (1997)

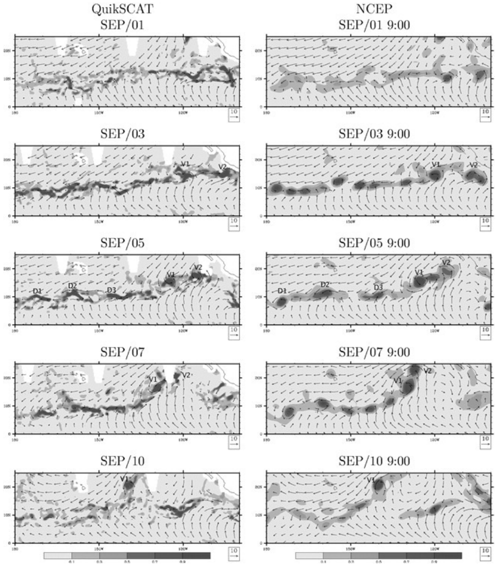
ITCZ dynamics



ITCZ breakdown (low-level wind, vorticity) ...

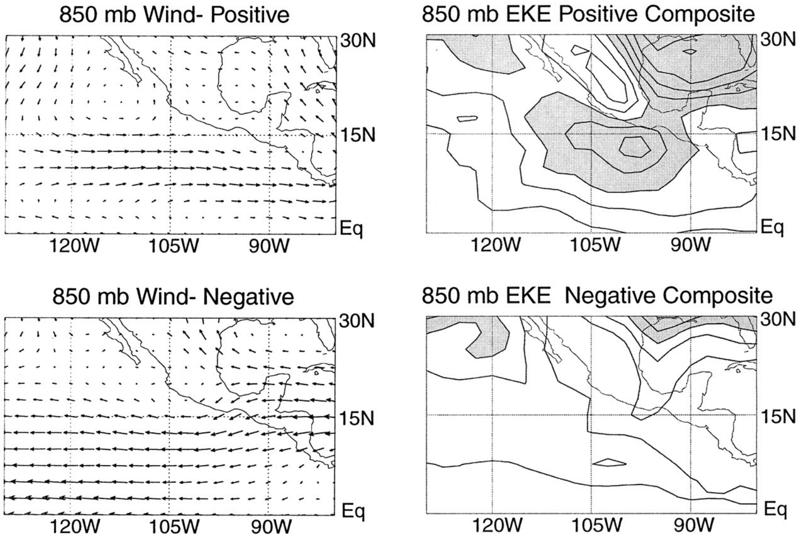


... and rollup [11]



[11] Ferreira and Schubert, 1997; Wang and Magnusdottir (2005, 2006)

MJO and East Pacific Hurricanes [12]



[12] Maloney and Hartmann (2001)