The Formation of Tropical Cyclones

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¹Work supported by US National Science Foundation and Office of Naval Research
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)
“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

Charney-Stern theorem

Latitudinal vorticity gradient changes sign

Strip of relative vorticity

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

- 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 $\Rightarrow$ low wind shear.

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\(^3\)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) \(^4\)

- Convective heating in rotating flow warms env, lowers surface pressure
- Lower surface pressure causes cyclonic circulation
- Frictional convergence forces convection

\(^4\) Charney and Eliassen (1964)
“... [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).”

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5Emanuel (1986)
Actual dynamics of spin up

Downdrafts can cause surface divergence

Surface fluxes alter thermodynamics, radial flow may not be in Ekman balance

Flux form of vorticity equation:

\[
\frac{\partial \zeta_a}{\partial t} = -\nabla_h \cdot \left( \mathbf{v}_h \zeta_a - \zeta_h \mathbf{v}_z + \hat{\mathbf{k}} \times \mathbf{F} \right) = \text{vort conv} + \text{tilting} + \text{frict}
\]
Ekman (im)balance

- Ekman balance in boundary layer (tilting not important there):
  \[ vort \ conv + frict = 0 \]
- Spin up cannot occur when Ekman balance holds!
- Understanding of spin up requires independent determination of vorticity convergence and hence mass convergence:
  \[ vort \ conv \approx vorticity \times mass \ conv \]
Observations of tropical cyclone formation

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.

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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

- 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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Raymond, Sessions, and López (2011); Gjorgjievsk and Raymond (2014)
Hagupit2: Not intensifying at this time

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

Hagupit2

warm

PV anomaly

Nuri2

warm

PV anomaly

cool
Temperature difference: nuri2 - hagupit2

- $z$ vs. $d$temp
- $z$ vs. $d$tvirt
Two key indices

Saturation fraction:

\[ SF = \frac{\int_{\text{surf}}^{\text{trop}} r \, dp}{\int_{\text{surf}}^{\text{trop}} r^* \, dp} \]

Instability index:

\[ II = \Delta s^* = s^*_1 - s^*_3 - s^*_5 - s^*_7 \]

Saturated moist entropy:

\[ s^* = C_p \ln \theta_e^* \]
Instability index for Nuri and Hagupit

Entropy (dashed) and saturated entropy (solid) profiles

- Hagupit2 -- II = 27, SF = 0.82
- Nuri1 -- II = 17, SF = 0.81
- Nuri2 -- II = 11, SF = 0.88
Mass flux profile and vorticity tendency

normal SF, II

larger SF, smaller II

top–heavy mass flux profile

bottom–heavy mass flux profile
Instability index vs. saturation fraction

8Raymond, Sessions, and López (2011); Gjorgjievska and Raymond (2014)
Mid-level vorticity vs. instability index

![Graph showing mid-level vorticity vs. instability index with green and red points representing N2 and H2 categories.](image)

green -- TS in 0-48 hr

mid-level vort (ks$^{-1}$)

instability index (J/K/kg)
Low-level vorticity tendency vs. instability index

green -- TS in 0-48 hr

N2

H2
Pathway to cyclogenesis

1. Enhanced top-heavy tropical convection in tropical disturbance
2. Mid-level vortex spins up
3. Mid-level vorticity results in reduced instability index
4. Reduced instability index results in increased saturation fraction
5. Smaller II and greater SF result in bottom-heavy convection and low-level spinup
6. Tropical cyclogenesis
References...


References continued...


References continued...

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

“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.”

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<sup>⁹</sup>Burpee (1972)
Barotropic instability in SW Caribbean and E Pacific

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

\(^{10}\text{Molinari et al. (1997)}\)
ITCZ dynamics

- vorticity increases
- vorticity decreases

latitude

height

vorticity increases

vorticity decreases

ITCZ
ITCZ breakdown (low-level wind, vorticity) ...
... and rollup\textsuperscript{11}

\textsuperscript{11}Ferreira and Schubert, 1997; Wang and Magnusdottir (2005, 2006)
MJO and East Pacific Hurricanes

\[ \text{850 mb Wind - Positive} \]

\[ \text{850 mb EKE Positive Composite} \]

\[ \text{850 mb Wind - Negative} \]

\[ \text{850 mb EKE Negative Composite} \]

\[ ^{12} \text{Maloney and Hartmann (2001)} \]