Tropical Cyclogenesis and Gross Moist Stability

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May 23, 2010
Circulation dynamics

circulation tendency = vorticity convergence + friction (+ tilting)
Surface friction

Friction acts in planetary boundary layer:

\[ \text{friction} \propto \frac{\text{velocity}^2}{\text{layer depth}} \]
Balance

- Vorticity balance (zero circulation tendency):
  \[
  \text{vorticity convergence tendency} = \text{frictional spindown}
  \]

- Ekman balance (equivalent to vorticity balance for weak circulations):
  \[
  \text{pressure gradient} + \text{Coriolis force} + \text{friction} = 0
  \]

- Ekman balance approximates vorticity balance for weak circulations.
Illustration of Ekman balance

lesser pressure

p_1

p_2

Ekman balance wind

gleostrophic wind

greater pressure

p_3

p_4
Ekman pumping

- Flow across isobars implies convergence in regions with low pressure and cyclonic circulation.
- This convergence is hypothesized to be linked to the convective vertical mass flux.
Observations of the development of typhoon Nuri (2008)

- Doppler radar and dropsonde observations used.
- Full vorticity budget calculated.
- Vorticity and circulation tendencies estimated.
Nuri 1 (tropical wave)

Nuri 1: relative winds, absolute vorticity (ks$^{-1}$)
Nuri 2 (tropical depression)

Nuri 2: relative winds, absolute vorticity (ks$^{-1}$)

- $z = 1.2$ km
- $z = 5.0$ km
Nuri 3 (tropical storm)

Nuri 3: relative winds, absolute vorticity (ks$^{-1}$)
Nuri 1 vorticity budget
Nuri 2 vorticity budget
Nuri3 vorticity budget (center)
Conclusion 1

- Convective mass flux (and hence precipitation) is not governed by Ekman pumping.
- If not, what does govern convection? Thermodynamics!!!

Saturation fraction:

\[
\text{saturation fraction} = \frac{\text{precipitable water}}{\text{saturated precipitable water}}
\]

More Nuri observations...
Saturation fraction in Nuri

Saturation fraction and strong reflectivity

Nuri 1

Nuri 2

Nuri 3 (below 650 hPa)

TCS030 (nondeveloping wave)
Soundings

Nuri Soundings

- nuri 1 (TW)
- nuri 2 (TD)
- nuri 3 (TS)

pressure (hPa)

entropy and saturated entropy (J/kg/K)
Conclusion 2

- As a tropical cyclone develops, the convective environment becomes moister and more stable.
- In the early stages the lower troposphere becomes cooler and moistening is limited to middle levels.
- Only gradually does a warm core develop downward.

What is going on here?
Normalized gross moist stability (NGMS)

\[
NGMS = \frac{TR(s_{out} - s_{in})}{L(r_{in} - r_{out})} \approx \frac{TR(F_{es} - F_{et})}{L(P - E)}
\]

\[\Rightarrow P = E + \frac{TR(F_{es} - F_{et})}{L \times NGMS}\]
Experiments with cloud-resolving model in weak temperature gradient (WTG) mode:

- In tropics buoyancy adjustment maintains weak (virtual) temperature gradient on isobaric surfaces.
- Cloud-resolving model mimics this by applying a temperature tendency which on the average keeps the model domain in buoyancy equilibrium with a reference profile.
- The mean vertical velocity producing dry adiabatic cooling consistent with this temperature tendency is called the WTG vertical velocity.
- The WTG vertical velocity advects moisture vertically and in regions of convergent flow entrains reference profile moisture into the convective domain.
Reference profile perturbations from RCE

A
- unperturbed
- $\delta\theta = \pm 0.5 \, \text{K}$
- $\delta\theta = \pm 1.0 \, \text{K}$
- $\delta\theta = \pm 2.0 \, \text{K}$

B
- unperturbed
- $\delta r = 0.25 \, \text{g/kg}$
- $\delta r = 0.5 \, \text{g/kg}$
- $\delta r = 1.0 \, \text{g/kg}$
Response of rain and NGMS to perturbations of reference profile

A

B

- unperturbed
- $\delta \theta = \pm 2.0 \text{ K}$
- $\delta r = 1.0 \text{ g/kg}$
Response of vertical mass flux to perturbations in reference profile

A

- unperturbed
- \( \delta \theta = \pm 0.5 \) K
- \( \delta \theta = \pm 1.0 \) K
- \( \delta \theta = \pm 2.0 \) K

B

- unperturbed
- \( \delta \theta = \pm 0.5 \) K
- \( \delta \theta = \pm 1.0 \) K
- \( \delta \theta = \pm 2.0 \) K
NGMS (and hence precipitation) is controlled by the convective environment.

- A moister environment results in smaller NGMS — more precipitation per unit surface entropy flux.
- A more stable environment results in smaller NGMS and lowers level of maximum vertical mass flux — more precipitation and shallower inflow layer.
Dynamical basis of environmental stabilization in developing tropical cyclone

- warm anomaly
- mid-level vortex
- cold anomaly
Conclusion 4

- As Nuri developed, the environment became more moist and more stable.
- Both factors acted to decrease the NGMS, resulting in more rain per unit surface moist entropy flux, stronger vertical mass flux, and hence more vorticity convergence.
- The mid-level vortex is essential in stabilizing the environment.
- The lowering of the level of maximum vertical mass flux concentrated the vorticity convergence in lower levels, enhancing low-level spinup.
- The increase in rain and the lowering of the level of maximum vertical mass flux due to environmental stabilization were instrumental in the intensification of Nuri.