Tropical Cyclogenesis and Gross Moist Stability

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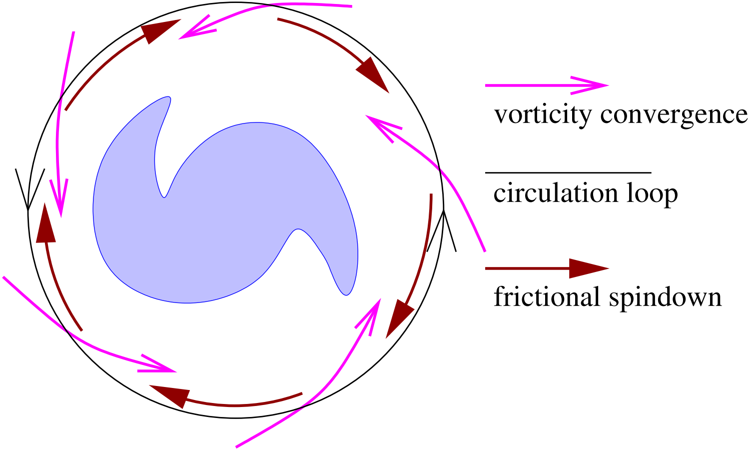
Circulation dynamics



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):

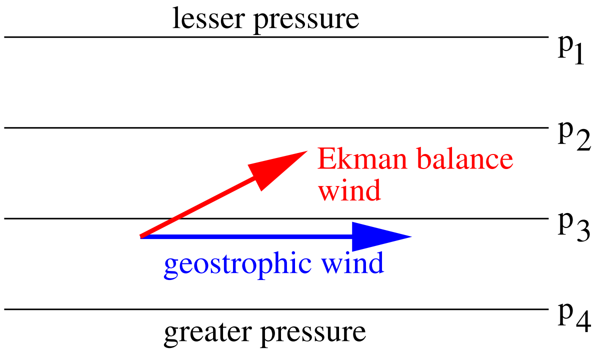
$$\text{vorticity convergence tendency} = \text{frictional spindown}$$

- 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



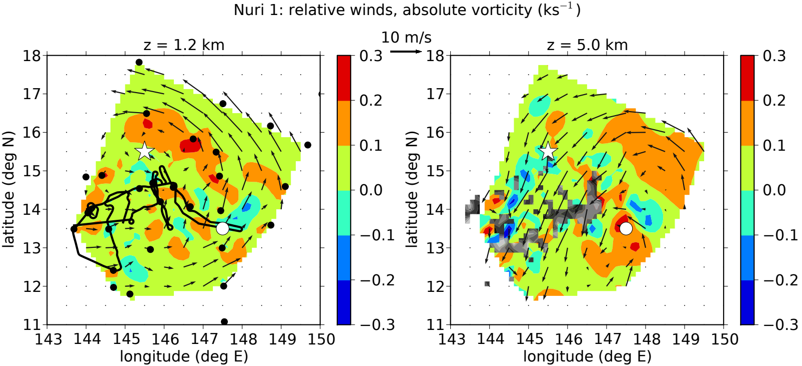
Ekman pumping

- 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.

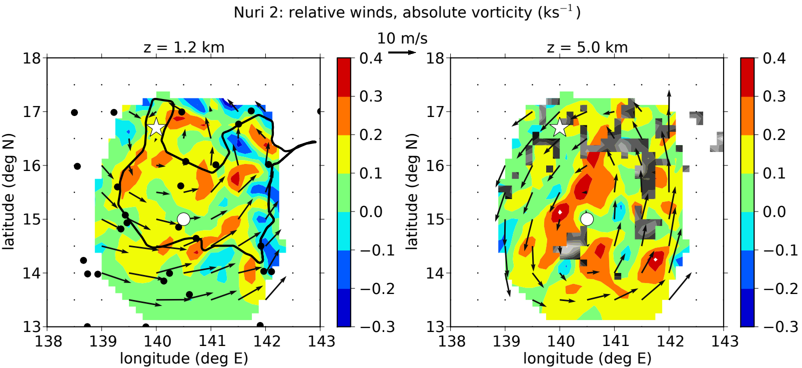
Observations of the development of typhoon Nuri (2008)

- Doppler radar and dropsonde observations used.
- Full vorticity budget calculated.
- Vorticity and circulation tendencies estimated.

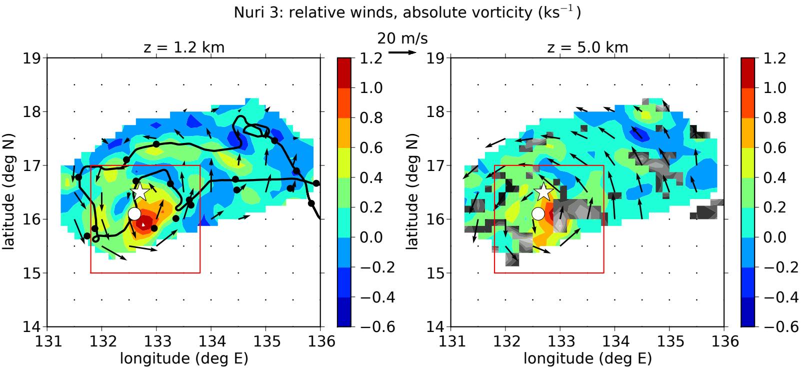
Nuri 1 (tropical wave)



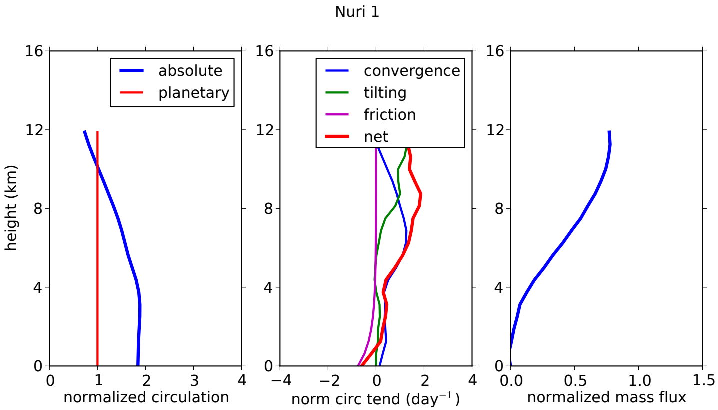
Nuri 2 (tropical depression)



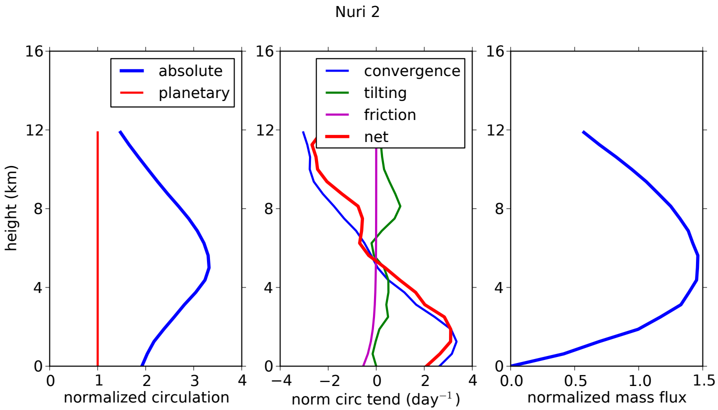
Nuri 3 (tropical storm)



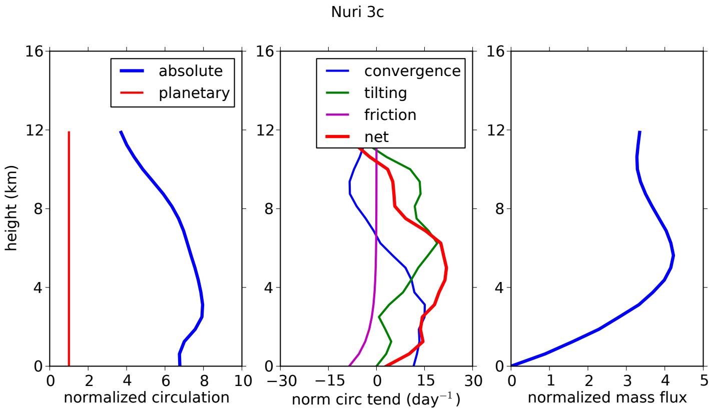
Nuri 1 vorticity budget



Nuri 2 vorticity budget



Nuri3 vorticity budget (center)



Conclusion 1

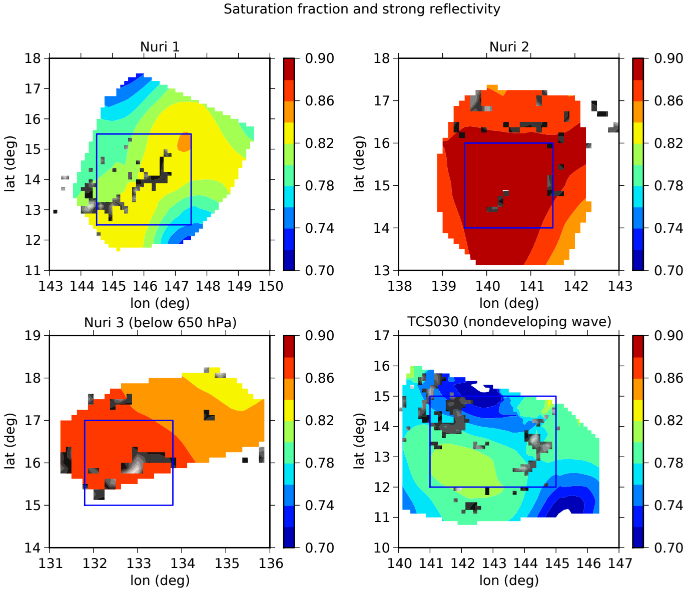
- Convective mass flux (and hence precipitation) is not governed by Ekman pumping.
- If not, what does govern convection? Thermodynamics!!!

Saturation fraction:

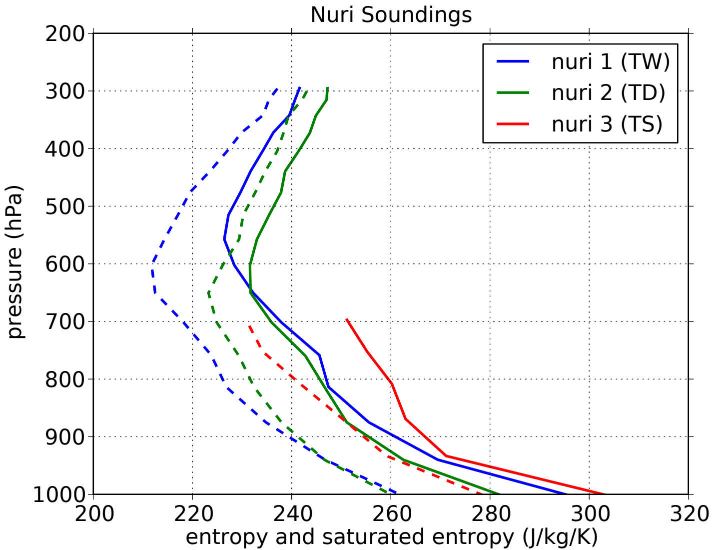
$$\text{saturation fraction} = \frac{\text{precipitable water}}{\text{saturated precipitable water}}$$

More Nuri observations...

Saturation fraction in Nuri



Soundings

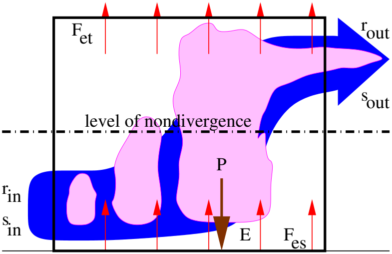

Nuri Soundings
nuri 1 (TW)
nuri 2 (TD)
nuri 3 (TS)
pressure (hPa)
200
300
400
500
600
700
800
900
1000
200
220
240
260
280
300
320
entropy and saturated entropy (J/kg/K)

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)



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

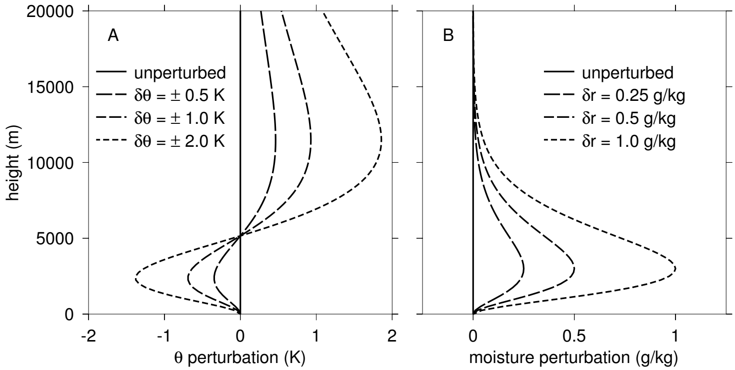
$$\Longrightarrow P = E + T_R(F_{es} - F_{et})/(L \times NGMS)$$

Raymond and Sessions (2007)

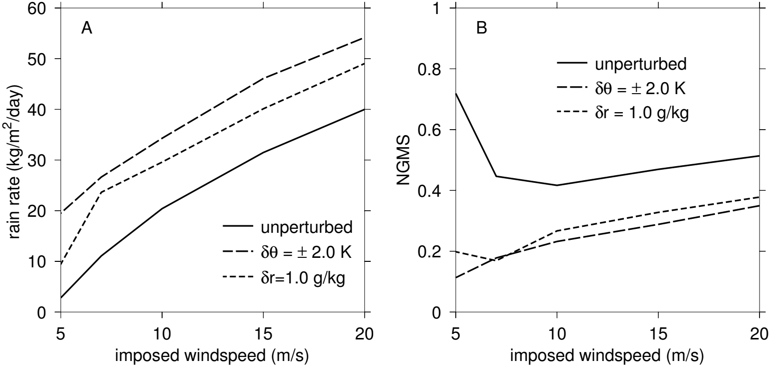
Experiments with cloud-resolving model in weak temperature gradient (WTG) mode:

- 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.

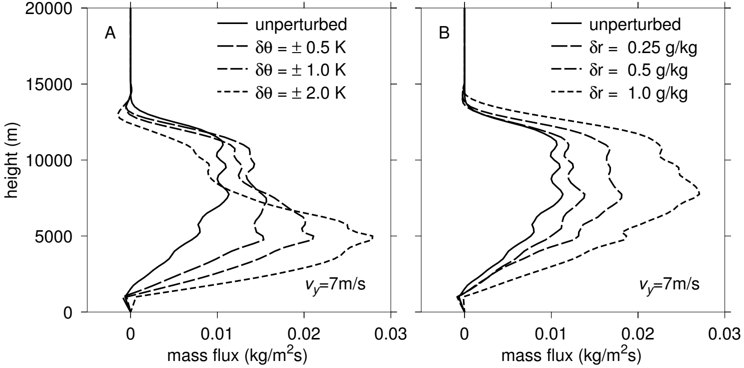
Reference profile perturbations from RCE



Response of rain and NGMS to perturbations of reference profile



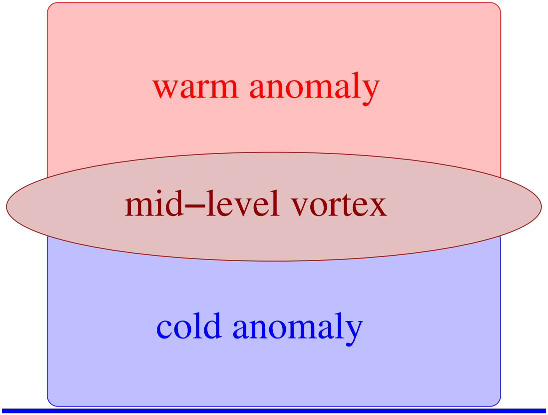
Response of vertical mass flux to perturbations in reference profile



Conclusion 3

- 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



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.