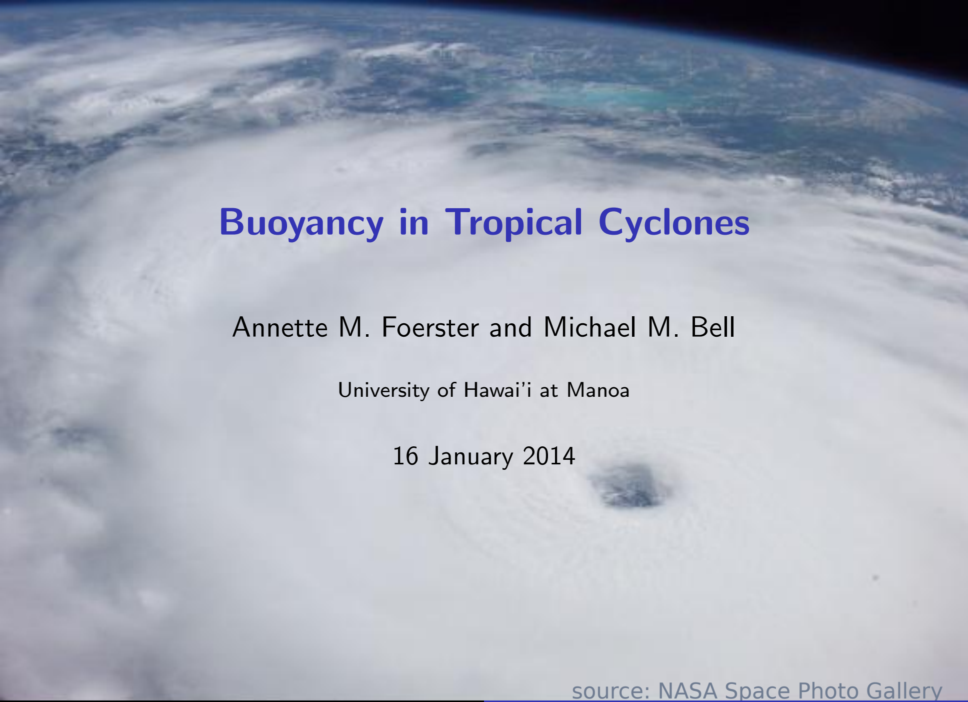

Buoyancy in Tropical Cyclones

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University of Hawai'i at Manoa

16 January 2014

source: NASA Space Photo Gallery

Importance of Eyewall convection

Pendergrass and Willoughby (2009):

- **Timing** and **Location** of repeated **convective bursts** seems critical in intensification efficiency
- Convective heating **inside the RMW** most efficient

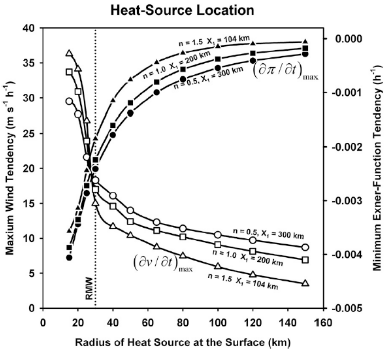
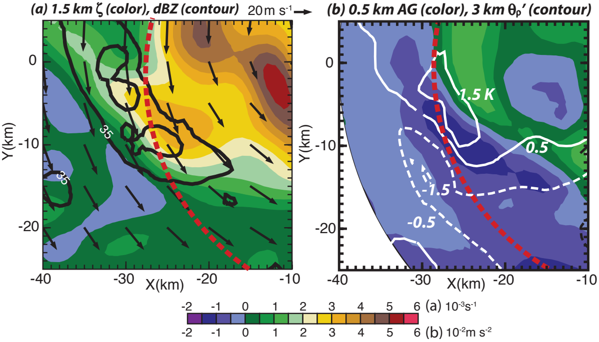


FIG. 12. Maximum rates to change of Exner function and swirling as a function of heat source radius for sharp ($n = 1.5$ and $X_1 = 104$ km), medium ($n = 1.0$ and $X_1 = 200$ km), and broad ($n = 0.5$ and $X_1 = 300$ km) vortex wind profiles.

Possible Internal Forcing Mechanisms

- Boundary layer dynamics (Shannon McElhinney)
- Vorticity anomalies
- **Buoyancy**

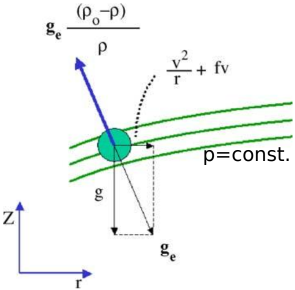


Buoyancy in a Tropical Cyclone

- Archimedes principle
  - Body lighter than environment $\rightarrow$ upward acceleration
  - $B = -g\frac{\rho'}{\rho_0}$
- More complicated in TC
  - Pressure not horizontally uniform
  - Choice of reference state critical for interpretation (see Zhang et al. (2000), Braun (2002) and Eastin el al. (2005))

$$\frac{Dw}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g = -\frac{1}{\rho}\frac{\partial p'}{\partial z} + b$$

$$with \quad p = p_0 + p'$$



Source: Smith et al. (2005)

Modelling studies

- **Zhang et al. (2000):**
  - MM5 simulation of Hurricane Andrew (1992) ($\Delta x = 6$ km)
  - Reference state: Running average over four neighboring points
- **Braun (2002):**
  - MM5 simulation of Hurricane Bob (1991) ($\Delta x = 1.3$ km)
  - Reference state: Wavenumber 0 and 1 of the Fourier decomposition (balanced vortex)
- **Comparison:**
  - Positive vertical accelerations (two large opposing terms)
  - Difference: **positively** buoyant (Braun), **negatively** buoyant (Zhang et al.)

Observation-derived Buoyancy

Ideally: High resolution thermodynamic and dynamic measurements with good spatial coverage

Flightlevel data (Eastin et al. 2005):

- Direct observations
- Limited spatial coverage
- Definition of reference state difficult
- Positive buoyancy

Radar data:

- Great spatial coverage
- No thermodynamic measurements
- Utilize radar data to estimate thermodynamic state of the atmosphere (following Gal-Chen (1978), Viltard and Roux (1998) and Liou (2001))

Thermodynamic Retrieval

- **Cylindrical** coordinate system
- Reference state is in **hydrostatic** and **gradient wind** balance

$$\left[\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + v\frac{\partial u}{r\partial\lambda} + (w + q_r W)\frac{\partial u}{\partial z} - F_u - 2\frac{\bar{v}v'}{r} - \frac{v'^2}{r} - fv'\right] = -c_p\bar{\theta}_\rho\frac{\partial\bar{\pi}}{\partial r}\left(\frac{\theta'_\rho}{\bar{\theta}_\rho}\right) - c_p\bar{\theta}_\rho\frac{\partial\pi'}{\partial r}$$

$$\left[\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial r} + v\frac{\partial v}{r\partial\lambda} + (w + q_r W)\frac{\partial v}{\partial z} + u(\frac{v}{r} + f) - F_v\right] = -c_p\bar{\theta}_\rho\frac{\partial\pi'}{r\partial\lambda}$$

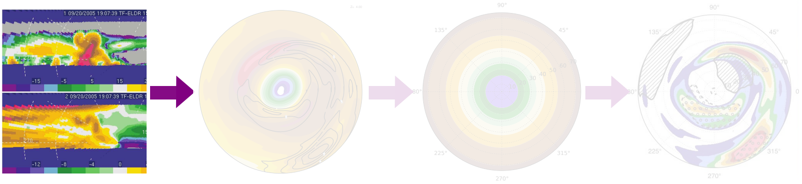
$$\left[\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial r} + v\frac{\partial w}{r\partial\lambda} + (w + q_r W)\frac{\partial w}{\partial z} - F_w\right] = g\left(\frac{\theta'_\rho}{\bar{\theta}_\rho}\right) - c_p\bar{\theta}_\rho\frac{\partial\pi'}{\partial z}$$

$$\left[\frac{\partial\theta'}{\partial t} + u\frac{\partial\bar{\theta}}{\partial r} + +w\frac{\partial\bar{\theta}}{\partial z}\right] = -u\frac{\partial\theta'}{\partial r} - v\frac{\partial\theta'}{r\partial\lambda} - w\frac{\partial\theta'}{\partial z} - F_\theta$$

- Using a variational approach to solve this set of equations

Retrieval Methodology

1) **Assimilate radar** and other observational data with variational approach
2) Calculate the **mean state** by integrating the thermal wind equation
3) Retrieve buoyancy and pressure perturbations with **thermodynamic retrieval**



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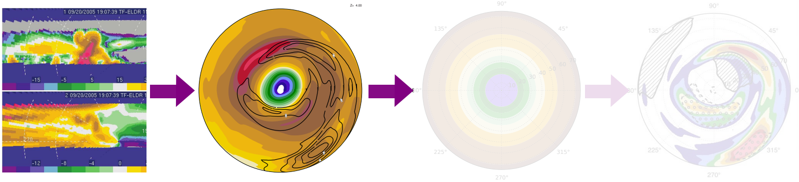

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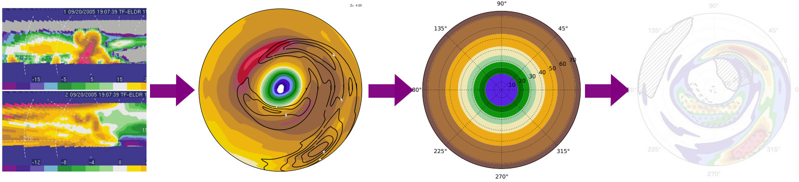

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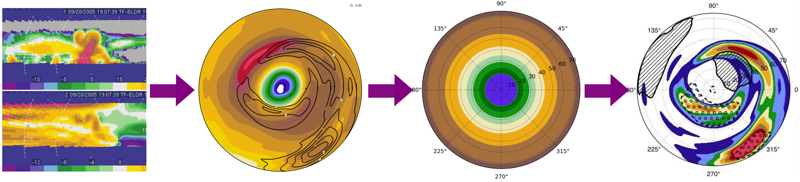
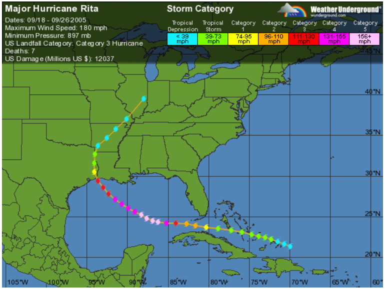
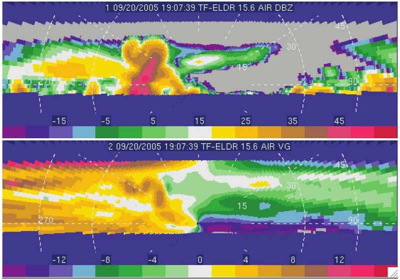
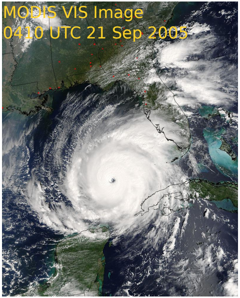
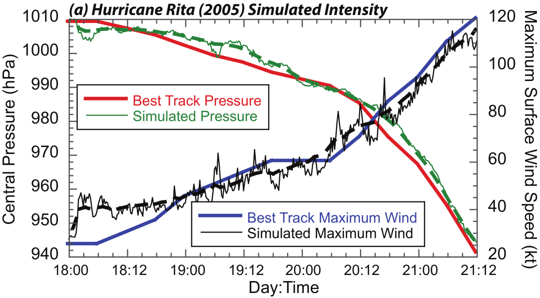


RAINEX Hurricane Rita (2005)







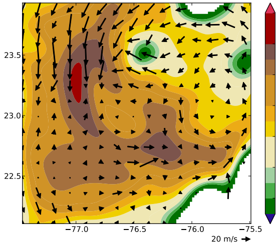


Step 1) Assimilation of Radar Data

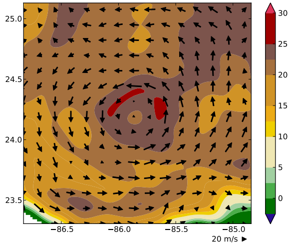
SAMURAI (**S**pline **A**nalysis at **M**esoscale **U**tilizing **R**adar and **A**ircraft **I**nstrumentation) Bell et al. (2012)

- Maximum likelihood estimate by minimizing a cost function
- Galerkin approach (basis are cubic B-splines)
- Incorporating multiple data sources
- Analysis output on regular grid (Cartesian or cylindrical)

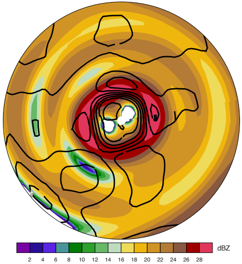
19 September 2005



21 September 2005



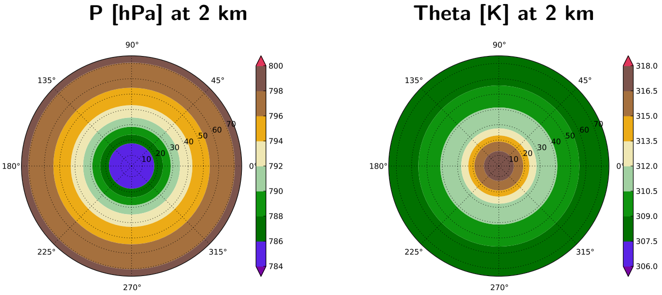
21 September 2005



Radar Reflectivity [dBZ] at 2 km

Step 2) Calculate Balanced Mean State

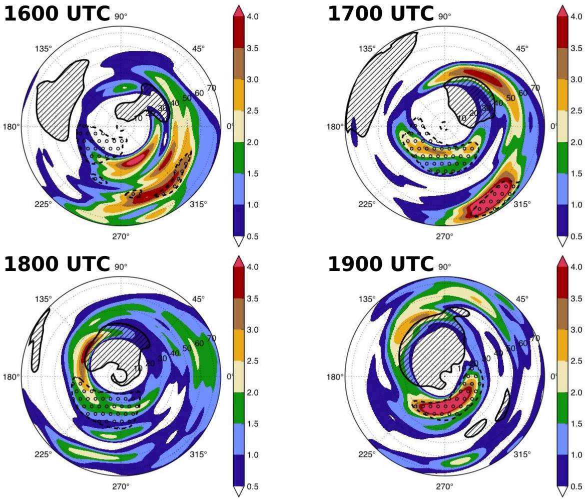
- Vortex in hydrostatic and gradient wind balance
- Start with sounding at the outer edge of the domain
- Integrate thermal wind balance inward along isobaric surfaces



- Retrieves pressure minimum and warm core
- Changes with radius and height

Step 3) Thermodynamic Retrieval (Synthetic Observations)

Precipitation mixing ratio [g/kg]

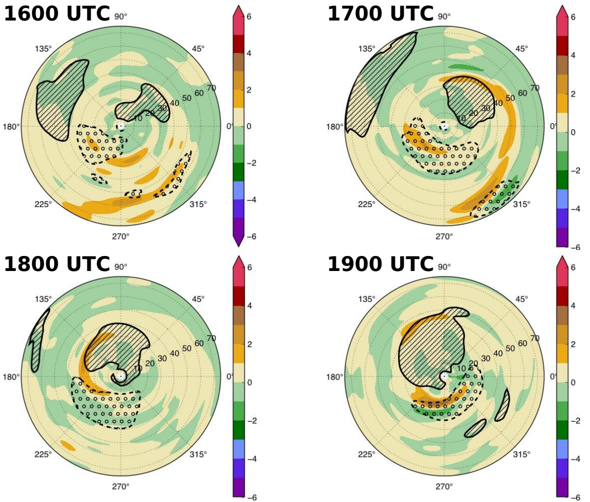


- Rainbands rotating cyclonically
- Buoyancy anomalies are associated with convection
- Mature convection shows waterloading

Buoyancy [m s^{-2}]: > 0.03 (hatched), < - 0.03 (stippled)

Step 3) Thermodynamic Retrieval (Synthetic Observations)

Vertical motion [m/s]

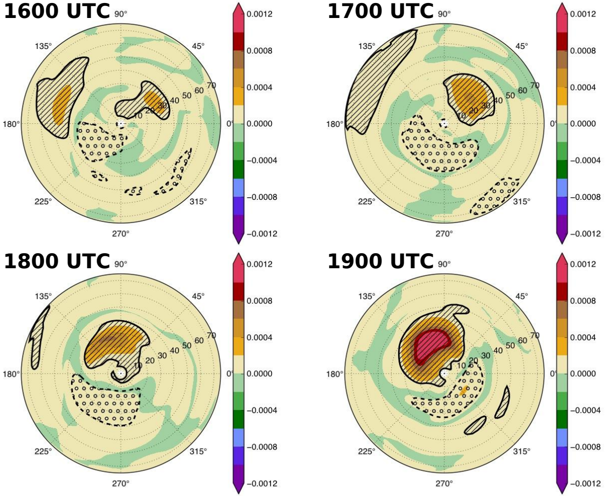


- Positive buoyancy anomalies are associated with upward motion
- Water loading is associated with downward motion

Buoyancy [m s^{-2}]: $>$ 0.03 (hatched), $<$ - 0.03 (stippled)

Step 3) Thermodynamic Retrieval (Synthetic Observations)

Perturbation pressure gradient [m s^{-2}]



$$\frac{dw}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g$$

$$= -c_p\bar{\theta}_\rho \frac{\partial \pi'}{\partial z} + g\left(\frac{\theta'_\rho}{\bar{\theta}_\rho}\right)$$

- Two large opposing terms

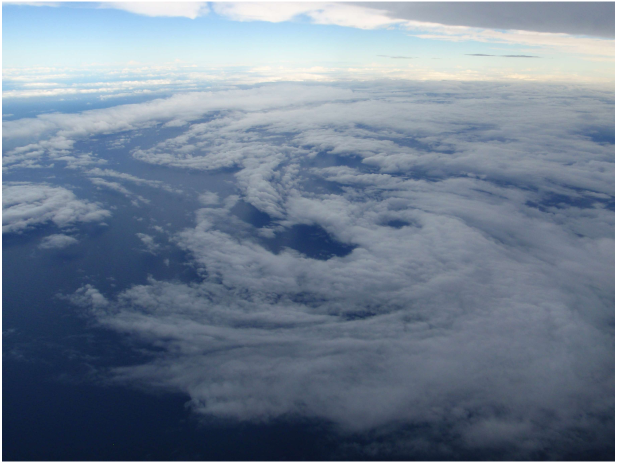
Buoyancy [m s^{-2}]: $>$ 0.03 (hatched), $<$ - 0.03 (stippled)

Summary

- **Location** of bursts seems critical in **intensification efficiency**
- **Buoyancy** is one of the possible internal forcing mechanisms
- Thermodynamic retrieval of buoyancy from **radar data** using variational approach
- Preliminary results are promising
- Future work
  - Calculate buoyancy for different stages of the TC **lifecycle**
  - Compare results for **simulated** and **real** radar data
  - Compare rapid **intensifiers** with **steady state** storms
  - Investigate the interaction between **buoyancy**, **vorticity asymmetries** and **agradient winds**

Thank you for your attention!

Questions?



Reference State

- **Zhang et al. (2000):**
    - MM5 simulation of Hurricane Andrew (1992)
    - Horizontal resolution $\Delta x = 6$ km
    - Running average over four neighboring points
- **Eastin et al. (2005):**
    - 1-Hz flight level data from 25 flights into 14 intense hurricanes
    - Running Bartlett filter with a 20-km window
- **Braun (2002):**
    - MM5 simulation of Hurricane Bob (1991)
    - Horizontal resolution $\Delta x = 1.3$ km
    - Wavenumber 0 and 1 of the Fourier decomposition (balanced vortex)