U.S. NAVAL RESEARCH LABORATORY

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Convective Envelopes in a Sheared, Rapidly Intensifying Tropical Cyclone

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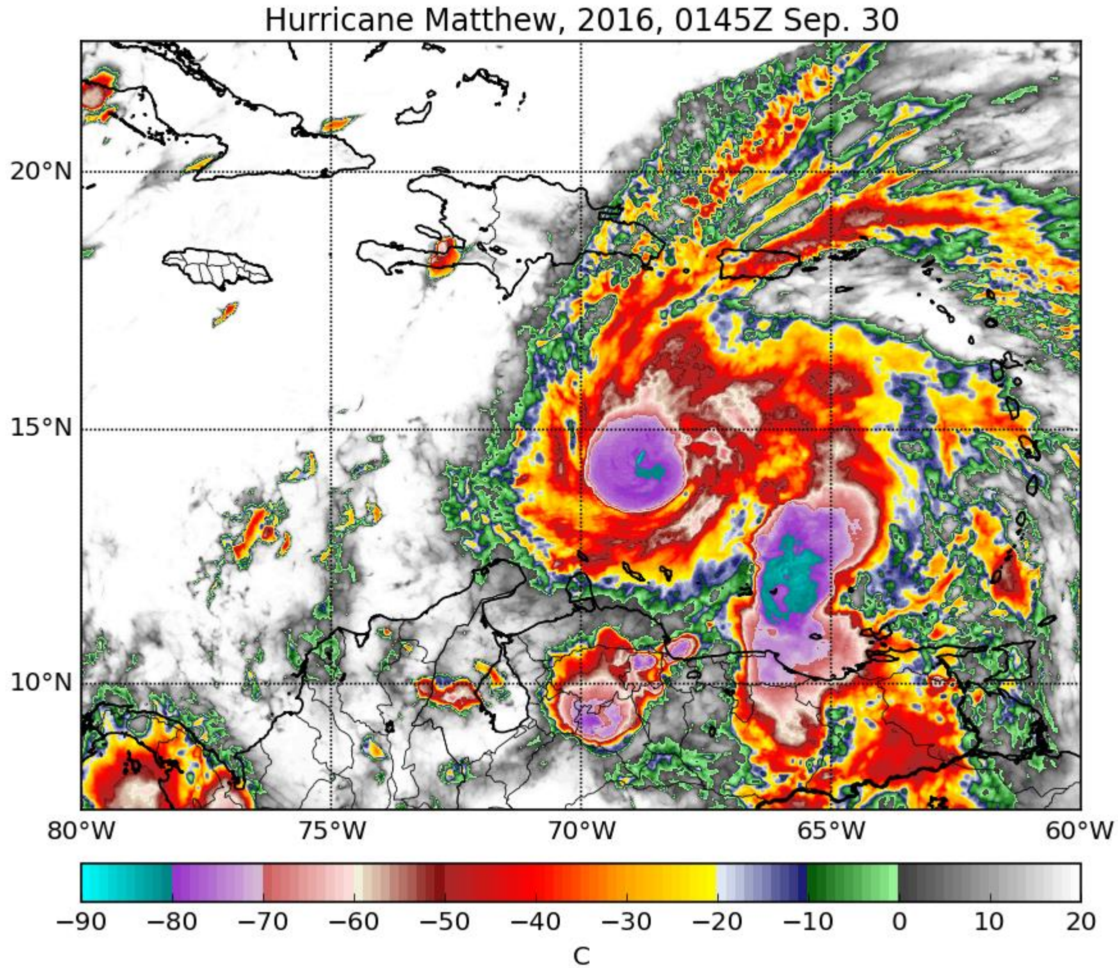
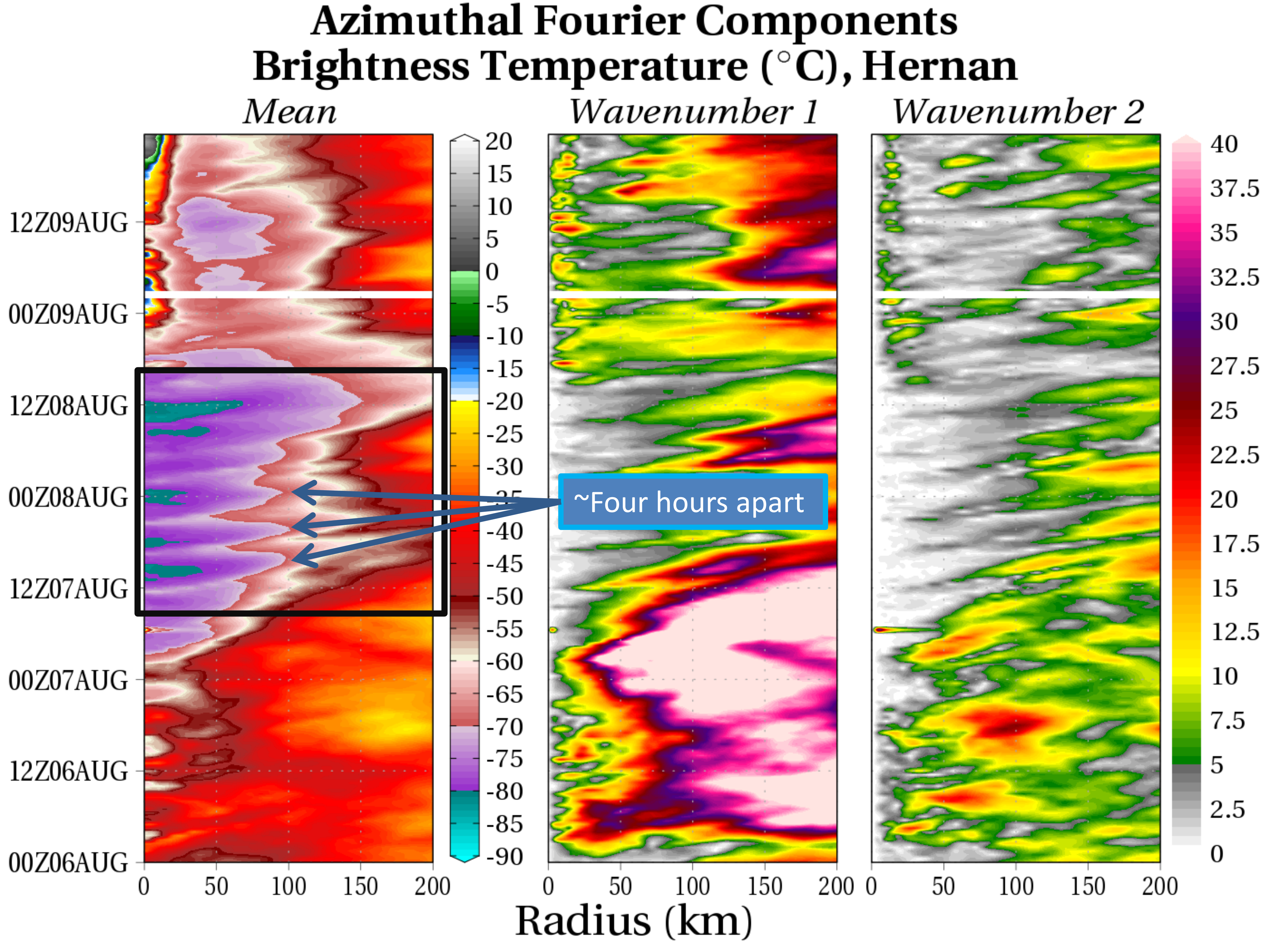
Objective

- Simulate a TC with periodic, repeating "convective envelopes" which also undergoes rapid intensification in moderate (~7 ms^{-1}) vertical wind shear
  - 1997 EPAC Guillermo
  - 2008 EPAC Hernan
  - 2008 EPAC Norbert
  - 2012 EPAC Daniel (NEW)
  - 2012 EPAC Fabio*
  - 2015 EPAC Hilda
  - 2015 NATL Joaquin
  - 2016 EPAC Blas (NEW)
  - 2016 EPAC Darby* (NEW)
  - 2016 NATL Matthew (NEW)



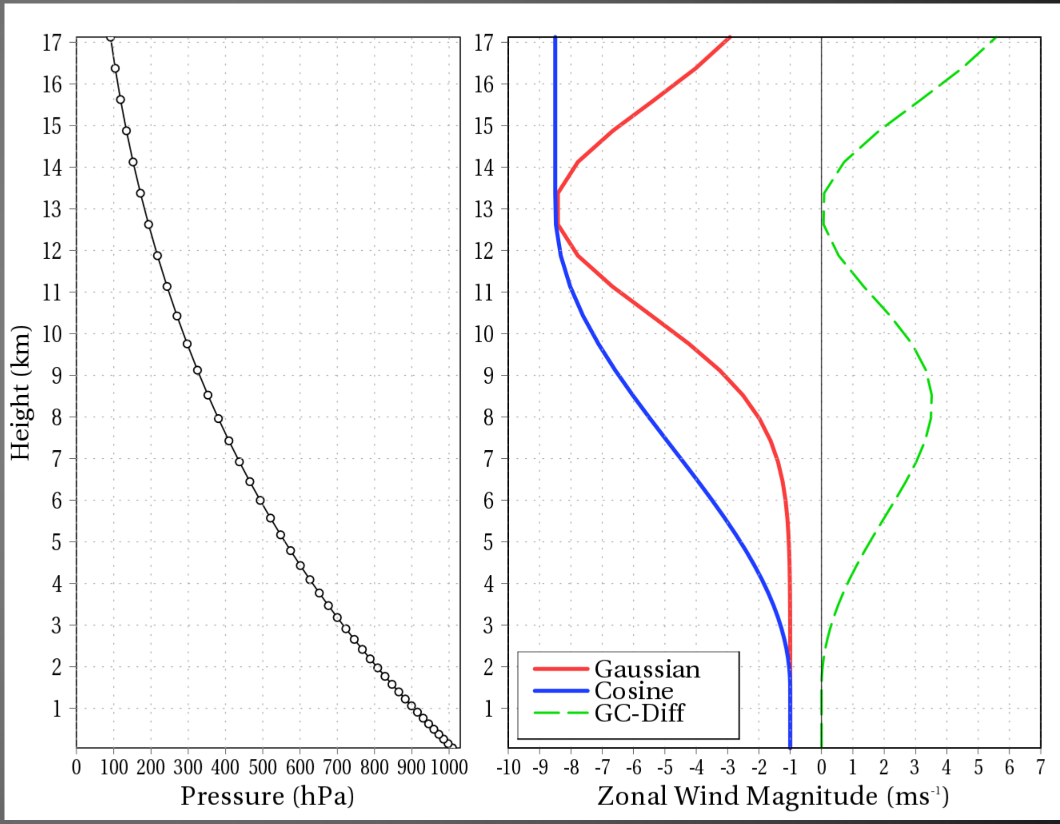
Hurricane Matthew, 2016, 0145Z Sep. 30
20°N
15°N
10°N
80°W
75°W
70°W
65°W
60°W
−90
−80
−70
−60
−50
−40
−30
−20
−10
0
10
20
C



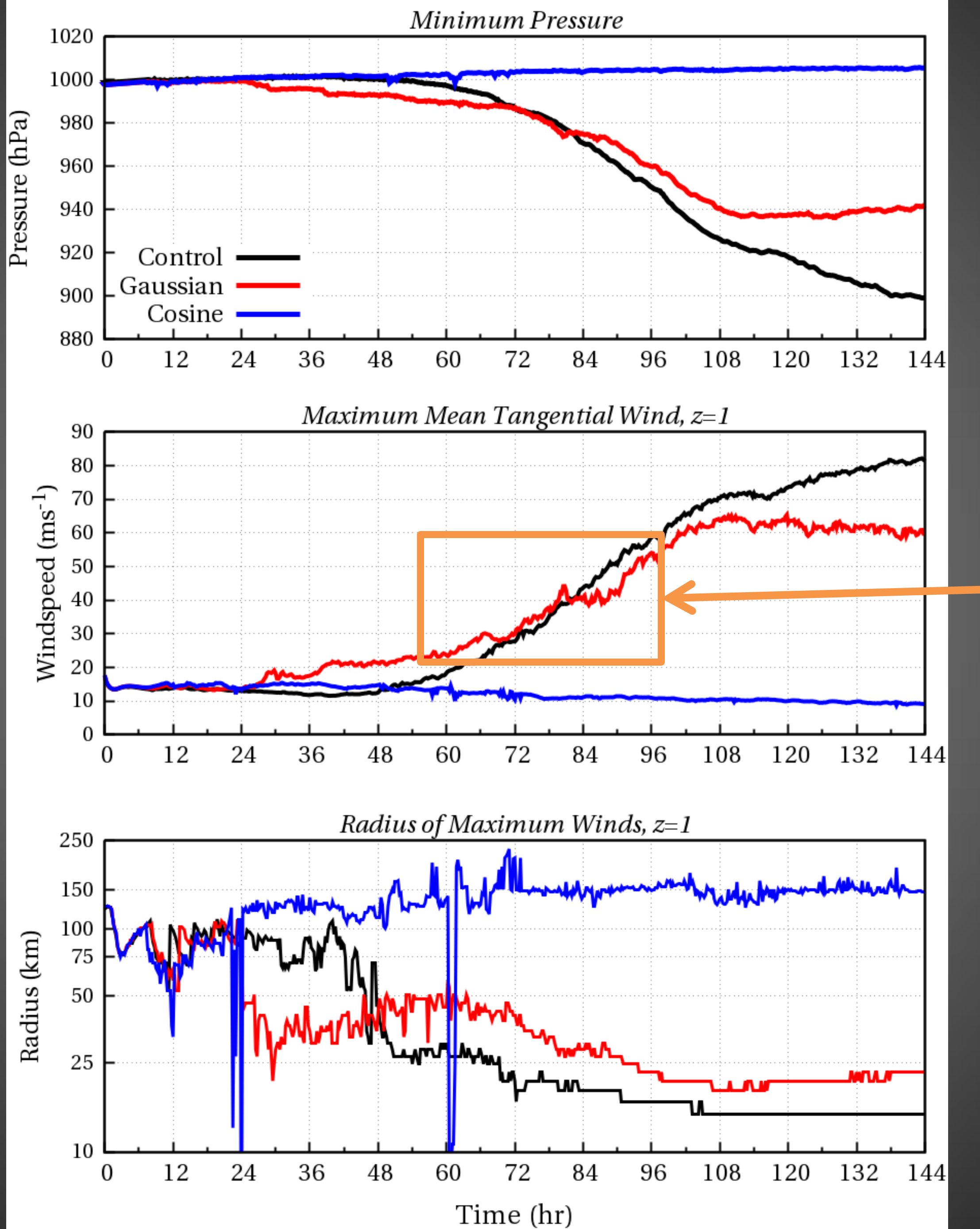
Azimuthal Fourier Components
Brightness Temperature (°C), Hernan
Mean
Wavenumber 1
Wavenumber 2
12Z09AUG
00Z09AUG
12Z08AUG
00Z08AUG
12Z07AUG
00Z07AUG
12Z06AUG
00Z06AUG
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-40
-45
-50
-55
-60
-65
-70
-75
-80
-85
-90
40
37.5
35
32.5
30
27.5
25
22.5
20
17.5
15
12.5
10
7.5
5
2.5
0
~Four hours apart
0
50
100
150
200
Radius (km)

Sheared TC Simulation

- Observations
  - All the TCs, except Matthew, are sheared by an upper-level anticyclone (UL AC)
  - UL ACs are, in an idealized sense, limited to near the tropopause
    - Matthew's background winds are similar
- Theory:
  - This wind profile allows for a special RI pathway
- Model:
  - CM1 (Bryan and Fritsch 2002)
  - 7.5 ms^{-1} shear (obs)



Diagnostics



Steady Growth, Levelling Off, Second Period of Rapid Growth

Vertical Tilt

- As with all sheared TCs, the simulated TCs tilt with height
- Unexpectedly, the storm rotates out of phase with respect to itself
  - Consistent, regardless of center-finding method

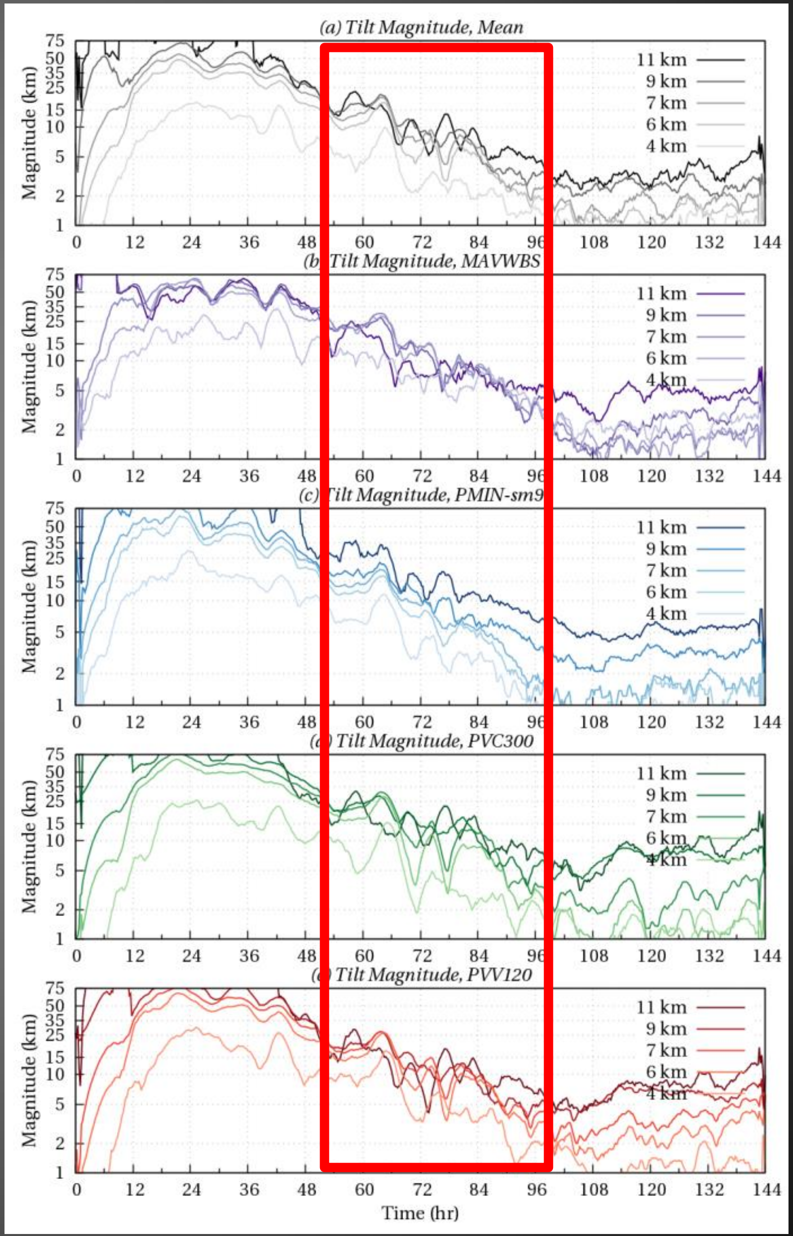
➢ MEANC: Mean of all centers

➢ MAVWBS: HRD method

➢ PMIN-SM9: Pressure minimum of smoothed pressure field

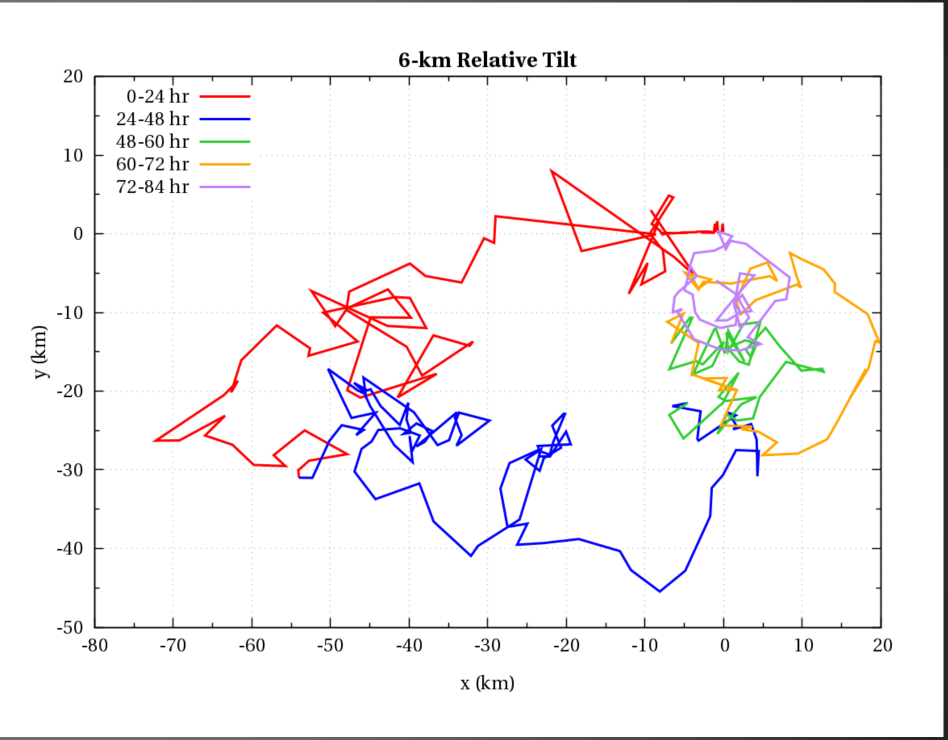
➢ PVC300: PV Centroid, 300 km box

➢ PVV120: PV-Vorticity centroid blend, 120 km box



Vertical Tilt (cont'd)

- Ultimately, the most important evolution is that of the mid-level center until the second RI period (90 hours)
- Tilt grows out to 24 hours, slowly begins the realignment, then orbits left-of-shear axis
- Right: 6 km storm-relative PVV120 center
- Agreement with idealized studies (Reasor and Montgomery 2015; Finocchio et al. 2016)

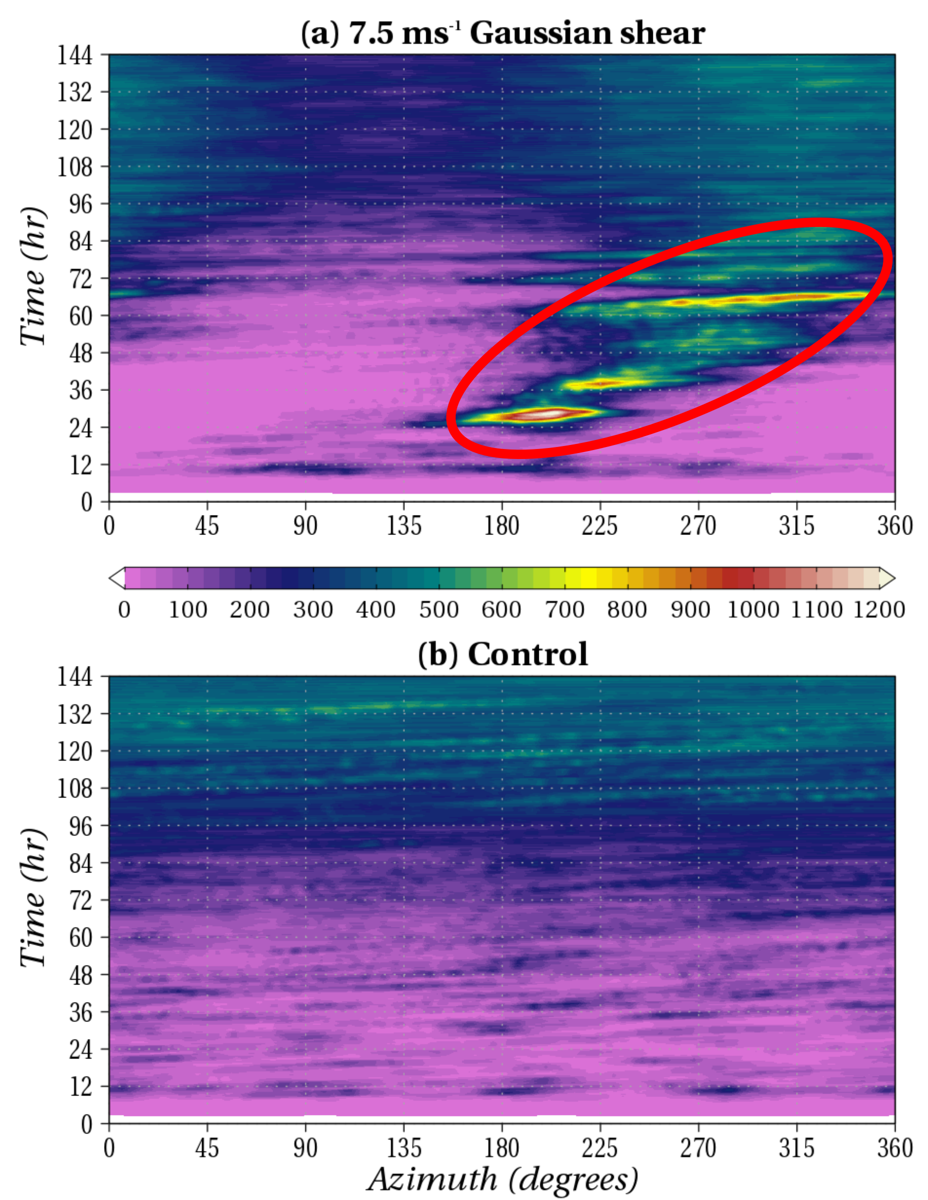


Convection

- A different way to view convection: Total Condensed Water of the Column (TCWC)

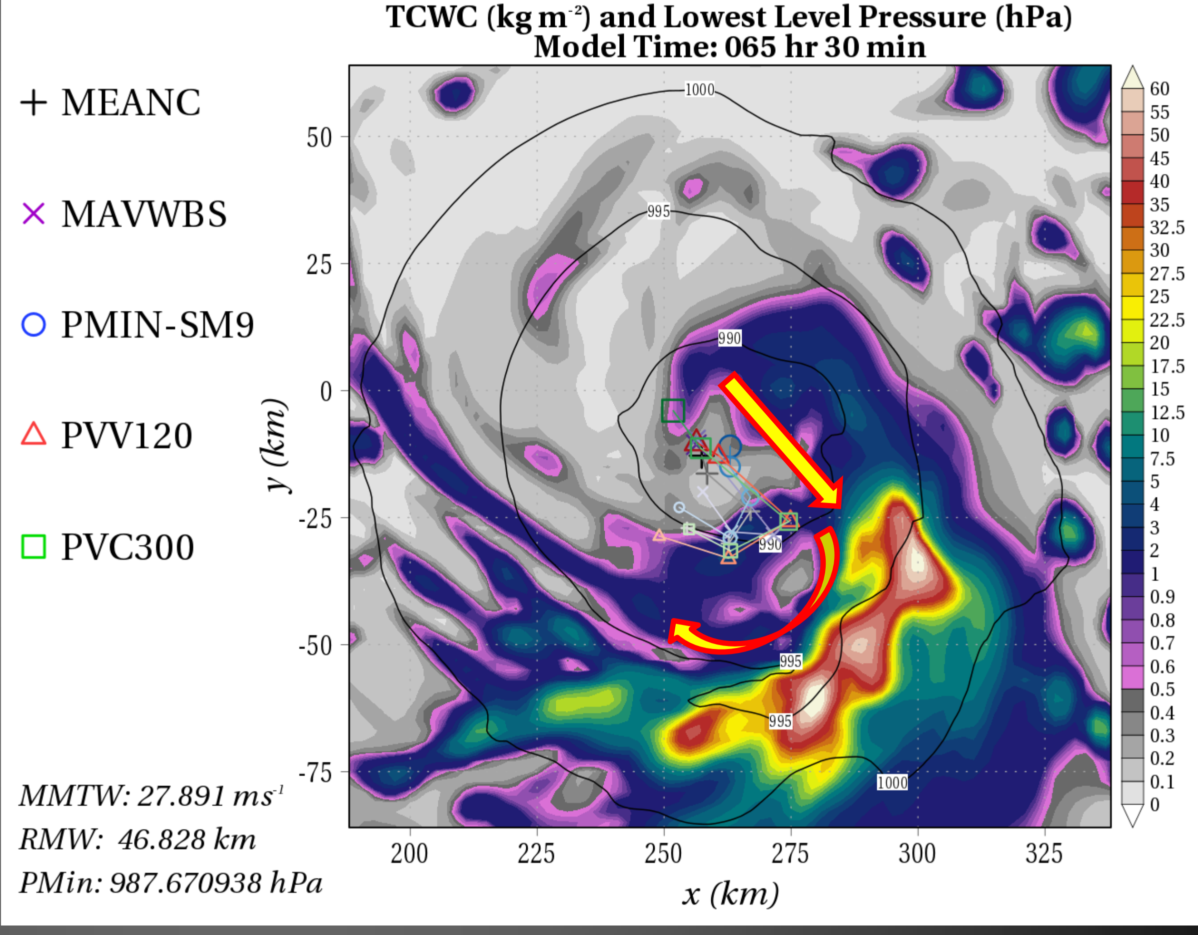
$$TCWC = \int_0^{z_{top}} \rho\left(r_c + r_r + r_i + r_s + r_g\right)dz$$

- Incorporates both liquid and ice water paths
- Vertically integrated throughout depth of column
- At right, radially summed (0 to 100 km) TCWC, smoothed 2.5-hour running mean



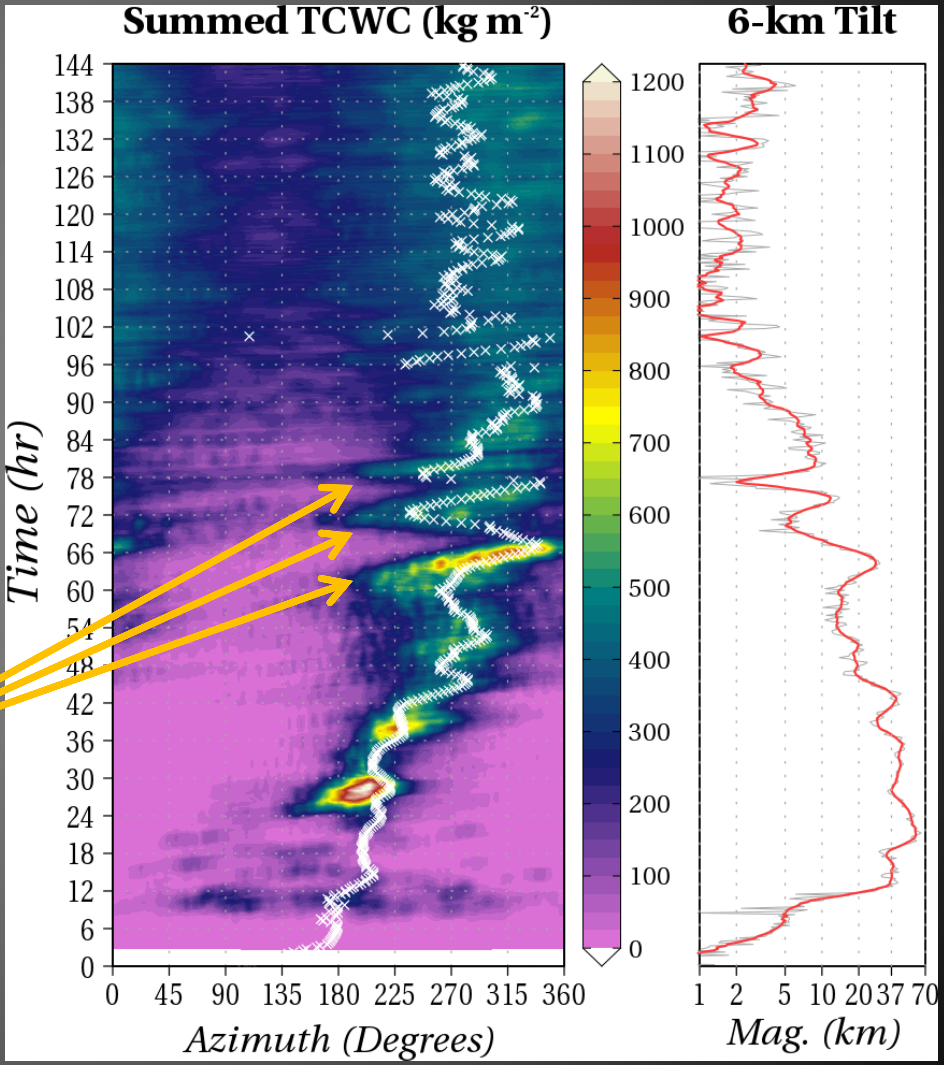
Convection and Tilt

- Right –
  - Darker, larger icons are lower levels
  - Centers at 1 km, 3 km, 6 km, 9 km, and 11 km
- Strongest convection and tilt angle up to mid-level center (6 km) appear to be co-located
- Tilt of vortex above 6 km bends back downshear



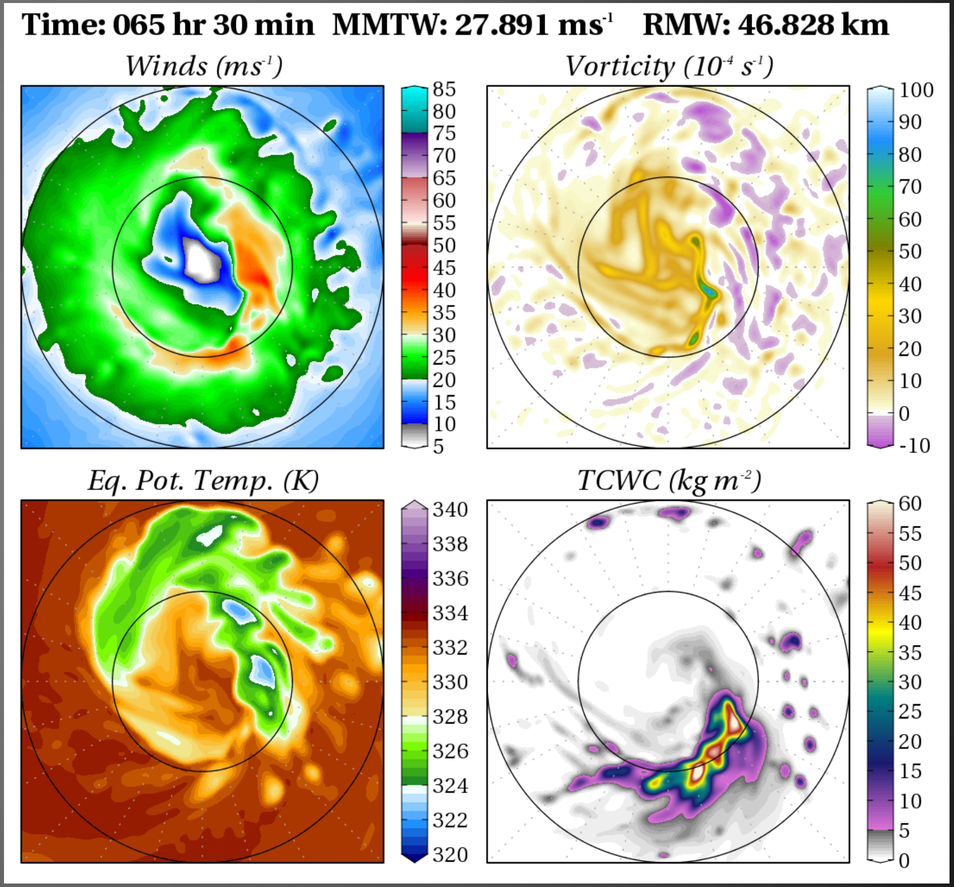
Convection and Tilt (cont'd)

- At right, radially-summed TCWC and 6-km tilt angle (white crosses), smoothed with 2.5-hour running mean
- Clear association between tilt and convection
- Strongest convection is associated with counter-clockwise tilt rotation
- Three convective envelopes



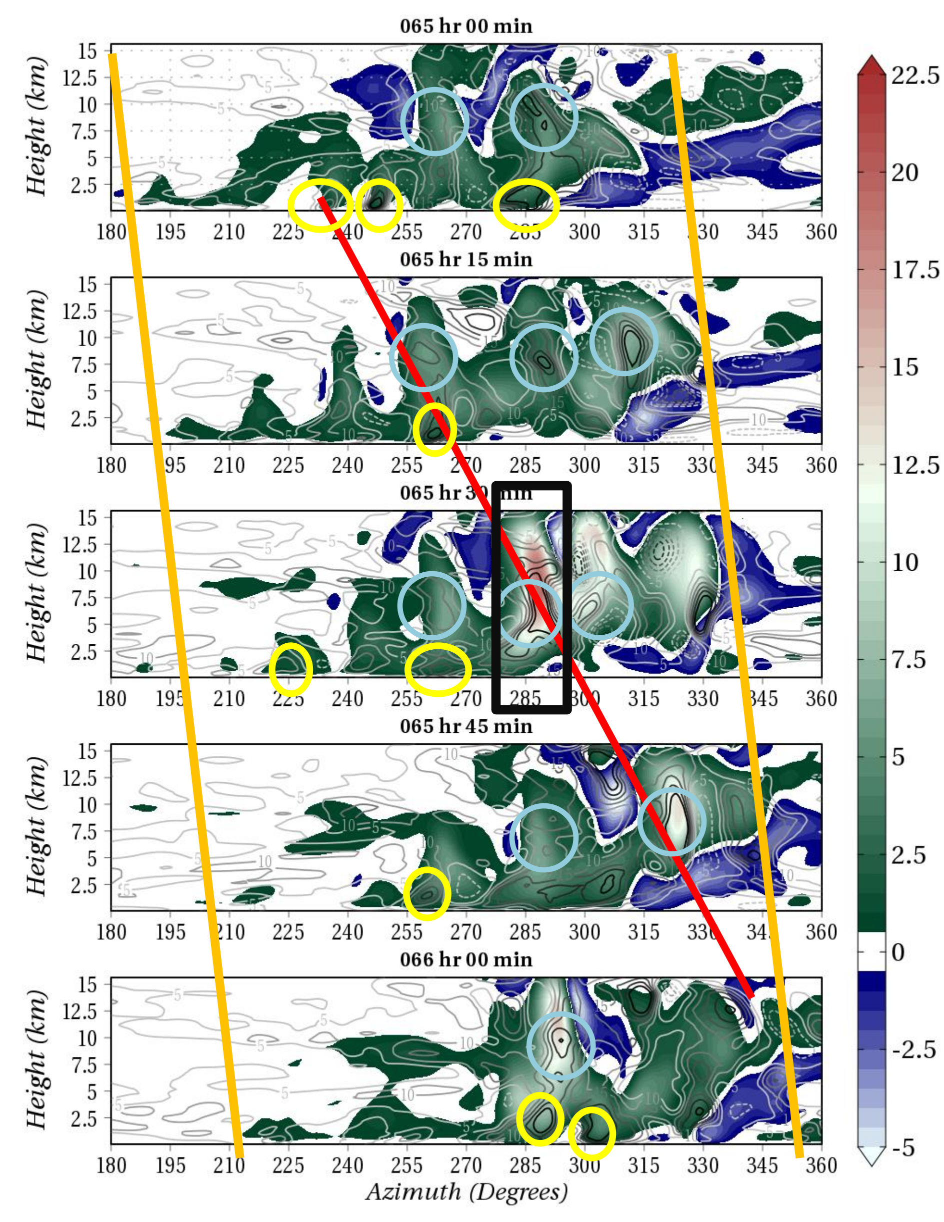
Low levels of the TC

- Convection maximum on southeastern side
- Wind and vorticity maxima are located downwind (eastern side)
- Depressed values in equivalent potential temperature also downwind (eastern to northern side)
  - Rain out
  - Downward flux of upper-level air caused by outflow-environment interface (different talk)



Azimuthal Cross-Section Through Convective Envelope

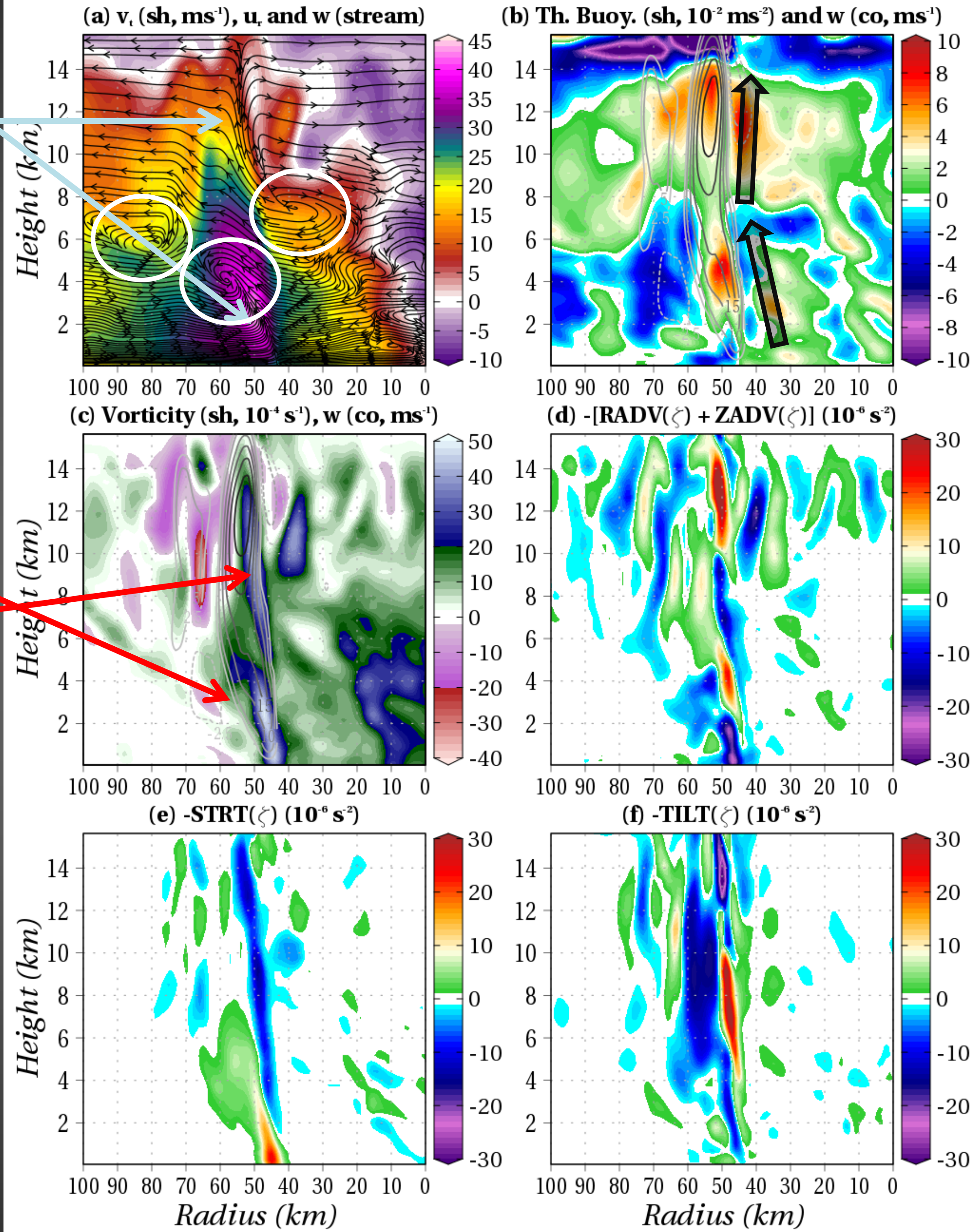
- Right: Vertical velocity (shaded), vertical vorticity (contour)
- Slowly-moving convective envelope
- Assuming cells move with tangential wind: 28 degrees per 15 minutes
- Localized vorticity maxima in boundary layer
- Secondary (in vertical) vorticity maxima at ~8 km
- Isolate strongest updraft:
  - 65 hr 30 min, 285°



- Two vertical velocity pathways
- Roll vortices?

- Two main vorticity regions
  - Inside updraft
  - Inner-edge

- Stretching at low levels (Montgomery et al. 2009)

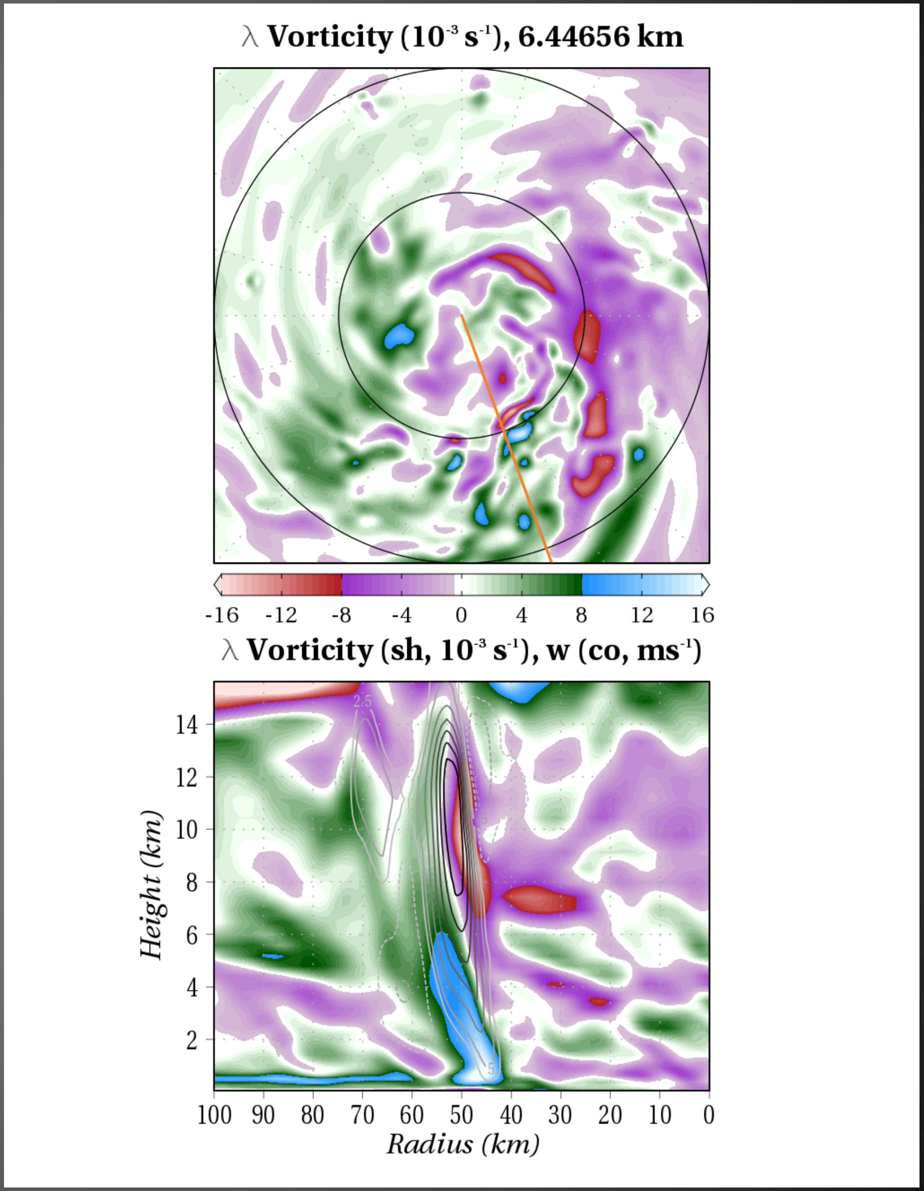


- Updraft shifts radially inwards
- Thermally buoyant all the way up (relative to time-mean field)
- (Contours are 2.5, 5, increment by 5 ms^{-1})

- Large tilting at middle levels (consistent for other updrafts in envelope)

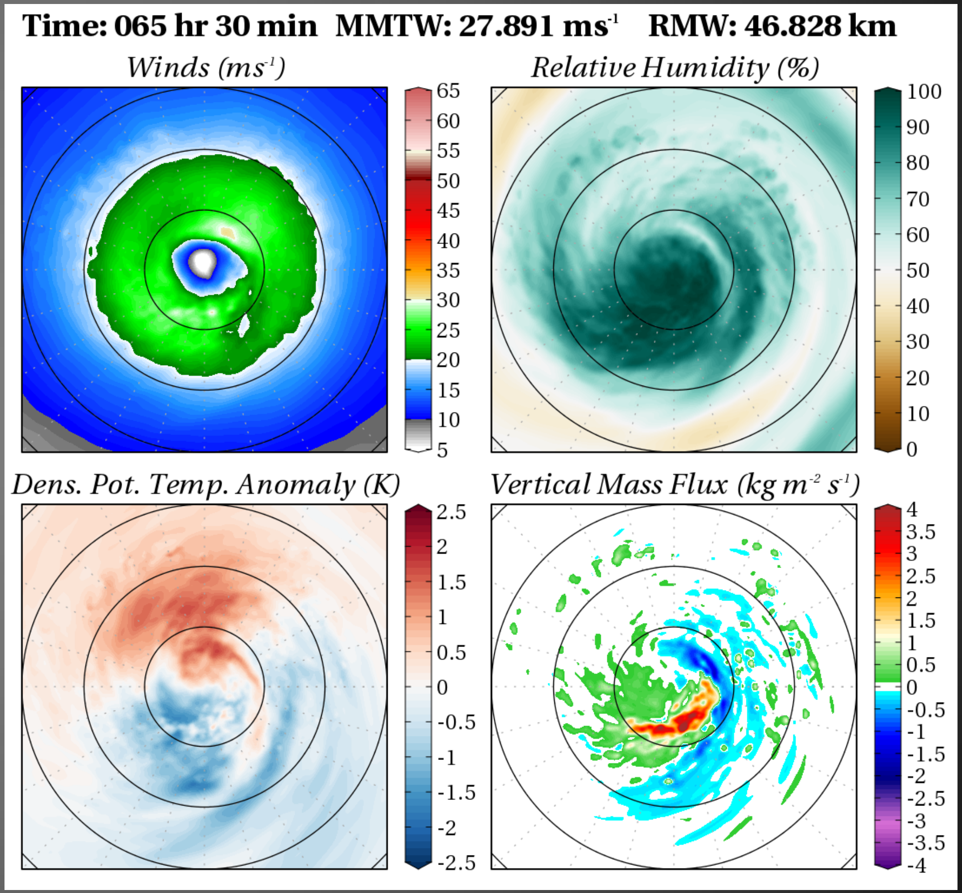
Roll vortices?

- Vertical velocity cores appear to be very intense
  - Nothing really comparable in the control run
- Updrafts create a series of roll vortex couplets, as per azimuthal vorticity
- Source of large tilting term appears to be roll vortex on inner edge
  - Angle shift aids this process?
  - Spins up the mid-level center (different talk)



Buoyant updrafts

- Fields filtered with 2.5-hour running mean
- From a *tilt-relative* perspective, cold anomaly exists down tilt
  - Thermal-wind-balanced response (Jones 1995)
  - Co-located with upward mass flux maximum and relative humidity maximum
- Large downward mass flux region is combination of rain-out and air forced downwards from outflow-environment interaction (different talk)



Summary/Conclusions

- Simulated a shear->RI tropical cyclone
  - Primed by background environmental flow, both depth and magnitude
- Strongest convection follows the precession of the mid-level tilt
  - Induces long-period convective anomalies, herein named "Convective Envelopes"
- Updrafts within these envelopes tilt outwards at low levels, become vertical at mid levels
  - Thermally buoyant throughout their existences
  - Create roll vortices, which then generate positive vertical vorticity by tilting
- Outflow from updrafts then blocks environment; tilting spins up mid-level vortex
  - "That's another show"

BONUS SLIDES!

Satellite imagery