Analysis of Rapid Intensification Mechanisms in Producing and Altering the Distribution of Intense Convection in Three Numerically Simulated Tropical Cyclones

Kathryn A. Shontz* and Kristen L. Corbosiero

Masters Thesis Research

Department of Atmospheric and Ocean Sciences

University of California Los Angles, Los Angeles CA 90025

STAR Science Forum Seminar

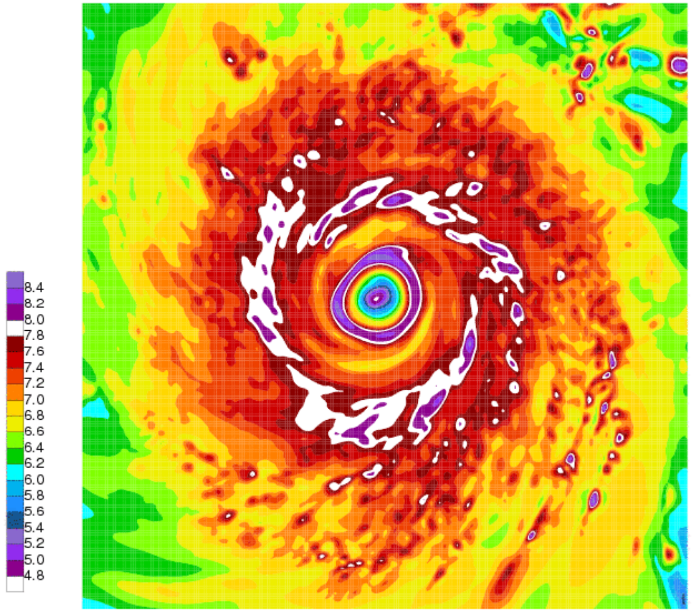
*Center for Satellite Applications and Research

National Environmental Satellite, Data, and Information Service

NOAA Science Center, Camp Springs MD 20746

March 12, 2010

Outline and Purpose

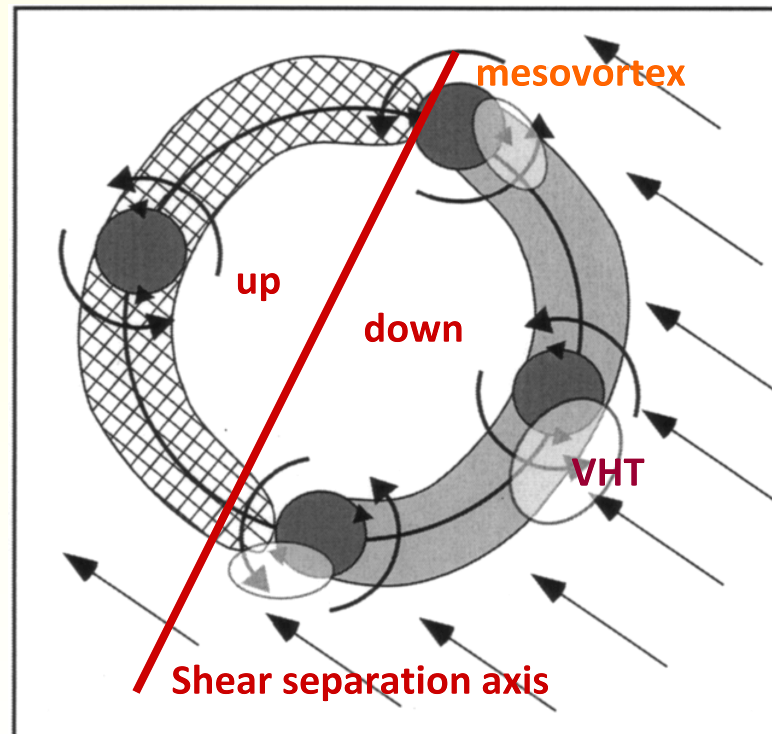


- Introduction
  - Motivation
  - Advanced Hurricane WRF model
  - Data analysis
- Simulated Cyclones Known to have Undergone Rapid Intensification
  - *Katrina* (24-29 August 2005)
  - *Gordon* (11-17 September 2006)
  - *Felix* (31 August - 5 September 2007)
- Summary and Conclusions

The goal of this work is to note how mechanisms associated with strong environmental vertical shear generate asymmetric convection within numerically simulated hurricanes which possess extreme values of storm-relative helicity and are historically known to rapidly intensify.

Motivation: Brief Literature Review

- Persing and Montgomery (2003) first introduced the concept of a "vortical" hot tower (VHT) to explain large convective bursts in the eyewall, created by advection of elevated eye θ_e, which locally enhance updrafts.
- Braun et al. (2006) intrinsically linked VHTs and eyewall mesovortices noting this is one process which can lead to rapid intensification (RI) in hurricanes.
- Molinari and Vollaro (2008) then combined the two concepts and asked whether VHTs are supercell thunderstorms and if the RI of Hurricane Bonnie (1998) follows the arguments Braun et al.:
  - Bonnie did undergo RI, coincident with a maximum in VHT production.
  - Though eyewall CAPE was modest, intense storm-relative helicity (SRH) values were extreme.
  - The environment was capable of supporting supercell thunderstorms via evaluation of the EHI and SCP supercell indices.



Braun et al. 2006

Motivation: Research Applications within NWP

- Rapid Intensification (RI) within a tropical cyclone is defined as a 24-hr change in:
  - Central pressure, decreasing at least 20 hPa.
  - Maximum sustained winds, increasing at least 15 m s^{-1}.
- How well do numerical simulations then represent this theory?
  - Current NWS operational models have great difficulty representing RI and it remains a pertinent concern to hurricane forecasting.
  - High-resolution models, on the order of 1 km grid spacing, have been shown to significantly improve forecasts RI. *(Davis et. al, 2007)*
- Solution is to test whether a high-resolution model can simulate some semblance of RI and be run in real-time.
- But the intensification may not only show up as a function of pressure—other diagnostic fields need to be evaluated to accurately gauge viability.

Hence this research is done using the Advanced Hurricane Weather Research and Forecasting (AHW) model which meets the aforementioned requirements.

Advanced Hurricane WRF (AHW)

- Used in this study is the AHW model, created at NCAR in Boulder, Colorado.
- AHW model runs were compiled at NCAR and employed at UCLA for post-processing of the output files using the wrf2gem program.
- Model specifics:
  - Forecasts are initialized at 0000 UTC with the GFDL model.
  - 12, 4 and 1.33 km nested grids are run; the latter are disturbance-following.
  - The 1.33 km nest begins to output data after a 12 h spinup period whereas the other two nests begin at 0000 UTC on the forecast date.
  - This grid spacing covers an area of 320 by 320 km and is centered on the hurricane and follows it through space-time.
  - Follows the WSM3 microphysics scheme which predicts only one cloud variable (water for $T > 0ºC$ and ice for $T < 0ºC$) and one hydrometeor variable (rain water or snow with the threshold again at 0ºC).
- Only in the 1.33km grid was there a signature of RI; it was one of the first models to capture some semblance of this phenomenon.

Thus, for purposes of this study, the 1.33 km gridded output is used.

Data Analysis

- Model output was verified against the National Hurricane Center's (NHC) Best Track Data set for the following fields:
  - Storm-center tracking of the 500 hPa low pressure center
  - Lowest central surface pressure
  - Maximum sustained surface winds
- Next, the deep-layer environmental shear direction and magnitude were computed by approximating the 850-200 hPa shear vector as a layer difference from the maximum/minimum asymmetrical components of the tangential wind field:

$$\boxed{Shear = \sqrt{(U_{200} - U_{850})^2 + (V_{200} - V_{850})^2}}$$

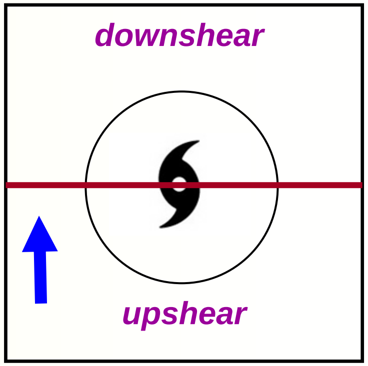
Where $U_{200} = (u_{\min} + u_{\max})_{200}$

for the u-component at the 200 hPa level

- Calculated values were found for the entire wind field, to a radius of 160 km, then validated against the ECMWF and the lowest resolution (12 km) AHW run environmental shears found over a 300 km radius from storm center.

Data Analysis

- Once proven viable, the data was used to create the following fields as GEMPAK graphics that were then rotated into a shear-relative reference frame:
  - Tangential winds at 10m with 850 hPa barbs
  - 850 hPa positive vorticity with contours of vertical velocity*
  - Precipitable water (PW) with 850 hPa positive vorticity contours*
  - 0-6 km storm-relative helicity (SRH) with high PW contours*
  - Most-unstable CAPE (MUCAPE) with high SRH contours*

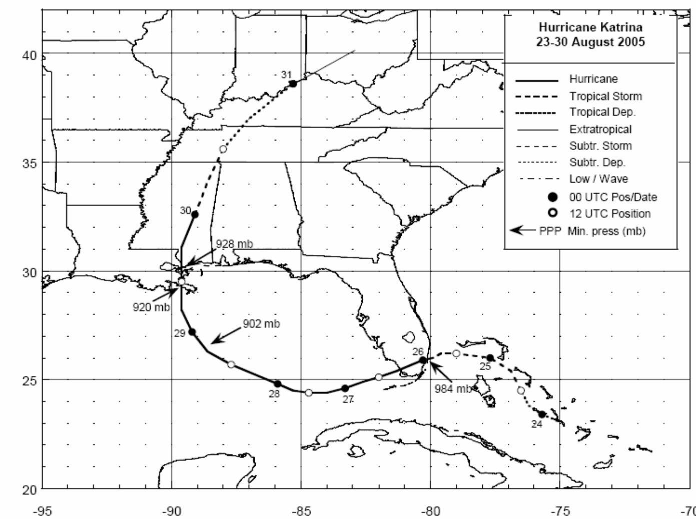


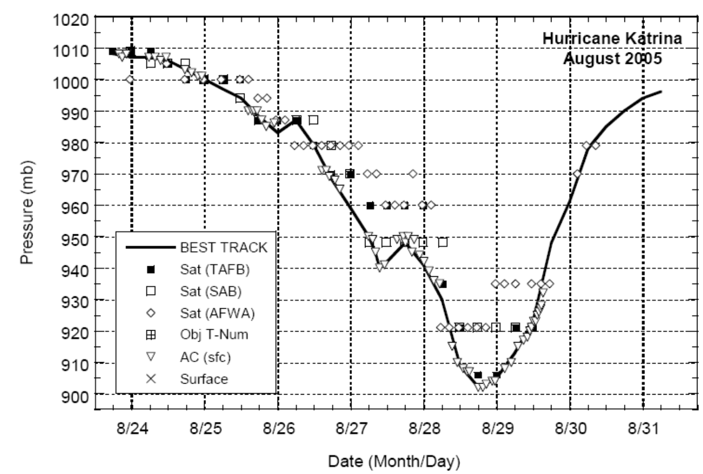
**The last 4 fields are zoomed onto the storm center, at a radius of ~50 km*

- All three tropical cyclones were analyzed when RI was historically the strongest, and data is presented 3 h intervals for this 27 h period.
- Graphics of the above fields were compared against one another and arguments were then made as to whether features resolved by the AHW are consistent with the literature.
- The SRH and MUCAPE fields were used to assess supercell potential within the eyewall; applications to hurricane forecasting were discussed.

Synoptic History of Katrina (24-29 August 2005)

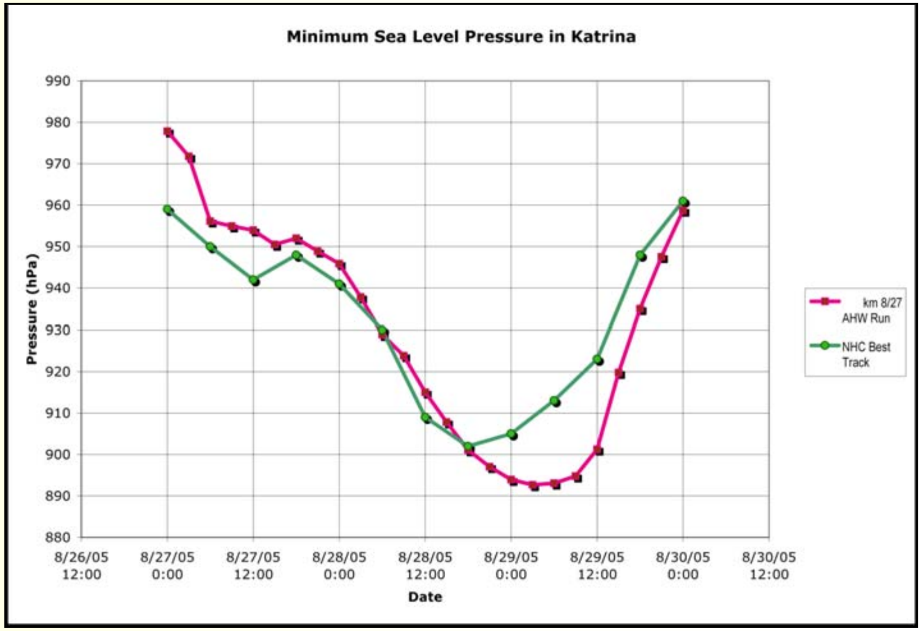
- Katrina strengthened as it interacted with a mid-latitude ridge after emerging from the Bahamas on 24 August.
- Sustained winds reached hurricane strength by 2100 UTC on 25 August as it made landfall in Southern Florida.
- Entering the Gulf of Mexico only 6 h later, the storm intensified with little shearing influenc
- RI began at 0600 UTC 26 August where winds increased 30 kts, making Katrina a Category 3 hurricane.
- An eyewall replacement cycle (ERC) began lat on 27 August, ending in another round of RI where Katrina attained Category 5 status in less than 12 h.
- Central surface pressure minimized at 902 hP and winds maximized at 145 kts before Katrina made a final landfall.

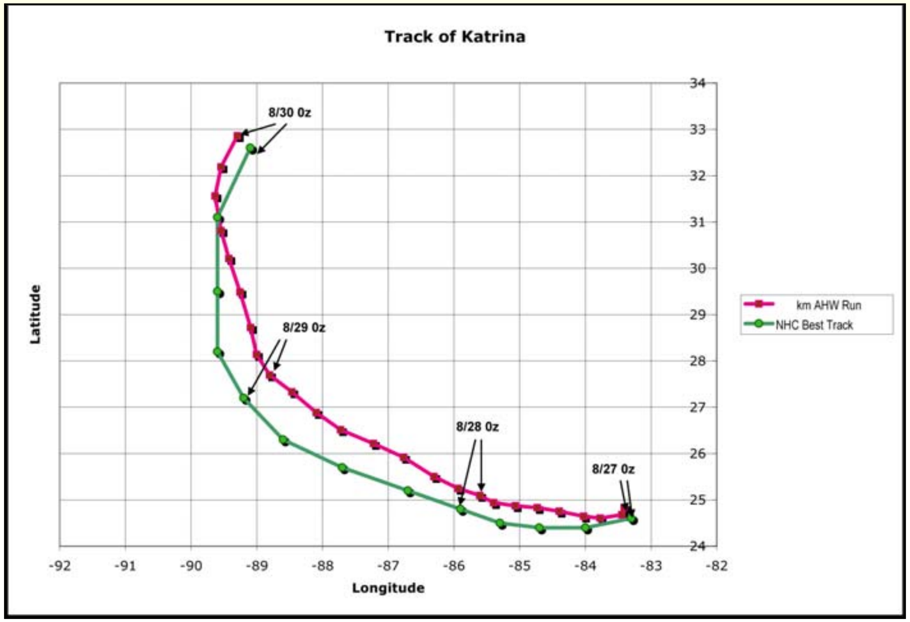


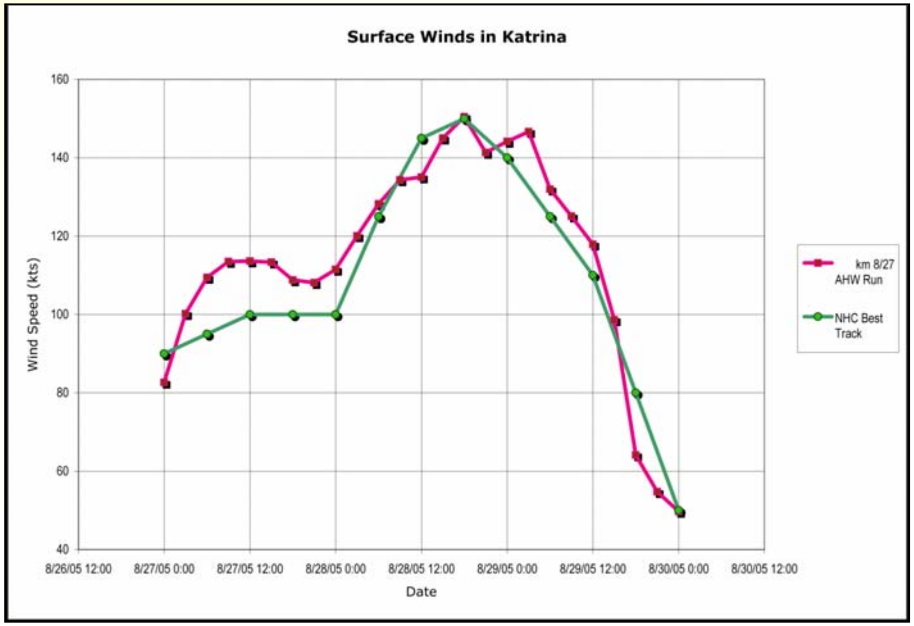


Verification of Katrina

- Track and intensity very well simulated by the AHW.
- This run is a reanalysis of Katrina using different microphysics to best show the intensification.
- But did the AHW capture RI by resolving the right mechanisms?







Calculated Shear in Katrina

Date/Time	Magnitude of Shear ECMWF	AHW12	AHW	Direction of Shear ECMWF	AHW12	AHW
8/27/05 0:00	3.96	5.98		5.64	357.64	2.60
8/27/05 3:00		9.24	21.82		335.16	275.70
8/27/05 6:00	4.61	9.48	28.62	14.67	334.54	347.94
8/27/05 9:00		8.75	23.63		333.76	315.05
8/27/05 12:00	3.43	6.02	30.69	47.34	352.24	67.77
8/27/05 15:00		5.59	10.08		5.15	69.43
8/27/05 18:00	4.10	3.82	2.43	54.89	4.64	54.07
8/27/05 21:00		2.19	6.90		355.94	93.19
8/28/05 0:00	4.43	2.73	11.51	27.05	338.89	98.67
8/28/05 3:00		4.91	21.11		337.82	19.25
8/28/05 6:00	4.32	5.39	12.38	330.56	346.15	352.67
8/28/05 9:00		4.56	9.30		353.29	12.09
8/28/05 12:00	6.08	2.79	12.46	346.20	348.32	36.91
8/28/05 15:00		0.29	3.52		310.39	50.26
8/28/05 18:00	2.24	1.14	8.99	56.49	250.83	315.91
8/28/05 21:00		2.07	9.66		261.52	203.02
8/29/05 0:00	0.68	4.66	5.32	248.66	252.28	290.06
8/29/05 3:00		6.64	23.41		249.27	286.80
8/29/05 6:00	6.56	5.97	26.32	254.14	256.99	277.27
8/29/05 9:00		6.51	18.95		241.09	264.47
8/29/05 12:00	10.10	8.60	26.71	234.64	227.03	207.15
8/29/05 15:00		10.87	23.83		214.34	224.55
8/29/05 18:00	11.71	14.54	33.91	223.77	221.18	217.32
8/29/05 21:00		20.37	41.01		231.89	230.74
8/30/05 0:00	13.44		38.31	228.47		241.20

- 1.33 km AHW shear magnitudes were found to be roughly double that of the other models.
- Directions were more consistent, with a spread of approximately 45˚ across all 3 models.
- Katrina is known to have developed in low shear, so the high-resolution AHW is generating environmental shear this is too strong.
- So did this model reanalysis resolve the previous intensity profiles by erroneously resolving strong shear?

Katrina: Low-Level Winds

- Tangential winds (m s^{-1}) for the entire 320 km radial grid:

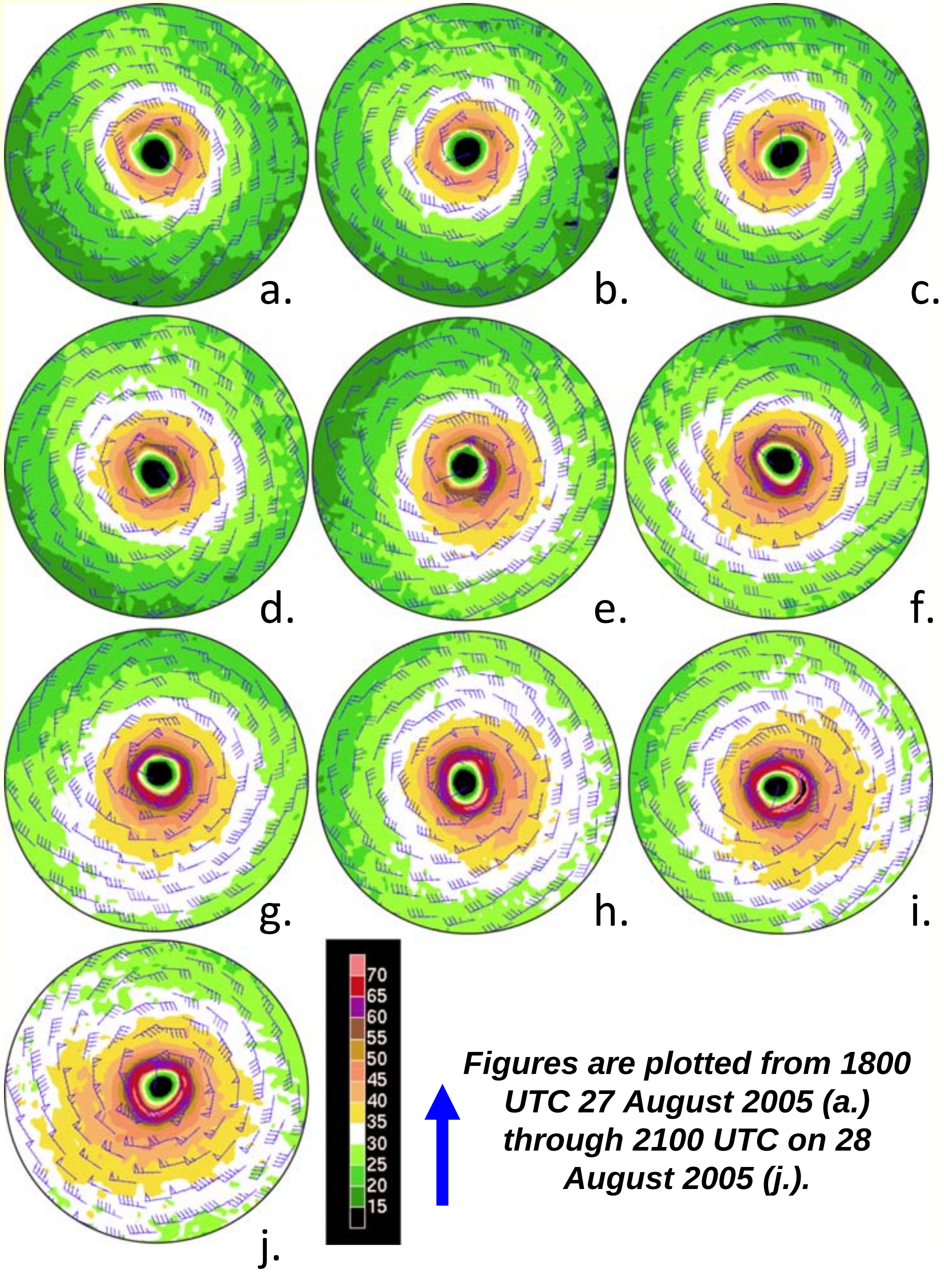
  - Colored filled fields represent the winds at 10 m.

  - 850 hPa tangential winds are given as barbs.

- Tangential winds at both levels increase as Katrina strengthens.

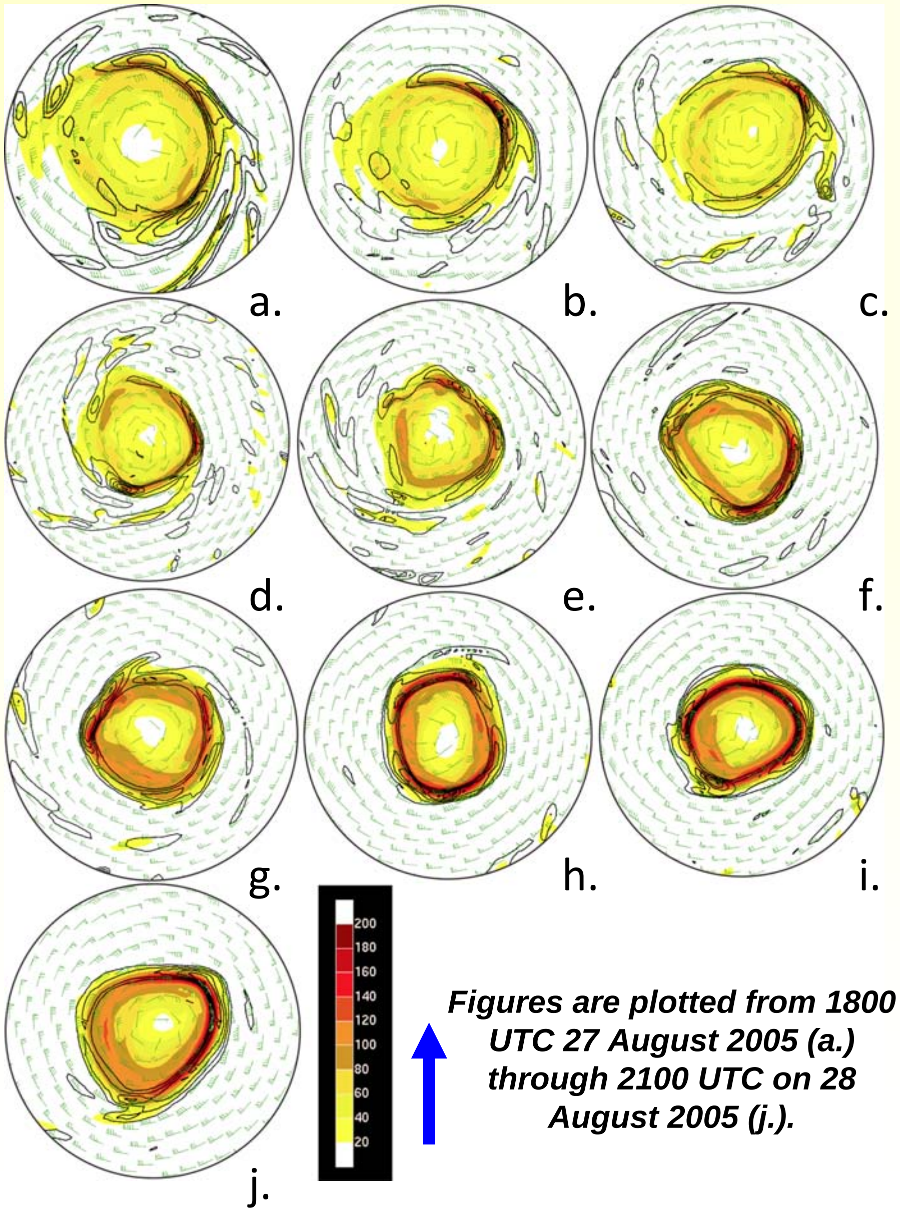
- The strongest eyewall winds show a preference for being stronger to the right of the shear vector.

- Clear maxima in the eyewall wind field are resolved, alluding to the possible existence of VHTs embedded within the eyewall.



Figures are plotted from 1800 UTC 27 August 2005 (a.) through 2100 UTC on 28 August 2005 (j.).

Katrina: Positive Vorticity and Vertical Velocity

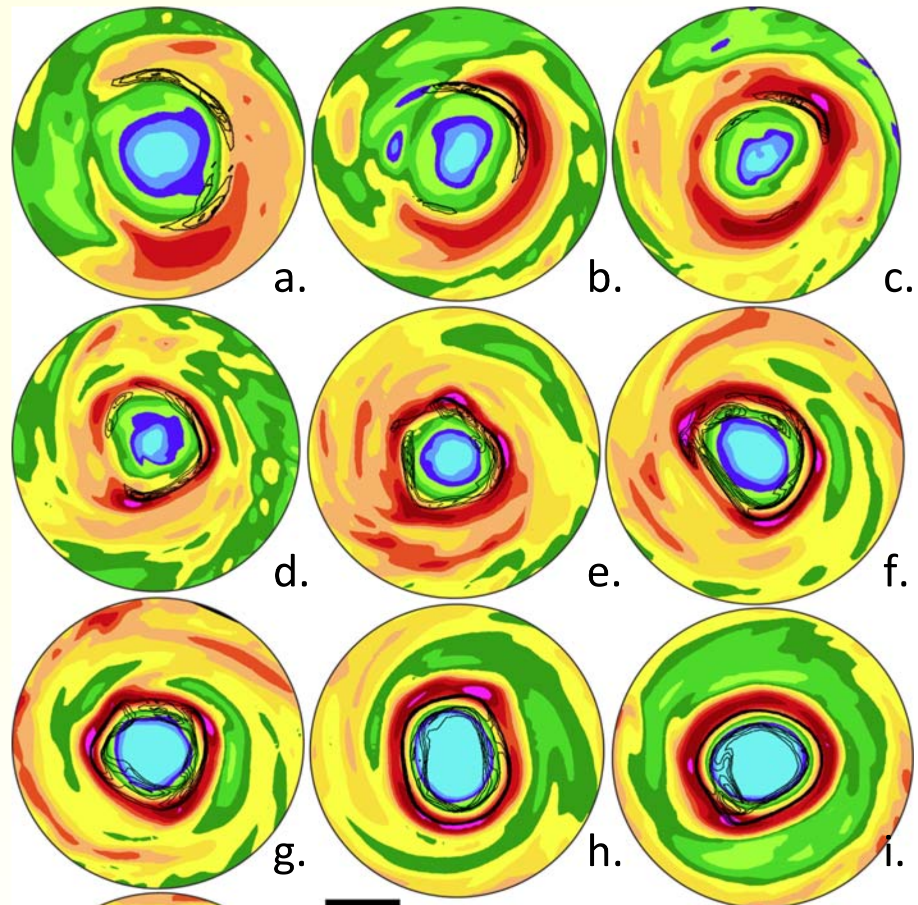


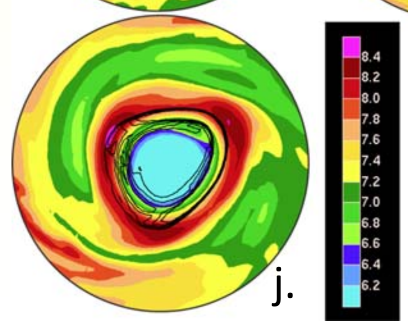
Figures are plotted from 1800 UTC 27 August 2005 (a.) through 2100 UTC on 28 August 2005 (j.).

- 850 hPa positive vorticity values (s^{-1}) define the colored field at a radius of 50 km.
- Overlain are the 850 hPa positive vertical velocity contours from 1-6 m s^{-1}, (plotted every 1 m s^{-1}) with the coordinating tangential winds.
- For the first 15 h analyzed, the low-level vorticity is maximized to the downshear right; strong rising motion lends that the eyewall is firing mesovortices.
- The vorticity becomes much more symmetrical without a regional preference but strong convective cells arise and propagate around the eyewall.

Katrina: Precipitable Water and Positive Vorticity

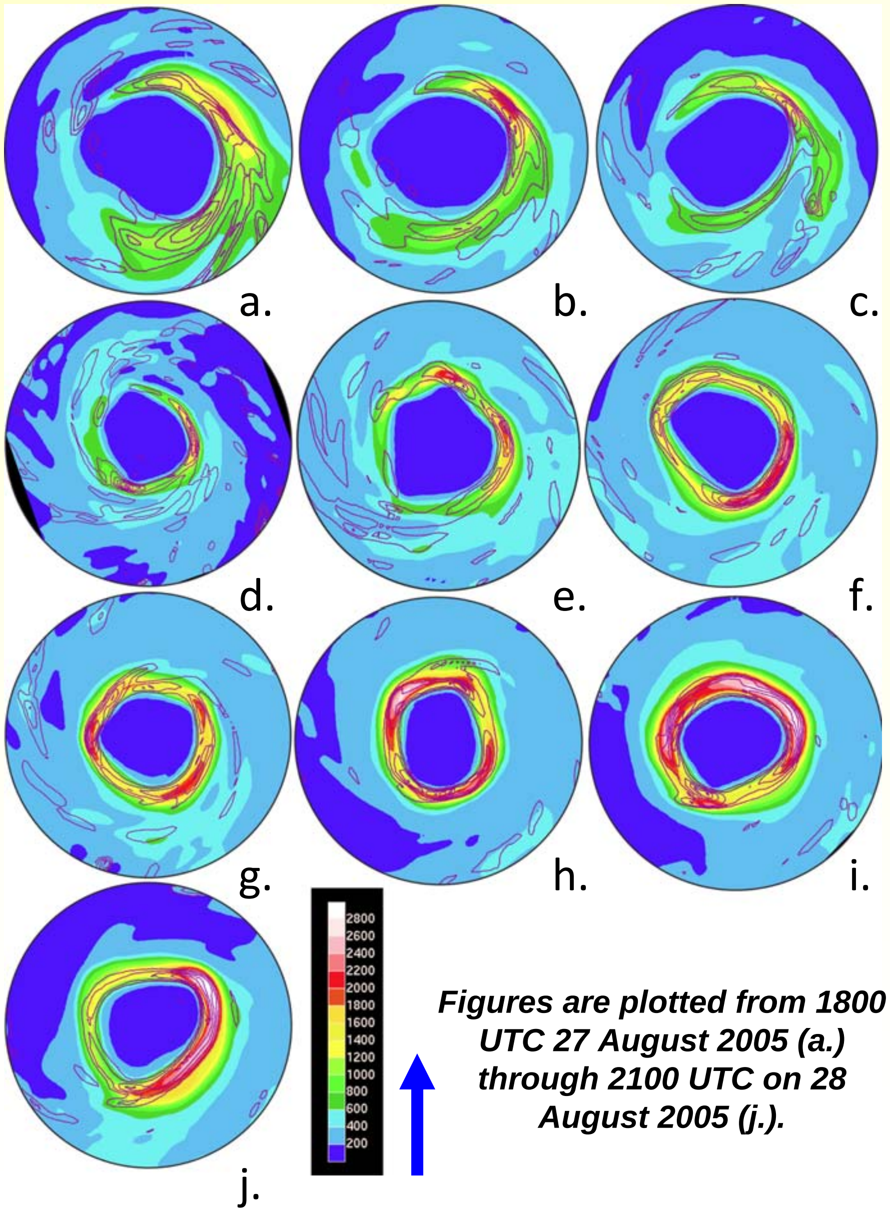
- Column-integrated PW (g kg^{-1}) is plotted as the color field while black contours represent the 850 hPa positive vorticity (contoured every 10 s^{-1} from 60-120 s^{-1}).
- PW highlights the deep convective bursts (VHTs) within the eyewall
- VHTs are reiterated by the vorticity contours and initially favored in the downshear right quadrant, implying the existence of mesovortices.
- The positive anomalies in both fields denote a wavenumber 1 convective asymmetry which then axisymmetrizes around the eyewall with time.





Figures are plotted from 1800 UTC 27 August 2005 (a.) through 2100 UTC on 28 August 2005 (j.).

Katrina: Storm-relative Helicity and Precipitable Water



Figures are plotted from 1800 UTC 27 August 2005 (a.) through 2100 UTC on 28 August 2005 (j.).

- 0-6 km SRH (m^2 s^{-2}) plotted as the the colored field with contours of 850 hPa vertical velocity (from 1-6 m s^{-1} plotted every 1 m s^{-1}).
- SRH highlights the amount of speed and directional change within the storm-relative winds, a measure of sustained deep convection.
- PW maxima and SRH are located atop one another.
- The helicity is an order of magnitude greater than of severe weather in the middle-latitudes.
- SRH and PW maxima are collocated, signaling that these VHTs have rotational potential to be viewed as supercell thunderstorms.

Katrina: MUCAPE and Storm-relative Helicity

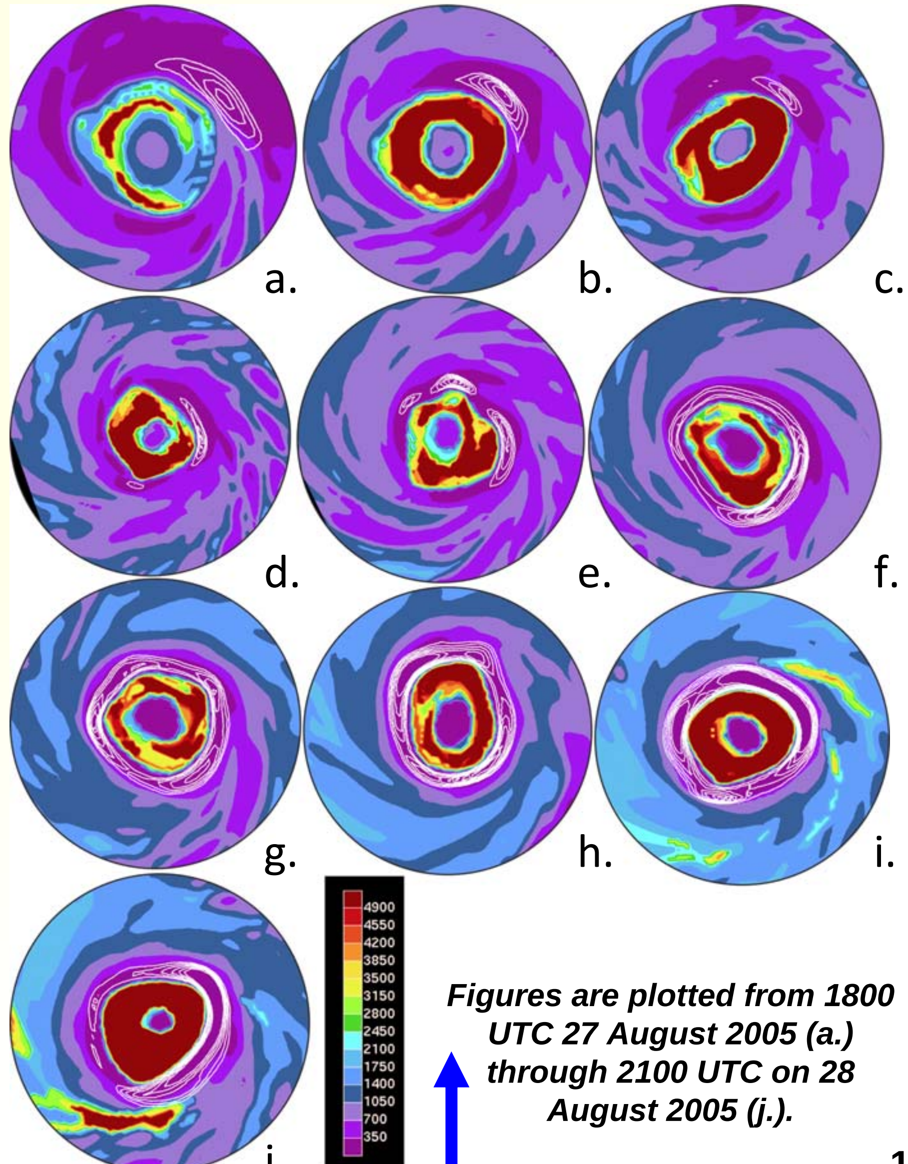
- MUCAPE (J kg^{-1}) plotted as the colored field with contours of 0-6 km SRH (from 1200-2200 s^{-1} plotted every 200 s^{-1}).

- The absence of high CAPE in the eyewall implies it was used up in convection, so it serves that the lowest values should be found there.

- High values of CAPE and SRH are found herein and when coupled, notes the likelihood of supercell development within the environment (EHI > 2.5):

$$EHI = \frac{MUCAPE}{1600}(\mathrm{J/kg}) \times \frac{SREH(0-3km)}{100}(\mathrm{m^2/s^2})$$

- The graphic, used as a visual proxy analysis, lends that supercells occurred in Katrina's eyewall.



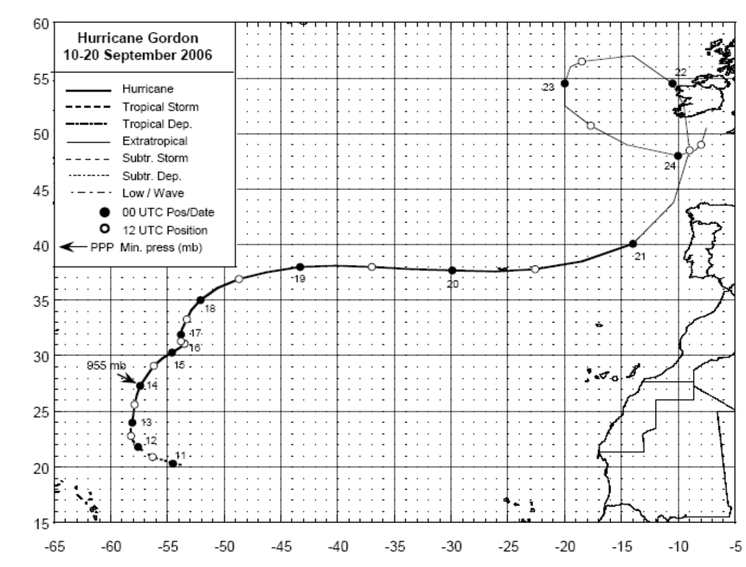
Figures are plotted from 1800 UTC 27 August 2005 (a.) through 2100 UTC on 28 August 2005 (j.).

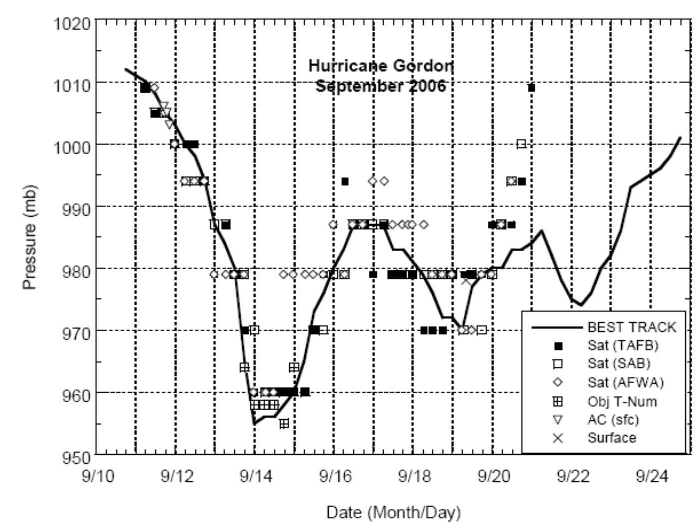
Summary of Katrina Results

- Track and intensity very well simulated by the AHW but the environmental shear was too strong.
- Mesovortices and coordinating VHTs are simulated by the model.
- They are initiated to the downshear right and then propagate around the eyewall, consistent with RI theory.
- SRH is an order of magnitude greater within the embedded mesovortices than in the supercell-producing environments of the middle latitudes.
- Simulated MUCAPE is extreme for the tropical environment.
- Visual analysis of the EHI allows for the logical extension that the eyewall convective and vorticity anomalies resolved within this run of Katrina can be approximated as supercell thunderstorms.

Synoptic History of Gordon (11-17 September 2006)

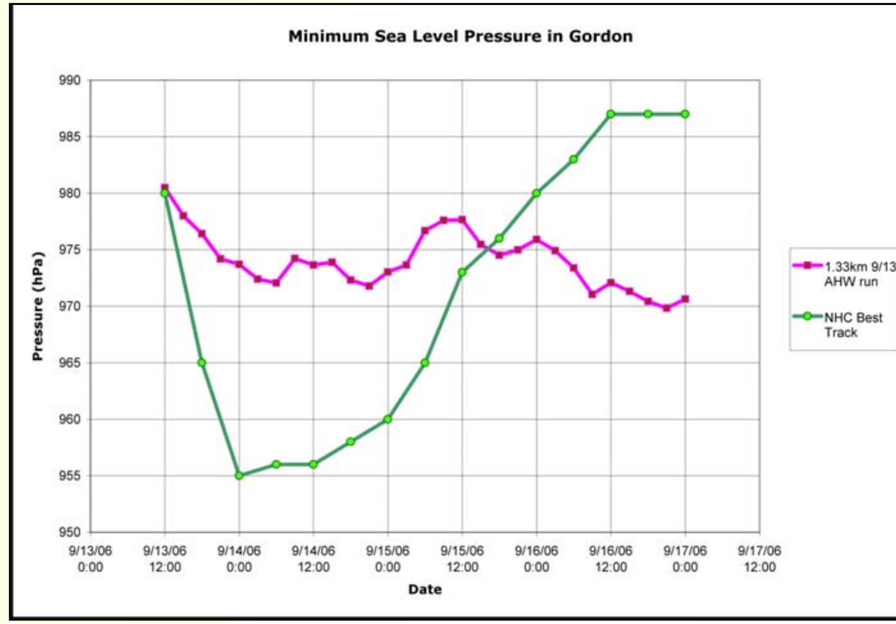
- Originating in the wake of Hurricane Florence (2006), strong shear from inhibited convective growth of Gordon.
- From 10 – 12 September, tropical storm Gordon gained strength slowly as it interacted with an upper-level trough.
- A 30 h period of RI began at 1800 UTC 12 September where winds increased 50 kts and allowed Gordon to reach peak intensity as a Category 3 hurricane.
- Cloud-top temperatures increased 14 September as northward progress stalled in coordination with a building mid-tropospheric ridge.
- Ridge-induced shear weakened the storm as it moved into the mid-Atlantic.

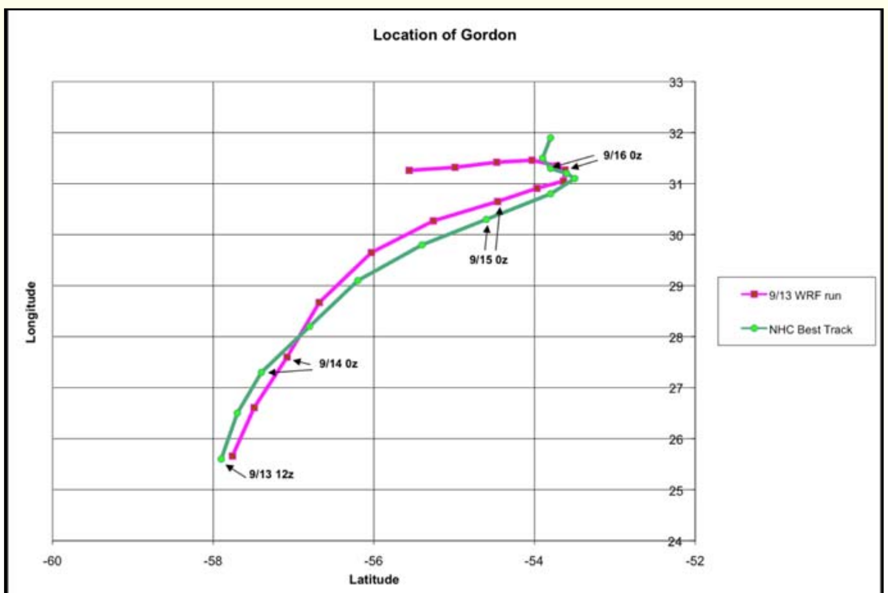


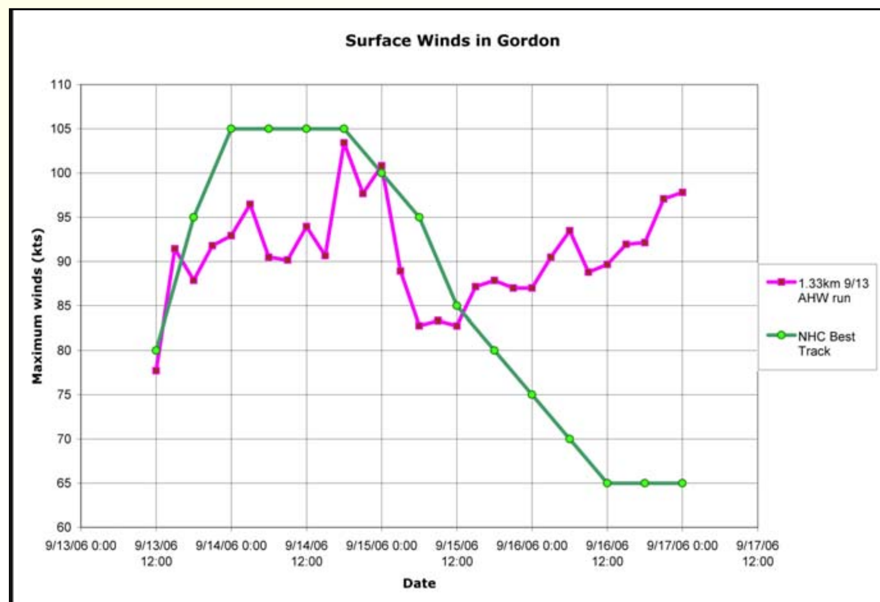


Verification of Gordon

- Track is well simulated, barring the recurvature near the end.
- Intensity change is poorly captured but an initial signature of RI resolved.
- So does the model fail to generate the mechanisms noted to occur for the Katrina run?







Calculated Shear in Gordon

Date/Time	Magnitude of Shear ECMWF	AHW12	AHW	Direction of Shear ECMWF	AHW12	AHW
9/13/06 12:00	5.24	12.48		285.57	289.43	279.13
9/13/06 15:00		13.77	18.23		291.21	302.20
9/13/06 18:00	4.29	13.61	15.99	289.96	289.57	287.80
9/13/06 21:00		15.02	13.95		288.56	301.79
9/14/06 0:00	4.71	15.90	26.55	284.57	291.23	280.22
9/14/06 3:00		15.81	20.89		284.20	271.30
9/14/06 6:00	5.62	14.96	27.24	282.44	277.43	249.03
9/14/06 9:00		15.85	17.83		265.18	274.98
9/14/06 12:00	5.90	18.33	12.81	274.83	255.42	248.81
9/14/06 15:00		19.68	13.55		256.34	211.84
9/14/06 18:00	5.08	19.93	19.48	282.44	258.79	217.89
9/14/06 21:00		19.61	17.19		261.06	294.23
9/15/06 0:00	4.44	18.76	16.57	260.18	262.67	266.05
9/15/06 3:00		18.45	17.21		260.53	251.60
9/15/06 6:00	5.52	17.51	10.59	264.20	261.62	271.06
9/15/06 9:00		16.95	18.67		263.36	182.65
9/15/06 12:00	7.24	16.14	14.98	268.93	265.16	255.71
9/15/06 15:00		15.96	4.02		267.86	317.66
9/15/06 18:00	4.58	16.20	8.83	259.41	266.97	254.74
9/15/06 21:00		16.02	14.75		275.82	258.07
9/16/06 0:00	4.06	15.19	5.30		284.20	222.65
9/16/06 3:00		14.01	11.27		290.02	122.05
9/16/06 6:00	9.49	13.76	3.83		292.64	212.77
9/16/06 9:00		14.41	9.37		294.51	94.78
9/16/06 12:00	10.52	15.57	8.55		294.48	23.84
9/16/06 15:00		16.24	6.23		294.74	77.33
9/16/06 18:00	4.34	17.05	12.92		293.90	84.14
9/16/06 21:00		18.09	12.63		296.00	81.66
9/17/06 0:00		18.93	15.32		300.80	61.11

- Both AHW shears are significantly higher than that of the ECMWF, though the 1.33 km AHW is not always the largest value.
- Directions are very consistent with a spread of approximately 20°.
- Moderate to strong NW shear is resolved for Gordon in all models.
- Strong shear (> 15 m s^{-1}) should rip a hurricane apart, per Davis et al. (2008), but with this case, RI ensues.
- Does the intense shear then help to provoke mesovortex spinup in the eyewall?

Gordon: Low-Level Winds

- Tangential winds (m s^{-1}) for the entire 320 km radial grid:

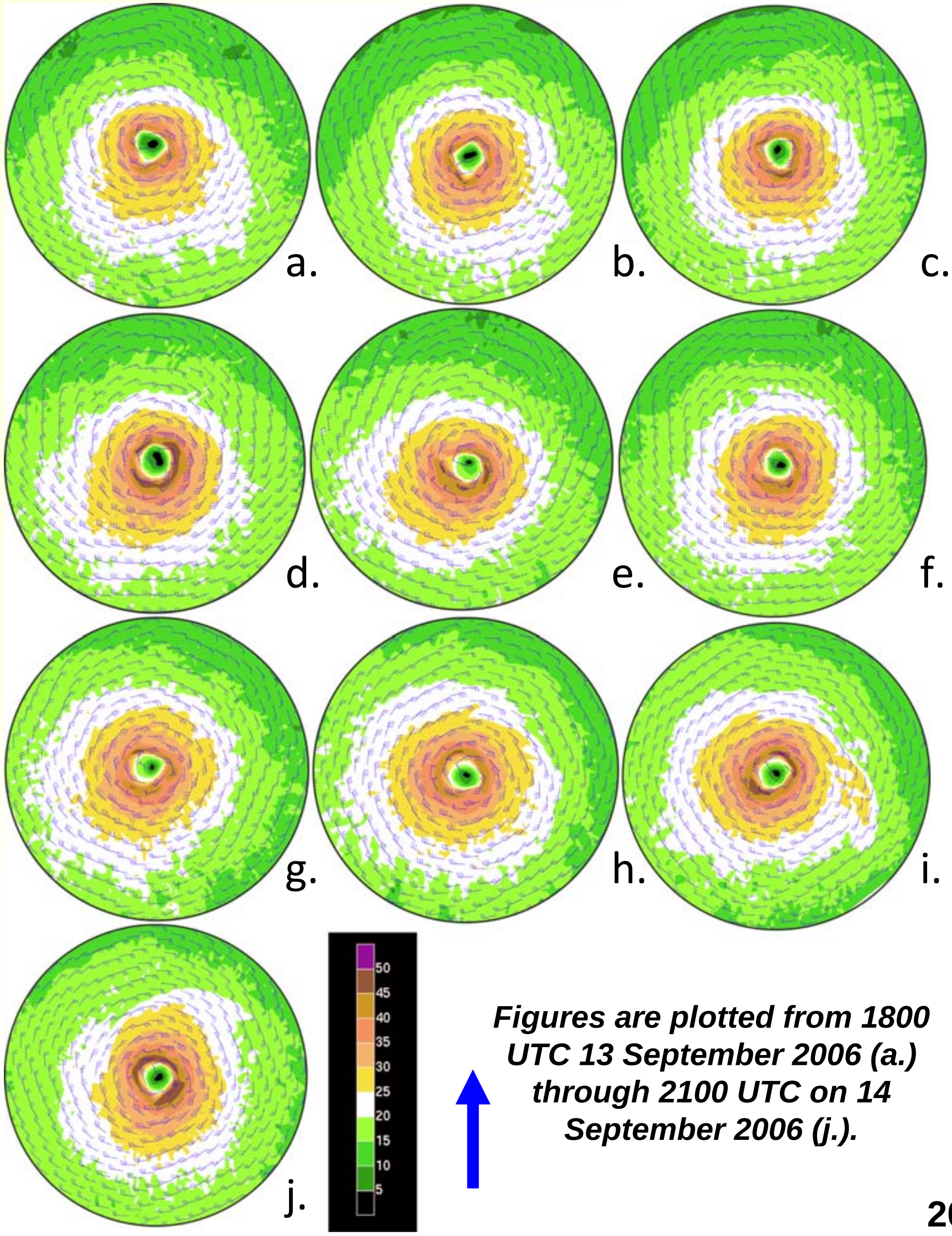
  - Colored filled fields represent the winds at 10 m.

  - 850 hPa tangential winds are given as barbs.

- Tangential winds barely change in intensity for the entire time period.

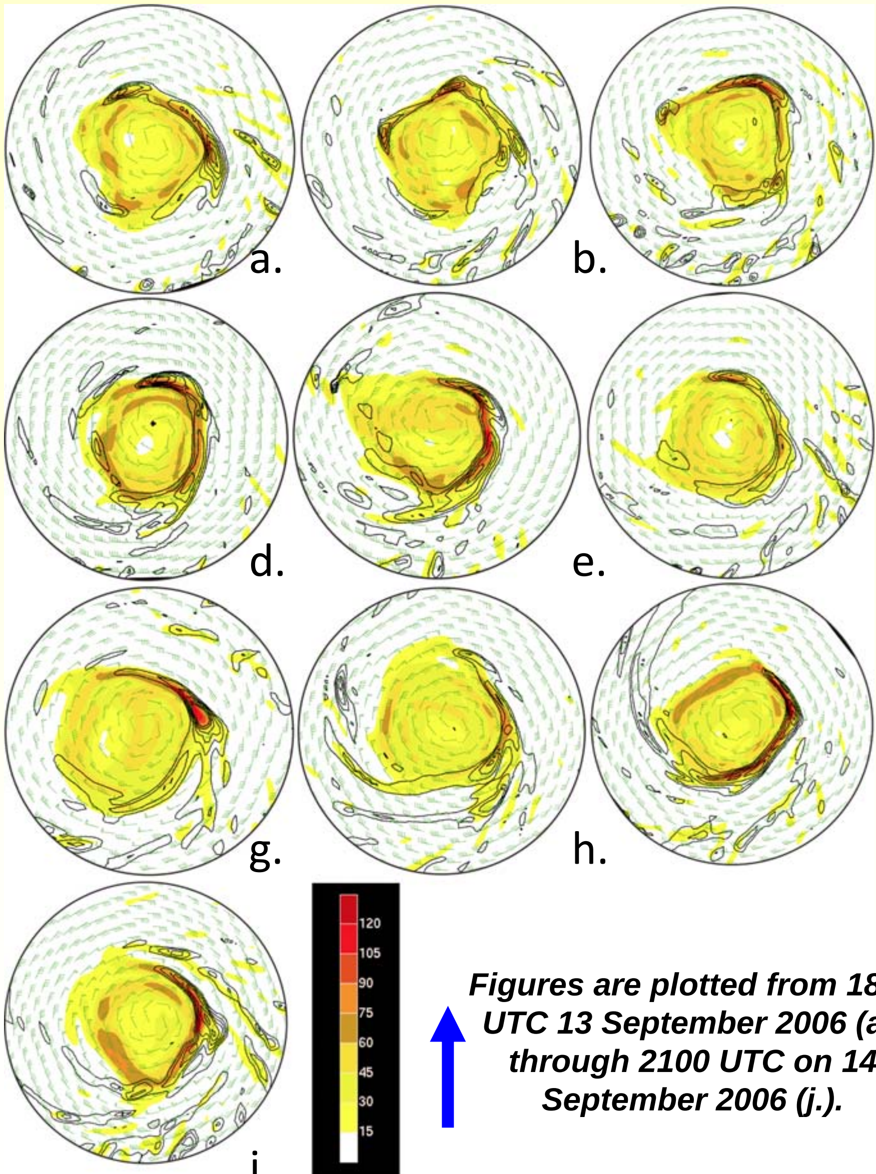
- Strong anomalies in the wind field are embedded within the eyewall.

- No real quadrant preference for these anomalies is readily visible.



Figures are plotted from 1800 UTC 13 September 2006 (a.) through 2100 UTC on 14 September 2006 (j.).

Gordon: Positive Vorticity and Vertical Velocity



Figures are plotted from 1800 UTC 13 September 2006 (a.) through 2100 UTC on 14 September 2006 (j.).

- 850 hPa positive vorticity values (s^{-1}) define the colored field at a radius of 50 km.
- Overlain are the 850 hPa positive vertical velocity contours from 1-6 m s^{-1}, (plotted every 1 m s^{-1}) with the coordinating tangential winds.
- Vorticity is maximized to the right of shear in coordination with the location of positive anomalies.
- There is a blatant convective asymmetry to the right of shear.
- The collocation of positive vorticity anomalies and convective updrafts alludes to the existence of mesovortices.

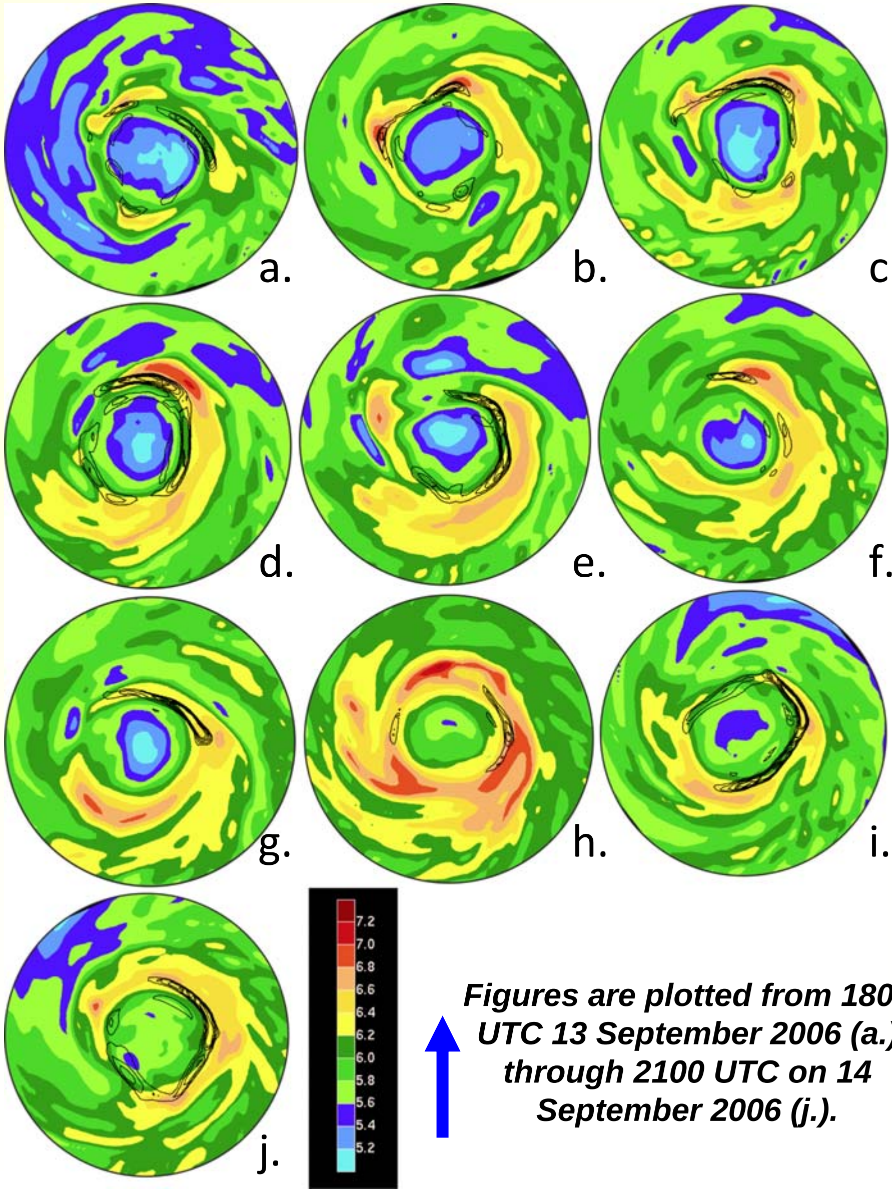
Gordon: Precipitable Water and Positive Vorticity

- Column-integrated PW ($g\ kg^{-1}$) is plotted as the color field while black contours represent the 850 hPa positive vorticity (contoured every 10 s^{-1} from 70-110 s^{-1}).

- The PW field shows that convection is more symmetrically distributed than vorticity.

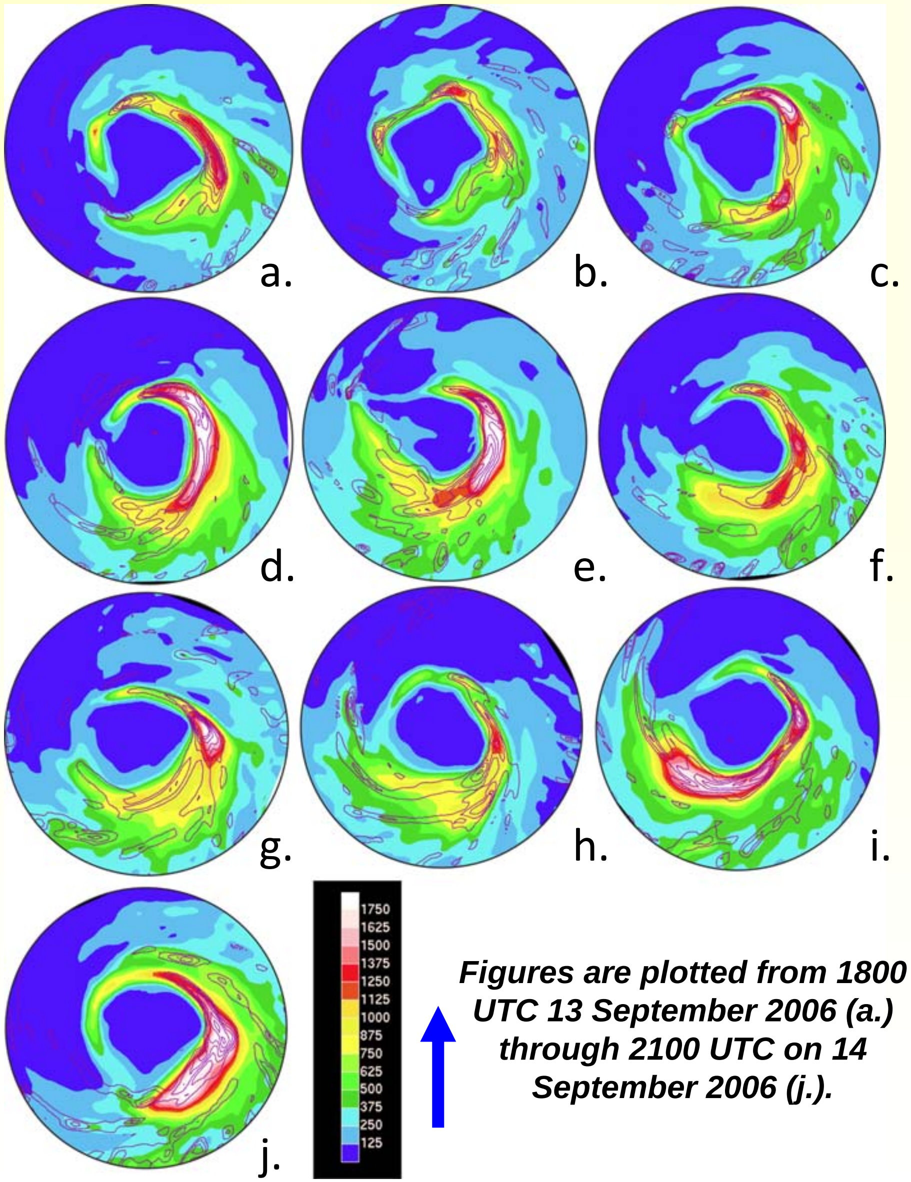
- Convective bursts are likely VHTs as they are generally associated with positive vorticity anomalies.

- The field does intensify throughout the analysis period consistent with what is seen in the pressure profile.



Figures are plotted from 1800 UTC 13 September 2006 (a.) through 2100 UTC on 14 September 2006 (j.).

Gordon: Storm-relative Helicity and Precipitable Water



Figures are plotted from 1800 UTC 13 September 2006 (a.) through 2100 UTC on 14 September 2006 (j.).

- 0-6 km SRH ($m^2\ s^{-2}$) plotted as the the colored field with contours of 850 hPa vertical velocity (from 1-6 $m\ s^{-1}$ plotted every 1 $m\ s^{-1}$).
- Values are again an order of magnitude higher than in middle-latitudes.
- PW and SRH maxima are collocated.
- The convective asymmetry to the right of the shear is obvious in the SRH field as are the presence of mesovortices.
- It is clear here that the simulation never axisymmetrizes despite the propagation of convection around the eyewall.

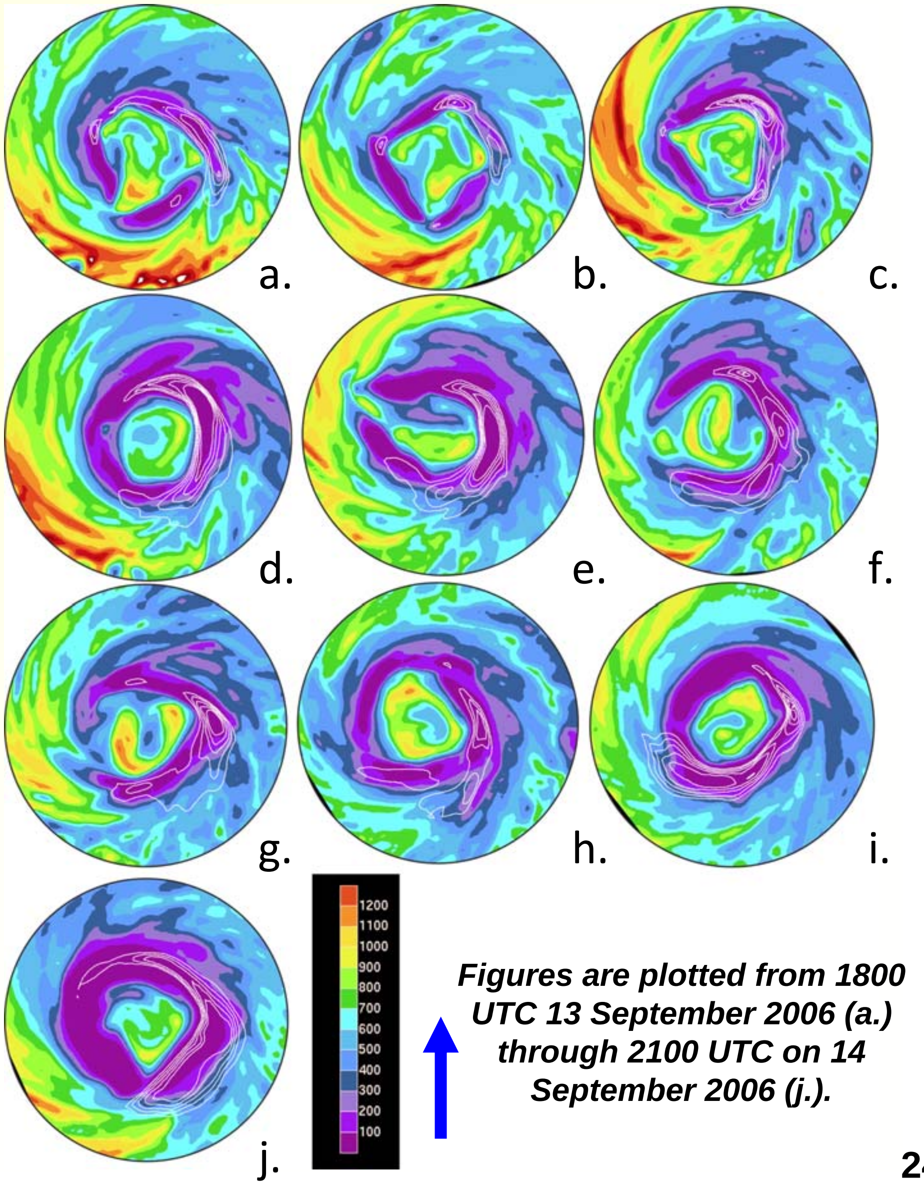
Gordon: MUCAPE and Storm-relative Helicity

- MUCAPE (J kg^{-1}) plotted as the colored field with contours of 0-6 km SRH (from 700-1700 s^{-1} plotted every 200 s^{-1}).

- More modest than that of Katrina, these high values still show significant convective potential for Gordon's environment.

- The lowest CAPE and highest SRH are collocated where VHTs are simulated.

- This gives a good visual measure of a proxy EHI and thus Gordon's eyewall could theoretically sustain supercell development.



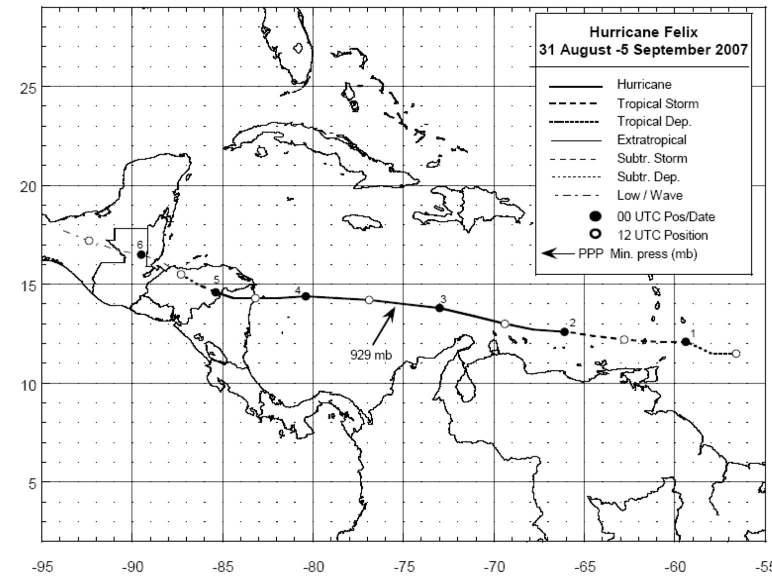
Figures are plotted from 1800 UTC 13 September 2006 (a.) through 2100 UTC on 14 September 2006 (j.).

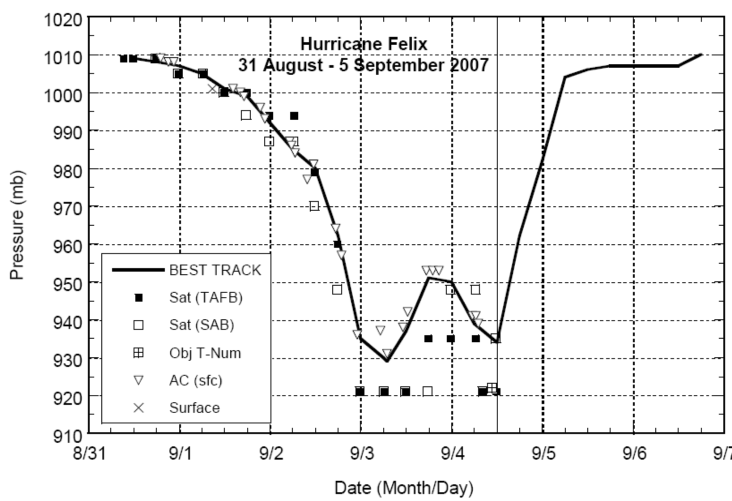
Summary of Gordon Results

- The simulated pressure and tangential wind profiles do not show much of a RI signature but rather slowly intensify Gordon.
- Calculations of the environmental shear were consistent across all 3 models, denoting moderate to strong shear.
- This shear is likely the cause of the omnipresent wavenumber 1 convective asymmetry seen throughout the analysis period.
- Mesovortices and VHTs were resolved in within the eyewall by the AHW, validating the shear-induction process discussed in the literature.
- The simulated shear produced the right features but this was not effectively translated to a period of RI.
- Both SRH and MUCAPE values were elevated with respect to the background tropical environment.
- Based on this, the convective bursts could be approximated as supercell thunderstorms following middle latitude forecasting techniques.

Synoptic History of Felix (31 August - 5 September 2007)

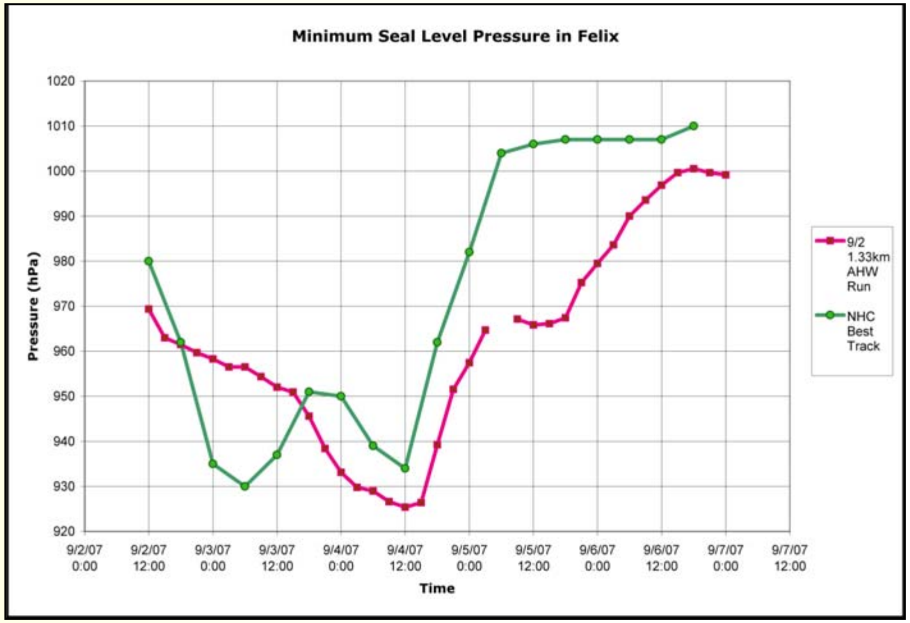
- By 1200 UTC 31 August convection associated with a tropical wave organized into a tropical depression.
- A tropical storm by 0000 UTC 1 September as it moved over Granada, Felix moved into the warm Caribbean.
- RI began at 0000 UTC 2 September, dropping central pressures 64 hPa in 32 h such that Felix became a Category 5 hurricane.
- An ERC began late on 3 September but the reintensification period associated with this phenomenon was cut short as Felix made landfall in Nicaragua as a Category 3 hurricane.

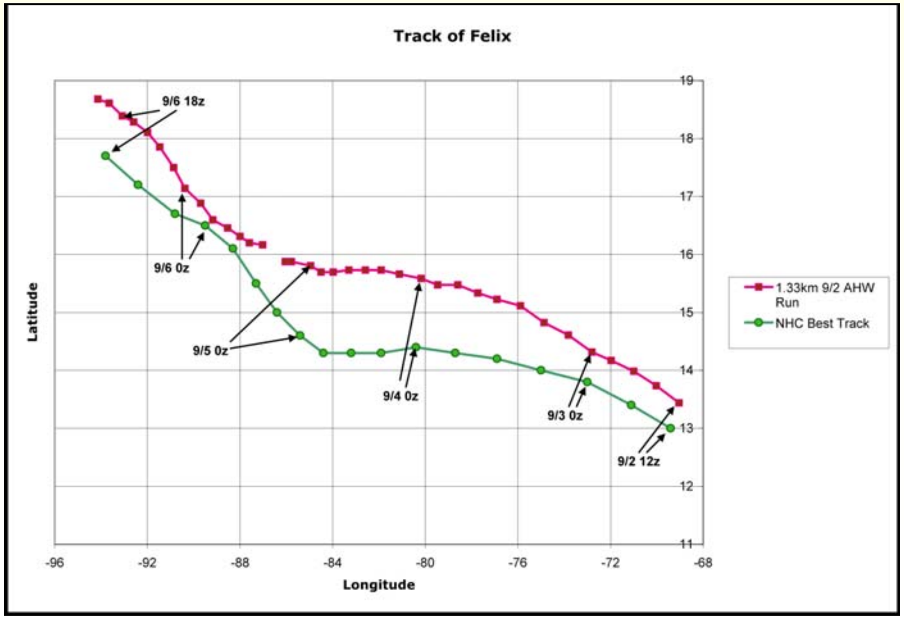


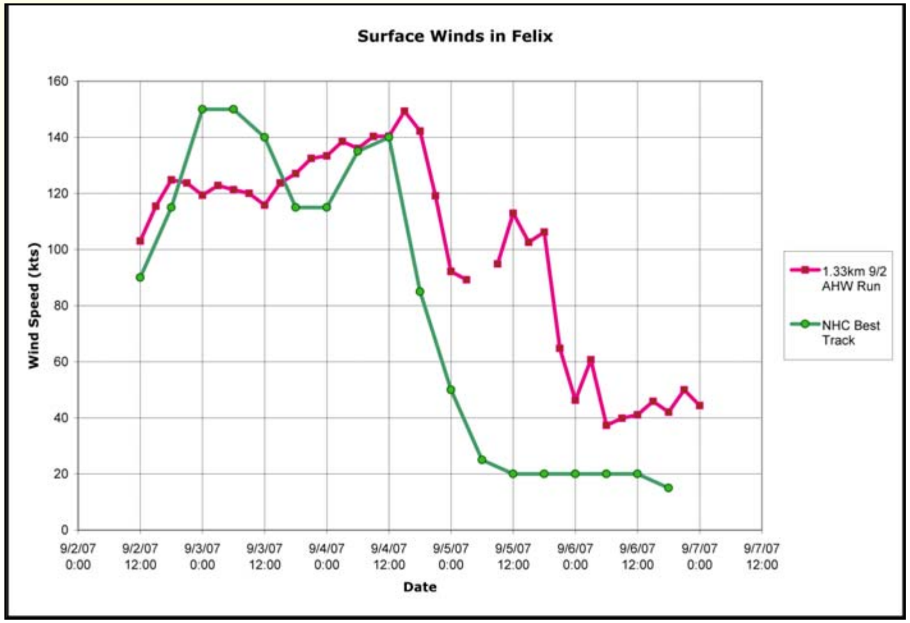


Verification of Felix

- The simulated storm tracks too far north, but paces well.
- AHW captures the second intensification cycle (associated with an eyewall replacement cycle), not the RI which occurs first.
- Is the model then resolving the right dynamics? Is there a spinup issue?







Calculated Shear in Felix

	AHW 1.33 km	
Date/Time	Magnitude	Direction
9/2/07 12:00		72.56
9/2/07 15:00	23.20	65.58
9/2/07 18:00	11.87	1.89
9/2/07 21:00	17.31	13.95
9/3/07 0:00	22.78	286.74
9/3/07 3:00	21.44	269.54
9/3/07 6:00	22.99	316.83
9/3/07 9:00	19.10	204.91
9/3/07 12:00	10.97	242.36
9/3/07 15:00	16.35	285.96
9/3/07 18:00	23.71	178.79
9/3/07 21:00	18.26	194.62
9/4/07 0:00	25.85	164.45
9/4/07 3:00	17.02	219.28
9/4/07 6:00	26.94	191.98
9/4/07 9:00	22.13	175.38
9/4/07 12:00	11.55	255.34
9/4/07 15:00	22.82	294.28
9/4/07 18:00	25.26	329.59
9/4/07 21:00	9.50	25.80
9/5/07 0:00	14.29	32.03
9/5/07 3:00	23.54	97.82
9/5/07 6:00	16.05	145.67
9/5/07 9:00	19.28	149.61
9/5/07 12:00	16.78	244.28
9/5/07 15:00	9.56	73.53
9/5/07 18:00	37.26	111.00
9/5/07 21:00	25.14	53.71
9/6/07 0:00	30.99	59.25
9/6/07 3:00	20.38	97.97
9/6/07 6:00	19.04	106.78
9/6/07 9:00	18.03	85.80
9/6/07 12:00	28.59	72.72
9/6/07 15:00	18.76	65.22
9/6/07 18:00	13.00	57.89
9/6/07 21:00	13.98	56.67
9/7/07 0:00	23.42	92.04

- The ECMWF and 12 km AHW shear calculations were unavailable for Felix; only the 1.33 km calculations are give.
- Since there is no means of comparison, it is assumed that these values follow the same pattern as the other hurricanes:
  - Calculated magnitudes are too large.
  - Directional values are valid.
- Magnitudes fluctuate between 10-25 m s^{-1}, denoting that there is strong environmental shear, though nothing is mentioned in the NHC best track.
- If such strong shears existed in reality, shear-induced VHTs should be responsible for Felix's RI and some hint of these should be captured by the AHW.

Felix: Low-Level Winds

- Tangential winds (m s^{-1}) for the entire 320 km radial grid:

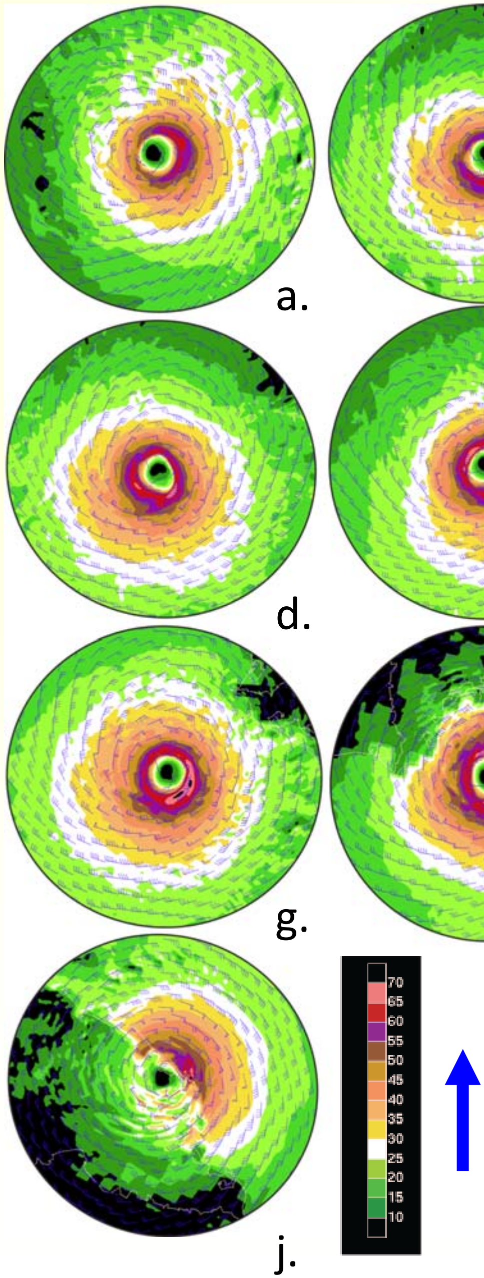
  - Colored filled fields represent the winds at 10 m.

  - 850 hPa tangential winds are given as barbs.

- Tangential winds increase as Felix deepens, most notably in the eyewall.

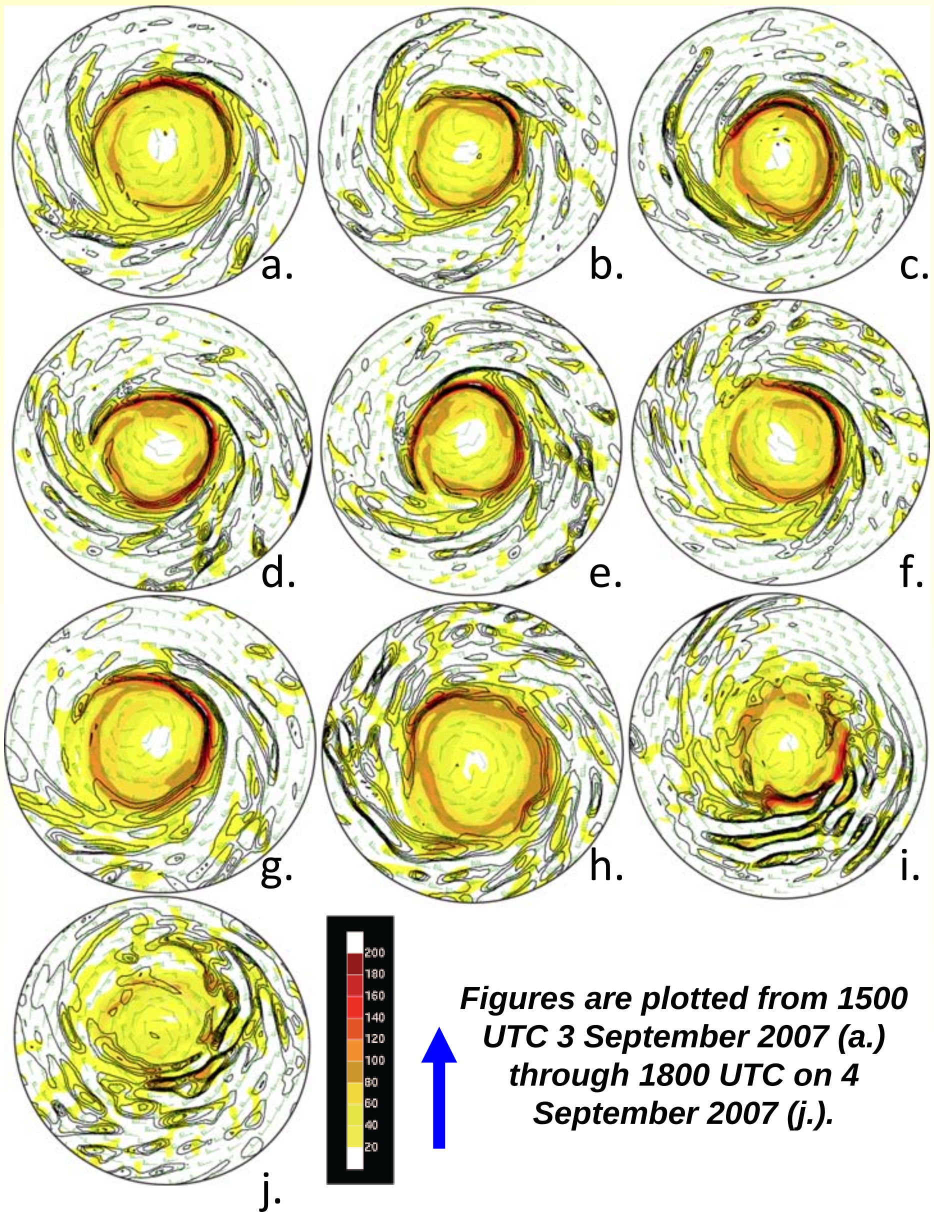
- Anomalies embedded within the eyewall are found to the right of shear when the tropical cyclone is intensifying most rapidly.

- During the final 4 time periods, Felix is interacting with land, so this clearly impacts winds and will do so to all subsequent fields.



Figures are plotted from 1500 UTC 3 September 2007 (a.) through 1800 UTC on 4 September 2007 (j.).

Felix: Positive Vorticity and Vertical Velocity



Figures are plotted from 1500 UTC 3 September 2007 (a.) through 1800 UTC on 4 September 2007 (j.).

- 850 hPa positive vorticity values (s^{-1}) define the colored field at a radius of 50 km.

- Overlain are the 850 hPa positive vertical velocity contours from 1-6 m s^{-1}, (plotted every 1 m s^{-1}) with the coordinating tangential winds.

- Vorticity is well distributed throughout the eyewall though is maximized downshear.

- Positive anomalies are readily visible and when coupled with strong updrafts, signal the existence of mesovortex structures.

Felix: Precipitable Water and Positive Vorticity

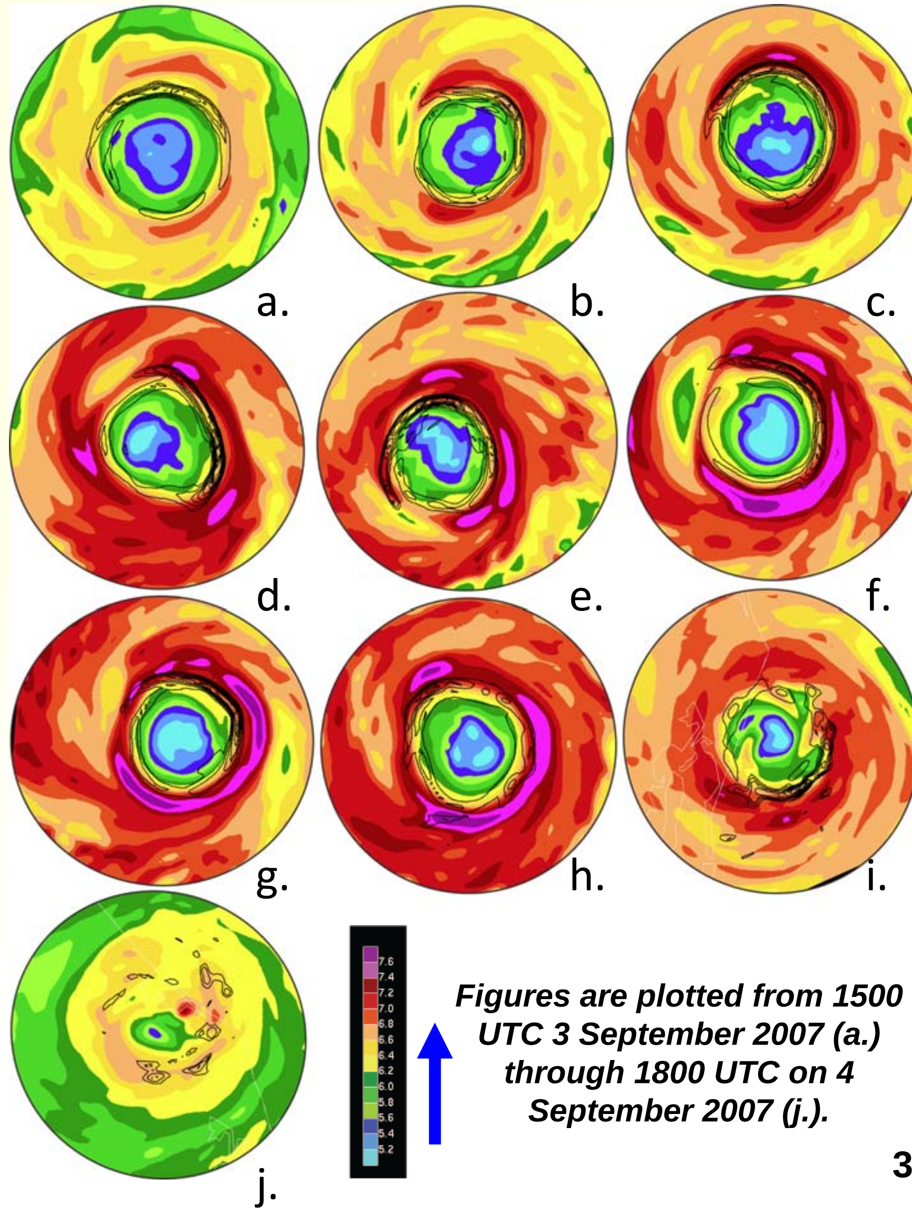
- Column-integrated PW (g kg^{-1}) is plotted as the color field while black contours represent the 850 hPa positive vorticity (contoured every 20 s^{-1} from 80-160 s^{-1}).

- There is a prominent wavenumber 1 convective asymmetry to the right of the shear vector.

- VHTs are likely being resolved as noted by the embedded convective bursts.

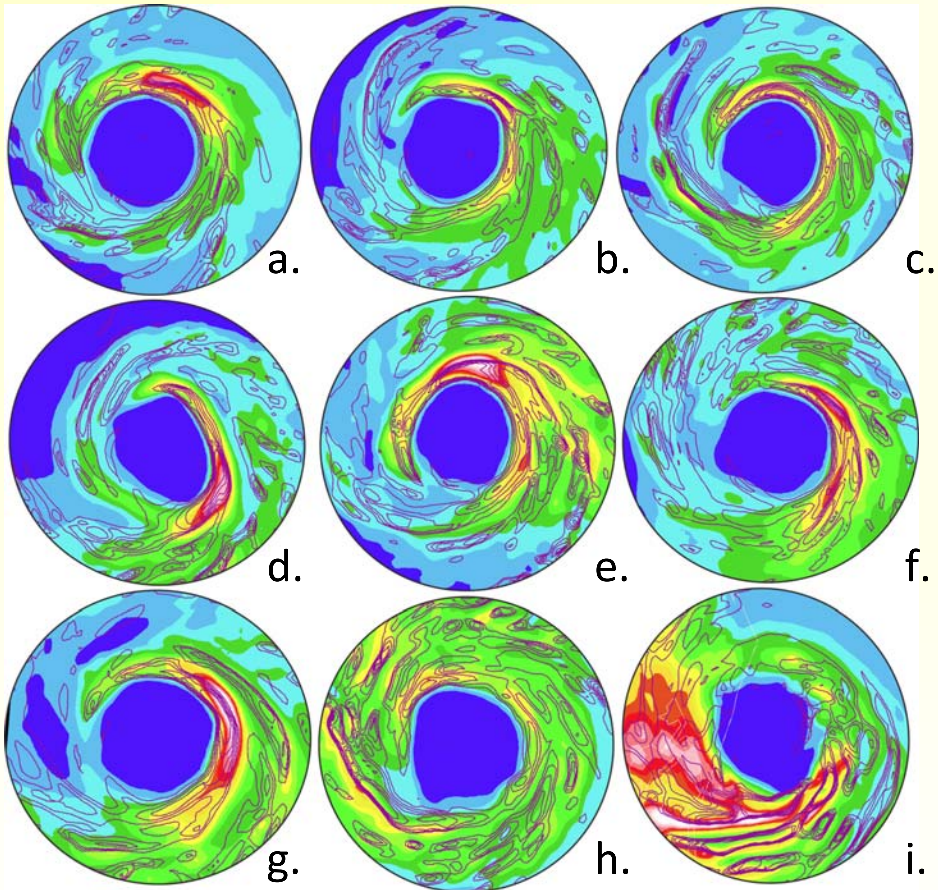
- These bursts are not constrained by the shear and propagate around the eyewall.

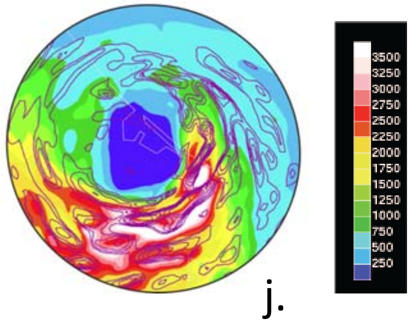
- VHTs are coupled with maxima in positive vorticity, again denoting mesovortex structures.



Figures are plotted from 1500 UTC 3 September 2007 (a.) through 1800 UTC on 4 September 2007 (j.).

Felix: Storm-relative Helicity and Precipitable Water





Figures are plotted from 1500 UTC 3 September 2007 (a.) through 1800 UTC on 4 September 2007 (j.).

- 0-6 km SRH ($m^2\ s^{-2}$) plotted as the the colored field with contours of 850 hPa vertical velocity (from 1-6 $m\ s^{-1}$ plotted every 1 $m\ s^{-1}$).
- With values approaching 3500 $m^2\ s^{-2}$, these SRH exceeds the highest reported helicity values by a factor of 2.
- Helicity and PW maxima are collocated, showing these are intense convective cells.
- SRH is maximized to the downshear right before frictional land interaction degrades the picture.
- Great supercell potential is a thus a logical extension.

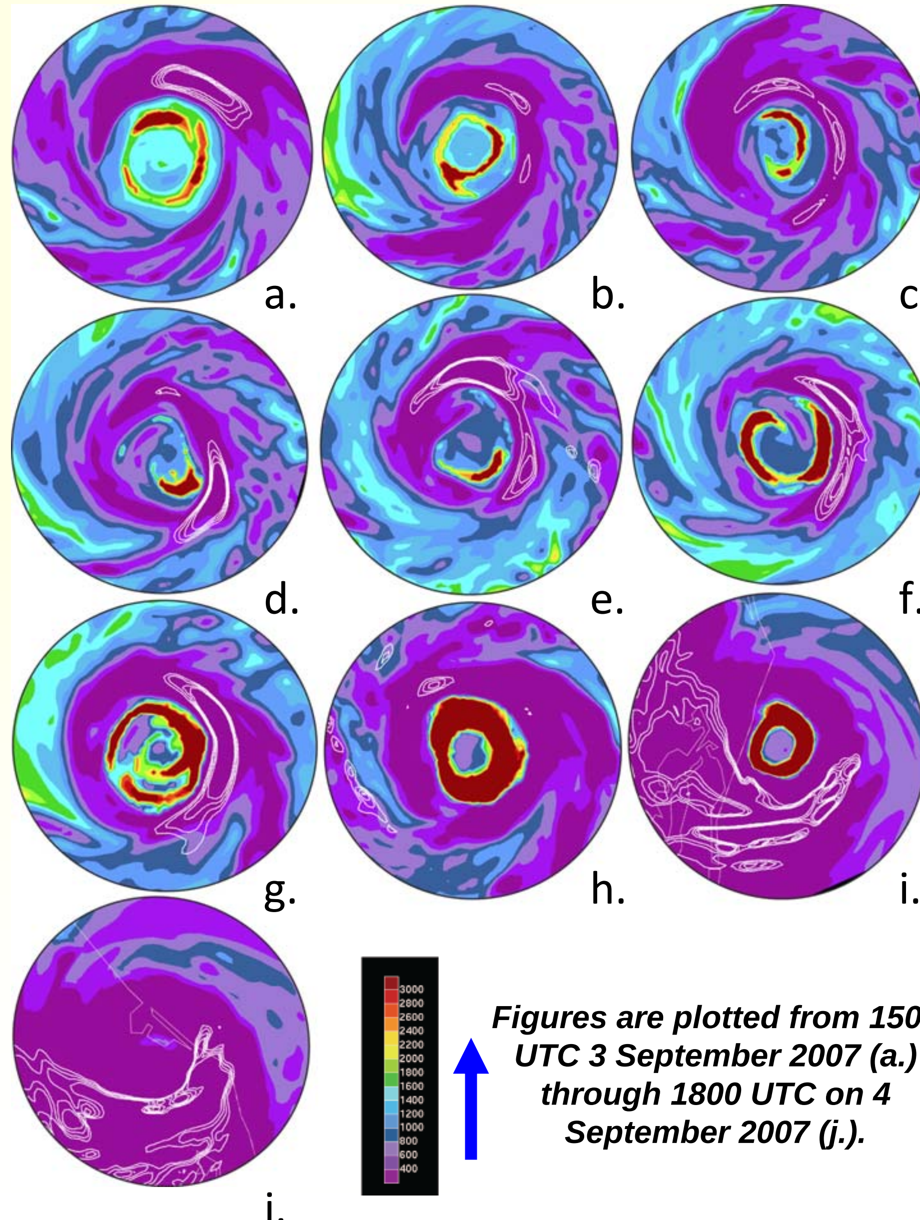
Felix: MUCAPE and Storm-relative Helicity

• MUCAPE (J kg^{-1}) plotted as the colored field with contours of 0-6 km SRH (from 1800-2400 s^{-1} plotted every 200 s^{-1}).

• Values of CAPE are once again extraordinarily high considering the background tropical environment.

• Lowest values and SRH maxima are collocated at the VHTs.

• Such extremely high values of each give proxy EHI values roughly an order of magnitude above the supercell threshold.



Figures are plotted from 1500 UTC 3 September 2007 (a.) through 1800 UTC on 4 September 2007 (j.).

Summary of Felix Results

- The track and ERC are poorly resolved but the model does pick up a significant period of RI coincident with Felix's reintensification; the first period may not have been simulated due to spinup errors.
- Shear values were high and were taken as being consistent with the other hurricane runs as there was no data to validate them.
- Mesovortex and VHT structures were resolved well before the cyclone interacted with land.
- The downshear preference for vorticity and right of shear preference for convection corroborate the literature on RI theory.
- SRH and CAPE values were extreme for the tropical environment.
- They point to the existence of supercell thunderstorms embedded in the eyewall based on middle latitude parameters.

Summary of Work

- In hurricanes historically known to undergo RI, the high-resolution 1.33 km gridded nest of the AHW model is able to simulate at least the hint of rapid deepening.

- The stronger the environmental shear the model resolves, the better the pressure and wind profiles are met but the values of SRH and MUCAPE are then improbably high.

- Shear is responsible for the convective asymmetries noted above.

- Strong shear likely served to inhibit the simulated rapid deepening in Gordon and may have also had an effect on Felix.

- Model data corroborates many aspects of the theory of RI presented in the literature by resolving mesovortices and VHTs within the eyewall in all simulations.

- These features do not always correctly translate an appropriate deepening of low pressure or an intensification in tangential velocities however.

- Mesovortices and coupled VHTs can thus be approximated as middle latitude supercell convective structures.

Conclusions and Forecasting Relevance

- Only high-resolution NWP models are able to capture RI signatures; for prognostic applications they also have to have the ability to run in real-time.
- There is some correlation between simulation of high environmental shear and how well the model captures the actual rapid deepening event.
- RI potential for hurricanes should be evaluated by more than just looking to central pressure and wind forecasts.
- The theory that shear can induce strong convection (asymmetrically) in tropical cyclones should be incorporated into models.
- Since RI is thought to be a function of shear-induced mesovortex and resulting VHT development, looking to vorticity and convective fields is necessary.
- Based on their similarity to mid-latitude supercells, forecasting parameters like the EHI could be useful tools in predicting RI.
- Evaluating MUCAPE and SRH fields, regardless of central pressure changes, still signals a RI event may occur as these fields show clear and significant maxima when mesovortices and VHTs are simulated.
- Lead times on RI can be improved by looking to these parameters operationally.

Acknowledgements

Much aid with this research was derived from a few key individuals:

- Robert Fovell and Kuo-Nan Liou, my secondary advisors and teachers.
- John Molinari and David Vollaro at SUNY Albany for their expert guidance on simulated RI.
- Steve Decker of Rutger's University for his help with wrf2gem.
- Wei Wang and James Done of NCAR for their contribution of the AHW model runs.

My devoted appreciation goes out to my research advisor at UCLA,

Dr. Kristen Corbosiero

Her guidance on this work was invaluable and inspired

Please contact me with any inquires at Kathryn.Shontz@noaa.gov

Copy of thesis and literature references available upon request

A final thank you to STAR, Bruce Ramsay and Ingrid Guch for their support with this presentation!