

<u>The Kinematics of Rapidly Intensifying</u> <u>Hurricanes in Moderate Vertical Wind Shear</u>

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Bottom Line Up Front

- Identification of similar features among specific class of sheared tropical cyclones (TC) which undergo rapid intensification (RI; 30 kt / 24 hr⁻¹) in deep-layer (200-850 mb) vertical wind shear values (VWS) greater than 5 m s⁻¹
 - Satellite: Convective envelopes appearing with 4- to 8-hour periodicity, upshear arcs, upshear clearing, downshear-left outflow jet
 - Reanalysis: Upper-level anticyclonic forcing
 - Favored in Northern Eastern Pacific basin due to climatological set up
 - Modeling: Can be replicated given correct environmental set up
 - Outflow blocks the environment; effects felt 1000 km upshear

Introduction

- Climatologically, based on the Statistical Hurricane Intensity Prediction System (SHIPS) the average deep-layer (200-850 hPa) shear value (SHDC) for RI is basin-dependent (Kaplan et al. 2010; hence KDK) and generally light:
 - Eastern North Pacific (EPAC): μ = 3.9 m s⁻¹, σ = 1.5 m s⁻¹
 - Northern Atlantic (NATL): μ = 5.1 m s⁻¹, σ = 2.0 m s⁻¹
 - Follow-on studies have tweaked these numbers (Rozoff et al. 2015; Kaplan et al. 2015)
- Generally, shear is greater in NATL

Introduction (cont'd)

 Focus of this talk will be on those TCs identified (so far) which undergo RI (or at least continue to strengthen) in SHDC values +1σ to +5σ greater than RI climatology and share similar satellite features

<u>The List</u>

The Originals

- 1997 EPAC Guillermo
- 2008 EPAC Hernan
- 2008 EPAC Norbert
- 2012 EPAC Fabio*
- 2015 EPAC Hilda
- 2015 NATL Joaquin

<u>The New Ones</u>

- 2012 EPAC Daniel
- 2014 EPAC Marie (?)
- 2016 EPAC Blas
- 2016 EPAC Darby*
- 2016 NATL Matthew

* Technically, did not meet RI requirements

Hurricane HERNAN

ZCZC MIATCDEP4 ALL TTAAOO KNNC DDHHBM HURRICANE HERNAN DISCUSSION NUMBER 12 NWS TPC/NATIONAL HURRICANE CENTER MIAMI FL EP092008 800 AM PDF SAT AUG 09 2008

THE EYE OF HERNAN HAS BECOME DRAMATICALLY MORE DISTINCT IN GOES INFRARED IMAGERY DURING THE PAST SEVERAL HOURS ... AND IT IS NOW SURROUNDED BY A SOLID RING OF CLOUD TOPS COLDER THAN -70C. AMSR-E MICROWAVE IMAGERY AT 0937 UTC DEPICTED A SINGLE COMPLETE EYEWALL AND AN EYE DIAMETER OF 20-25 N MI. THERE SEEMS LITTLE DOUBT THAT HERRAN HAS BECOME A MADIA HURHCANE... HAVING UNDERCOME FAPIL INTENSIFICATION SINCE YESTERDAY. THIS FRVIDES YET ANOTHER EXAMPLE THE INABILITY OF MODEL GUIDANCE...AND THEREFORE THE HUMAN RECASTER...TO CAPTURE AND CONVEY THE TIMING AND MAGNITUDE OF THES ISODES WITH A DETERMINISTIC INTENSITY FORECAST. THE EXACT INITIAL INTENSITY IS A LITTLE UNCERTAIN. SUBJECTIVE DVORAK ESTIMATES AT 12Z FROM TAFB AND SAB WERE BOTH 102 KT...WHILE OBJECTIVE ESTIMATES ARE ABOUT 115 KT. THE ADVISORY INTENSITY COMPROMISES AT 105 KT...BUT WITHOUT ACTUAL WIND DATA TO KNOW ANY BETTER...IT IS POSSIBLE HERNAN IS A LITTLE STRONGER THAN THIS ESTIMATE. UNDERLYING SEA-SURFACE TEMPERATURES ARE ABOUT 27 CELSIUS NOW...AND ALONG THE FORECAST TRACK THE HURRICANE WILL CROSS THE 26 CELSIUS ISOTHERM IN ROUGHLY 24 HOURS ... SO A GRADUAL WEAKENING TREND IS FORECAST TO BEGIN AROUND THAT TIME. A FASTER DECLINE IS FORECAST IN A COUPLE OF DAYS ONCE THE CYCLONE REACHES SUBSTANTIALLY COOLER WATERS. THE OFFICIAL FORECAST IS ABOVE THE OBJECTIVE GUIDANCE FOR THE NEXT DAY OR TWO...THEN SHOWS A FASTER WEAKENING THAN THE MODELS DUE TO THE SMALL SIZE OF THE CYCLONE.

HERNAN HAS TURNED A LITTLE MORE TO THE RIGHT..AND ONE MUST GIVE SOME OF THE MODELS CREDIT FOR CORECTLY FORECASTING THIS BEND YESTERDAY. THE INITIAL MOTION ESTIMATE IS 295/8..BUT A GRADUAL TURN BACK TO THE LEFT IS FORECAST BY ALL OF THE DUNAMICAL MODELS AS THE SUBRFORCIAL RIDGE BUILDS WESTWARD OVER THE EASTERN PACIFIC DURING THE NEXT COUPLE OF DAYS. BEYOND THAT THE...A WEAKENING HERNAN IS EXPECTED TO BECOME A MORE SHALLOW SYSTEM AND TURN WESTWARD AND EVENTUALLY WEST-SOUTIWESTWARD IN THE LOW- TO MID-LEVEL FLOW. THE NEW OFFICIAL TRACK FORECAST IS ALMOST IDENTICAL TO THE PREVIOUS OWE AND IS CLOSE TO THE MODEL CONSENSUS.

FORECAST POSITIONS AND MAX WINDS

INITI/	AL.	09/1500Z	15.7N	123.3W	105	\mathbf{KT}
12HR	VT	10/0000Z	16.2N	124.4W	105	KT
24HR	VT	10/1200Z	16.8N	125.9W	95	KT
36HR	VT	11/0000Z	17.3N	127.3W	80	KT
48HR	VT	11/1200Z	17.6N	128.7W	65	KT
72HR	VT	12/1200Z	18.ON	131.OW	45	KT
96HR	VT	13/1200Z	17.5N	133.5W	35	KT
120HR	VT	14/1200Z	16.5N	136.0W	30	KT

\$ S



<u>Intensity v. Shear</u>

- Gray boxes isolate time period from best-track genesis time to appearance of the eye in geostationary satellite infrared (IR) imagery for each
- Average shear:
 - SHDC (vort removed): 7.3 m s⁻¹
 - SHRD (annulus): 7.8 m s⁻¹

– <u>7.5 m s⁻²</u>

Large-Scale Predictors

- Shear is never the whole story
- To streamline synoptic discussion, focus on three "largescale" RI predictors (KDK):
 - SHDC: Deep-layer shear, vortex removed
 - RHLO: Average relative humidity, 700-850 mb, 200-800 km radius
 - D200: 200 mb divergence, 1000 km radius
- RHLO is ~climatological average
- SHDC is 2-3σ greater than D200



"Classic" RI

- Lots of possibilities
 - 2005 EPAC Wilma
 - 2009 EPAC Rick
 - 2012 EPAC Emilia
 - 2015 EPAC Patricia
- Low shear, high divergence
 - Flipped relationship from previous six



Geostationary Satellite Imagery

- GOES 8, 9, 11, 12, 13, and 15 data are used
- Infrared (IR) and Water Vapor (WV) channels

– IR

- 10.20 to 11.20 μm
- 4 km effective grid spacing
- -WV
 - 6.50 to 7.00 μm for GOES-8 to GOES-11 (late 2011)
 - 5.77 to 7.33 μm for GOES-12+
 - 8 km effective grid spacing for GOES-8 to GOES-11; 4 km thereafter
- Interpolated to polar coordinates around storm center
 - Best track (HURDAT2) or ARCHER (Wimmers and Velden 2016)

2008 EPAC Hernan

- Prototype case
 - Visually, the easiest to see the phenomena
- Shear pointing west-southwest, mostly consistent
- Repeating cloud structures of similar shape, then eye appears
 - Convective envelope
 - Confined within -70 °C isotherm



2008 EPAC Hernan (cont'd)

20

10

0

-10

-20

-30

-40

-50

-60

-70 -80

-90





<u>Areal Coverage – Periodicity</u>

- Compute area within -70 °C contour within 200 km
- Filter using low-pass filter
 - Windowed-sinc $F(t) = f(t) * \operatorname{sinc}\left(2f_c\left(t \frac{N-1}{2}\right)\right)\left(a_0 a_1 \cos\left(\frac{2\pi t}{N-1}\right) + a_2 \cos\left(\frac{4\pi t}{N-1}\right) a_3 \cos\left(\frac{6\pi t}{N-1}\right)\right)$
 - Blackman-Nuttall window (Nuttall 1981)
 - Cutoff frequency (f_c) of 12.5 hr
- Filter using band-pass filter
 - Faster than 12.5 hr, slower than 2.5 hr
- Normalize by low-pass maximum

Normalized Area: Hernan



Guillermo



Normalized Area: Guillermo (5.5 hr cutoff)



Convective Envelope

- In each of the six, a convective envelope can be identified
 - Periodicity between 4 and 8 hours
 - Encapsulated inside -70 °C isotherm
 - "Embedded center"
 - Coldest temperatures below -80 °C
 - Oblong-D shape with tail
 - Broadest side angled towards upshear semicircle



Water Vapor

• Two key identifiers

- Upshear arcs
 - -40 to -55 °C; 20-30 km in width
 - Appear to be tied to envelopes
- Upshear warming/clearing
 - WV imagery gets progressively warmer/drier
 - N.B.: WV weighting function is maximized at 300 mb
 - Upper-tropospheric response





Upshear arcs (WV)

- All arcs are separated by a warm gap
- Consistently upshear
 - Red arrows = shear directions

Outflow Jets

- Atmospheric Motion Vectors (AMVs; Velden et al. 1997) indicate outflow jets located downshear-left
- Windspeeds of 50-70 knots (25-35 m s⁻¹)



200-mb winds, ERA-Interim

- Final component that links all six together
- All six TCs are being sheared by upper-level anticyclones
 - Location relative to TC doesn't appear to matter
 - Four are north of TC (Guillermo, Hernan, Fabio, Hilda)
 - One is east (Norbert)
 - One is west (Joaquin)



Upper-level anticyclones (ULAC)

- Why does this matter?
- ULACs, compared to their cyclonic counterparts, are much more shallow in the vertical (Hoskins et al. 1985; Wirth 2001)
- Studies have shown/alluded to this being less detrimental to a TC's development (Elsberry and Jeffries 1996; Finocchio et al. 2016)



Observations Summary

- Environmental set-up
 - Shear: 7.5 m s⁻¹
 - Winds confined to upper levels of troposphere
 - SSTs: 28 °C (in bonus slides)
- Markers
 - Intense convection with 4 to 8-hour periodicity
 - Upshear arcs
 - Oblong-D-with-tail cloud shape
 - Confined within -70 °C isotherm
 - Downshear-left outflow jet
 - Upshear drying/warming

Idealized Modeling

- Slightly modified CM1 (Bryan and Fritsch 2002)
 - Added cosine Coriolis terms
 - Anelastic mass balance to background wind
- 27.5 °C SSTs
- Dunion Moist Tropical sounding
- Deep-layer shear equivalent: 13 km minus 1.5 km
 - CM1 is height coordinate model
- Three shear profiles + control (no shear)
- 2-km *dx, dy*; 100-m -> 750-m *dz*



Idealized Modeling: IC



Idealized Modeling: Intensity Evolution

- Control develops (of course)
- Cosine-7.5 and Gaussian-11.5 do not develop
- Gaussian-7.5 does
 - Multiple segments, as opposed to control
 - Also has "late" RI
 - Intensification halts for 10-hour period before abrupt intensification
 - RMW shrinks, then expands, then shrinks again, then expands again



Idealized Modeling: Markers

- Synthetic satellite imagery from Community Radiative Transfer Model (CRTM; Grasso et al. 2008)
 - Left column: sheared
 - Right column: control
- Requirements
 - Oblong-D shape in IR, upshear-angled
 - Thin upshear arcs in WV
 - Downshear-left outflow jet
 - Periodic convection...



<u>Tilt Evolution</u>

- Can't talk to about this behavior without talking about the tilt
- Calculated multiple different ways
 - Storm wobbles out of phase with itself
 - PVV120: PV-Vorticity centroid hybrid, 120x120 km weighting area



<u>Tilt Evolution (cont'd)</u>

- In a 2-D sense, there are two important parts of the tilt
 - Realignment
 - Days
 - Wobble
 - Hours
- Method: PVV120



Idealized Modeling: Convection

- Assumption
 - Periodicity of clouds is tied to underlying convection
- Define convection as Total Condensed Water of the Column (TCWC)

$$TCWC = \int_{0}^{z_{top}} \rho \left(r_c + r_r + r_i + r_s + r_g \right) dz$$

 At right, storm-relative radial sums of TCWC per azimuth in time



Idealized Modeling: Convection (Cont'd)

- At right, Gauss-7.5 TCWC with mid-level tilt considerations
 - White crosses are smoothed angle of 6-km center
 - Red line is smoothed magnitude of 6-km tilt
- Convection and mid-level center are locked together, regardless of magnitude
 - Increased CCW tilt movement is co-located with incr. convection
 - Three convective envelopes
 - Approx. 6-8 hours apart



Tilt Angle within Envelope



- All center finding methods are oriented upshear-left up to 6 km
- Bend back downshear above that

Why "Envelope?"

- Meant in a wave-analysis type sense
 - Individual cells moving through a larger packet
 - Phase speed and group speed differences
- At right, azimuthal cross section through envelope



Why "Envelope?"

- Meant in a wave-analysis type sense
 - Individual cells moving through a larger packet
 - Phase speed and group speed differences
- At right, azimuthal cross section through envelope
 - Envelope frame
 - Individual updraft



Upper-Level Effects

- Tilt envelope localizes convection
- Positively buoyant updrafts all the way to the top (13 km)
 - Rising through tilt-induced vortexscale cold anomaly
- Erodes environmental forcing



This is <mark>upshear</mark> radial wind



"Local" Deep-Layer Shear



- TC Outflow blocks/diverts the environment
- Shear calculated in 200-km circle is reduced by half
- Note that it increases again late in the simulation

Cap on intensification



Vertical Structure of the Block

- Outflow of the TC blocks the environment
- What is the vertical structure of this blocking
 - i.e., why does the depth of the environmental wind matter?
- Launch trajectories from environment (48-96 hours)
 - From 10 km to 14 km height, upwind of TC, spaced 5 km apart meridionally, 0.5 km vertically
 - 120 parcels per level



Trajectories

- 10.5 km
 - Entrainment
- 12.0 km
 - Some blocking
 - Deflection evident on southern side
- 13.0 km
 - Very few entrained (4/120)
 - Mostly deflection
- 14.0 km
 - All are deflected/reflected



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Vertical Structure

- Upshear/Downshear dichotomy
- In Control (bottom panel), outflow moistens 11 km and up within 500 km
 - Drying/sinking from 250 km outwards
- Upshear, sinking/drying is closer to vortex core
 - Also starts from higher in environment



The Outflow Jet

- Trajectories are diverted to the left
 - Some entrained parcels are ejected into jet
 - The block appears to force leftward (southward) movement
- Two parts
 - Vortex Part
 - Environment Part



Outflow Jet: Vortex Part

- Environmental flow creates region of negative absolute angular momentum (AAM) on left-of-shear side
- From ensuing convection, AAM minimum back builds to upshear, increases in magnitude
- Locally, inertially unstable



Outflow Jet: Environmental Part

- Slightly more complicated requires more prep work
- Perform Helmholtz (ψ - χ) Decomposition
 - Since background winds are constant by initialization, they are completely filtered out
 - (Almost) all changes in the flow are a result of the TC
 - Spurious convection, effects small
- How far away does the environment "know" about the TC?

Outflow Jet: Environmental Part (cont'd)

- In figure, ~12.5 km Cartesian winds + density, upshear:
 - Rotational, Divergent, and Total
 - Environment forced to the left
- Environment "knows" about TC 1000 km away
 - Bow wave
 - Forced by lower density air
 - Subtle sinking starts as well



About those WV Arcs...



Morrison microphysics

Morrison et al. (2012)
CRTM is picking up on number concentration

Zonal cross section indicates arcs are 1.5-km deep under tropopause

N² >= 2 (10⁻⁴ s⁻¹)
They are the outer

 They are the outer bounds of the upshear radial outflow

Tying This Together (Summary)

- Given the correct environmental wind set-up, with moderately strong environmental winds confined to near the tropopause, a TC can progress on an atypical path to RI
 - Shear produces tilt
 - Shear depth allows mid-level center to return upshear
 - Tilt wobble linked to enhanced convection
 - Outflow of enhanced convection blocks the environmental flow









Summary (cont'd)

- Arcs in WV imagery provide visual guidance of outflow push back
- Upshear sinking is also associated with this block
 - Warmer/dryer signature in WV imagery
- To explain WV imagery...



Arcs are extent of outflow. Drying/warming beyond that is environmental air forced downwards at and upwind of interface.

Distance from arc to nearest cloud upshear is ~6° longitude. Bow wave in CM1 was ~700 km from interface.



That's all for now.