The Kinematics of Rapidly Intensifying Hurricanes in Moderate Vertical Wind Shear

David Ryglicki
Naval Research Laboratory
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david.ryglicki@nrlmry.navy.mil

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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): $\mu = 3.9\ m\ s^{-1}$, $\sigma = 1.5\ m\ s^{-1}$
  - Northern Atlantic (NATL): $\mu = 5.1\ m\ s^{-1}$, $\sigma = 2.0\ m\ s^{-1}$
  - 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 $+1\sigma$ to $+5\sigma$ greater than RI climatology *and* share similar satellite features

The List

The Originals

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

The New Ones

- 2012 EPAC Daniel
- 2014 EPAC Marie (?)
- 2016 EPAC Blas
- 2016 EPAC Darby*
- 2016 NATL Matthew
- 2017 EPAC Kenneth

** Technically, did not meet RI requirements*

Hurricane HERNAN

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ZCZC MIATCDEP4 ALL
TTAA00 KNHC DDHHMM
HURRICANE HERNAN DISCUSSION NUMBER  12
NWS TPC/NATIONAL HURRICANE CENTER MIAMI FL   EP092008
800 AM PDT 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
HERNAN HAS BECOME A MAJOR HURRICANE... HAVING UNDERGONE RAPID
INTENSIFICATION SINCE YESTERDAY.  THIS PROVIDES YET ANOTHER EXAMPLE
OF THE INABILITY OF MODEL GUIDANCE...AND THEREFORE THE HUMAN
FORECASTER...TO CAPTURE AND CONVEY THE TIMING AND MAGNITUDE OF THESE
EPISODES 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 CORRECTLY 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 DYNAMICAL MODELS AS
THE SUBTROPICAL RIDGE BUILDS WESTWARD OVER THE EASTERN PACIFIC
DURING THE NEXT COUPLE OF DAYS.  BEYOND THAT TIME...A WEAKENING
HERNAN IS EXPECTED TO BECOME A MORE SHALLOW SYSTEM AND TURN
WESTWARD AND EVENTUALLY WEST-SOUTHWESTWARD IN THE LOW- TO MID-LEVEL
FLOW.  THE NEW OFFICIAL TRACK FORECAST IS ALMOST IDENTICAL TO THE
PREVIOUS ONE AND IS CLOSE TO THE MODEL CONSENSUS.



FORECAST POSITIONS AND MAX WINDS

INITIAL      09/1500Z 15.7N 123.3W   105 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 18.0N 131.0W    45 KT
 96HR VT     13/1200Z 17.5N 133.5W    35 KT
120HR VT     14/1200Z 16.5N 136.0W    30 KT

$$
FORECASTER KNABB
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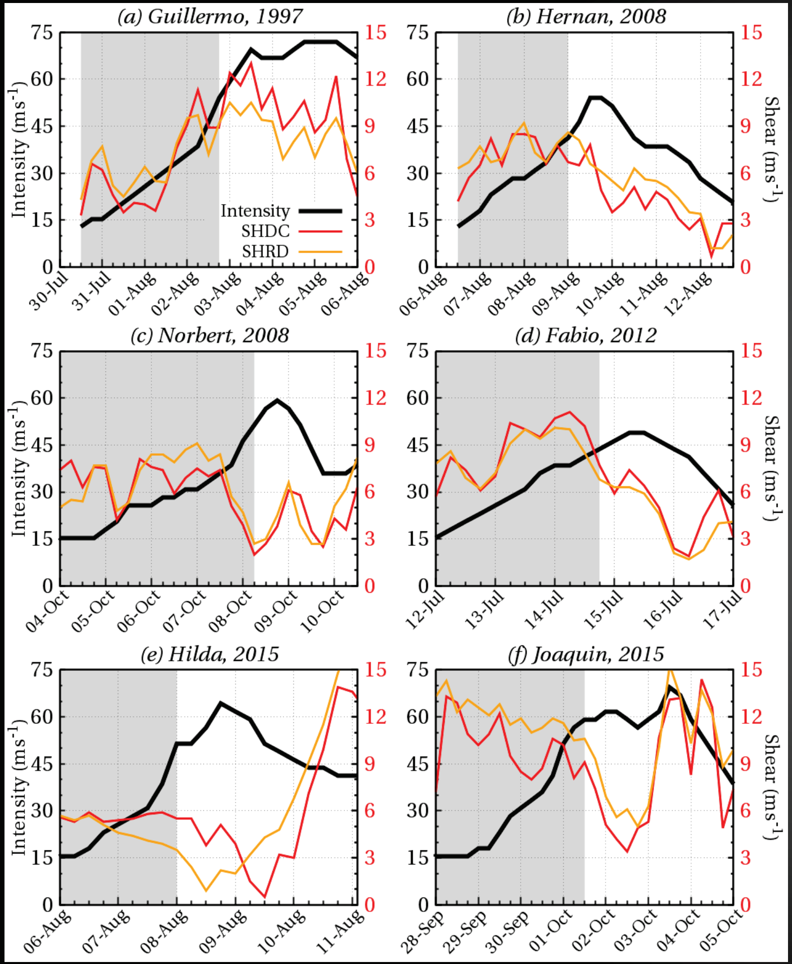
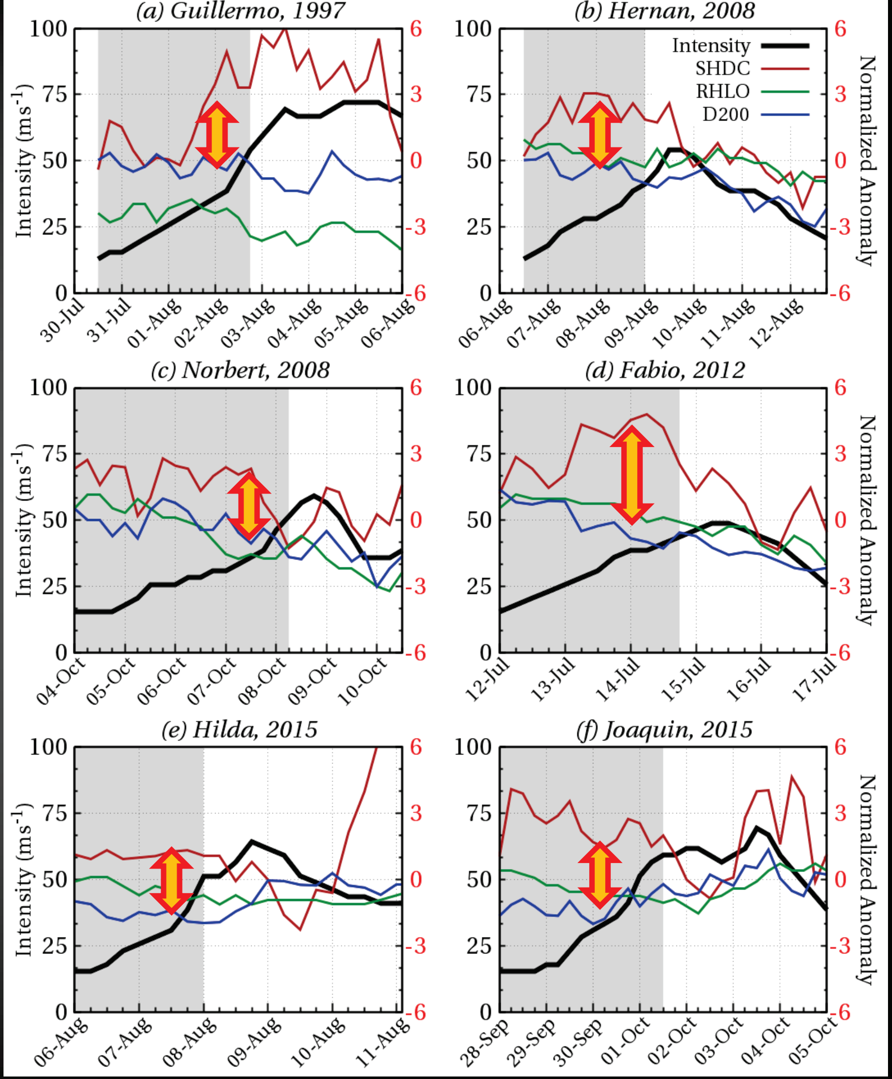
Intensity v. Shear



- 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}
  - ***7.5 m s^{-1}***

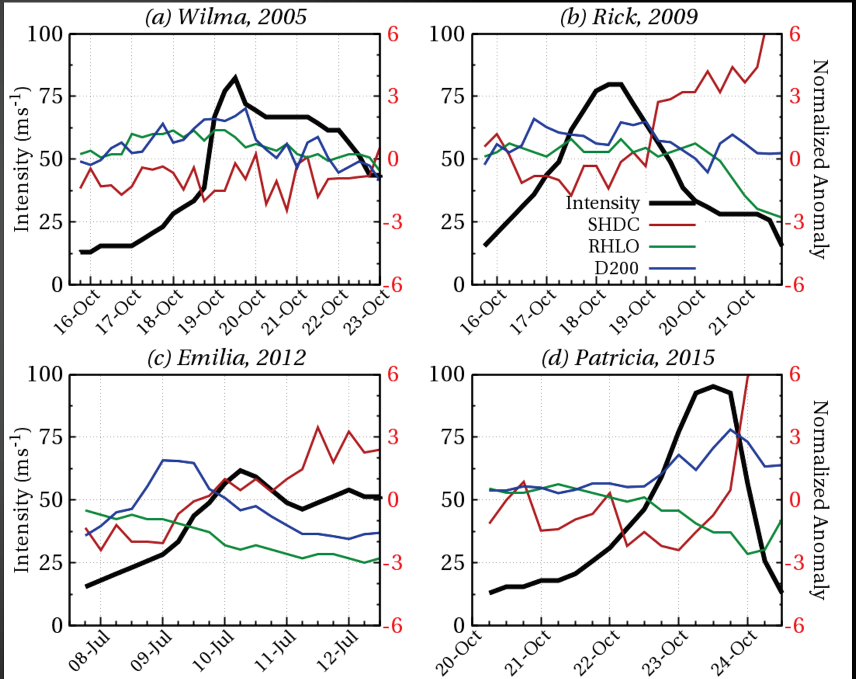
Large-Scale Predictors

- Shear is never the whole story
- To streamline synoptic discussion, focus on three "large-scale" 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 NATL Wilma
  - 2009 EPAC Rick
  - 2012 EPAC Emilia
  - 2015 EPAC Patricia
- Low shear, high divergence
  - Flipped relationship from previous six

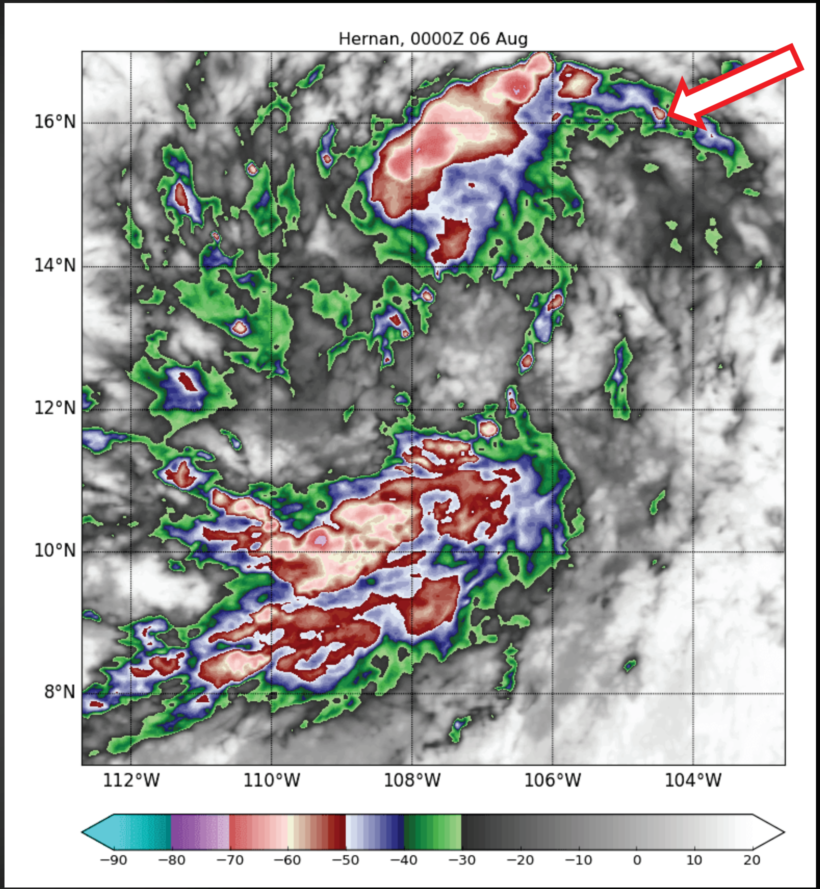


Geostationary Satellite Imagery

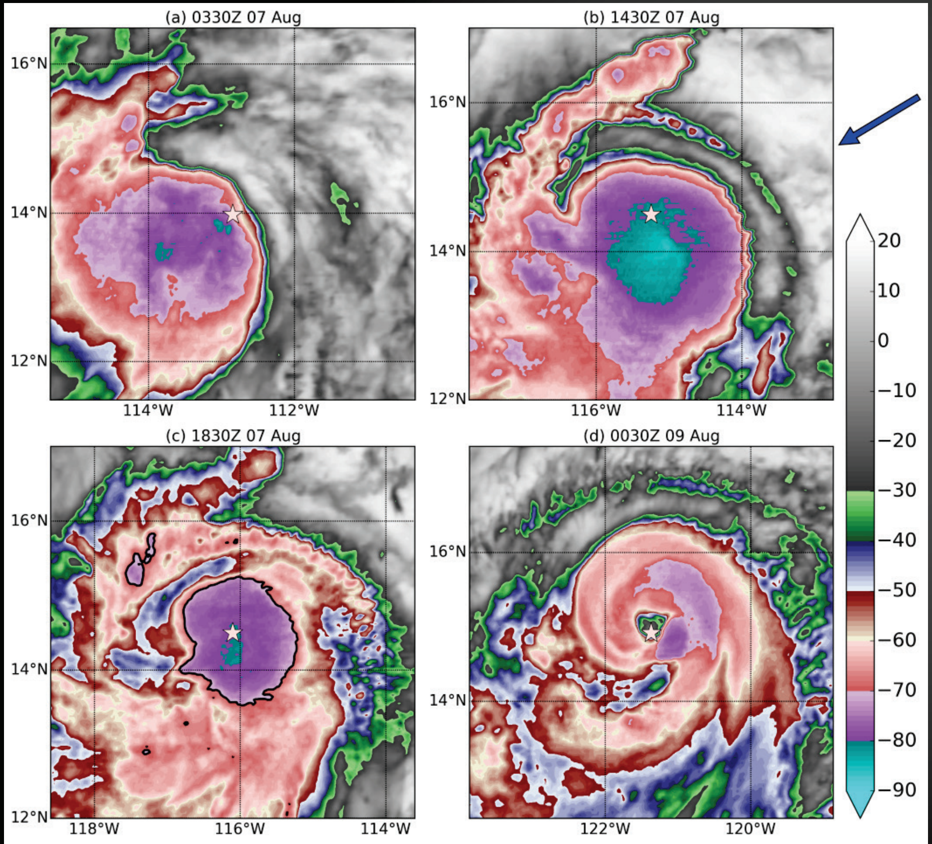
- GOES 8, 9, 11, 12, 13, and 15 data are used
- Infrared (IR) and Water Vapor (WV) channels
  - IR
    - 10.20 to 11.20 µm
    - 4 km effective grid spacing
  - WV
    - 6.50 to 7.00 µm for GOES-8 to GOES-11 (late 2011)
    - 5.77 to 7.33 µm for GOES-12+
    - 8 km effective grid spacing for GOES-8 to GOES-11; 4 km thereafter
- Interpolated to polar coordinates around storm center
  - Best track (HURDAT2)

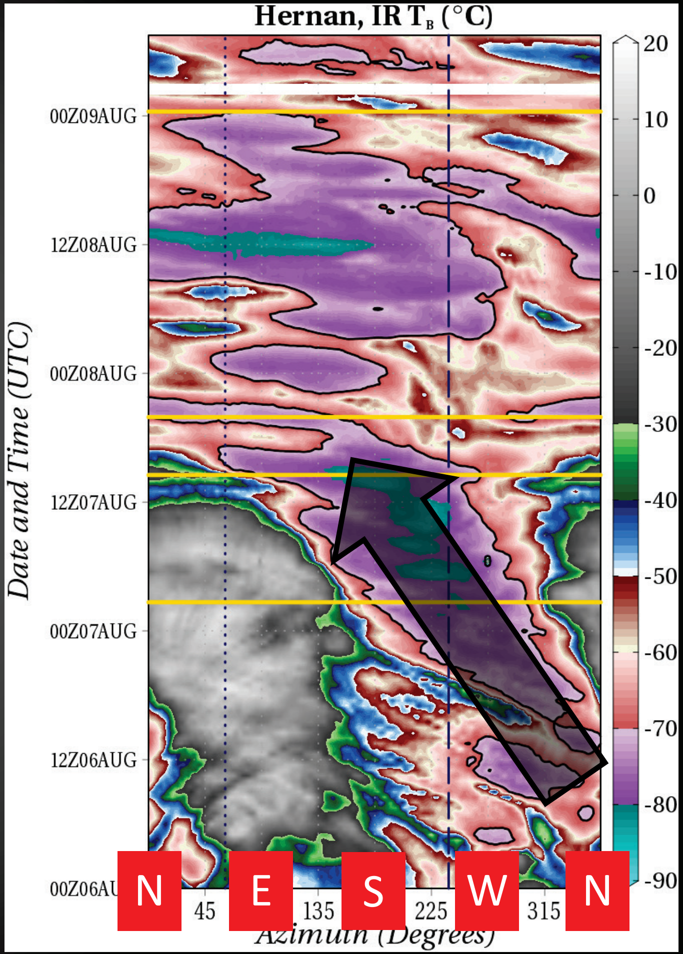
2008 EPAC Hernan

- 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)

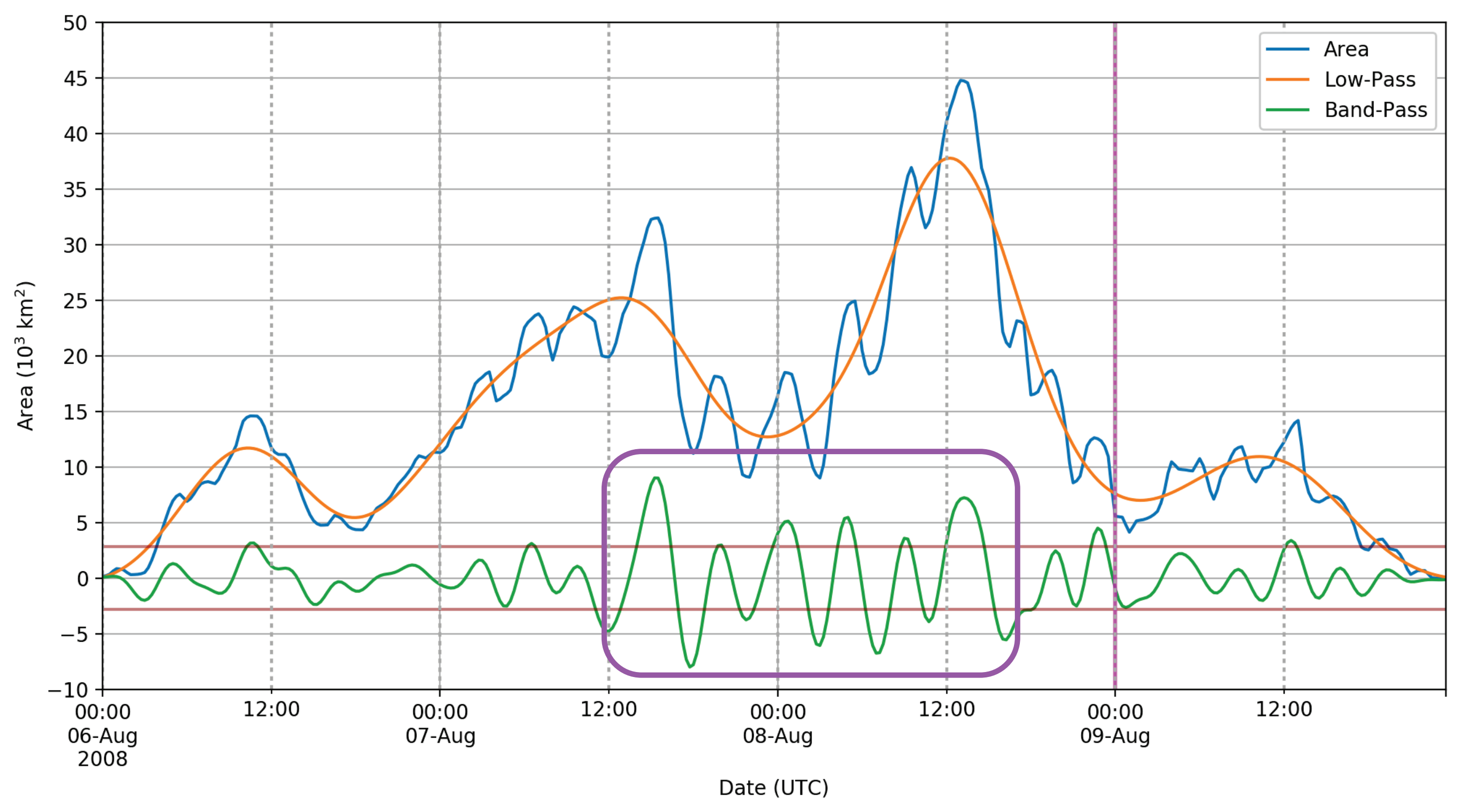




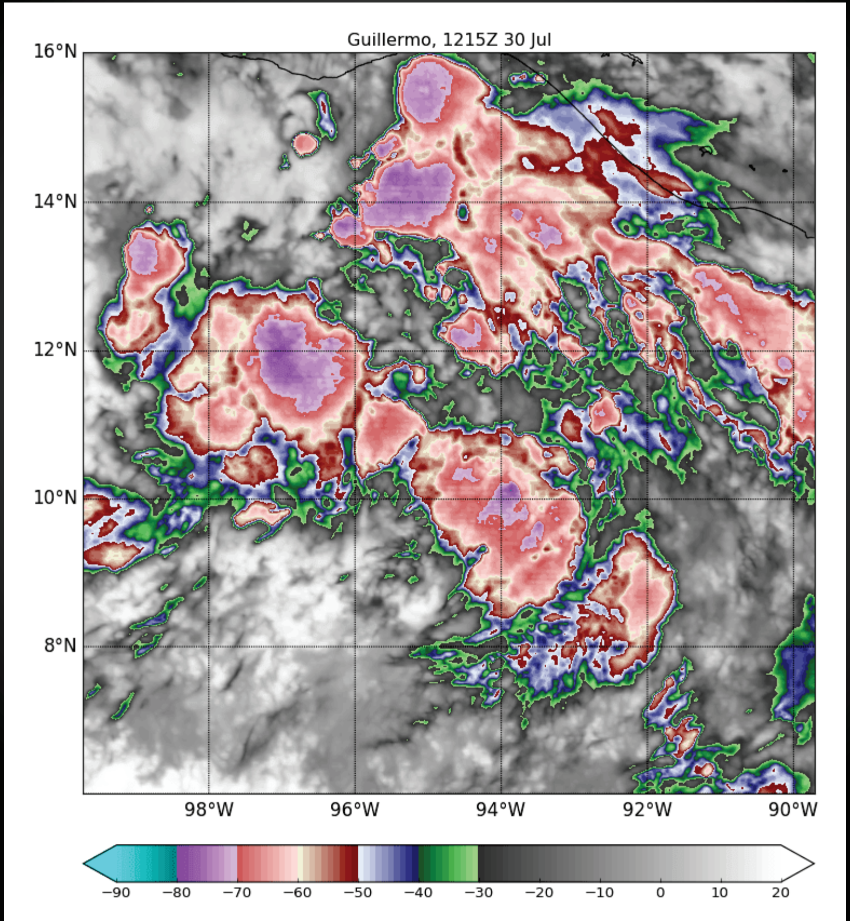
Areal Coverage – Periodicity

- Compute area within -70 °C contour within 200 km
- Filter using low-pass filter
  - – Windowed-sinc $$F(t) = f(t) * \operatorname{sinc}\left(2 f_c \left(t - \frac{N-1}{2}\right)\right)\left(a_0 - a_1 \cos\left(\frac{2\pi t}{N-1}\right) + a_2 \cos\left(\frac{4\pi t}{N-1}\right) - a_3 \cos\left(\frac{6\pi t}{N-1}\right)\right)$$
    - 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
  - – Informed by a wavelet analysis (not shown)

Area: Hernan

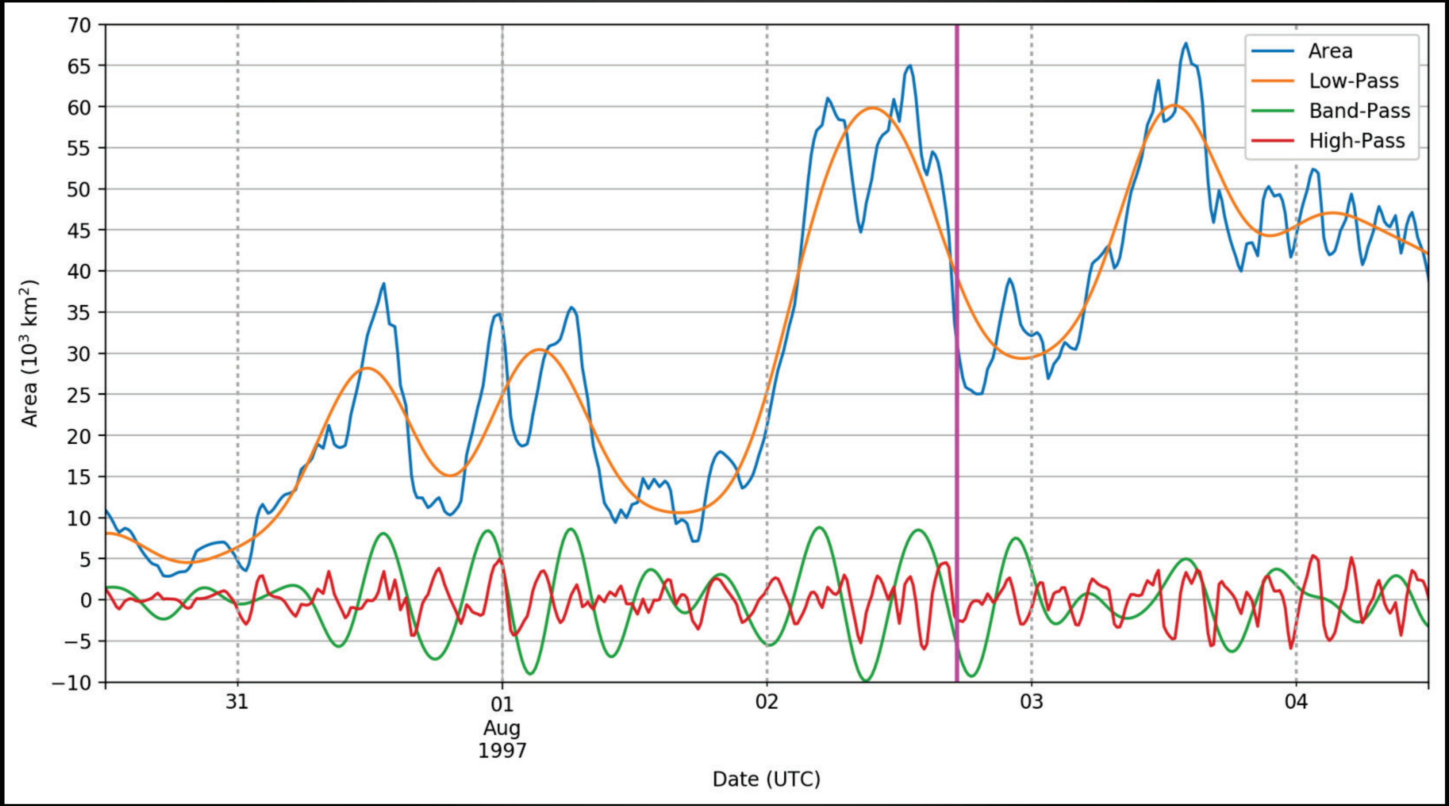

Area
Low-Pass
Band-Pass
Area (10³ km²)
50
45
40
35
30
25
20
15
10
5
0
−5
−10
00:00
06-Aug
2008
12:00
00:00
07-Aug
12:00
00:00
08-Aug
12:00
00:00
09-Aug
12:00
Date (UTC)

Guillermo



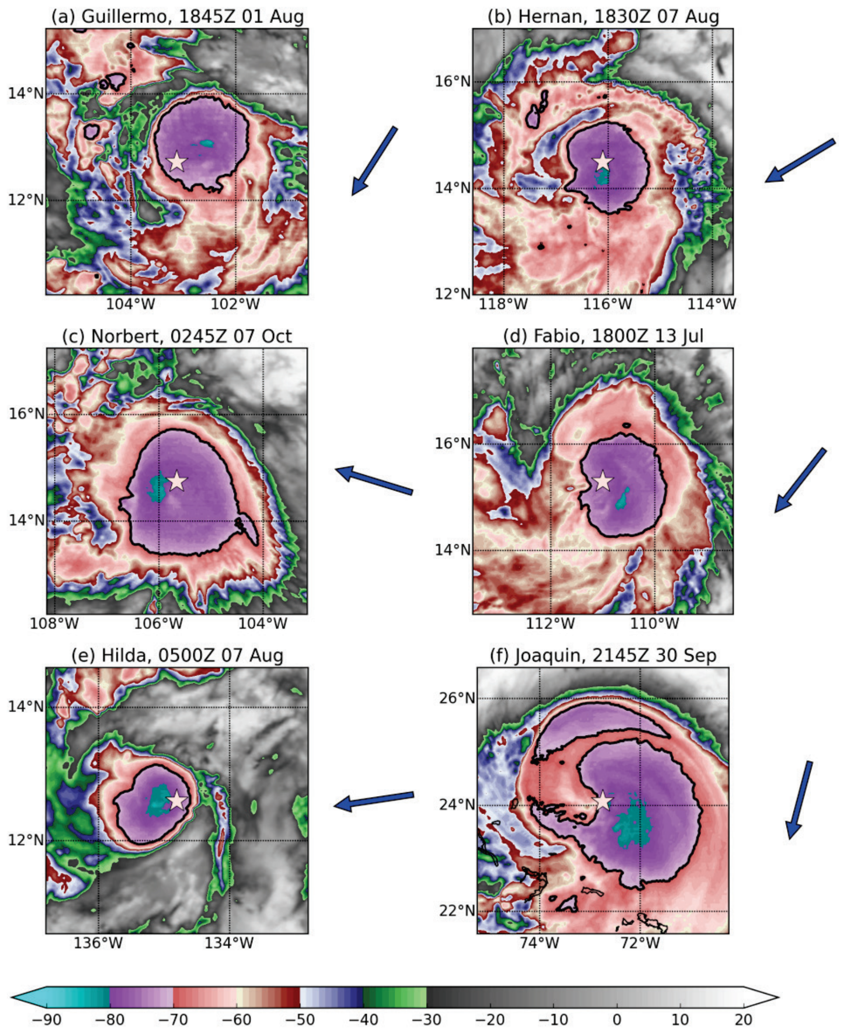
Guillermo, 1215Z 30 Jul
16°N
14°N
12°N
10°N
8°N
98°W
96°W
94°W
92°W
90°W
−90
−80
−70
−60
−50
−40
−30
−20
−10
0
10
20

Normalized Area: Guillermo (5.5 hr cutoff)



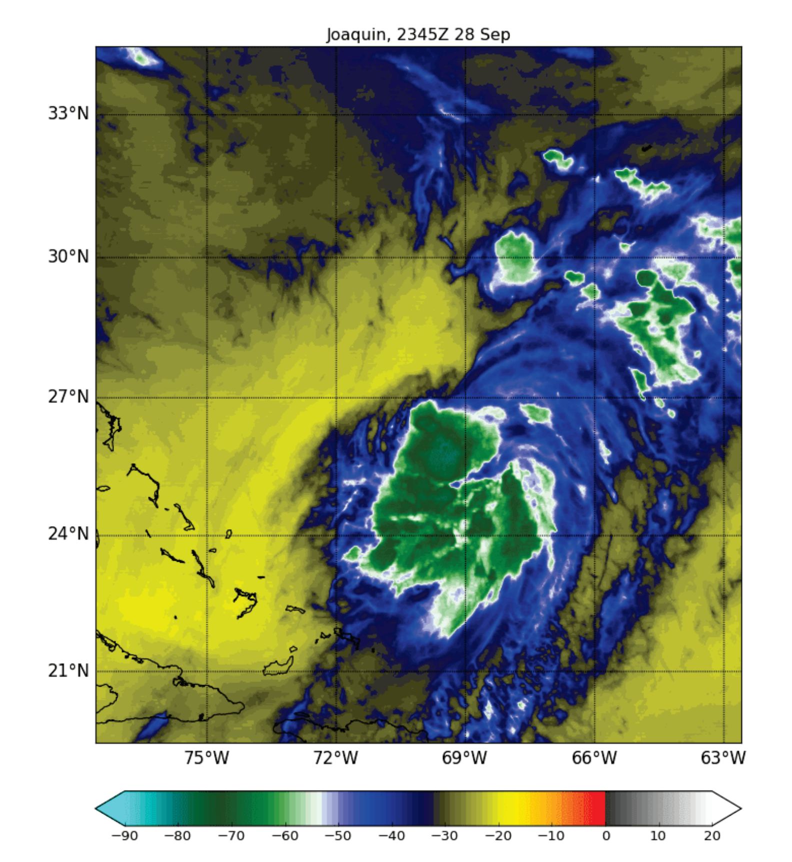
Convective Envelope

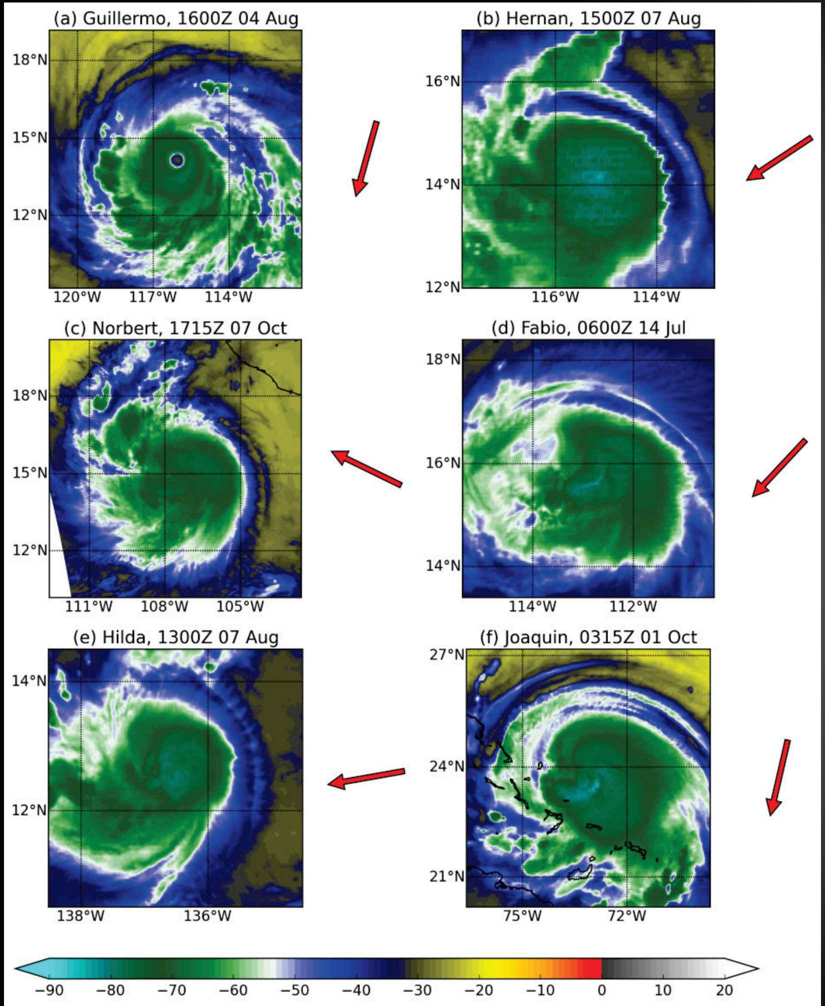
- In each of the six, a convective envelope can be identified
  - Periodicity between 4 and 8 hours
  - Encapsulated inside -70 °C isotherm
  - “Embedded center”
  - Coldest temperatures below -80 °C
  - Oblong-D shape with tail
  - Broadest side angled towards upshear semicircle



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



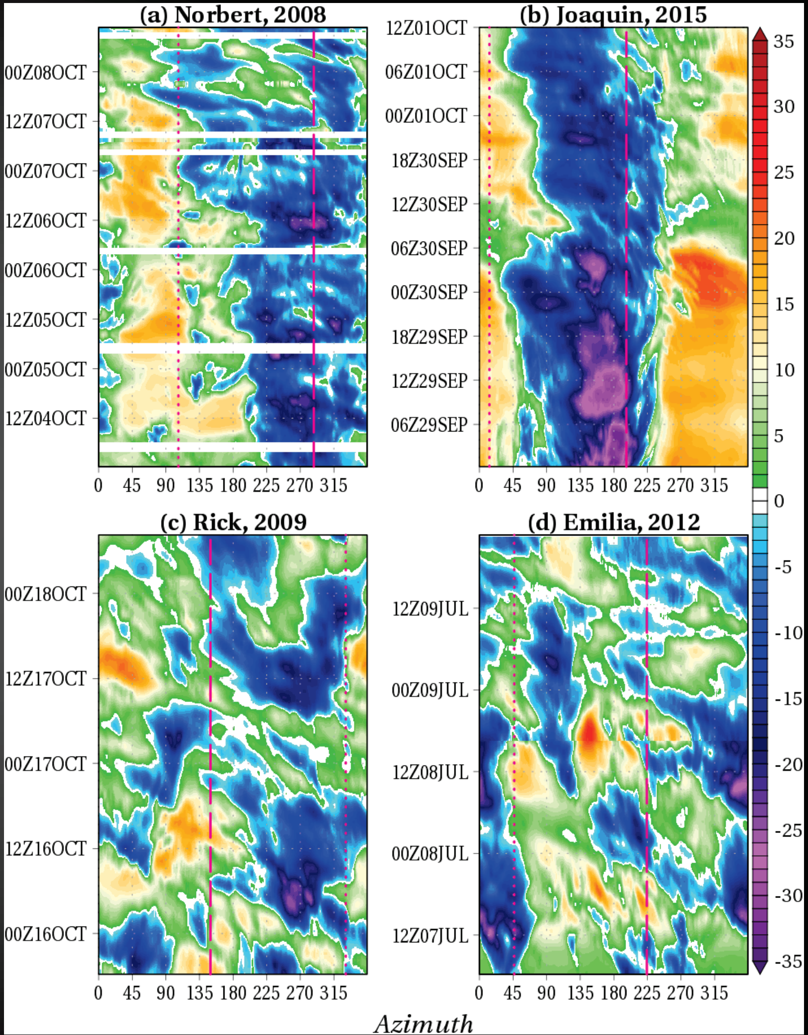


Upshear arcs (WV)

- All arcs are separated by a warm gap
- -40 °C to -60 °C
  - 20-30 km in width
- Consistently upshear
  - Red arrows = shear directions

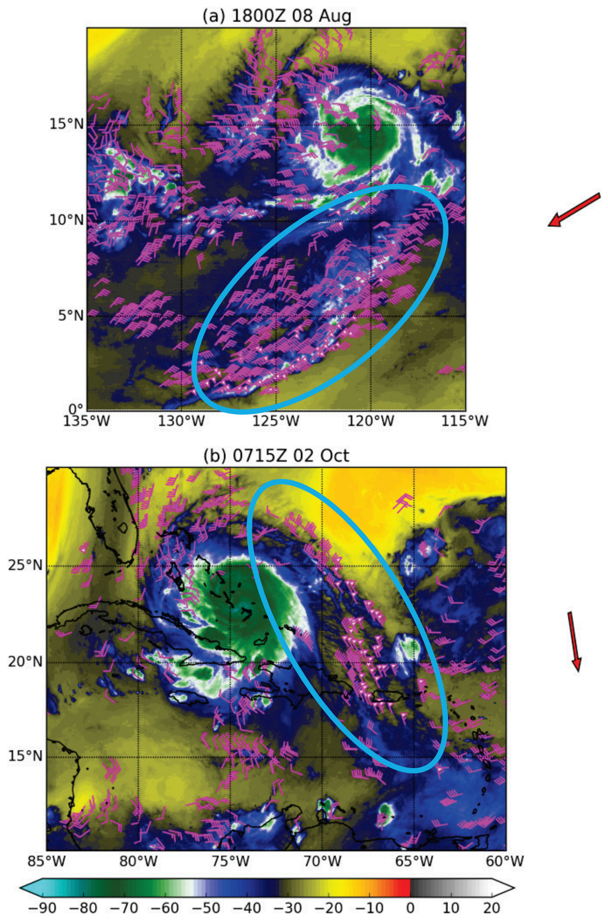
Upshear Drying

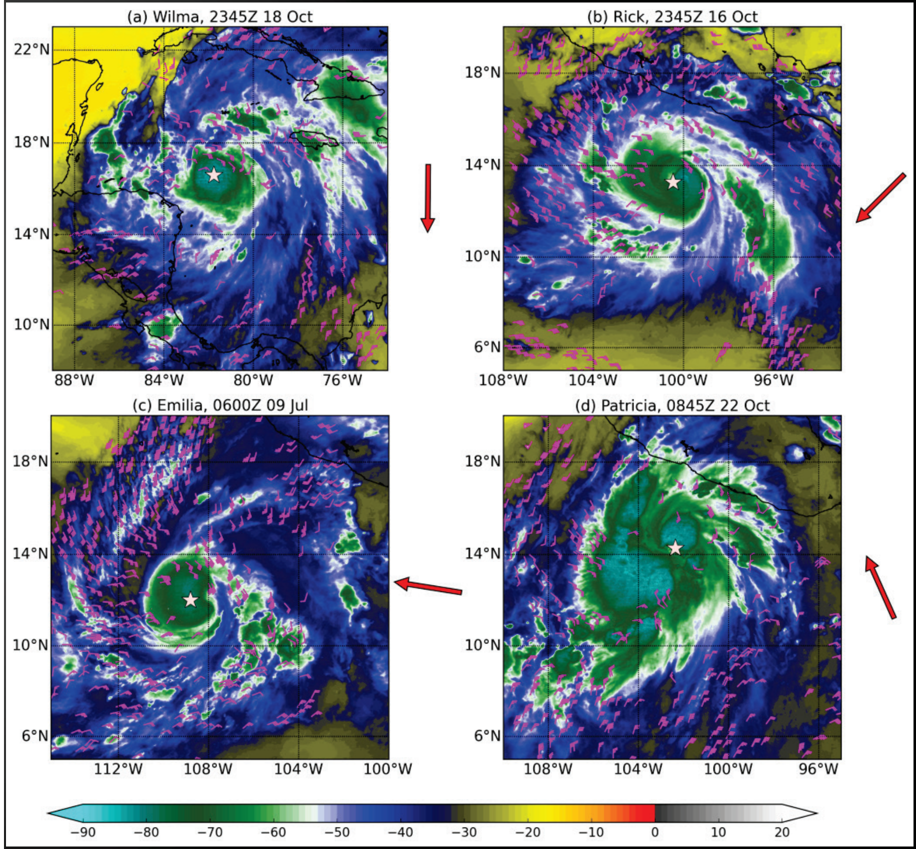
- At right, WV brightness temperatures averaged over 250-350 km annulus
  - Deviation from azimuthal mean
  - Dashed: downshear
  - Dotted: upshear
- Norbert and Joaquin have WV T_B dipole
- No such signal in “classic” Rick or Emilia



Outflow Jets

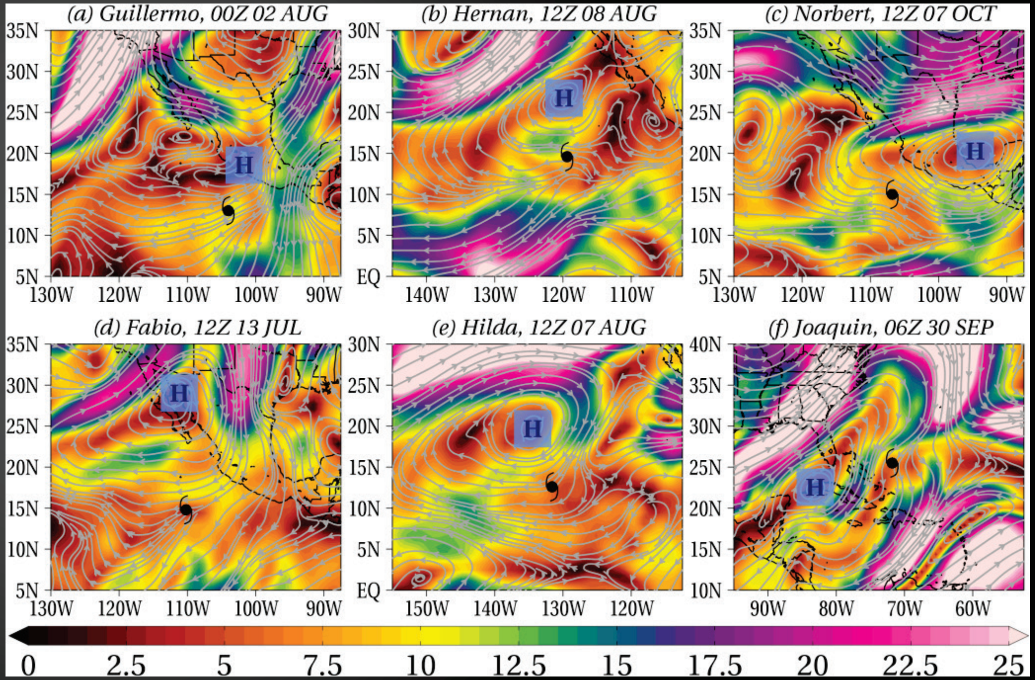
- Atmospheric Motion Vectors (AMVs; Velden et al. 1997) indicate outflow jets located downshear-left
- Windspeeds of 50-70 knots (25-35 m s^{-1})





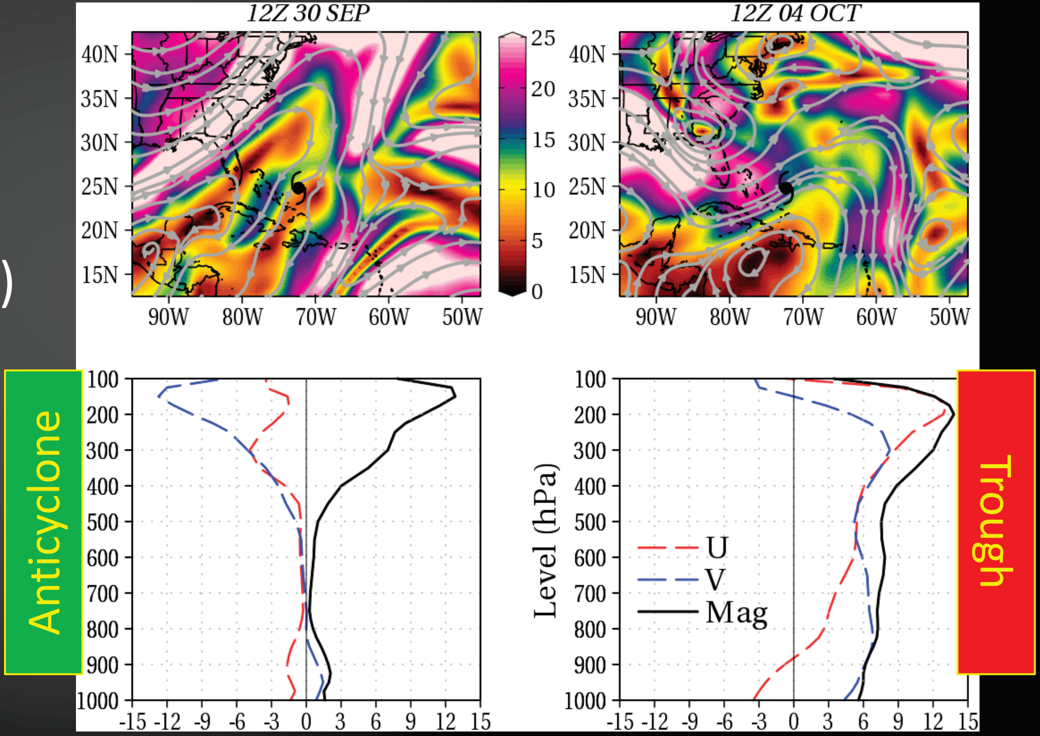
200-mb winds, ERA-Interim

- 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)

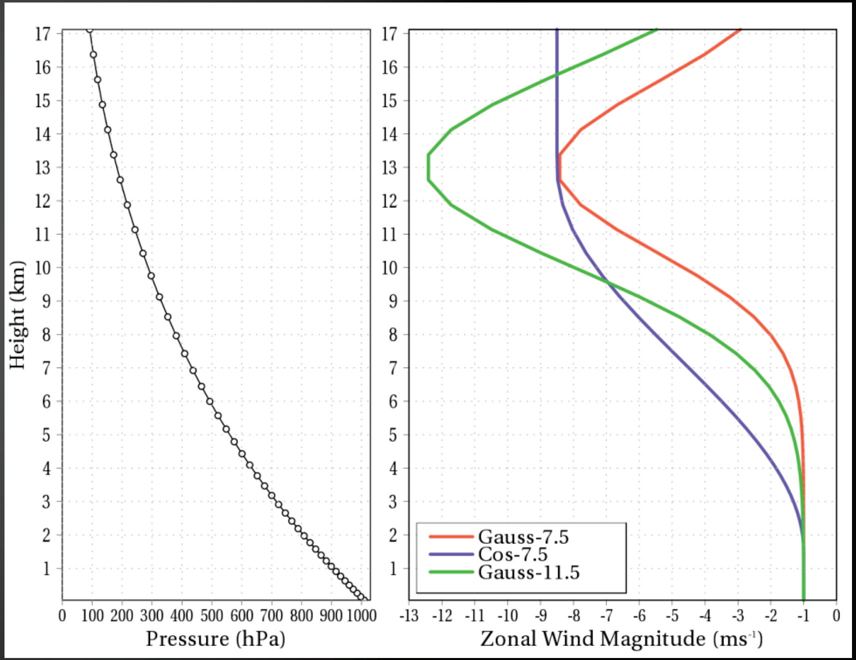


Observations Summary

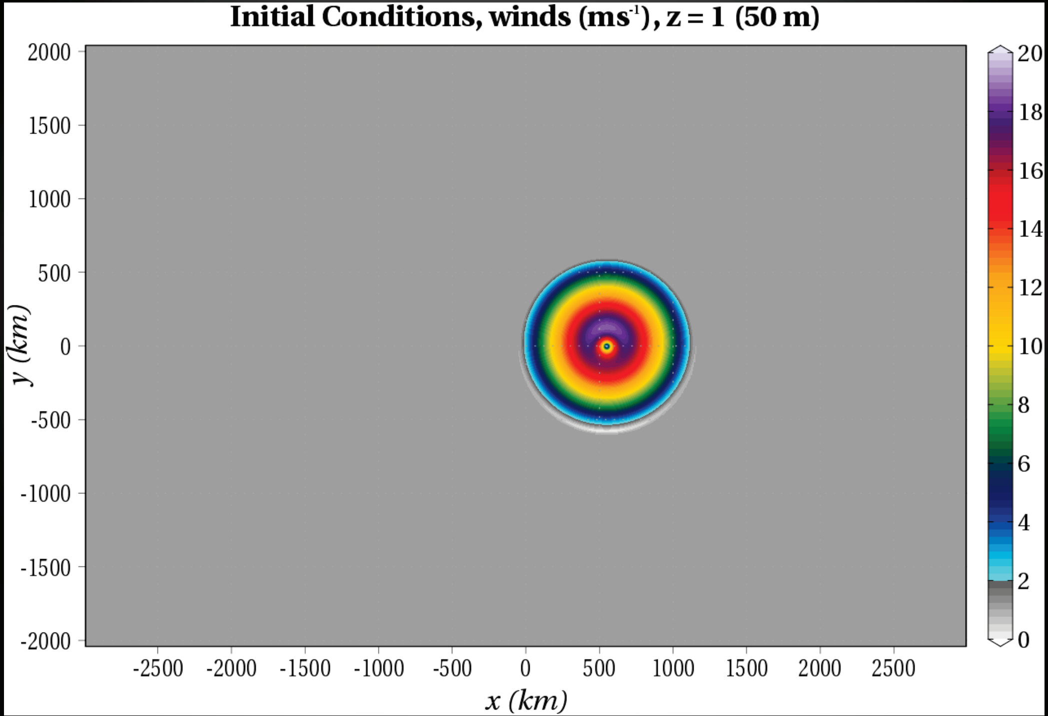
- Environmental set-up
  - Shear: 7.5 m s^{-1}
  - Winds confined to upper levels of troposphere
  - SSTs: 28 °C (in bonus slides)
- Markers
  - Intense convection with 4 to 8-hour periodicity
  - Upshear arcs
  - Oblong-D-with-tail cloud shape
    - Confined within -70 °C isotherm
  - Downshear-left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

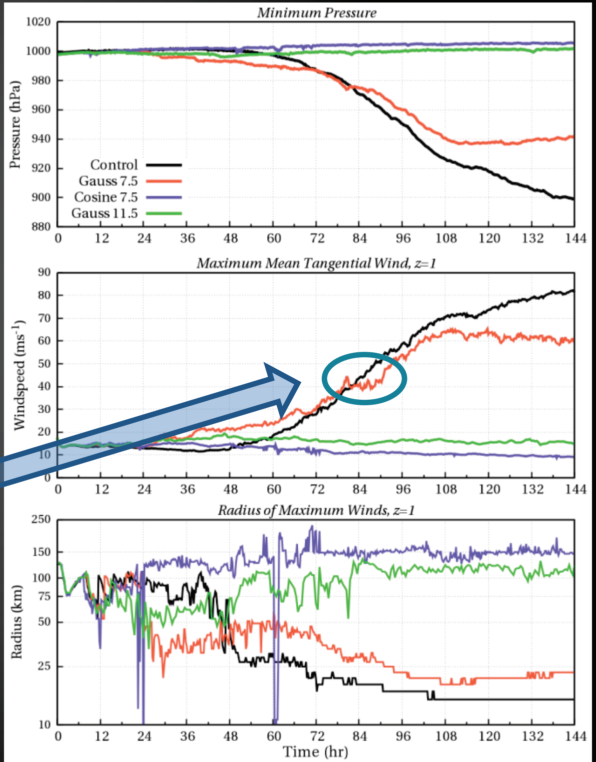


Idealized Modeling: IC



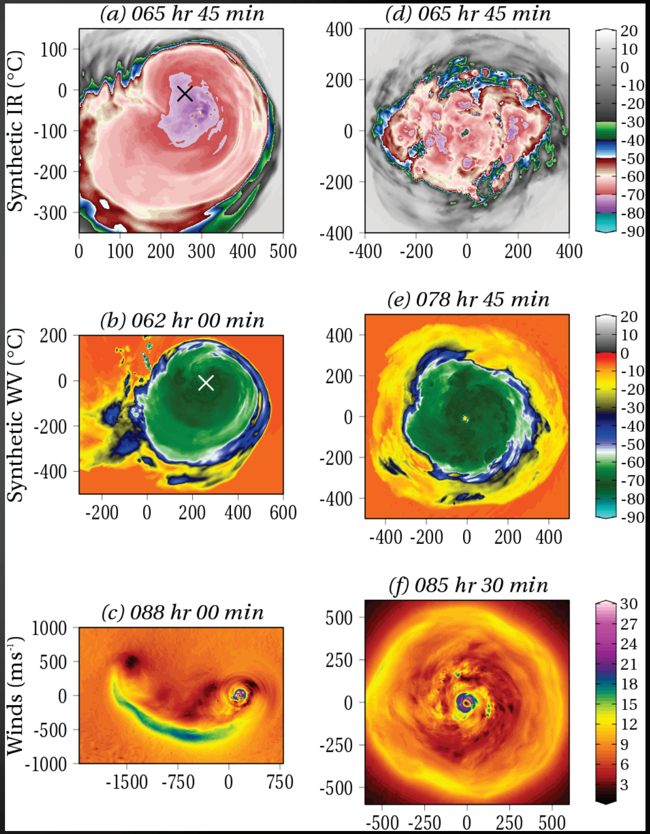
Idealized Modeling: Intensity Evolution

- 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



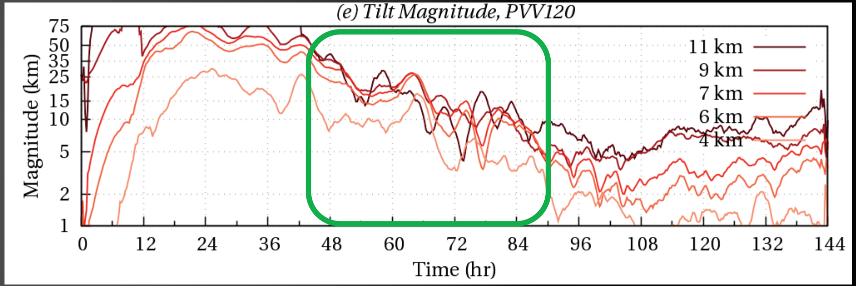
Idealized Modeling: Markers

- 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…



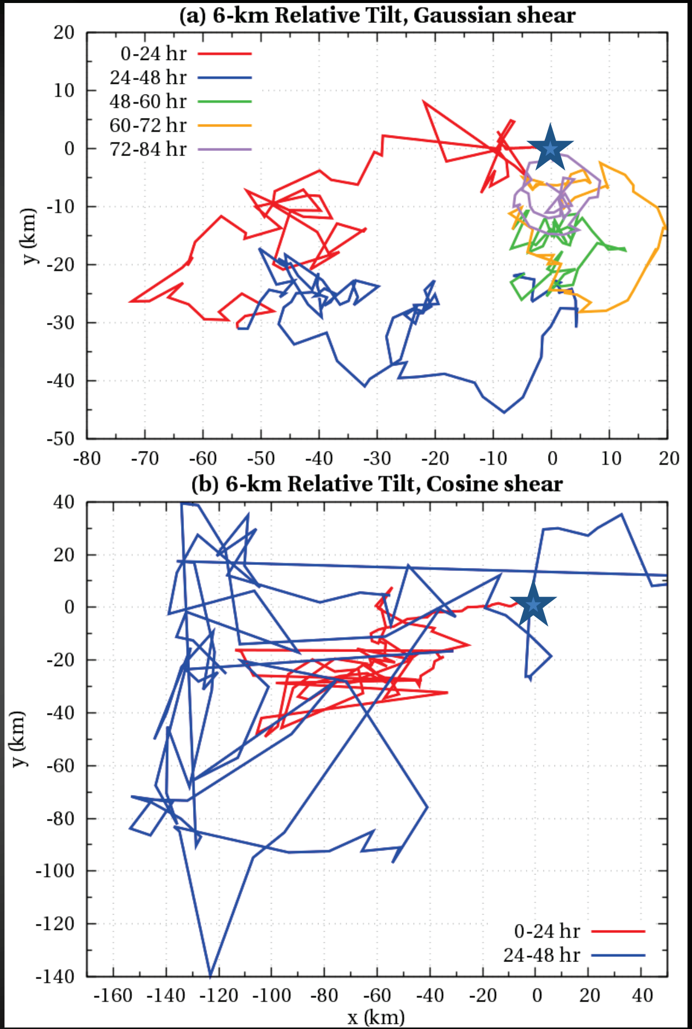
Tilt Evolution

- 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



Tilt Evolution (cont'd)

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

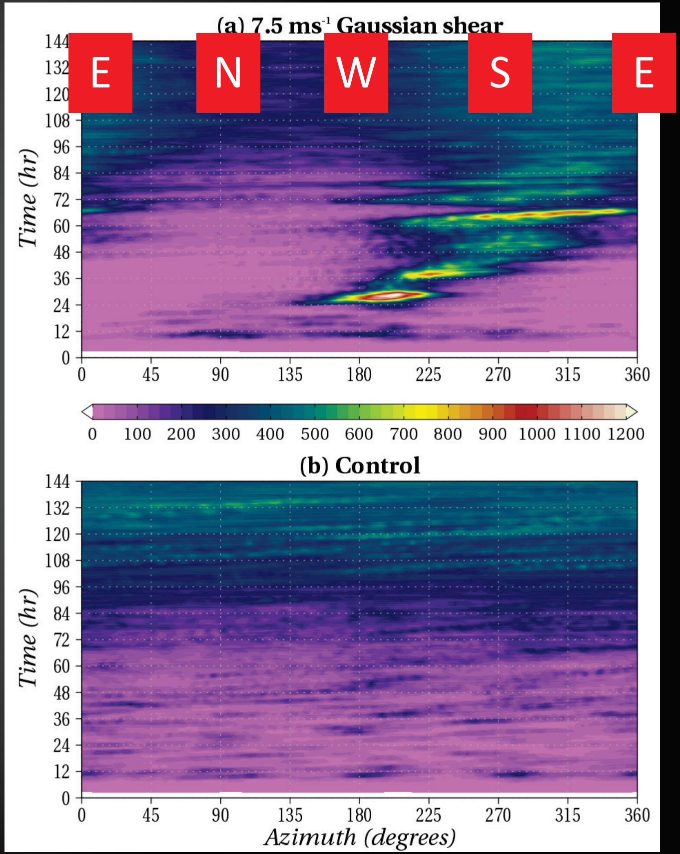


Idealized Modeling: Convection

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

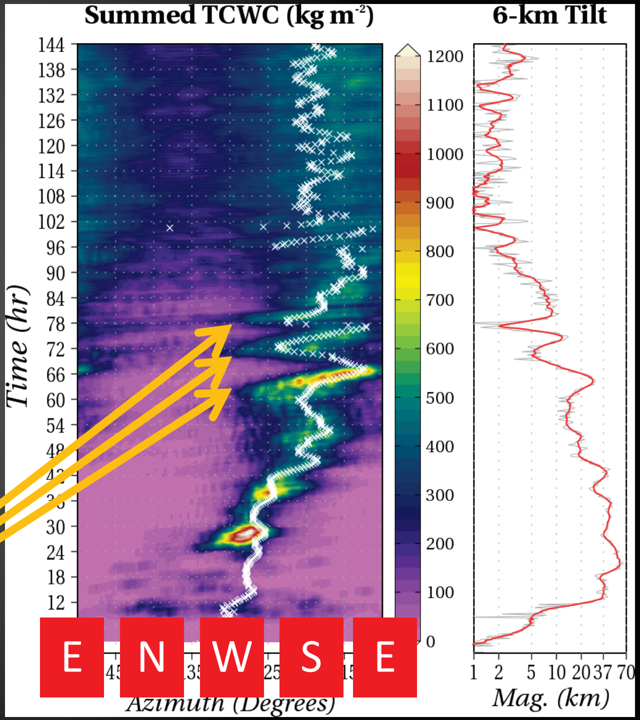
$$TCWC = \int_0^{z_{top}} \rho \left(r_c + r_r + r_i + r_s + r_g \right) dz$$

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

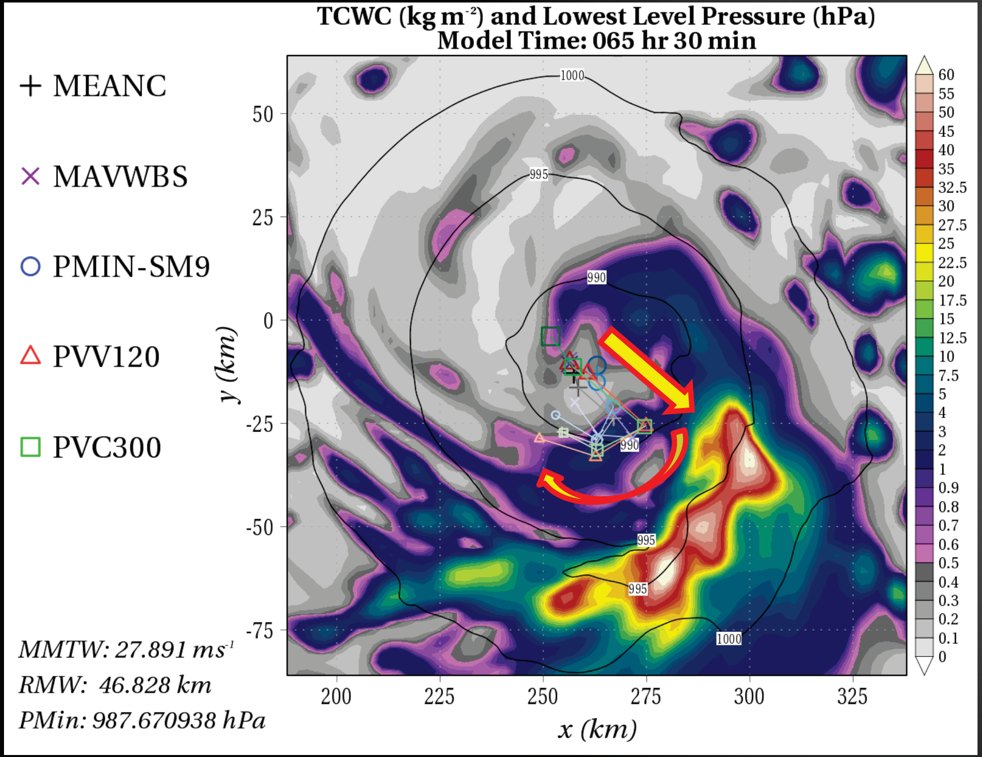


Idealized Modeling: Convection (Cont'd)

- 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

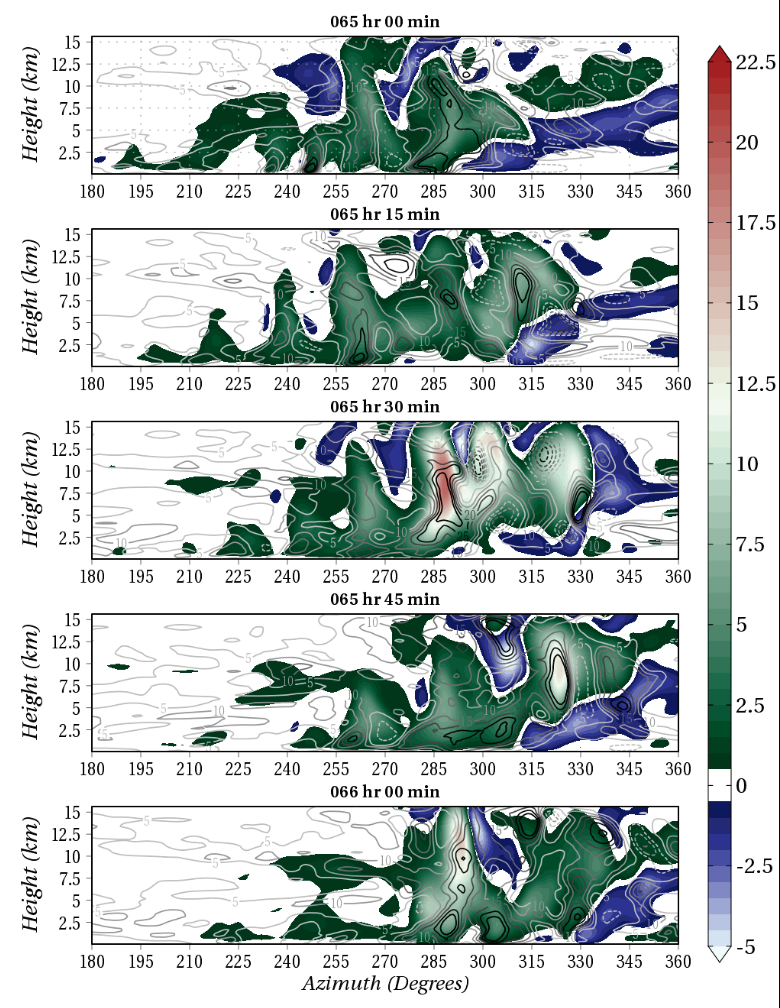


- All center finding methods are oriented upshear-left up to 6 km
- Bend back downshear above that

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

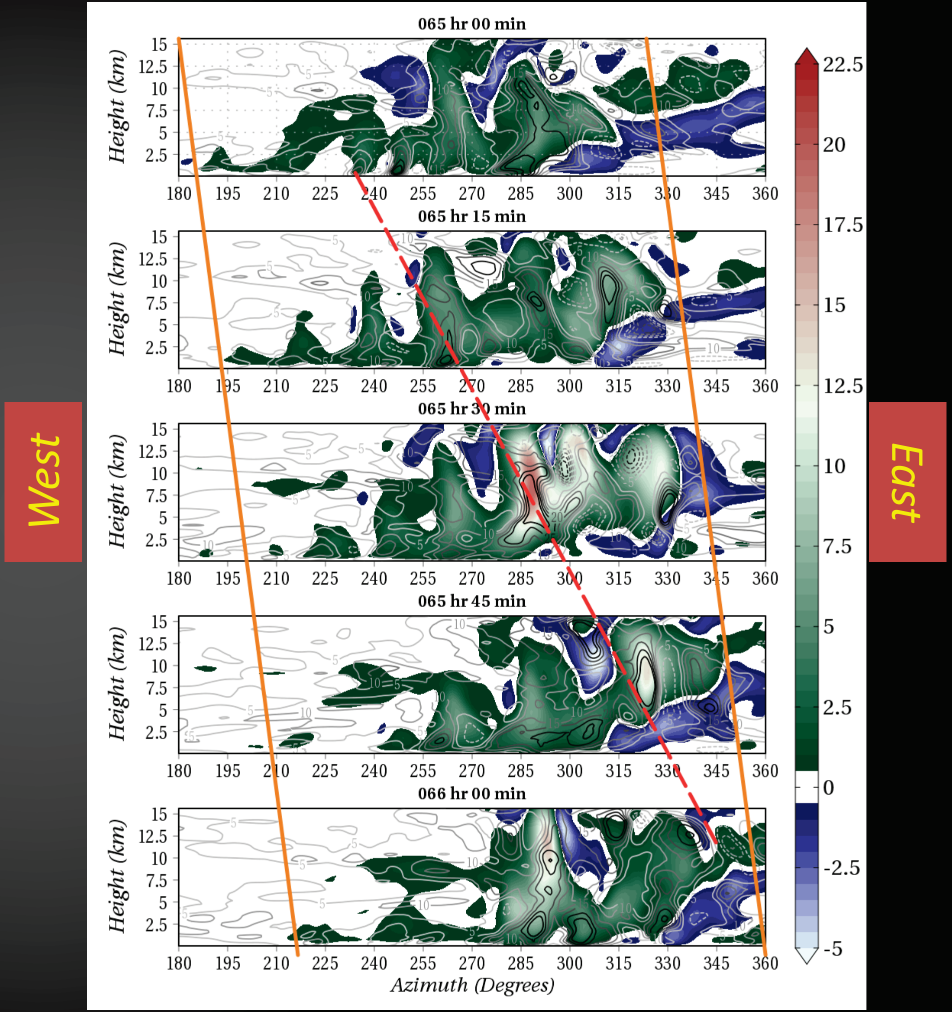
West



East

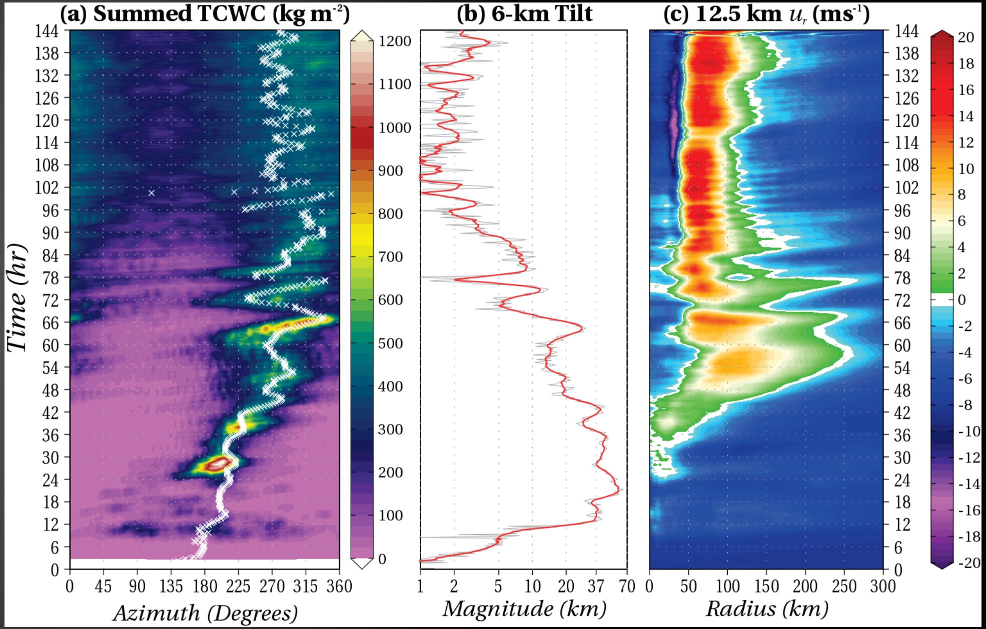
Why "Envelope?"

- 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

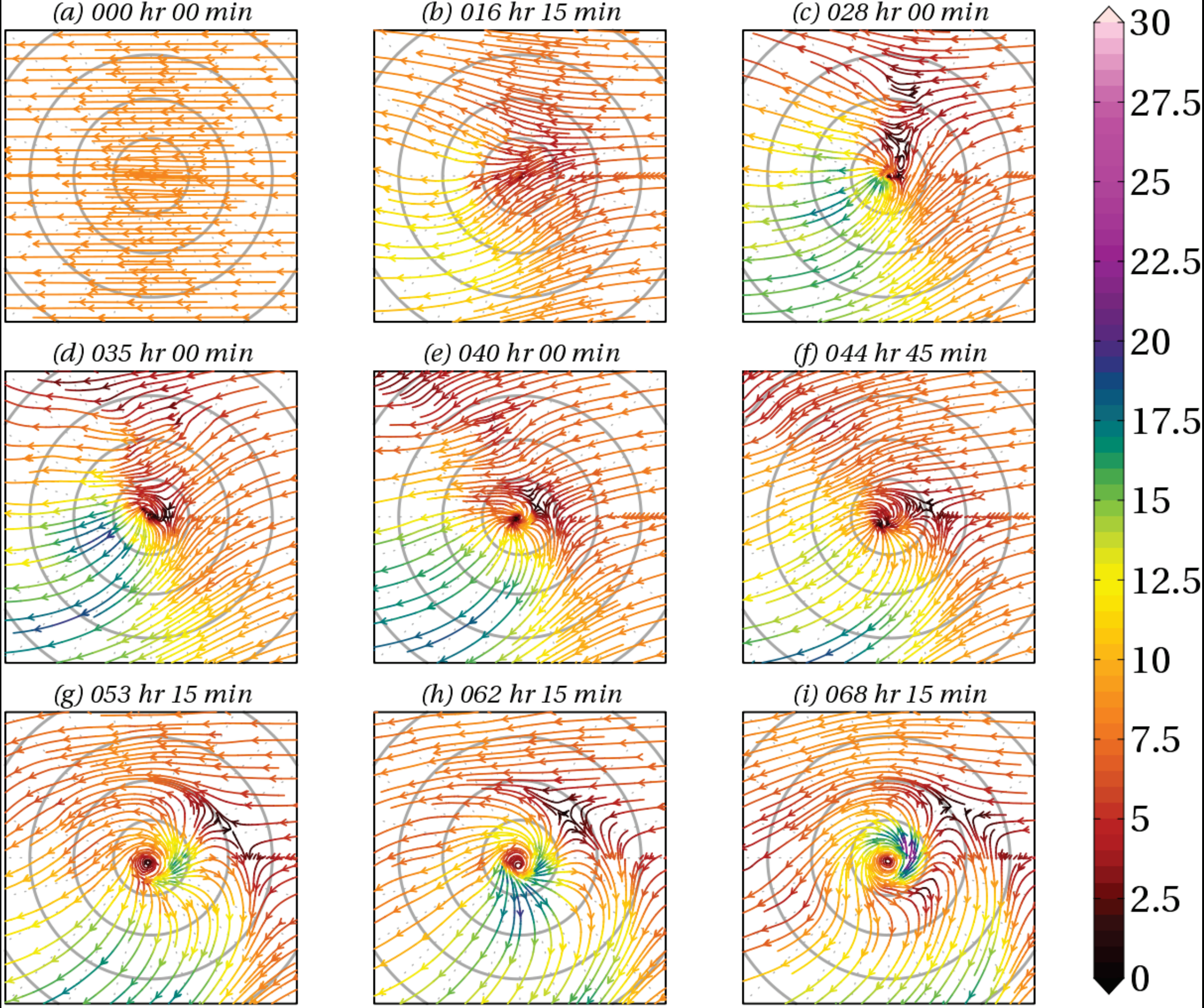


Upper-Level Effects

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



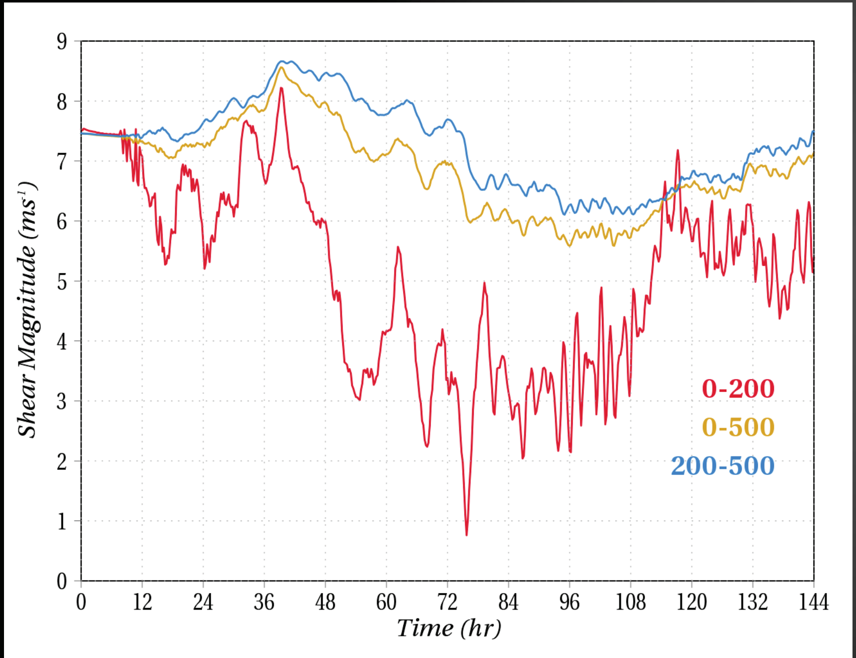
This is ***upshear*** *radial wind*



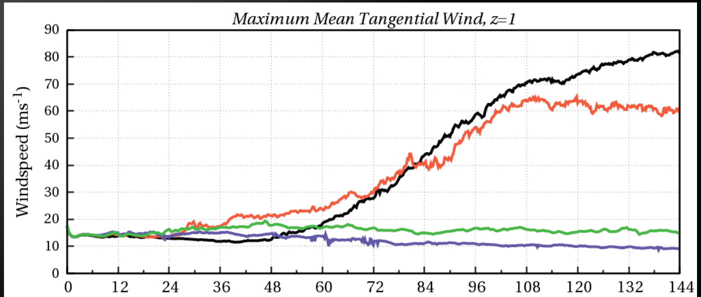
12.5 km tilt-relative (MAVWBS) winds (ms^{-1}), 2.5-hour running mean

Gray rings = 100 km interval

“Local” Deep-Layer Shear

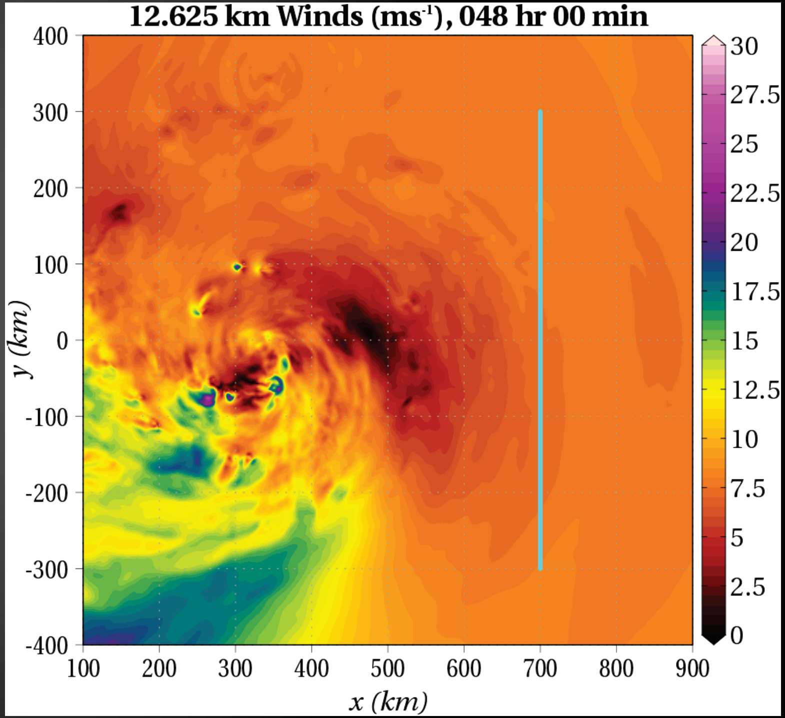


- TC Outflow blocks/diverts the environment
- Shear calculated in 200-km circle is reduced by half
- Note that it increases again late in the simulation
  - Cap on intensification



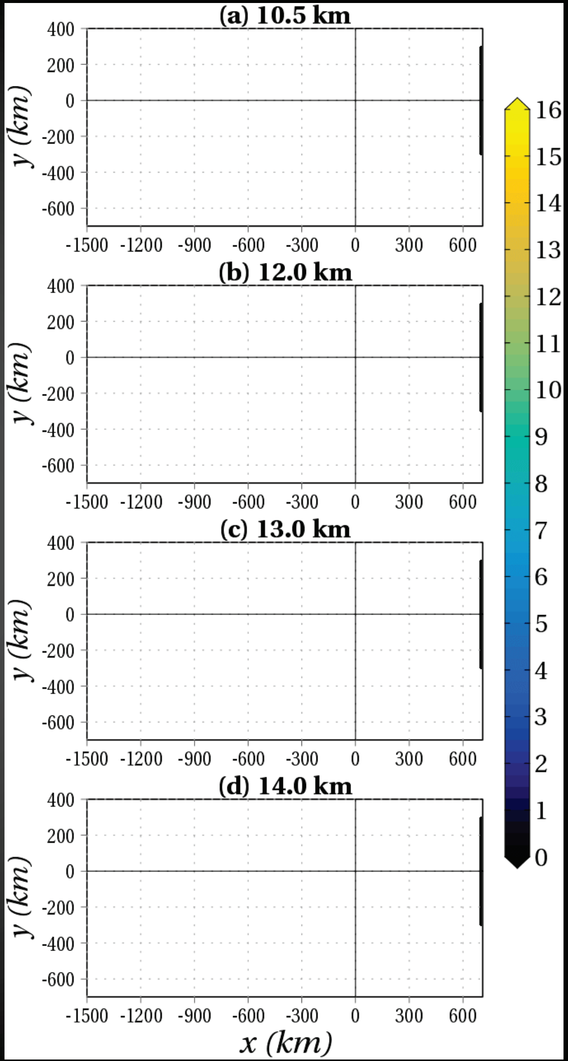
Vertical Structure of the Block

- 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



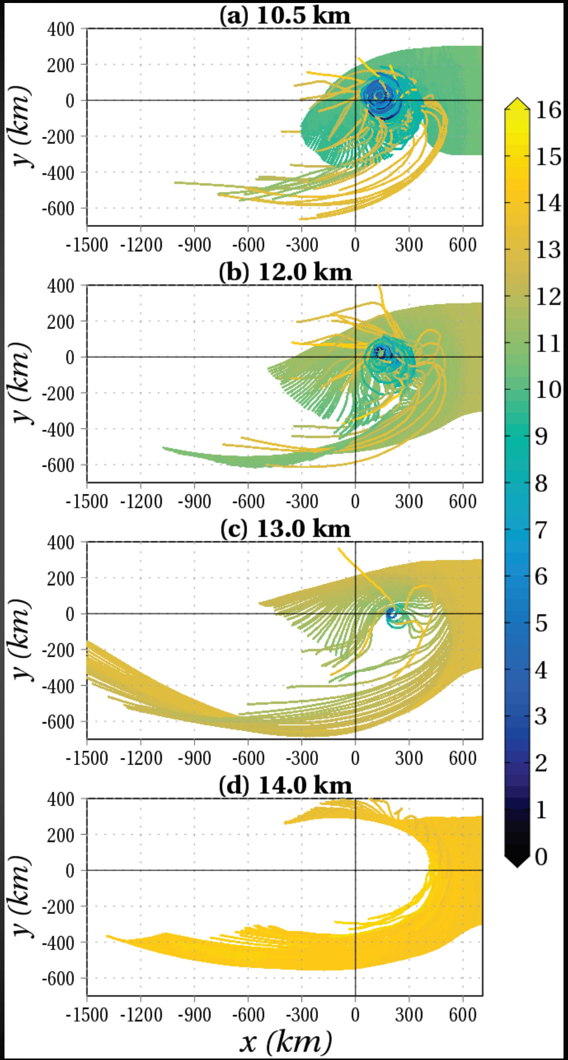
Trajectories

- 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



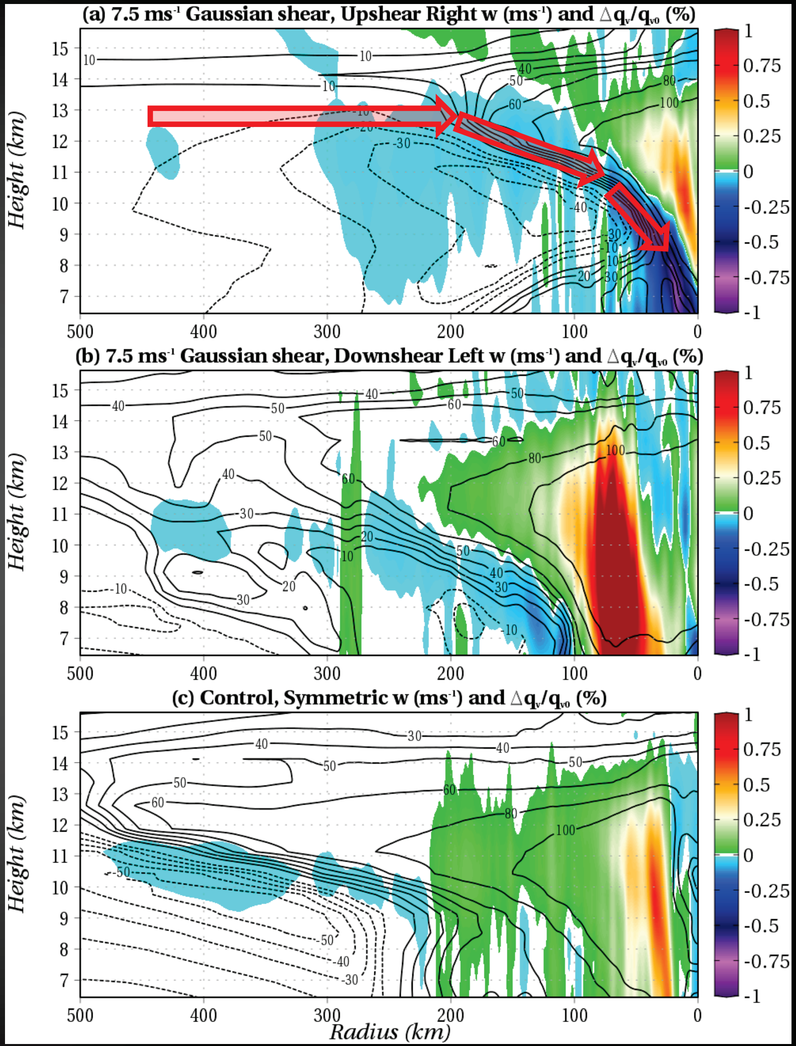
Trajectories

- 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



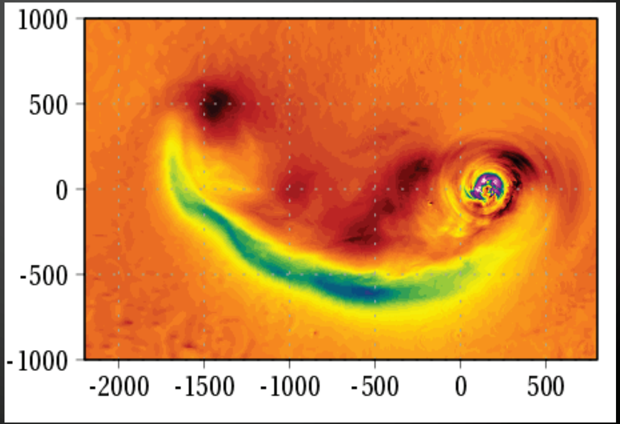
Vertical Structure

- 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



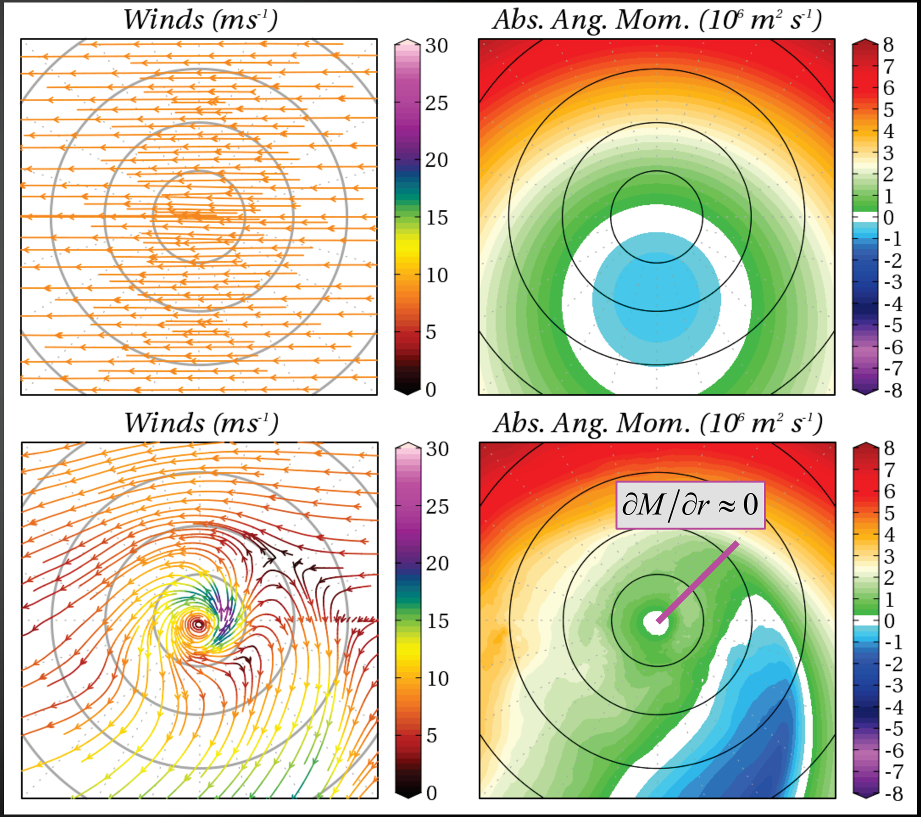
The Outflow Jet

- 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

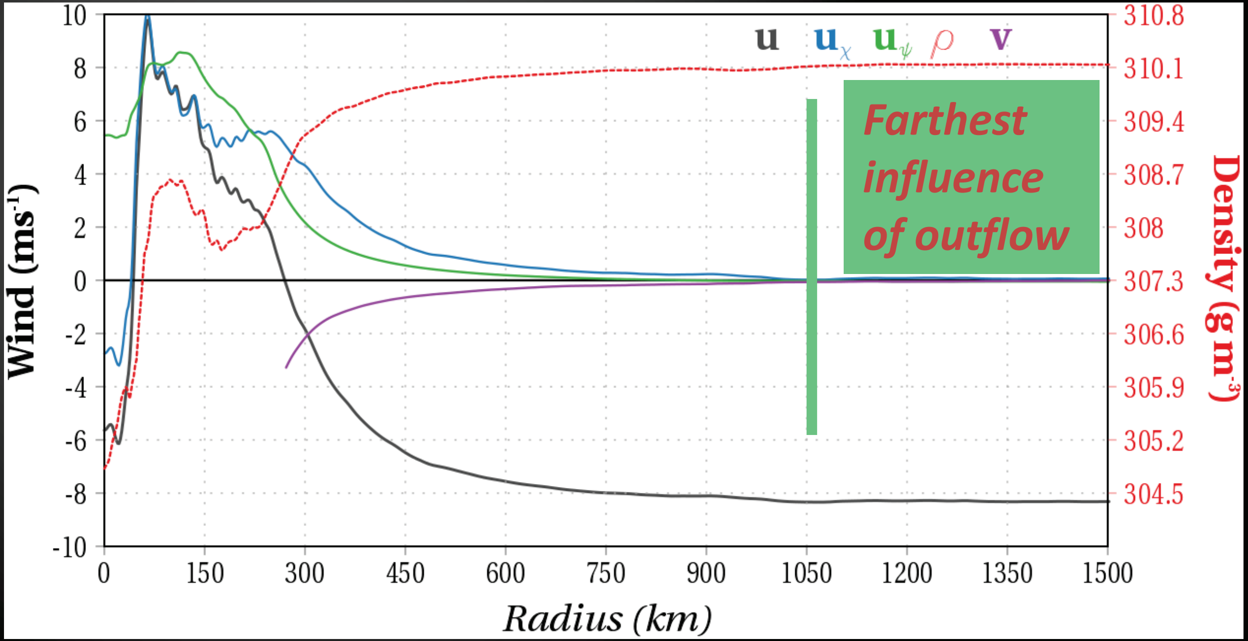


Outflow Jet: Environmental Part

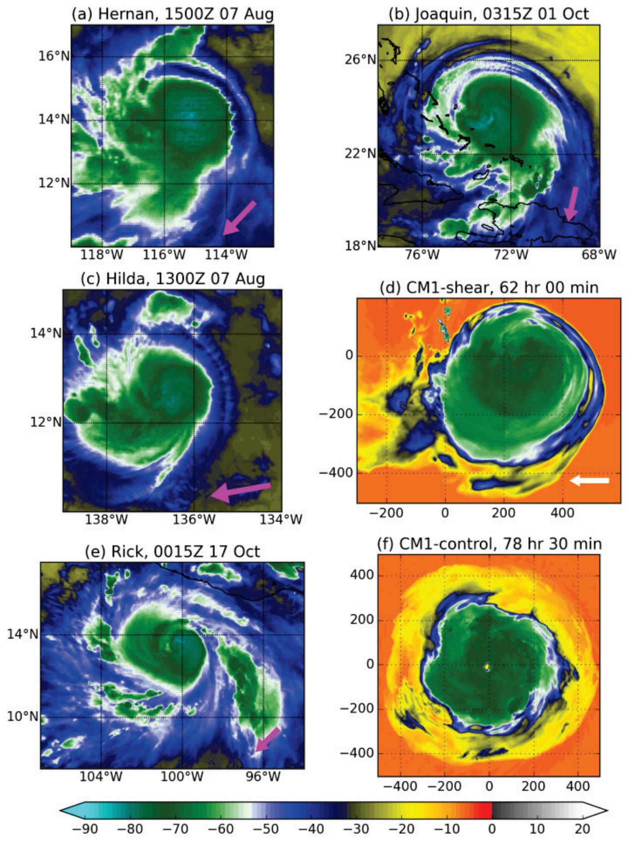
- Slightly more complicated – requires more prep work
- Perform Helmholtz (ψ-χ) Decomposition
  - Since background winds are constant by initialization, they are completely filtered out
  - (Almost) all changes in the flow are a result of the TC
    - Spurious convection, effects small
- How far away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

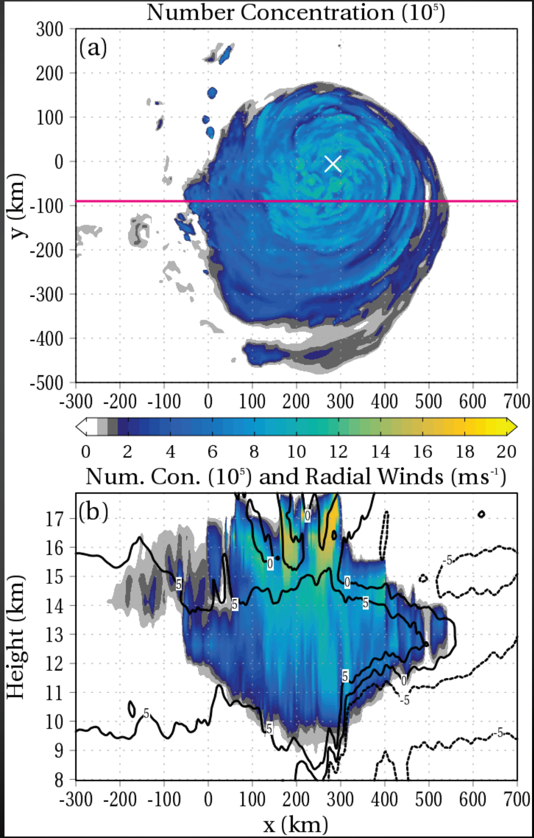
Outflow Jet: Environmental Part (cont'd)

- 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…

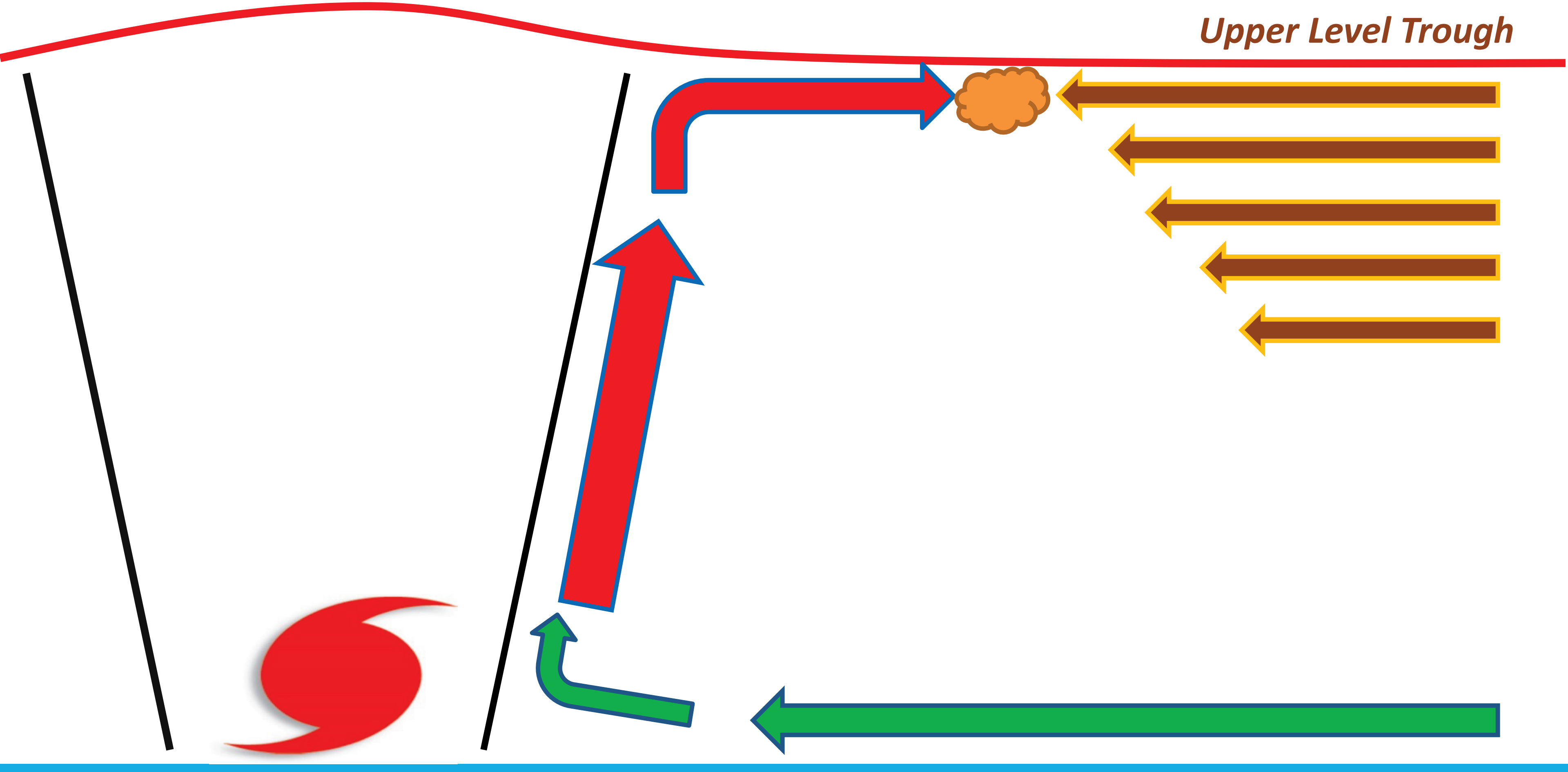


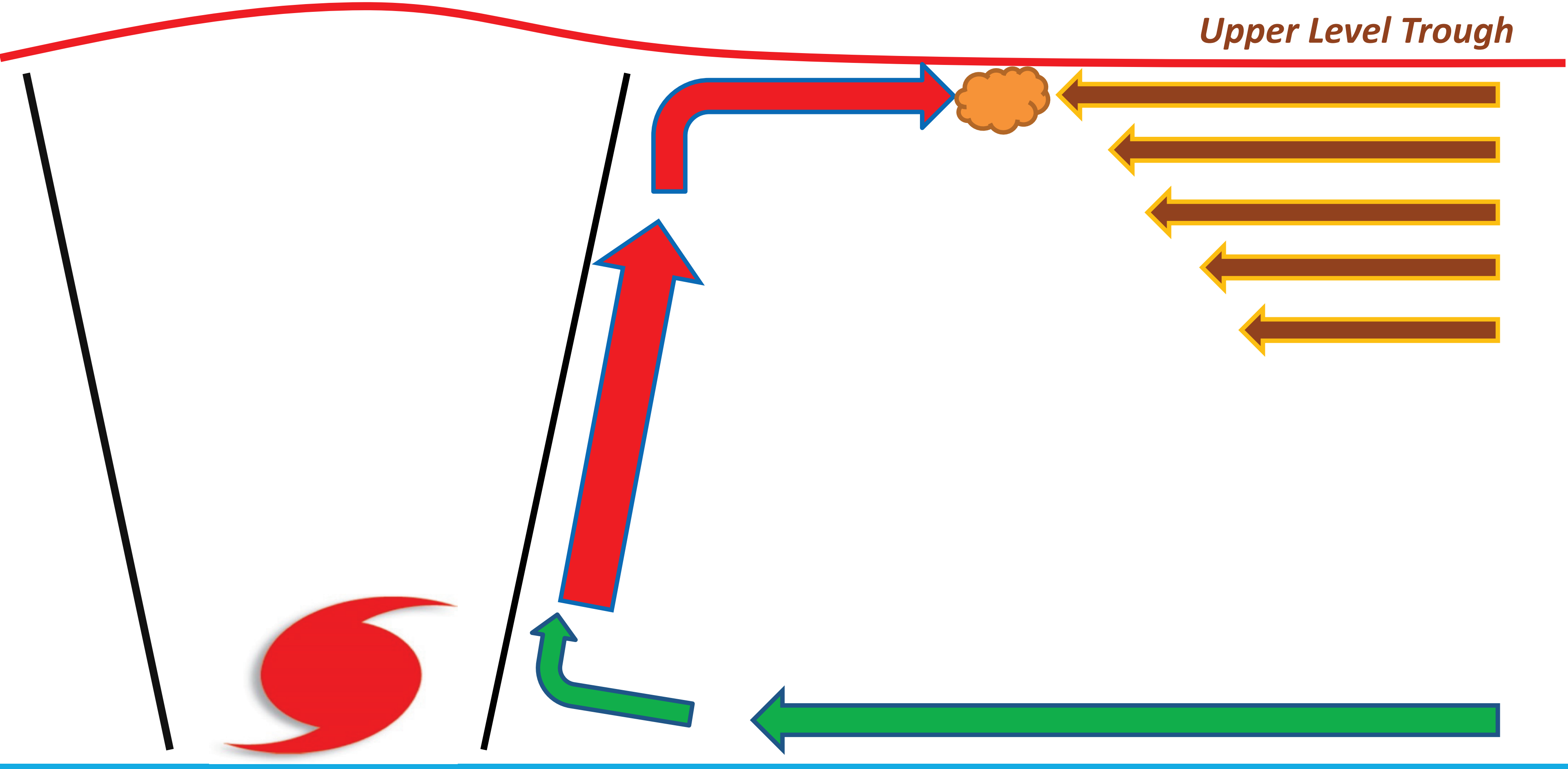


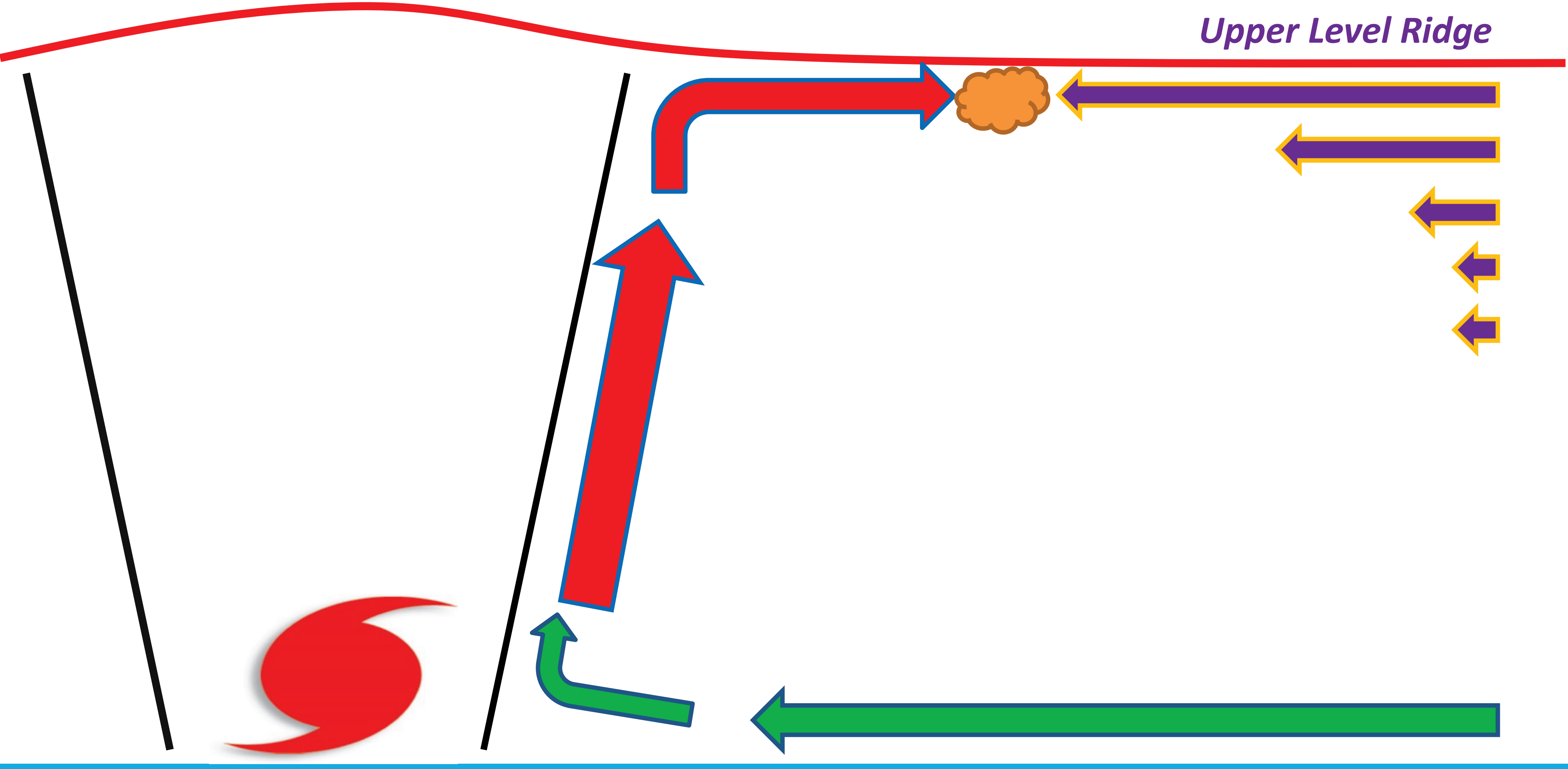
- Morrison microphysics
  - Morrison et al. (2012)
  - CRTM is picking up on number concentration
- Zonal cross section indicates arcs are 1.5-km deep under tropopause
  - $N^2 >= 2\ (10^{-4}\ s^{-1})$
  - They are the outer bounds of the upshear radial outflow

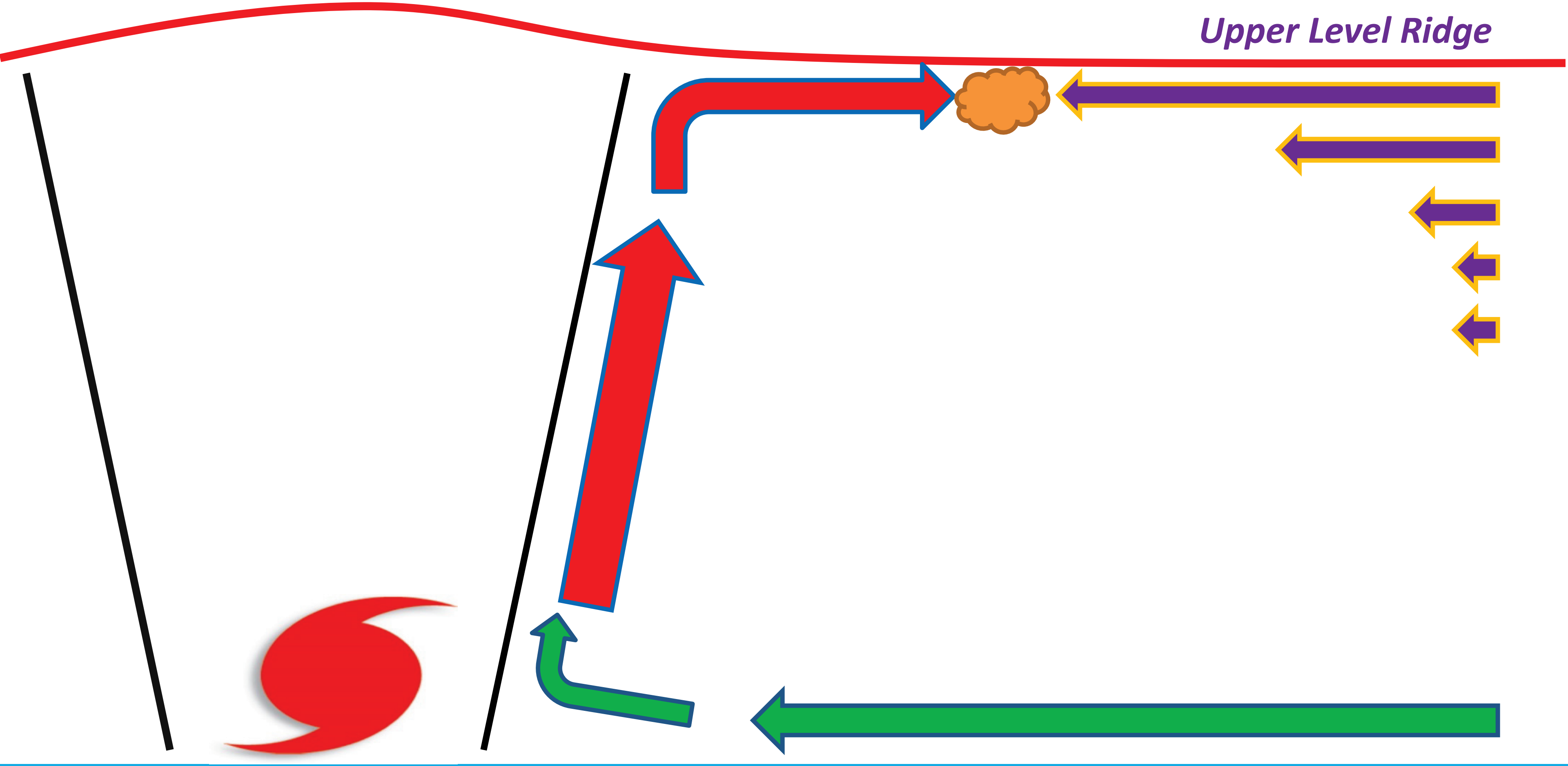
Tying This Together (Summary)

- 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


Upper Level Trough

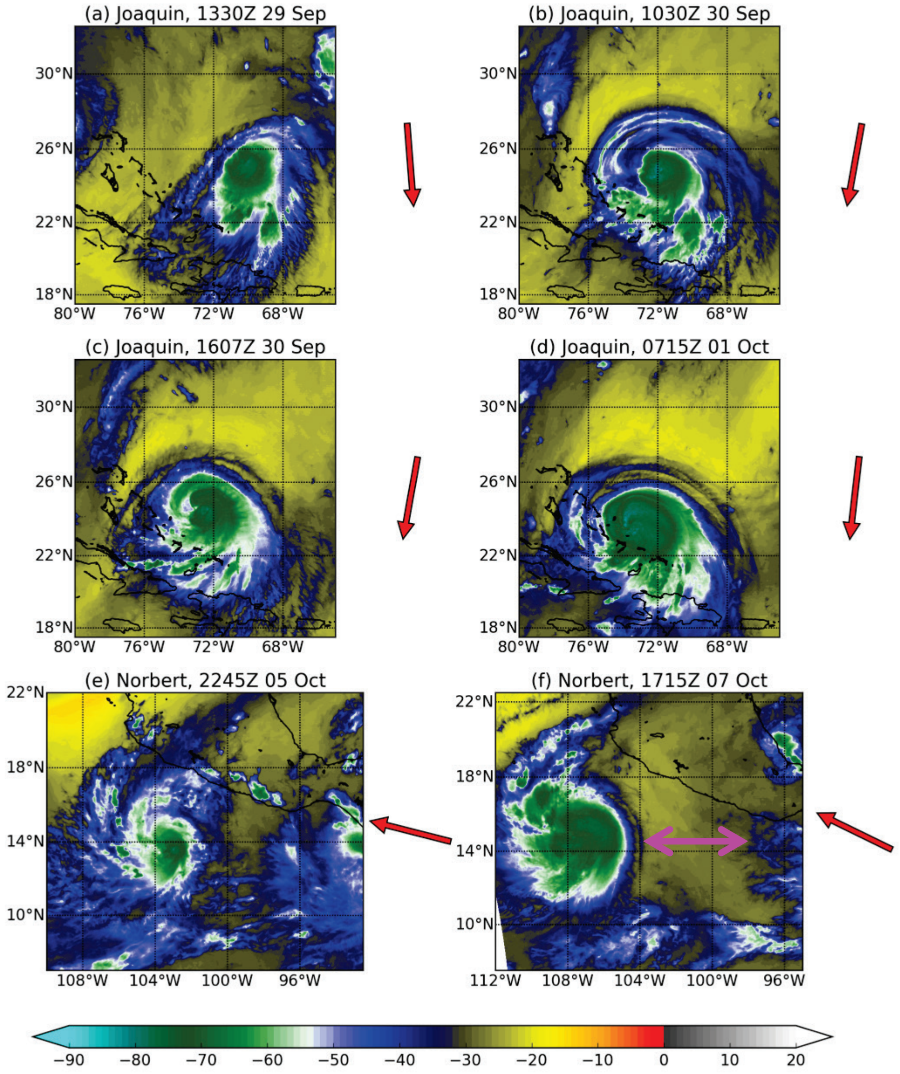

Upper Level Trough


Upper Level Ridge


Upper Level Ridge

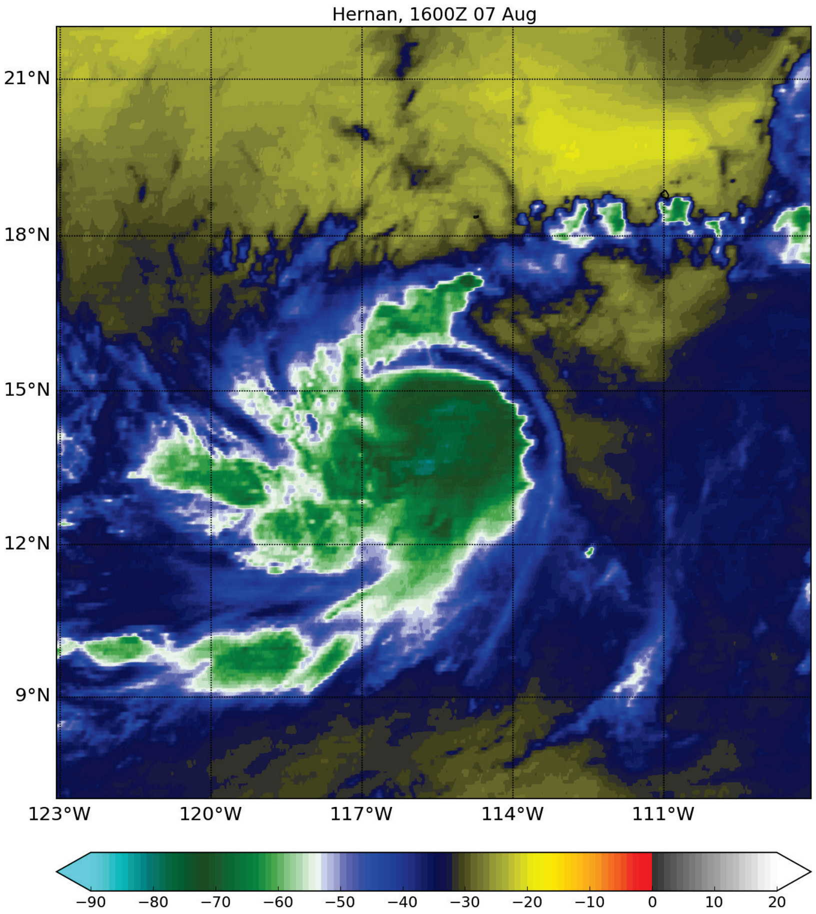
Summary (cont'd)

- 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.

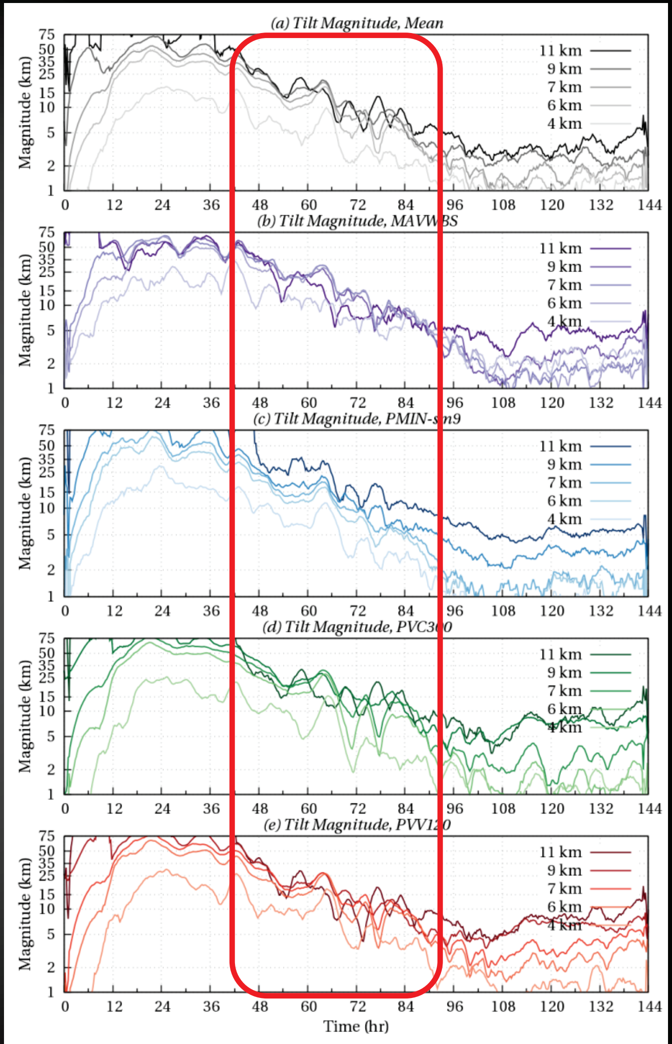
Distance from arc to nearest cloud upshear is ~6° longitude. Bow wave in CM1 was ~700 km from interface.


Hernan, 1600Z 07 Aug
21°N
18°N
15°N
12°N
9°N
123°W
120°W
117°W
114°W
111°W
−90
−80
−70
−60
−50
−40
−30
−20
−10
0
10
20

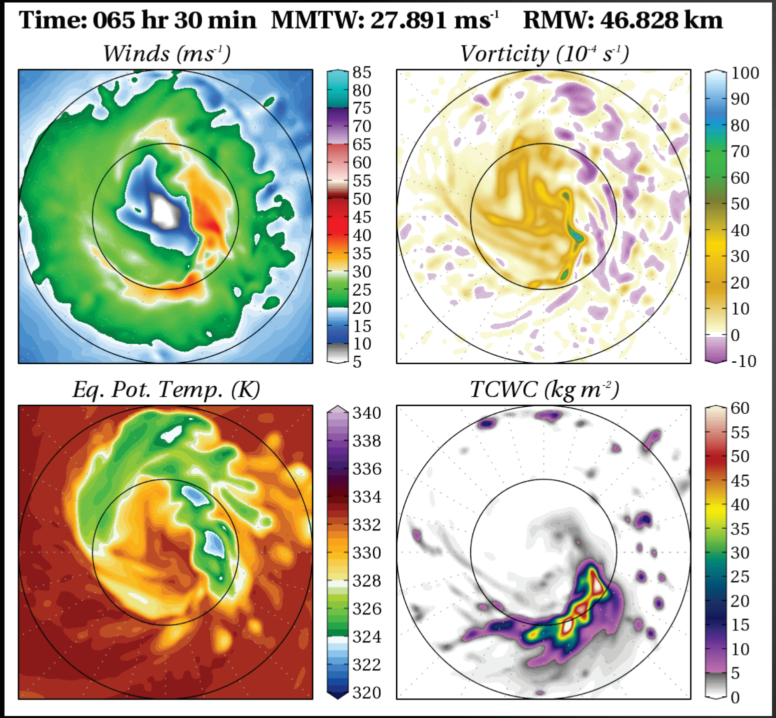
That's all for now.

Tilt Evolution

- 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
    - Consistent with most center-finding methods



Structure Around Envelope



- Strongest winds and highest vorticity values are *down wind* of envelope
  - Upshear side
- Depressed theta-e values past that
- Convection rises below tilt-induced cold anomaly