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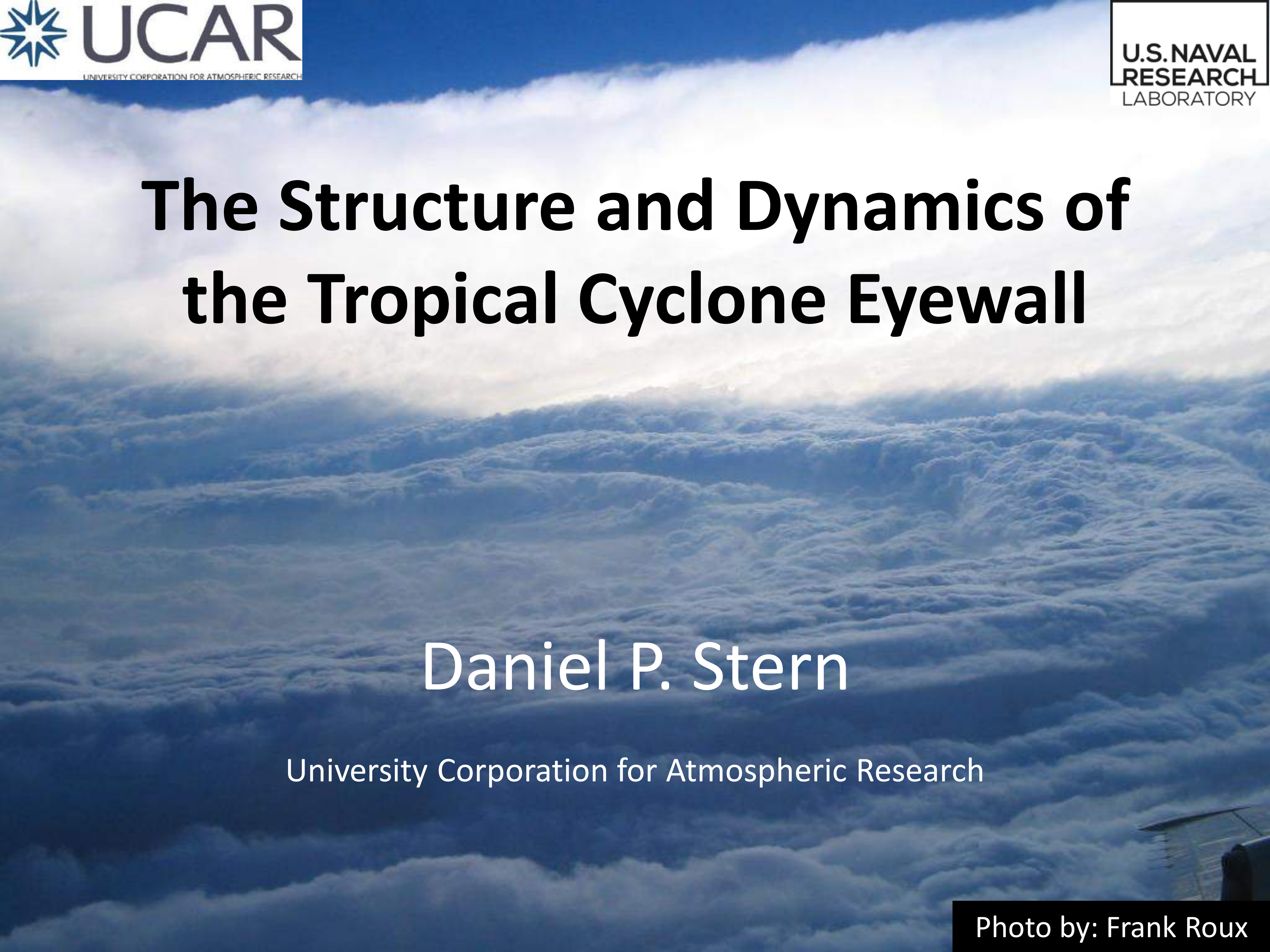
The Structure and Dynamics of the Tropical Cyclone Eyewall



Daniel P. Stern

University Corporation for Atmospheric Research

Photo by: Frank Roux

Outline of Topics

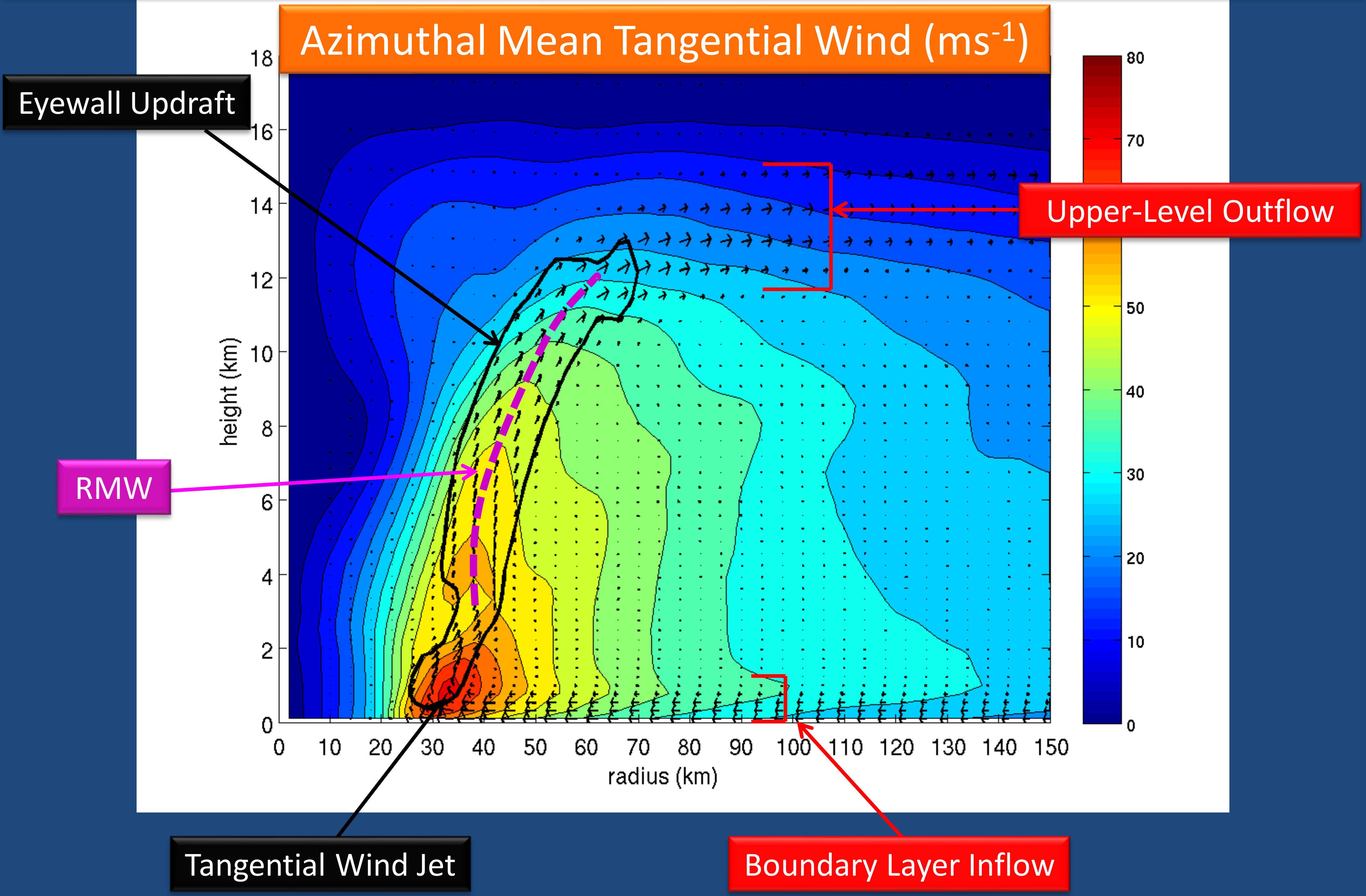
1. Climatology of the Radius of Maximum Wind (RMW)

2. Radial/vertical structure of the wind field

3. Slope of the eyewall

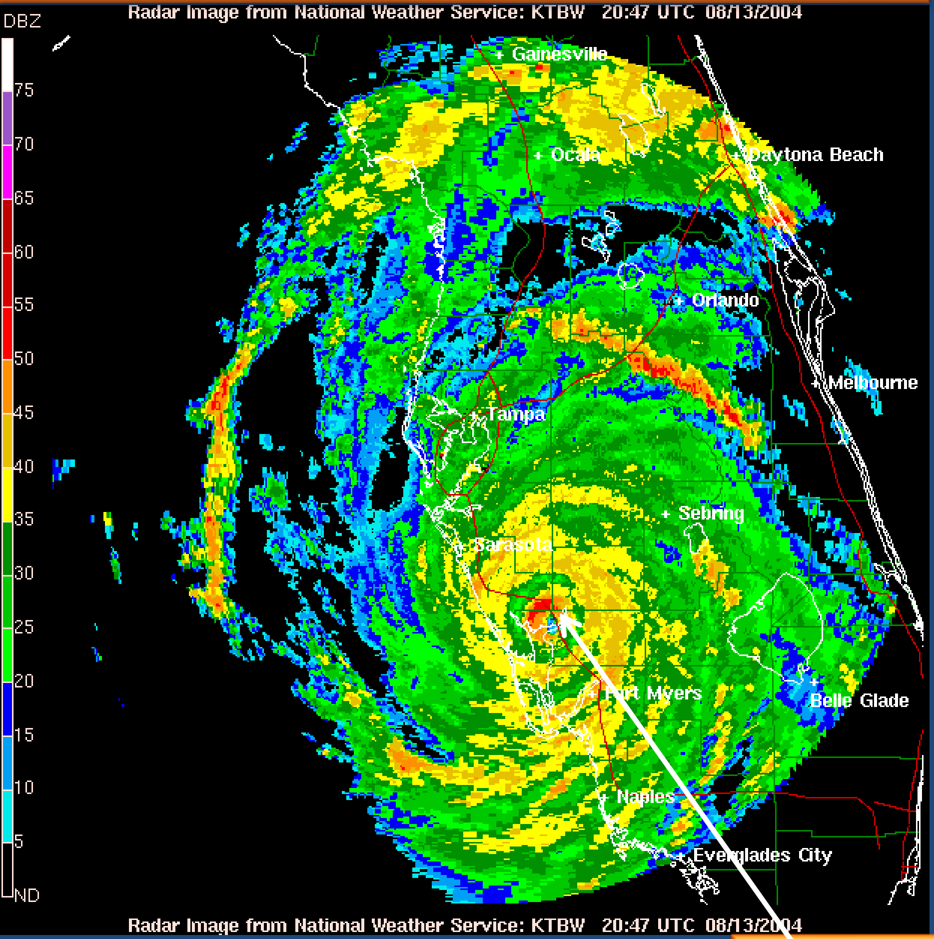
4. Contraction of the RMW

Structure of the TC Inner Core

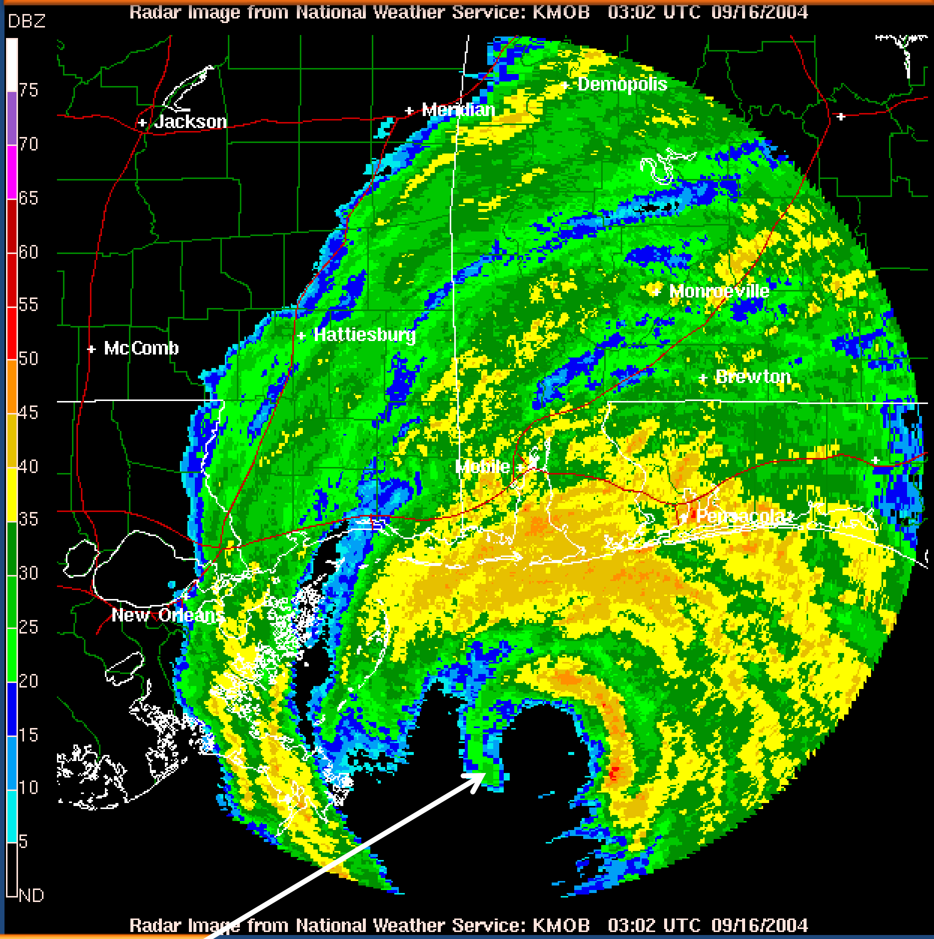


TC Inner-Core Size Varies Substantially

Hurricane Charley (2004)



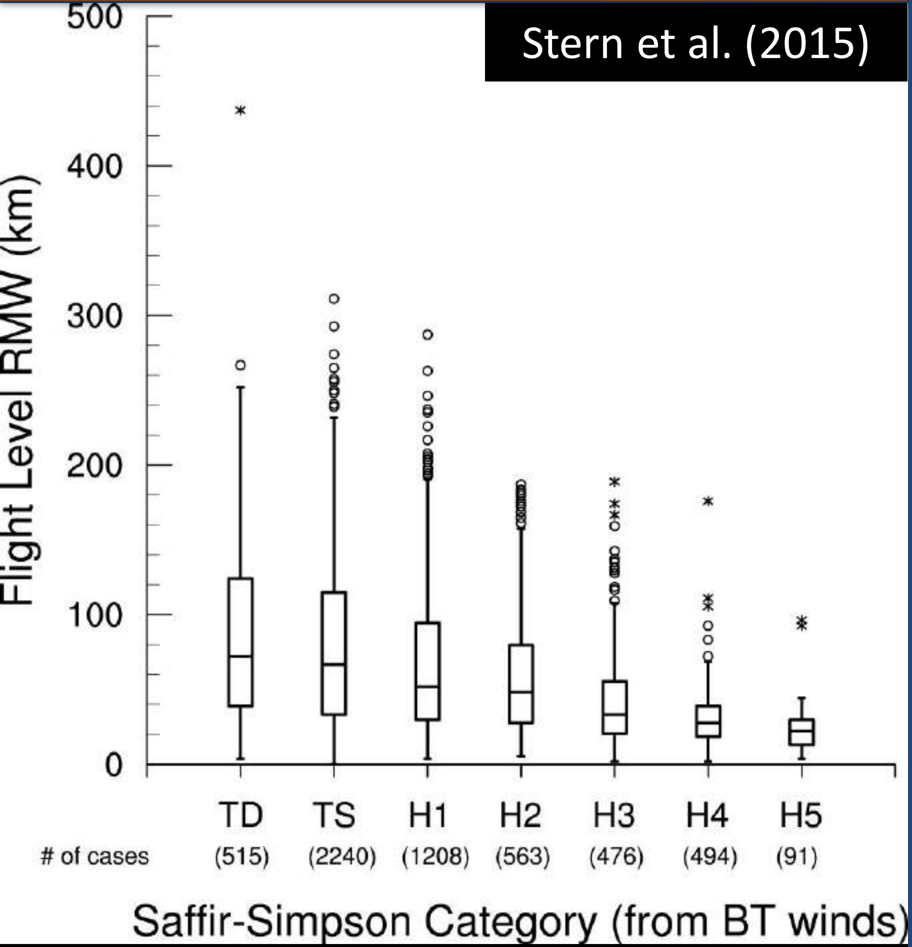
Hurricane Ivan (2004)



Eyewall

Climatology of the RMW

RMW Distribution vs Intensity



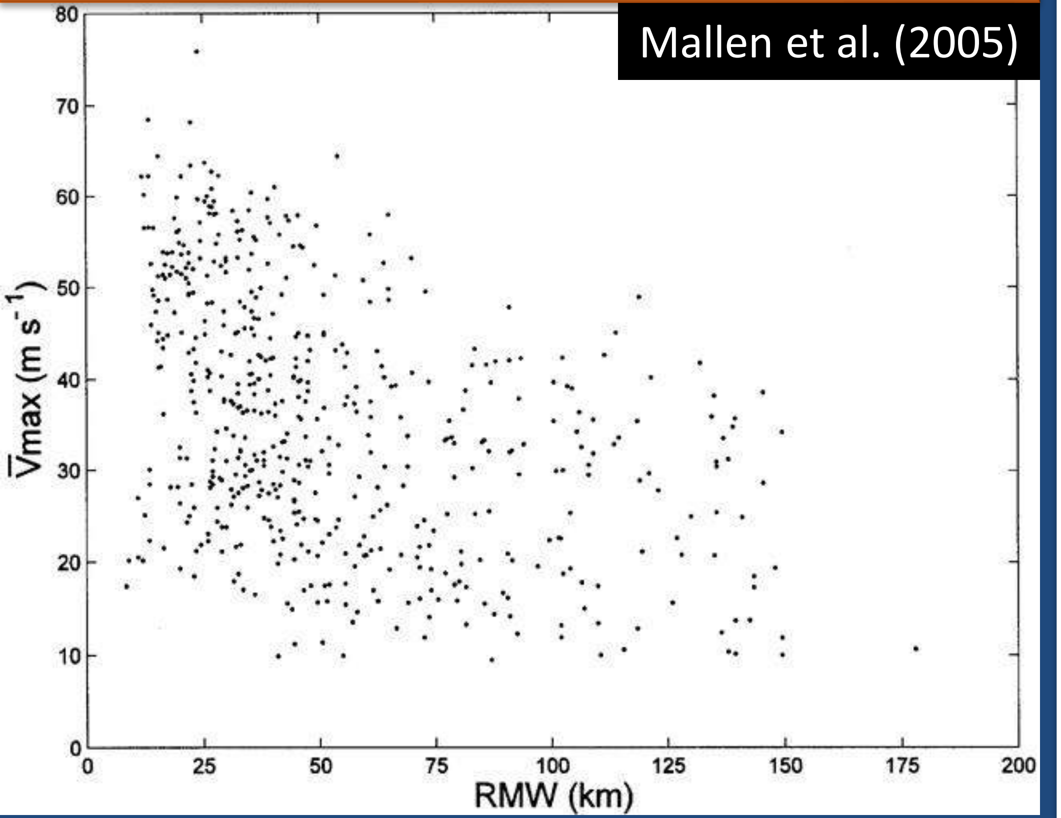
Stern et al. (2015)

Analysis by Jonathan Vigh

- On average, strong TCs have smaller RMWs than weak TCs.
- The typical range in size gets narrower with increasing intensity.
- There is still substantial variability in size at all intensities.

Climatology of the RMW

RMW vs. Intensity



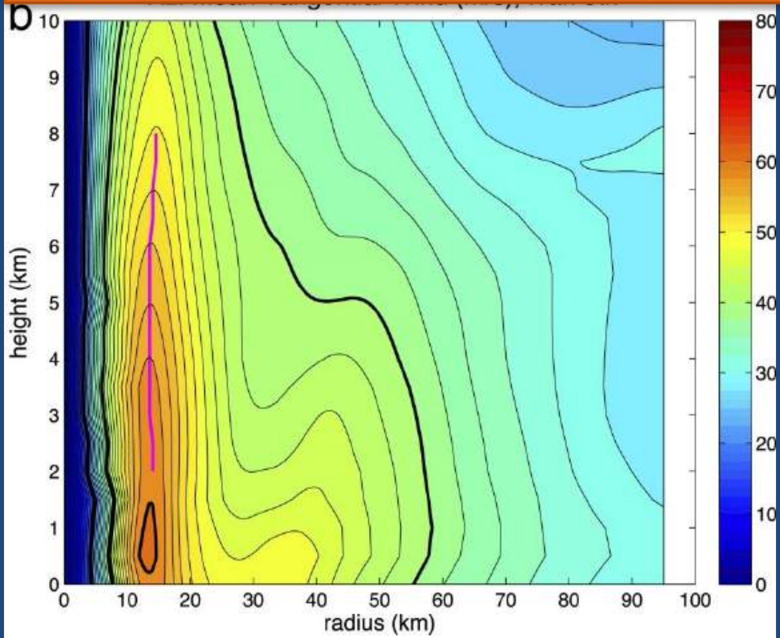
Mallen et al. (2005)

- Although size and intensity are correlated, the relationship is rather weak.
- Small RMWs (<25 km) can be found at nearly any intensity.
- Large RMWs (>50 km) are rarely found in intense TCs.

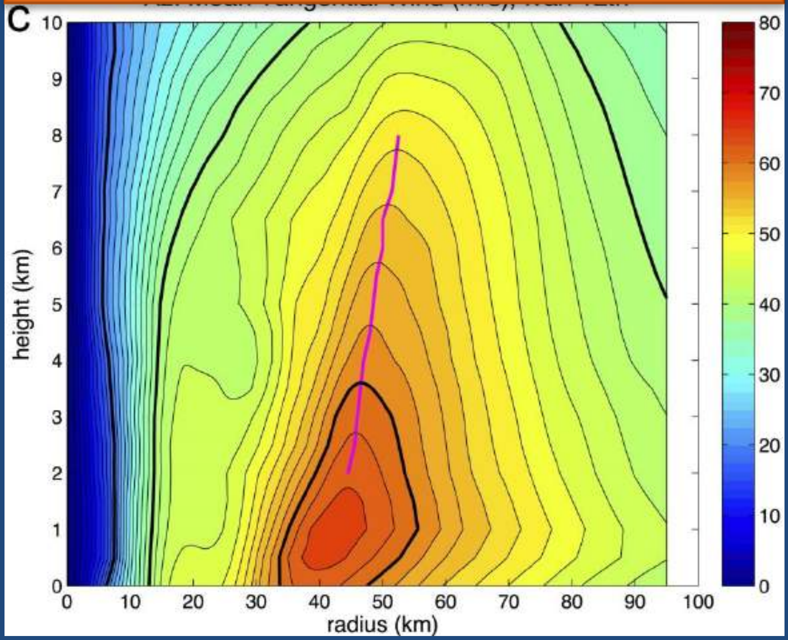
Examples of Intense TCs of Different Sizes

Azimuthal-Mean Tangential Wind
from Doppler Radar Analyses

Ivan 9th



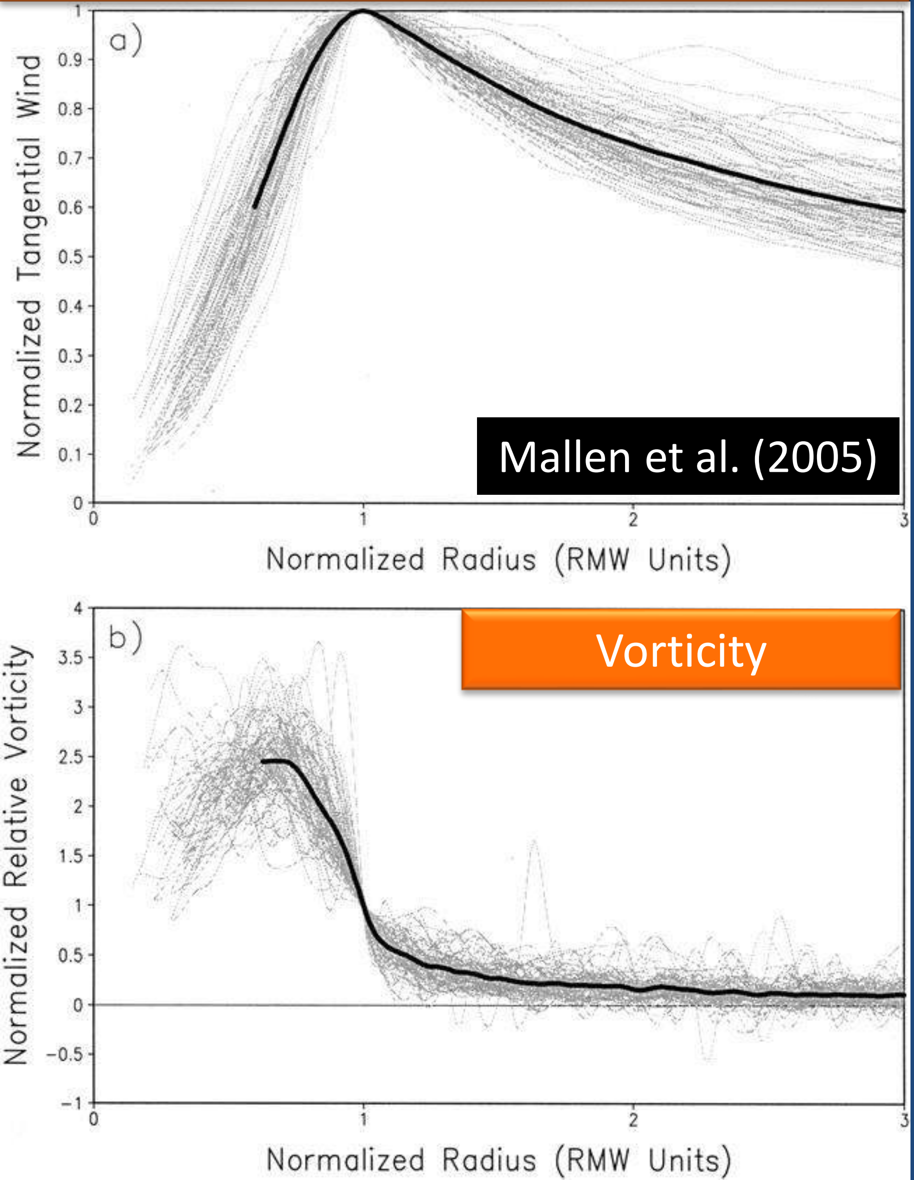
Ivan 12th



Stern et al. (2014)

Radial Structure of the Wind Field

Flight-Level Winds from Major Hurricanes



Mallen et al. (2005)

Vorticity

- When we normalize the tangential wind by Vmax and radius by the RMW, a common structure emerges.
- Tangential wind decays much more rapidly inside the RMW than outside.
- In strong TCs, peak vorticity is found slightly inside the RMW, while in weaker TCs vorticity is maximized near the storm center.

Radial Structure of the Wind Field

A commonly used parametric representation of the tangential wind is the "modified Rankine vortex".

$$v = v_{max}\left(\frac{r}{RMW}\right) \quad , r \leq RMW$$

$$v = v_{max}\left(\frac{RMW}{r}\right)^{\alpha} , r > RMW$$

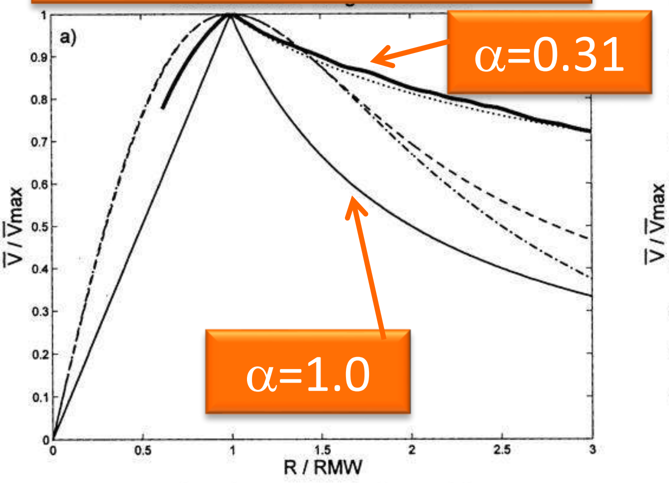
α: Decay Parameter

- Inside of the RMW, the wind increases linearly with radius.
- This linear profile has constant angular velocity (*V*/*r*), or "solid body rotation."
- Outside of the RMW, the wind decreases with an inverse power α.

Radial Structure of the Wind Field

- On average, the modified Rankine vortex is a relatively good approximation.
- As intensity increases, the RMW tends to become sharper and the winds decay more rapidly outside of the RMW (larger α).

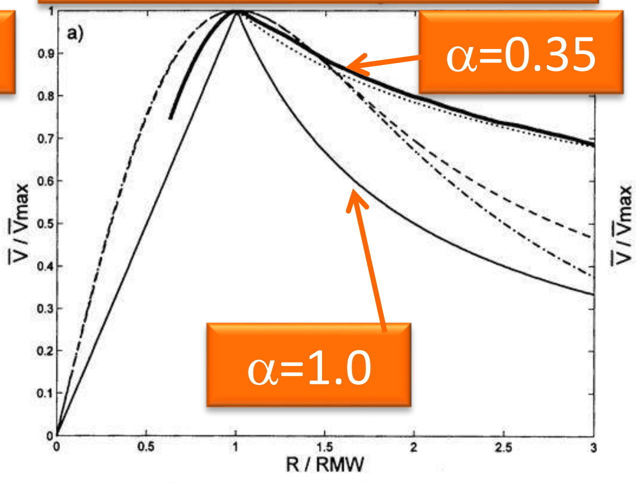
Tropical Storms



α=0.31

α=1.0

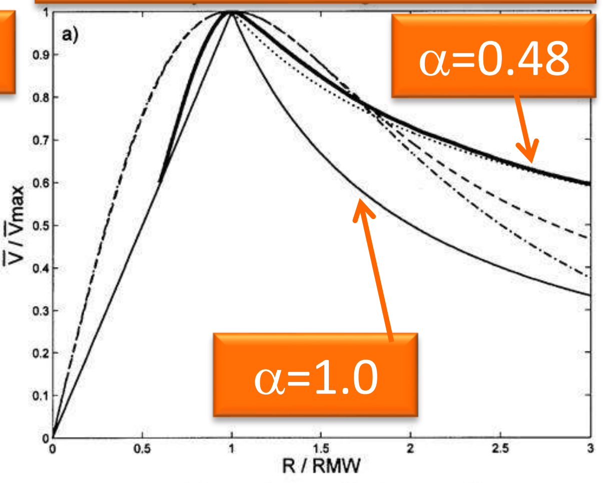
Category 1-2



α=0.35

α=1.0

Category 3-5



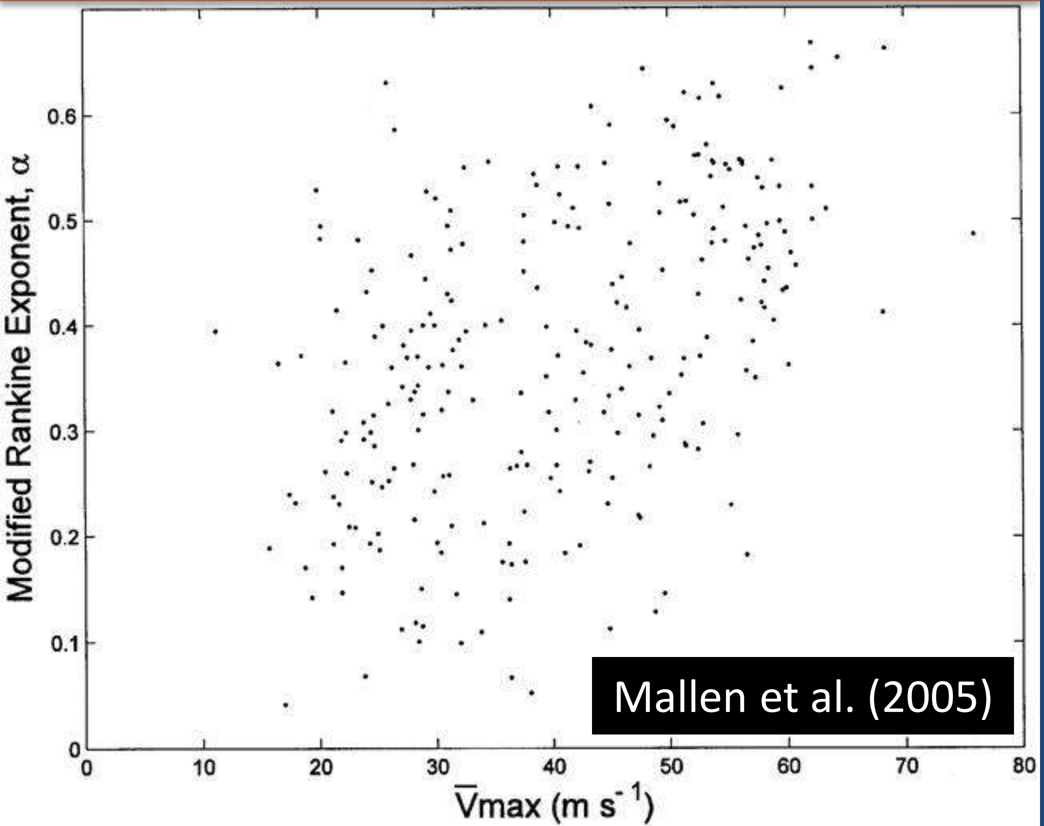
α=0.48

α=1.0

Mallen et al. (2005)

Radial Structure of the Wind Field

Rankine Decay Exponent vs. Intensity

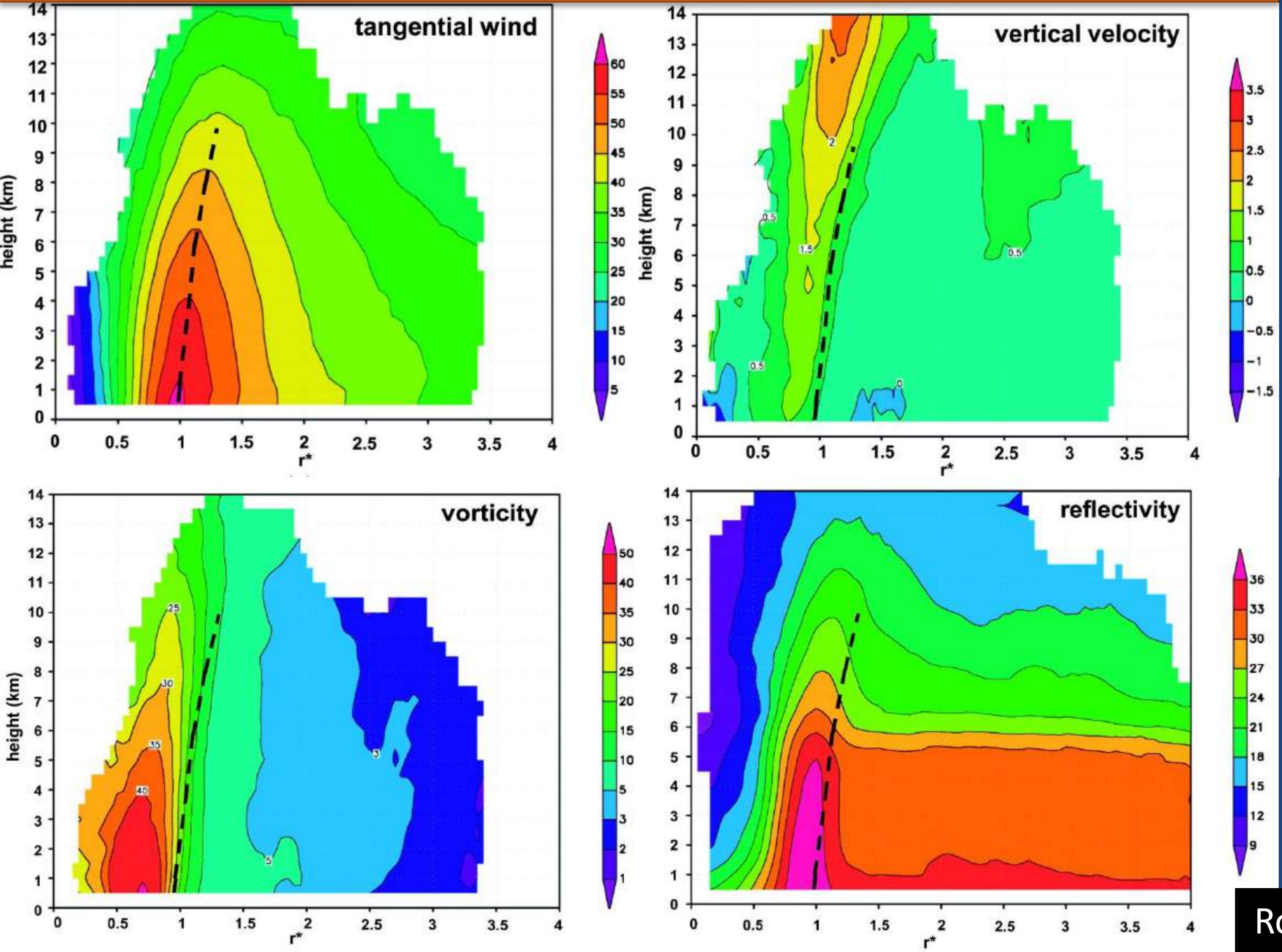


Mallen et al. (2005)

- α increases with intensity, but there is a large amount of variability.
- There are still intense TCs with broad wind fields, and weak TCs with relatively narrow wind fields.

Composite Structure of the Eyewall

Doppler Radar Composite Analysis of Major Hurricanes

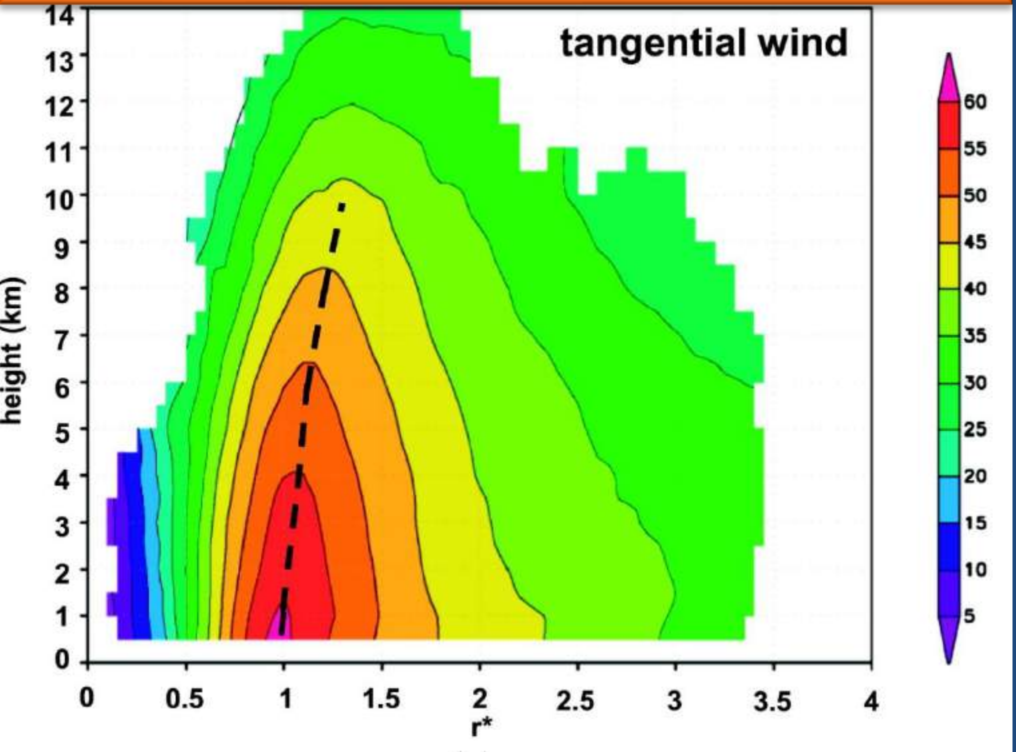


RMW

Rogers et al. (2012)

Composite Structure of the Eyewall

Composite Tangential Wind



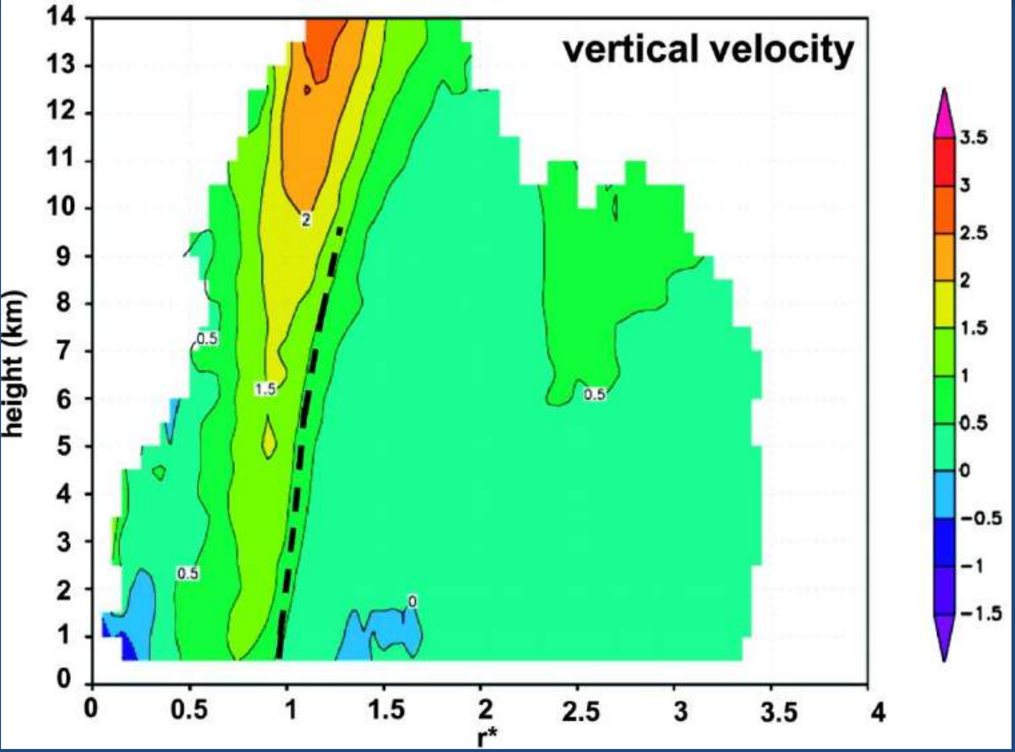
- Wind maximum in the boundary layer
- RMW slopes outwards with increasing height.

RMW

Rogers et al. (2012)

Composite Structure of the Eyewall

Composite Tangential Wind



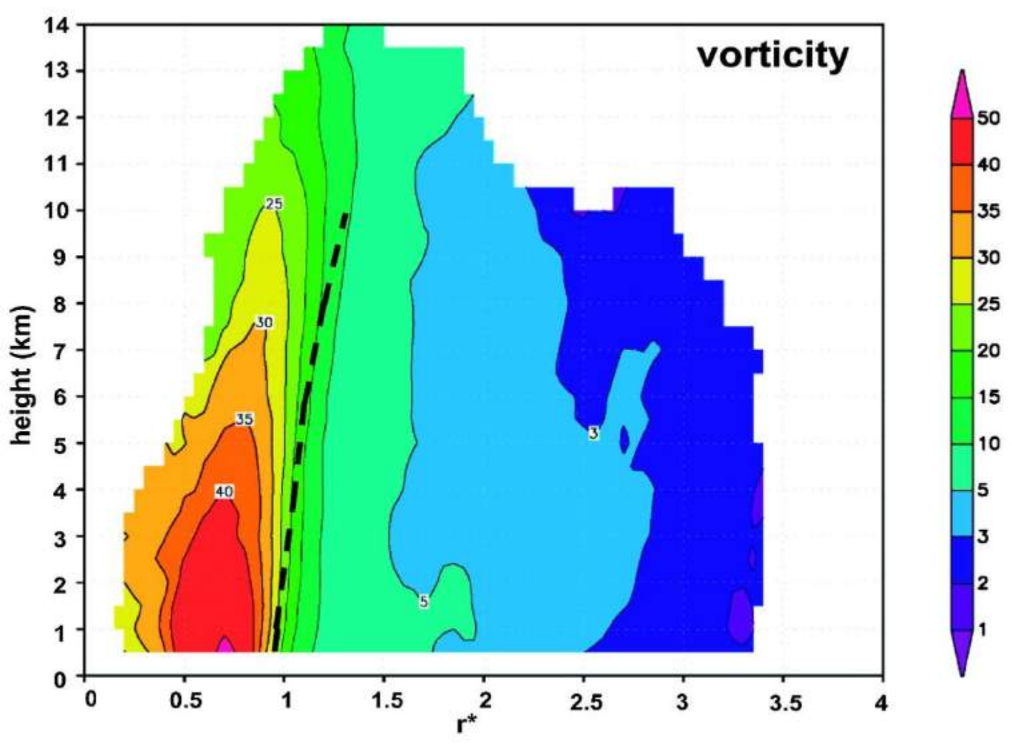
┆ **RMW**

- Eyewall updraft is on average slightly inward of the RMW.
- Away from the eyewall, mean vertical motion is small.
- Updraft slopes outward with increasing height.
- Mean updraft strength tends to increase with height.

Rogers et al. (2012)

Composite Structure of the Eyewall

Composite Tangential Wind



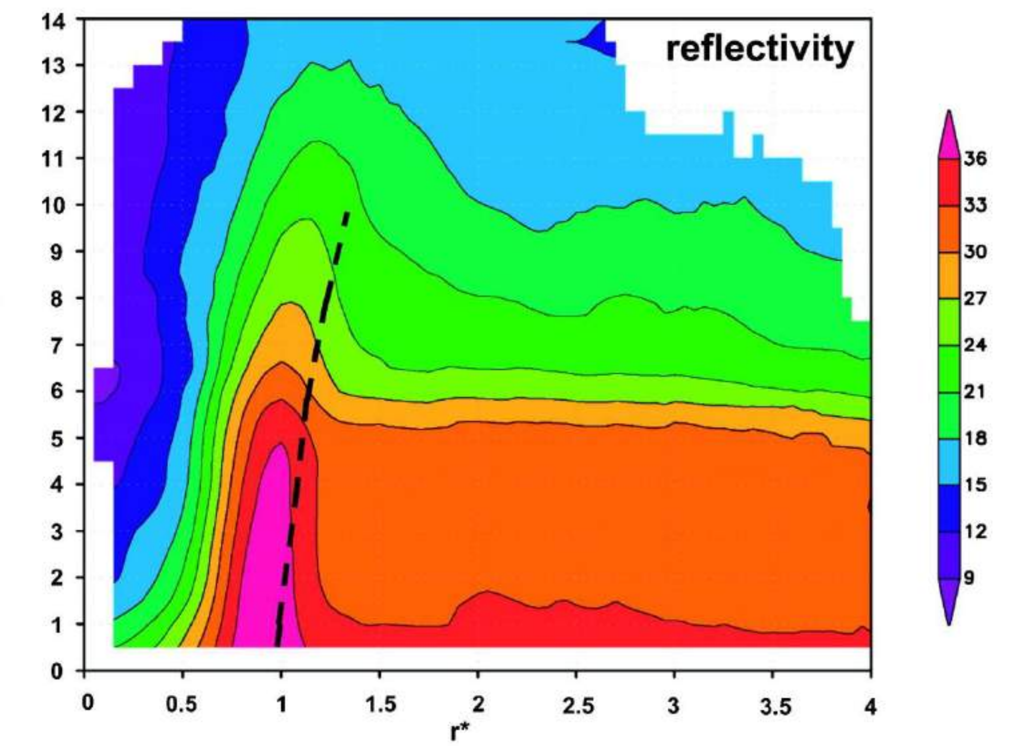
┆ **RMW**

- Vorticity is greatest slightly inwards of the RMW.
- Vorticity maximum is closely aligned with the eyewall updraft, as vorticity is produced primarily by stretching.
- Weak but non-zero vorticity extends a great distance from the TC center.

Rogers et al. (2012)

Composite Structure of the Eyewall

Composite Tangential Wind



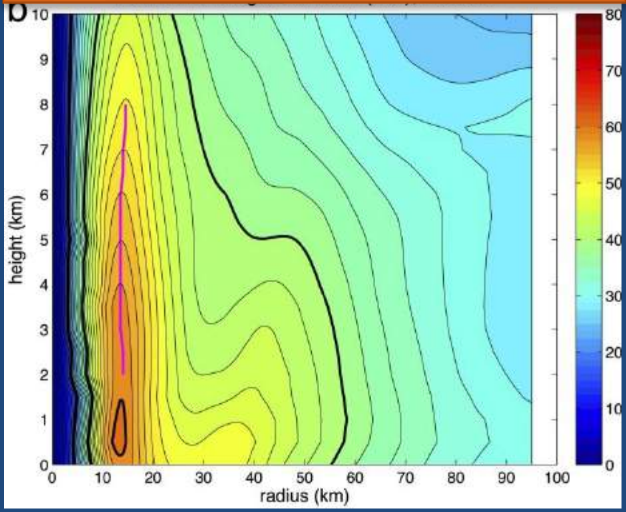
- Reflectivity maximum is closely aligned with the mean eyewall updraft.
- Reflectivity decreases rapidly with height above the freezing level.
- This is related to the fact that there is not much supercooled liquid water in TCs, and mean updrafts are relatively weak.

Rogers et al. (2012)

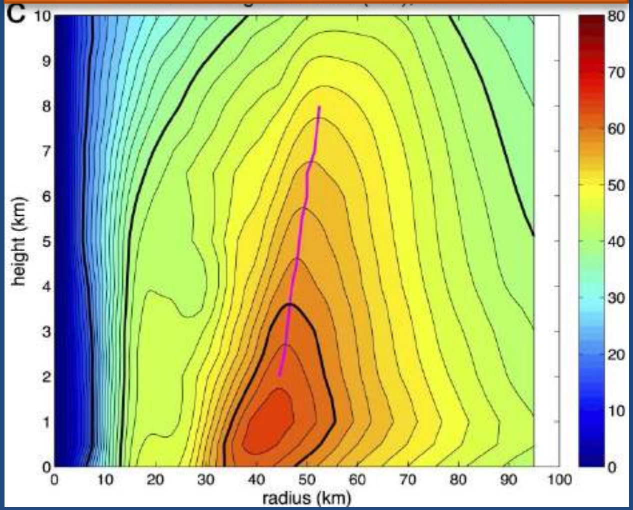
Vertical Structure of the Wind Field

- The eyewall wind speed generally decreases with height, above a boundary layer maximum.
- What determines this structure, and how does it vary with TC intensity and/or size?

Ivan 9th



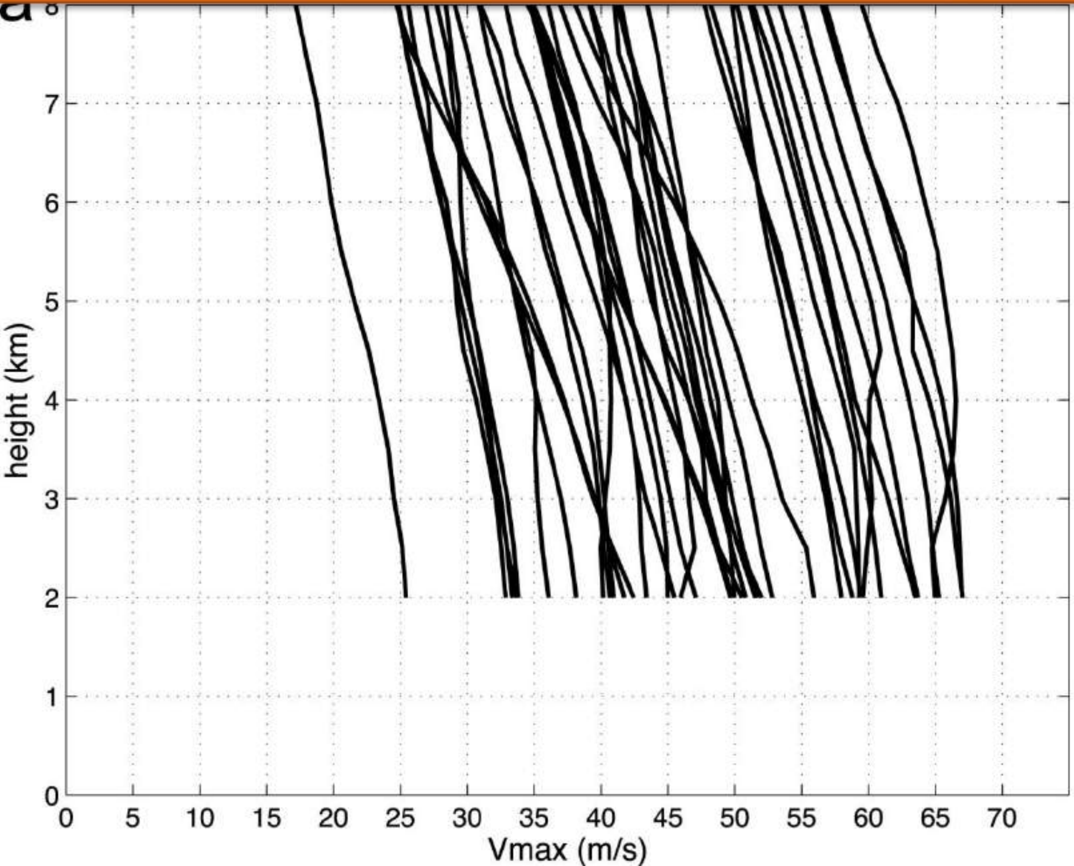
Ivan 12th



Stern et al. (2014)

Tangential Wind Decreases Slowly with Height

Max Tangential Wind vs Height



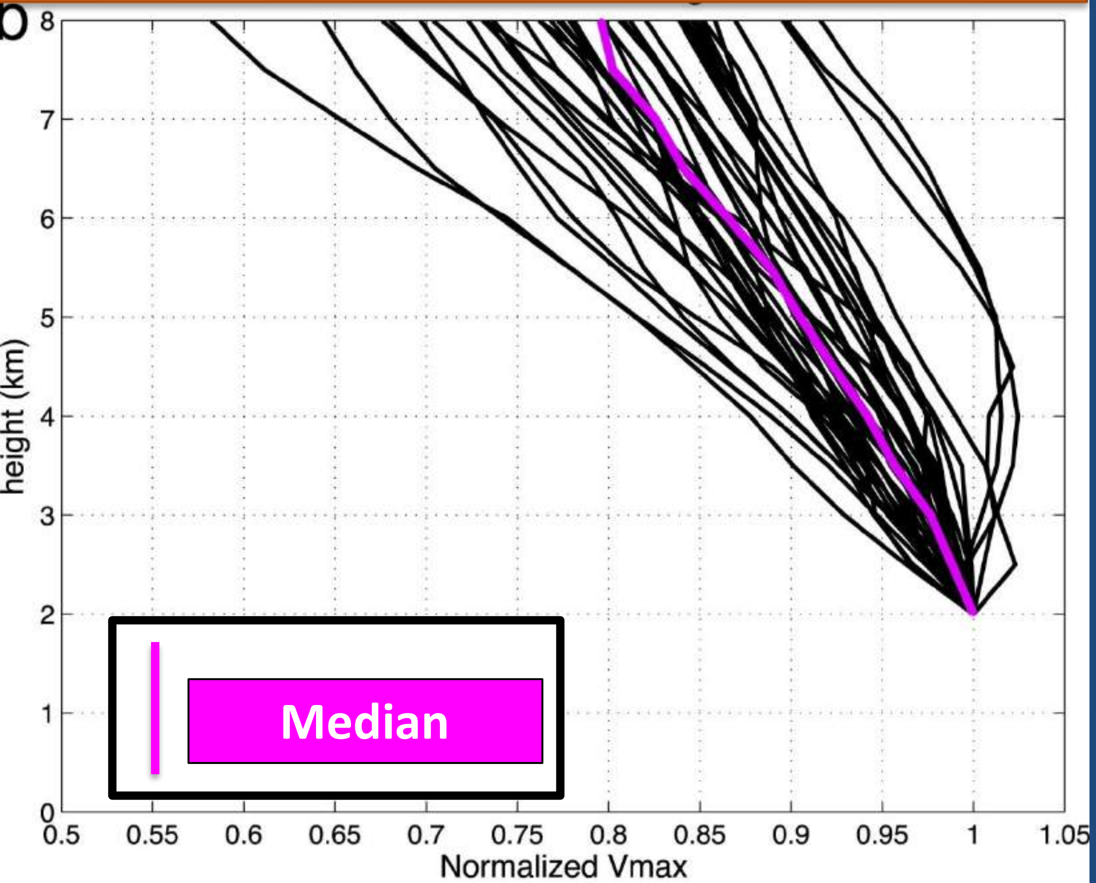
- Profiles from 39 flights into 14 different hurricanes
- Max winds generally decay slowly with height, but it is difficult to assess variability because of wide range of intensity.

Stern et al. (2014)

Tangential Wind Decreases Slowly with Height

We can normalize each profile of maximum wind speed by its respective value at z=2 km.

Normalized Max Wind vs Height



- Peak winds in most TCs decrease by about 15-25% from 2 to 8 km height.
- This relatively slow decrease of peak winds with height implies that most of the decay occurs in the upper troposphere (above 8 km).

Stern et al. (2014)

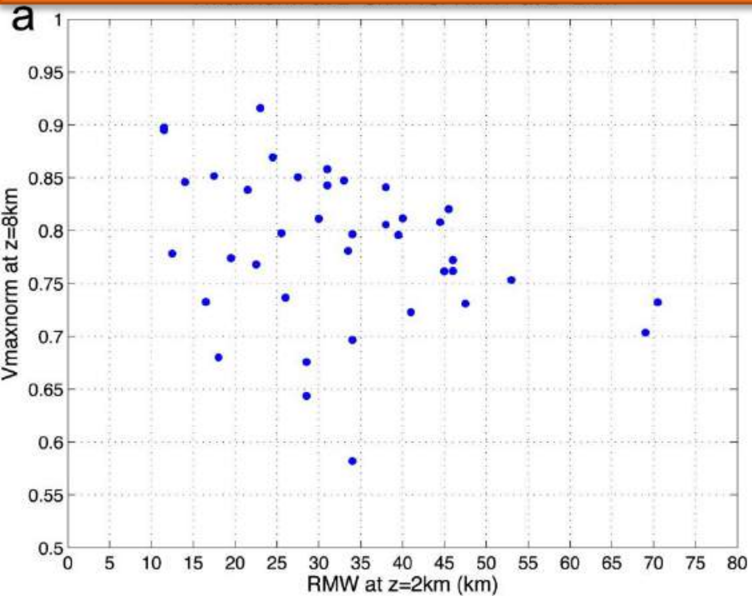
Relationship of Decay Rate with Size and Intensity

- There is a moderate relationship between the vertical decay rate of Vmax and TC size and intensity.

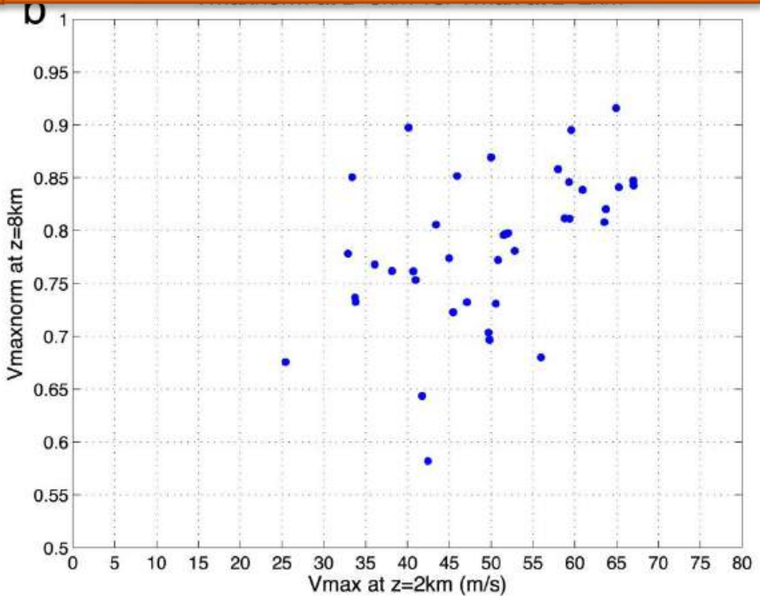
- Vmax decreases with height at a greater *percentage* rate for larger storms and for weaker storms.

- However, these effects are relatively small.

Normalized Vmax vs RMW



Normalized Vmax vs Vmax

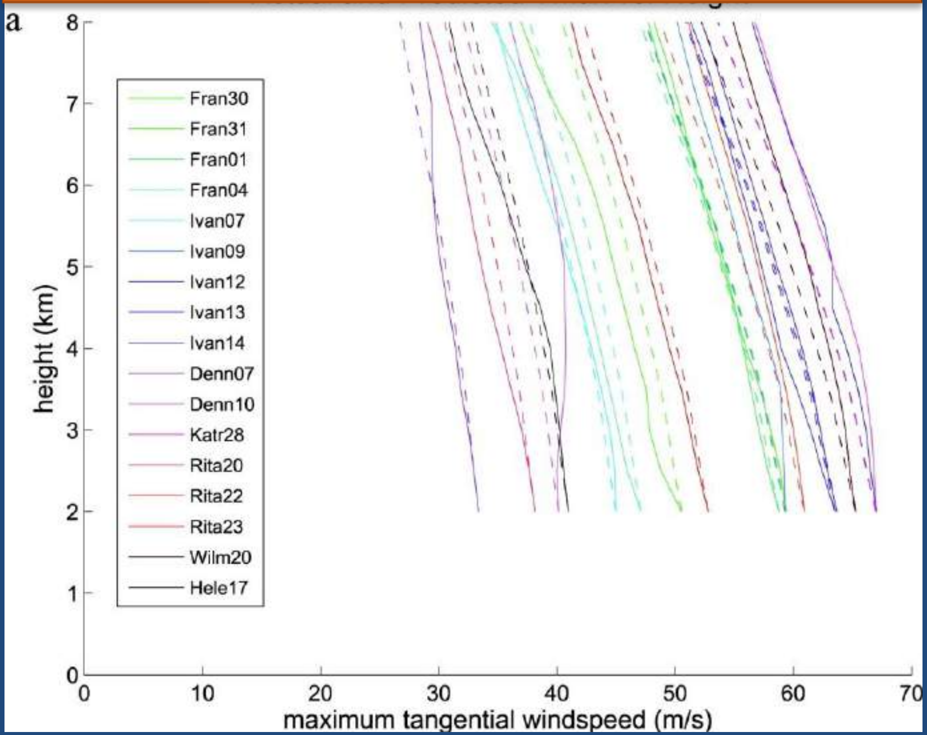


Stern et al. (2014)

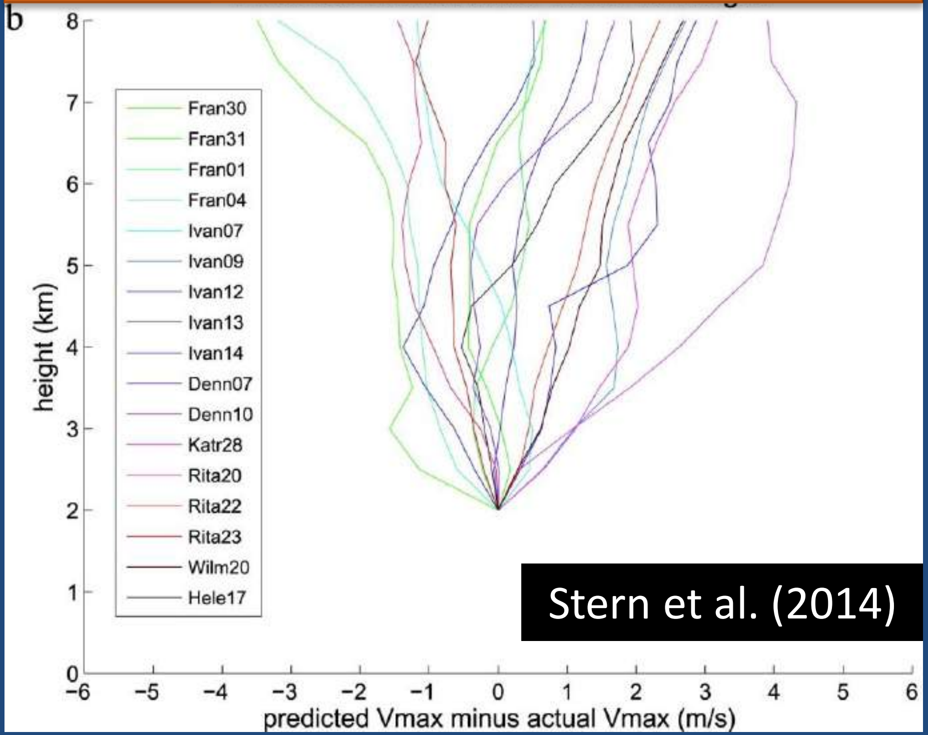
Most TCs Exhibit Similar Profiles of Maximum Wind

- We can take the **mean** normalized wind profile and apply it to each case to estimate the individual profile.
- For most TCs, the error from assuming a mean decay profile is relatively small.

Actual (solid) and Predicted (dashed) Vmax



Error in Predicted Wind Speed



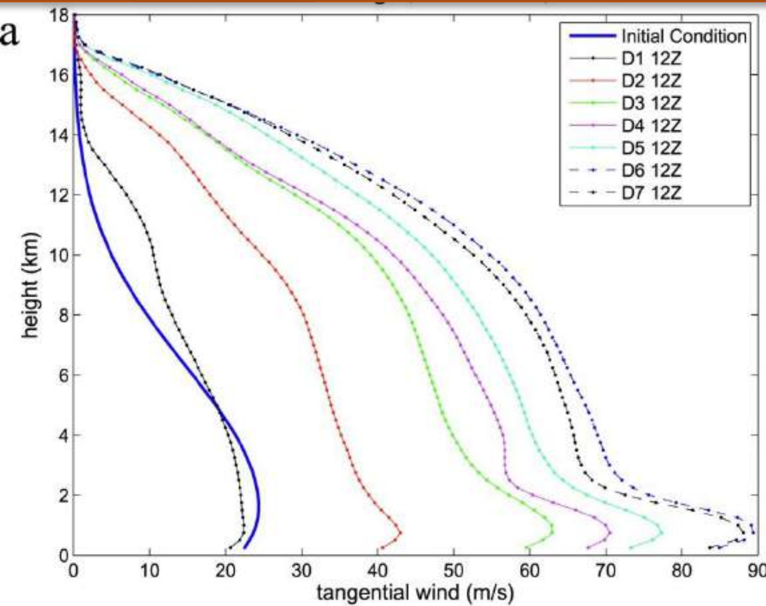
Stern et al. (2014)

Max Wind Speed vs Height in Simulations

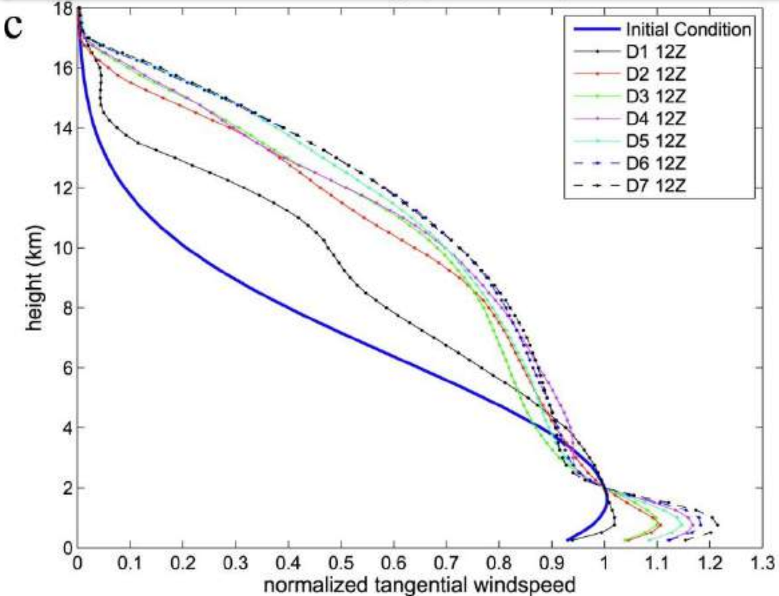
- Initial Condition: Weak vortex with rapid vertical decay

- Soon after intensification begins, the TC has already adjusted to a nearly steady normalized structure, with slow decay in the lower and middle troposphere.

Vmax vs Height



Normalized Vmax vs Height



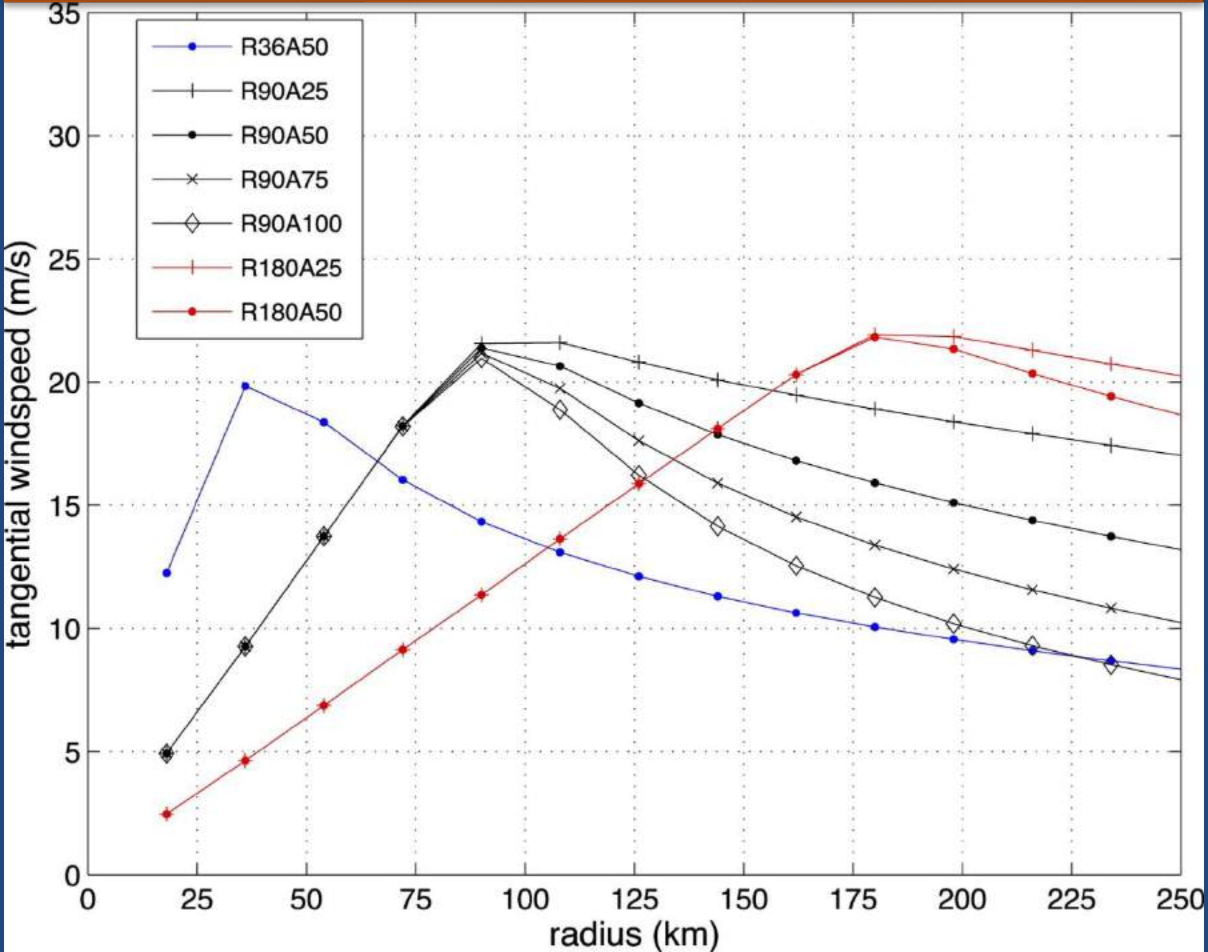
Legend indicates successive 12-h periods

Stern and Nolan (2011)

Simulations of Varying Size

- Starting with vortices of differing initial size and/or different Rankine decay rates:

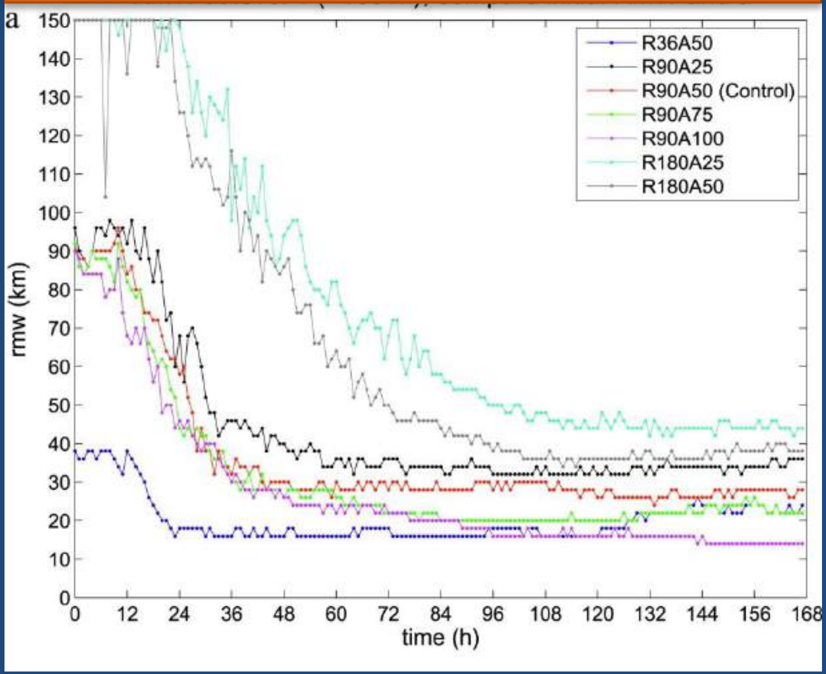
Radial Profile of Tangential Wind in Initial Condition



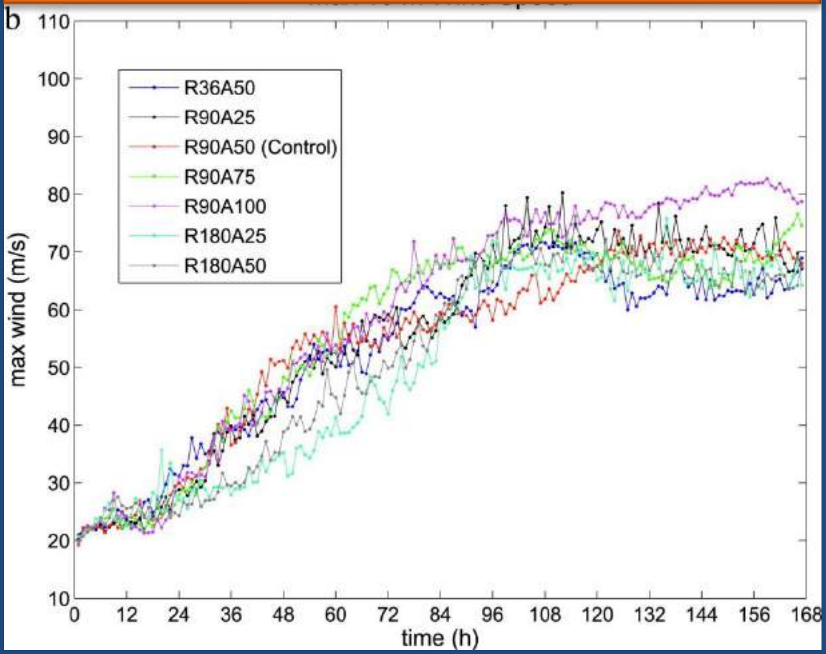
Simulations of Varying Size

- Simulations achieve similar quasi-steady intensities, but with systematically varying size.
  - Initially large storms remain larger.
  - TCs with initially broader wind fields are larger.

RMW vs Time



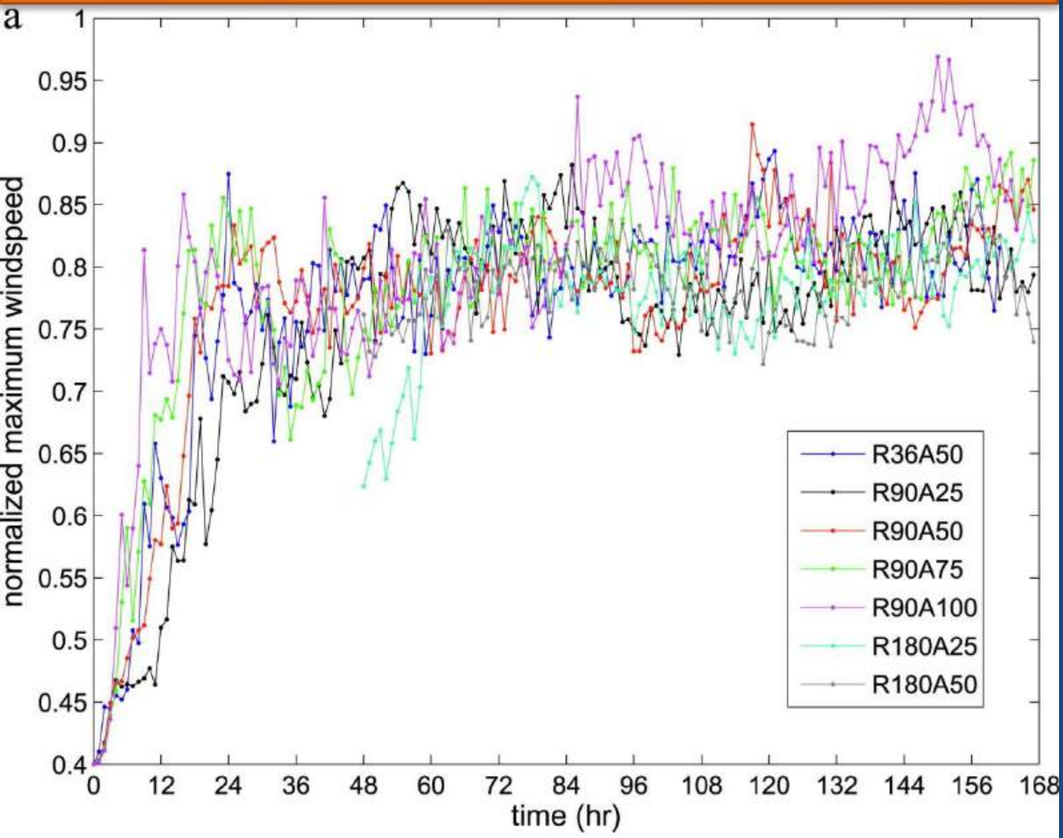
Max 10-m Wind Speed vs Time



Stern and Nolan (2011)

Vertical Decay Rate is Similar for Differing Sizes and Intensities

Normalized Vmax at z=8 km vs Time



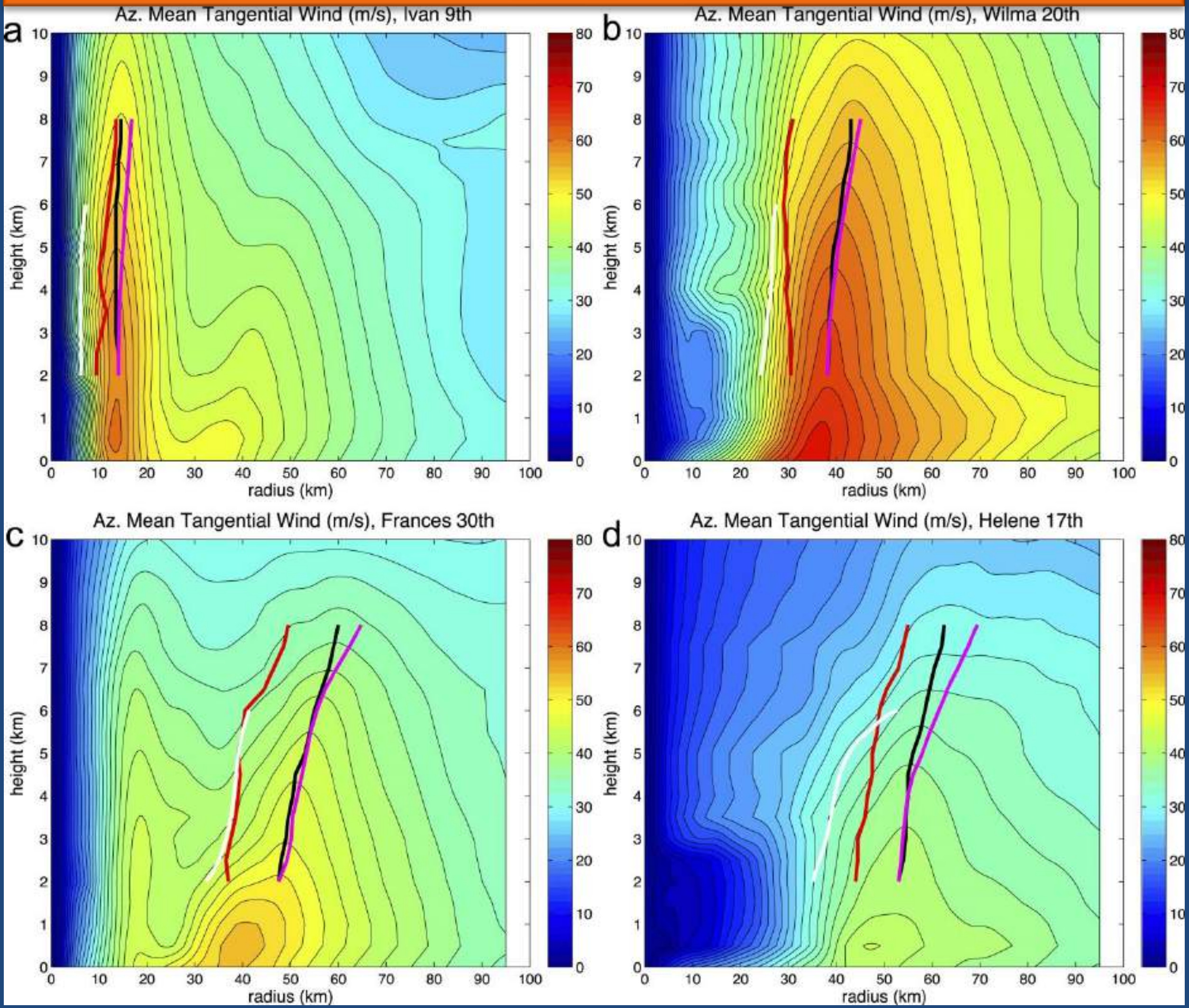
- Simulated TCs adjust from an arbitrary initial structure once deep convection becomes established.

- Across a wide range of storm sizes and intensities, the peak winds decrease by about 20% from 2 to 8 km height, similar to observations.

Stern and Nolan (2011)

Slope of the Radius of Maximum Wind

Tangential Wind from Doppler Analyses

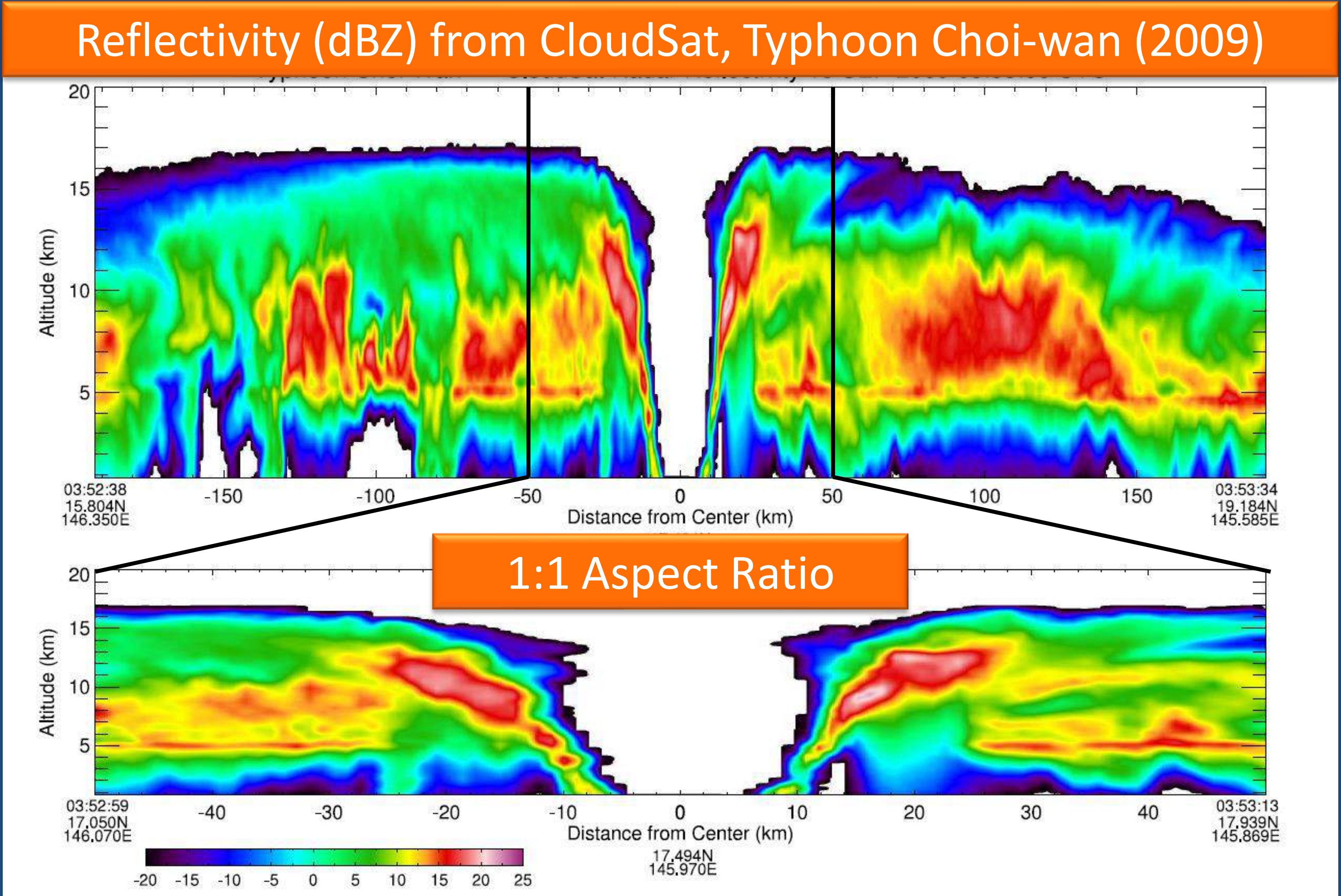


- ▮ **RMW**
- 🟥 **Updraft**
- ▯ **20-dBZ**
- ▮ ***M* Sfc**

- RMW and eyewall slope outwards with increasing height

Stern et al. (2014)

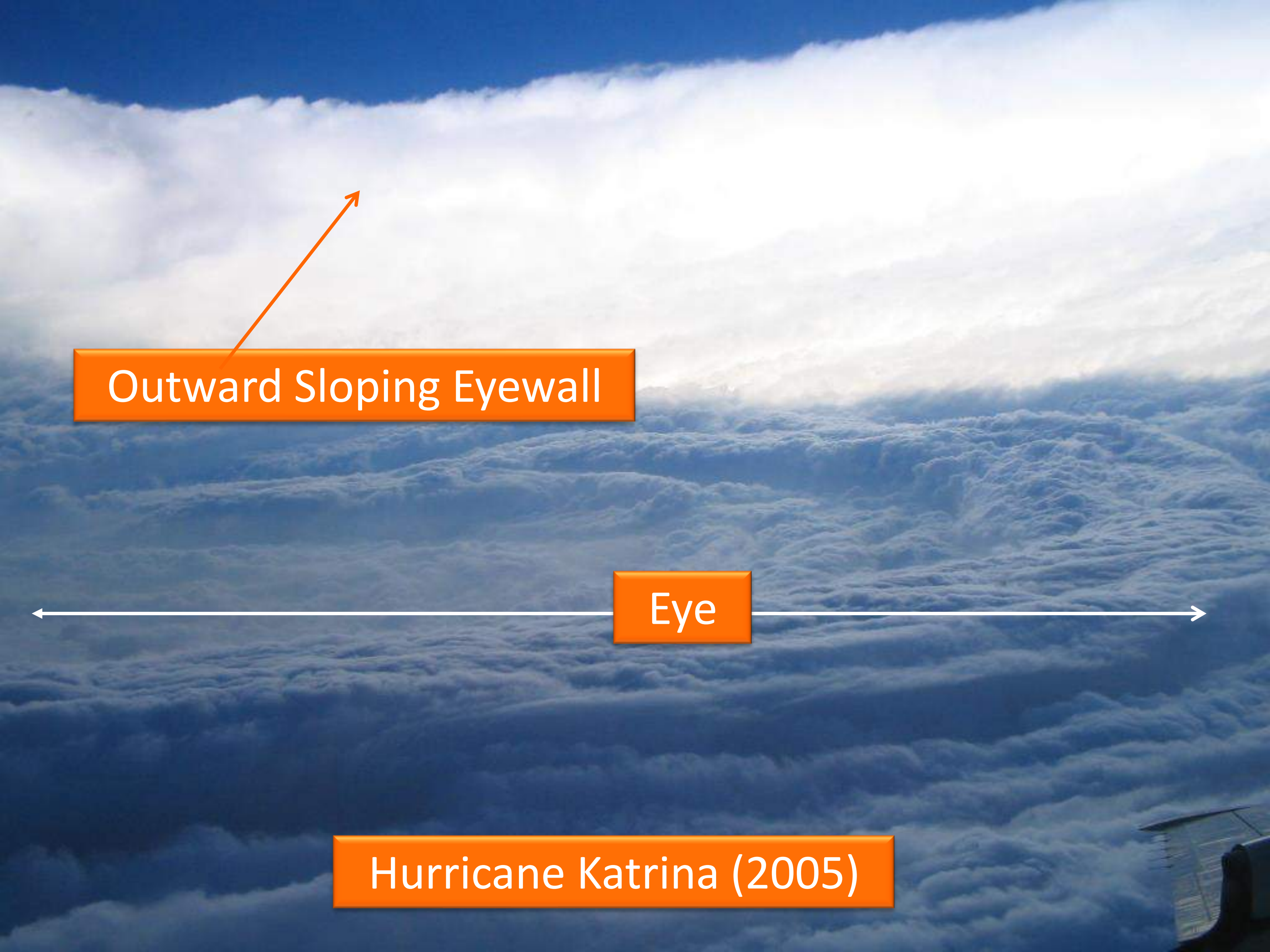
Eyewall Slope is Greater than Appears



Reflectivity (dBZ) from CloudSat, Typhoon Choi-wan (2009)

1:1 Aspect Ratio

Schubert and McNoldy (2010)



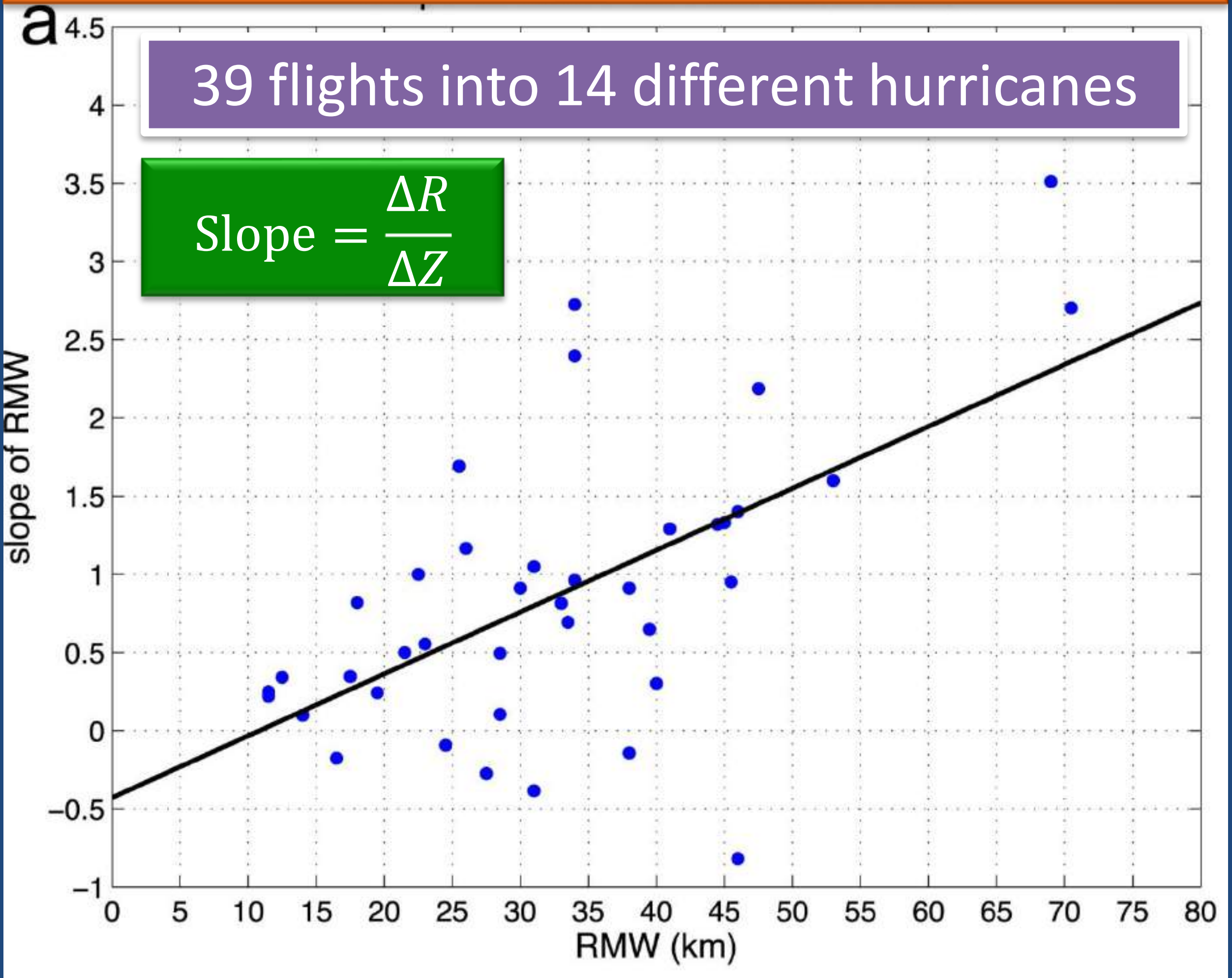
Outward Sloping Eyewall

Eye

Hurricane Katrina (2005)

Outward Slope Increases with Size

Slope of RMW vs RMW



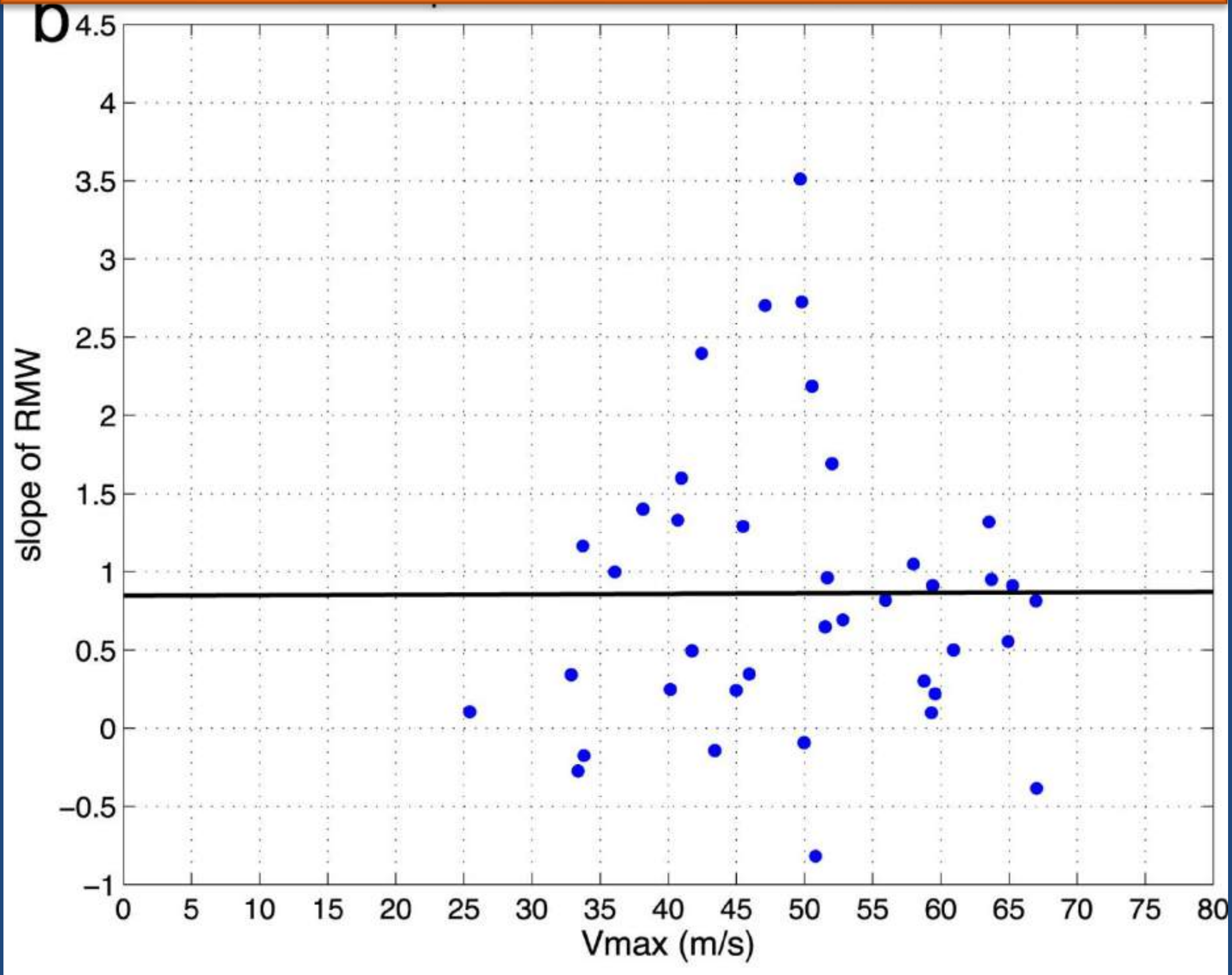
39 flights into 14 different hurricanes

$$\text{Slope} = \frac{\Delta R}{\Delta Z}$$

Stern et al. (2014)

RMW Slope is Unrelated to Intensity

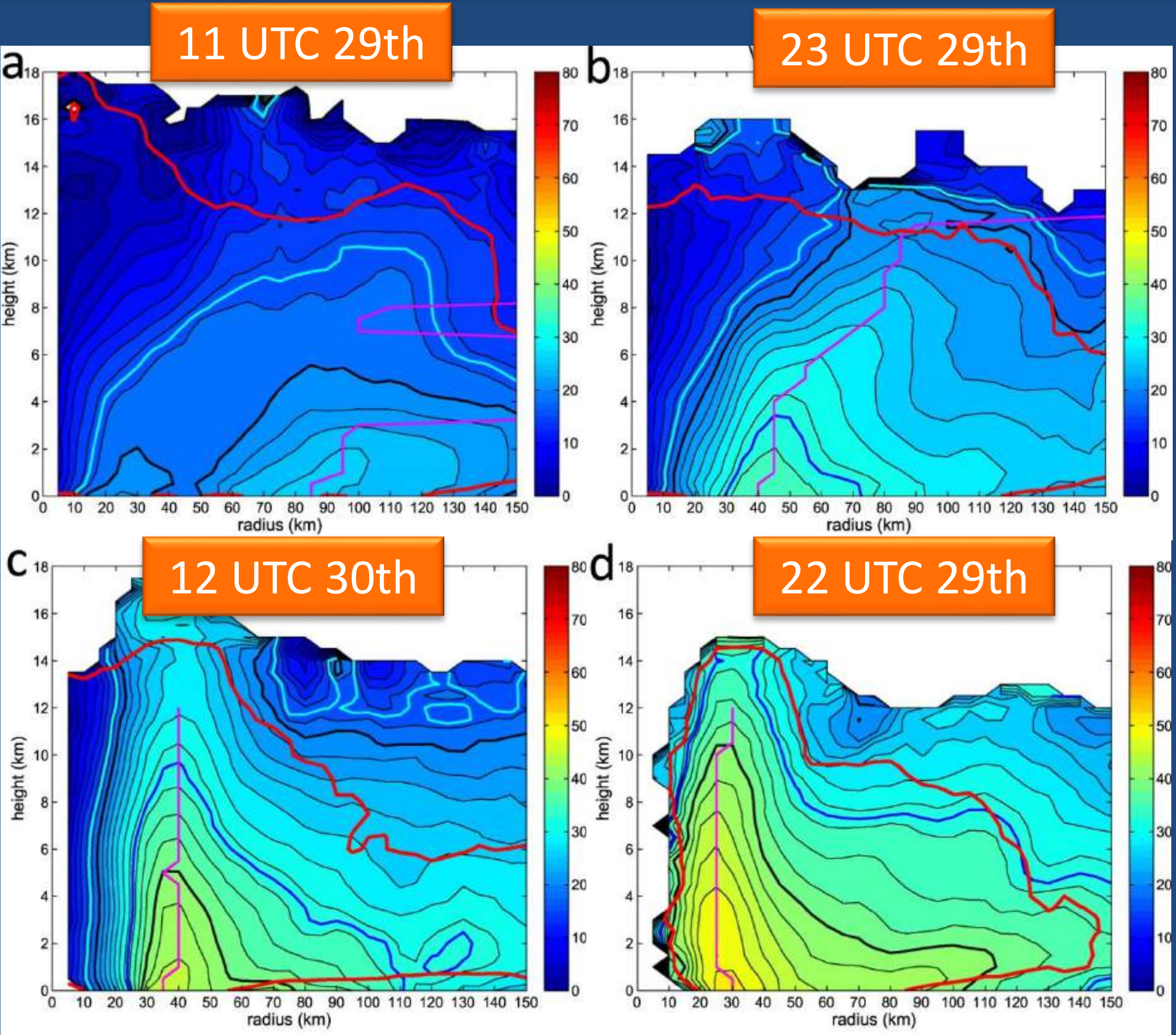
Slope of RMW vs Intensity



Stern et al. (2014)

Observations of Eyewall Contraction

Tangential Wind in Earl (2010) from Radar


11 UTC 29th

23 UTC 29th

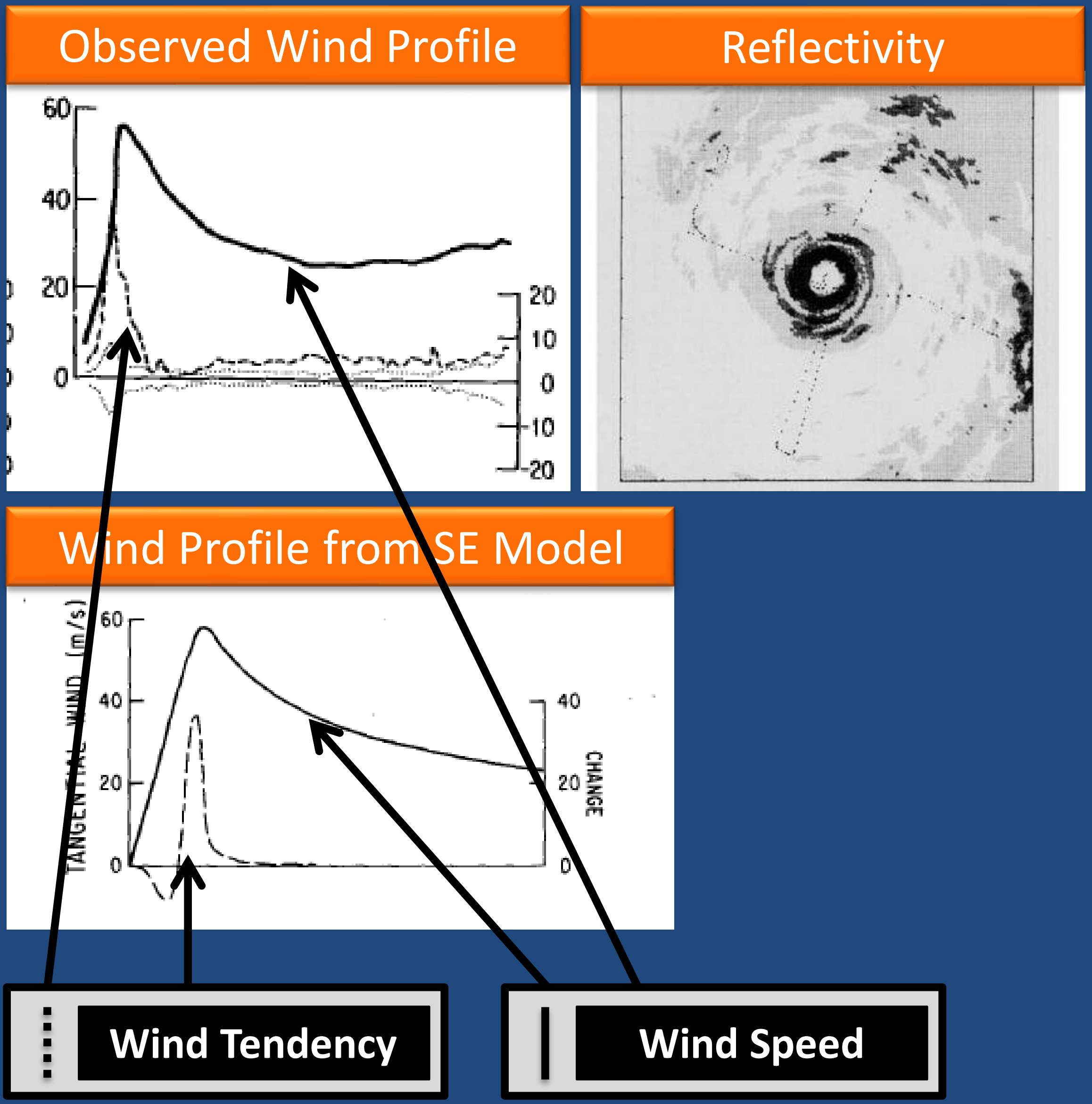
12 UTC 30th

22 UTC 29th

- RMW tends to contract during intensification
- Also note the decrease in eyewall slope as the RMW gets smaller.

Stern and Zhang (2016)

Contraction Occurs as a Balanced Response to Eyewall Heating



Observed Wind Profile

Reflectivity

Wind Profile from SE Model

Wind Tendency

Wind Speed

- For Hurricane Allen (1980), the maximum wind tendency during intensification was inward of the RMW, and so the RMW contracted.
- Willoughby et al. (1982) used a Sawyer-Eliassen model to reproduce this observation.

Willoughby et al. (1982)

Contraction Occurs as a Balanced Response to Eyewall Heating

Wind Tendency from Idealized Heating Calculations

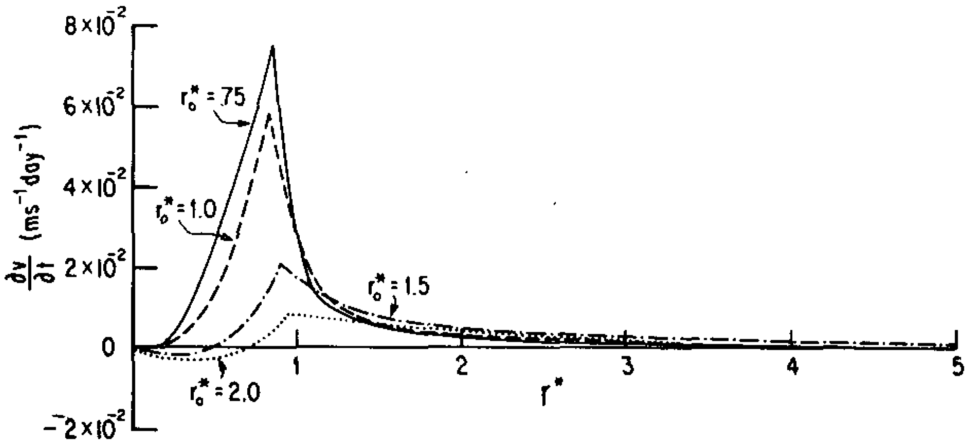


FIG. 11. The surface tendencies of pressure height and tangential wind produced by heat sources at $z_0^* = 0.5$ and $r_0^* = 0.75, 1.0, 1.5$ and 2.0.

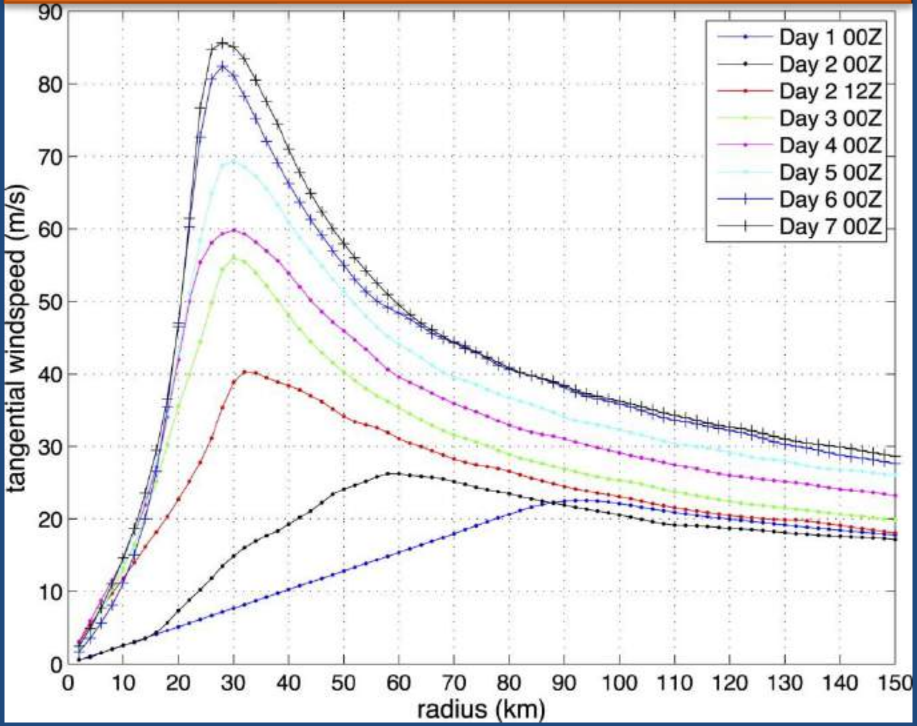
- In general, heating located at or inside the RMW results in a peak wind tendency located inward of the RMW.

- Since the observed eyewall updraft is usually inward of the RMW, this leads to contraction of the RMW.

Shapiro and Willoughby (1982)

Intensification Continues without Contraction

Wind Profiles from a Simulation



- In idealized simulations, contraction slows down and stops, while intensification continues at a nearly fixed RMW.

- The slowing of contraction occurs as the profile becomes more sharply peaked.

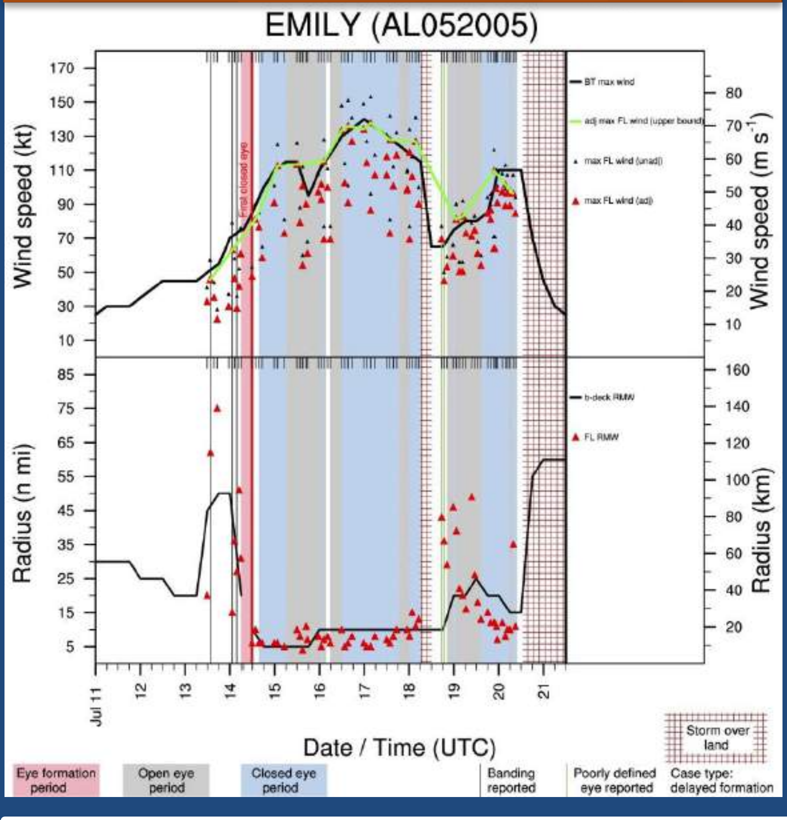
$$\frac{dRMW}{dt} = -\left.\frac{\frac{\partial}{\partial r}\left(\frac{\partial V}{\partial t}\right)}{\frac{\partial^2 V}{\partial r^2}}\right|_{\text{RMW}}$$

Diagnostic Contraction Equation

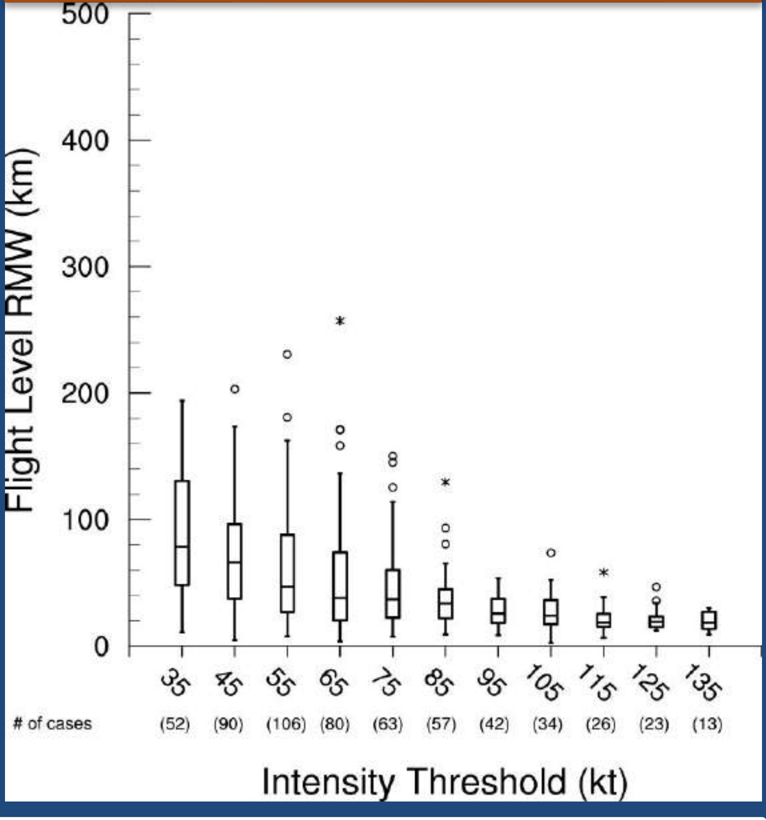
Stern et al. (2015)

Observations of Contraction

Intensity and RMW vs. Time



RMW as Function of Intensity



- There is observational evidence to support the idea that contraction often stops during the middle of intensification.

Stern et al. (2015)

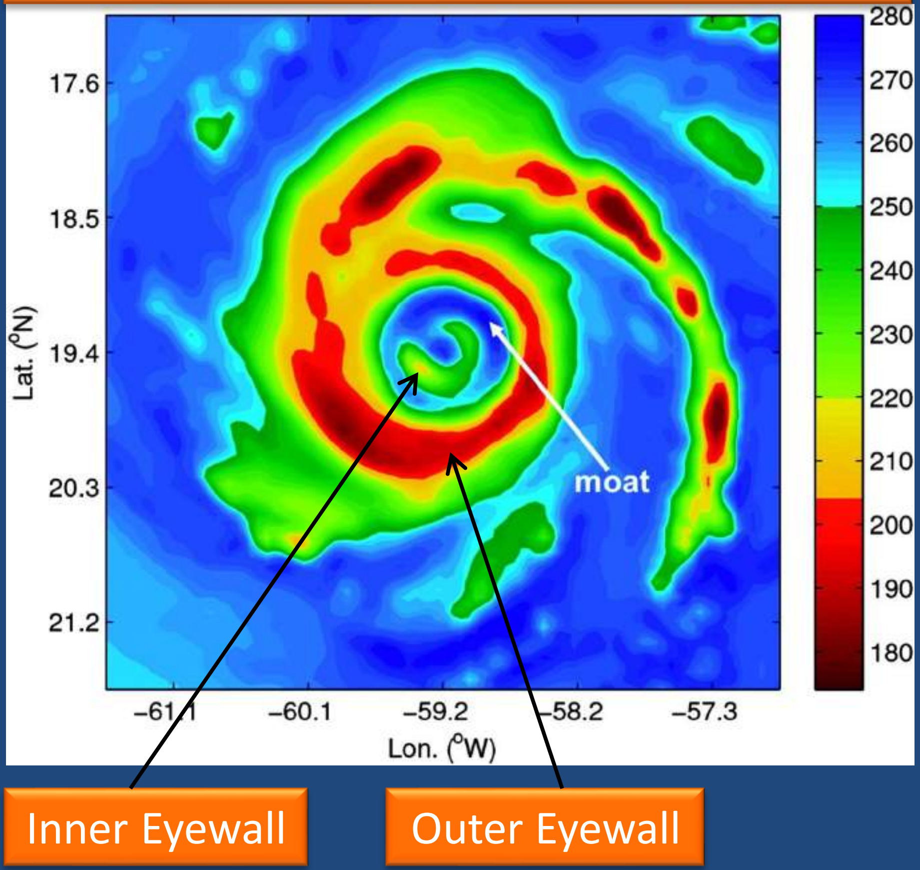
Summary

- The RMW and eyewall tend to become smaller with increasing intensity, but there is substantial variability.
- The maximum winds decrease with height at a similar rate for most TCs.
- The RMW and eyewall slope outwards with height, and this slope increases with size.
- The RMW and eyewall tend to contract during the beginning of intensification, but contraction often stops within the middle of intensification.

Bonus Slides!

Eyewall Replacement Cycles (ERCs)

85-GHz AMSR-E Brightness Temp
Hurricane Frances (2004)



Inner Eyewall

Outer Eyewall

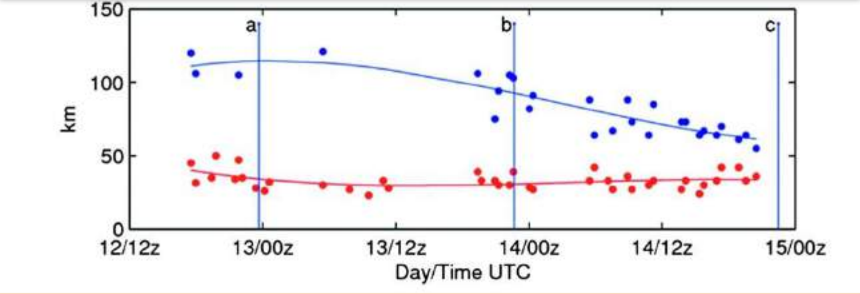
- In strong TCs, convection outside the eyewall can develop into a concentric ring, forming a new outer eyewall.
- Often the inner eyewall will decay and the outer eyewall will replace the inner eyewall.

Sitkowski et al. (2011)

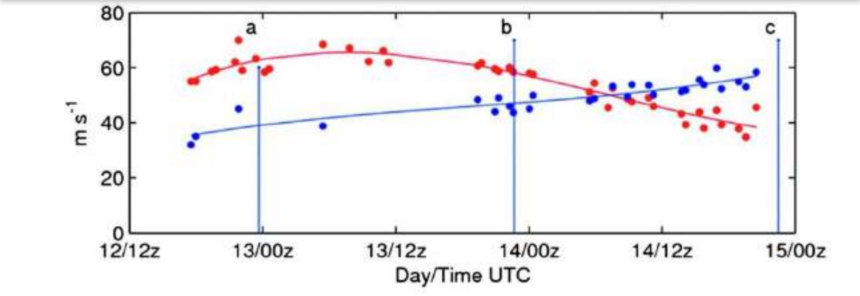
Typical Evolution of Wind Field During ERC

Evolution of ERC in Floyd (1999)

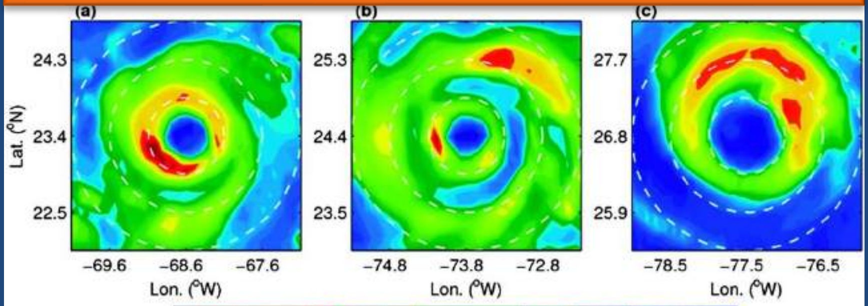
Inner (red) and outer (blue) RMW



Inner (red) and outer (blue) Vmax



Microwave Brightness Tempertature

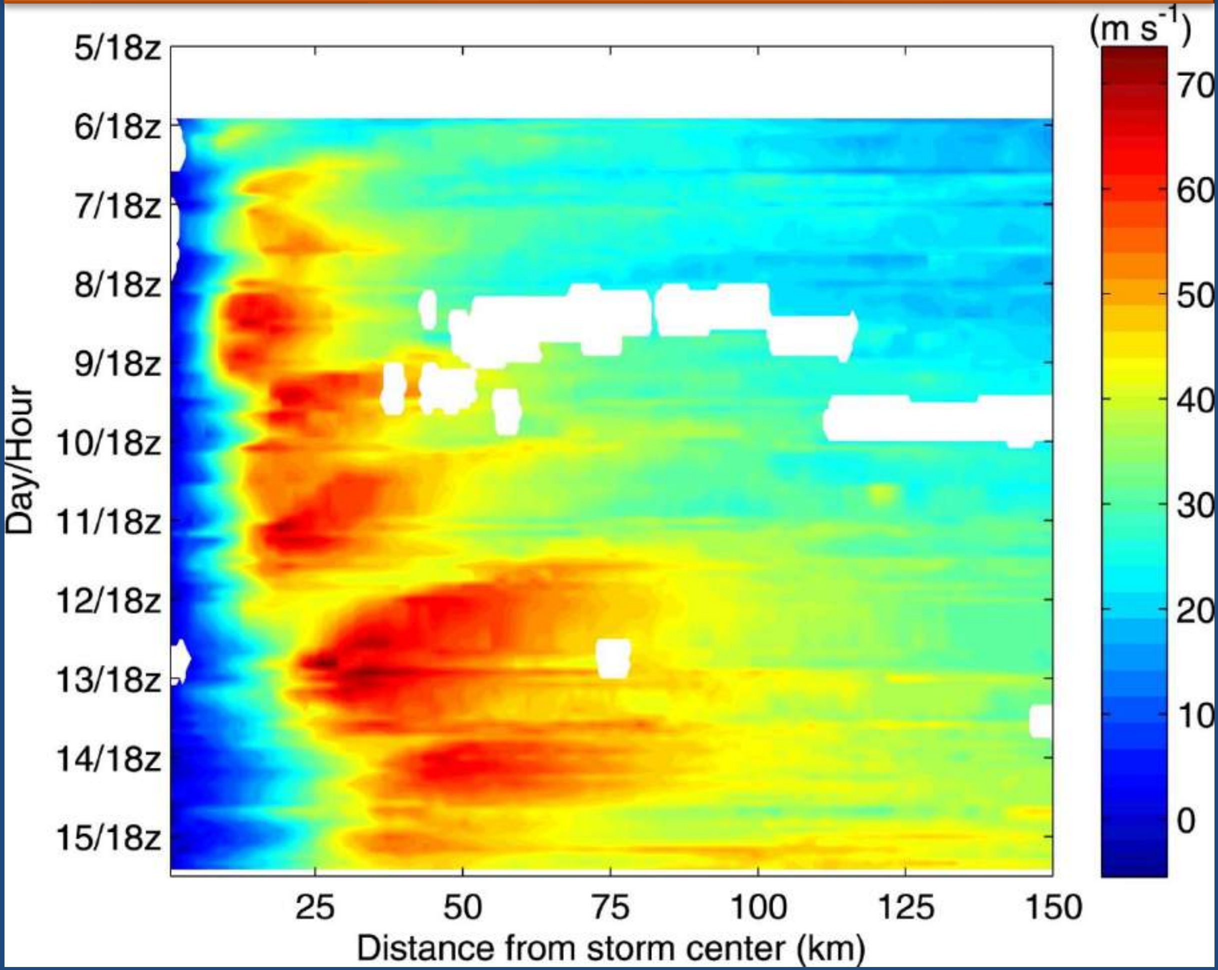


- In a typical ERC, an outer wind maximum forms at 2-3 times the RMW, while the inner maximum is still intensifying.
- The inner eyewall begins to weaken as the outer eyewall contracts and intensifies.
- Eventually the outer maximum becomes stronger and the overall TC intensity increases again.

Sitkowski et al. (2011)

ERCs Lead to a Systematic Expansion of the RMW

Radius-Time Tangential Wind for Ivan (2004)



- Repeated ERCs can occur, with each subsequent event leading to an increase in the RMW.
- This is also a primary mechanism by which the outer wind field of TCs expands.

Sitkowski et al. (2011)