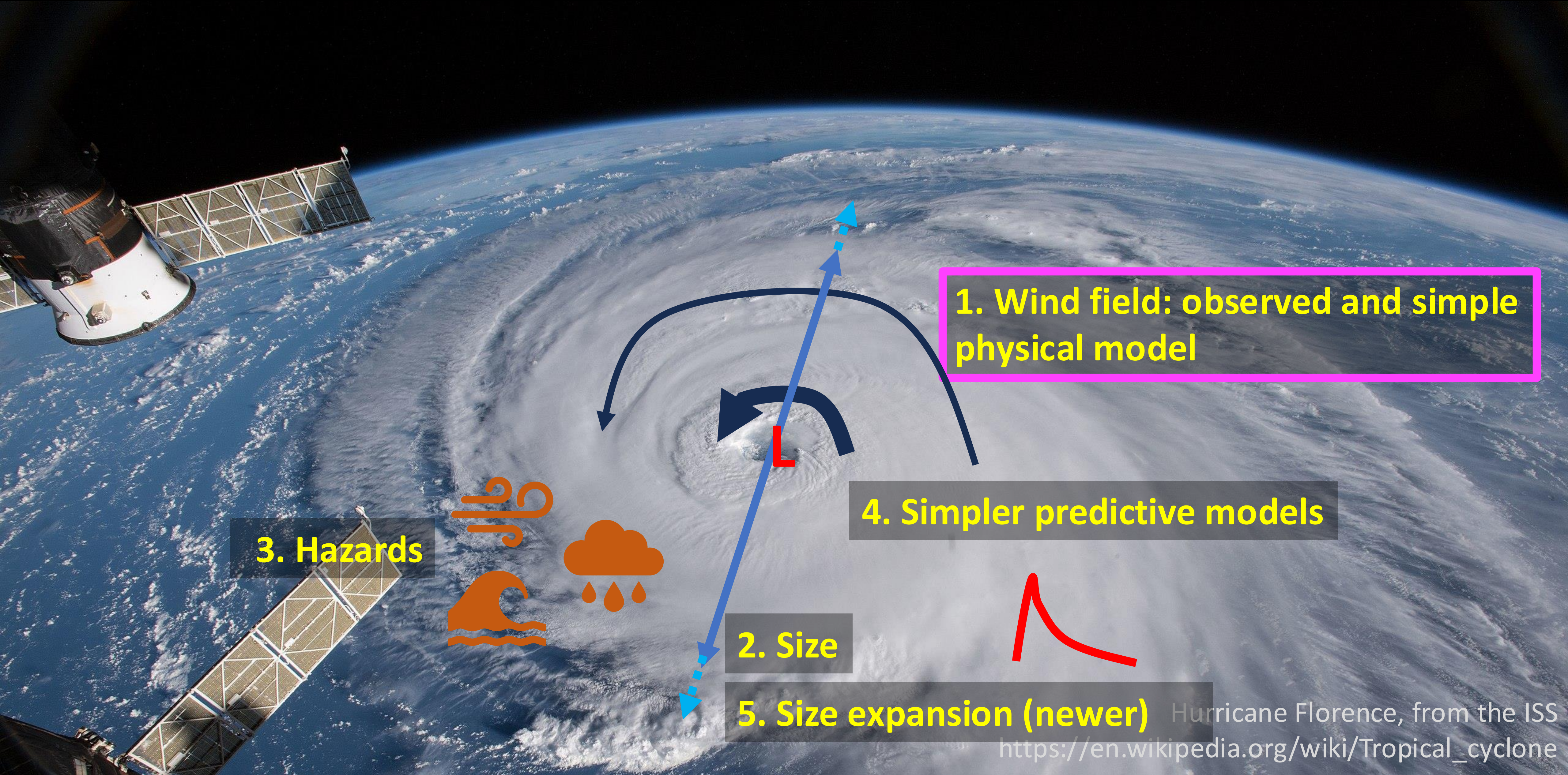
Roadmap

0. Intro: two recent events



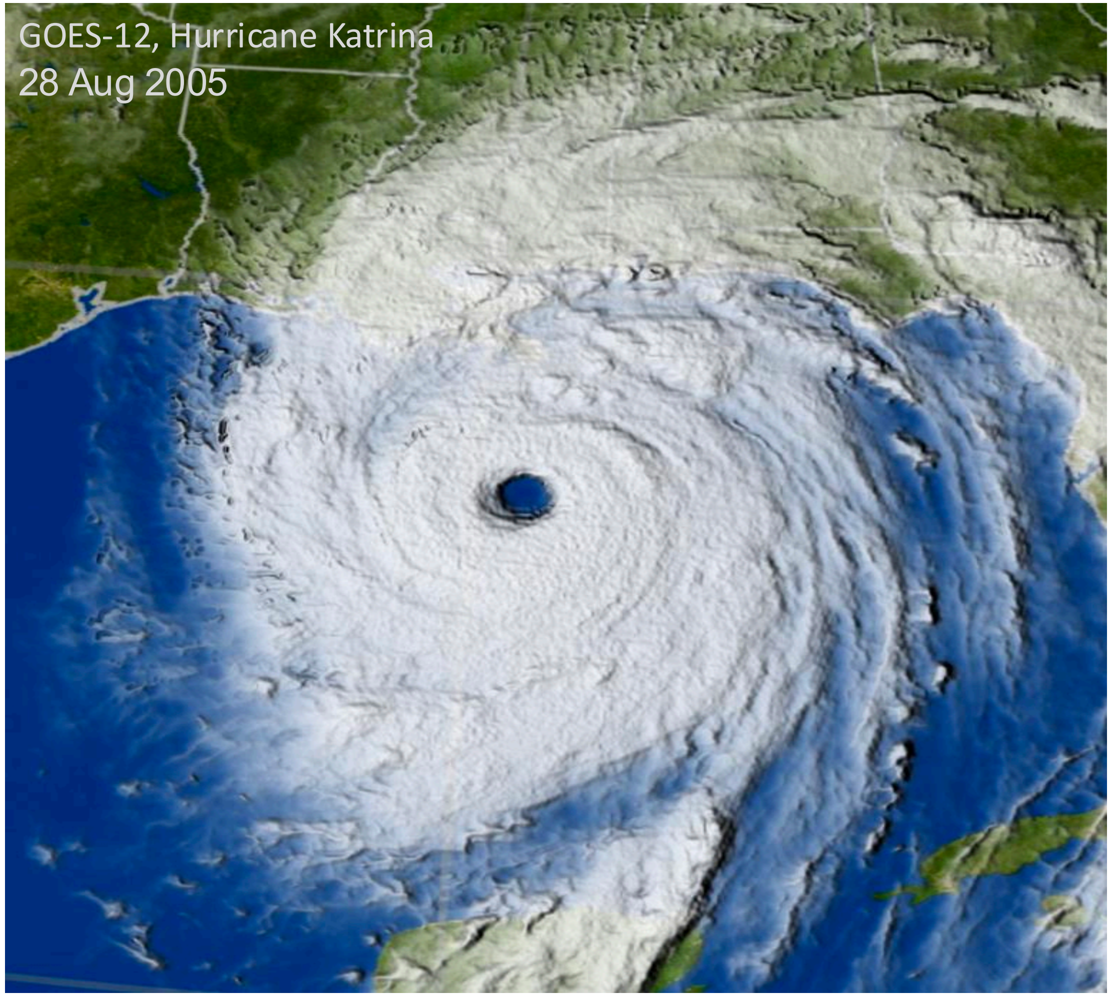
Hurricane Florence, from the ISS
https://en.wikipedia.org/wiki/Tropical_cyclone

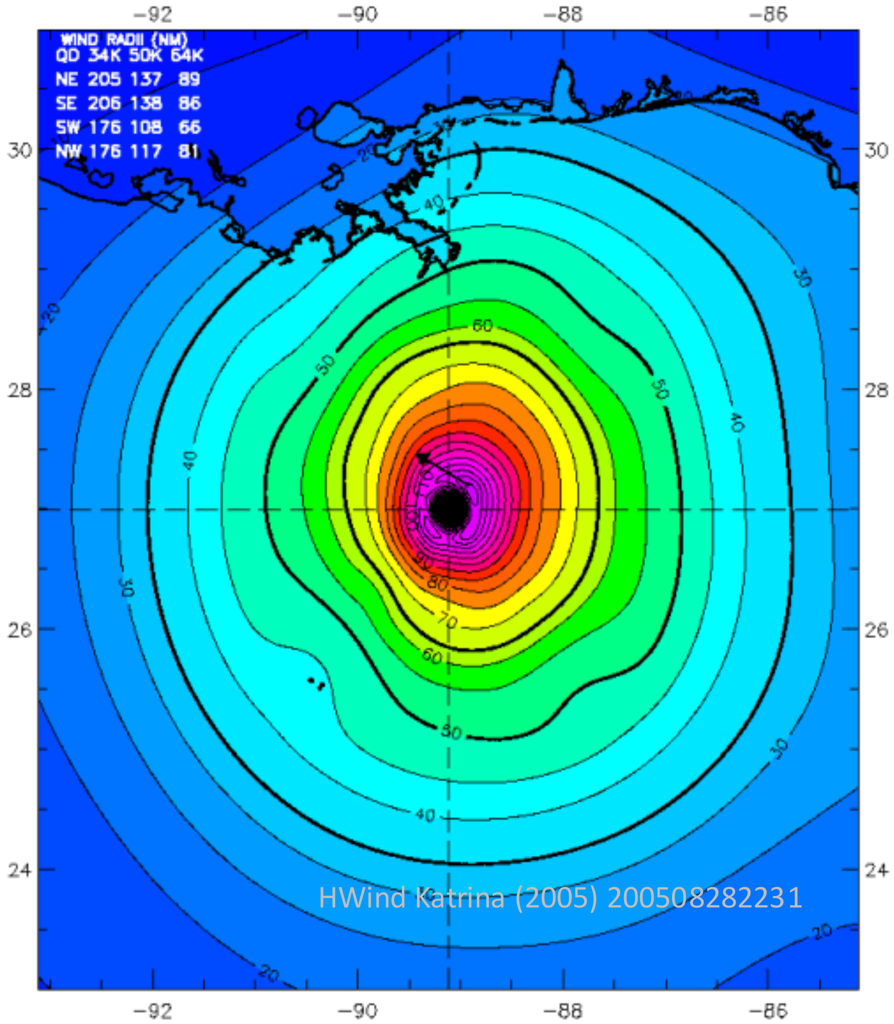
1. The tropical cyclone wind field

- Observed structure and variability
- Physical model
- Response to warming

observed structure and variability

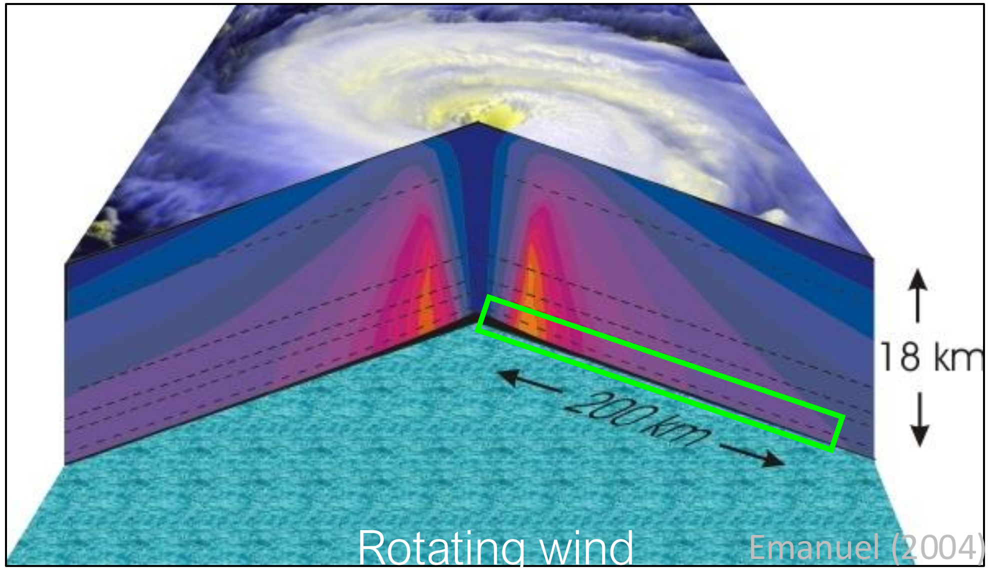
Near-surface wind field wind field

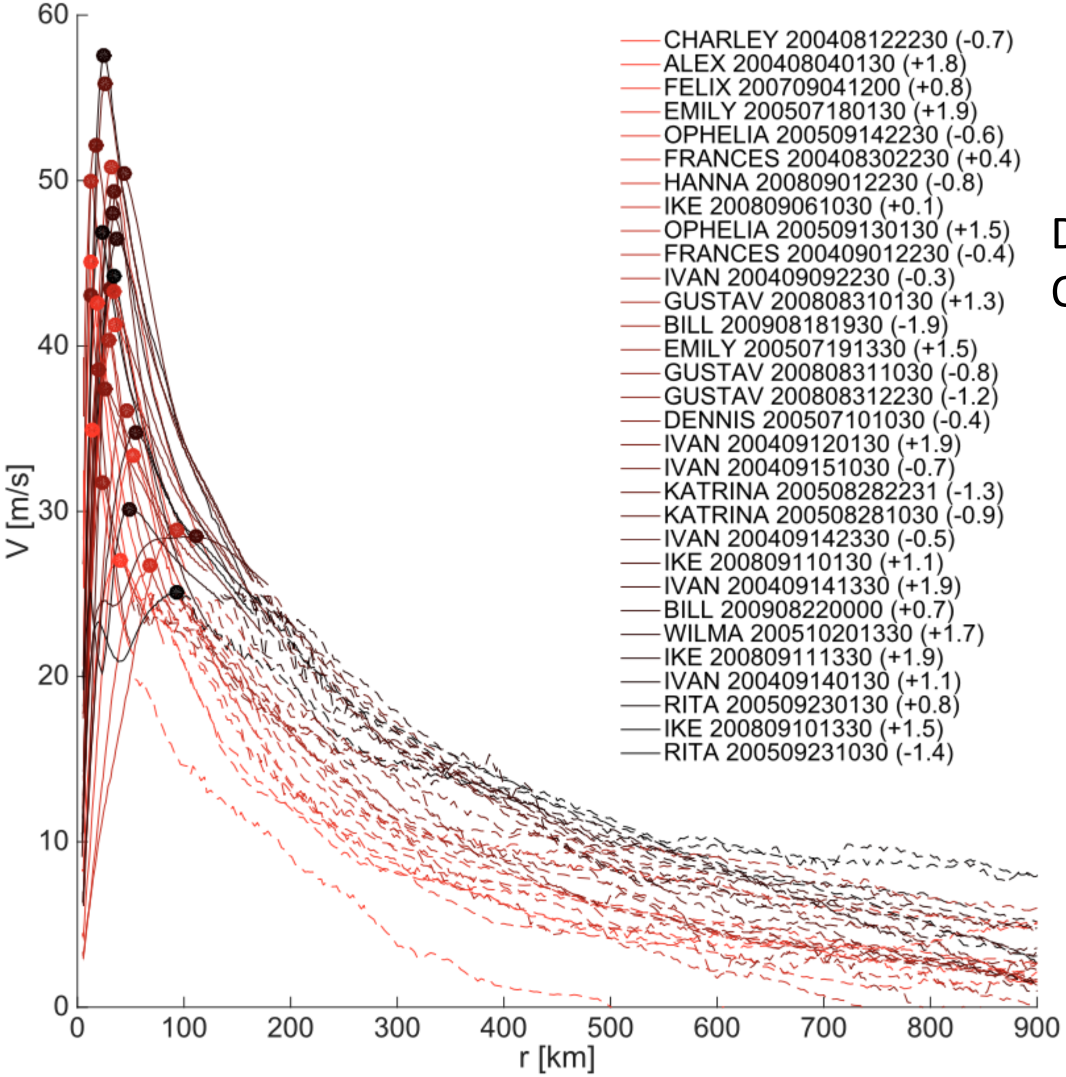




Near-surface (z = 10 m AGL) 1-min wind speed distribution

Radial profile of the near-surface azimuthal wind

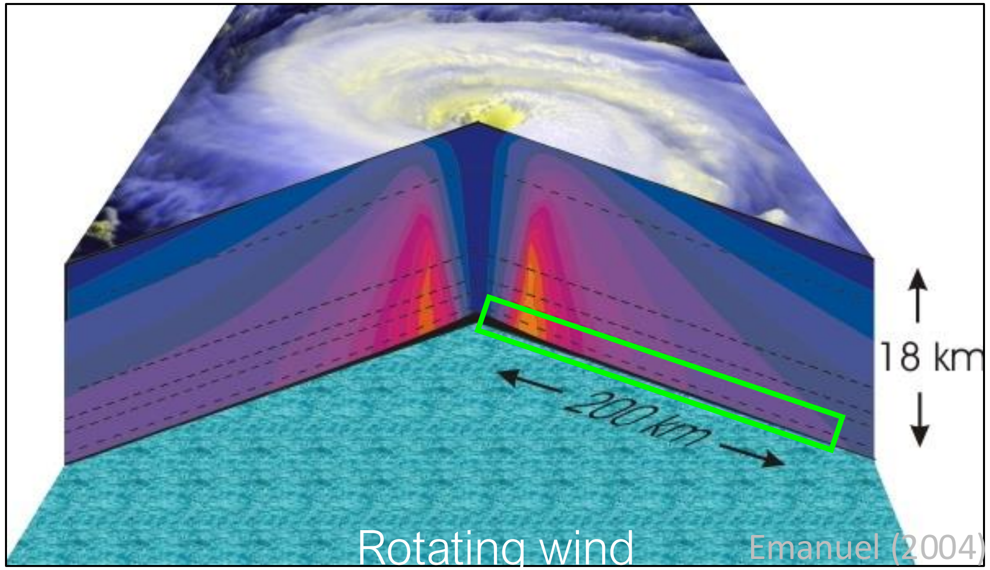


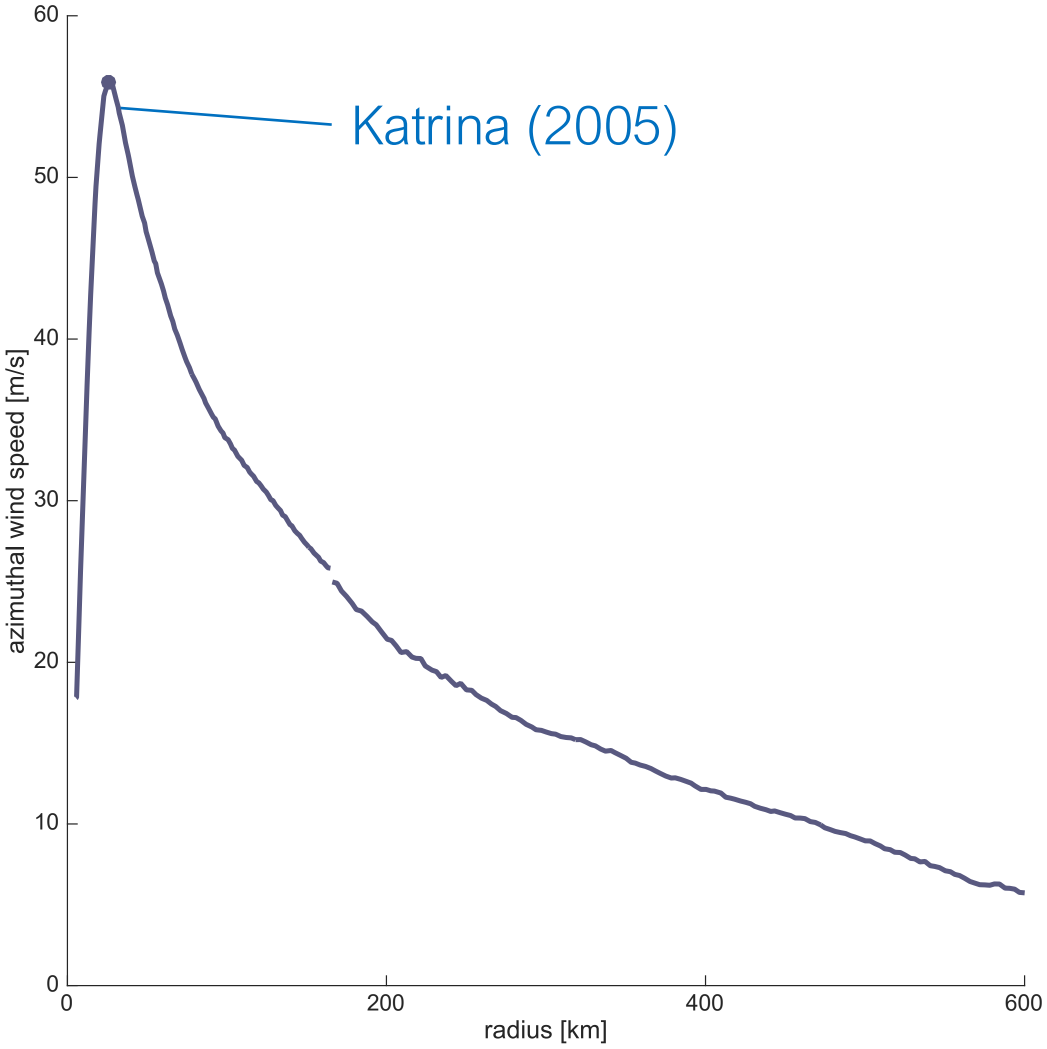


Data sources:
QuikSCAT, HWind

Chavas et al. (2015)

Radial profile of the near-surface azimuthal wind





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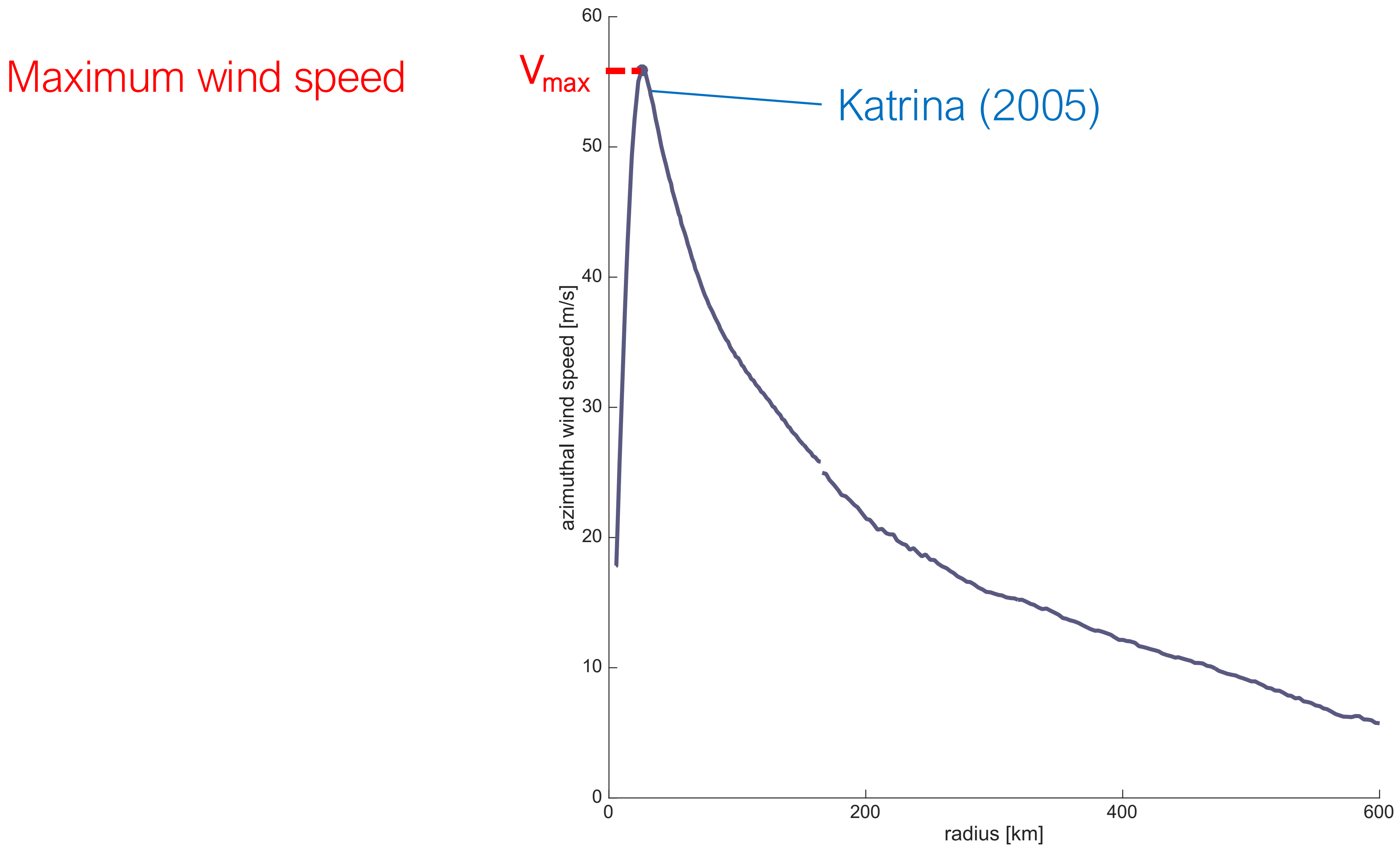
Chavas and Lin (2016)

Radial profile of the near-surface azimuthal wind



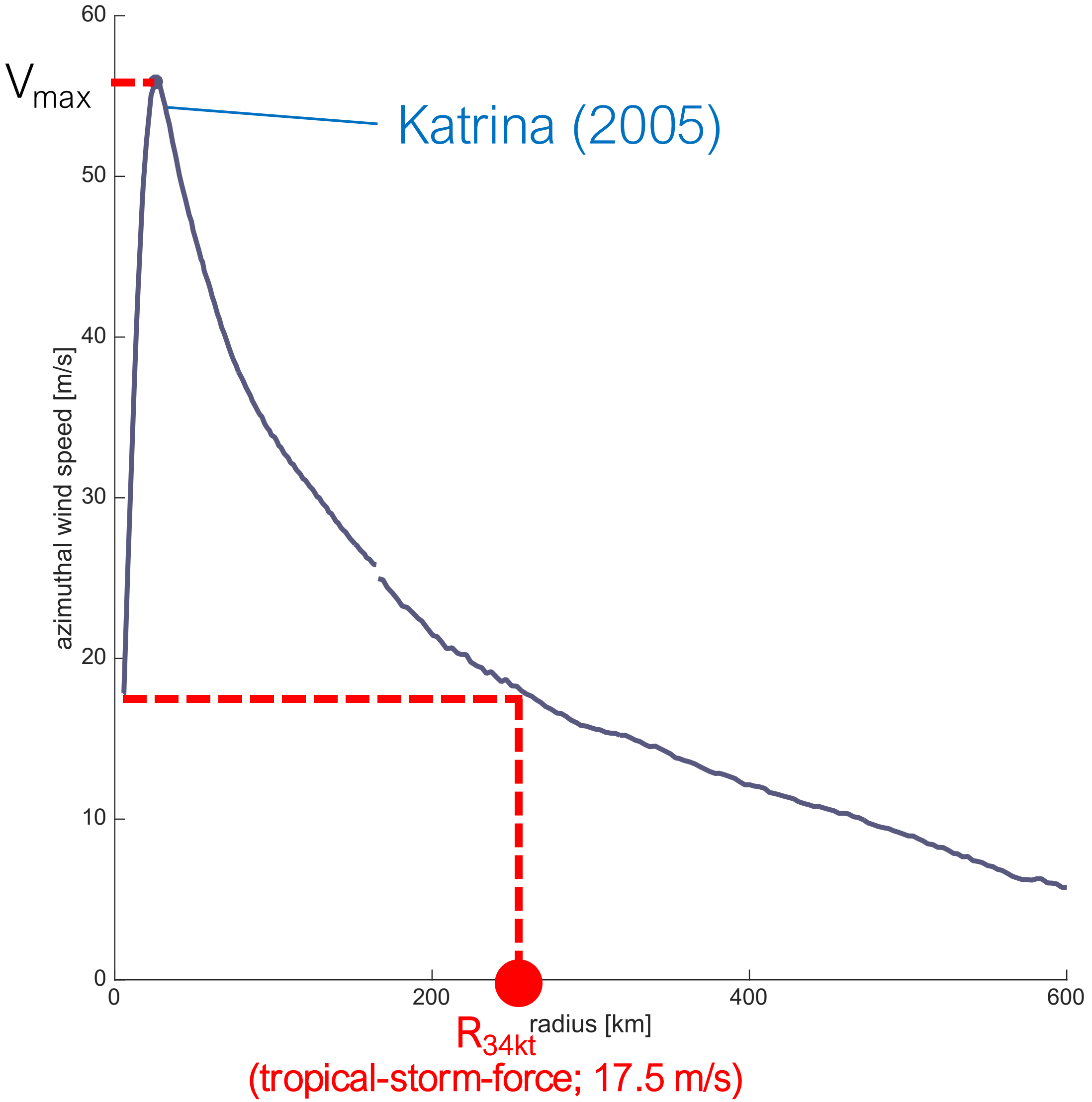
Data sources:
QuikSCAT, HWind

Chavas and Lin (2016)

Radial profile of the near-surface azimuthal wind

Maximum wind speed

Size: some absolute radius

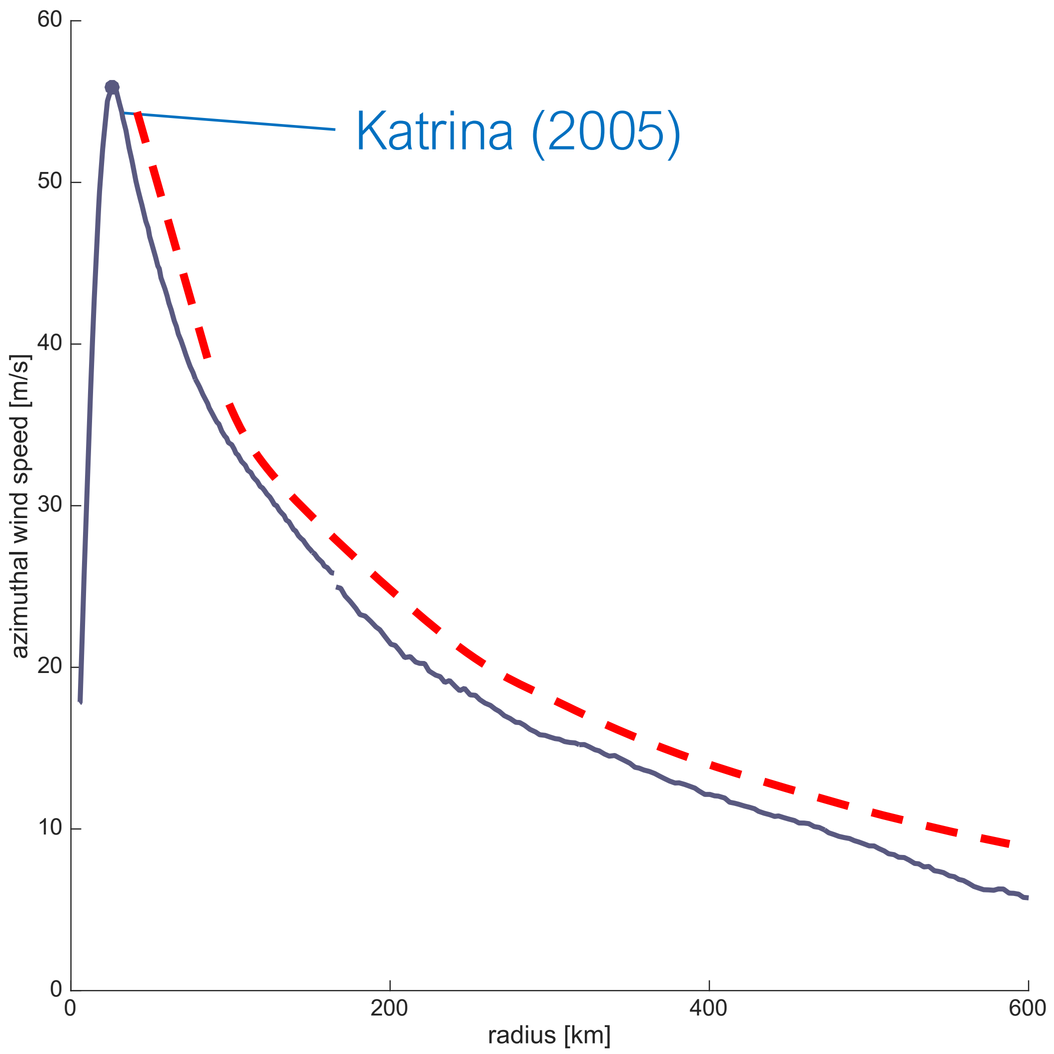


Data sources:
QuikSCAT, HWind

Chavas and Lin (2016)

Radial profile of the near-surface azimuthal wind

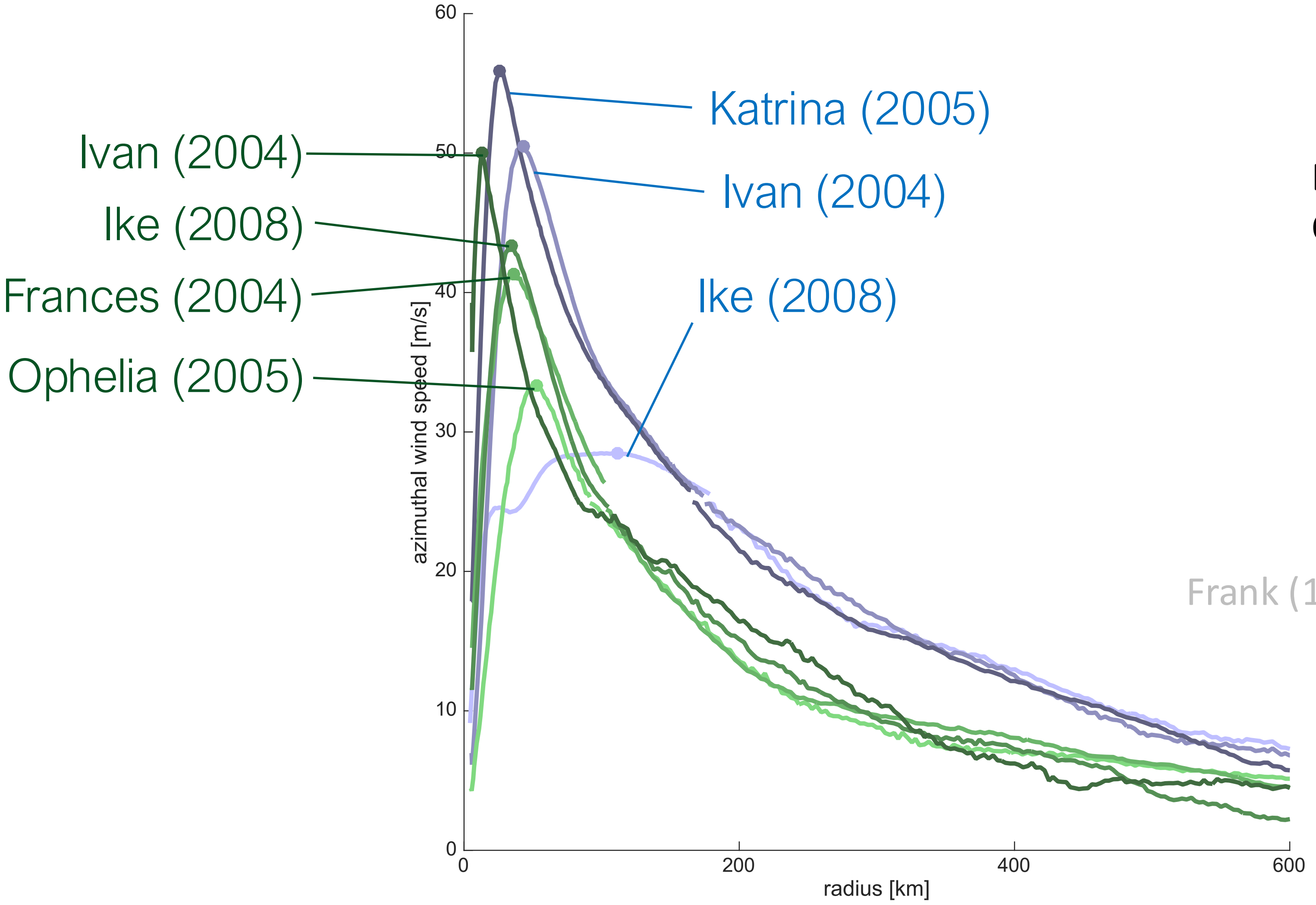
Maximum wind speed
Size
Structure: change with radius



Data sources:
QuikSCAT, HWind

Chavas and Lin (2016)

The wind field varies in two distinct ways

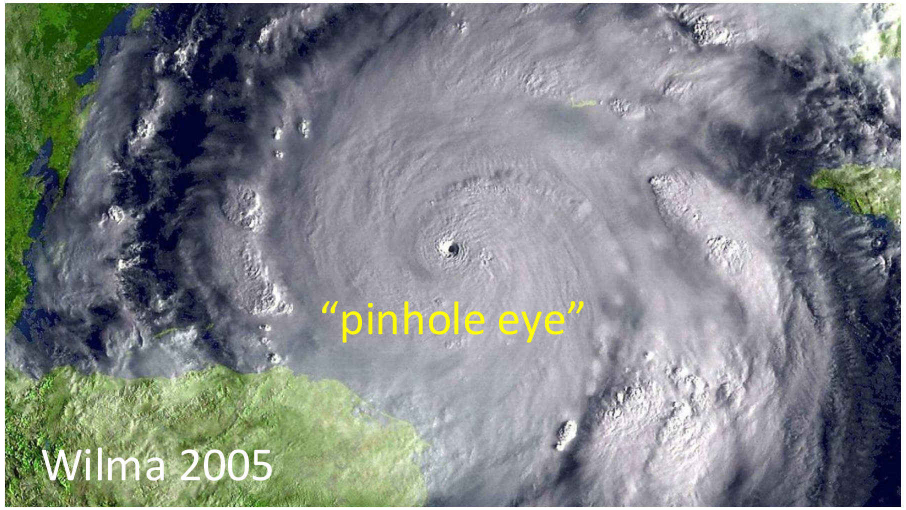


Data sources:
QuikSCAT, HWind

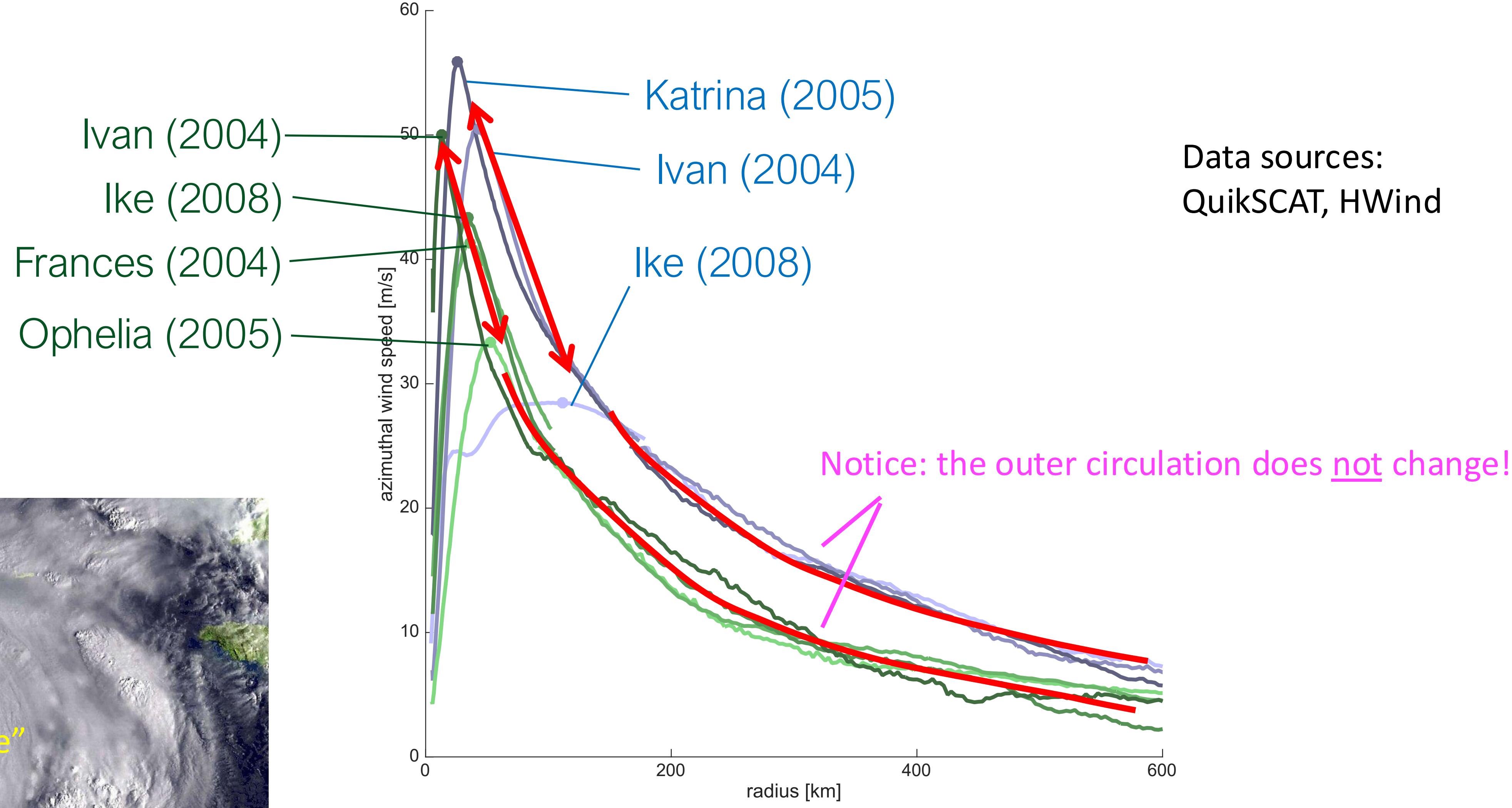
See also:
Frank (1977), Merrill (1984),
Chavas et al. (2016)

Chavas et al. (2015), Chavas and Lin (2016)

1) Radius of maximum wind contracts as storm intensifies



https://baynews9.com/fl/tampa/weather/2020/10/06/the-dreaded-pinhole-eye

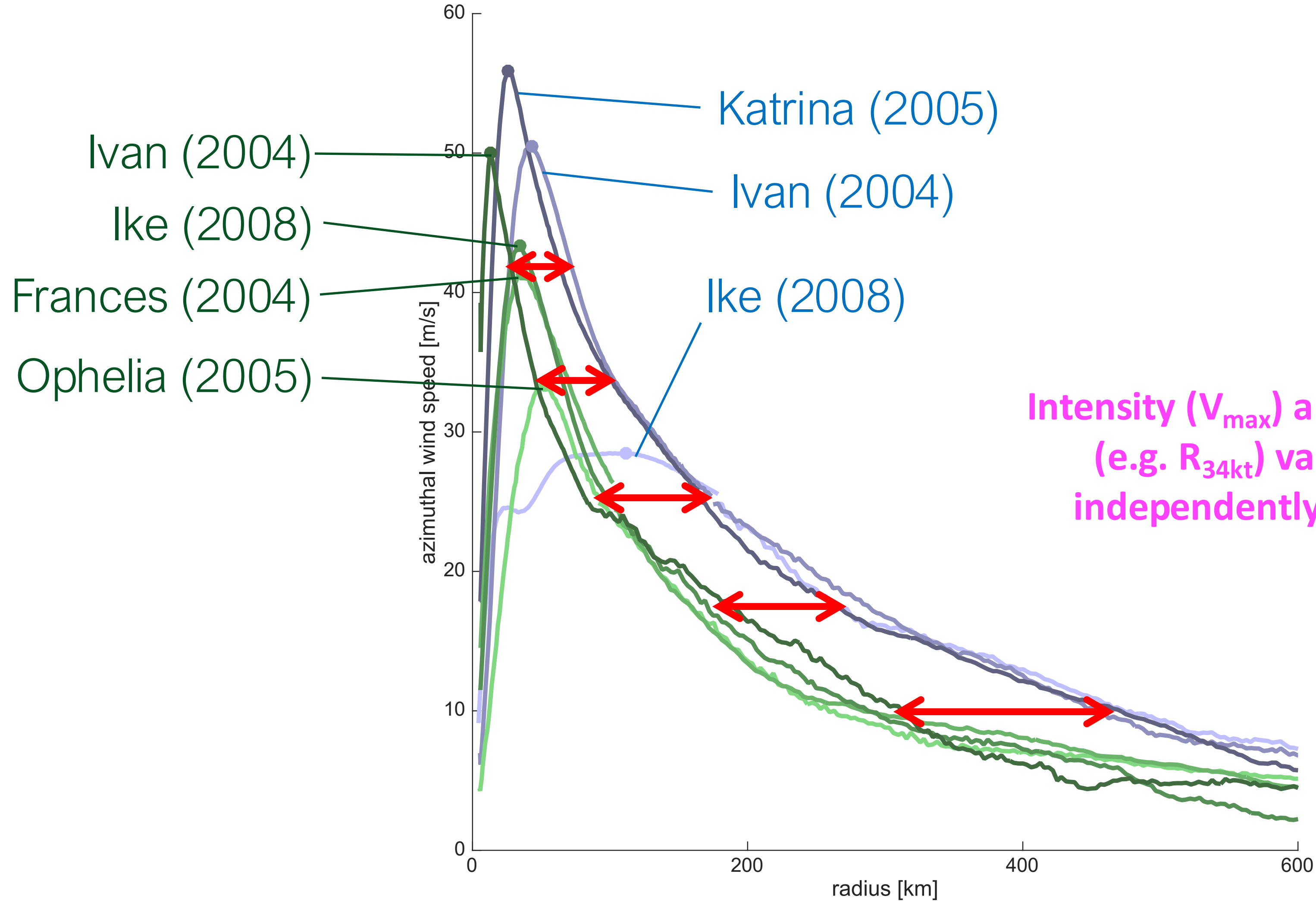


Chavas et al. (2015), Chavas and Lin (2016)

Data sources:
QuikSCAT, HWind

See also:
Frank (1977), Merrill (1984), Chavas et al. (2016)

2) Storms can have same intensity/structure, but different sizes



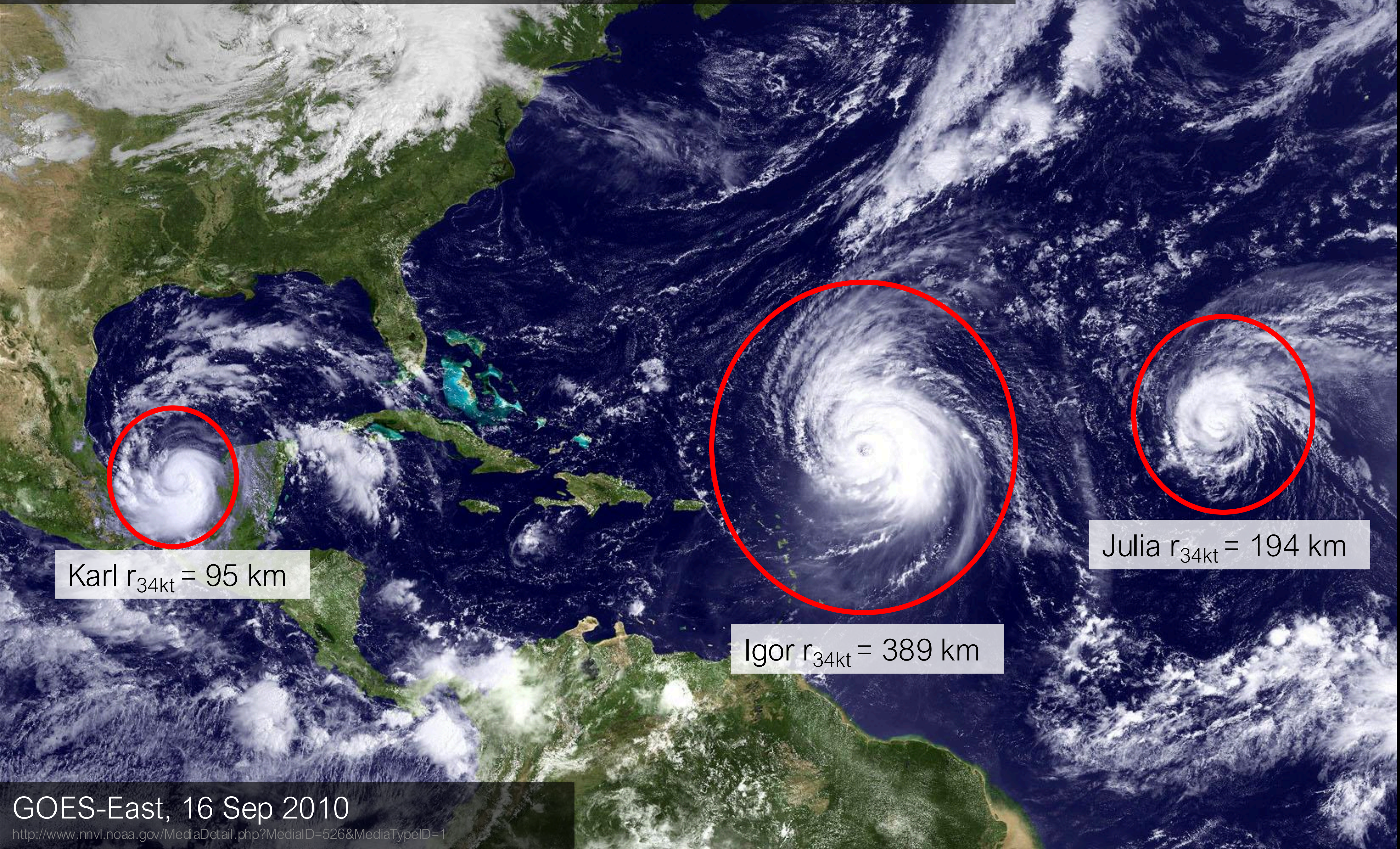
Chavas et al. (2015), Chavas and Lin (2016)

Data sources:
QuikSCAT, HWind

Intensity (V_{max}) and outer size (e.g. R_{34kt}) vary nearly independently in nature

See also:
Frank (1977), Merrill (1984), Chavas et al. (2016)

Size varies a lot in nature – independent of intensity



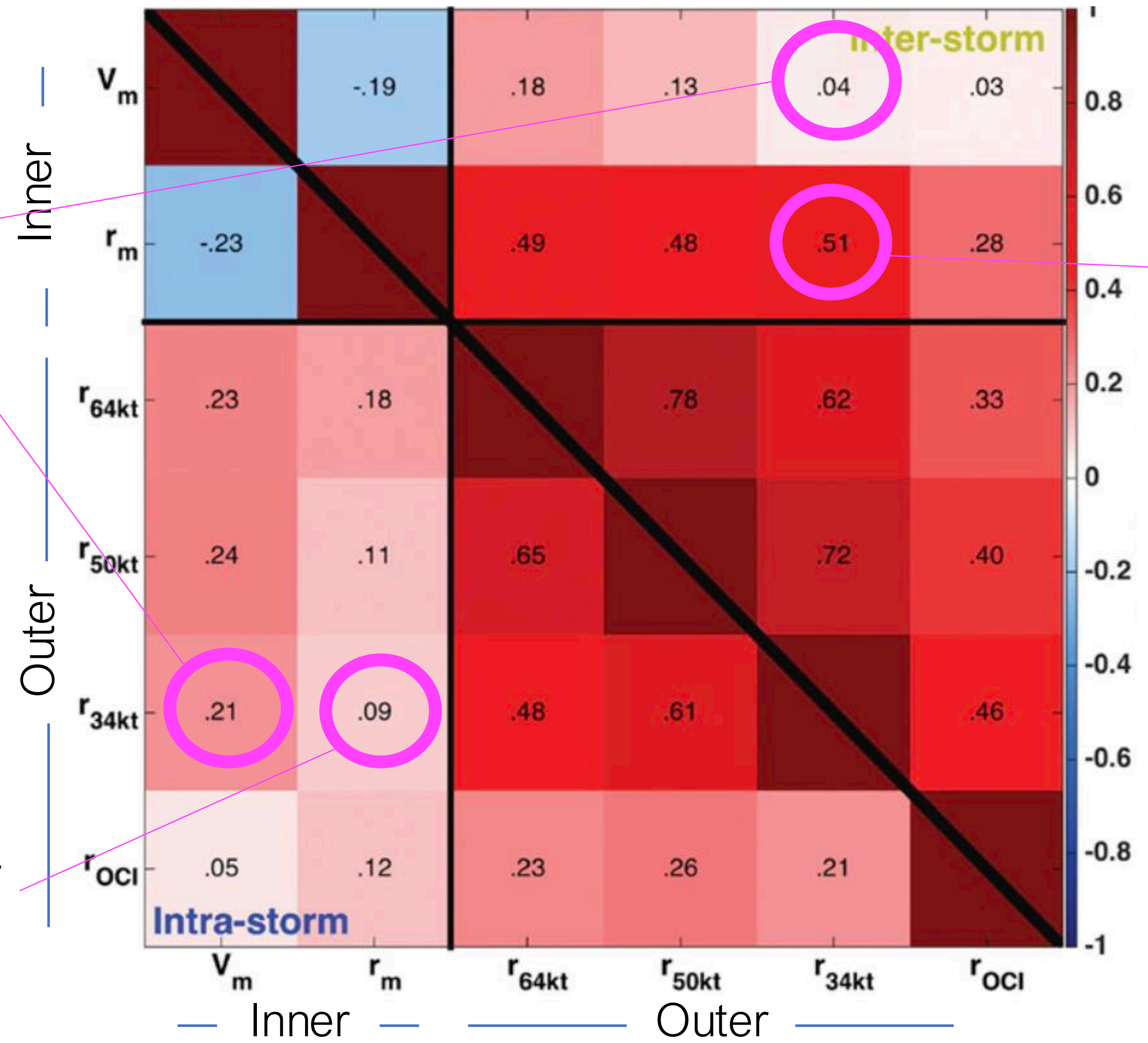
All $V_{max} \approx 50 \frac{m}{s}$
within 24 hr

Storm size varies strongly between storms, less so during storm lifecycle

Rank correlation: intra-storm \ inter-storm
Extended Best Track database Atlantic (1988–2012) and east Pacific (2001–12)

Intensity and outer size are very weakly correlated (see also Weatherford and Gray 1988)

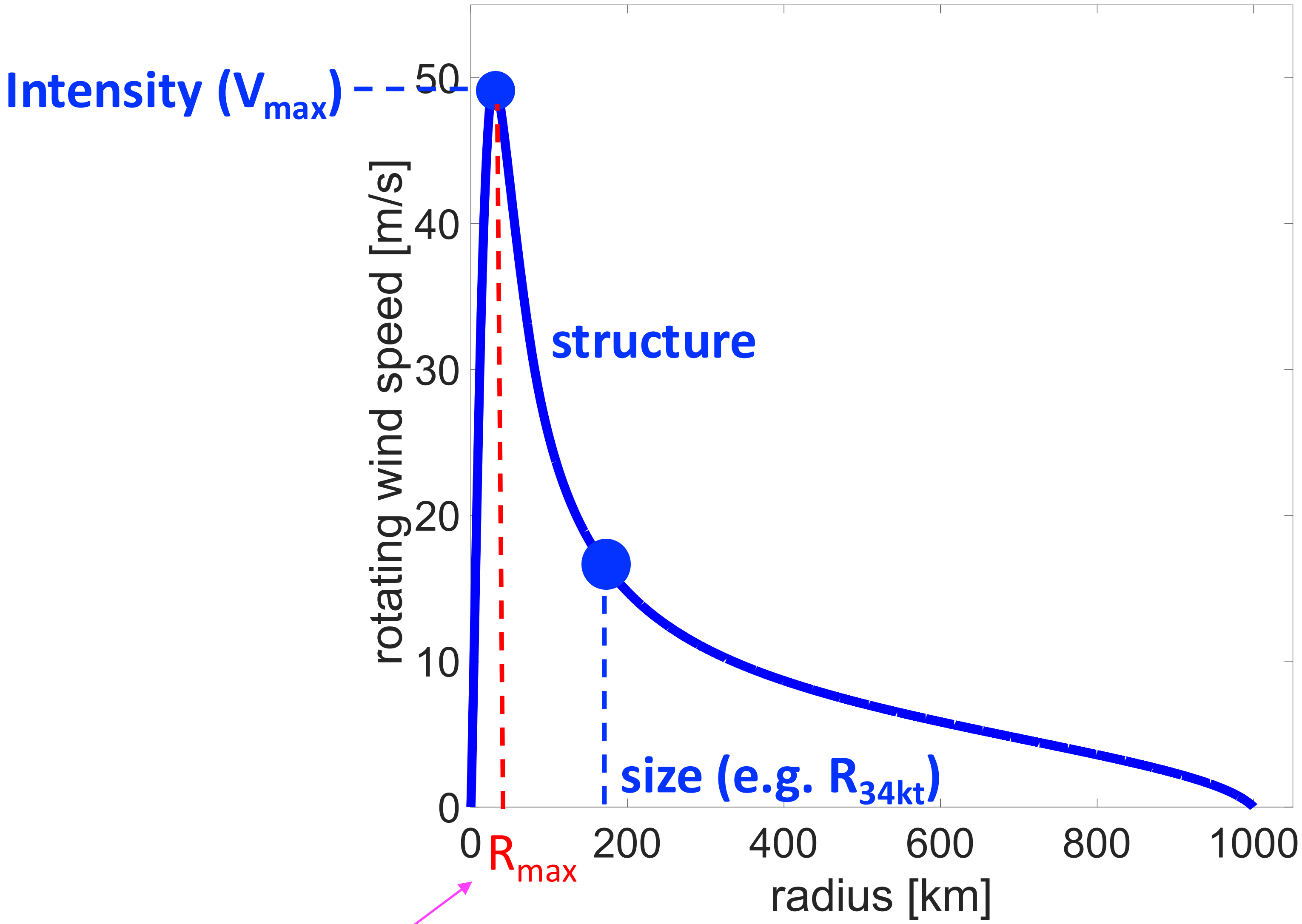
Within the lifecycle of an **individual storm**, Rmax covaries **weakly** with R34kt (mode #1 – variations in intensity at relatively constant size)



Between storms, Rmax covaries **strongly** with R34kt (mode #2 – variations in size at relatively constant intensity)

Chavas et al. (2016)

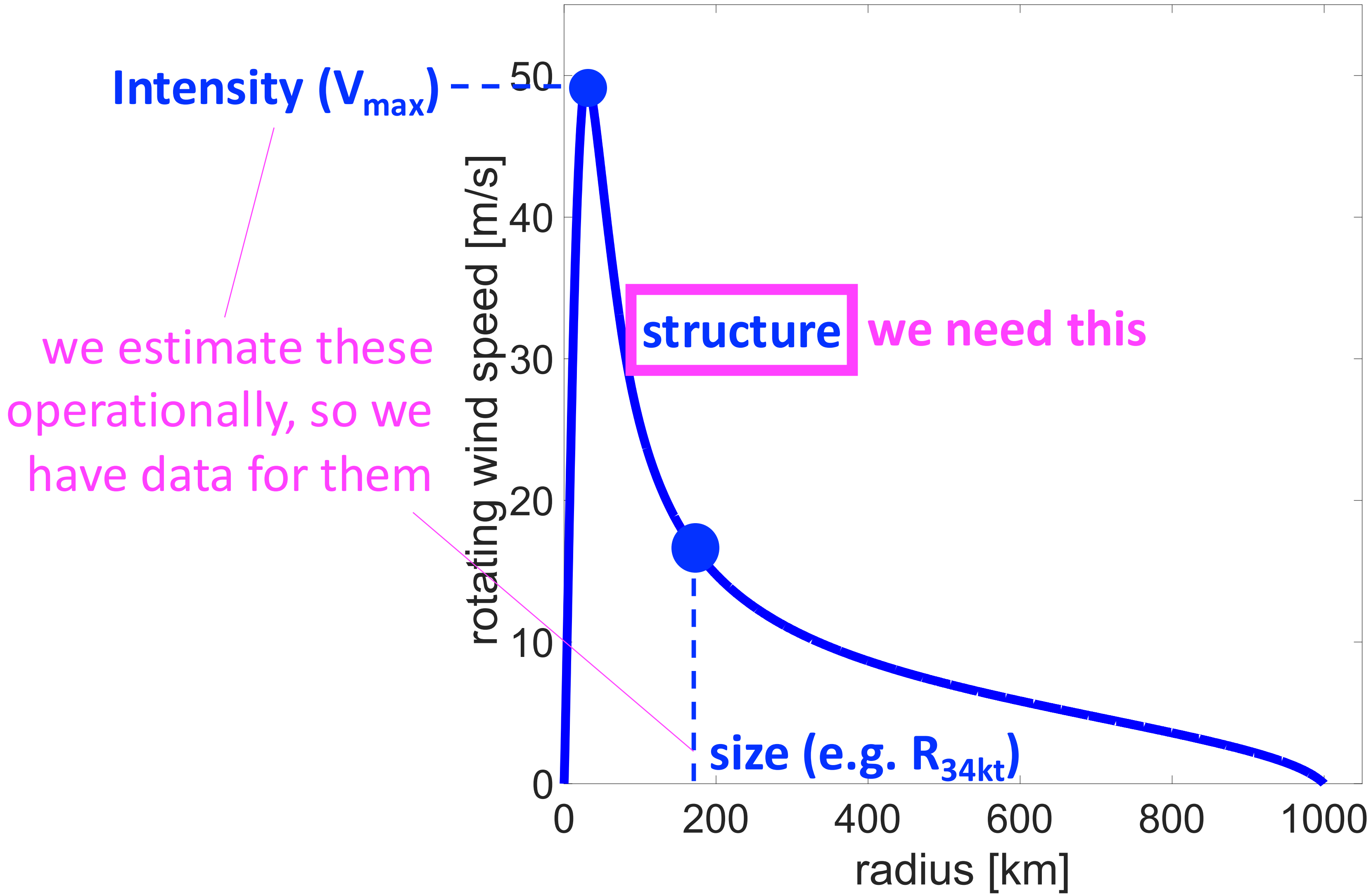
Three essential components to the wind field



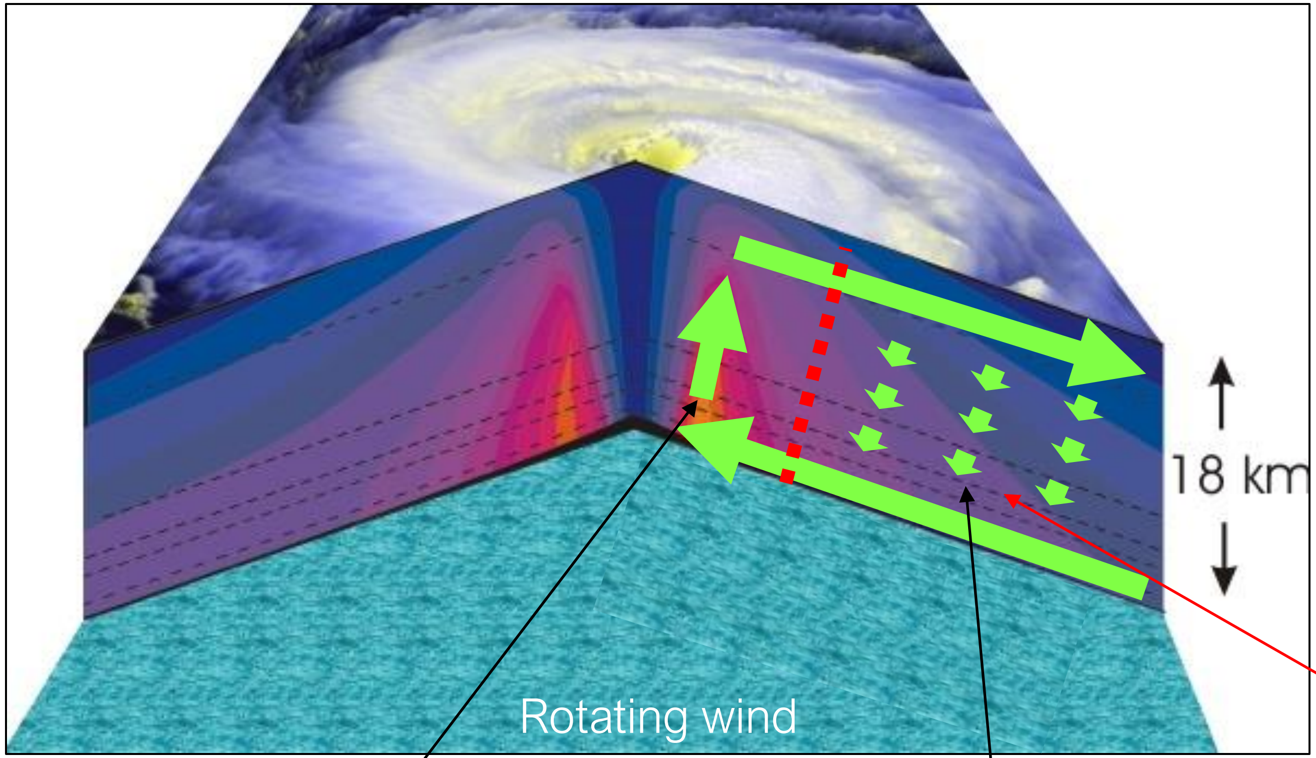
these three should *predict*

Physical model

Three essential components to the wind field

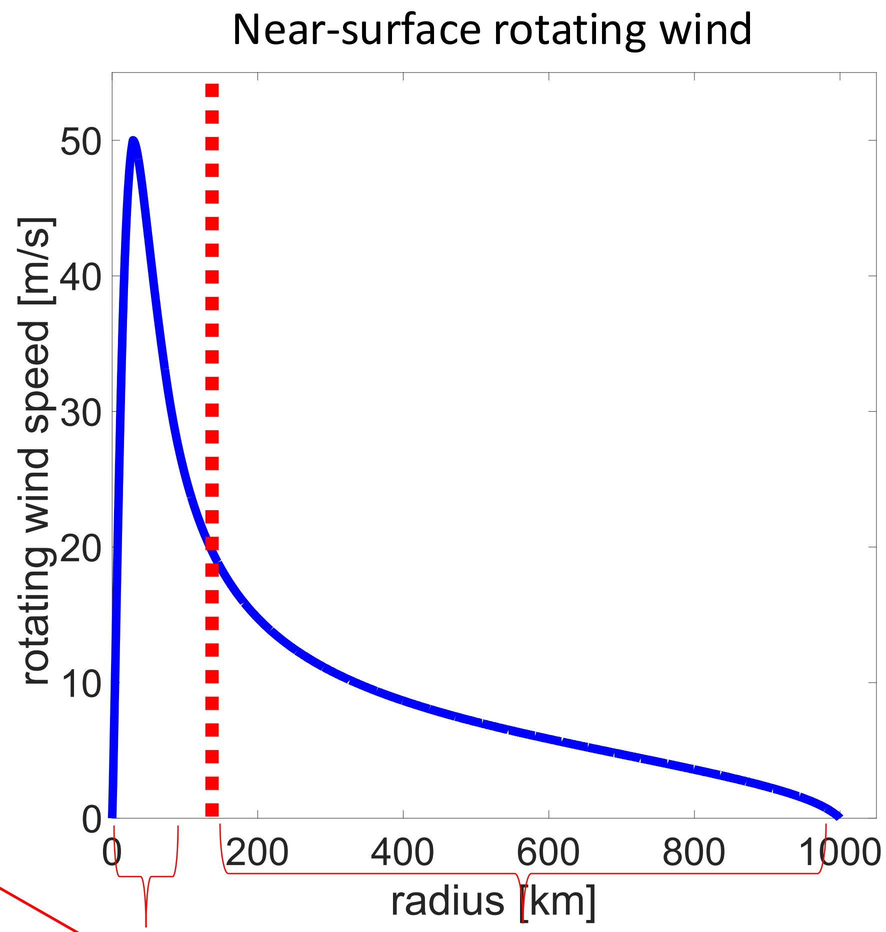


The 3D dynamical/thermodynamic structure are tightly coupled



Inner convecting region

Outer non-convecting region: air subsides very slowly (~2 mm/s) as it cools radiatively



$\zeta \gg 0$
(strongly positive)

$\zeta < 0$
(weakly negative)

Ekman *suction* downwards into the boundary layer

$$\zeta = \frac{1}{r}\frac{\partial(rV)}{\partial r}$$

More info:
Chavas et al. (2015), Chavas and Lin (2016)

The 3D dynamical/thermodynamic structure are tightly coupled

This also follows from **Kelvin's circulation theorem**:

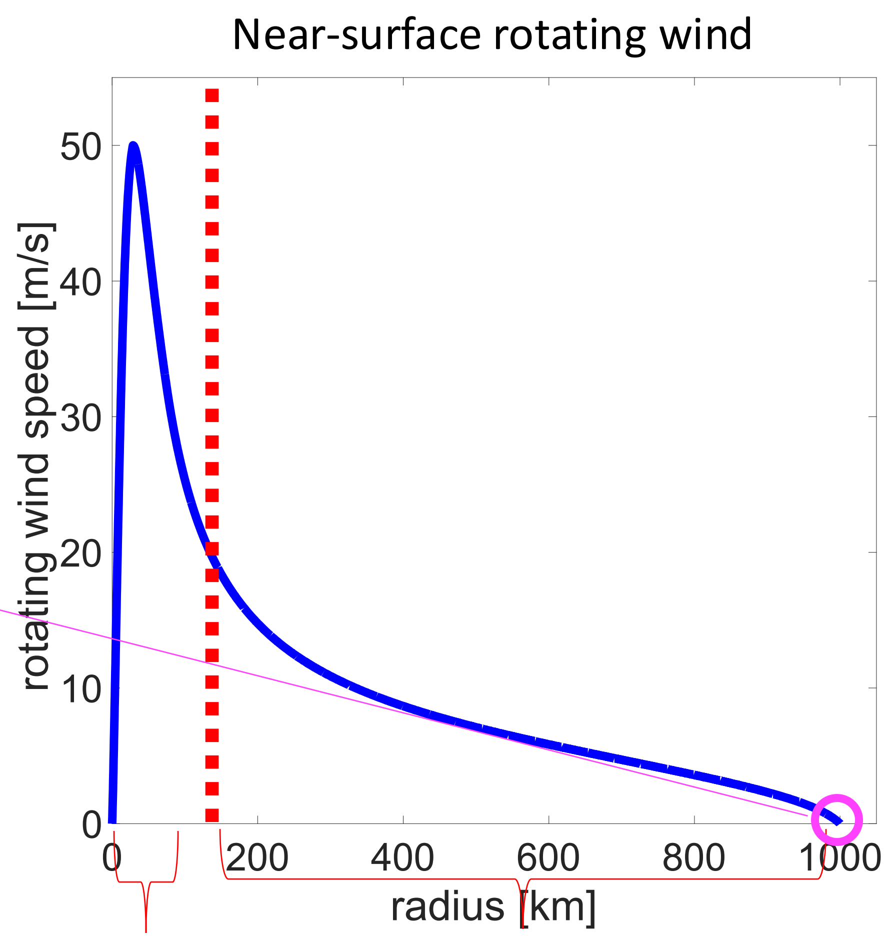
$$\int_0^{r_0} \zeta \, r dr = \oint_{r_0} u \, dl = 0$$

Total vorticity in cyclone ($r \leq r_0$)

Circulation around cyclone boundary ($r = r_0$)

If the inner core has strong positive vorticity, **there must be negative vorticity around it.** (weaker, spread out over much larger area)

Otherwise the cyclone is totally unbounded!

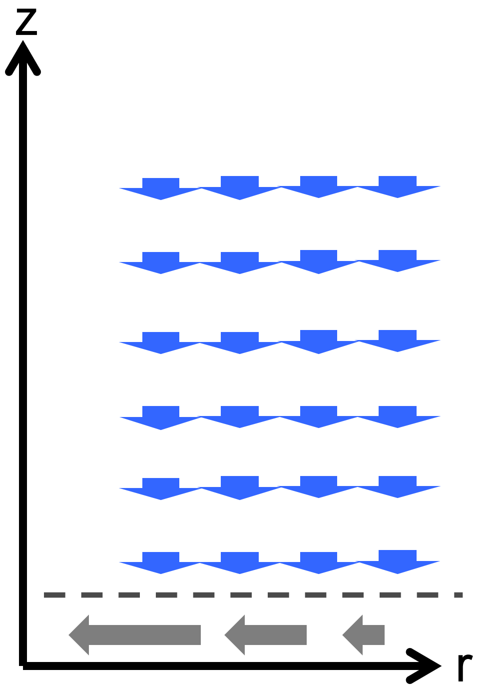


$\zeta \gg 0$ (strongly positive)

$\zeta < 0$ (weakly negative) Ekman *suction* downwards into the boundary layer

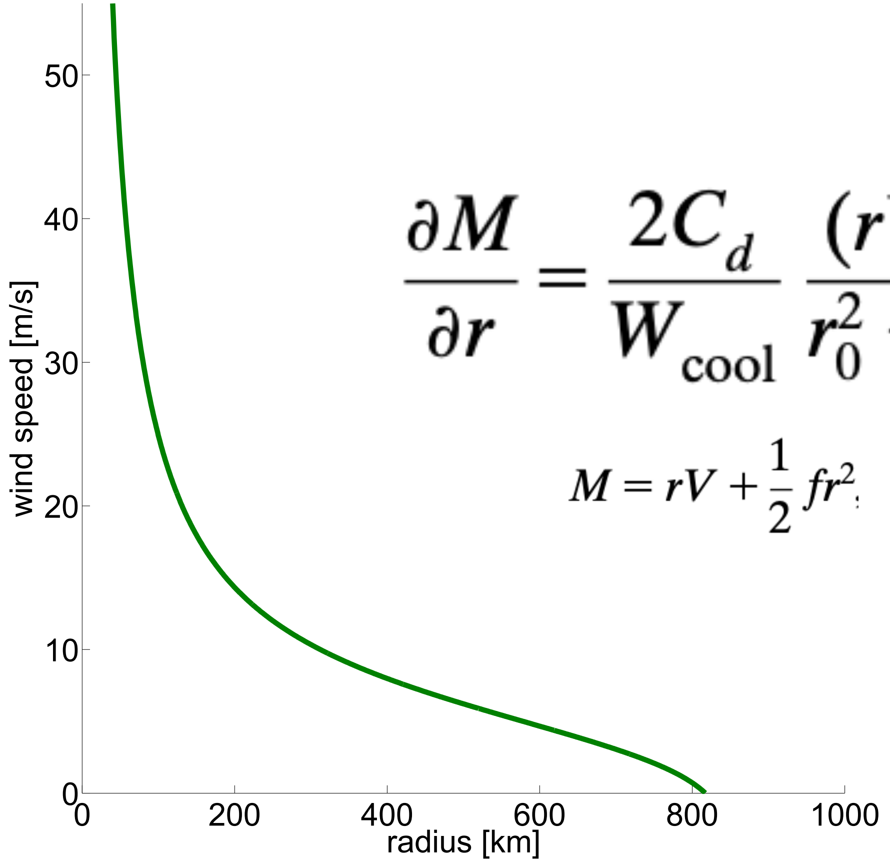
$$\zeta = \frac{1}{r}\frac{\partial (rV)}{\partial r}$$

A model for the outer, non-convecting region



Air subsides due to radiative cooling at subsidence rate $\mathbf{w_{cool}}$

Negative vorticity = Ekman suction into the boundary layer at rate $\mathbf{w_{Ek}}$, which must = $\mathbf{w_{cool}}$



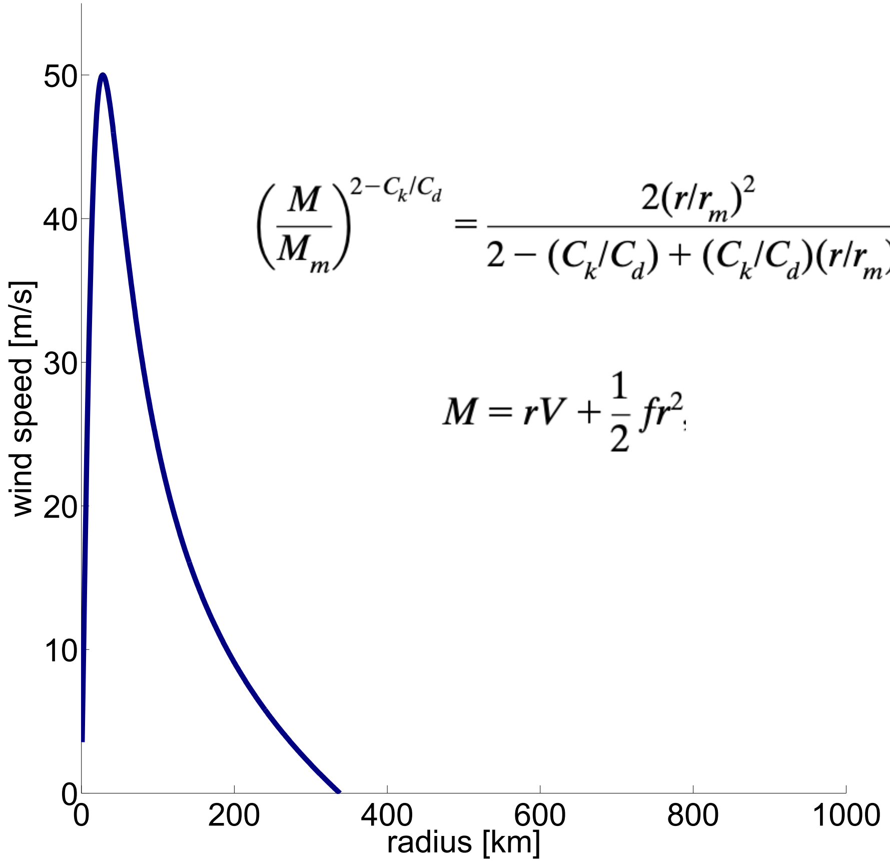
$$\frac{\partial M}{\partial r} = \frac{2C_d}{W_{cool}} \frac{(rV)^2}{r_0^2 - r^2}$$

$$M = rV + \frac{1}{2} fr^2$$

Outer solution: descending
Emanuel (2004)
Physics: radiatively-driven subsidence

Chavas et al. (2015), Chavas and Lin (2016)

A model for the inner, convecting region

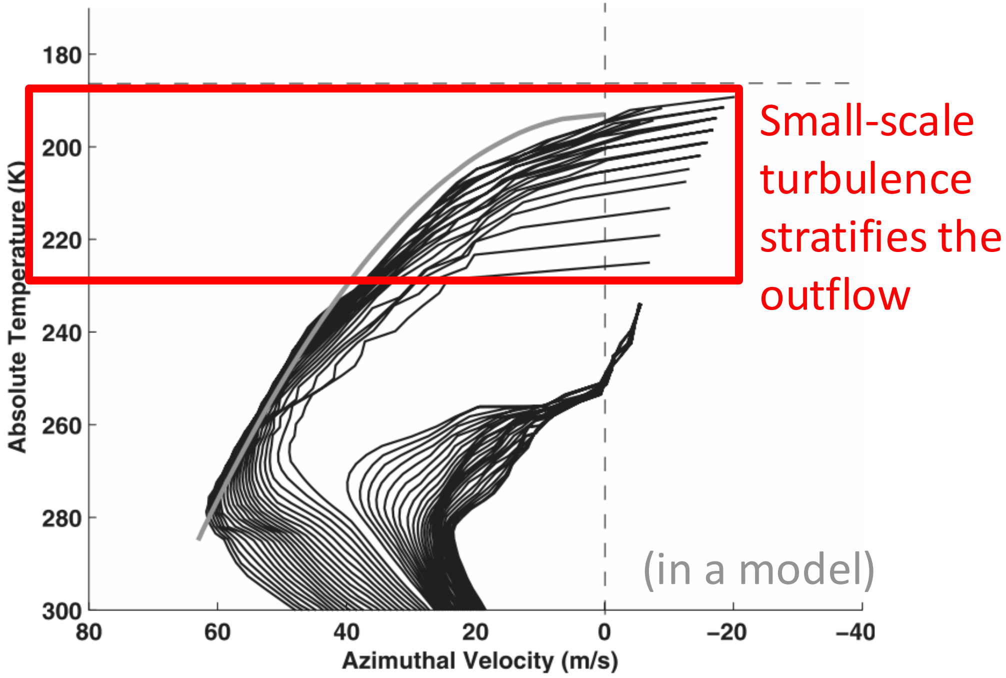


$$\left(\frac{M}{M_m}\right)^{2-C_k/C_d} = \frac{2(r/r_m)^2}{2-(C_k/C_d)+(C_k/C_d)(r/r_m)^2}$$

$$M = rV + \frac{1}{2} fr^2$$

Inner solution: ascending
Emanuel and Rotunno (2011)
Physics: turbulence in outflow

$$V_p = \sqrt{\frac{T_s - T_0}{T_0}\frac{C_k}{C_d}\Delta k}$$



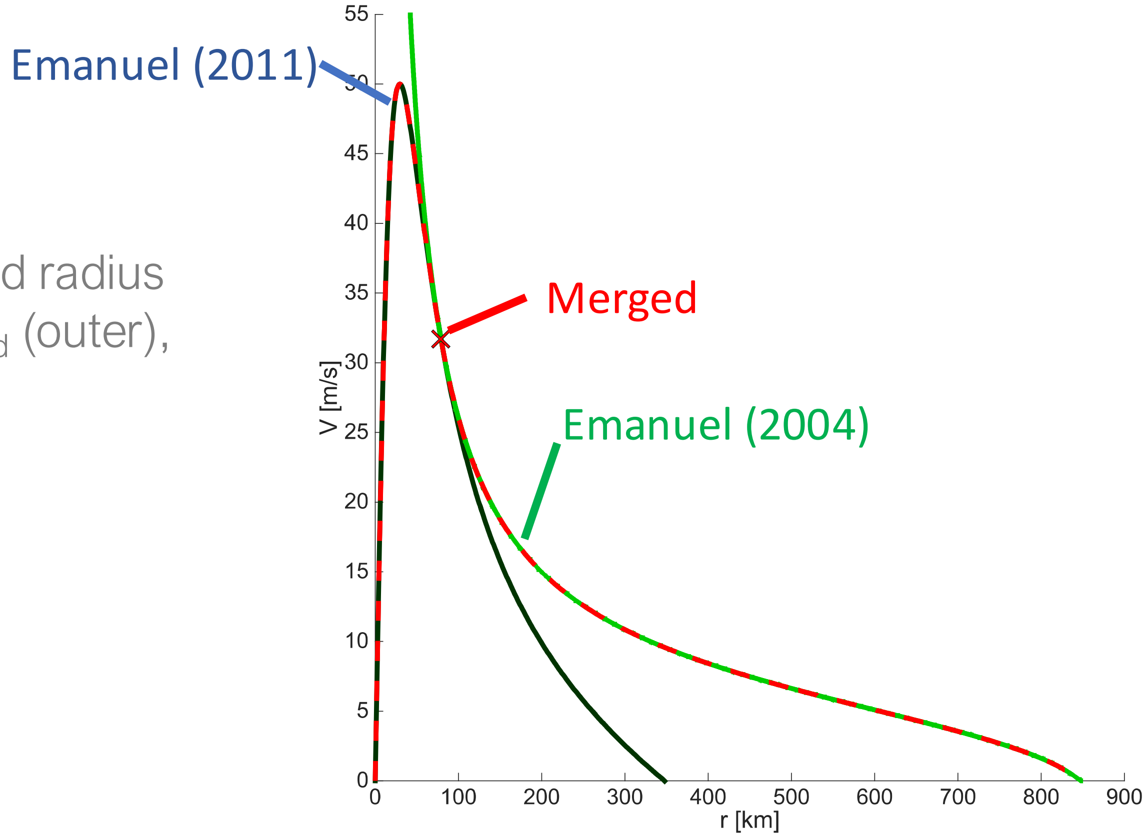
→ Wind speed varies with radius because of warmer outflow temp

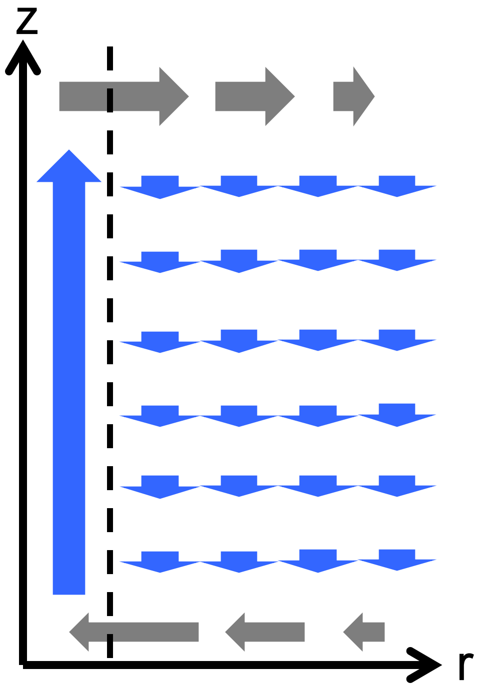
A model for the complete structure

Chavas et al. (2015), Chavas and Lin (2016)

Parameters:
Storm: V_{max}, f, any wind radius
Environment: w_{cool} / C_d (outer), C_k / C_d (inner)

No arbitrary empirical parameters.

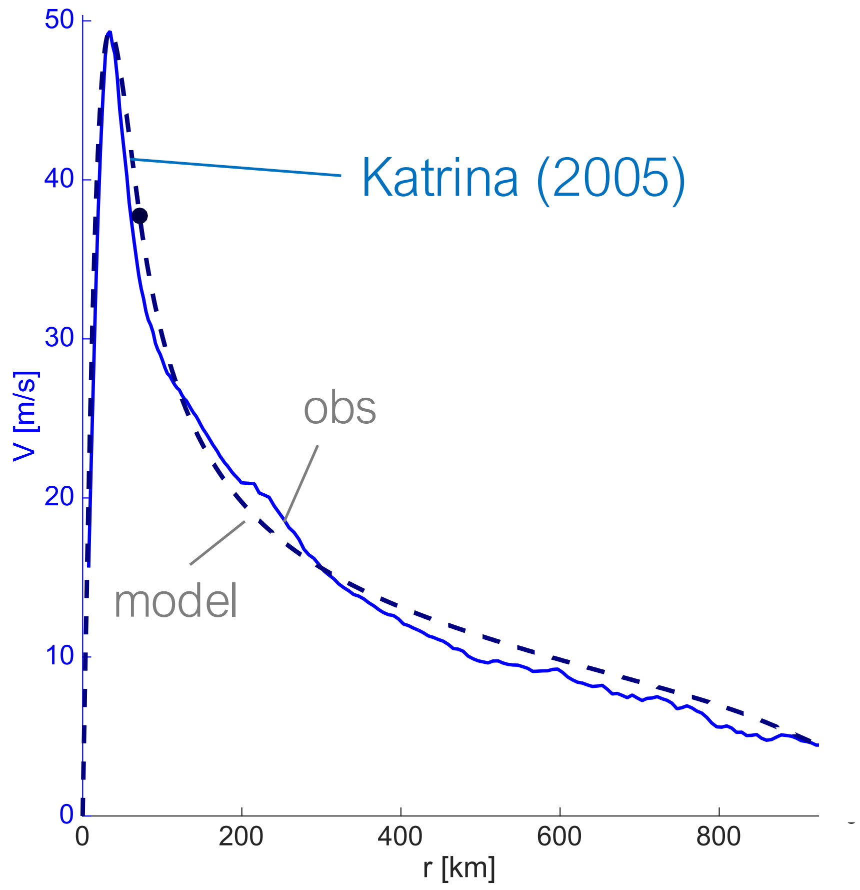




The simplest model for the complete storm structure + overturning circulation

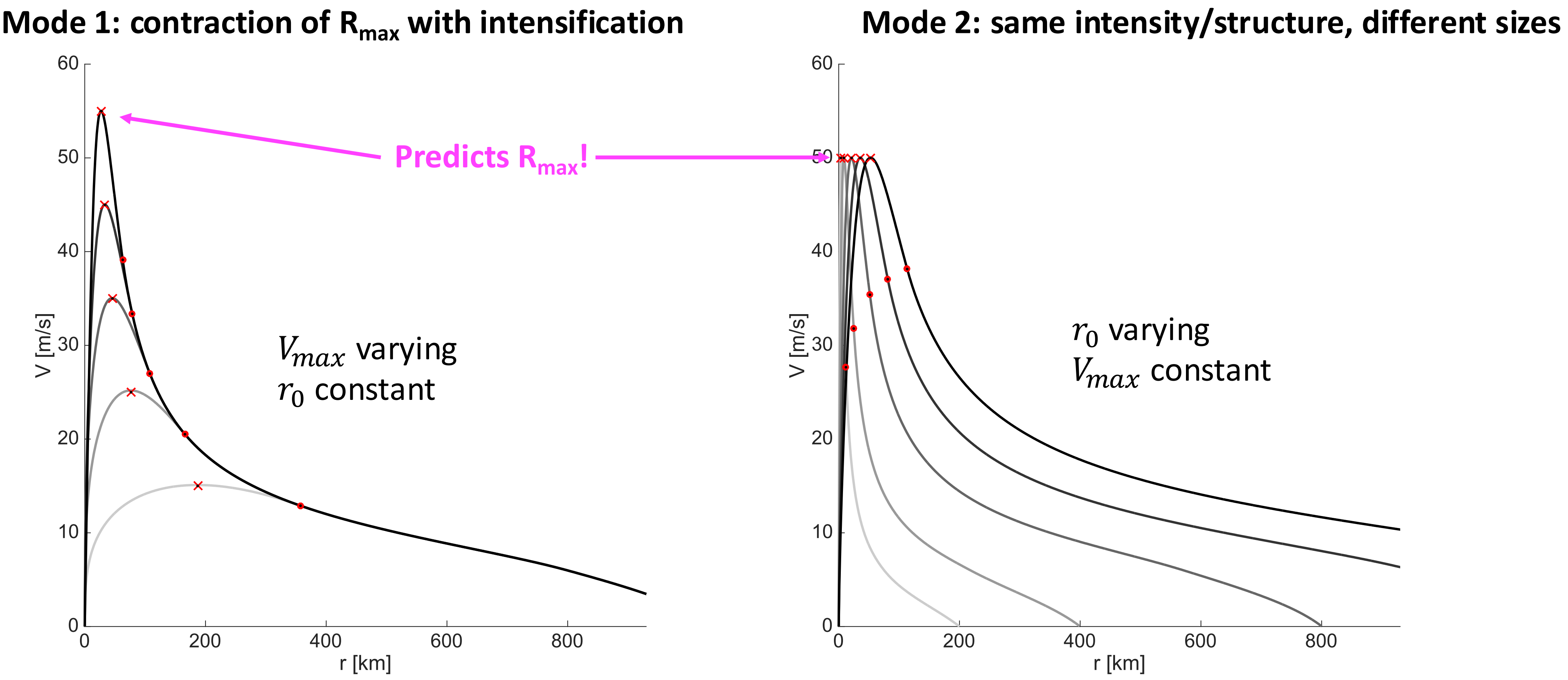
The model captures observed wind field structure well

Chavas et al. (2015), Chavas and Lin (2016)



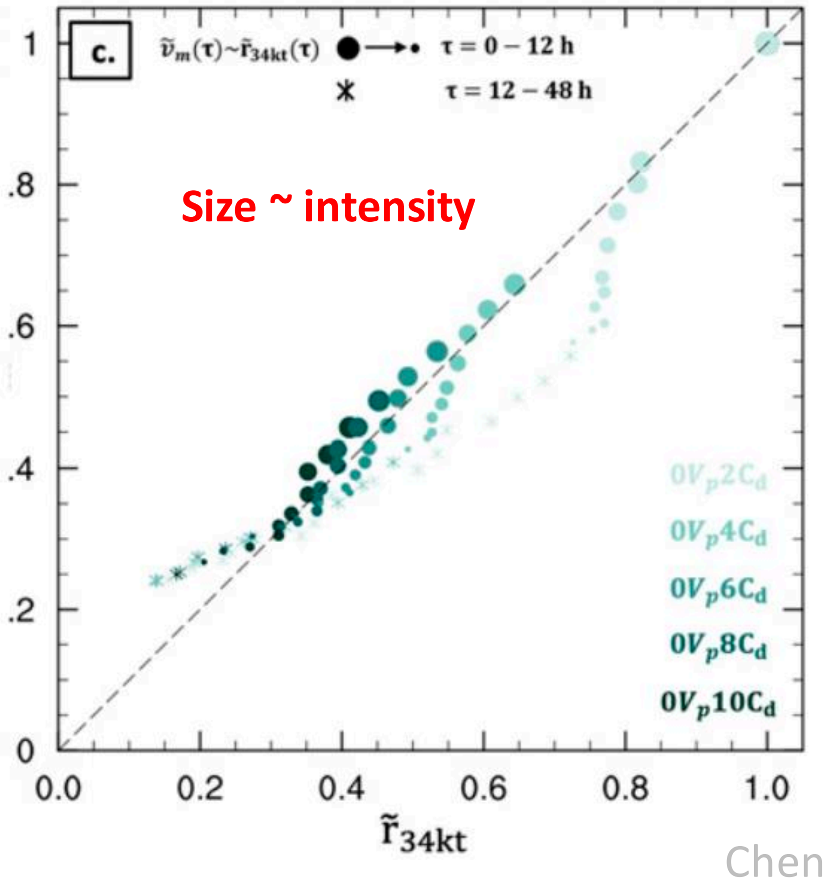
The model compares observed wind field variability, too

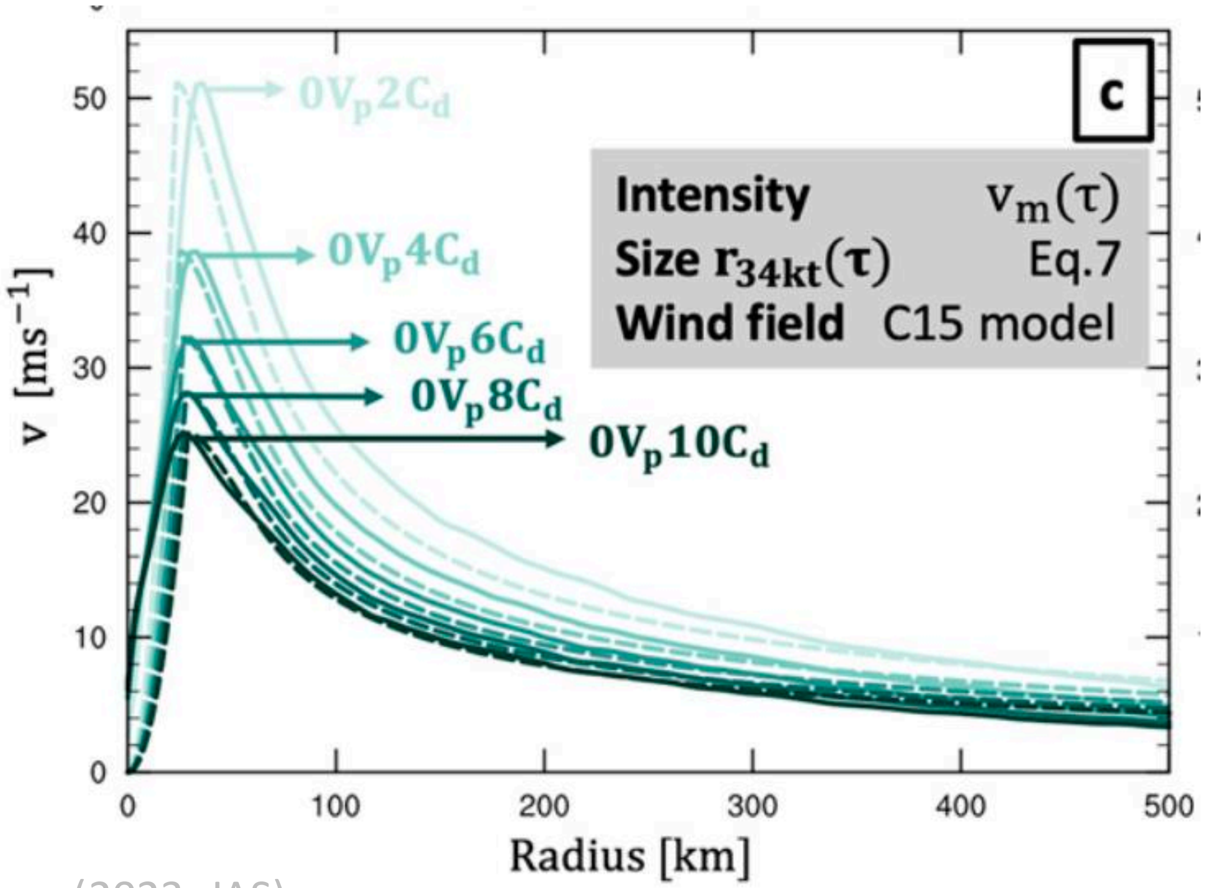
Chavas et al. (2015), Chavas and Lin (2016)



The model can work over land too – though real landfall is fundamentally asymmetric

Simple landfall simulations: surface is instantly roughened+dried beneath a tropical cyclone.



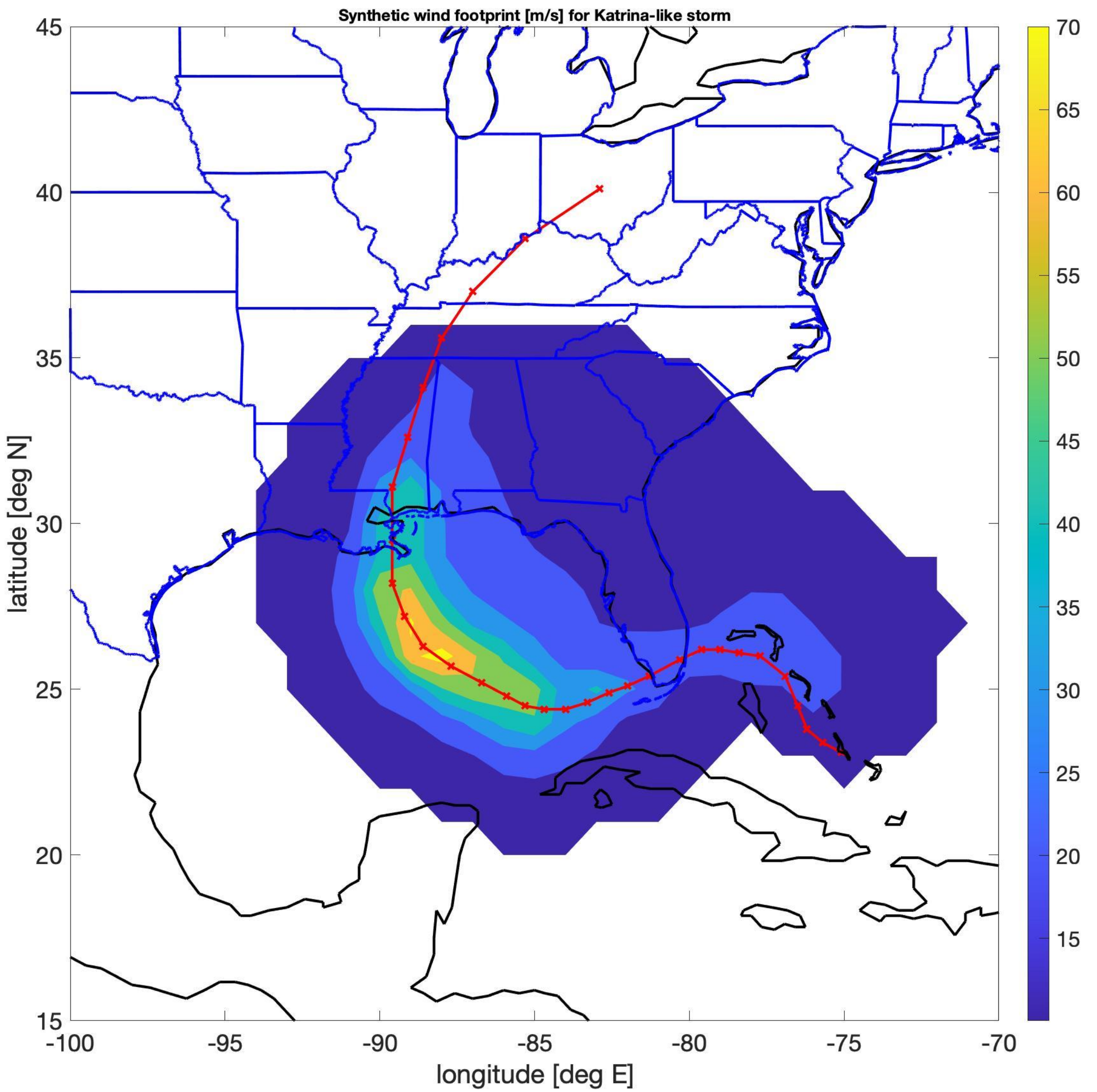


Chen and Chavas (2023, JAS)

Closest analog: a storm moving rapidly from ocean to land

Real landfalls are much more complex: fundamentally asymmetric process

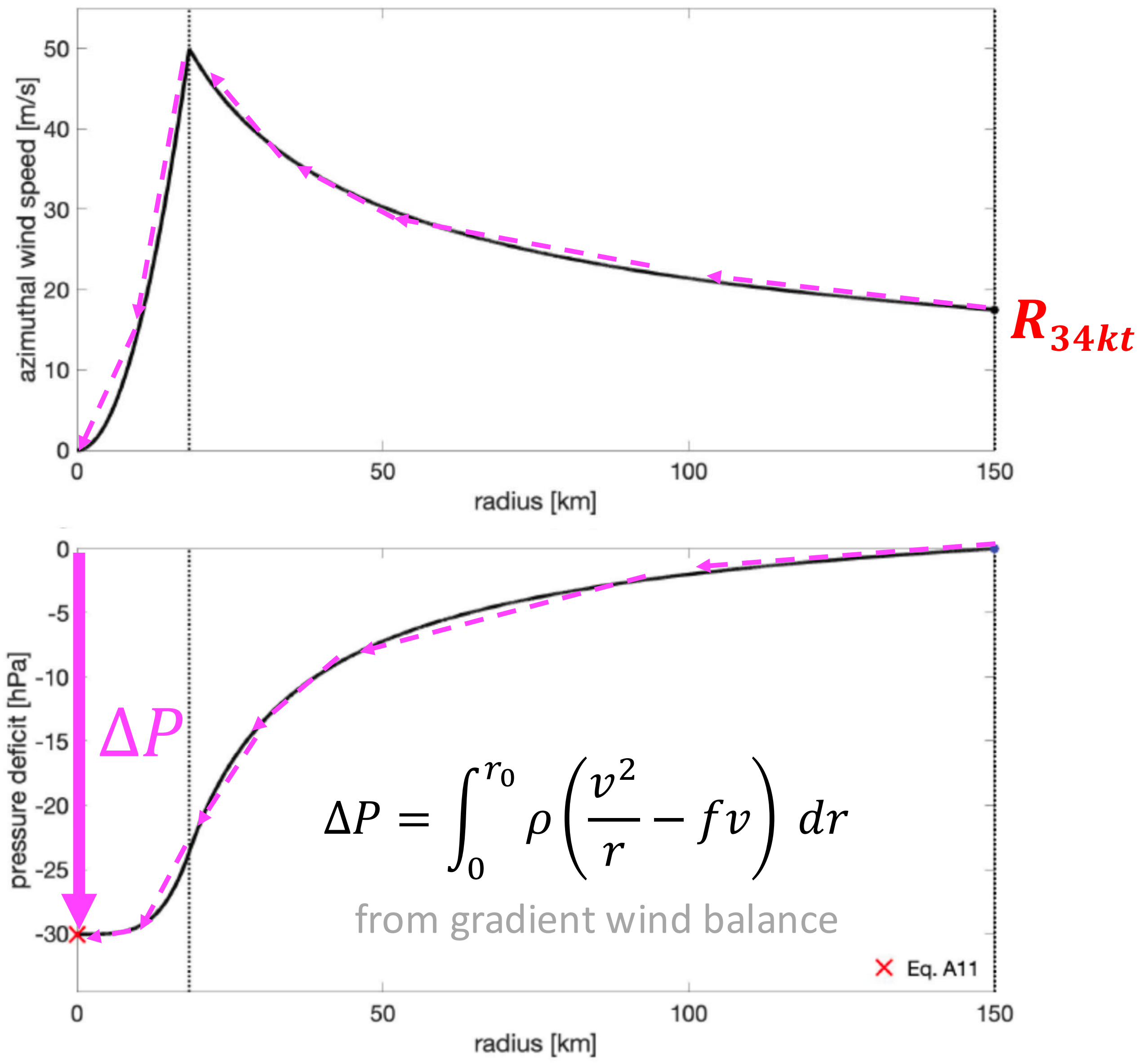
Putting pieces together: a physics-based wind footprint



Example: track of Katrina (2005)

Pressure, too

If we know the wind field, we can predict the minimum pressure at the center



$$\Delta P = \int_0^{r_0} \rho \left(\frac{v^2}{r} - f v \right) \, dr$$

from gradient wind balance

The central pressure (deficit) is an integrated measure of the wind field!

Pressure deficit is larger for:

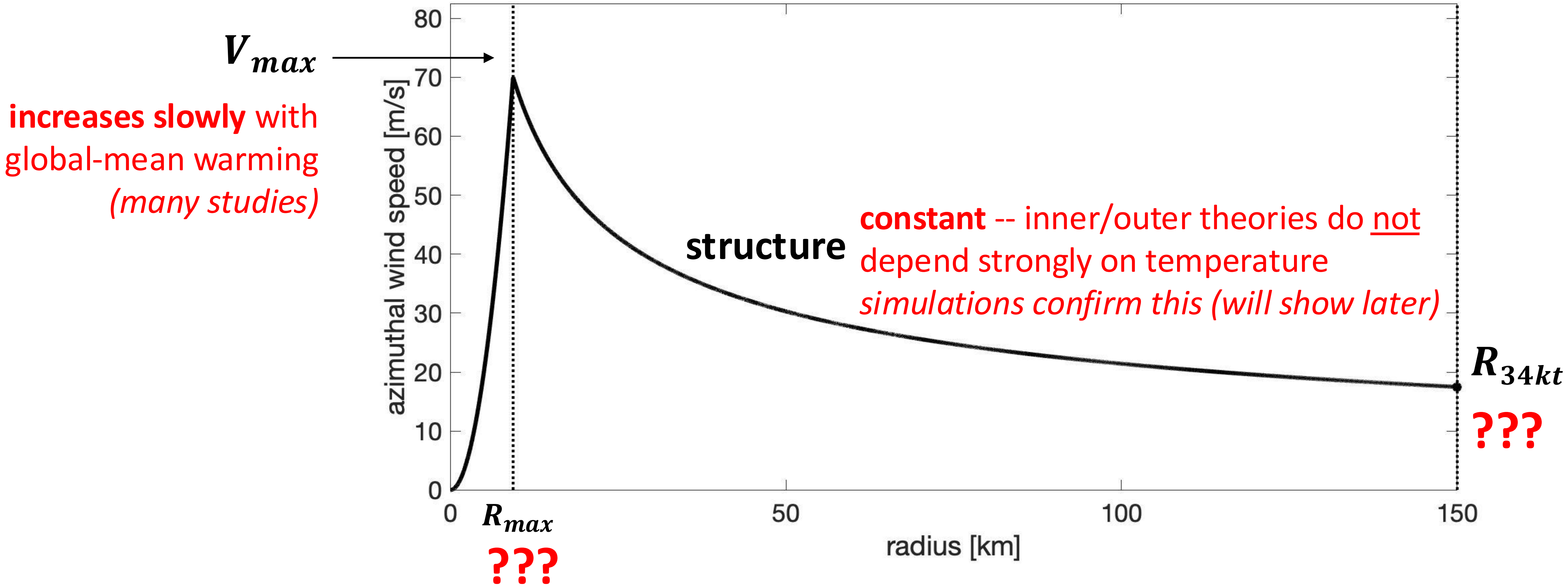
1. **Higher intensity V_{max},**
2. **Larger storm (e.g. R_{34kt})**
3. Higher latitude (larger f)

Knaff and Zehr (2007), Chavas et al. (2017)

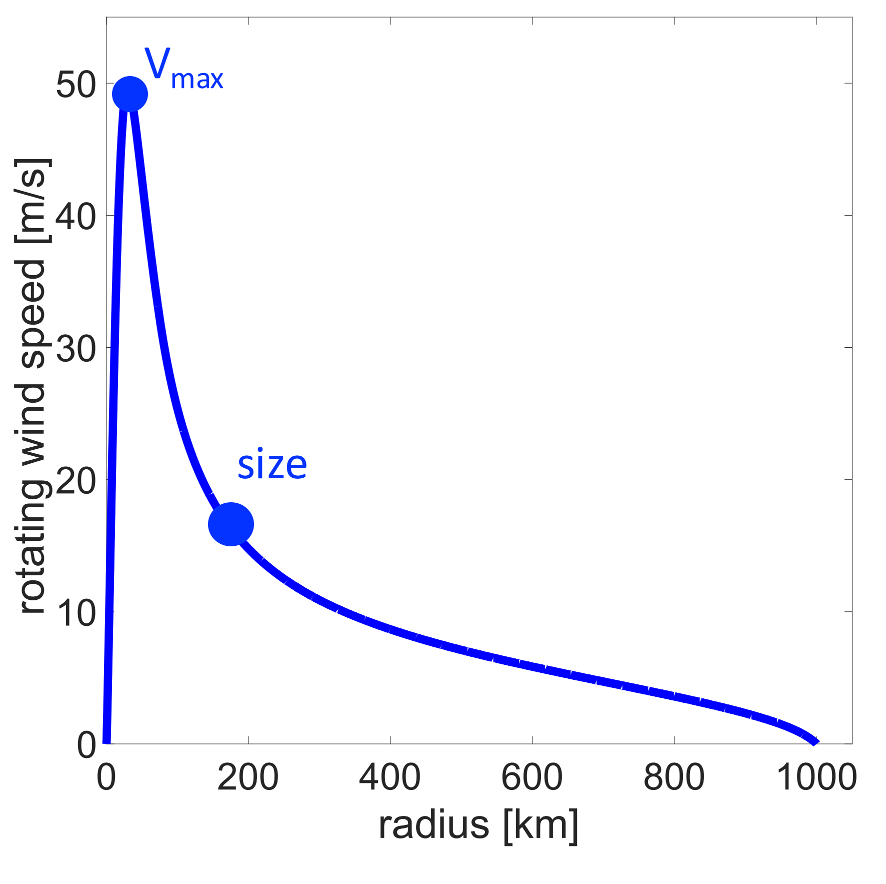
We'll come back to P_{min} later on...

Response to warming

Structure is the first step



A good, fast, physics-based model for the tropical cyclone wind field structure



What about outer size (e.g. R_{34kt})?

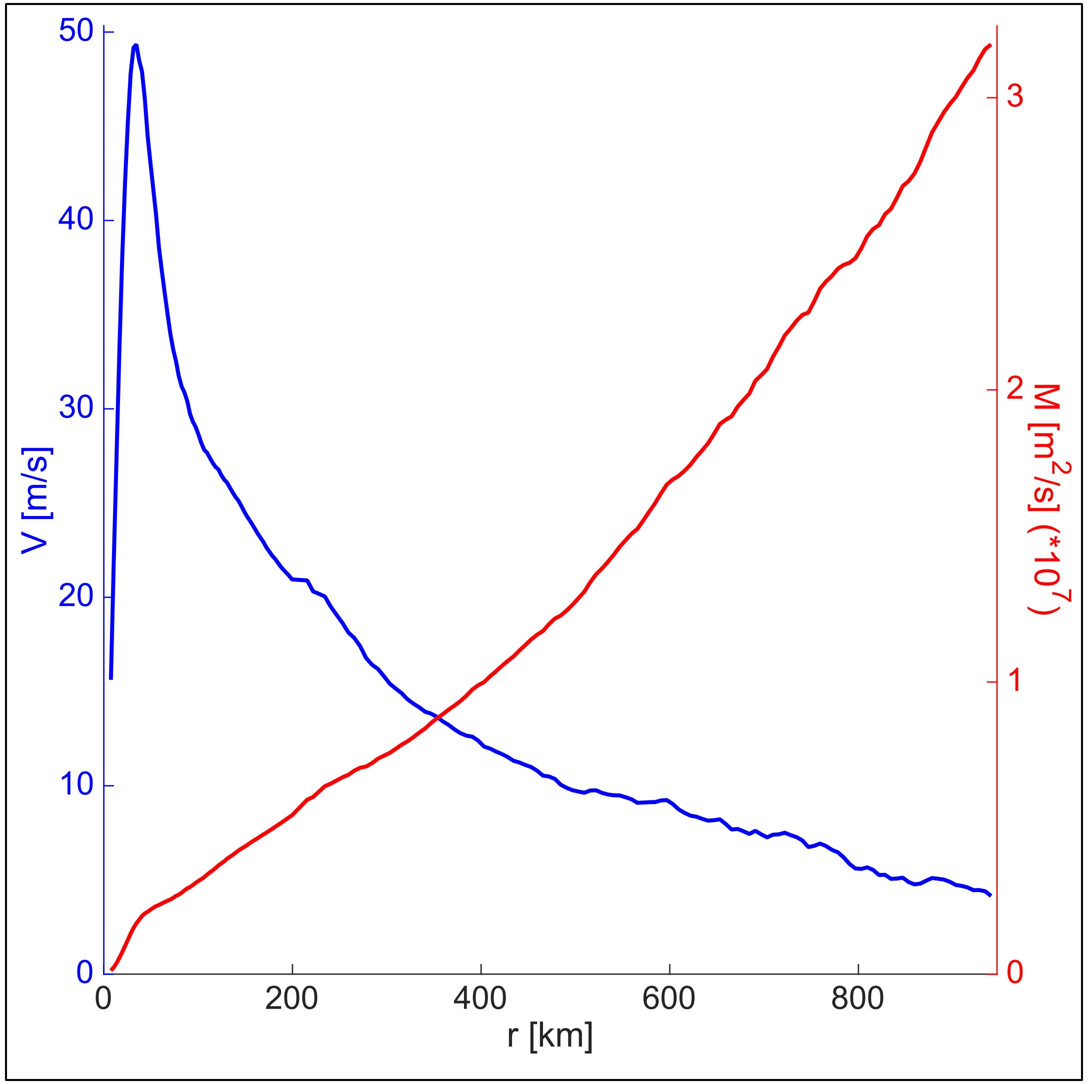
This is the missing piece to understand + model the entire wind and pressure fields

Break for questions!

Absolute angular momentum

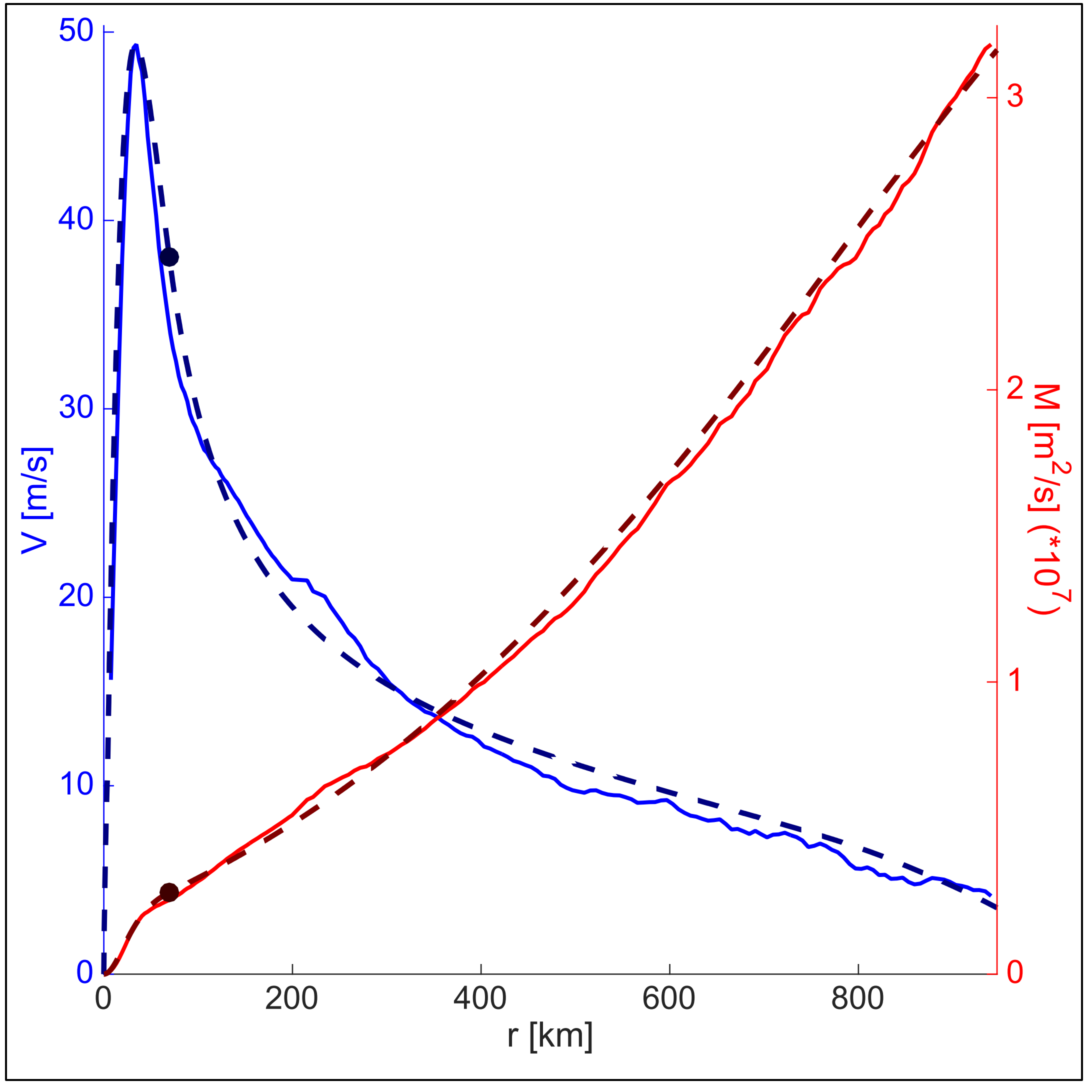
$$M = rv + \tfrac{1}{2} f r^2$$

M_{TC} M_{Earth}



A complete model for absolute angular momentum

Inputs: V_{max}, r_{max}, f
w_{cool} = 2 mm/s
C_k/C_d = 1

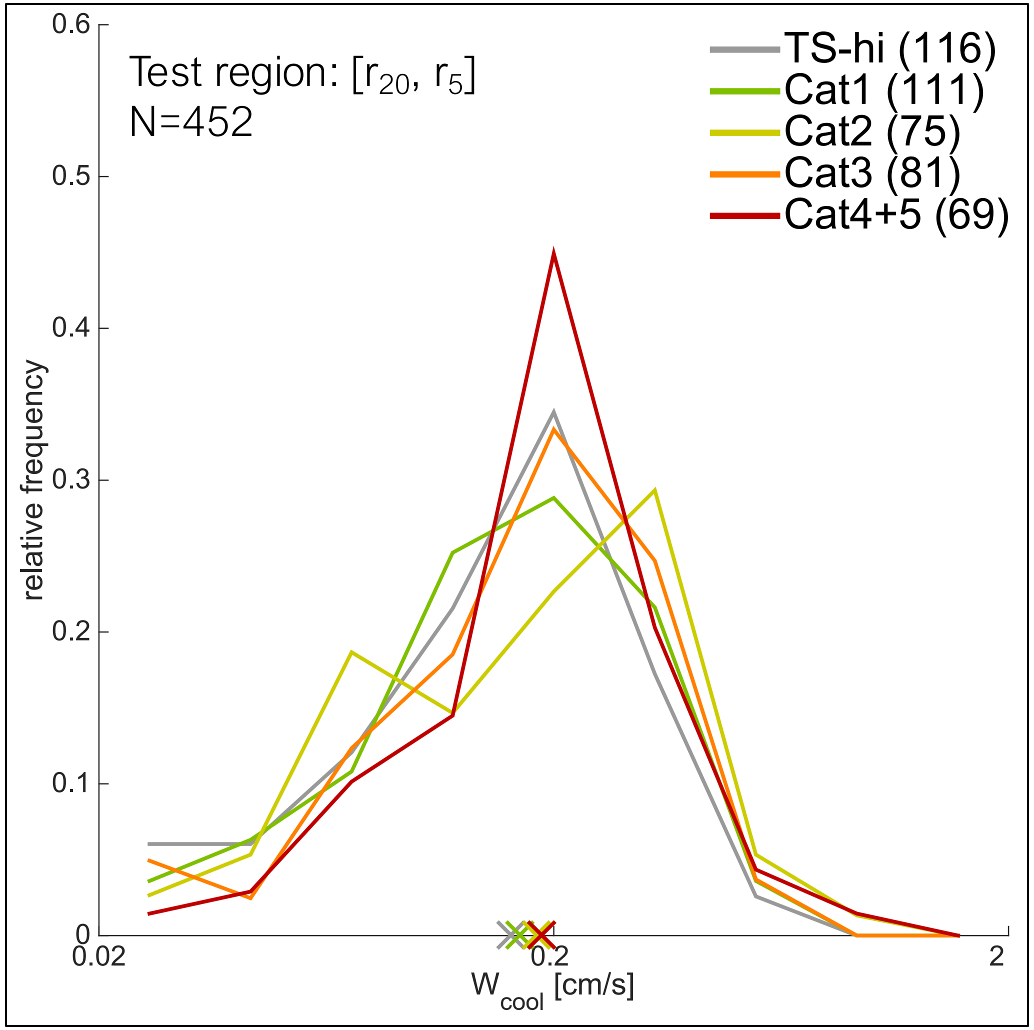


Chavas et al. (2015)

Outer model: estimating w_{cool} (QuikSCAT)

Median $w_{cool} \approx 2$ mm/s
Invariant with intensity

Matches prediction for a moist adiabat with:
302 K SST
80% surface RH
1 K/day radiative cooling

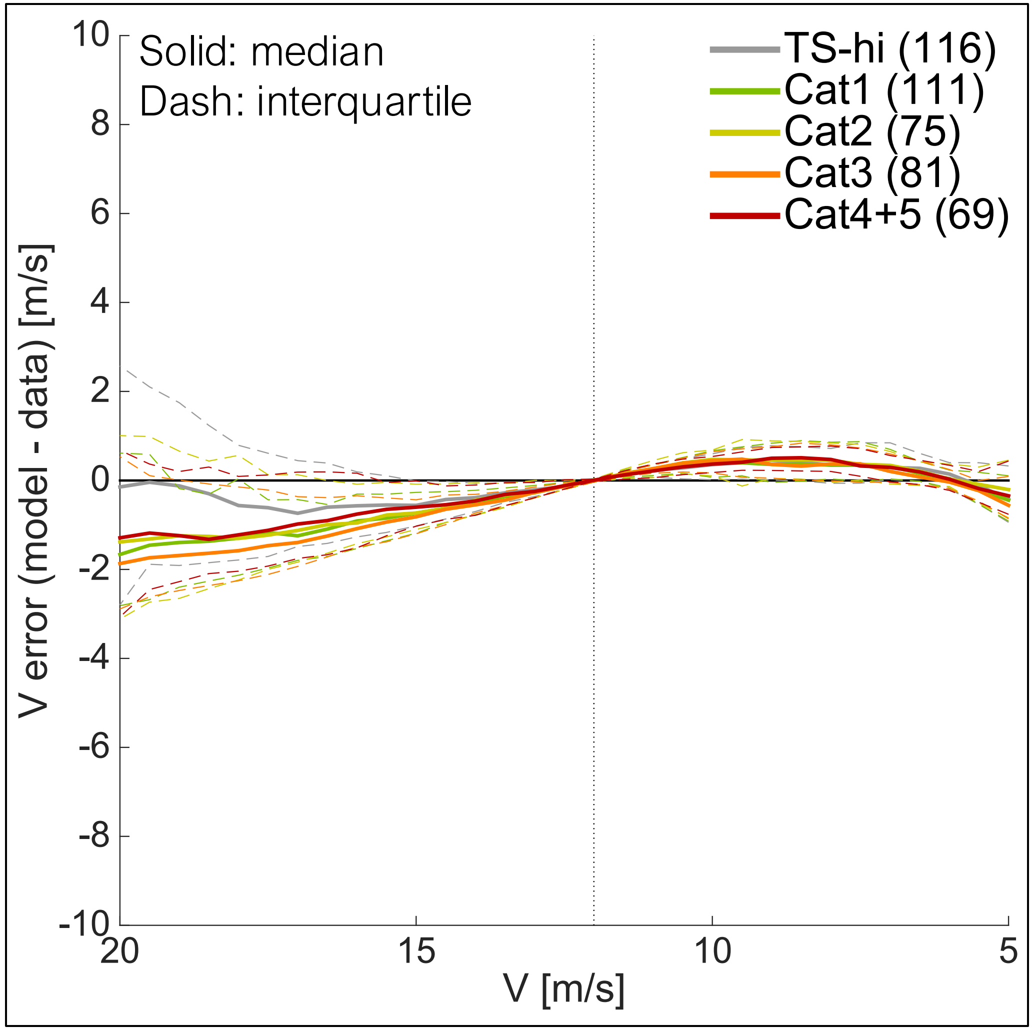


Chavas et al. (2015), *in review*

Outer model: estimating w_{cool} (QuikSCAT)

Best-fit w_{cool}

Median width of annulus is ~600 km, invariant with intensity



Chavas et al. (2015

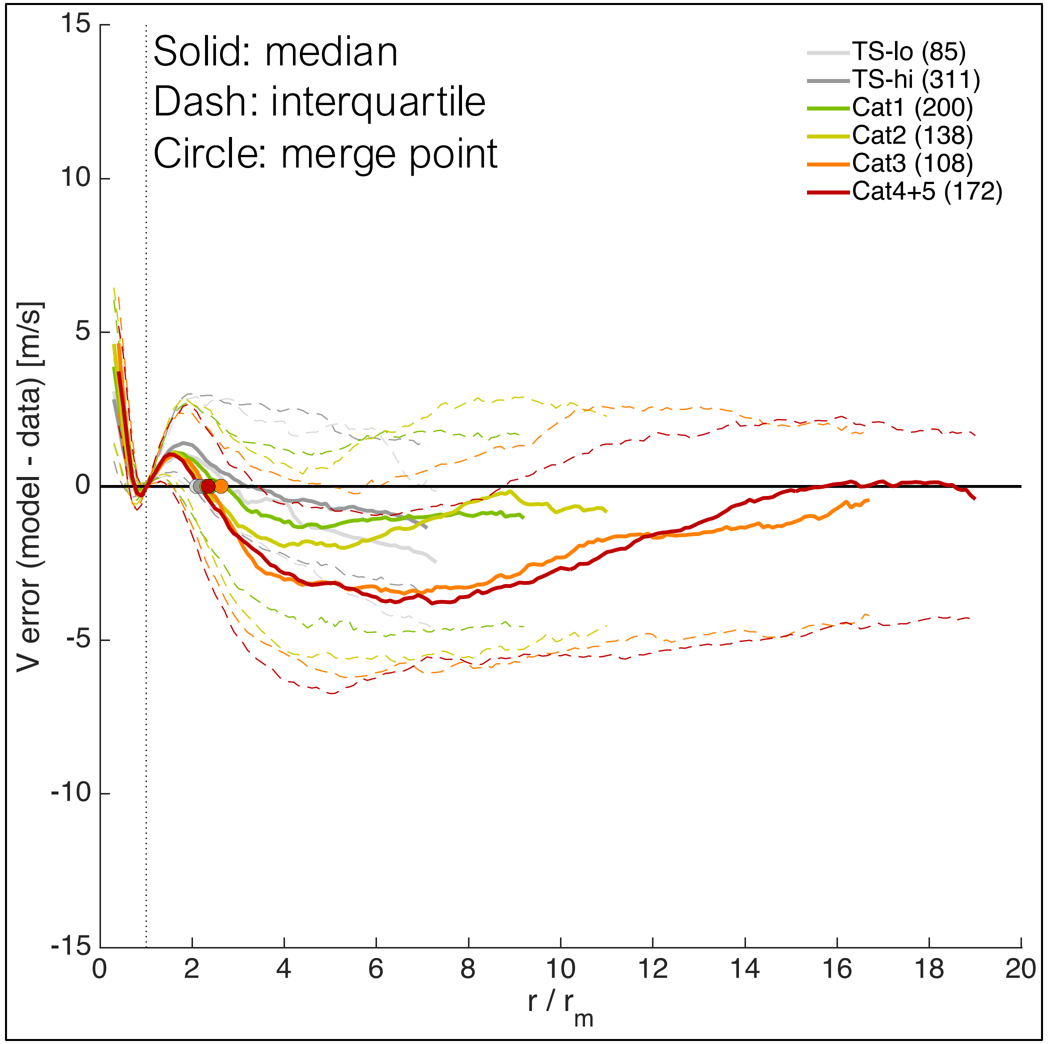
Complete model performs well

Inputs: V_{max}, r_{max}, f
w_{cool} = 2 mm/s
$C_k/C_d = F(V_{max})$ [0.5-1]

Model error vs. HWind

- Residual underestimation at intermediate radii
- Works fairly well even at low intensities, surprisingly

Note: C_k/C_d not well constrained, though correct order of magnitude



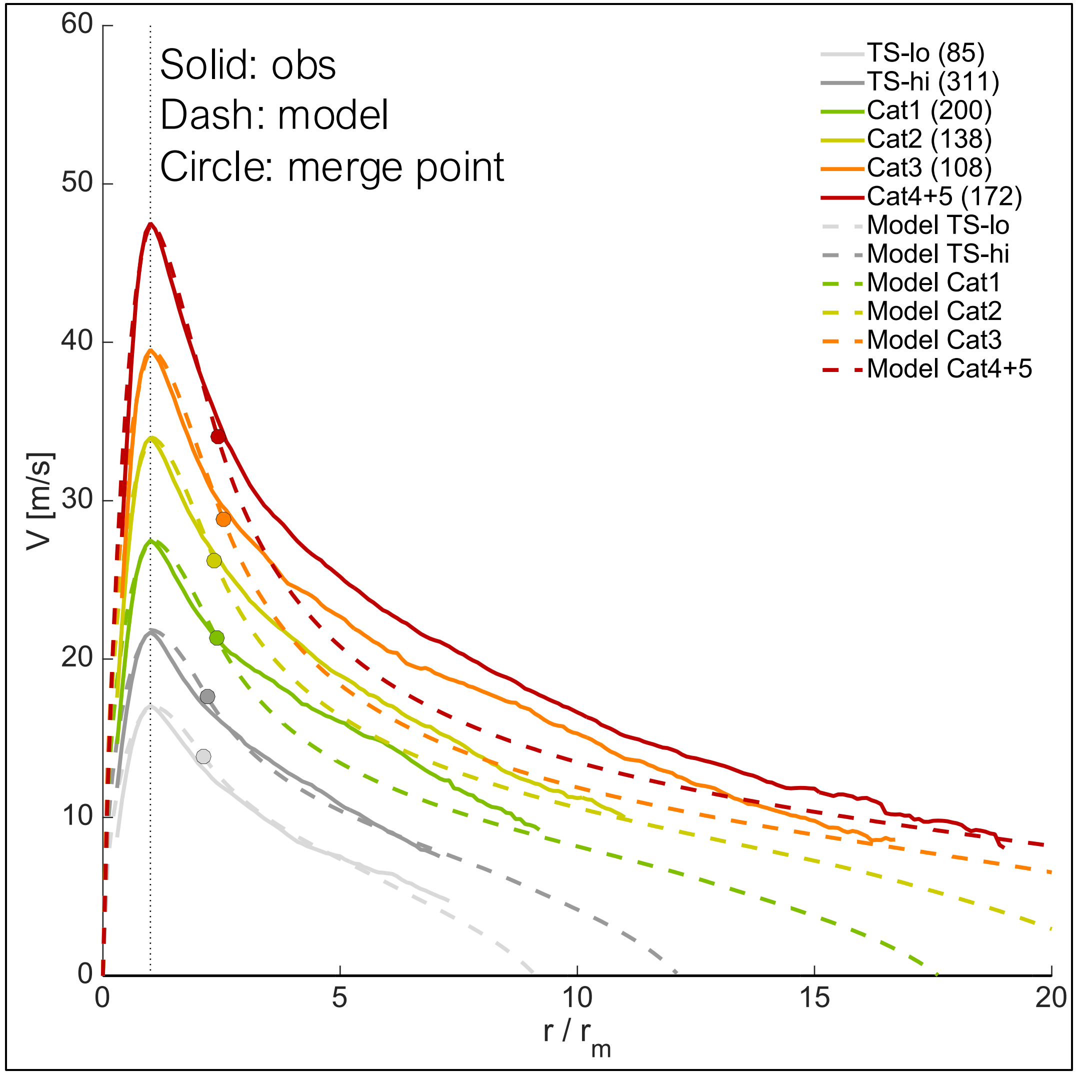
Chavas et al. (2015)

Complete model performs well

Inputs: V_{max}, r_{max}, f
w_{cool} = 2 mm/s
$C_k/C_d = F(V_{max})$ [0.5-1]

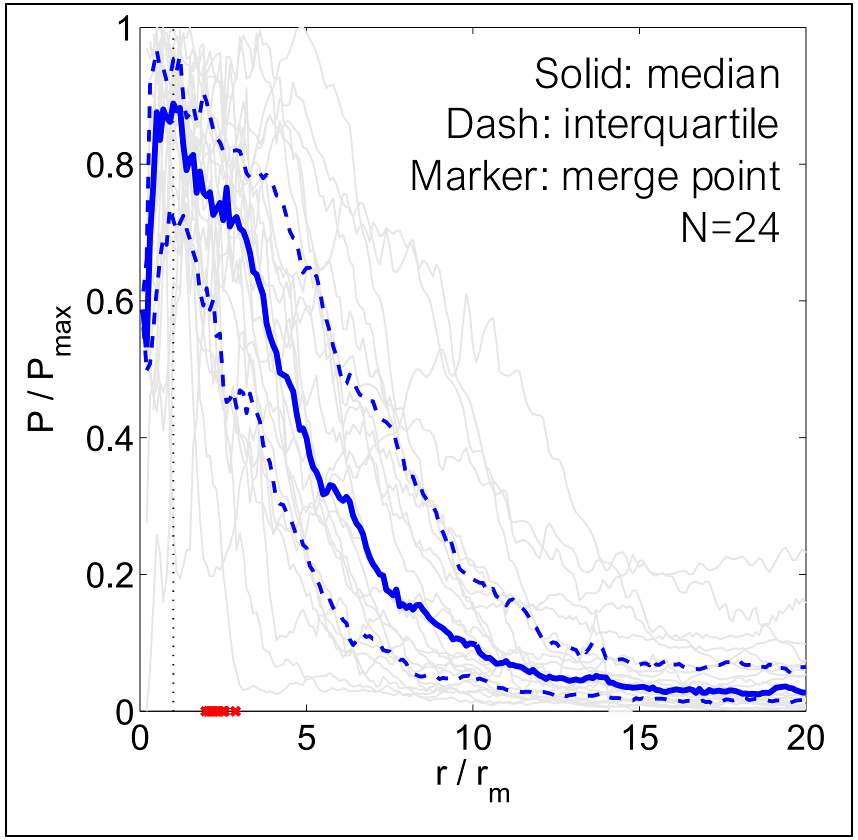
Model vs. HWind (median)

- Residual underestimation at intermediate radii
- Works fairly well even at low intensities, surprisingly



Chavas et al. (2015)

Model low bias: the role of intermittent convection?



Chavas et al. (2015)

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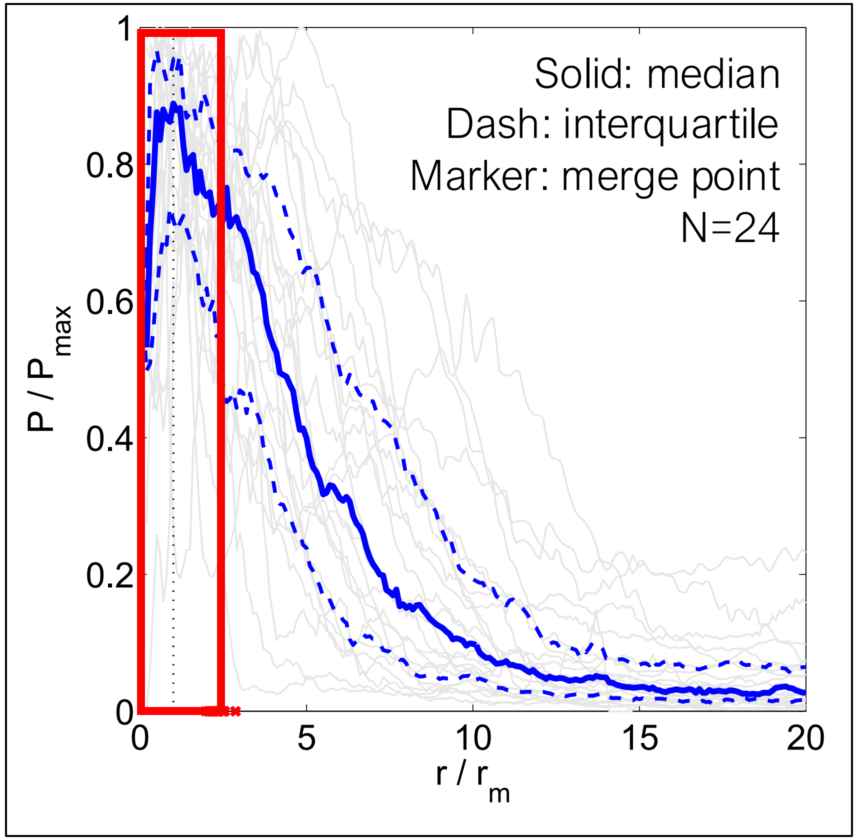
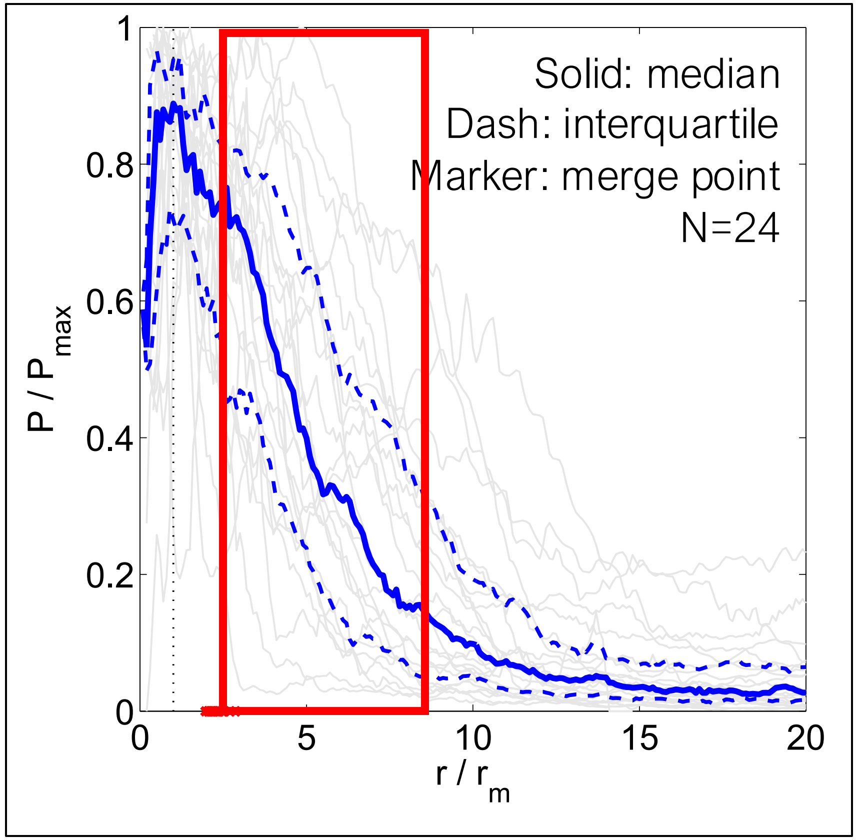


Strong convection inside of merge point

Chavas et al. (2015)

Model low bias: the role of intermittent convection?



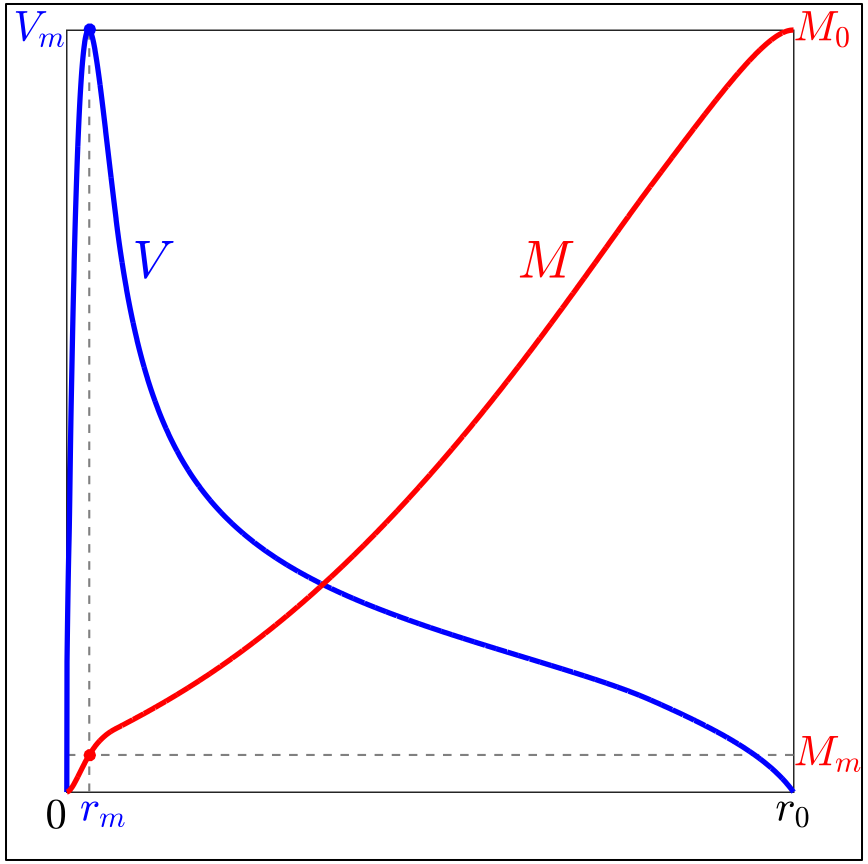
Intermittent convection beyond merge point
This effect can enhance radial import of M (e.g. Xu and Wang 2010)

Chavas et al. (2015)

Summary: complete structure model

A physical model for the complete radial structure of the wind field

- Merges existing inner ascending and outer descending region solutions
- Nature may not be too far off!
- Residual underestimation at intermediate radii (spiral bands?)



Chavas et al. (2015), *in review*