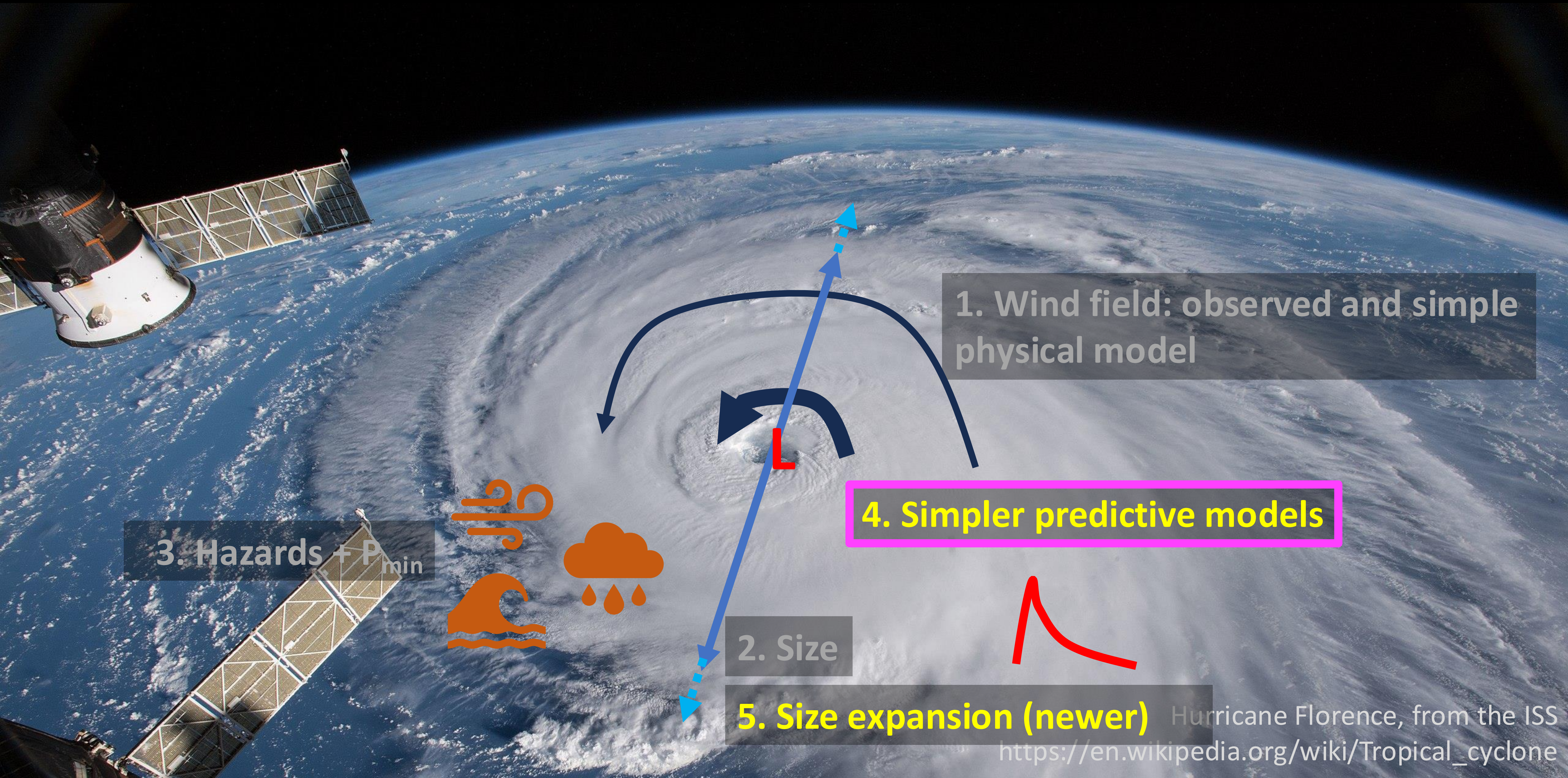
Roadmap

0. Intro: two recent events



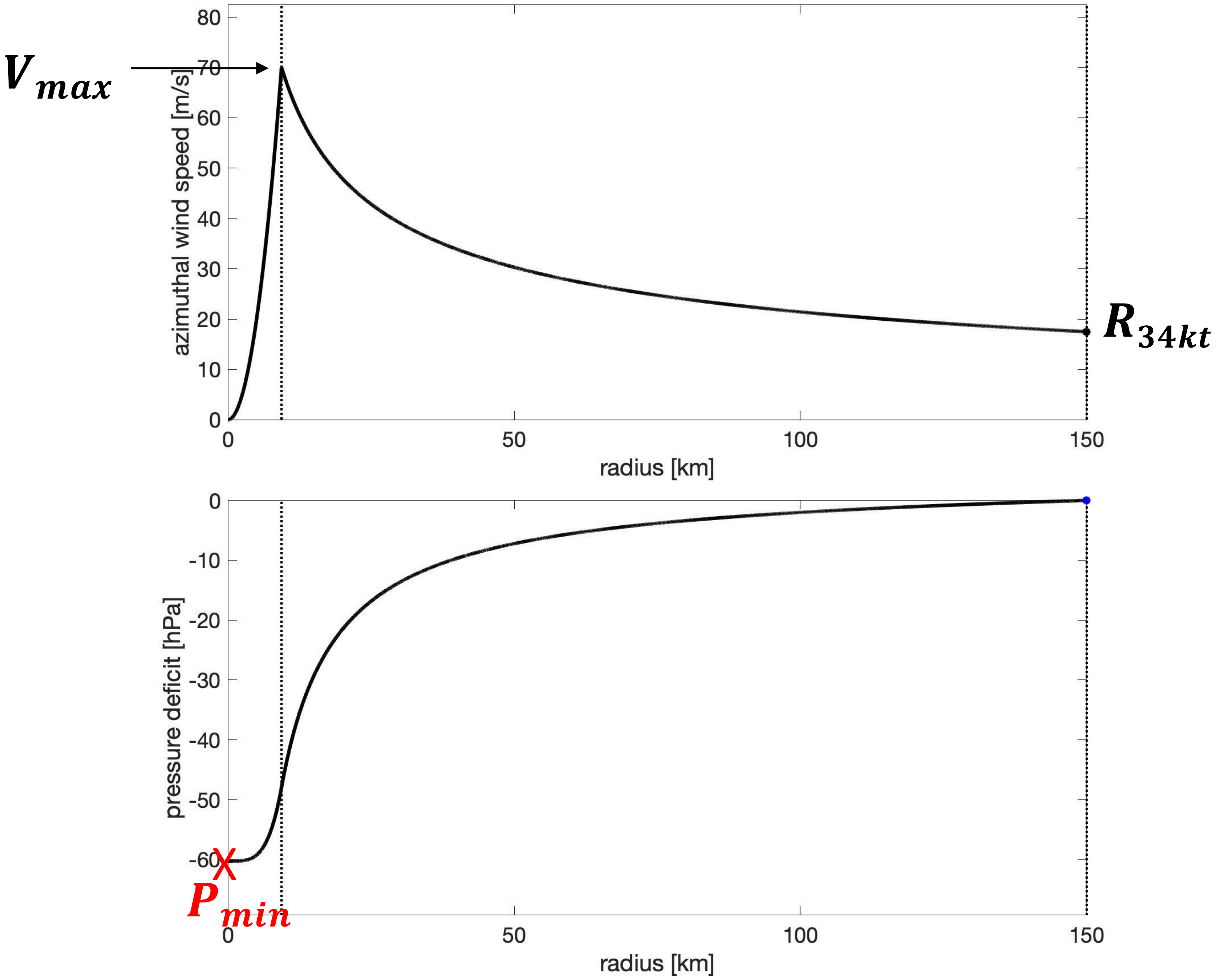
4. Simpler predictive models

- P_{min}
- R_{max}
- New analytic wind model

Marry physics + observations

Theory alone is too rigid!

P_{min}



V max
R 34kt
P min
azimuthal wind speed [m/s]
radius [km]
pressure deficit [hPa]
radius [km]

A Simple Model for Predicting Tropical Cyclone Minimum Central Pressure from Intensity and Size

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(Manuscript received 21 February 2024, in final form 22 July 2024, accepted 15 August 2024)

Known (Dvorak 1975, Knaff and Zehr 2007, Chavas Knaff Reed 2017):
P_{min} is lower for higher V_{max}, larger R_{34kt}, higher latitude

We need an easy-to-use equation to predict P_{min}
from routinely-estimated (+ Best Tracked) data!

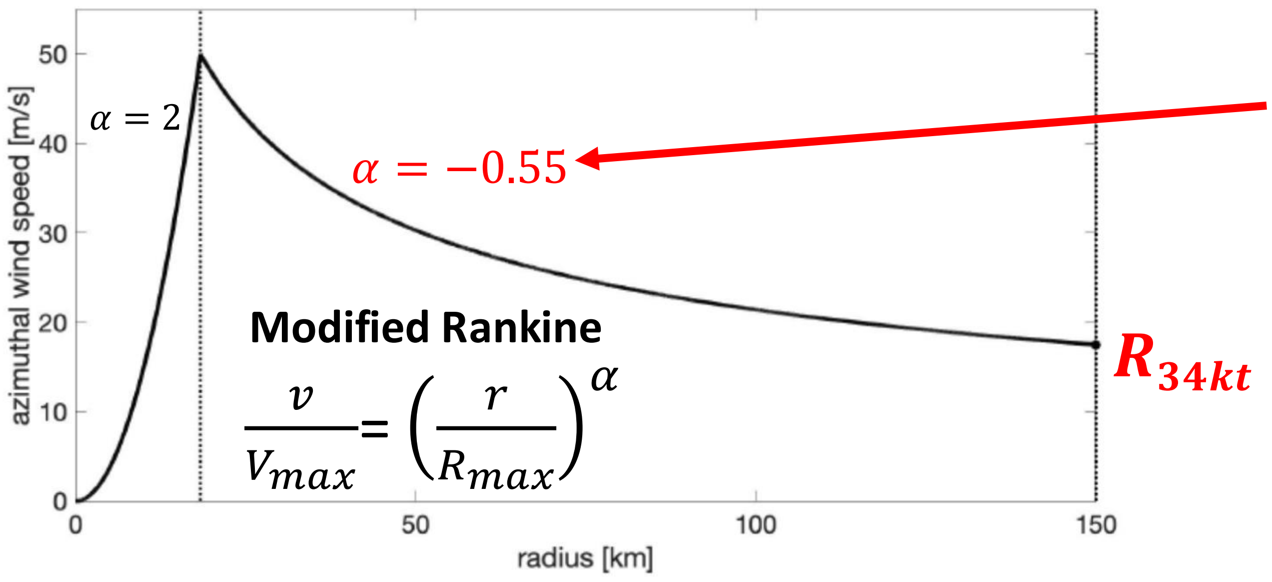
$$\Delta P = P_{env} - P_{min}$$

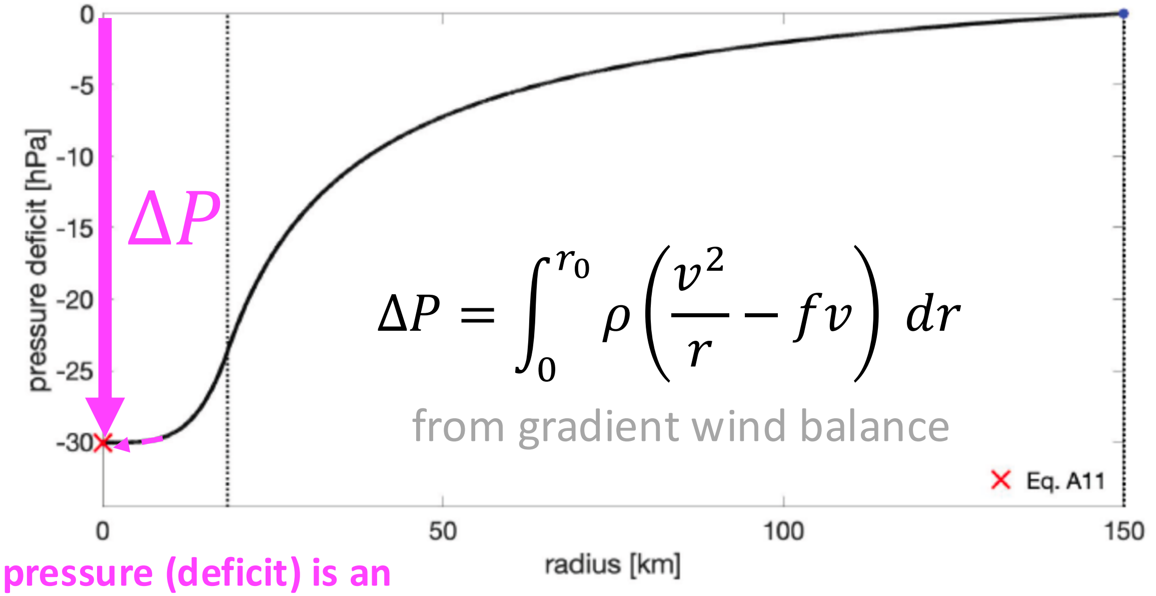
Pressure deficit

Environmental pressure

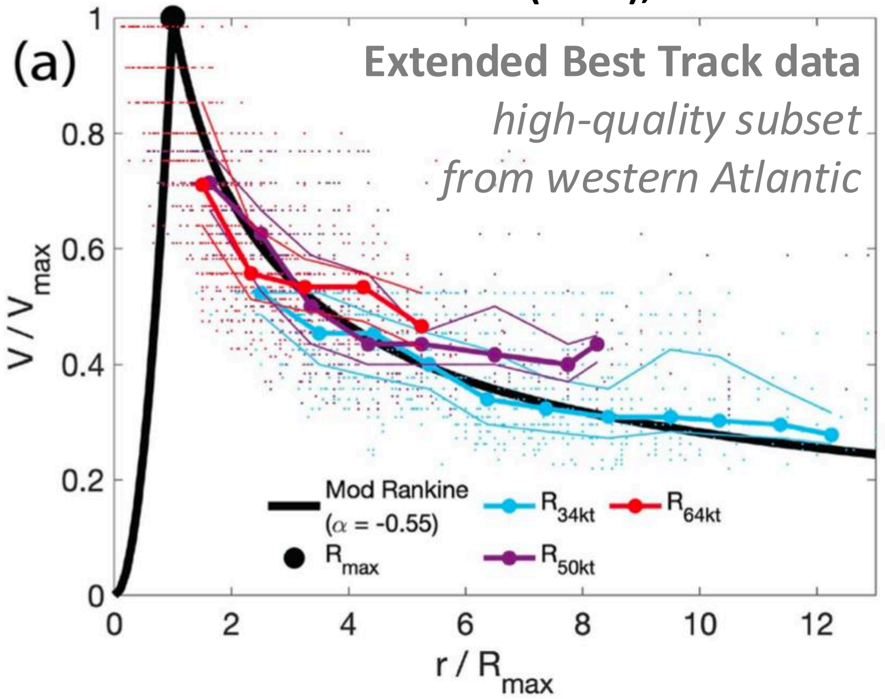
Central pressure

The pressure deficit from a very simple wind field model





Klotzbach et al. (2022), *JGR-A*



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

Analytic solution (with approximations)

Approximations:

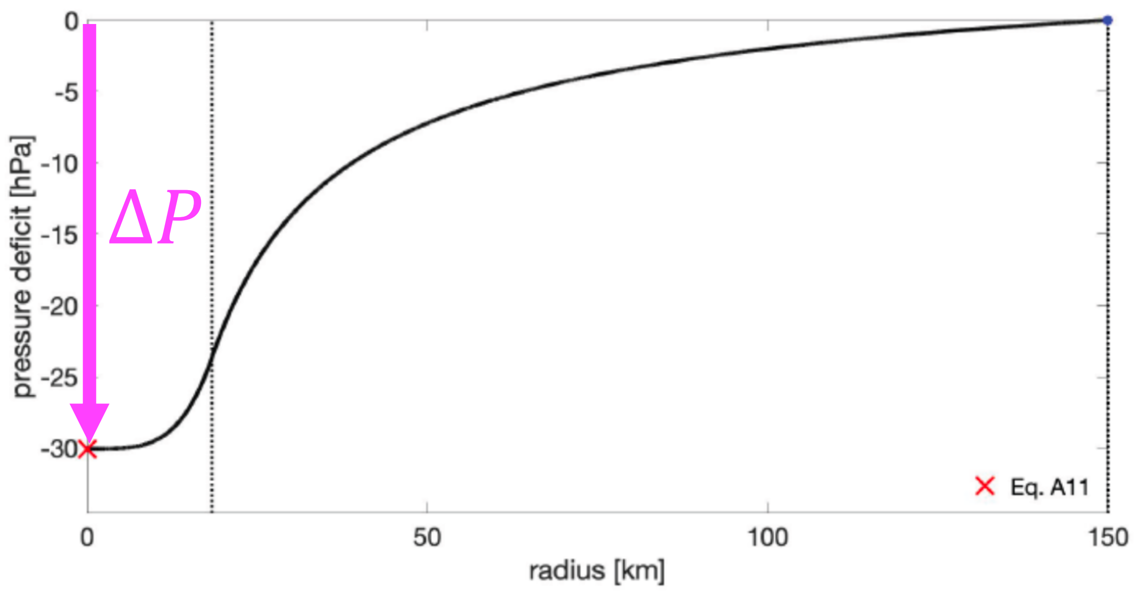
- $\alpha_o = -0.5$
- ρ constant
- Complicated boundary layer stuff

$$\Delta P_{theo} = \rho\left[V_0^2 - \frac{5}{4}\left(V_{max}^2\right) - 4V_o\left(\frac{1}{2}fR_o\right) + \frac{10}{3}V_o^2\left(\frac{\frac{1}{2}fR_o}{V_{max}}\right)\right]$$

Max wind speed (squared)

Size x Coriolis

Their ratio (a small modification)



Theory: physics constrains the problem to 2 parameters.
But theory has biases, and hard to calculate (not analytic)

Observations: unbiased truth (ideally), but relationships to other parameters are unconstrained

Idea: Empirical model

Use the **physics** to **define the predictors.**

Use the **data** to **estimate the actual relationships in nature**.

A linear empirical model instead, with coefficients estimated from data

Size = R_{34kt}

$$\Delta P_{hPa} = \beta_0 + \beta_{V_{max^2}} \left(V_{max}^2\right) + \beta_{fR} \left(\frac{1}{2} f \overline{R}_{34kt}\right) + \beta_{fRdV} \left(\frac{\frac{1}{2} f \overline{R}_{34kt}}{V_{max}}\right)$$

physics → **predictors**

data → **coefficients**

A linear empirical model instead, with coefficients estimated from data

$$\Delta P_{hPa} = \beta_0 + \beta_{Vmax^2}\left(V_{max}^2\right) + \beta_{fR}\left(\frac{1}{2} f \overline{R}_{34kt}\right) + \beta_{fRdV}\left(\frac{\frac{1}{2} f \overline{R}_{34kt}}{V_{max}}\right)$$

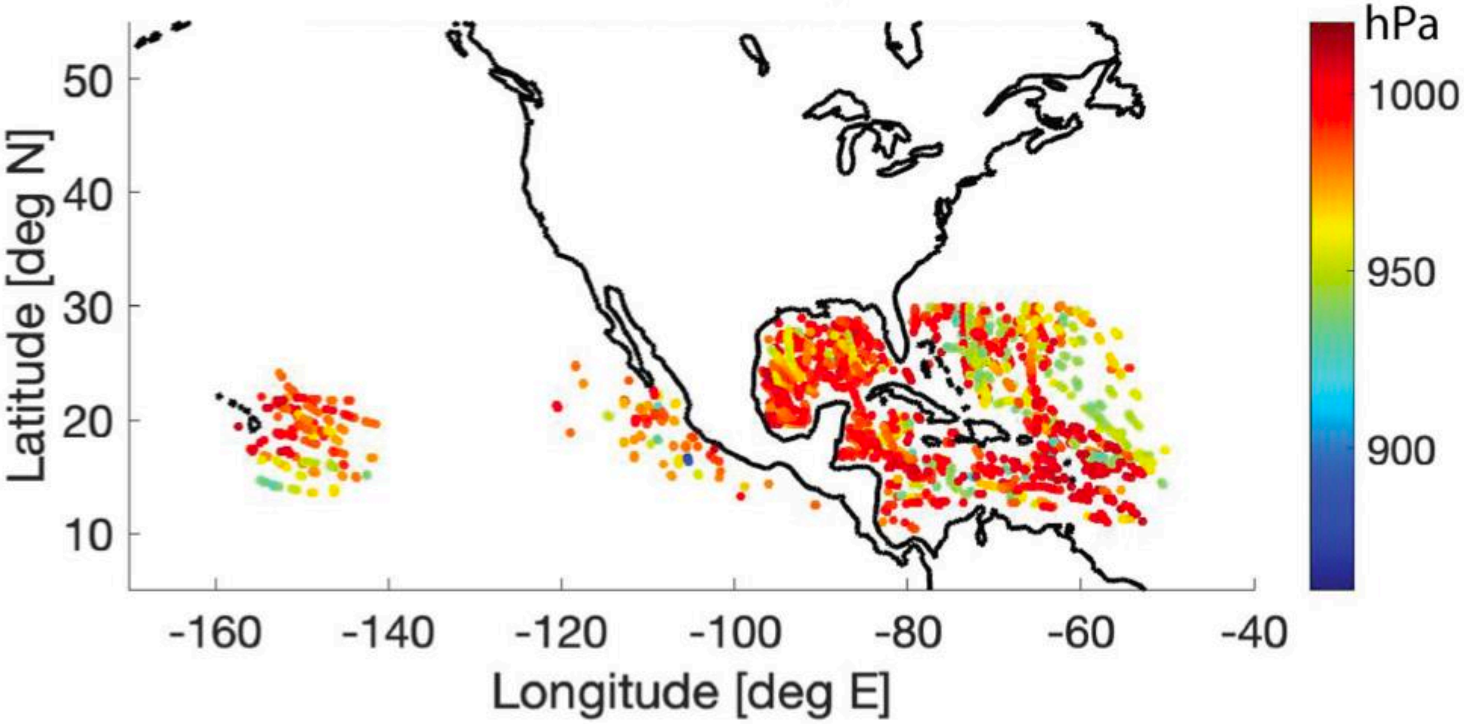
Data: 2004-2022

- P_{min}: aircraft estimates (ATCF)
- P_{env}: NCEP CFS (2004-05) and GFS analyses (2006+)
- Other variables: ATCF/Extended Best Track, interpolated to P_{min} times

Filters:

- West of 50N, South of 30N
- $d_{coast} \geq \overline{R}_{34kt}$
- $V_{max} > 20\,\frac{m}{s}$
- 3+ quadrants R_{34kt} data

Fit to data binned in (Vmax, f, and $\overline{R}_{34kt}$)



A linear empirical model instead, with coefficients estimated from data

$$\overline{V}_{\max} = V_{\max} - 0.55 V_{\text{trans}}$$

$$\Delta P_{\text{hPa}} = -6.60 - 0.0127(\overline{V}_{\max}^2) - 5.506\left(\frac{1}{2} f \overline{R}_{34\text{kt}}\right) + 109.013\left(\frac{\frac{1}{2} f \overline{R}_{34\text{kt}}}{\overline{V}_{\max}}\right)$$

Lower pressure if — 1) stronger wind — 2) larger / higher lat — amplifies 1 / reduces 2

Data: 2004-2022

- **P_{min}: aircraft estimates (ATCF)**
- P_{env}: NCEP CFS (2004-05) and GFS analyses (2006+)
- Other variables: ATCF/Extended Best Track, interpolated to P_{min} times

Filters:

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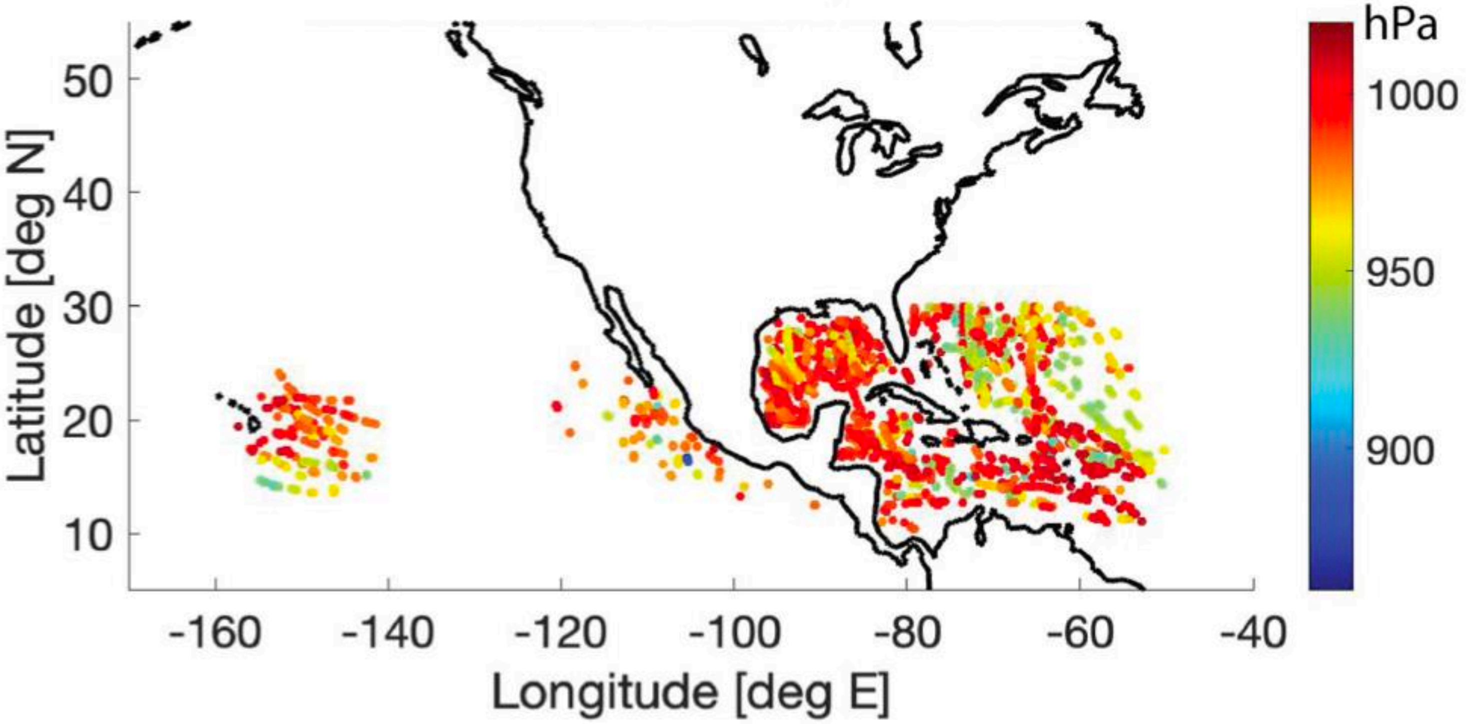
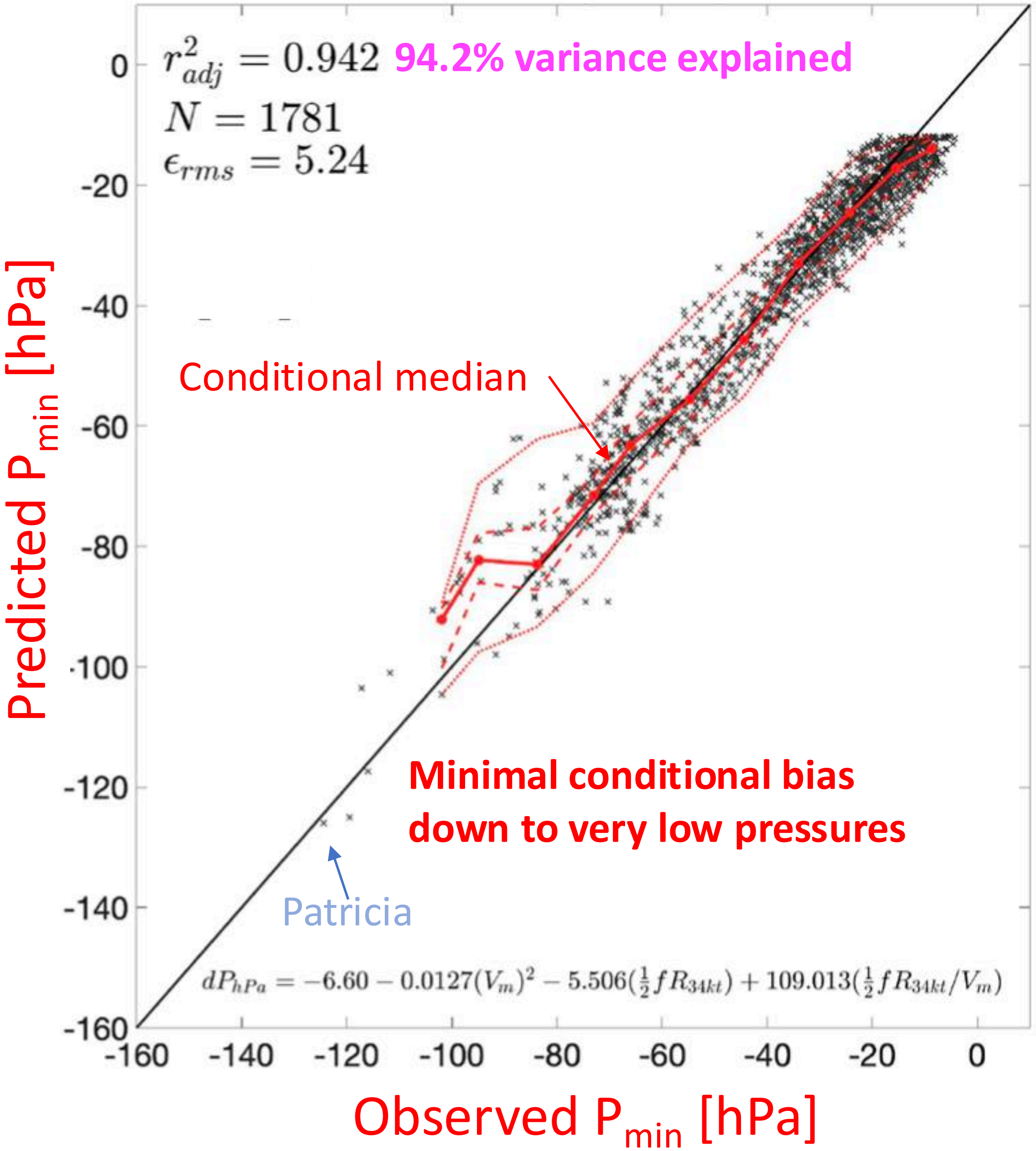
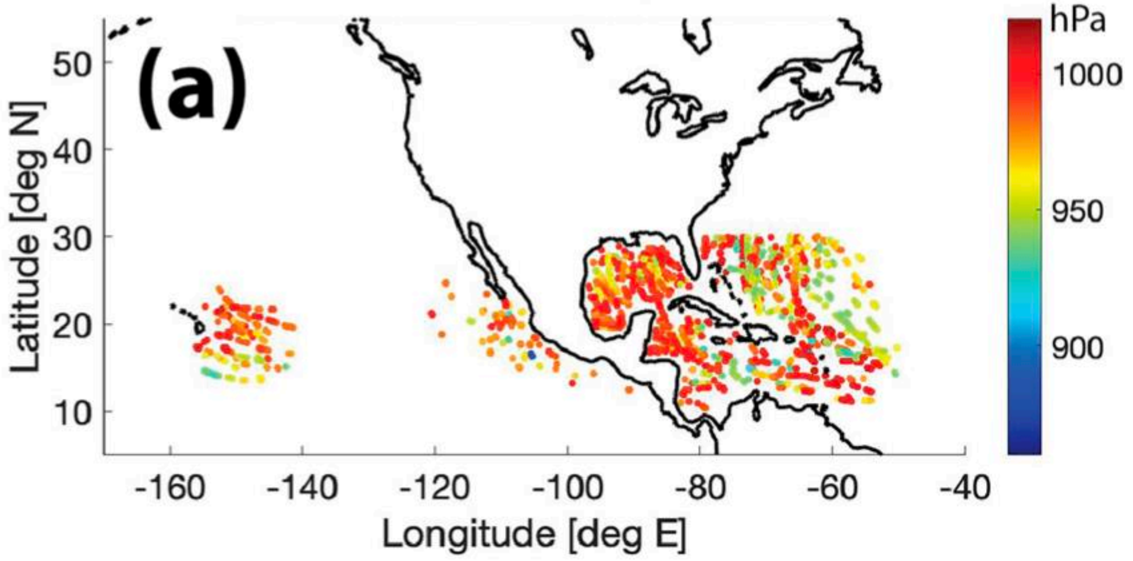


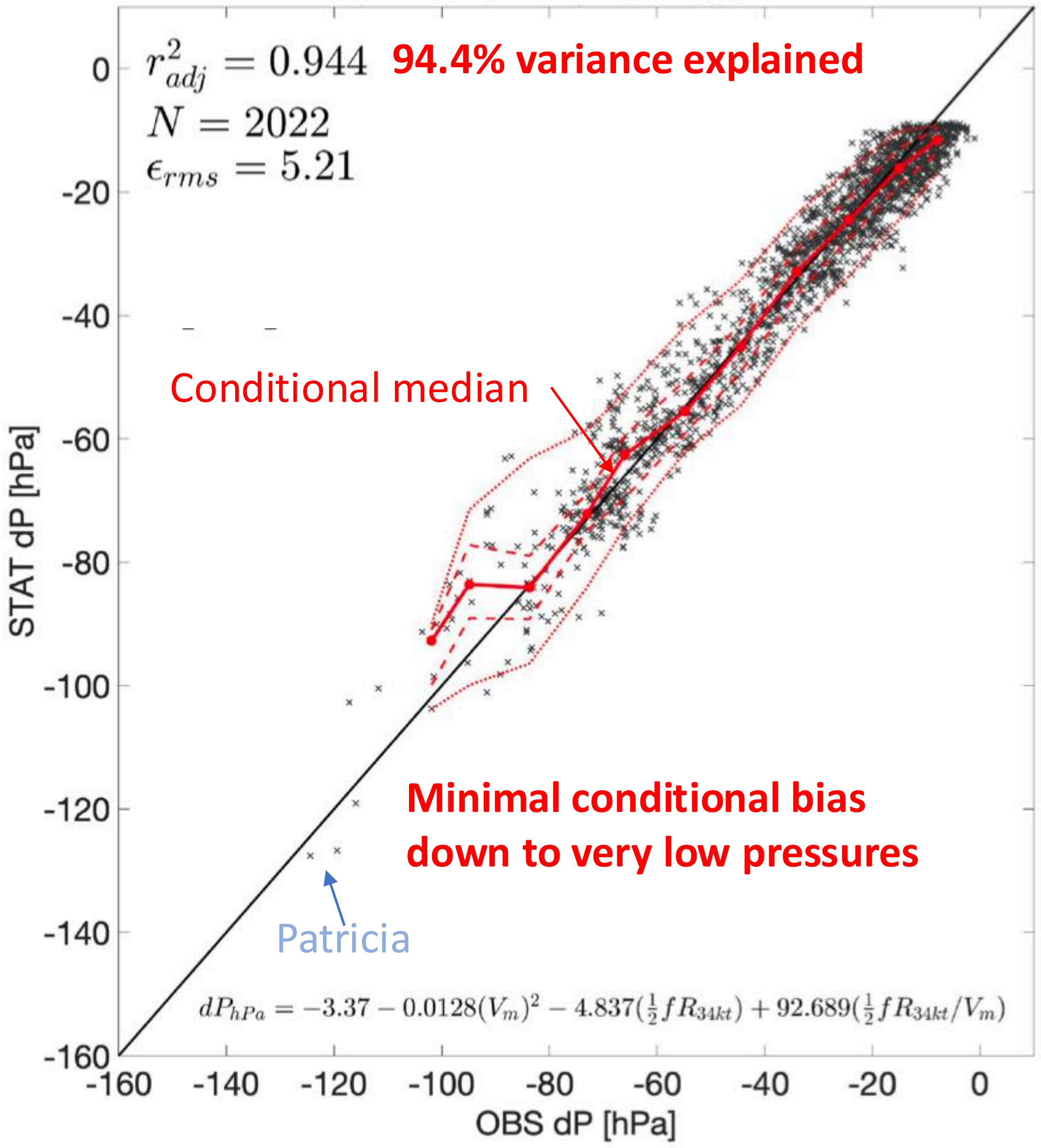
Fit to data binned in (Vmax, f, and $\overline{R}_{34kt}$)

Model predicts P_{min} well, even at very low pressures





The model works well, even at very low pressures



1) All three predictors are useful

Model	*Expl. var.* $(100 \times r^2_{adj})$
Final model (Eq. (3))	**94.4**
V^2_{max} and $\frac{1}{2} f \overline{R}_{34kt}$ only	92.9
V^2_{max} only	86.3

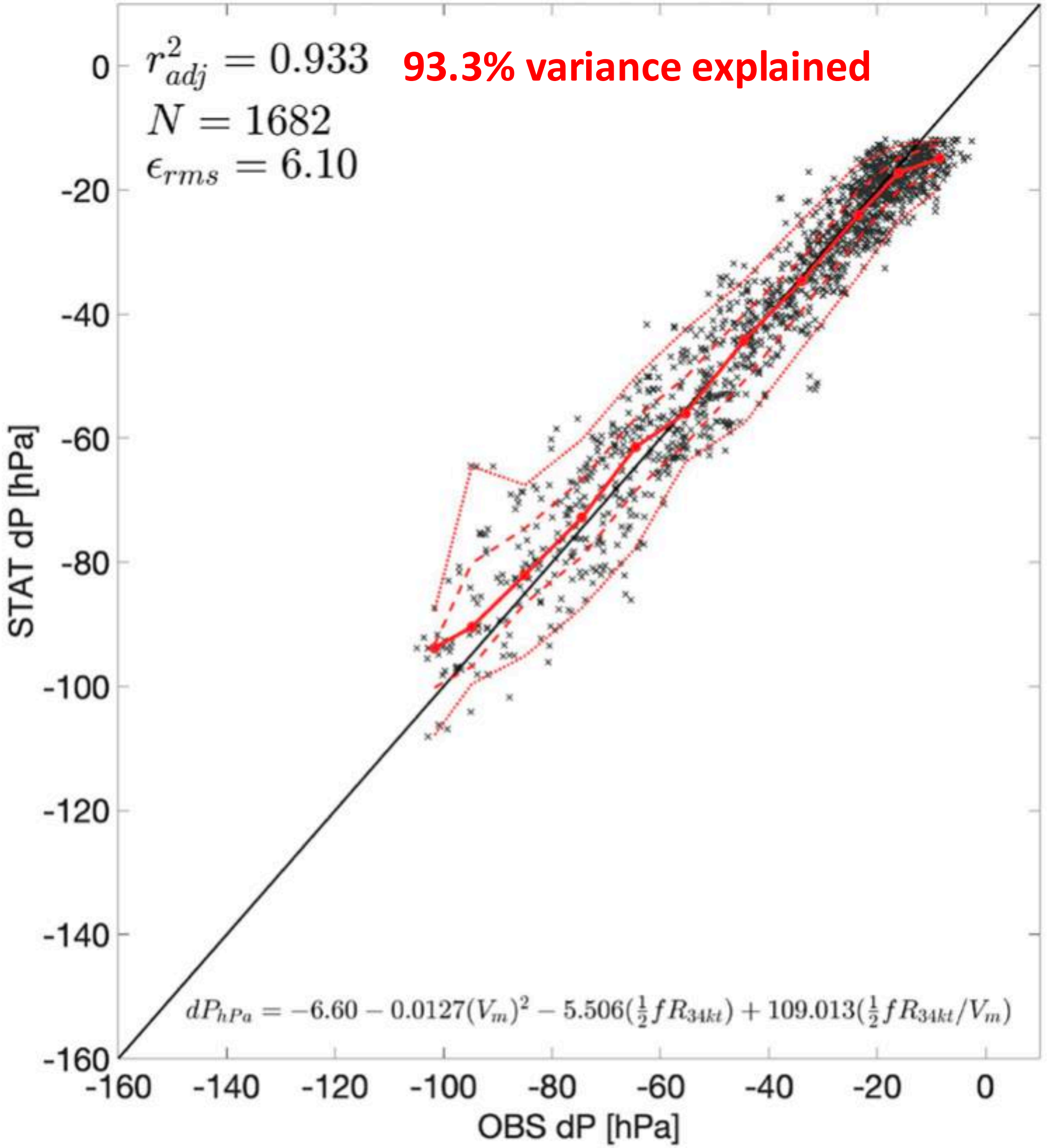
Drop ratio term

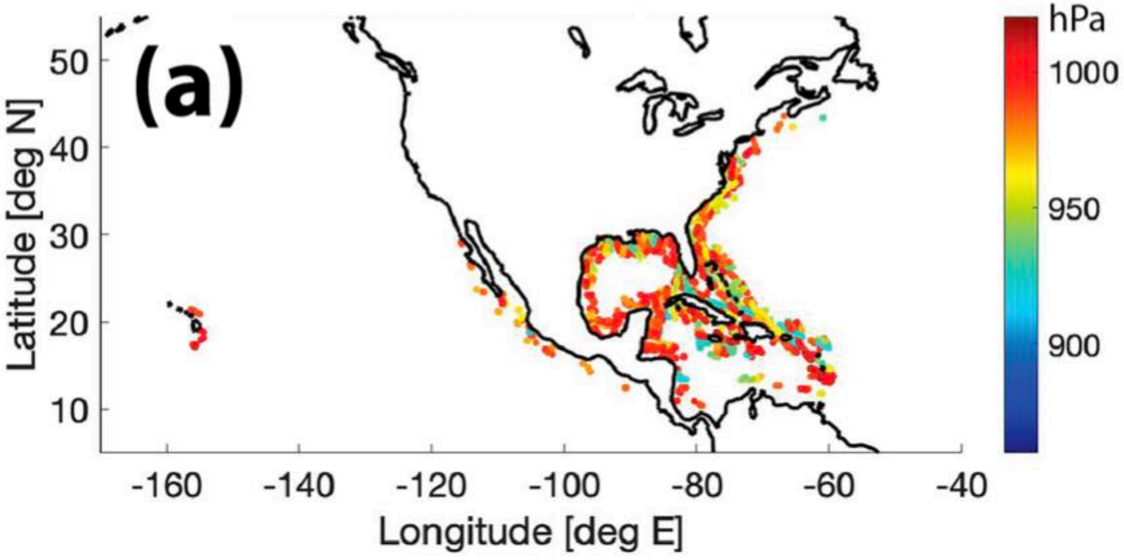
Drop size/Coriolis term

2) This model does better than any other simple combination of V_{max}, $\overline{R}_{34kt}$, f

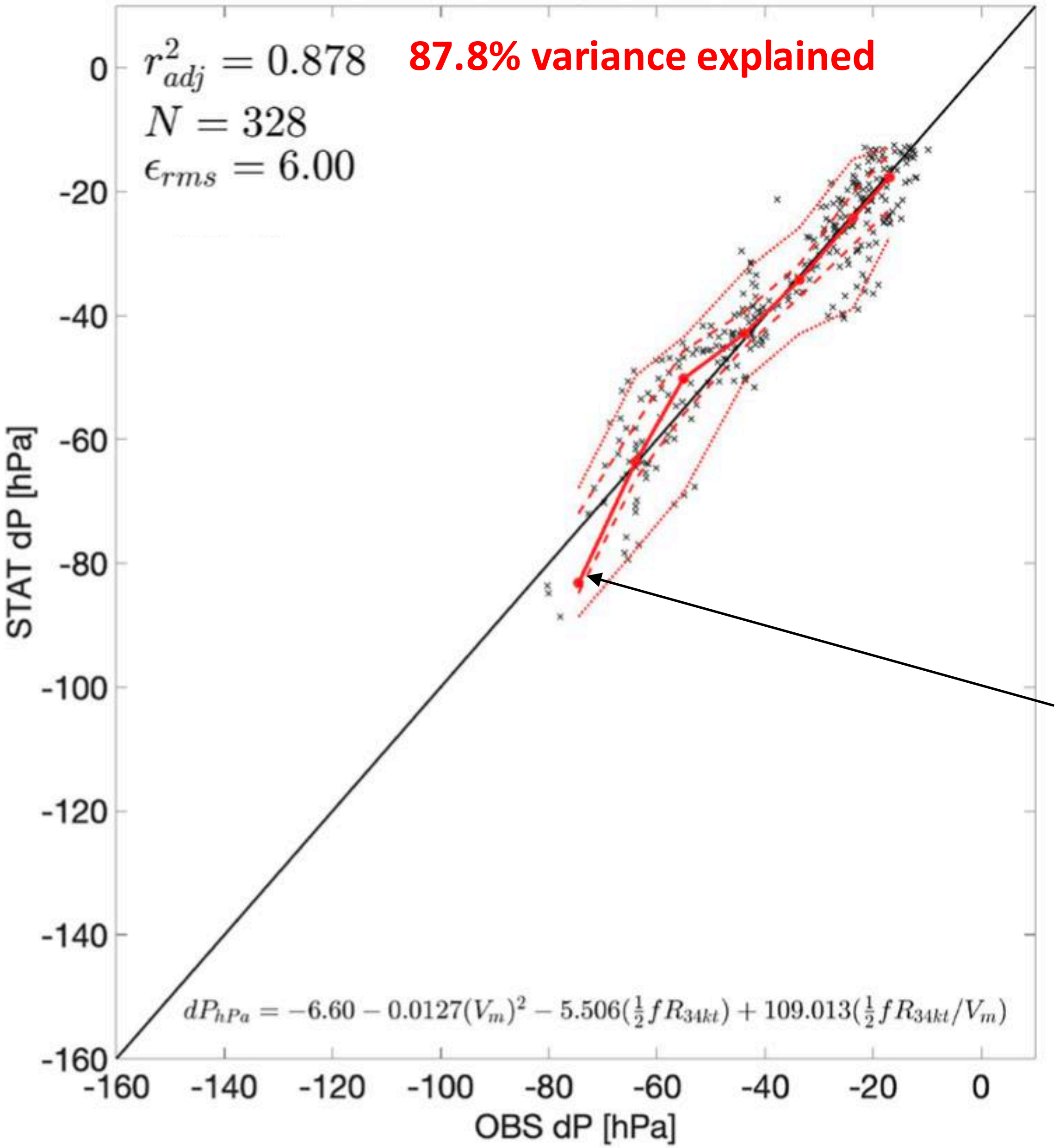
The physics was incredibly helpful for defining the correct predictors!

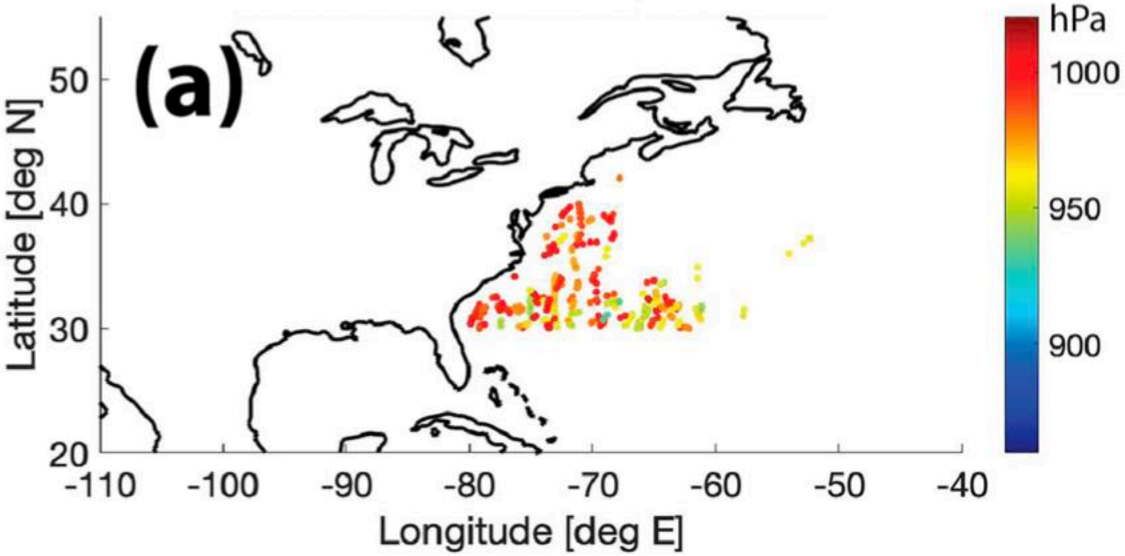
Model predicts P_{min} well applied close to land, too





The model works reasonably well applied at higher latitudes

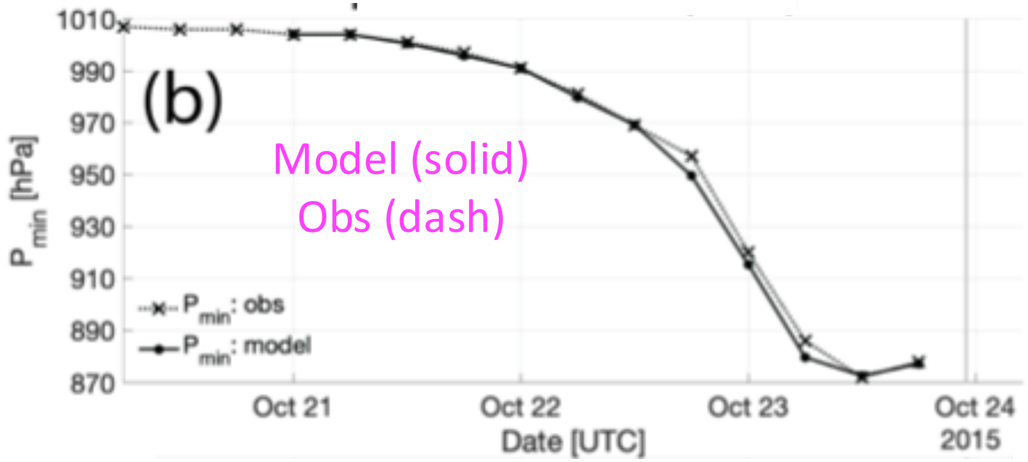




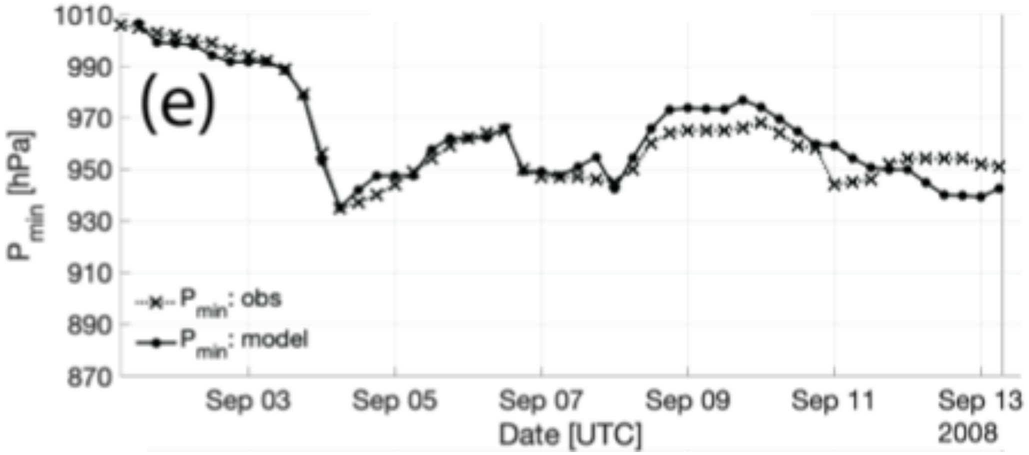
Evidence of systematic low bias (too intense) at very low pressures

Works pretty well for case studies with different intensity/size evolutions

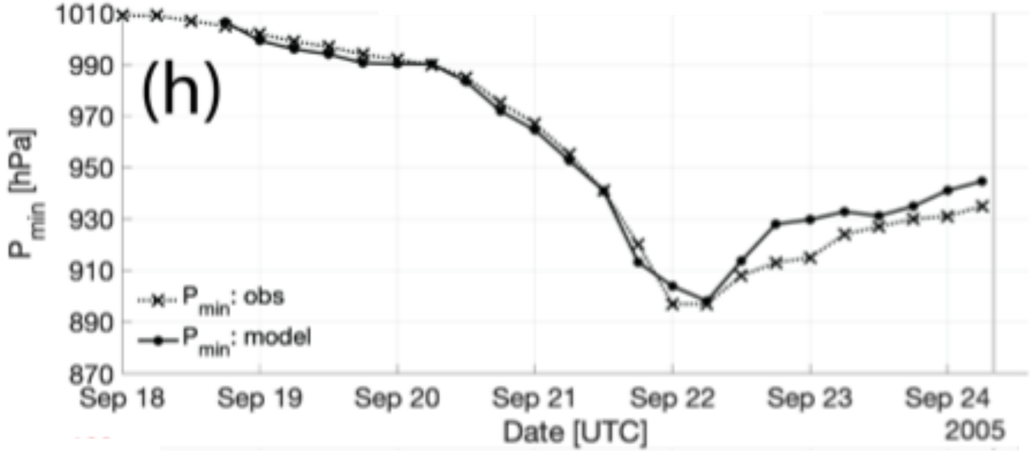
Patricia 2015
extremely intense



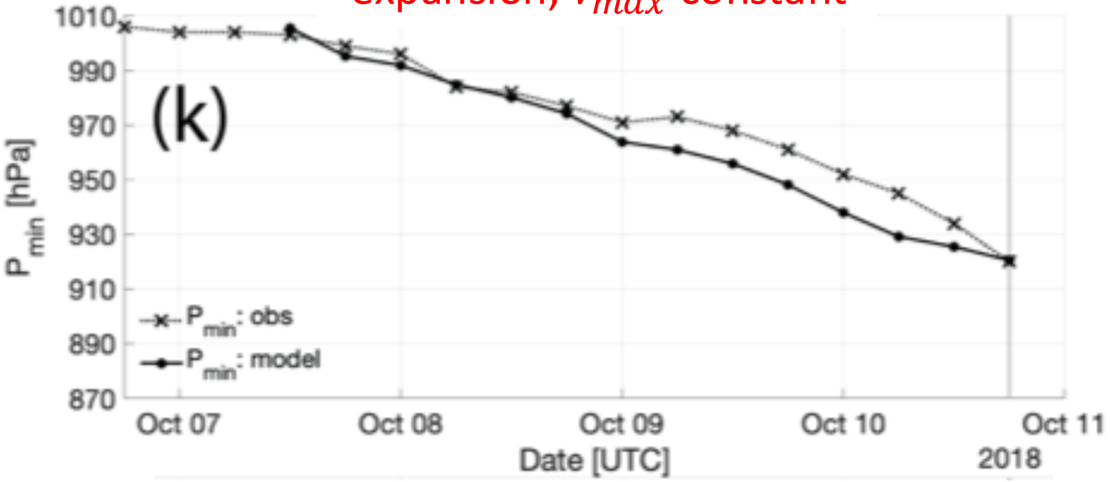
Ike 2008
variable size and intensity



Rita 2005
expansion + rapid intensification

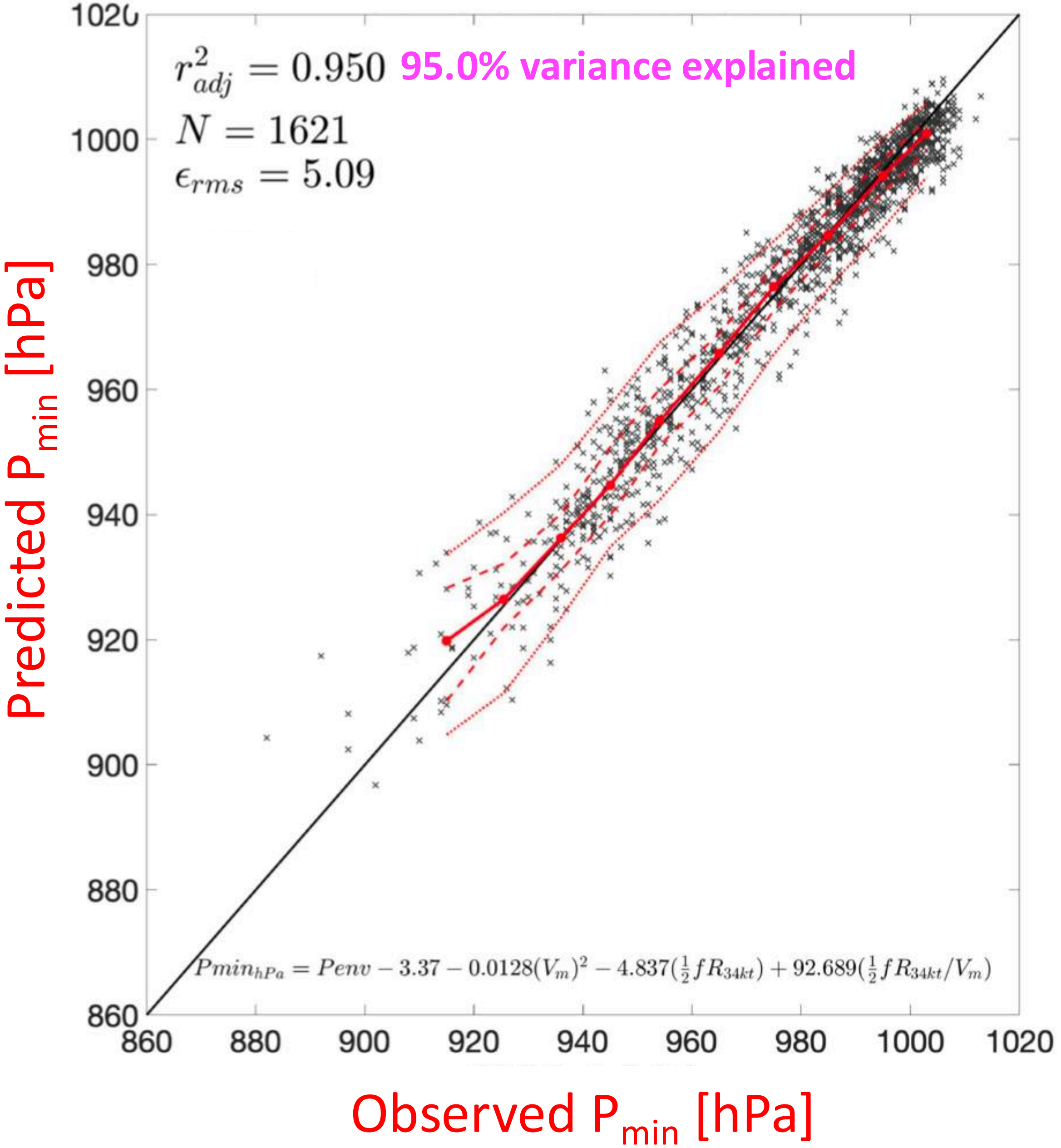


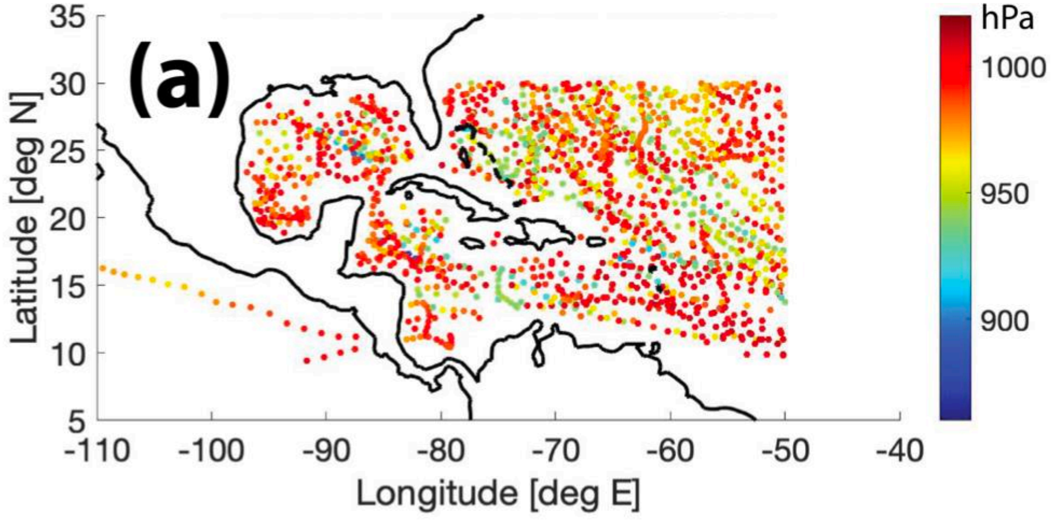
Michael 2018
expansion, V_{max} constant



The times with significant discrepancy mostly occur during/following disruptive interaction with land

Model works well in "operational" mode too (Ext BT data only)





$$P_{min} = P_{env} - \Delta P$$

$$P_{env} = P_{oci} + 2\ hPa$$

Our model

offset agrees with
Courtney and Knaff (2009)

Model P_{min} in three steps

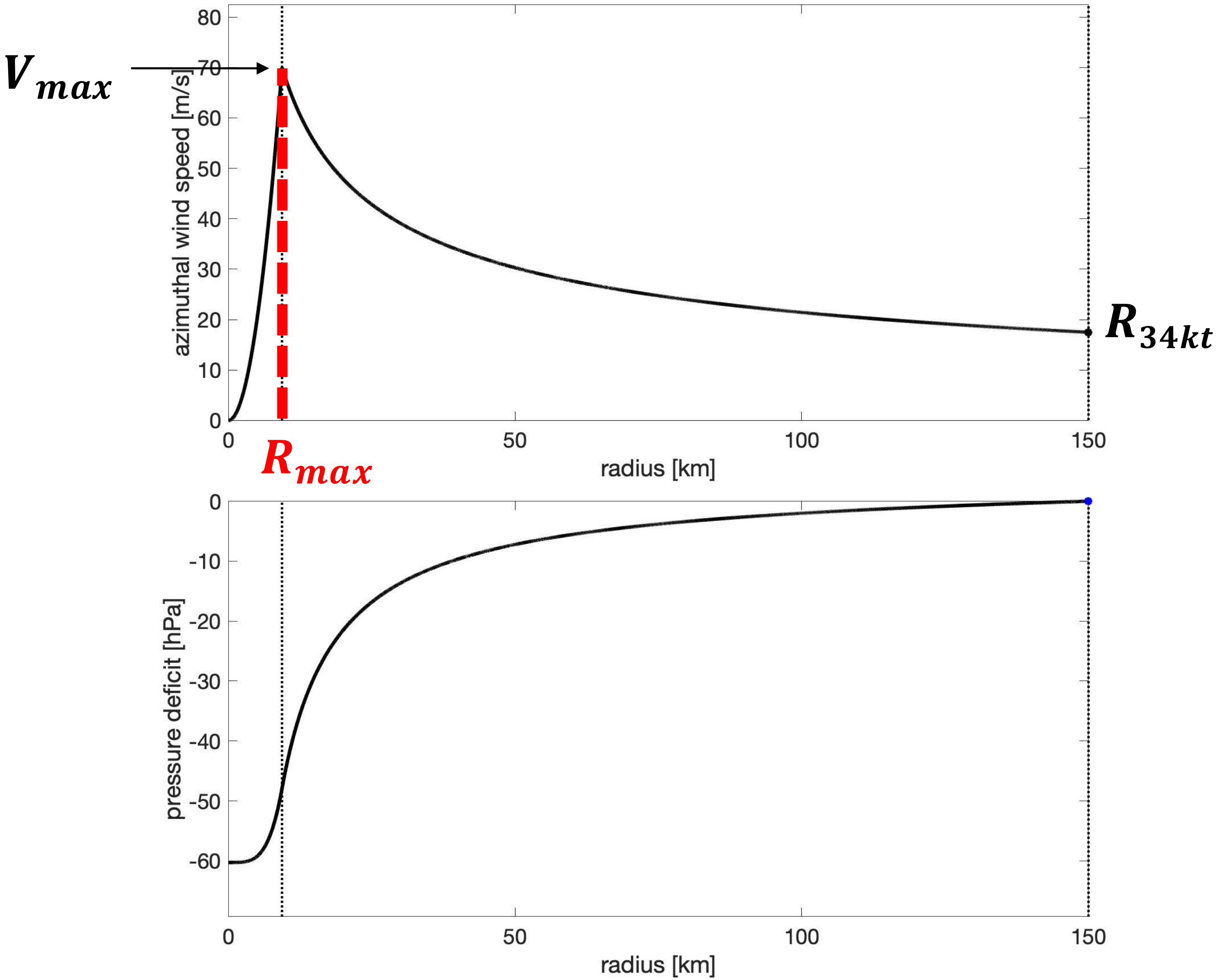
1) $$\Delta P_{\mathrm{hPa}} = -6.60 - 0.0127(\overline{V}^2_{\mathrm{max}}) - 5.506\left(\frac{1}{2}f\overline{R}_{34\mathrm{kt}}\right) + 109.013\left(\frac{\frac{1}{2}f\overline{R}_{34\mathrm{kt}}}{\overline{V}_{\mathrm{max}}}\right)$$

2) $$P_{\mathrm{env}} = P_{\mathrm{oci}} + 2\,\mathrm{hPa}$$

$$\overline{V}_{\mathrm{max}} = V_{\mathrm{max}} - 0.55V_{\mathrm{trans}}$$

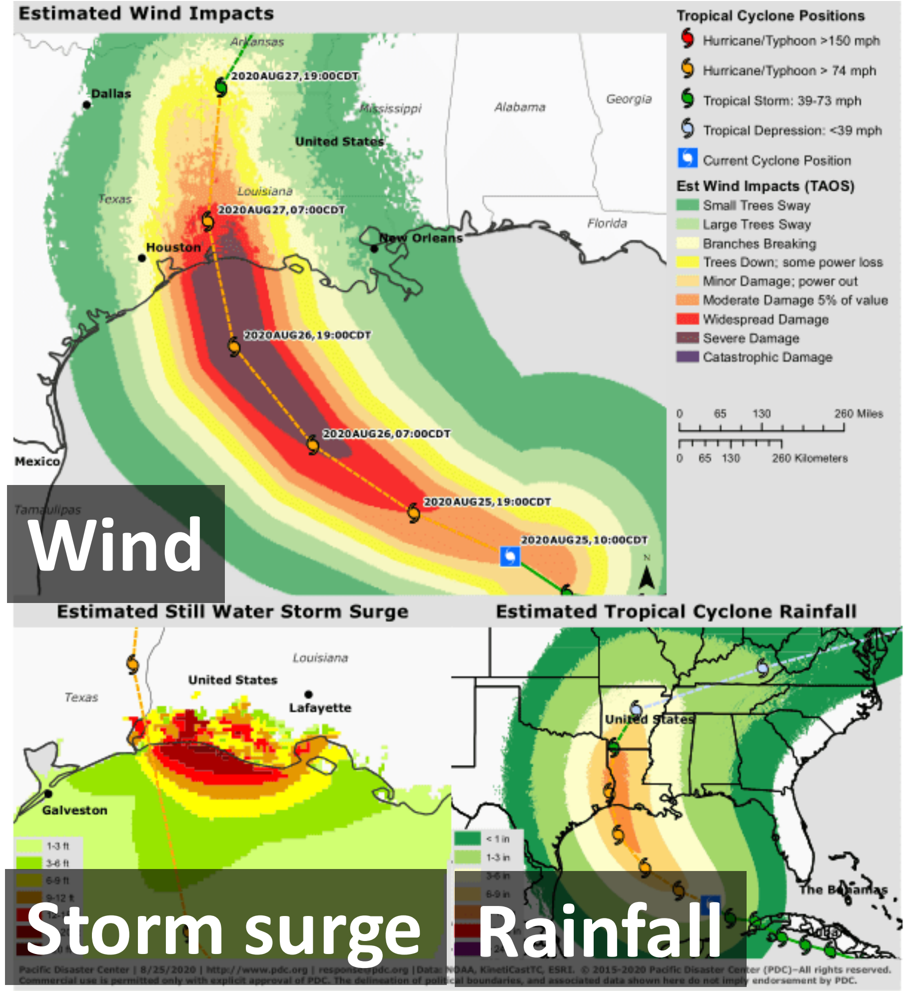
3) $$P_{min} = P_{env} + \Delta P_{hPa}$$

R_{max}

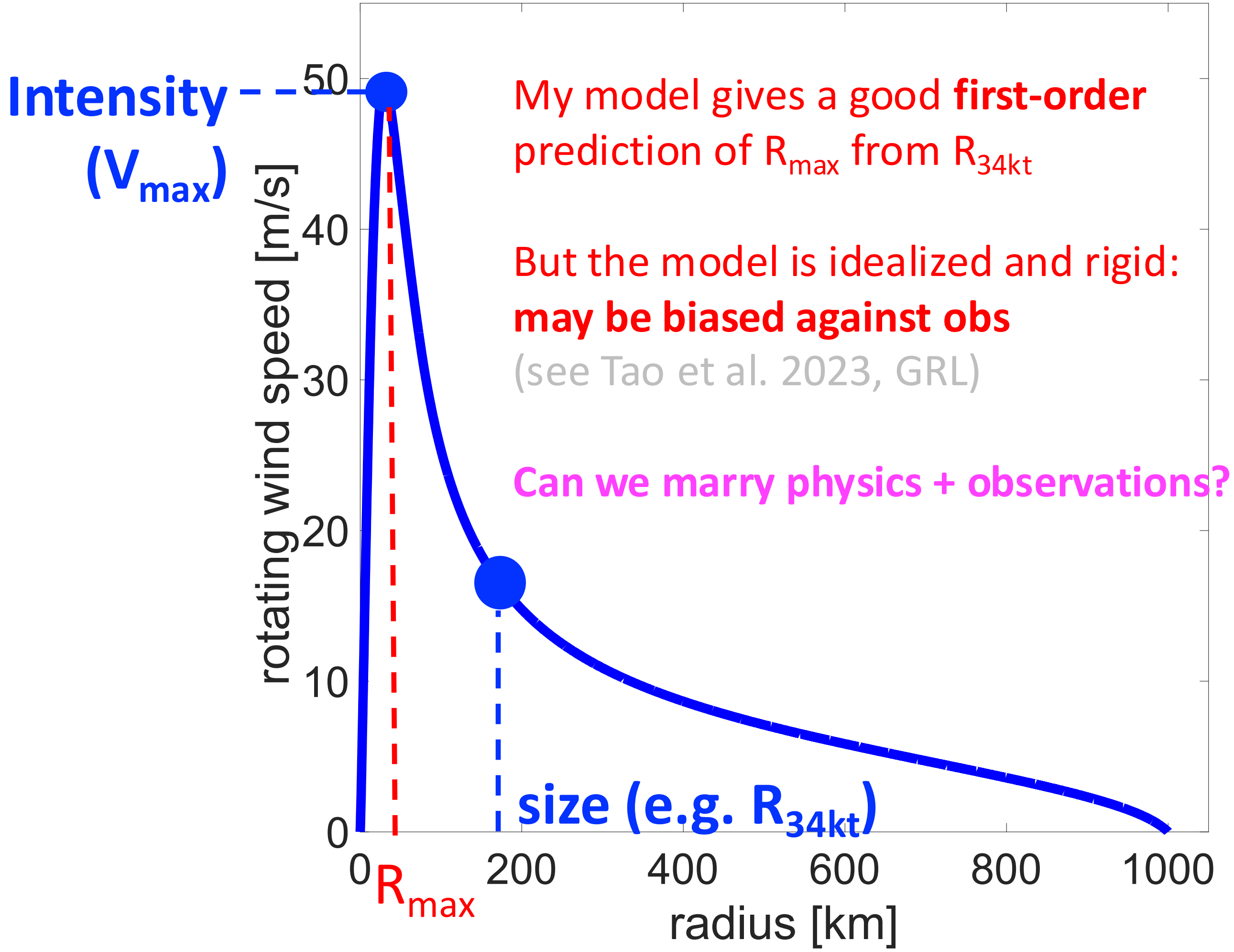


V_{max}
azimuthal wind speed [m/s]
80
70
60
50
40
30
20
10
0
0
50
100
150
radius [km]
R_{max}
R_{34kt}
pressure deficit [hPa]
0
-10
-20
-30
-40
-50
-60
0
50
100
150
radius [km]

R_{max} sets the footprint of the worst hazards



Hurricane Laura (2020)



Source: https://reliefweb.int/map/united-states-america/hurricane-laura-estimated-impacts-advisory-23-25-august-2020-1000-cdt

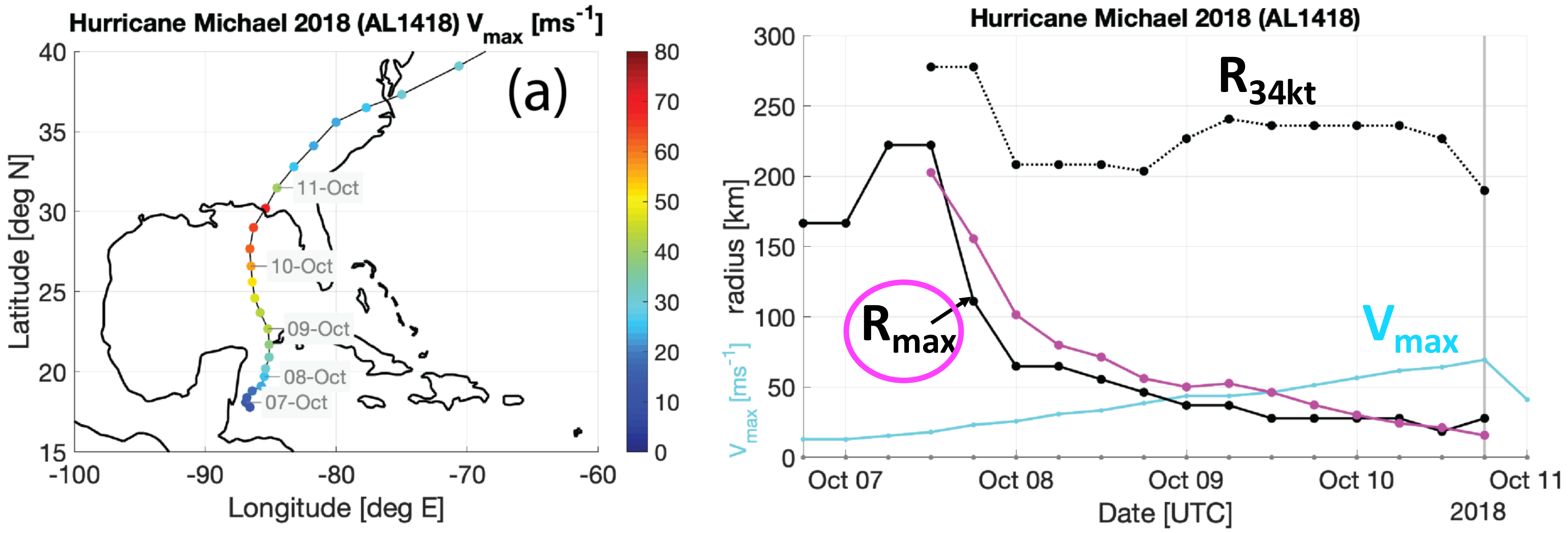
R_{max} is notoriously difficult to estimate

- Highly turbulent
- Very sensitive to horizontal resolution in models (Gentry and Lackmann, Reed and Jablanowski 2011, Rotunno and Bryan 2012)

The outer circulation is much less sensitive to turbulence/resolution.

Can we get estimate R_{max} from R_{34kt}?

Known: R_{max} is smaller for larger V_{max} , smaller R_{34kt} and lower latitude



V_{max} , outer size, and latitude are all changing at the same time!

Obs R_{max} dependencies: Kossin (2007), Chavas and Lin (2016)

A Simple Model for Predicting the Tropical Cyclone Radius of Maximum Wind from Outer Size

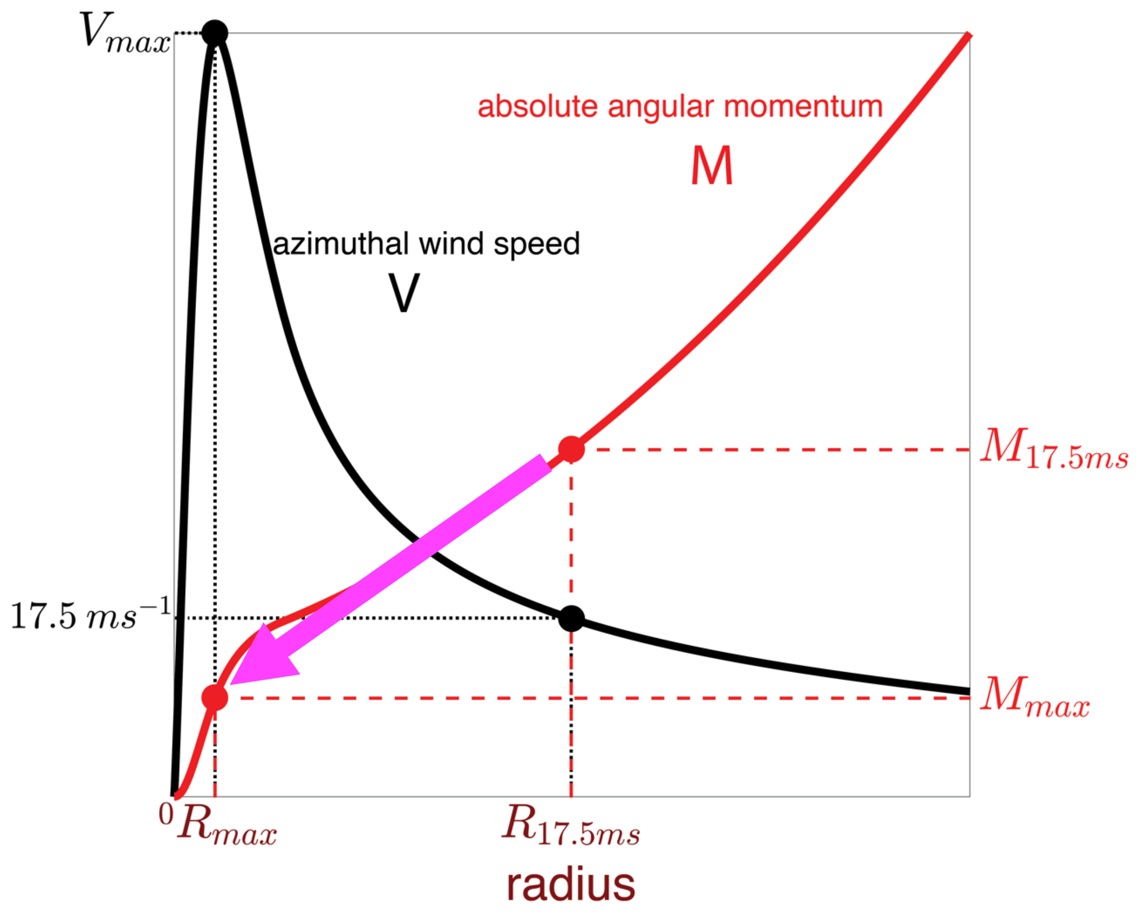
DANIEL R. CHAVAS[a] AND JOHN A. KNAFF[b]

We need an easy-to-use equation to predict $\boldsymbol{R_{max}}$ from routinely-estimated (+ Best Tracked) data!

Physically, the radial structure is set from the outside moving inwards

Inflowing air gradually loses **angular momentum** to surface friction

That which is retained is gradually converted from planetary to relative angular momentum – spinning up the cyclone



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

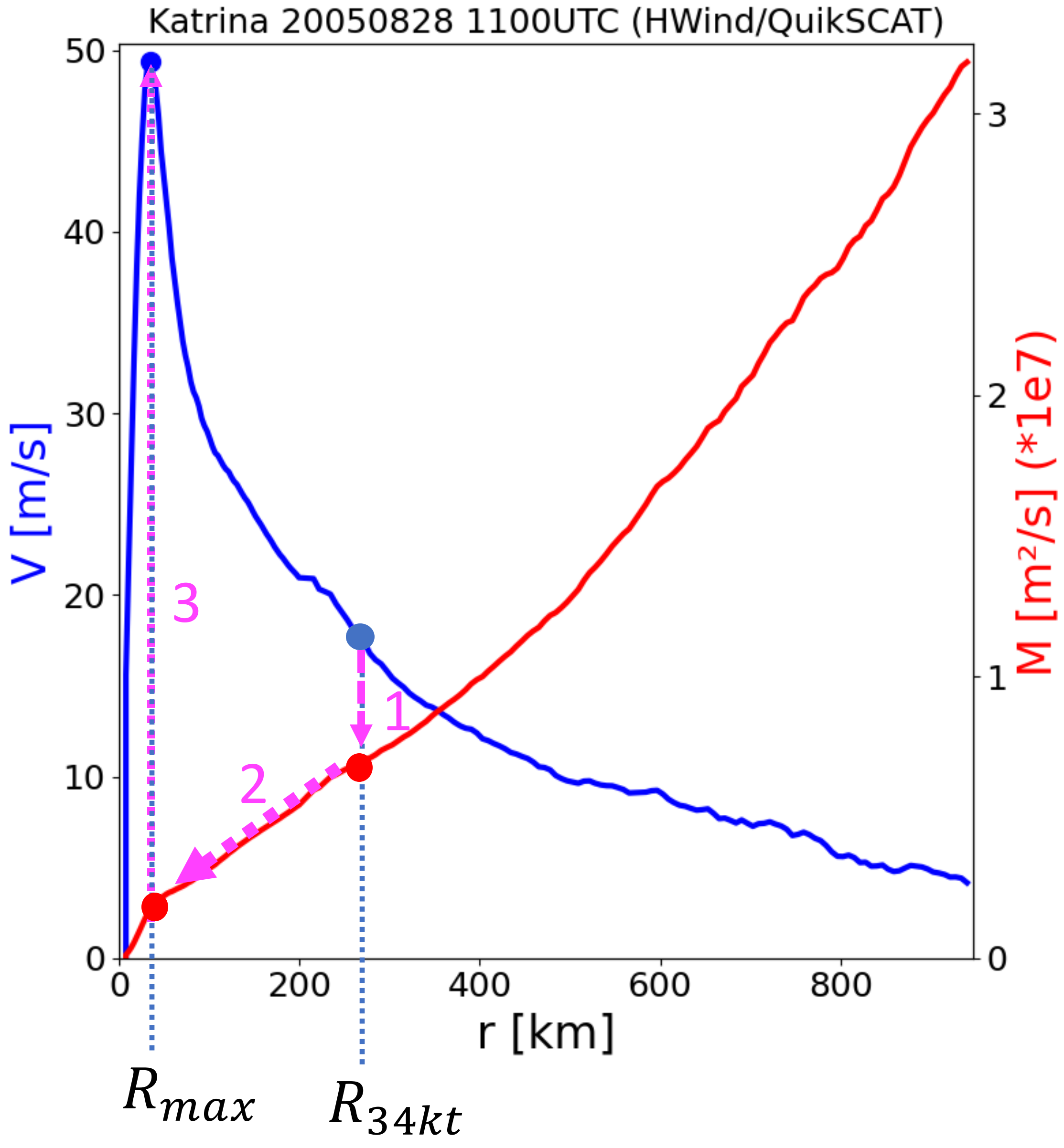
Model R_{max} in three steps

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

1) $M_{17.5ms} = R_{17.5ms} * (17.5\ ms^{-1}) + \frac{1}{2} f R_{17.5ms}^2$

2) $M_{max} = \left(\frac{M_{max}}{M_{17.5ms}}\right) M_{17.5ms}$

3) $R_{max} = \frac{V_{max}}{f}\left(\sqrt{1 + \frac{2 f M_{max}}{V_{max}^2}} - 1\right)$



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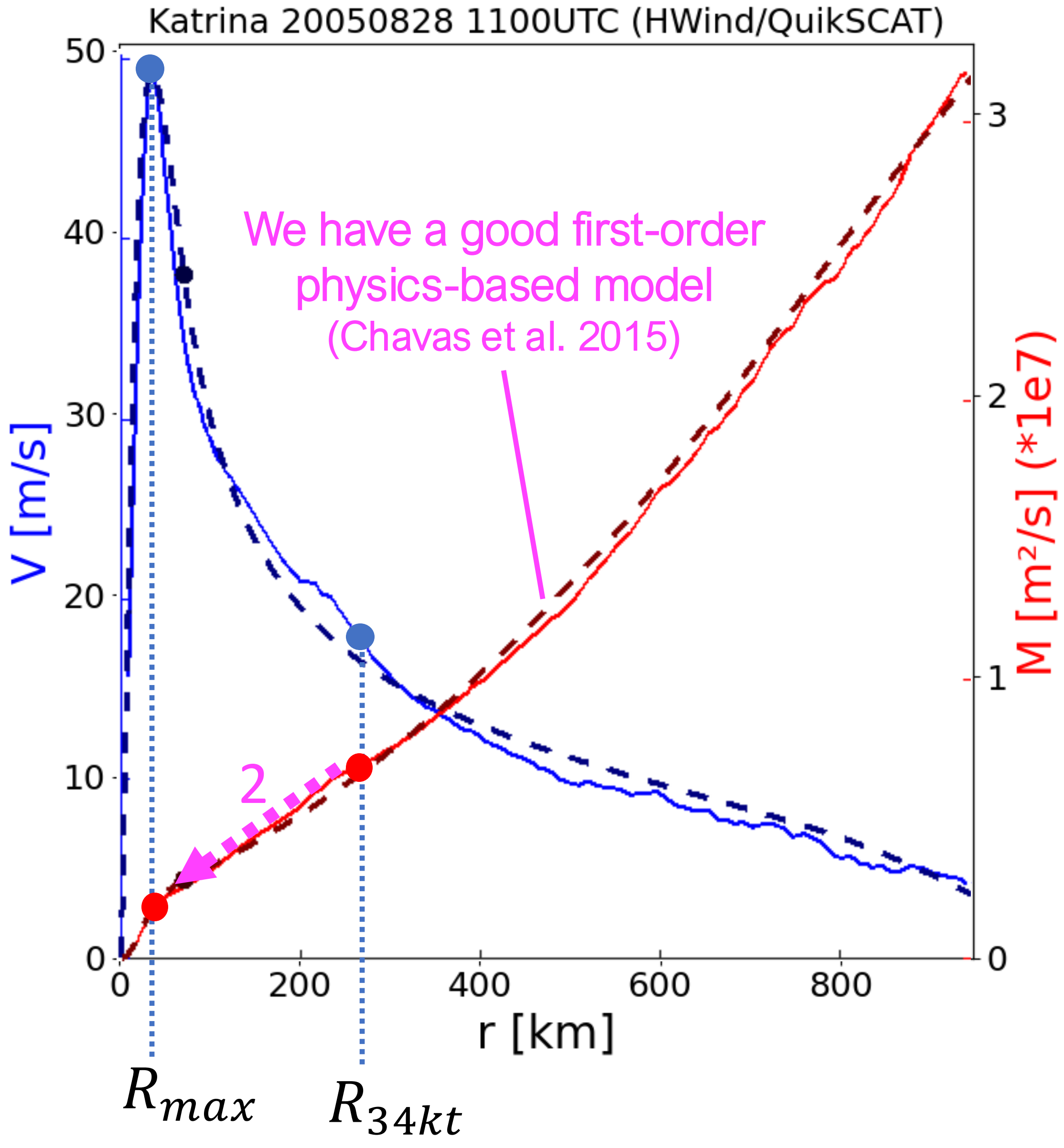
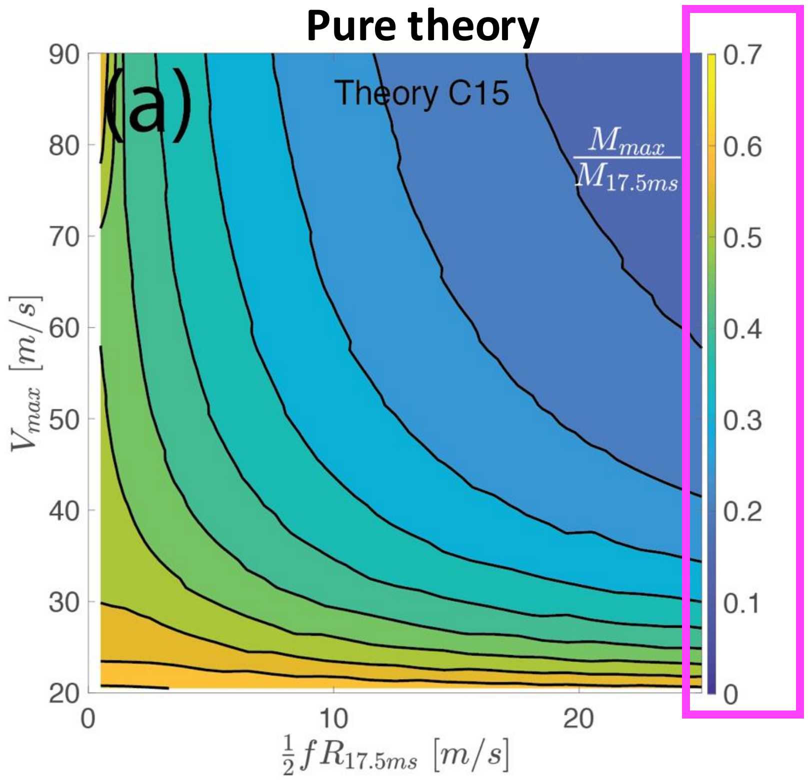


Empirical model, using parameters from the wind field physics

$$ln\left(\frac{M_{max}}{M_{17.5ms}}\right) = \beta_0 + \beta_{Vmax}(V_{max} - 17.5\ ms^{-1}) + \beta_{VfR}(V_{max} - 17.5\ ms^{-1})\left(\frac{1}{2}fR_{17.5ms}\right) + \epsilon$$

positive definite quantity

Why this form?



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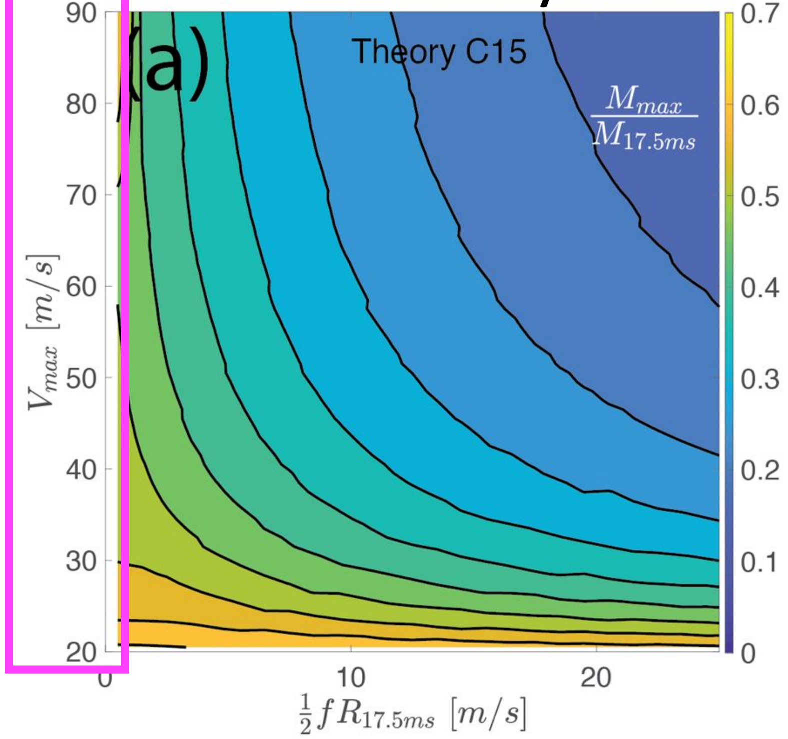
positive definite quantity

V_{max} must be $\geq$ 17.5 m/s

Why this form?

Pure theory



Empirical model, using parameters from the wind field physics

$$ln\left(\frac{M_{max}}{M_{17.5ms}}\right) = \beta_0 + \beta_{Vmax}(V_{max} - 17.5\ ms^{-1}) + \beta_{VfR}(V_{max} - 17.5\ ms^{-1})\left(\frac{1}{2}fR_{17.5ms}\right) + \epsilon$$

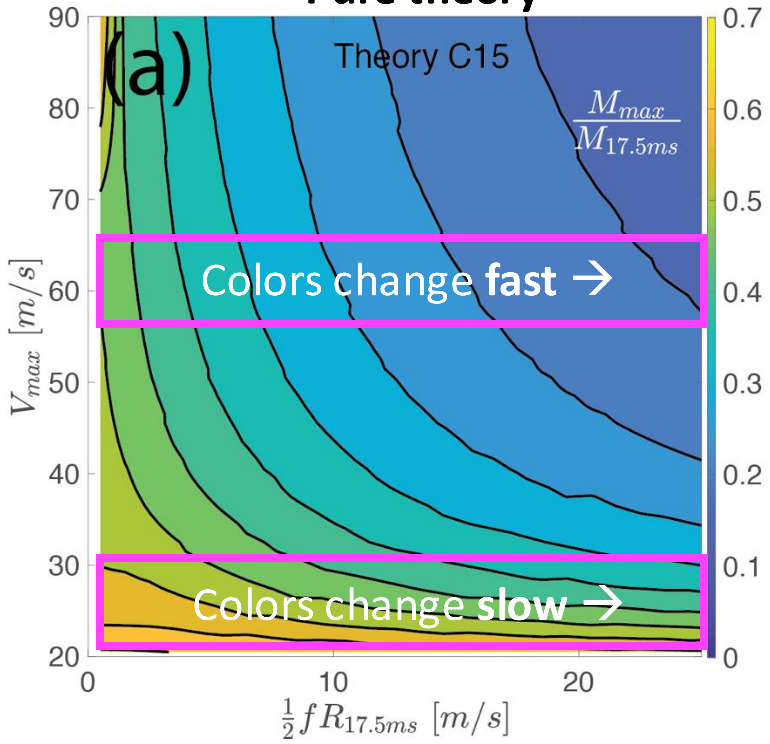
positive definite quantity

V_{max} **must be** $\geq$ **17.5 m/s**

Dependence on $\frac{1}{2}fR_{17.5ms}$ is **stronger** at **larger** V_{max}

Why this form?

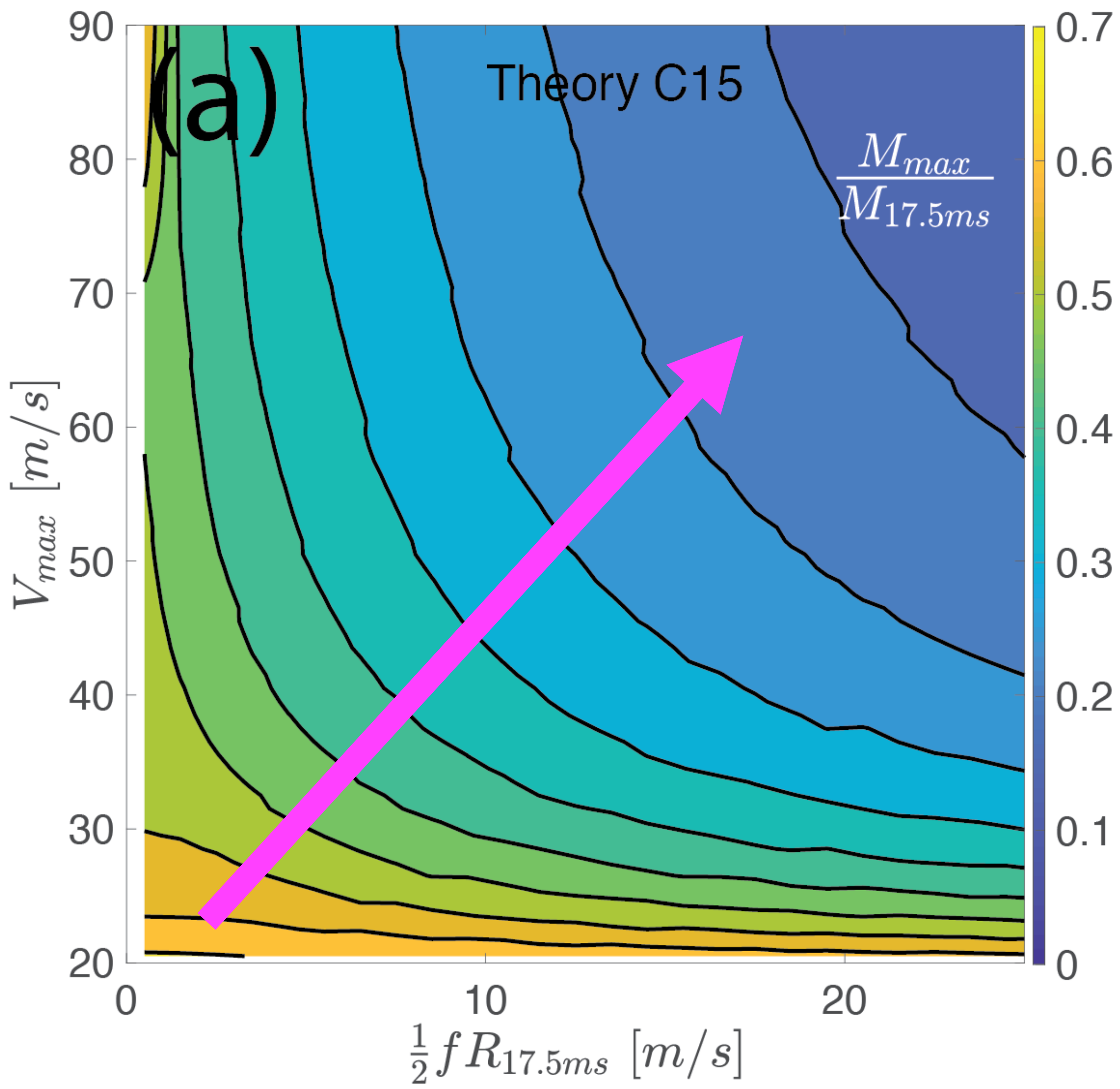
Pure theory



Better than:

- *simpler linear model (less powerful)*
- *more complex 3-term model (not more powerful)*

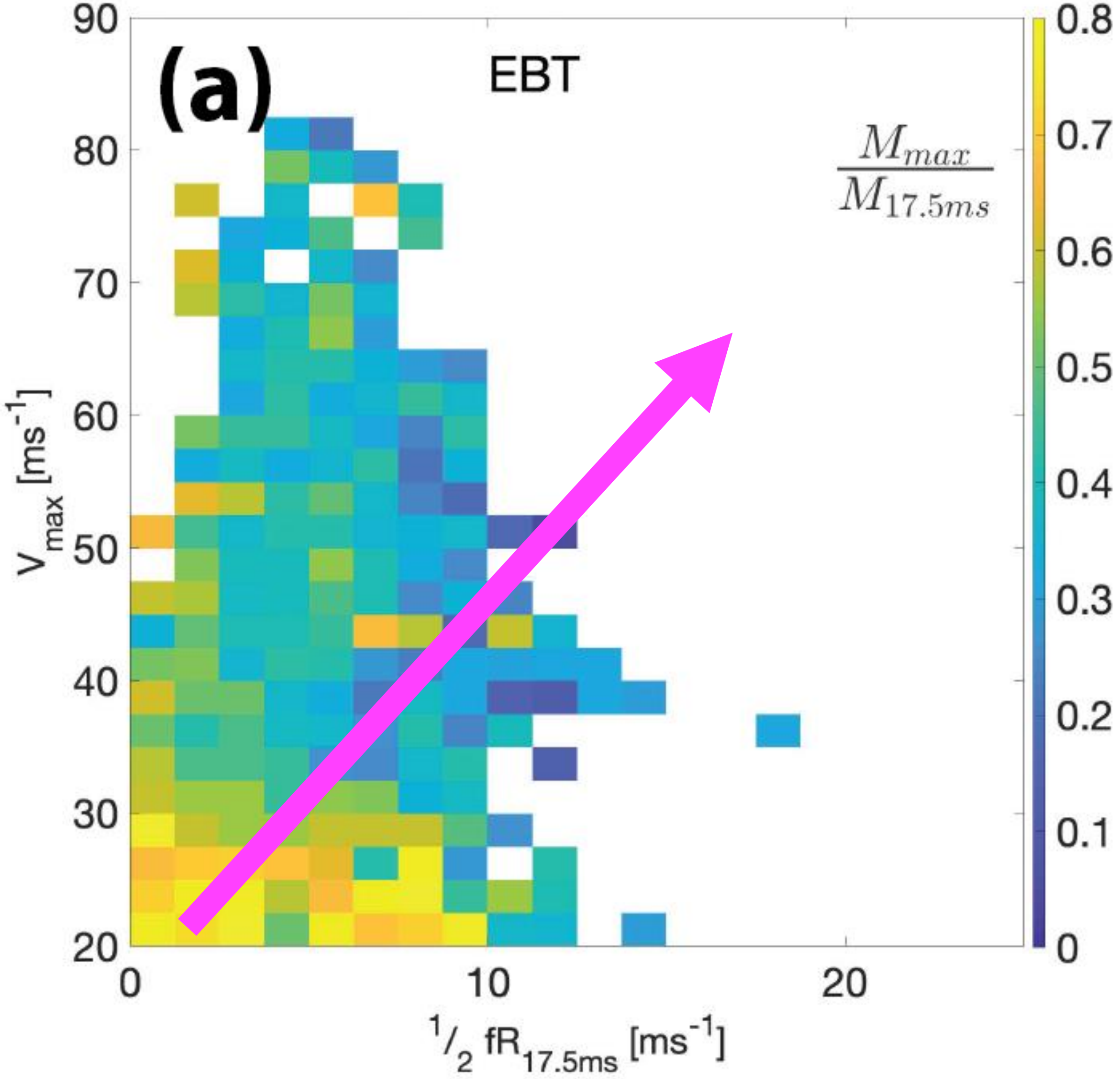
Theory predicts $\frac{M_{R_{max}}}{M_{R_{17.5ms}}}$ is a function of $(V_{max}, \frac{1}{2} f R_{17.5ms})$



The structure is non-linear...

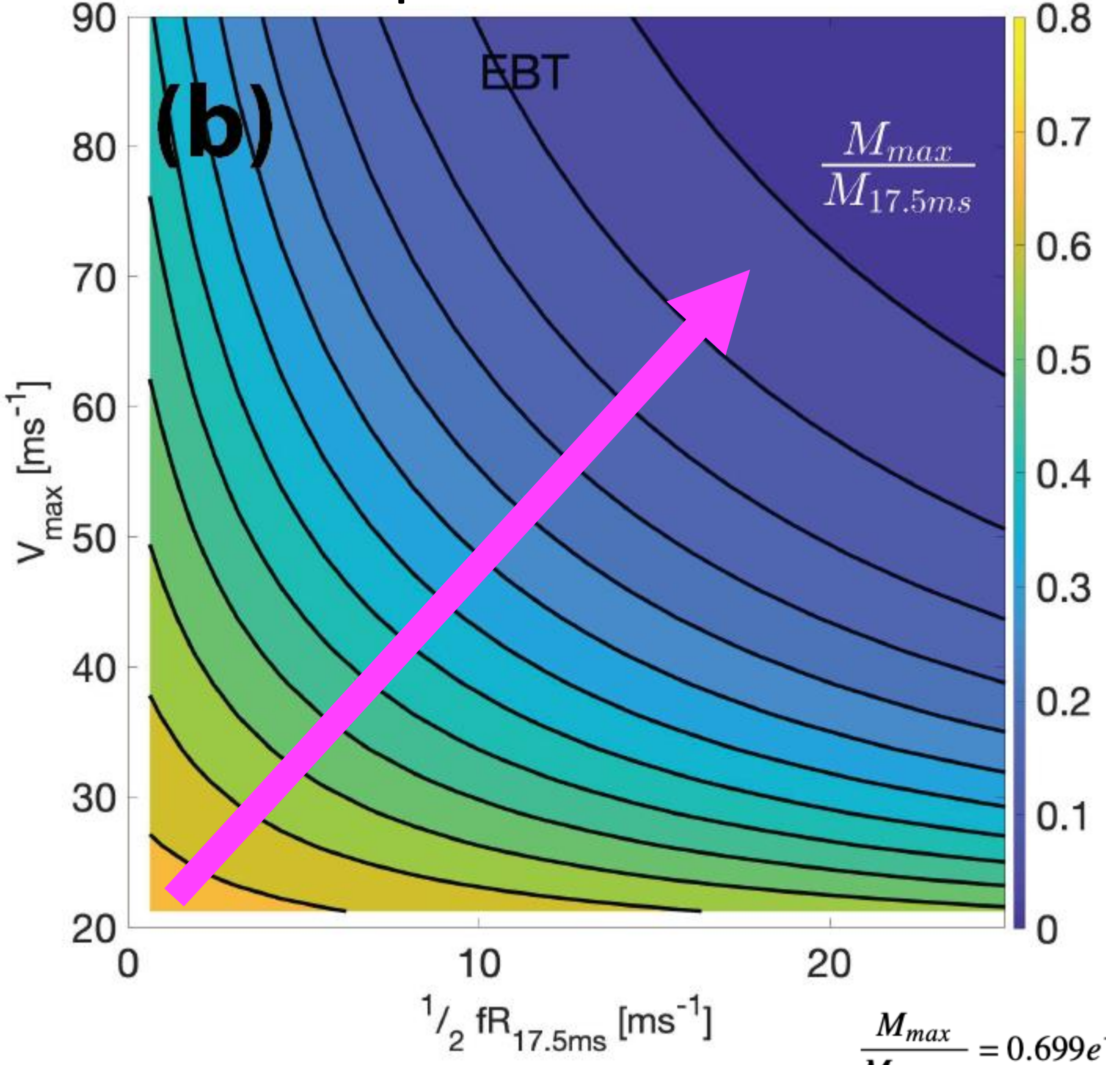
Model design

Observed $\frac{M_{R_{max}}}{M_{R_{17.5ms}}}$ has a similar qualitative structure to theory



Model fit to obs data yields a reasonable $\frac{M_{R_{max}}}{M_{R_{17.5ms}}}$ dependence

Empirical model fit to obs



$$\frac{M_{max}}{M_{17.5ms}} = 0.699e^{-0.00618(V_{max}-17.5ms^{-1})-0.00210(V_{max}-17.5\,ms^{-1})\left(\frac{1}{2}fR_{17.5ms}\right)}$$

Model R_{max} in three steps

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

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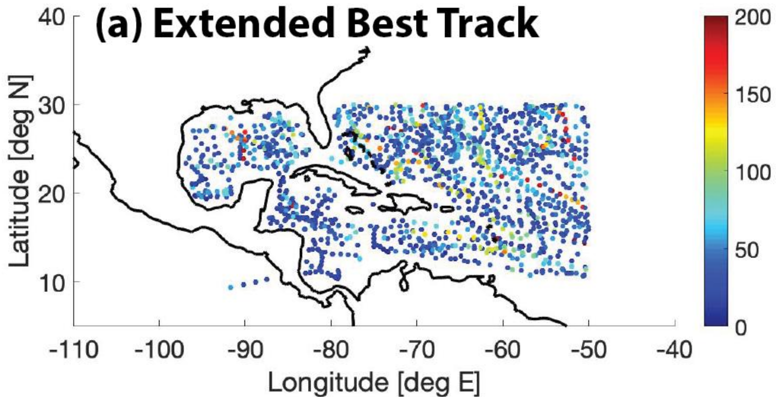
3) $R_{max} = \frac{V_{max}}{f}\left(\sqrt{1 + \frac{2 f M_{max}}{V_{max}^2}} - 1\right)$

physics → **predictors**

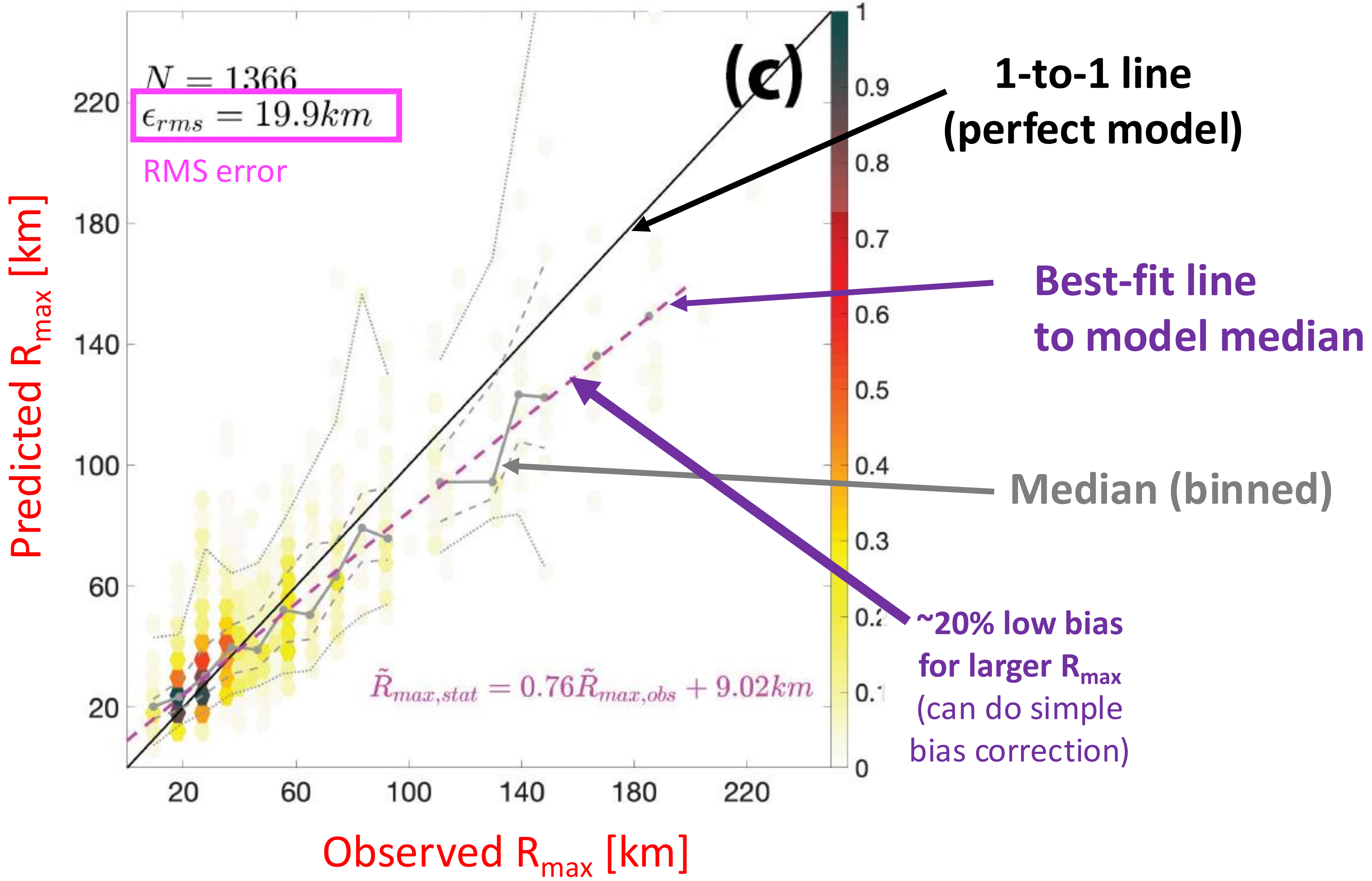
data → **coefficients**



Coefficients estimated from high-confidence data

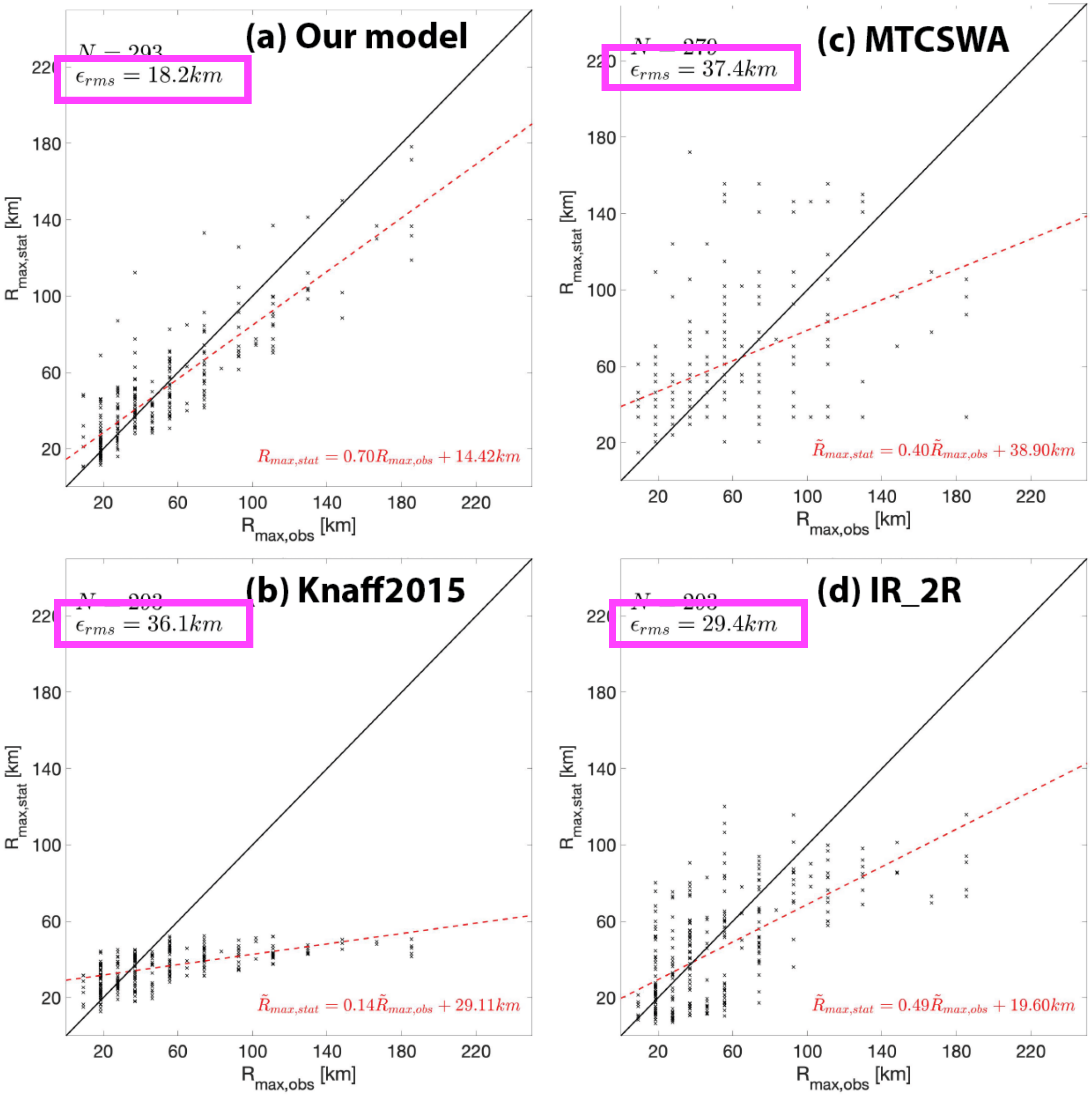
Ext Best Track data 2004-2020

Model predicts R_{max} pretty well



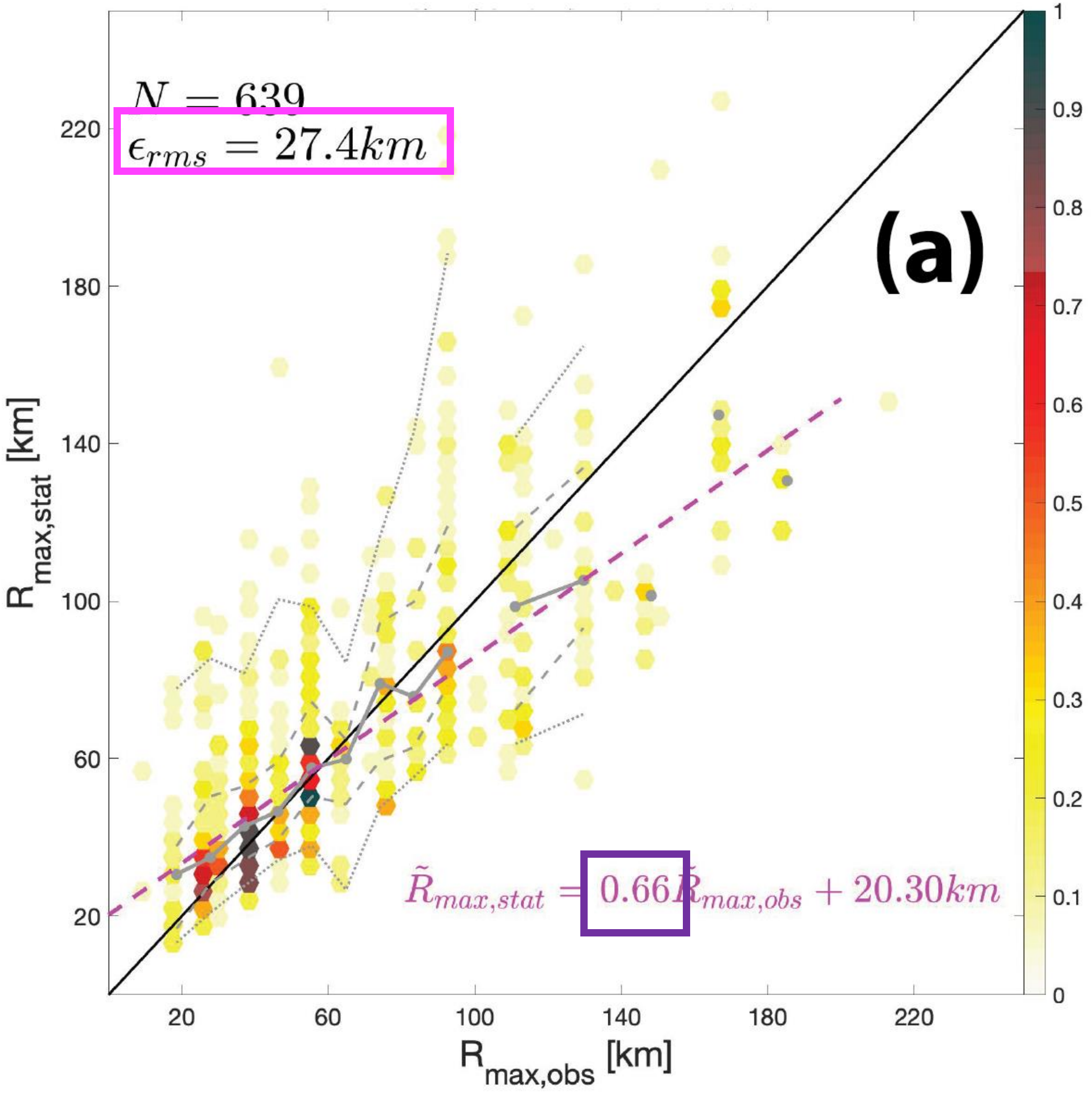
Much better than existing models

Out of sample test
2018-2020
Model retrained on
<2018 data
(similar result)

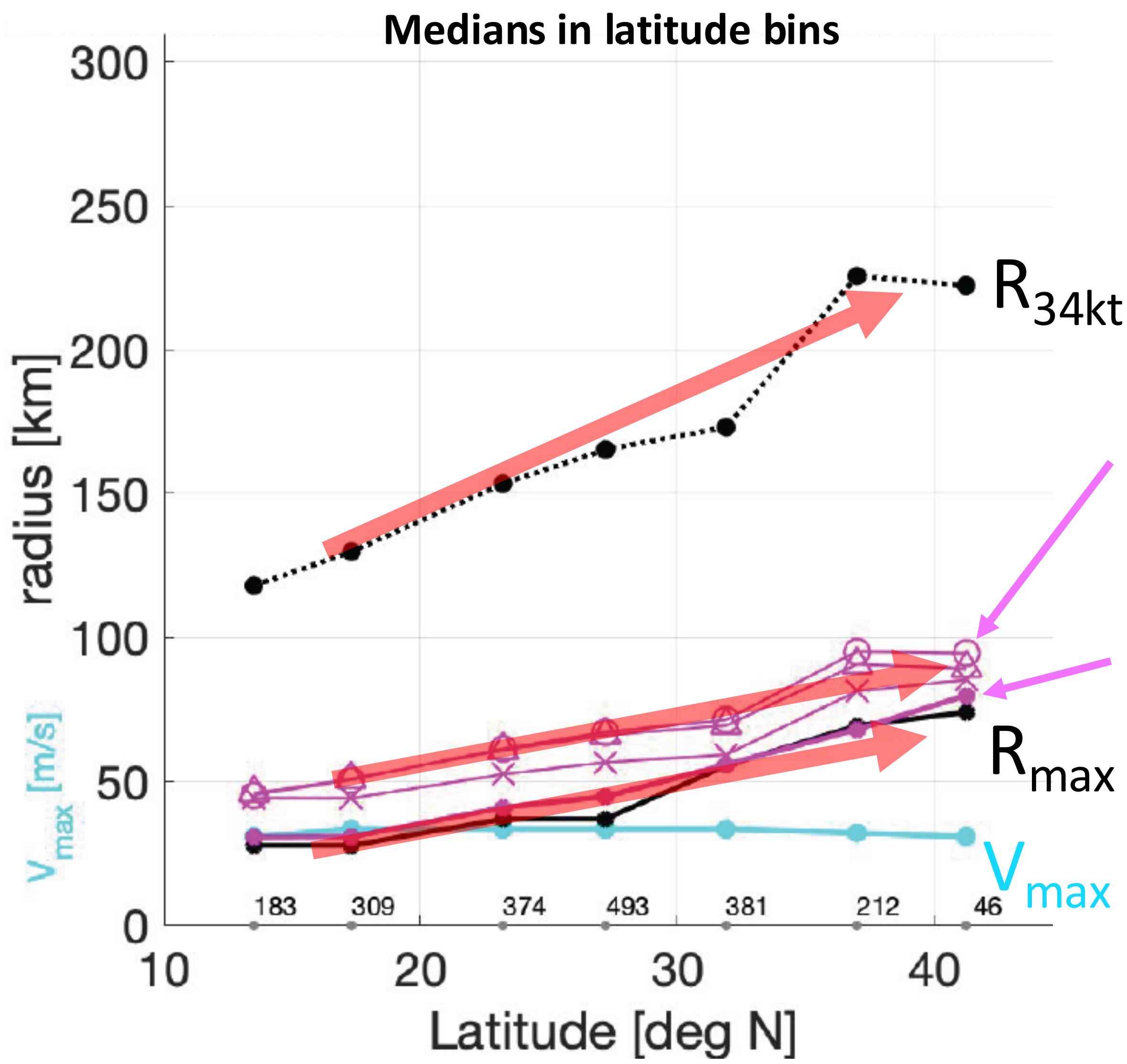


Model applied to high latitudes works pretty well too (*not* refit)

Noisier.
Storms more asymmetric (interaction with extratropical systems, land)



Poleward increase in R_{max} is due to poleward increase in R_{34kt}



Statistically, R_{max} ↑ as latitude ↑

Kossin (2007)

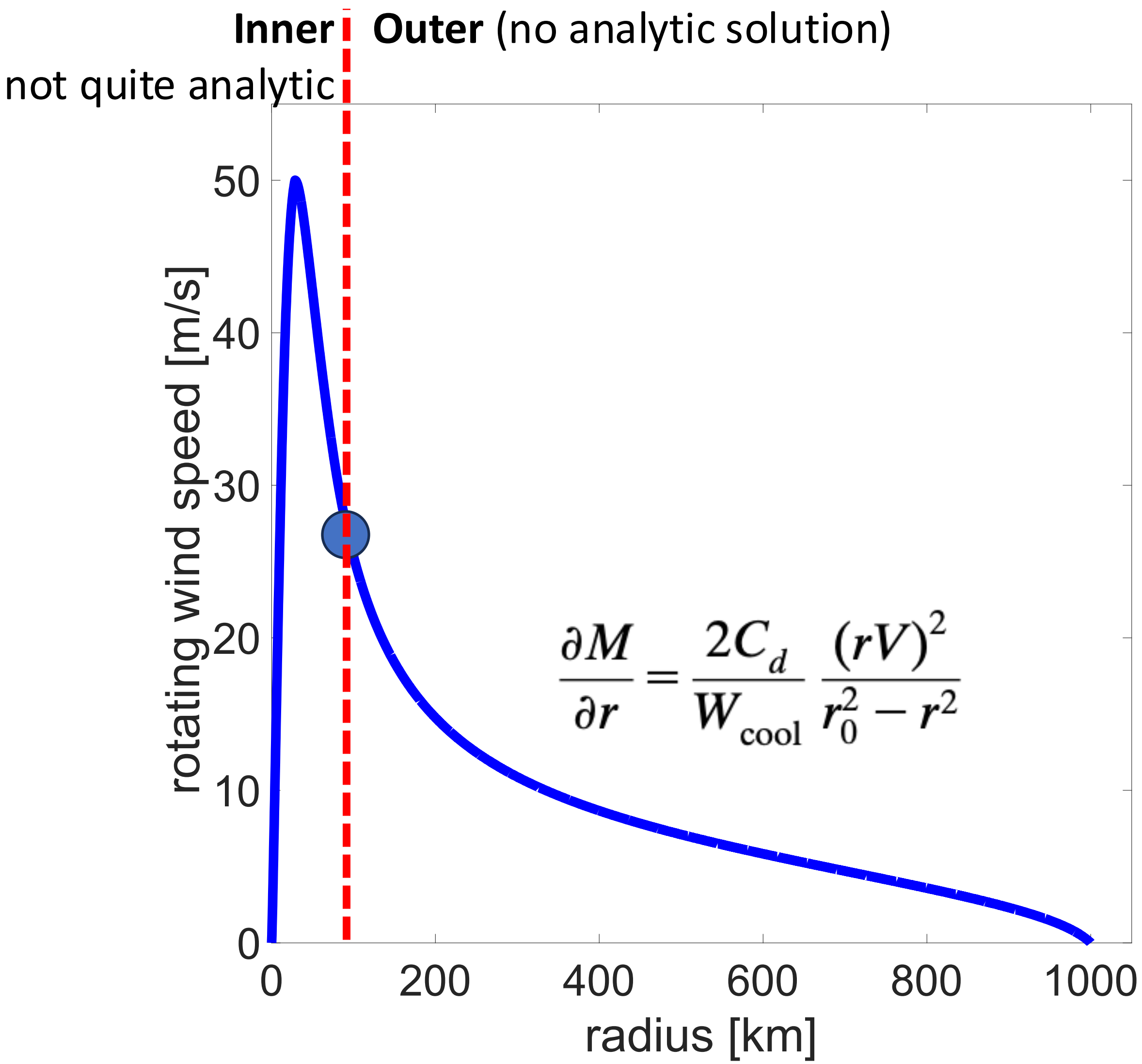
“Experiments”: fit model to medians, turn on/off variation in V_{max}, latitude

→ **slope does not change**

Predicted R_{max}

New analytic wind model

Old model



Inputs V_{max}, R_{34kt} , (and latitude)

Problems:

- Requires numerical solver – code is slower, harder to use
- Fixed relationship between angular momentum at R_{34kt} and R_{max} – too rigid for real storms (Tao et al. 2023, GRL)

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

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

New model

Tao, Nystrom, Chavas, Avenas (2025, GRL) *minor revision*

(1) Eye: linear

$$V(r) = V_m \frac{r}{r_m}, r \leq r_m.$$

(2) Inner core (R_{max} → R_{34kt}): linear M-slope

(Tao et al. 2023, GRL)

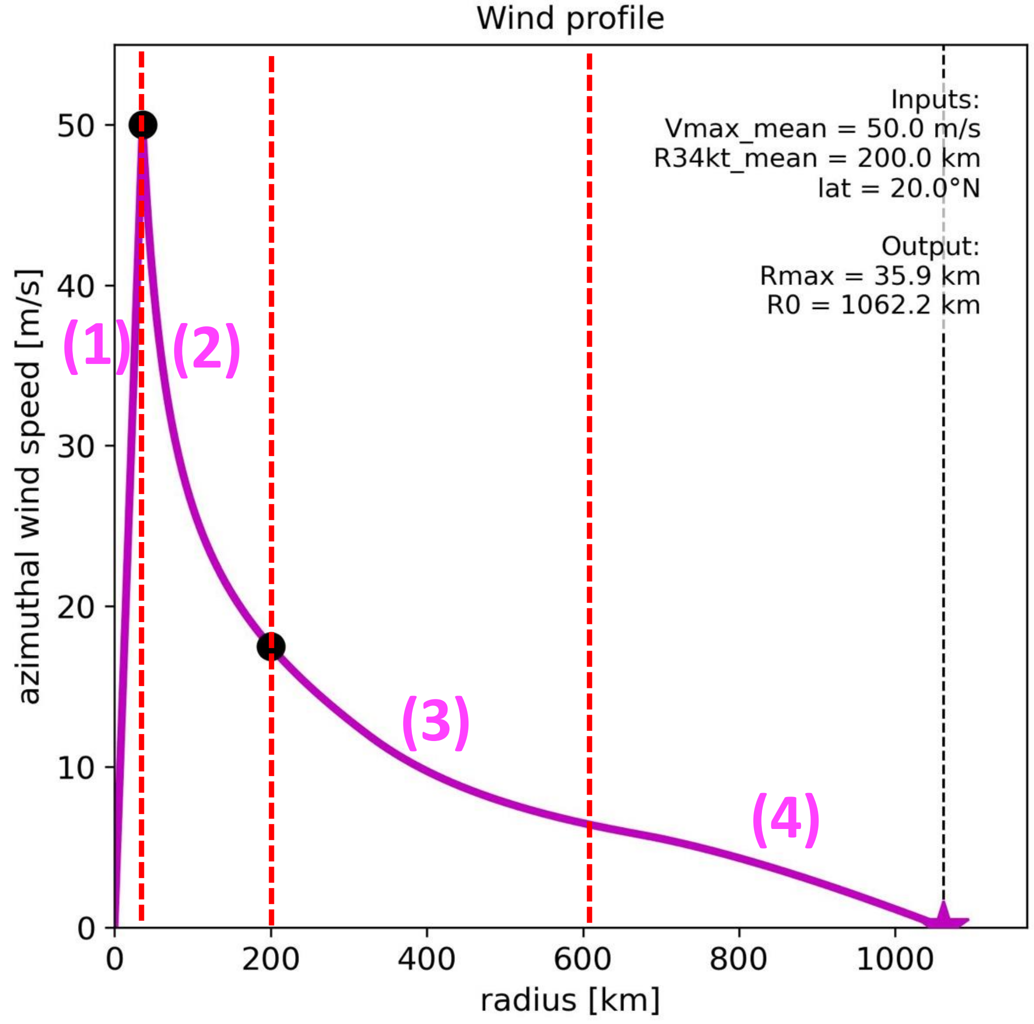
$$V(r) = \left[\left(\frac{r}{r_m} - 1 \right) SL_{17.5} + 1 \right] \frac{M_m}{r} - \frac{1}{2} f r, r_m \leq r \leq r_a;$$

(3) Intermediate (R_{34kt} → R_{trans}): Mod-rankine

$$V(r) = Ar^{-1}, r_a \leq r \leq r_b;$$

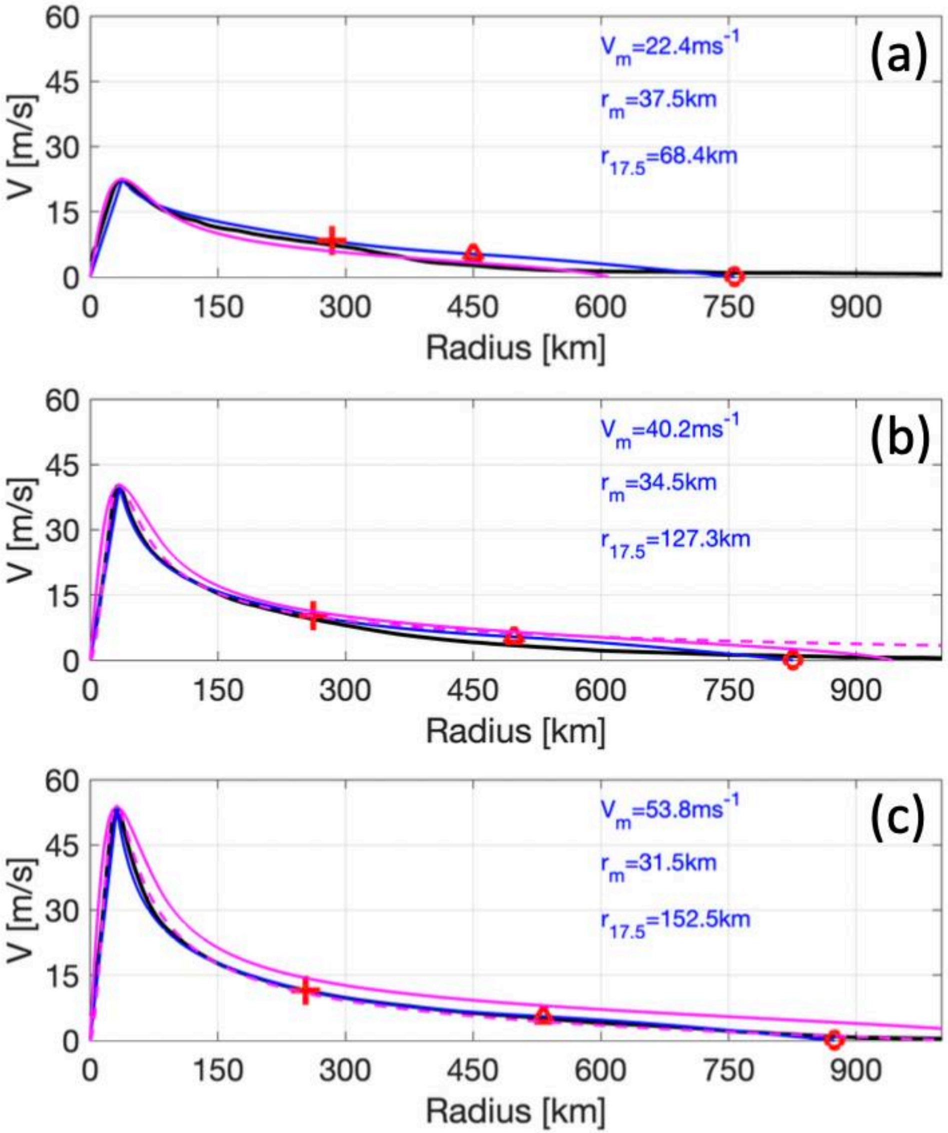
(4) Outer (R_{trans} → R_0): analytic approx to physical outer wind model (new!)

$$V(r) = \frac{A - \frac{1}{2} f r_b^2}{r} + f r_b - \frac{1}{2} f r, r_b \leq r \leq r_0.$$



Inputs V_{max}, R_{34kt} , R_{max} (and latitude) – allows for variation in R_{max} → R_{34kt}

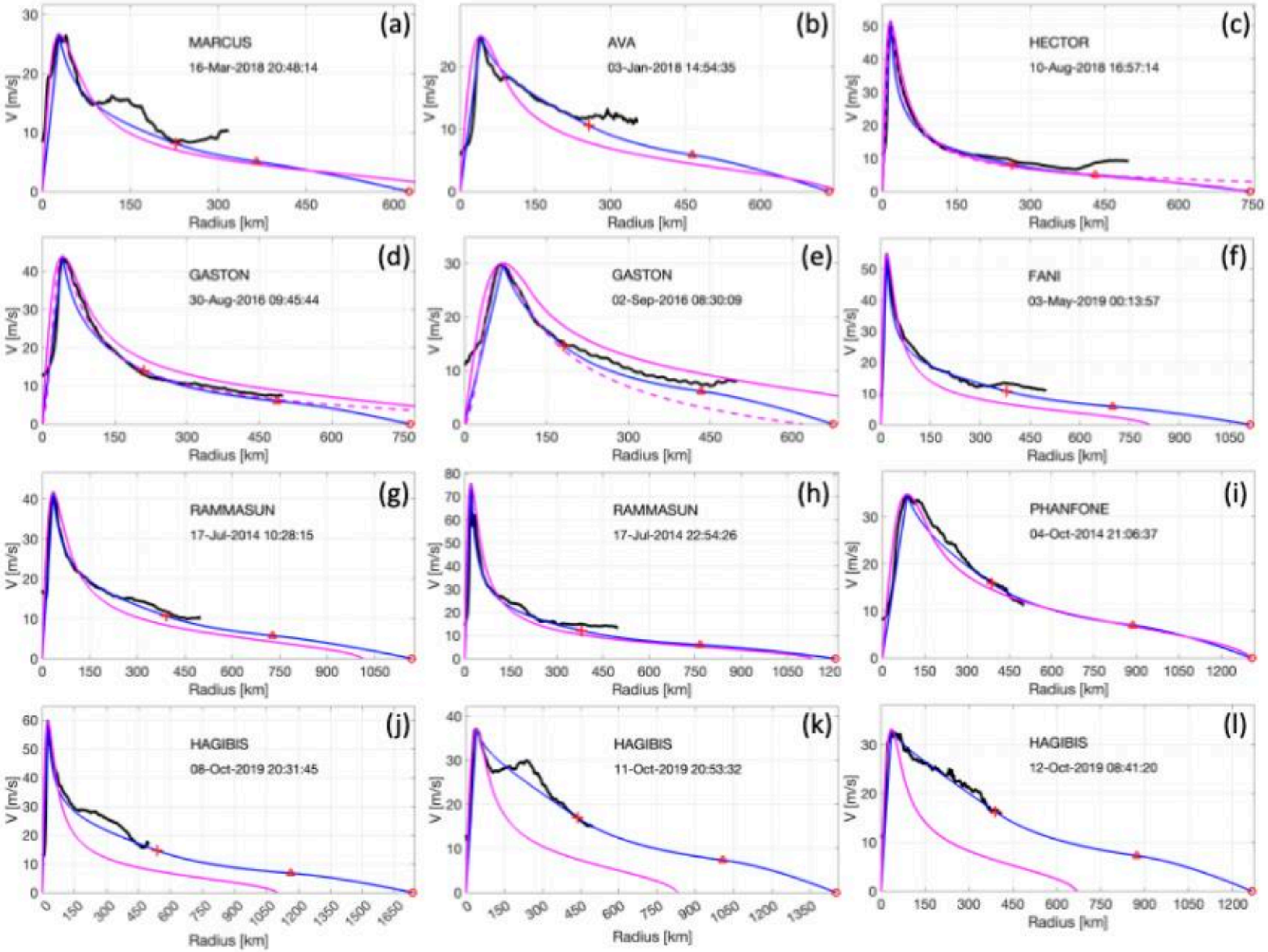
Better captures CM1 simulations

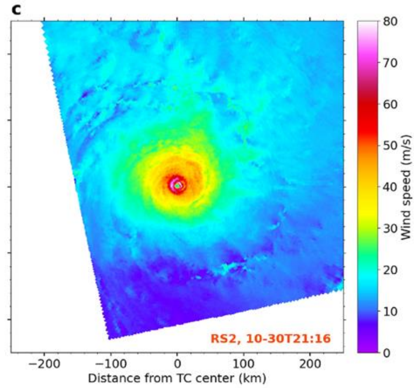


C15 model (solid)
New model

Tao, Nystrom, Chavas, Avenas (2025, GRL) *minor revision*

Better captures SAR observed profiles



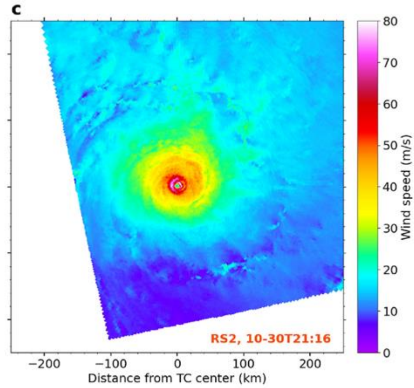


Avenas et al. (2025, Sci. Rep.)

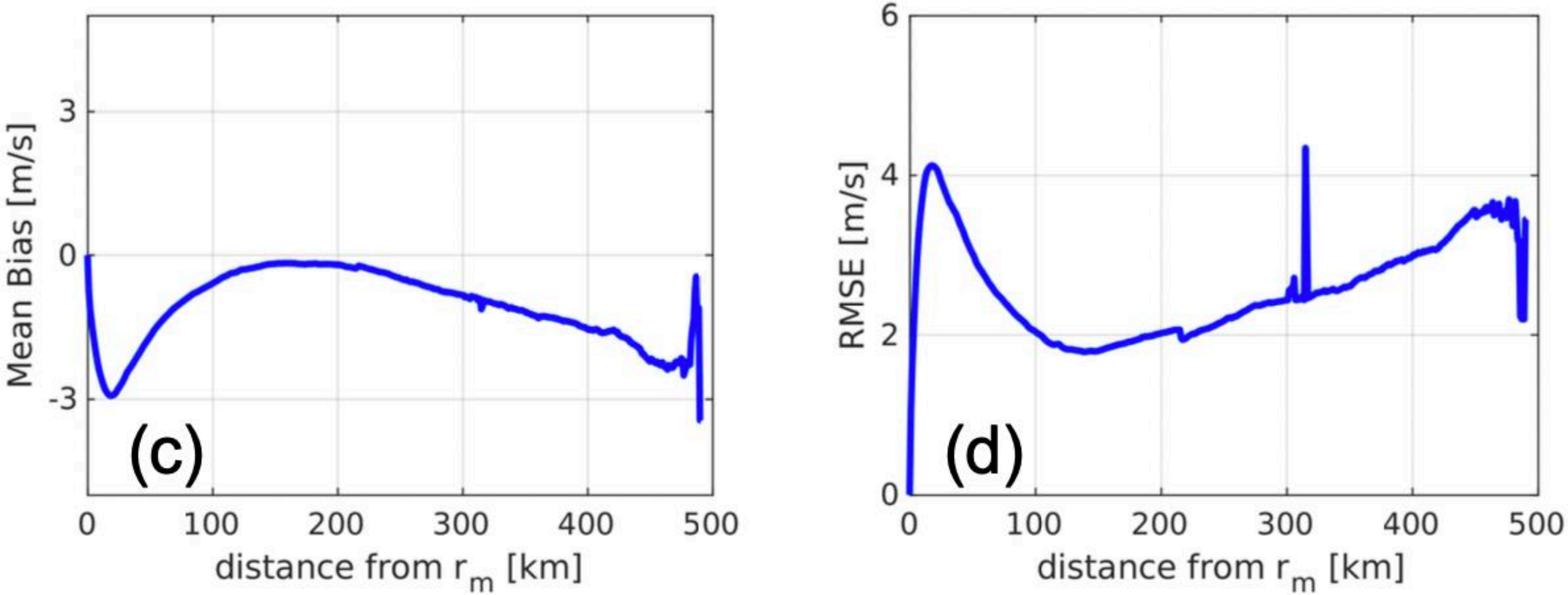
C15 model (solid)
New model

Tao, Nystrom, Chavas, Avenas (2025, GRL) *minor revision*

Better captures SAR observed profiles



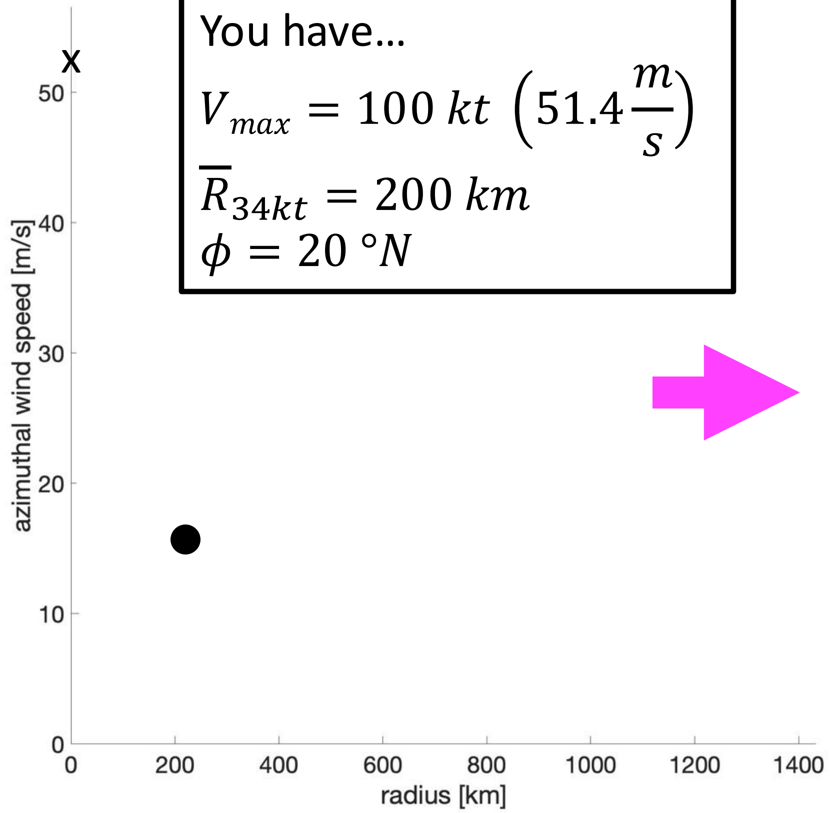
Avenas et al. (2025, Sci. Rep.)



Tao, Nystrom, Chavas, Avenas (2025, GRL) *minor revision*

Put the pieces together:
a complete model

A fast, analytic wind+pressure model: rooted in physics, fit to observations



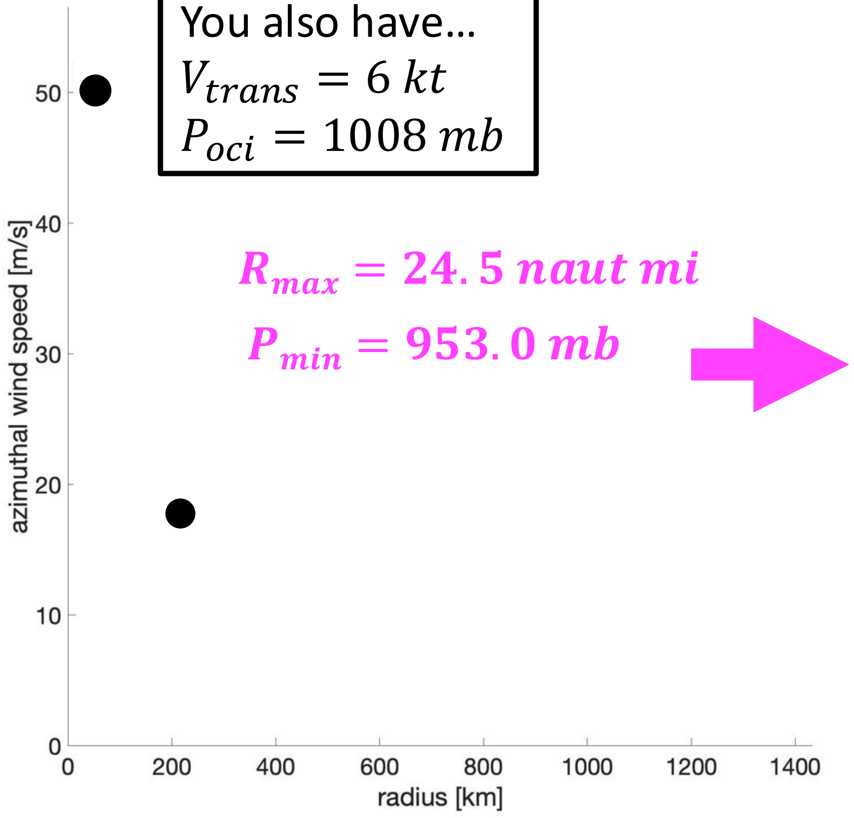
You have...

$V_{max} = 100\ kt\ \left(51.4 \frac{m}{s}\right)$

$\overline{R}_{34kt} = 200\ km$

$\phi = 20\ °N$

Note: these are the parameters we typically are most confident in



You also have...

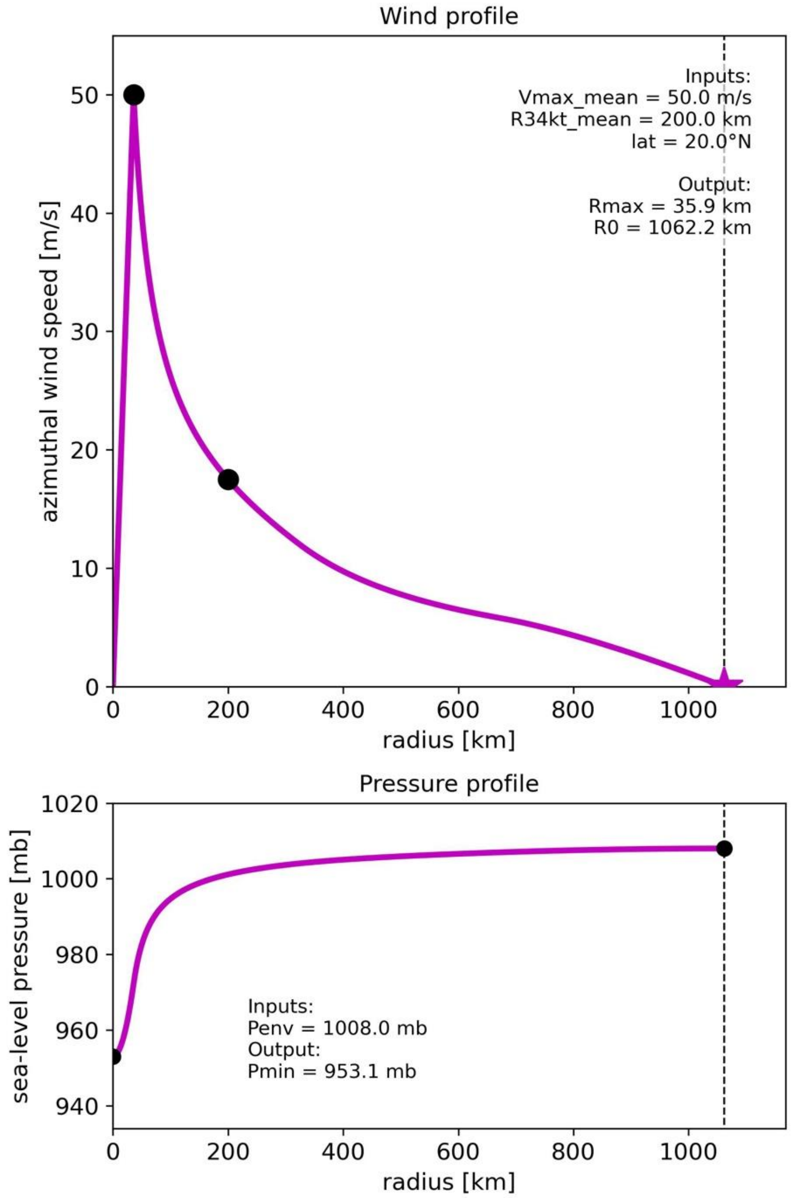
$V_{trans} = 6\ kt$

$P_{oci} = 1008\ mb$

$\boldsymbol{R_{max} = 24.5\ naut\ mi}$

$\boldsymbol{P_{min} = 953.0\ mb}$

or you can use observed estimate of R_{max} if you have it



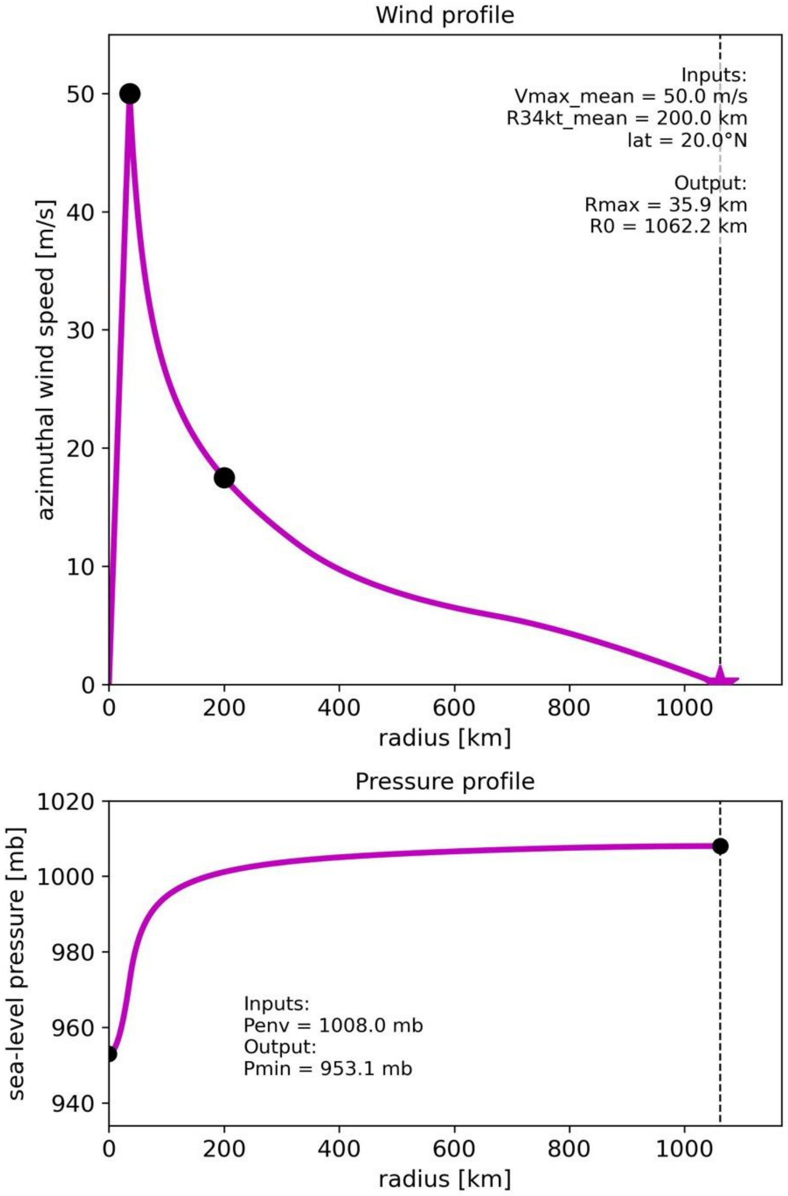
‘tcwindprofile’ python package

doi:10.4231/CZ4P-D448

https://web.ics.purdue.edu/~dchavas/codedata.html

Pieces together recent models validated against observational datasets
(Best Track, QuikSCAT, aircraft, SAR)

Inputs: V_{max}, R_{34kt}, track, P_{env}
Output: full wind and pressure profiles



Simple "operations-ready" models for R_{max}, P_{min}, and wind profile

Easy to implement, could be updated based on new data and/or modified to suit operational needs.

MAY 2022 CHAVAS AND KNAFF 563

A Simple Model for Predicting the Tropical Cyclone Radius of Maximum Wind from Outer Size

DANIEL R. CHAVAS[a] AND JOHN A. KNAFF[b]

FEBRUARY 2025 CHAVAS ET AL. 333

A Simple Model for Predicting Tropical Cyclone Minimum Central Pressure from Intensity and Size

DANIEL R. CHAVAS,[a] JOHN A. KNAFF,[b] AND PHIL KLOTZBACH[c]

[a] *Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, Indiana*
[b] *NOAA/Center for Satellite Applications and Research, Fort Collins, Colorado*
[c] *Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado*

(Manuscript received 21 February 2024, in final form 22 July 2024, accepted 15 August 2024)

manuscript submitted to *Geophysical Research Letters*

A fast analytical model for the complete radial structure of tropical cyclone low-level wind field

Dandan Tao[1], Robert G. Nystrom[2], Daniel R. Chavas[3], Arthur Avenas[4,5]

tcwindprofile 2.0.3

`pip install tcwindprofile`

Latest version

Released: 5 minutes ago

Create a fast and robust radial profile of the tropical cyclone rotating wind and pressure field from inputs Vmax, R34kt, latitude, translation speed, and environmental pressure

Manage project

Navigation

- Project description
- Release history
- Download files

Verified details

These details have been verified by PyPI

Project description

A fast, robust, physics-based model for the complete radial profile of tropical cyclone wind and pressure

Author: Dan Chavas (2025)

https://pypi.org/project/tcwindprofile/ : A package that creates a fast, robust, physics-based radial profile of the tropical cyclone rotating wind and pressure from input Vmax, R34kt, latitude, translation speed, and environmental pressure. Based on the latest observationally-validated science on the structure of the wind field and pressure.

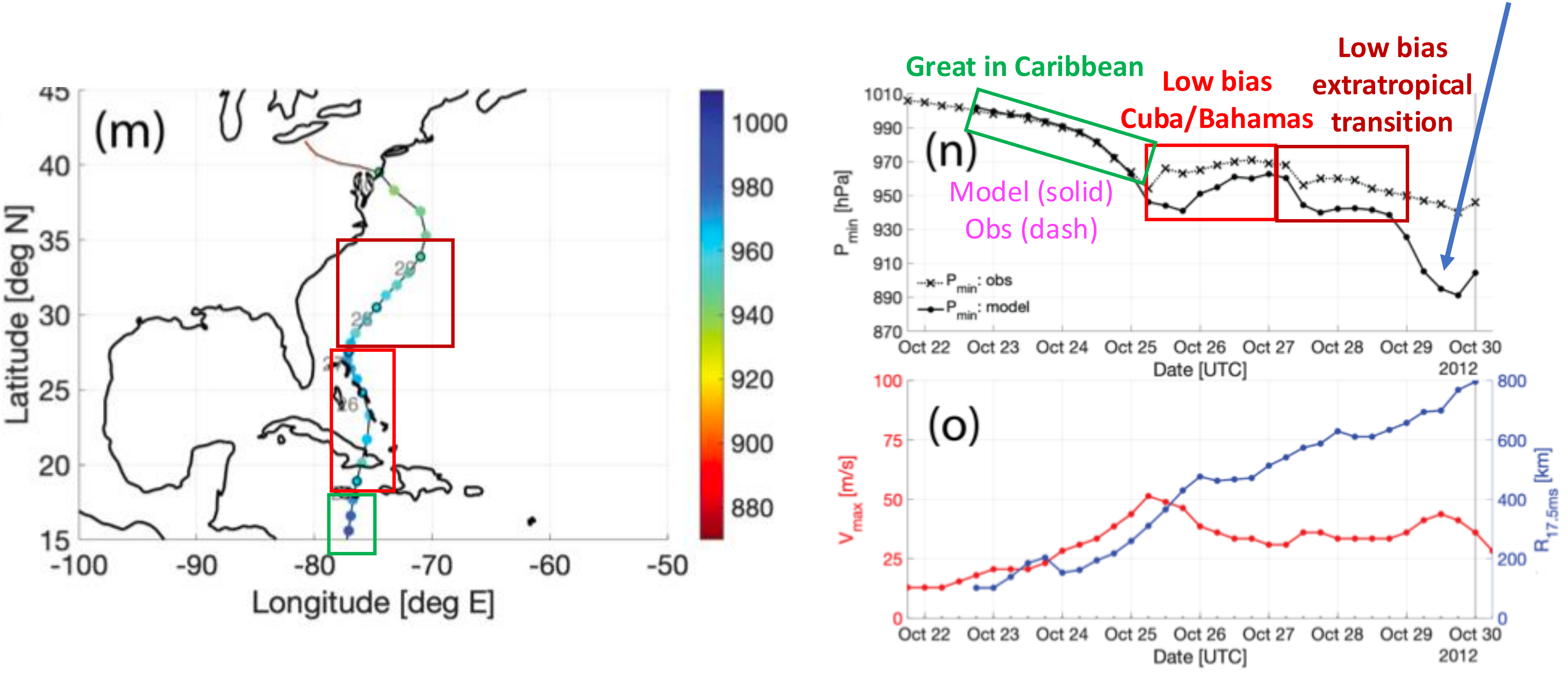
doi:10.4231/CZ4P-D448

https://web.ics.purdue.edu/~dchavas/codedata.html

EXTRA

Sandy (2012): the most difficult test case

a massive, hybrid tropical/extratropical storm



Plenty of uncertainty in the data for such a large storm,

but also likely indicates that for extratropical systems the model assumptions do break down

Eye: $$\Delta P_e = -\frac{1}{4}\rho V_{max}^2 - \frac{2}{3}\rho V_o^2 \left(\frac{\frac{1}{2} f R_o}{V_{max}} \right)$$

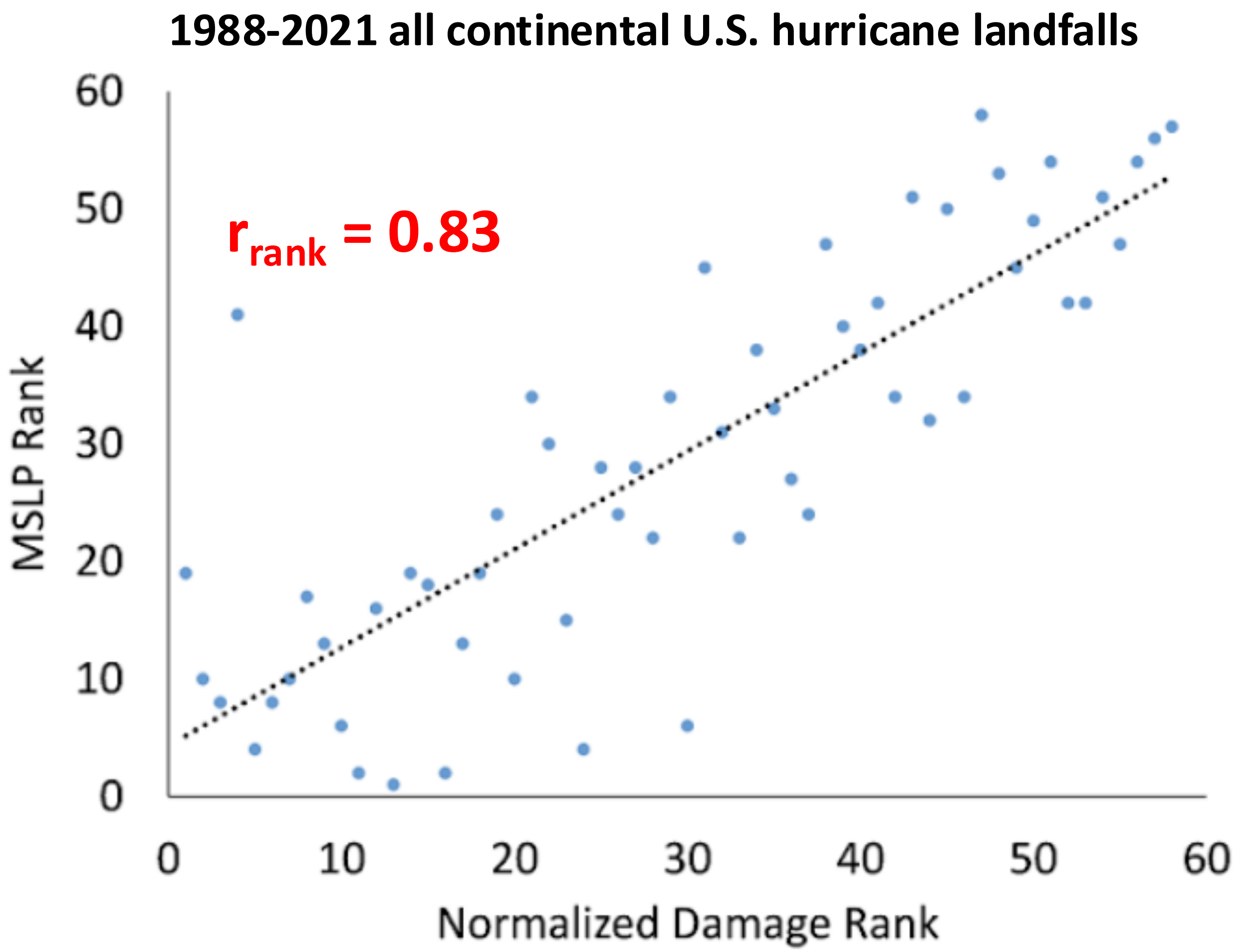
Outside eye: $$\Delta P_o = -\rho V_{max}^2 + \rho V_o^2 - 4V_o \left(\frac{1}{2} f R_o \right) + 4V_o^2 \left(\frac{\frac{1}{2} f R_o}{V_{max}} \right)$$

Sum: $$\Delta P_{theo} = \rho \left[V_0^2 - \frac{5}{4} \left(V_{max}^2 \right) - 4V_o \left(\frac{1}{2} f R_o \right) + \frac{10}{3} V_o^2 \left(\frac{\frac{1}{2} f R_o}{V_{max}} \right) \right]$$

@R_{34kt}: $$\Delta P_{hPa,theo} = 3.0625 - 0.0125 \left(V_{max}^2 \right) - 0.70 \left(\frac{1}{2} f R_o \right) + 10.208 \left(\frac{\frac{1}{2} f R_o}{V_{max}} \right)$$

P_{min} has a lot of important practical benefits

- We know the hazard print depends on the entire wind field
- P_{min} is an integrated measure of the wind field
- P_{min} is a remarkably good predictor of damage from continental U.S. hurricane landfall -- better than V_{max} and IKE/PDI
- V_{max} is a very poor predictor of damage along the U.S. East Coast
- P_{min} is relatively easy to estimate and varies smoothly



Klotzbach et al. (2022), *JGR-Atmos.*