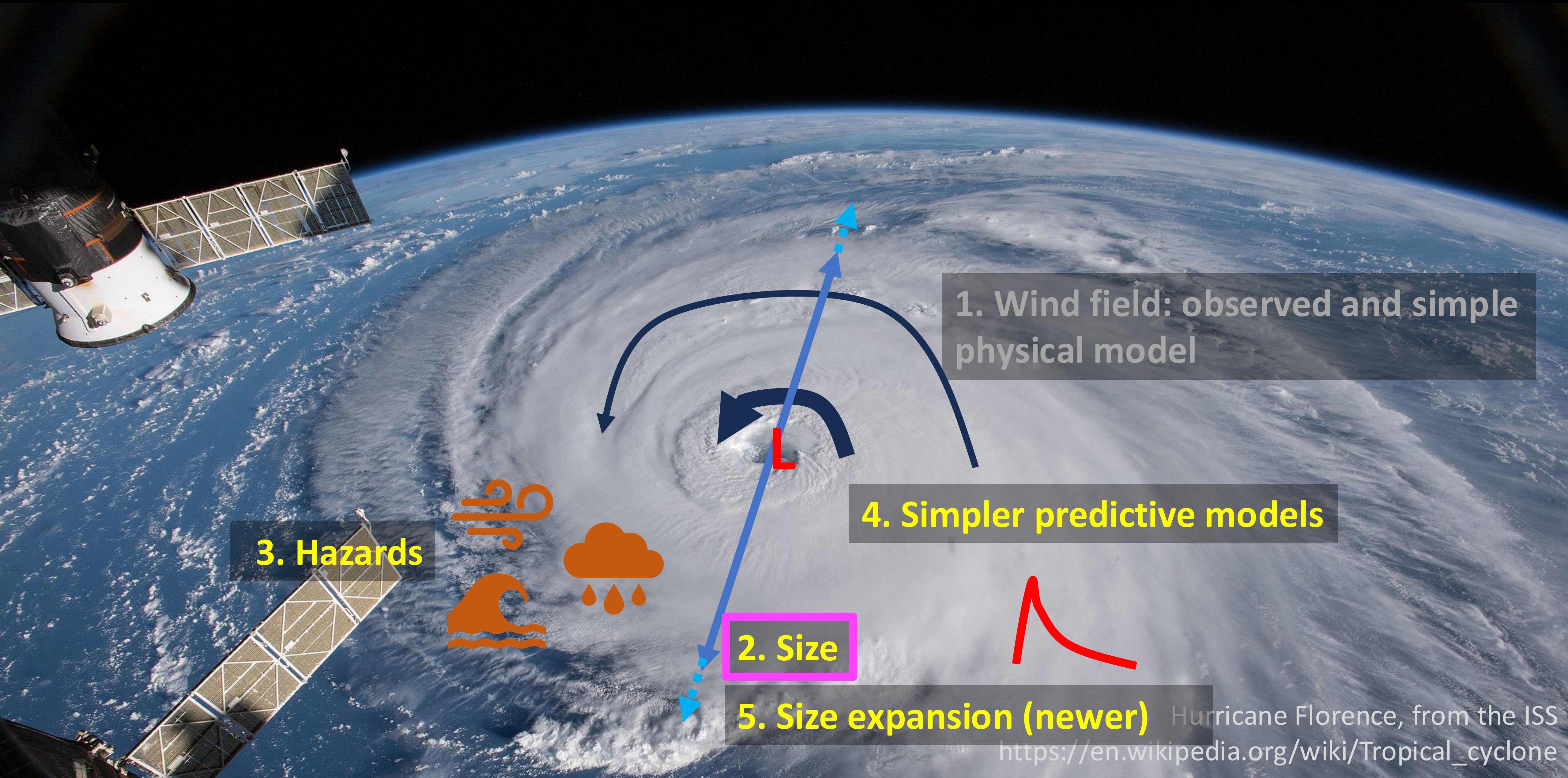
Roadmap

0. Intro: two recent events

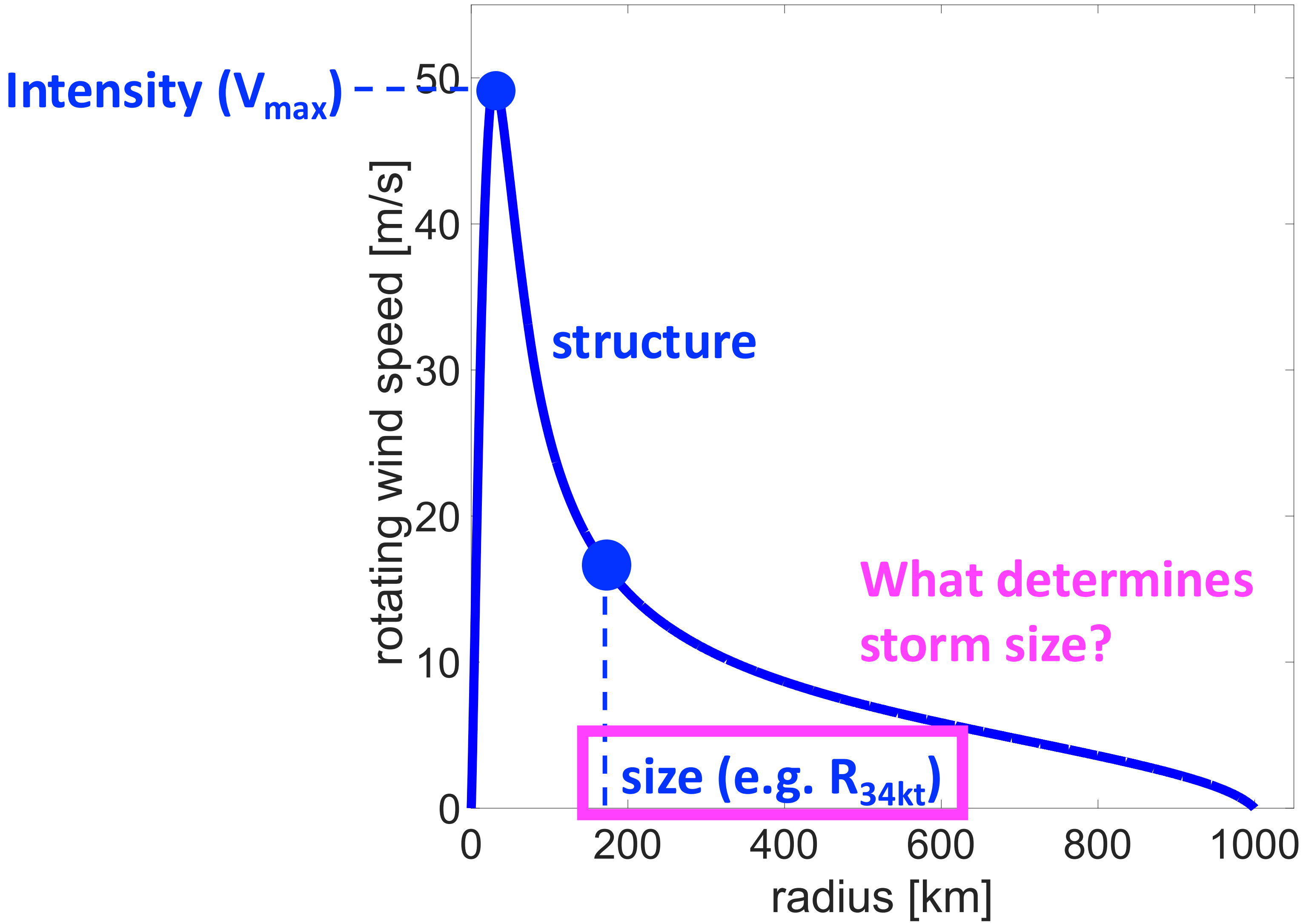


2. Tropical cyclone size

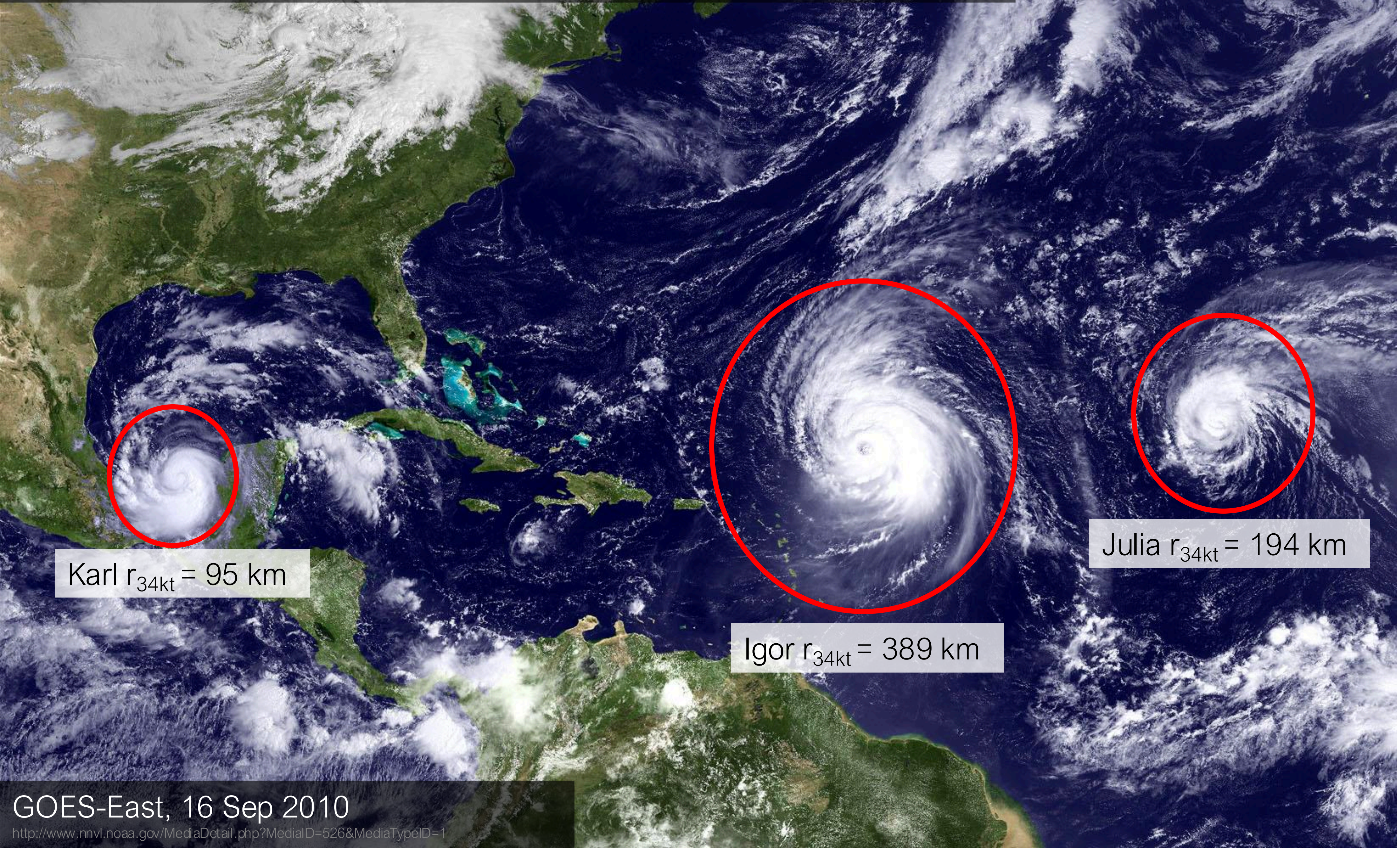
- Observations
- f-plane
- sphere (beta)
- Response to warming

Observations

Three essential components to the wind field



Size varies a lot in nature – independent of intensity

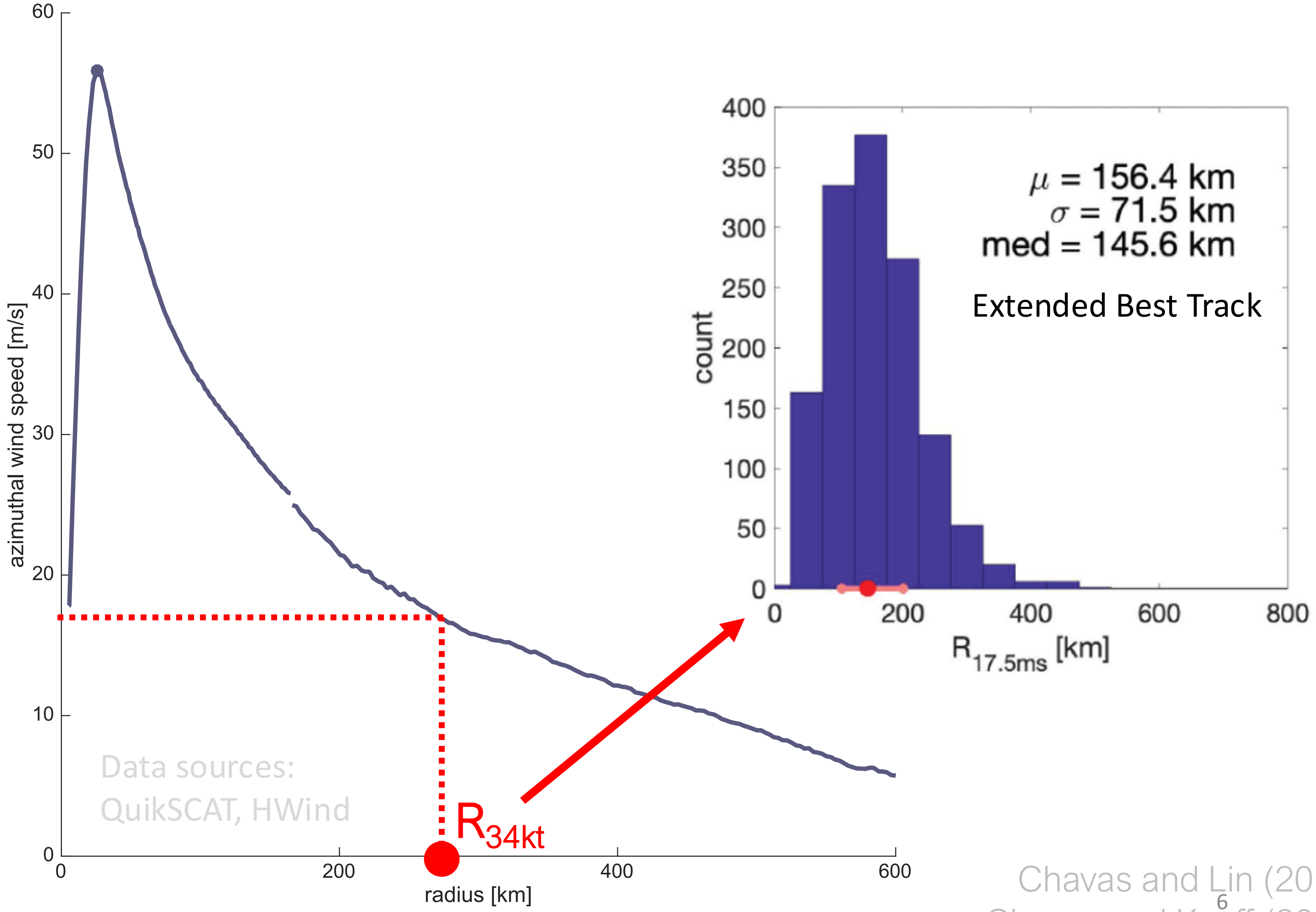


All $V_{max} \approx 50 \frac{m}{s}$ within 24 hr

Size varies widely in nature

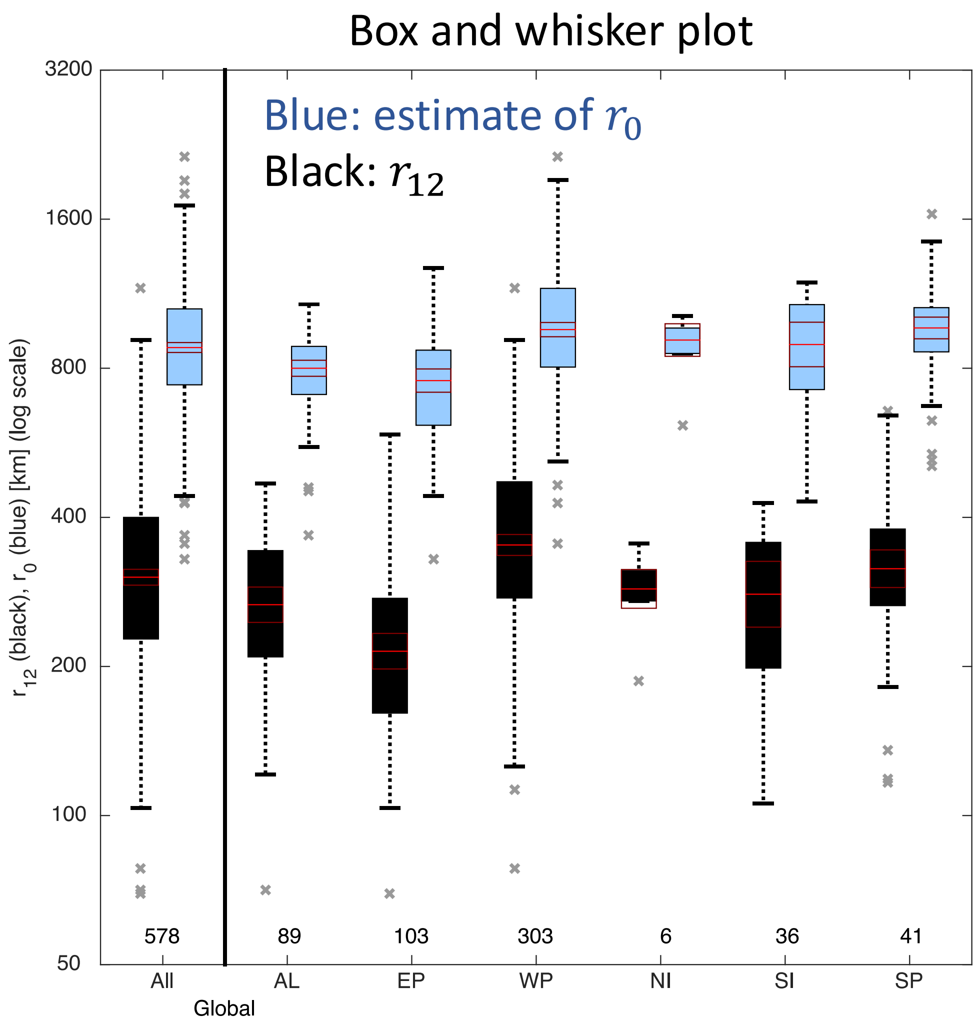
Size can vary significantly between storms, but typically changes more gradually during lifecycle.

Hence, TC size is often set by size of initiating disturbance.



Chavas and Lin (2016)
Chavas and Knaff (2022)

Largest storms in West Pac, smallest in East Pac

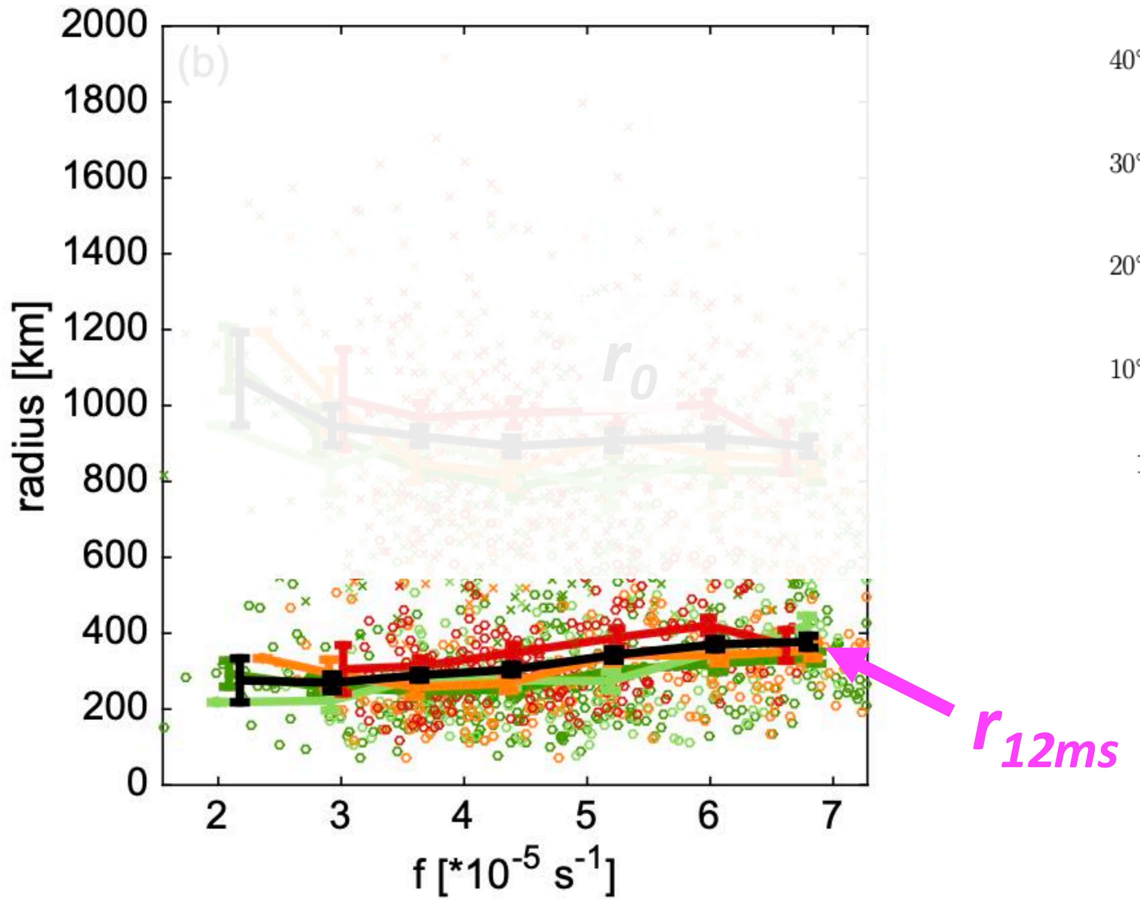


Outer size distribution is approximately **log-normal**

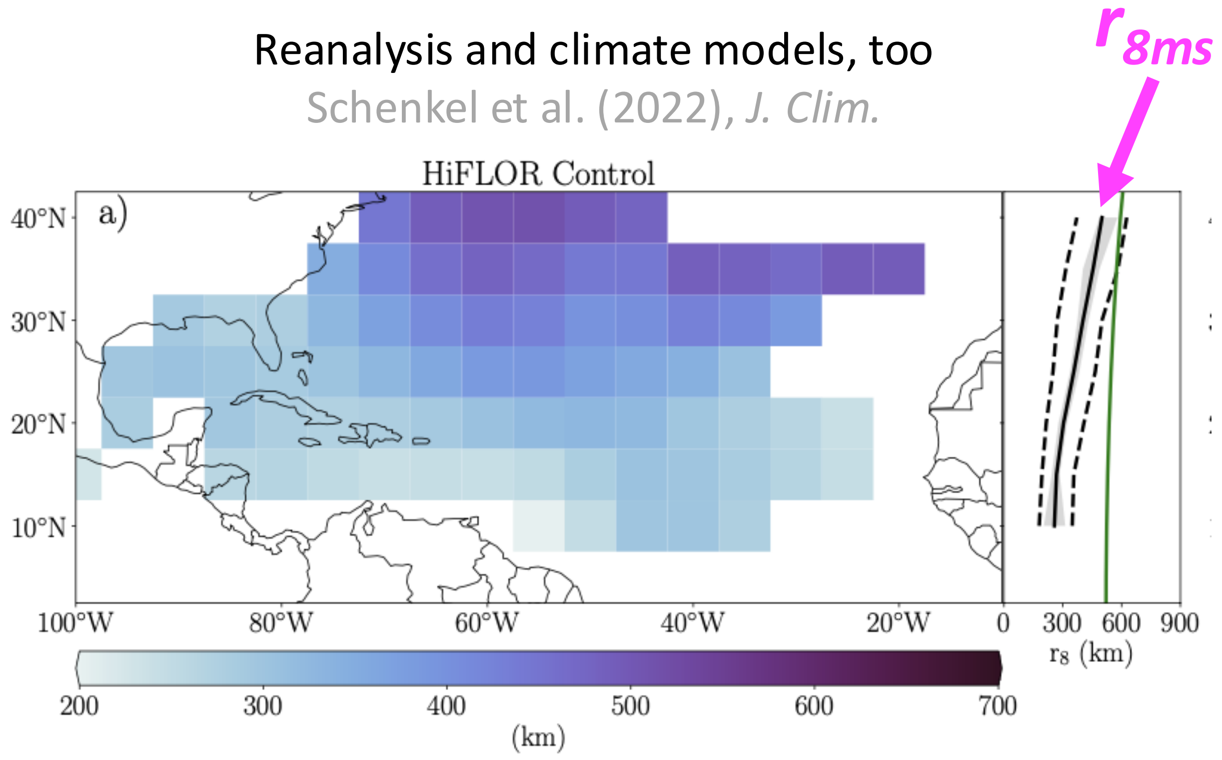
Chavas et al. (2016)

Size increases very slowly with latitude in the tropics

Observed storm size
QuikSCAT 1999-2009
Chavas et al. (2016) *J. Clim.*



Reanalysis and climate models, too
Schenkel et al. (2022), *J. Clim.*



Why?

This is a critical test.

Research questions

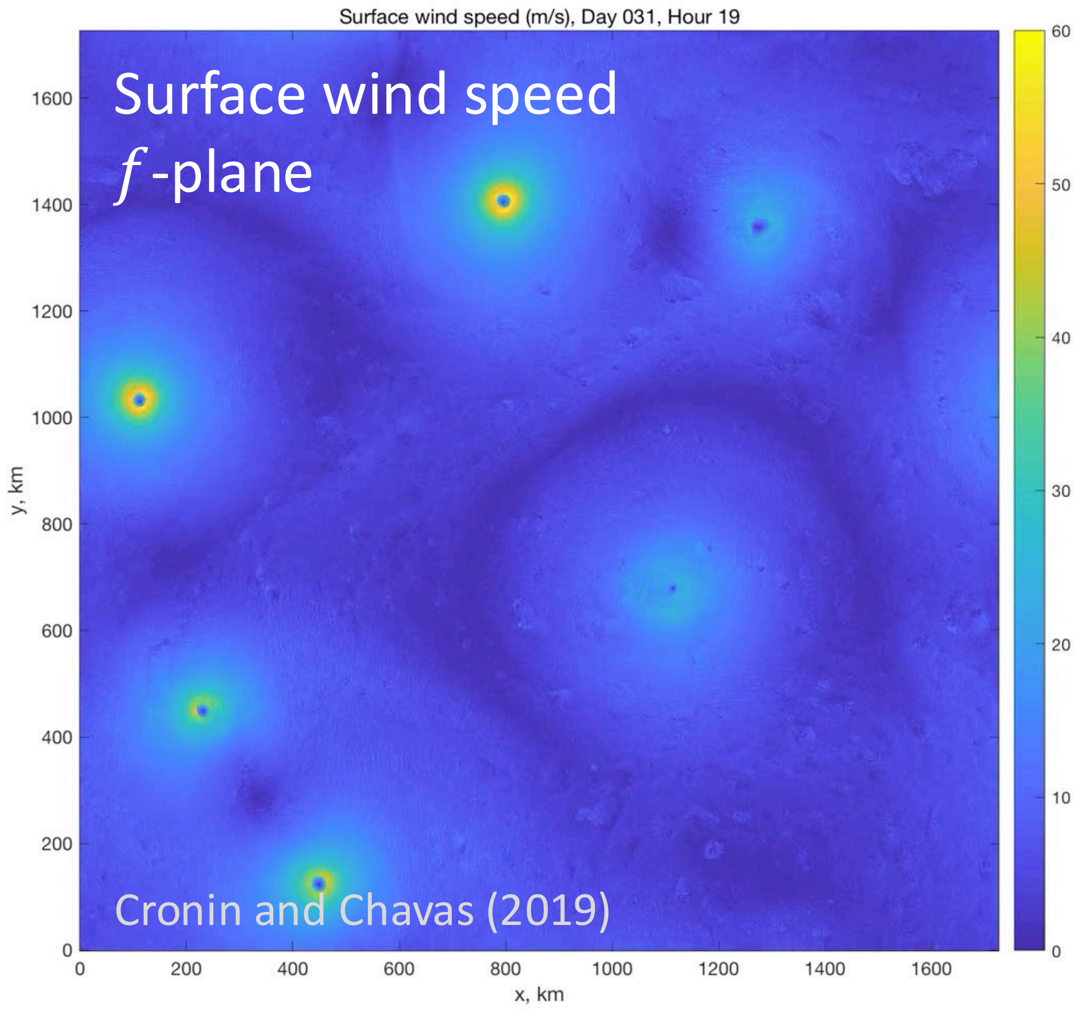
1. What sets tropical cyclone size on Earth?

2. Why the Rhines scale?

3. Will size change in the future?

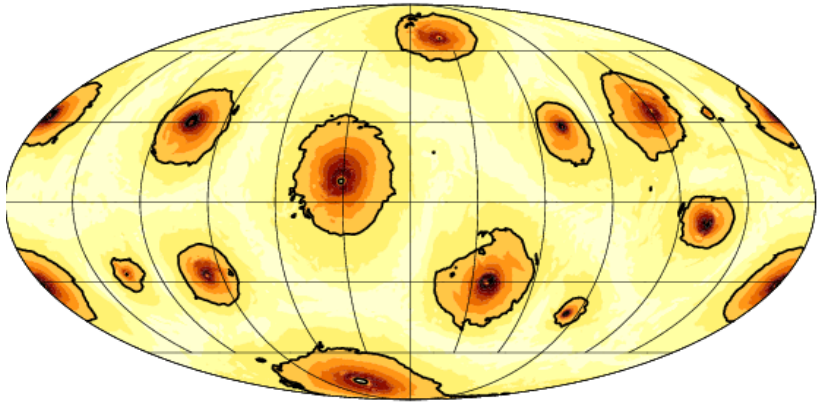
Simplest world:
the f-plane

Prevailing theory: size ~ $1/f$



On the f-plane, tropical cyclones form **spontaneously...** and fill up the domain.

On the f-sphere, too!

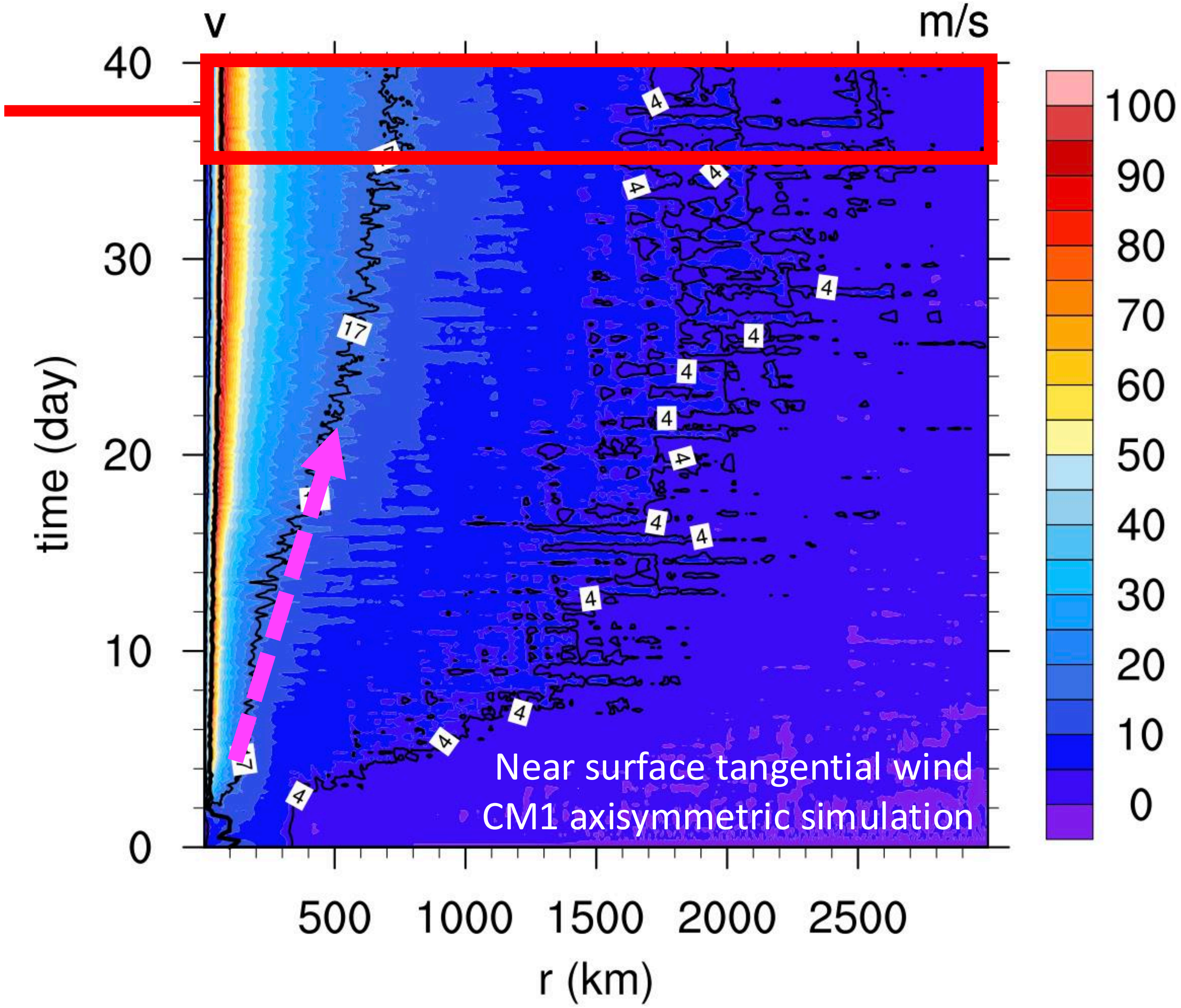


Reed and Chavas (2015)

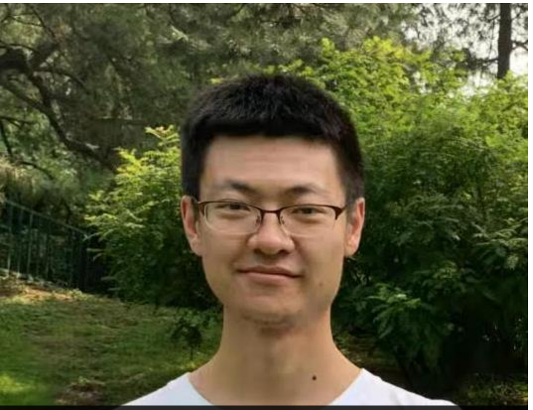
Khairoutdinov and Emanuel 2013, Chavas and Emanuel 2014, Zhou et al. 2014, Merlis et al. 2016, Zhou et al. 2017, Cronin and Chavas 2019

f-plane: TCs expand toward an equilibrium "potential size"

Potential size $\sim \frac{V_p}{f}$

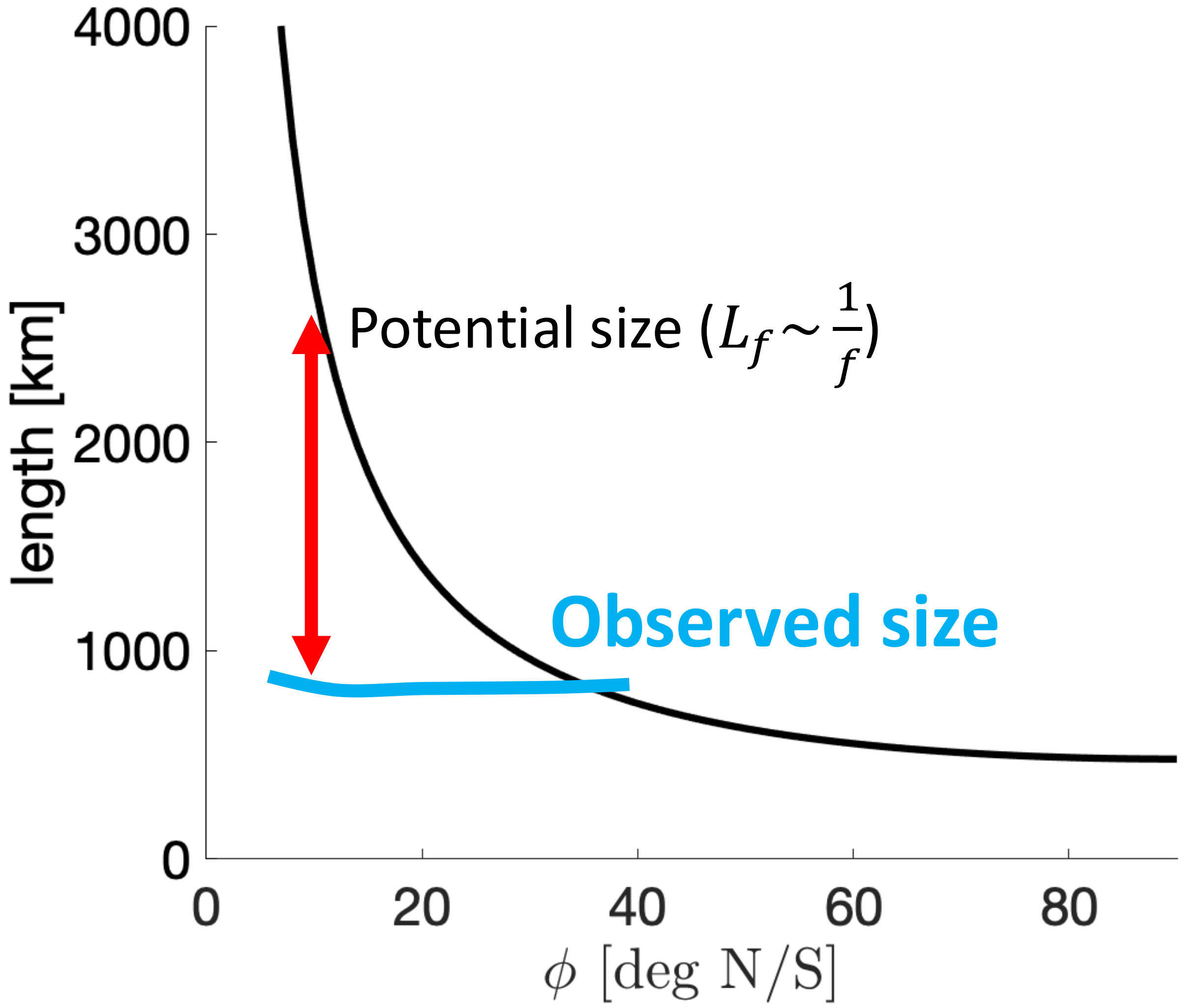


See also:
Fudeyasu and Wang (2011)
Chavas and Emanuel (2014)
Martinez et al. (2020)



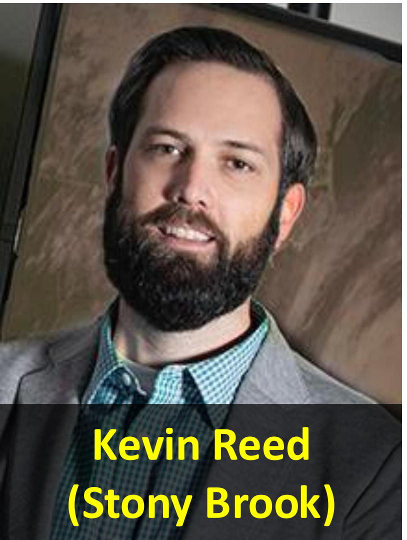
Postdoc Danyang Wang

Wang D., Lin Y. , and D. R. Chavas (2022)*. Tropical cyclone potential size, J. Atmos. Sci.* (theory later!)



But a $\frac{1}{f}$ scaling clearly does not explain observed size vs. latitude.

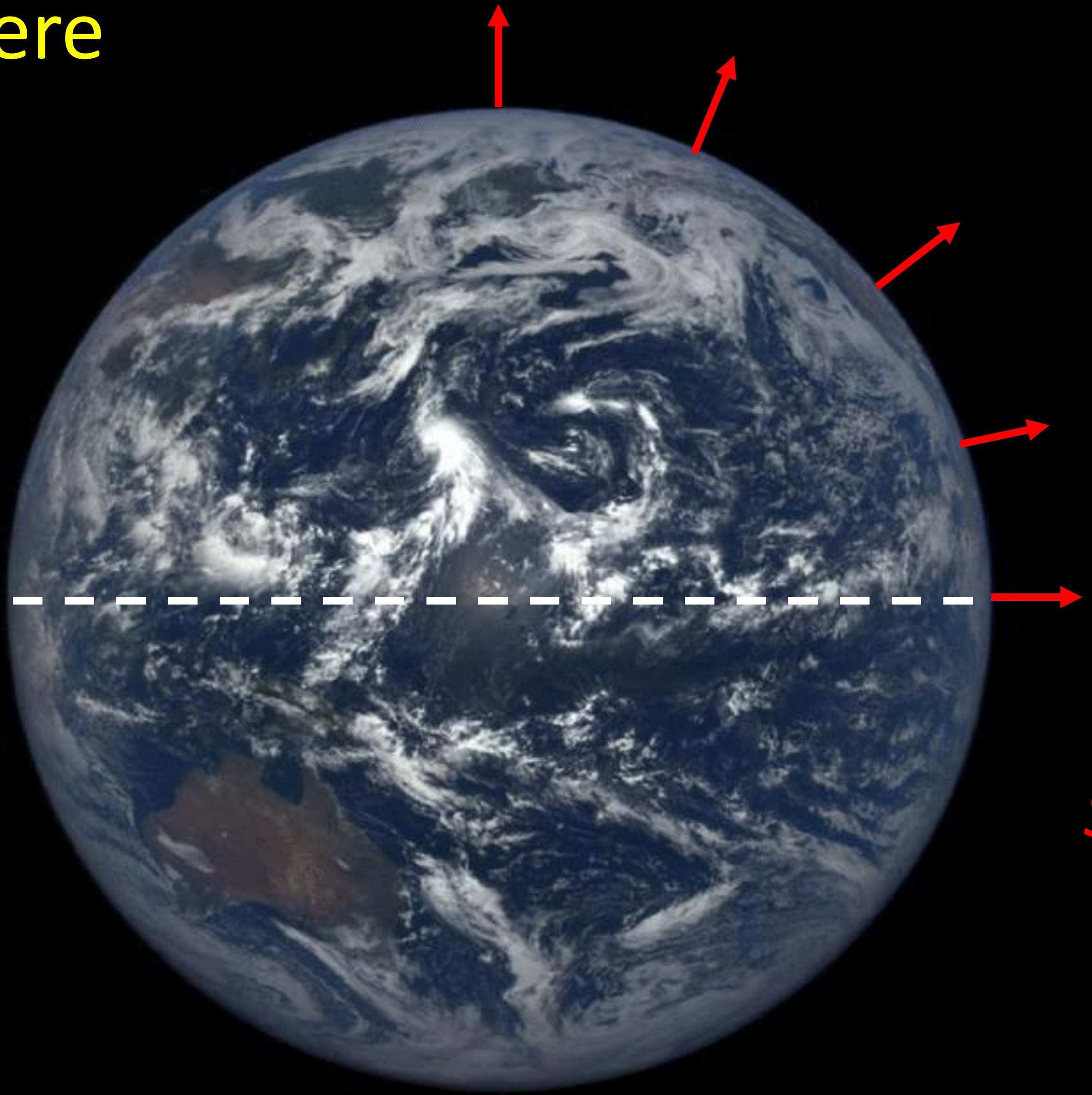
Consider the sphere (beta)



Chavas D. R. and K. A. Reed (2019). Dynamical aquaplanet experiments with uniform thermal forcing: system dynamics and implications for tropical cyclone genesis and size. ***J. Atmos. Sci.***, 76(8), pp.2257-2274.

The rotating sphere

$f = 2\Omega$ $\beta = 0$



$$f = 2\Omega sin\phi$$

$$\beta = \frac{\partial f}{\partial y} = \frac{2\Omega}{a} cos\phi$$

$f = 0$ $\beta = \frac{2\Omega}{a}$

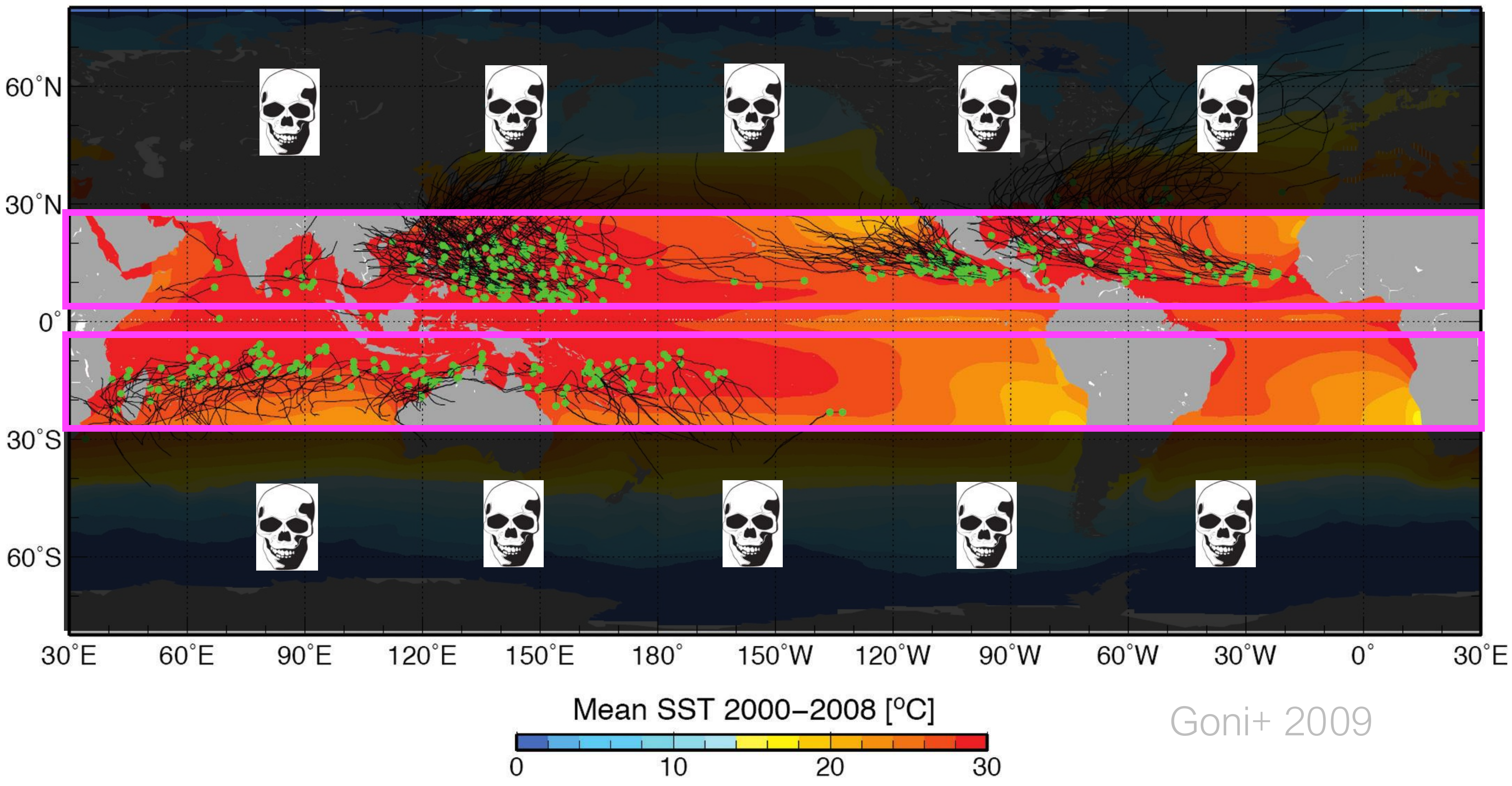
Source of rotation

Rossby waves!

https://media.giphy.com/media/o2XbUUi1CXKTe,

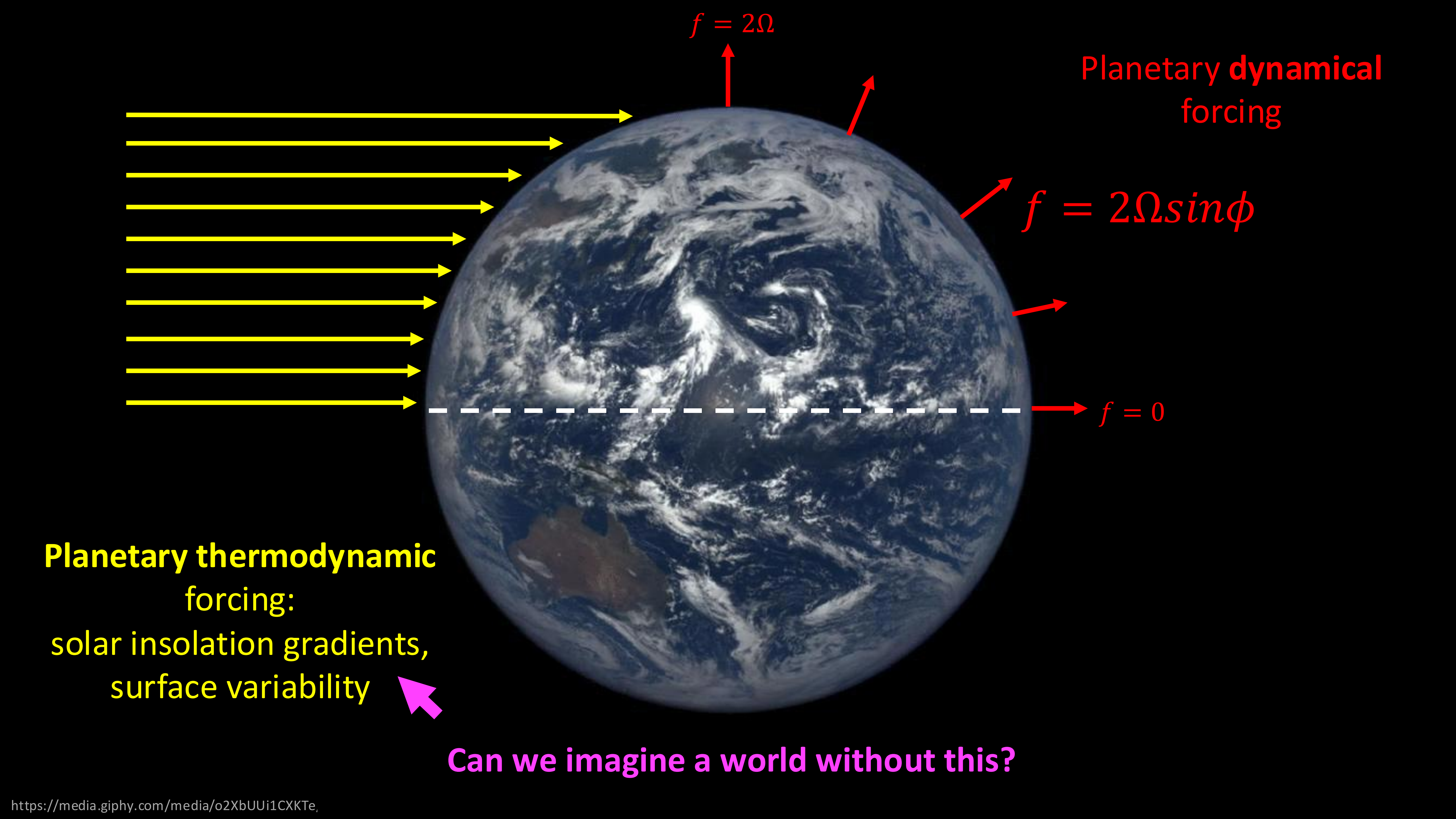
On Earth, hurricanes are confined *thermodynamically* to the tropics

2000-2008



This makes it difficult to understand fundamental **dynamical** controls.

But what if they weren't?

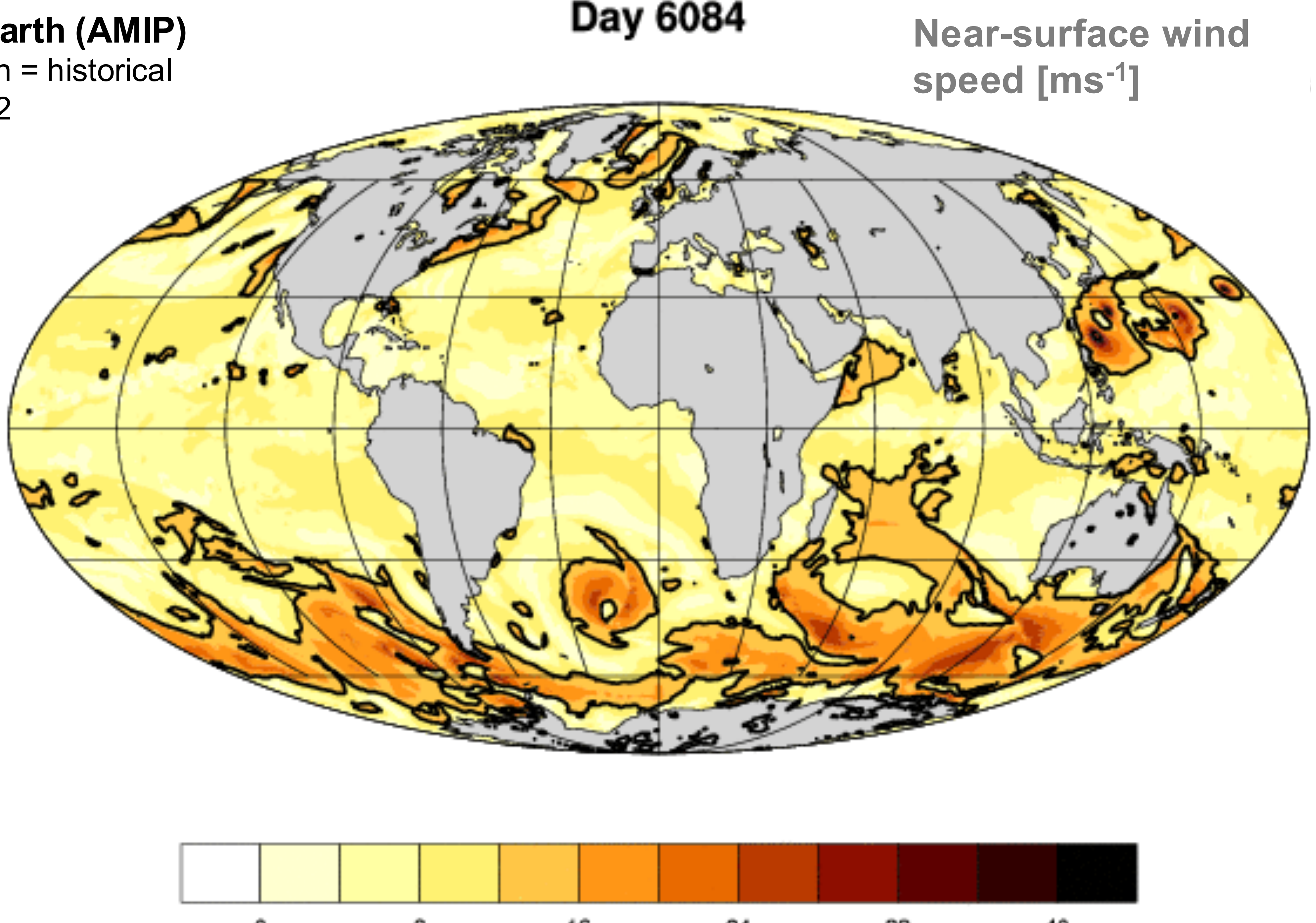

$f = 2\Omega$
Planetary **dynamical** forcing
$f = 2\Omega sin\phi$
$f = 0$
Planetary thermodynamic forcing:
solar insolation gradients,
surface variability
Can we imagine a world without this?
https://media.giphy.com/media/o2XbUUi1CXKTe/

Experimental laboratory:
NCAR Community Atmosphere Model v5.3

Horizontal resolution:
~25 km

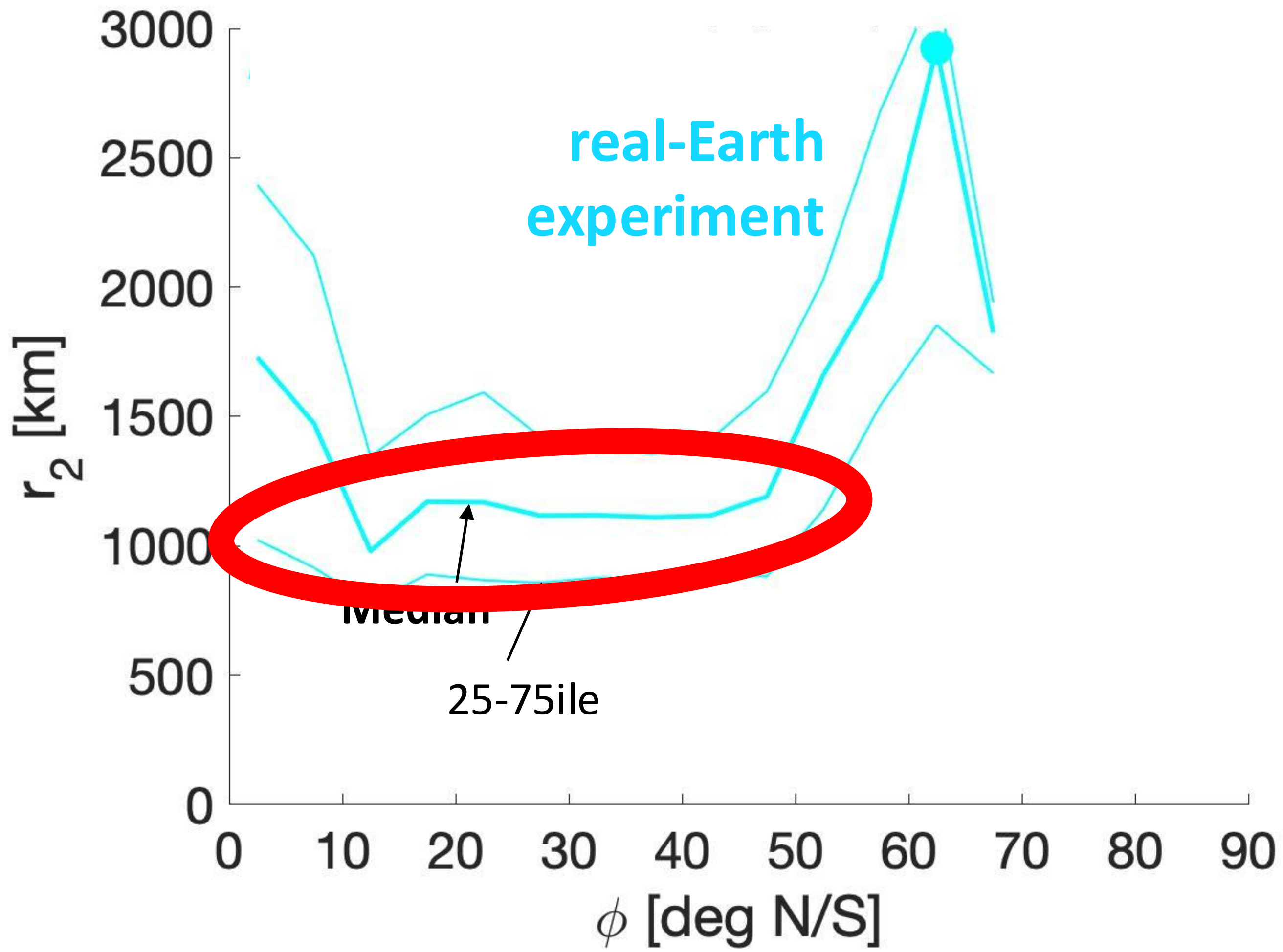
Historical Earth (AMIP)

SST/Insolation = historical
T = 1979-2012



GCM can reproduce observed size vs. latitude

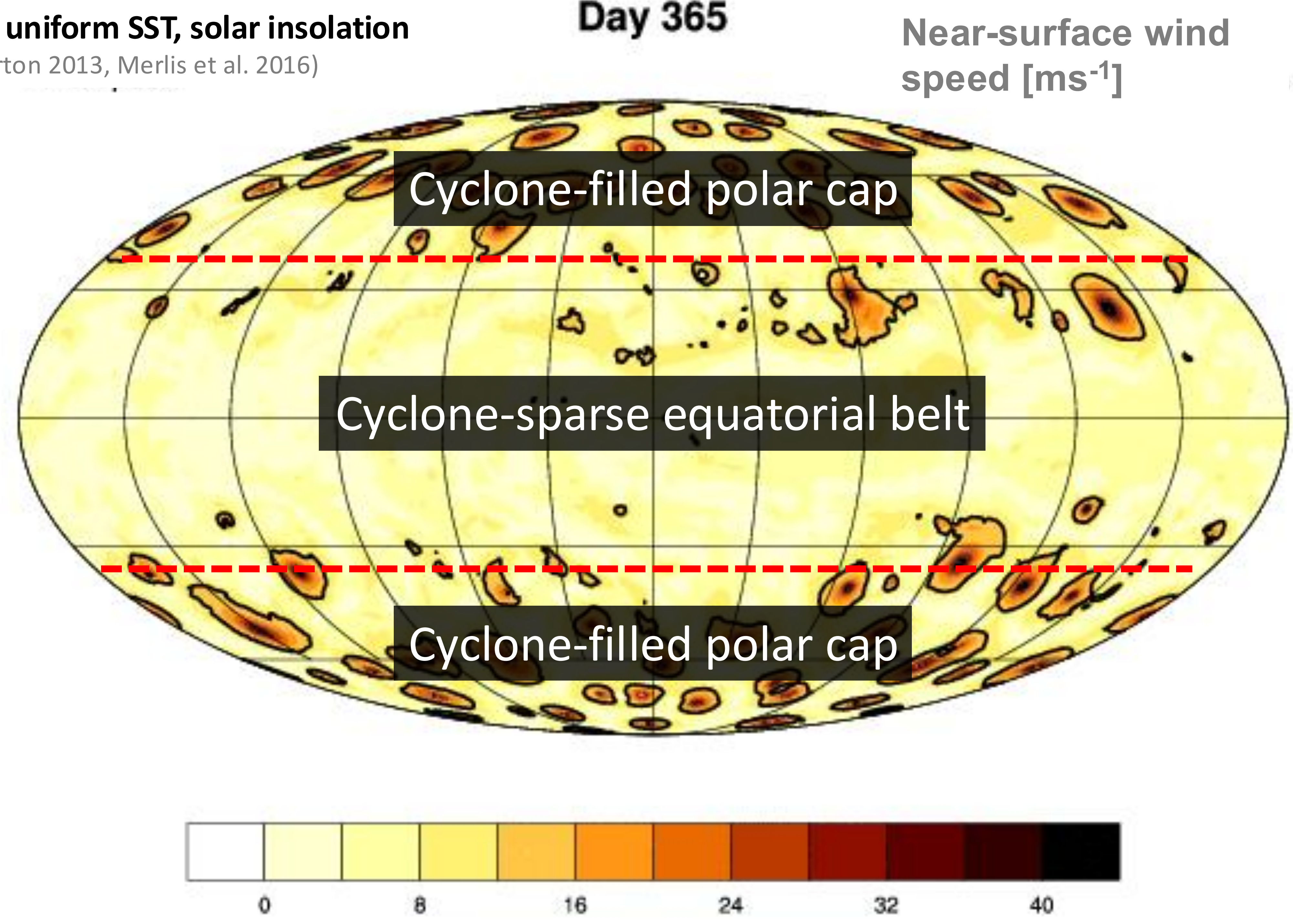
Model: CAM5



Chavas and Reed (2019), J. Atmos. Sci

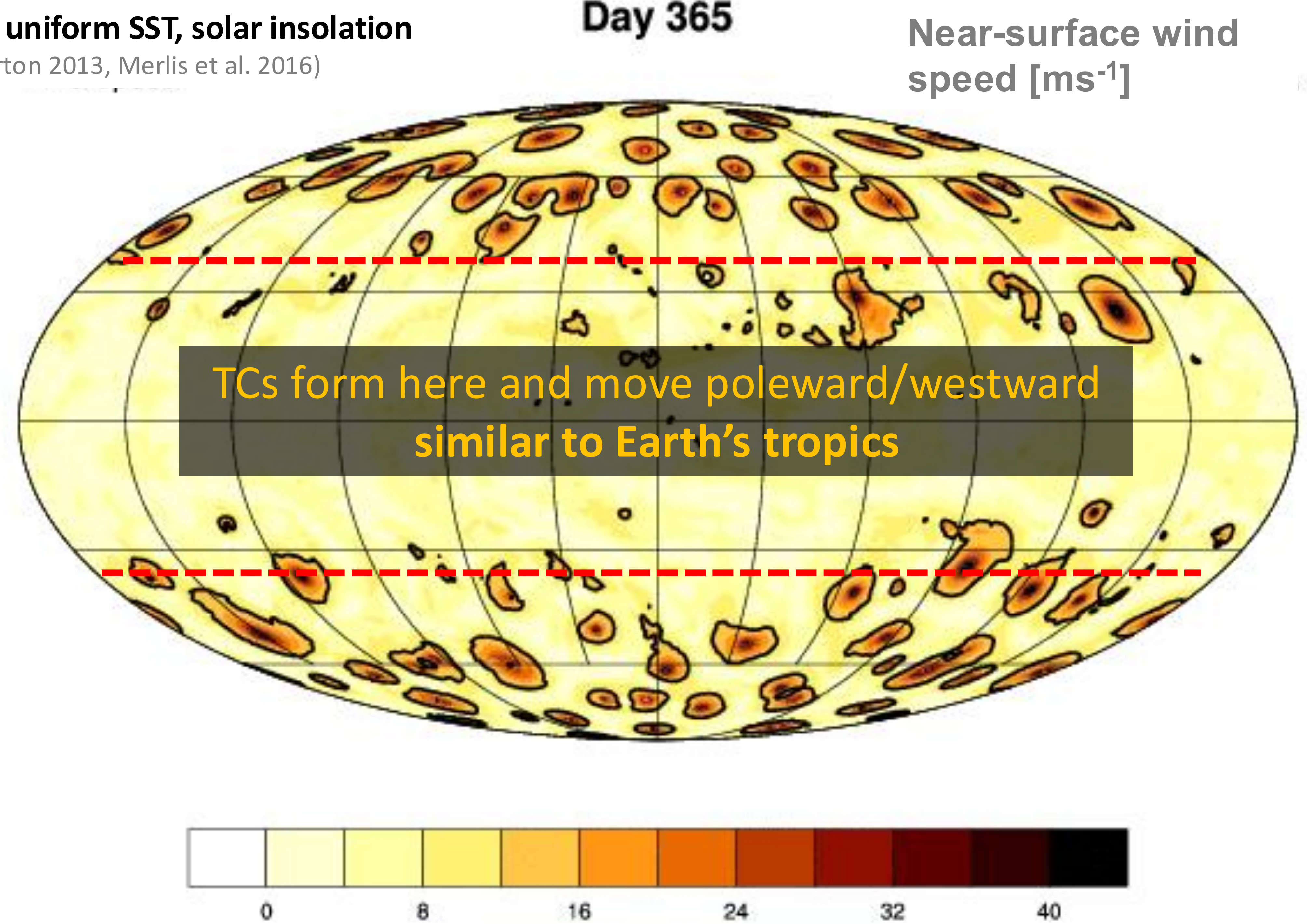
Aquaplanet, uniform SST, solar insolation

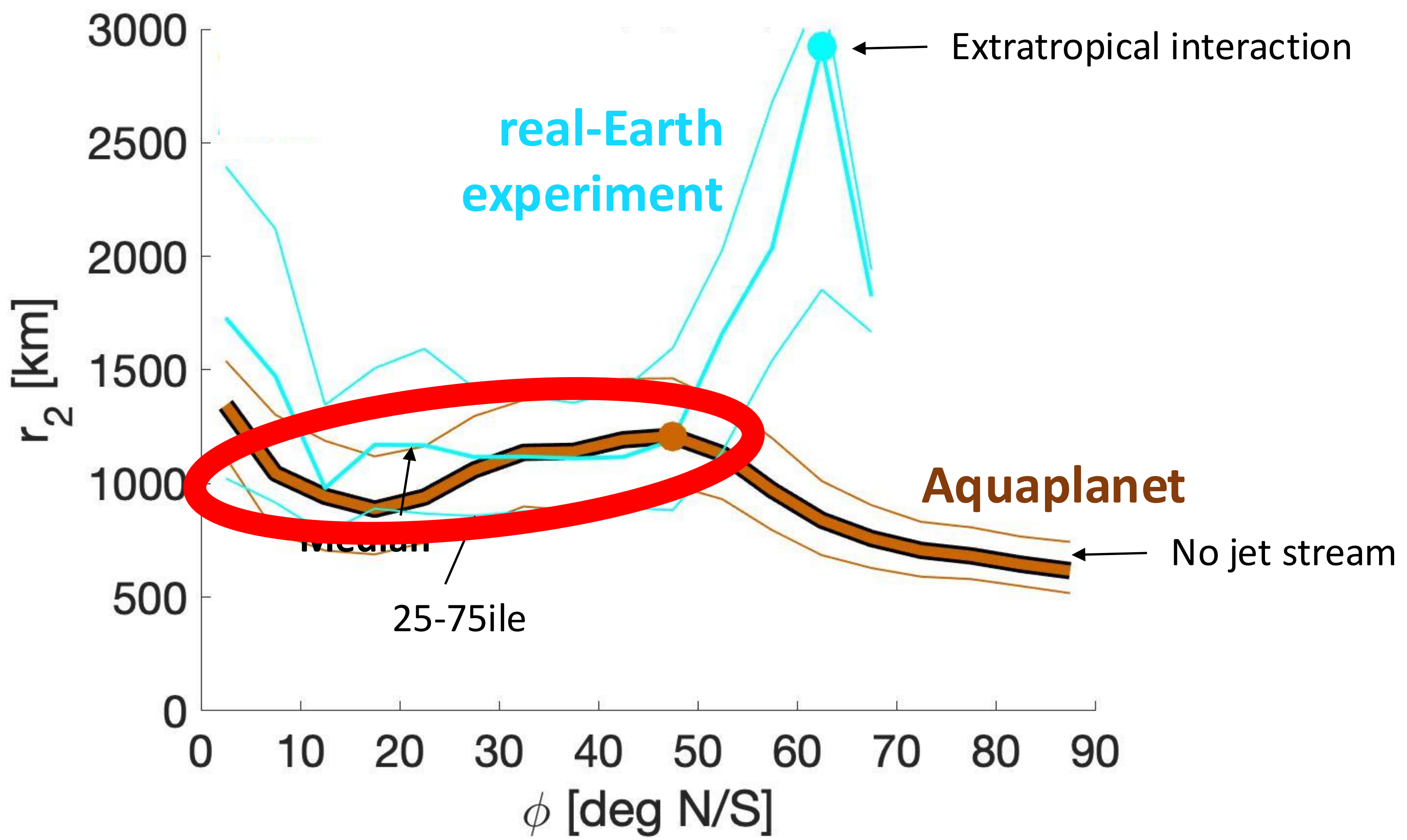
(Shi and Bretherton 2013, Merlis et al. 2016)



Aquaplanet, uniform SST, solar insolation

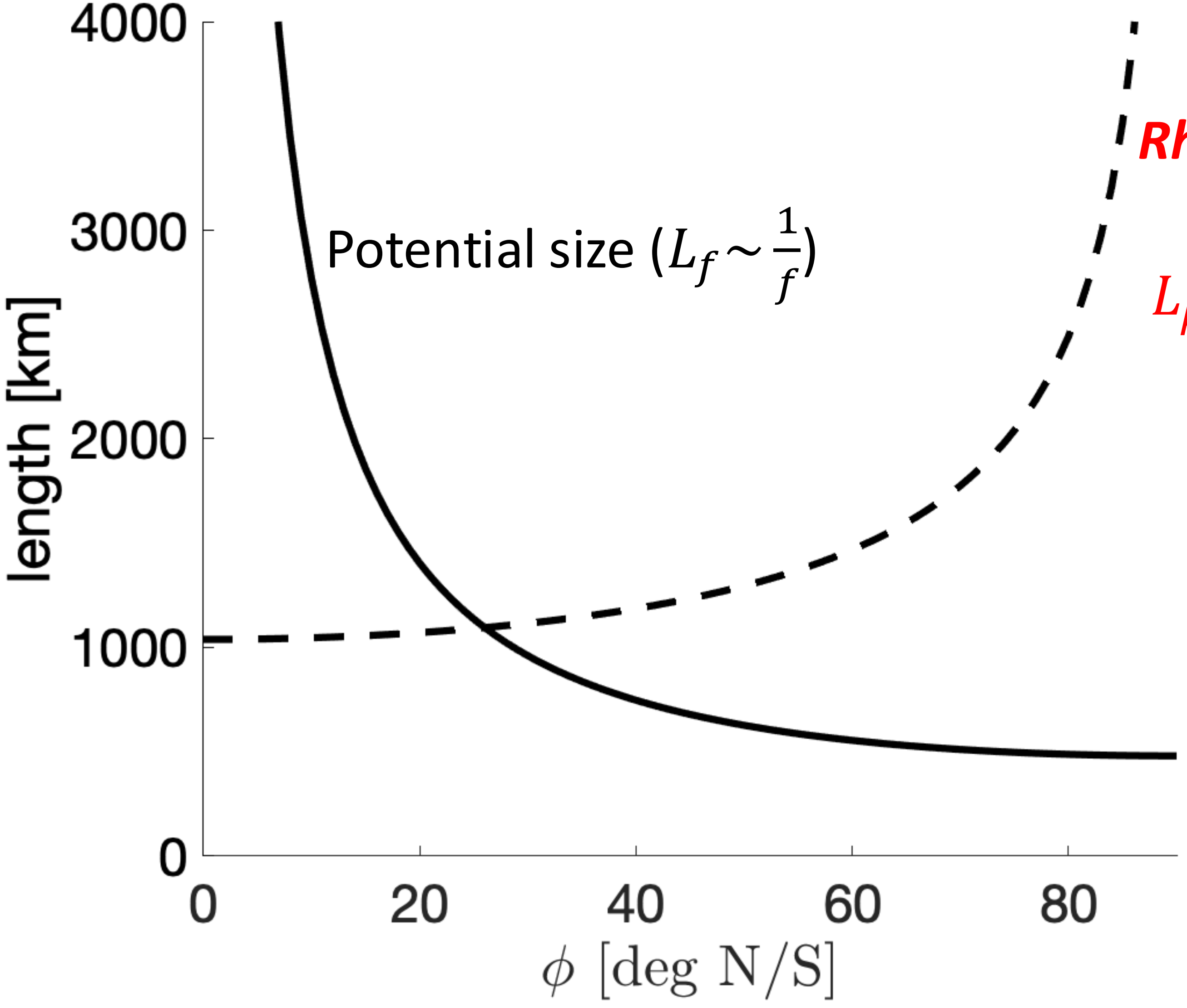
(Shi and Bretherton 2013, Merlis et al. 2016)





Model: CAM5

Chavas and Reed (2019), J. Atmos. Sci



Rhines scale *(Rhines 1975)*

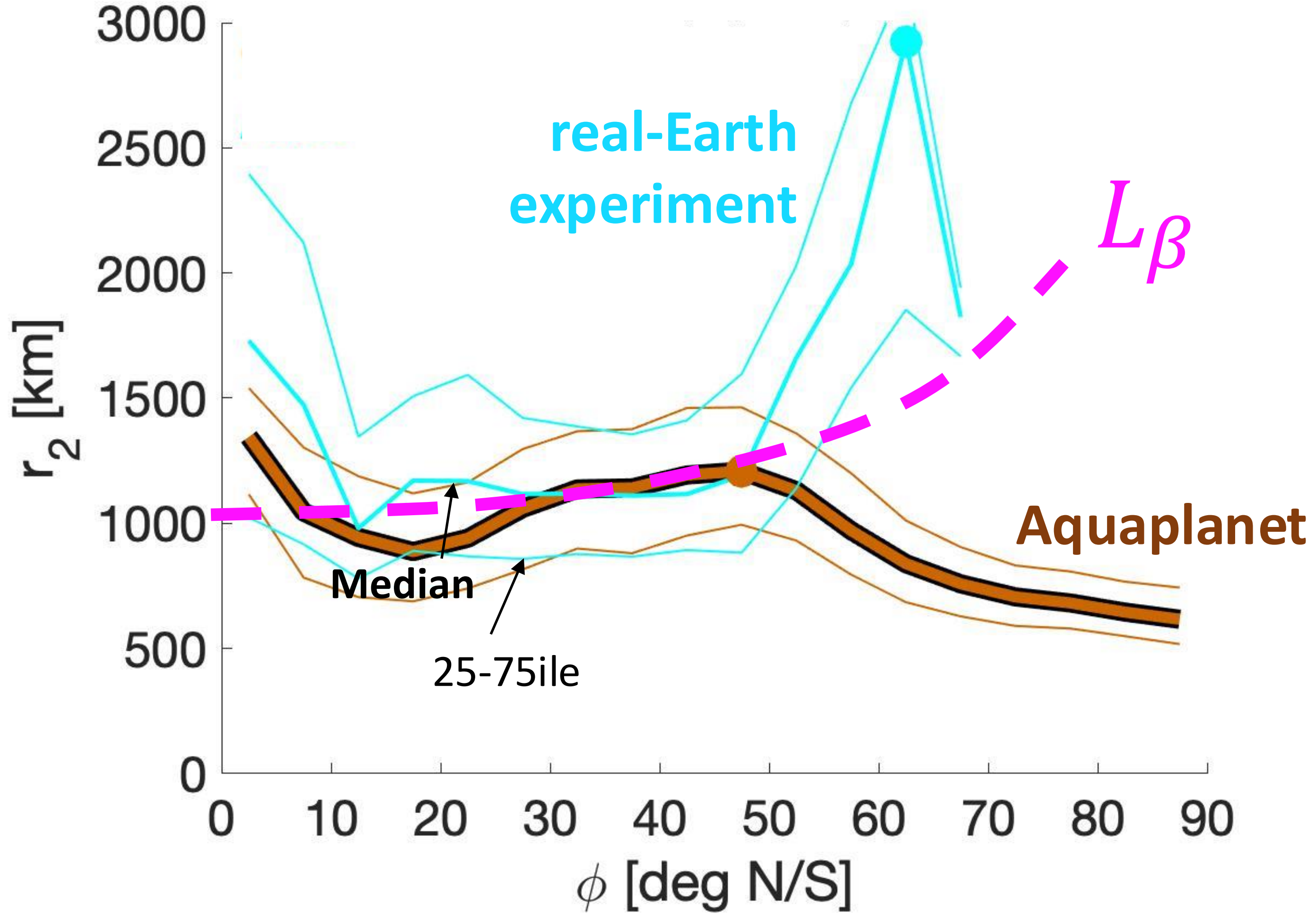
$$L_\beta = \frac{\pi}{2}\sqrt{\frac{U_\beta}{\beta}}$$

$U_\beta = 10\ m/s$

Governs wave-vortex transition

(Vallis 2017, p. 446)

Chavas and Reed (2019), J. Atmos. Sci



Vortices on beta plane:
Vallis and Maltrud (1993), McDonald (1998), Flor and Eames (2002), Flierl and Haines (1994)

Chavas and Reed (2019), J. Atmos. Sci

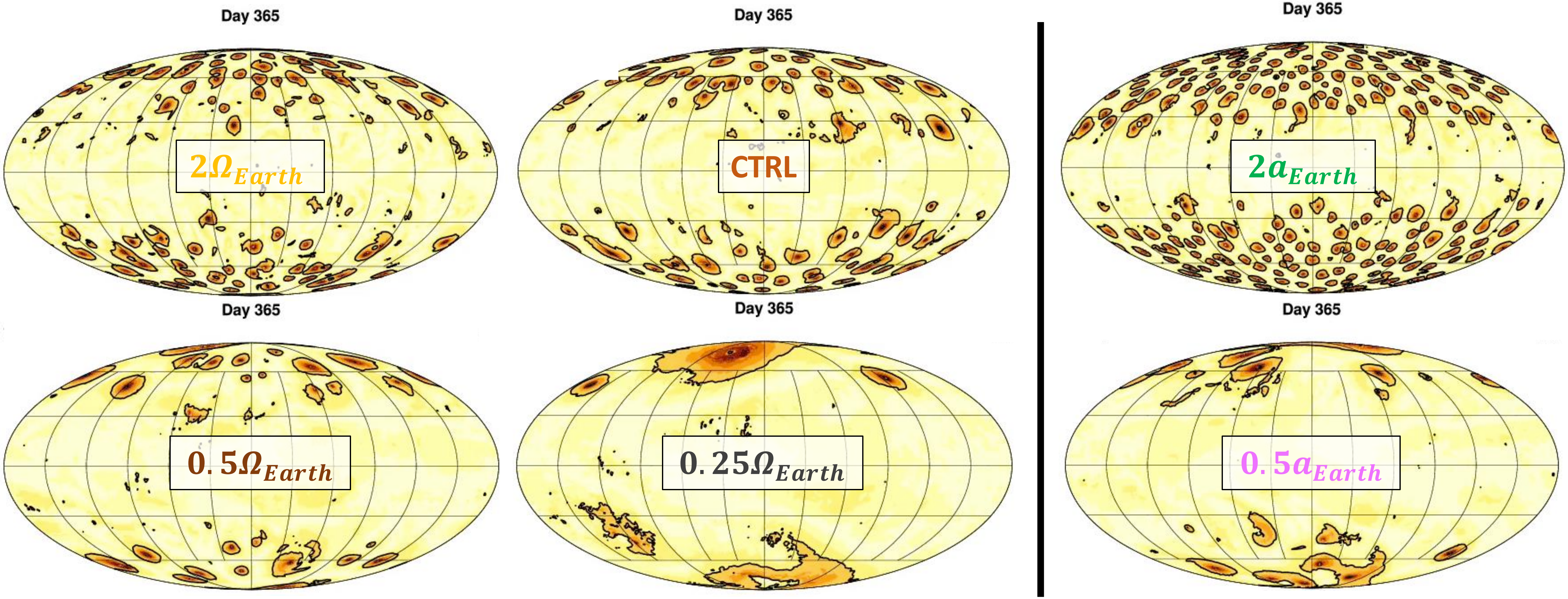
$$f = 2\Omega sin\phi$$

$$\beta = \frac{\partial f}{\partial y} = \frac{2\Omega}{a} cos\phi$$

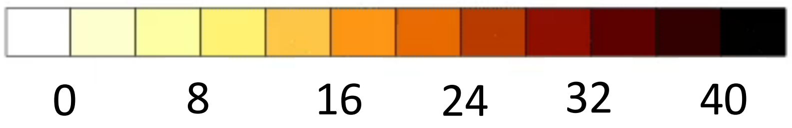
https://upload.wikimedia.org/wikipedia/commons/2/2c/Rotating_earth_%28large%29.gif

Varying Ω

Varying a



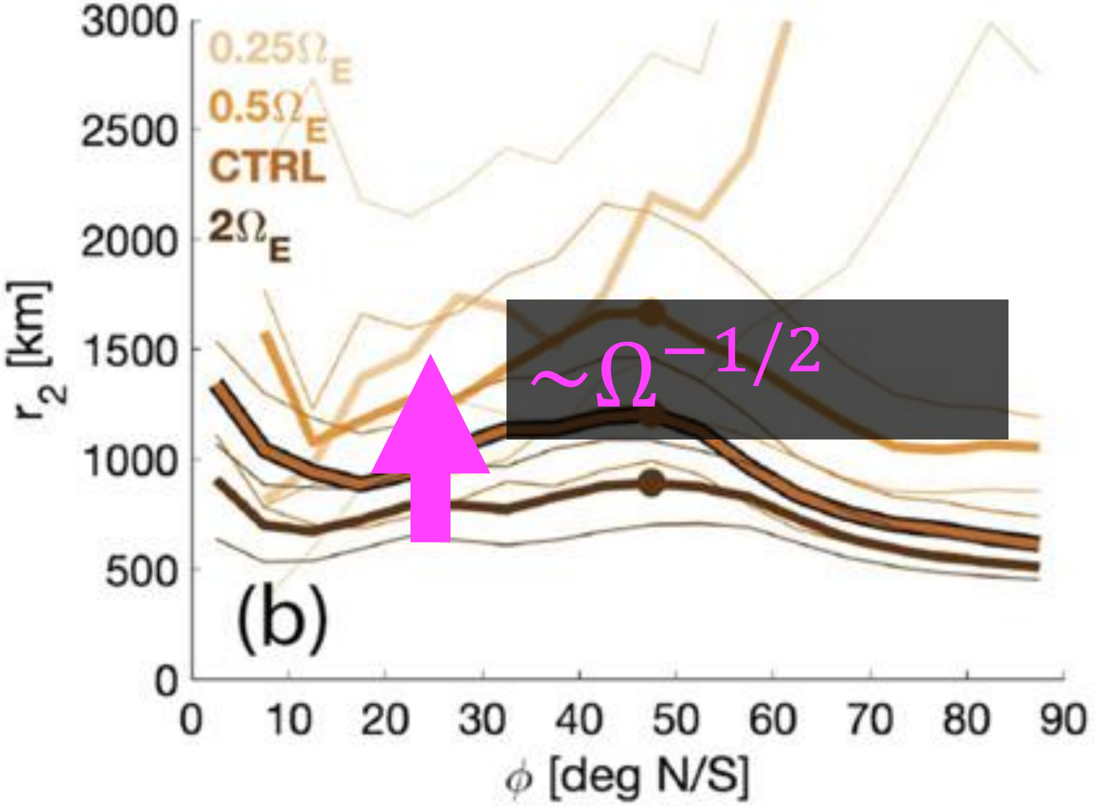
Near-surface wind speed [ms^{-1}]



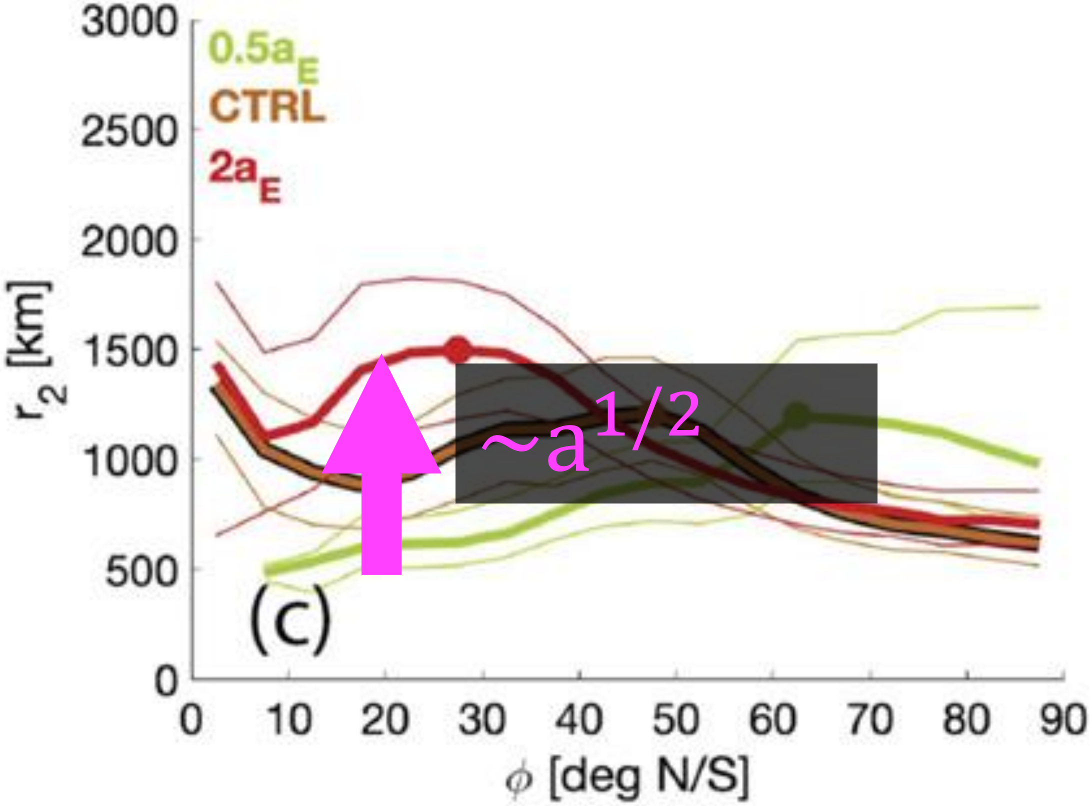
Warning: not drawn to scale!

Chavas and Reed (2019)

Varying rotation rate



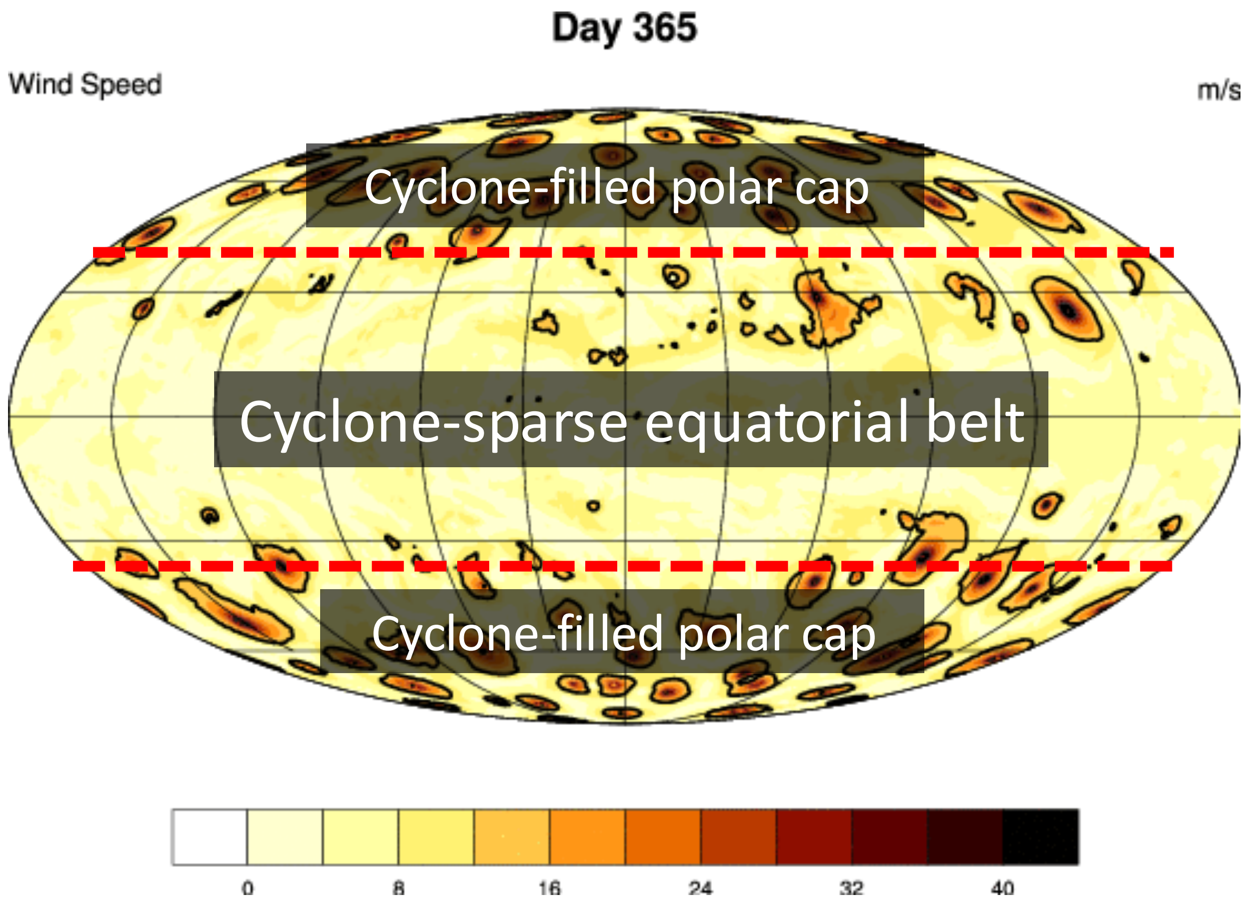
Varying planet size

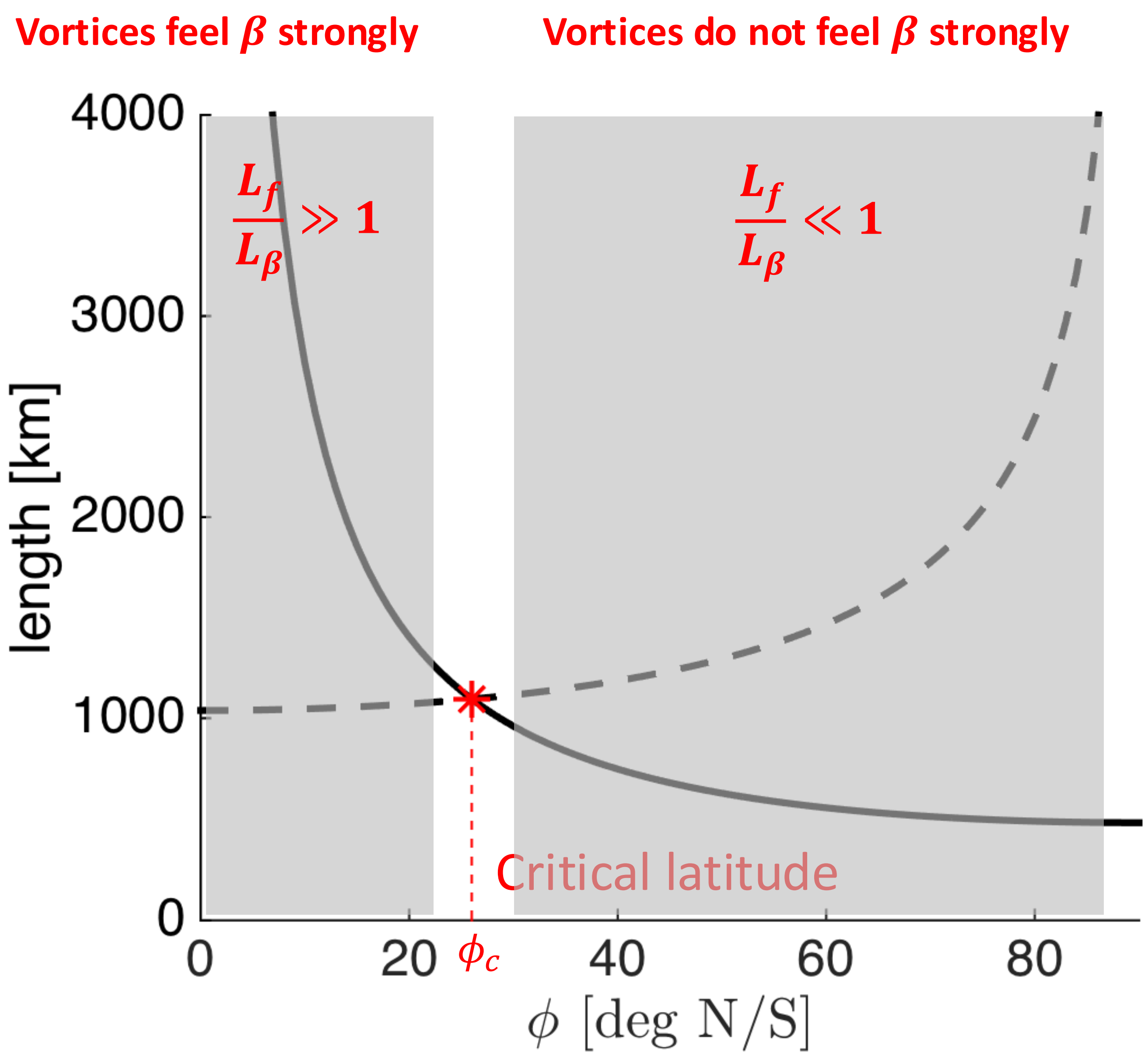


Size follows a Rhines scaling in low/mid latitudes in GCM

Bridging the f-plane and the sphere

Why is this the qualitative state?

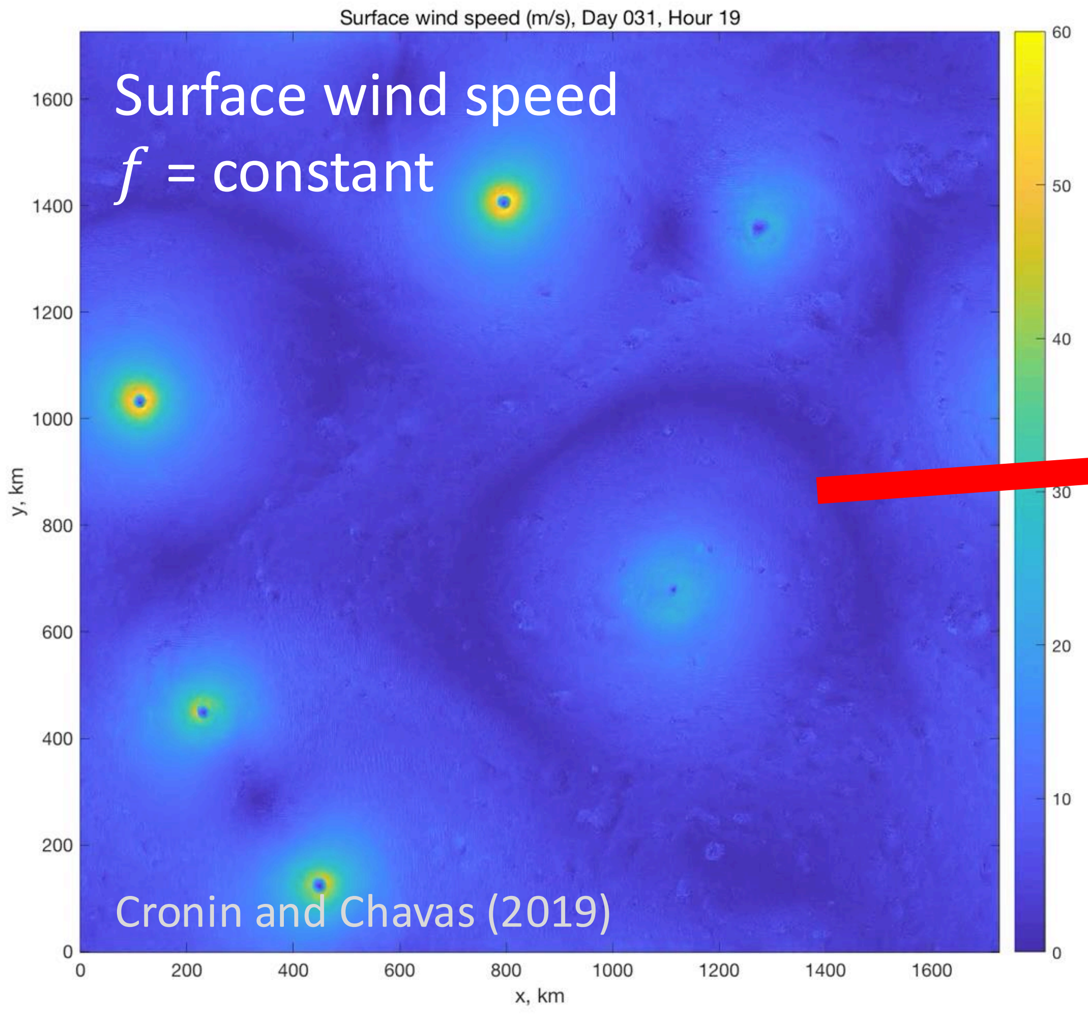


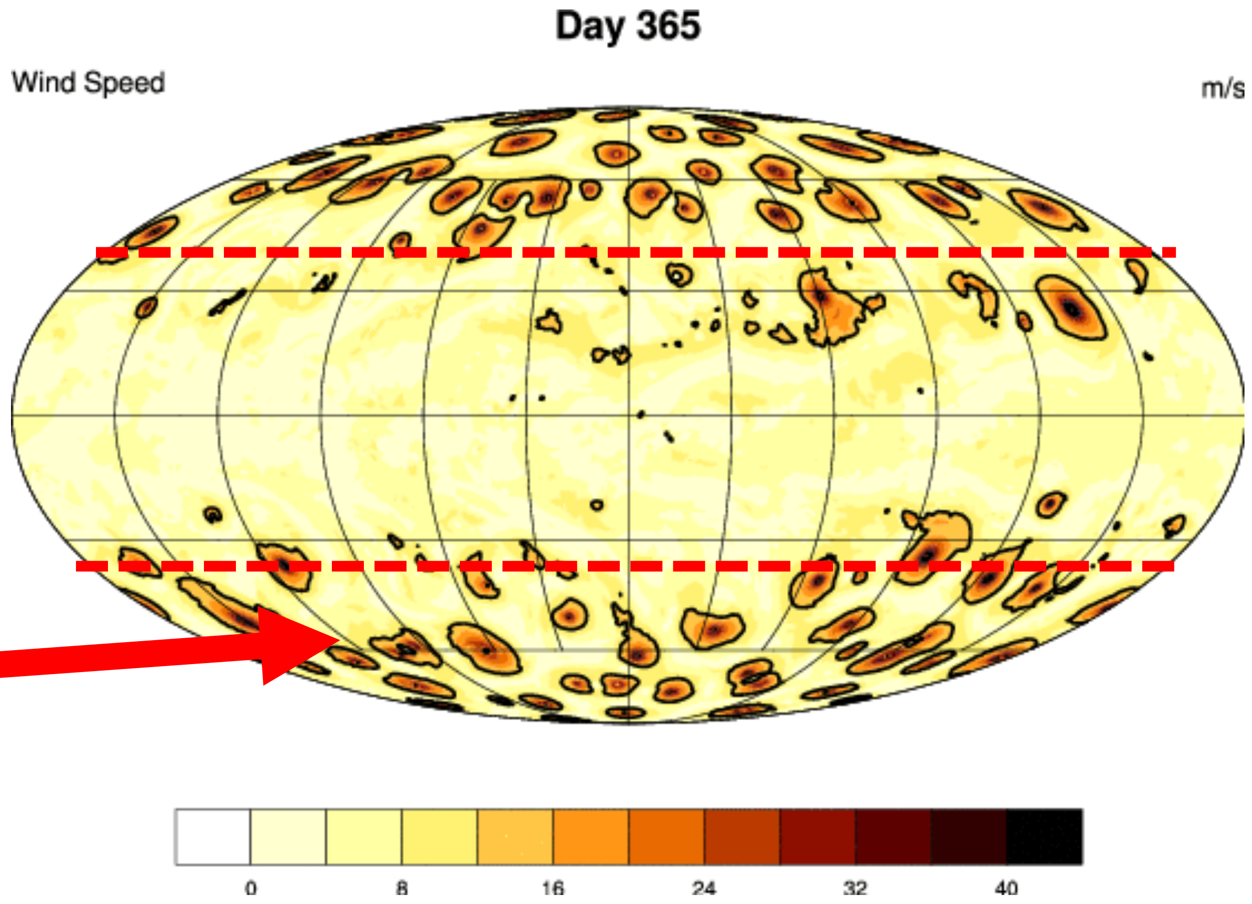


$\frac{L_f}{L_\beta} = f(\Omega a)$

$\frac{\Omega a}{U}$ is lone dynamical non-dimensional parameter in primitive equations (Frierson 2006)

First proposed by Theiss (2004), JPO



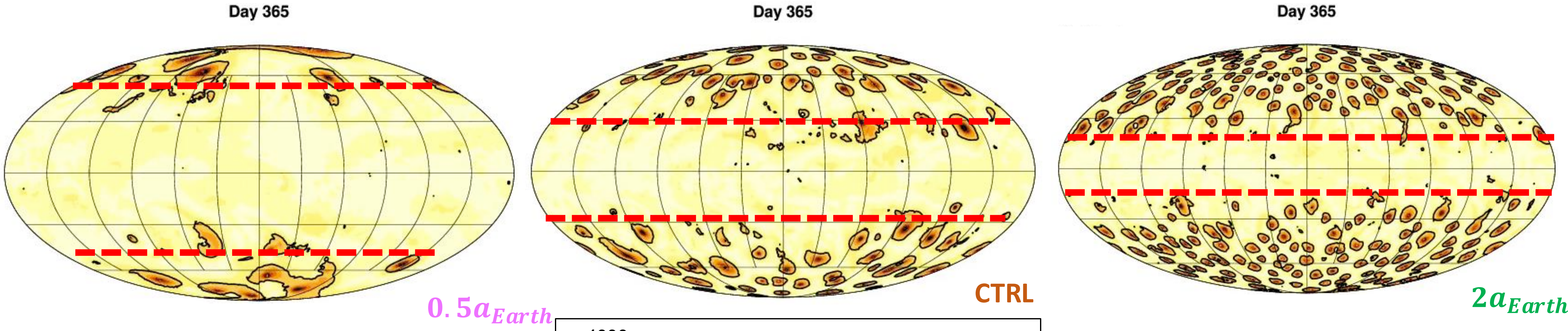


The cyclone-filled polar caps behave like an f-plane

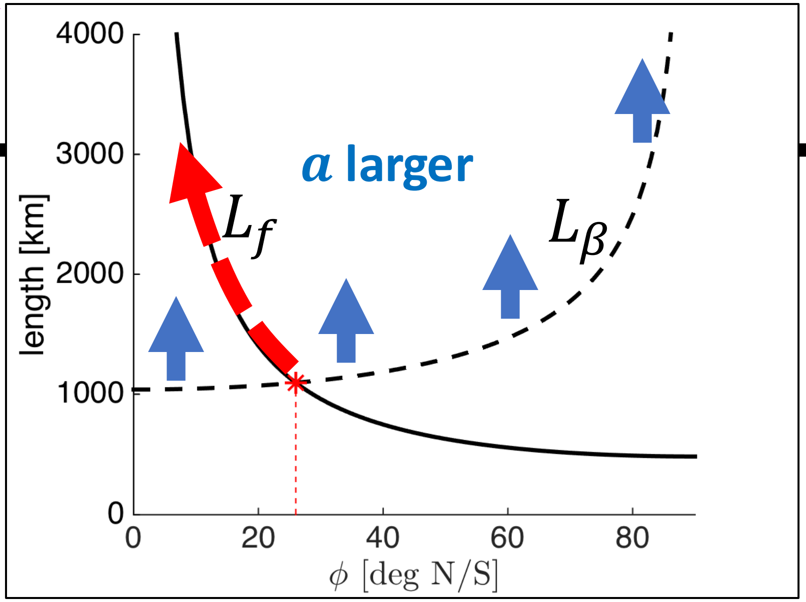
Without variations in f (i.e. β), there are no Rossby waves to disrupt the vortices. So vortices **last a very long time**.

Chavas and Reed (2019), J. Atmos. Sci.

Larger planets = larger fraction of surface covered in cyclones



Smaller planet → **Larger planet**



Chavas and Reed (2019), J. Atmos. Sci.

Two other notable results

Genesis rate vs latitude? $\sim f$ (absolute vorticity)

Minimum genesis distance from the equator? $\sim L_{\beta,EQ}$

equatorial deformation/Rhines scale

Chavas D. R. and K. A. Reed (2019). Dynamical aquaplanet experiments with uniform thermal forcing: system dynamics and implications for tropical cyclone genesis and size. ***J. Atmos. Sci.***, 76(8), pp.2257-2274.

Research questions

1. What sets tropical cyclone size on Earth?

$\sim L_\beta$ Rhines scale

***2.* Why the Rhines scale?**

“Why would a hurricane care about the Rhines scale?”

- Reviewer #2

Dr. Kuan-Yu Lu (PhD 2024)

Lu K. and D. R. Chavas (2022)*. Tropical cyclone size is strongly limited by the Rhines scale: experiments with a barotropic model. J. Atmos. Sci.*

$$\underbrace{\frac{\partial \zeta}{\partial t}}_{\text{Tendency term}} = \underbrace{-\vec{\mathbf{u}} \cdot \nabla \zeta}_{\text{Non-linear Advection term}} \underbrace{-\beta v}_{\text{Beta term}}$$

moves vorticity around

makes Rossby waves

Rhines number

$$Rh \equiv \frac{\vec{\boldsymbol{u}} \cdot \nabla \zeta}{\beta v} \approx \frac{\frac{U_c^2}{2\pi R^2}}{\beta U_c} = \frac{U_c}{2\pi \beta R^2}$$

Only one factor of 2π

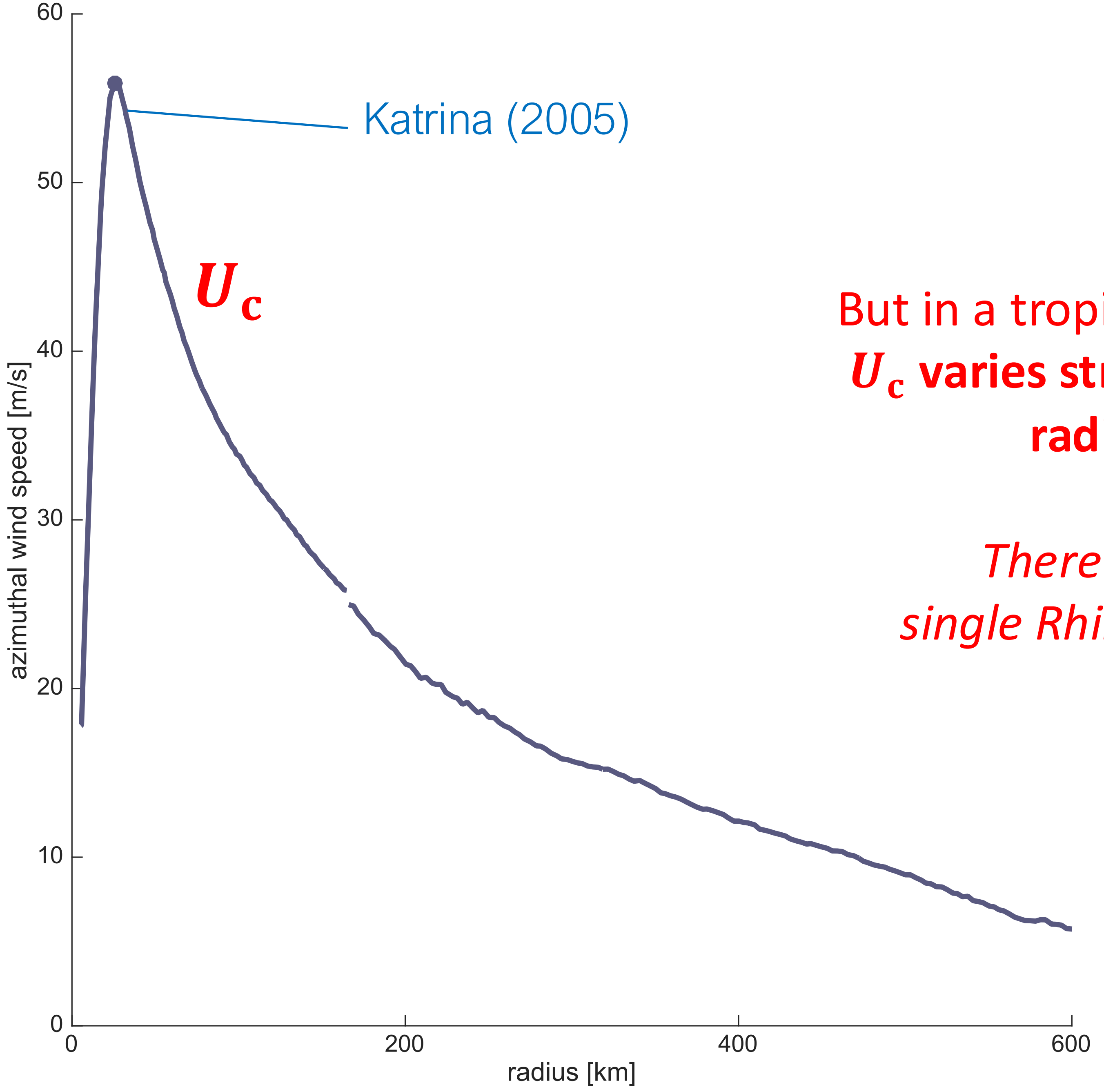
$\vec{\boldsymbol{u}} \cdot \boldsymbol{\nabla}$: azimuthal gradient ($\sim 2\pi R$)

ζ: radial gradient ($\sim R$)

Set $Rh = 1$ → $\boldsymbol{L_{Rh}} = \sqrt{\frac{\boldsymbol{U_c}}{\boldsymbol{2\pi\beta}}}$

A "characteristic" flow velocity (e.g. $\boldsymbol{U_{RMS}}$)

Rhines scale



But in a tropical cyclone, **U_c varies strongly with radius**

There is no single Rhines scale

$$R_{Rh} = \sqrt{\frac{U_c}{2\pi\beta}}$$

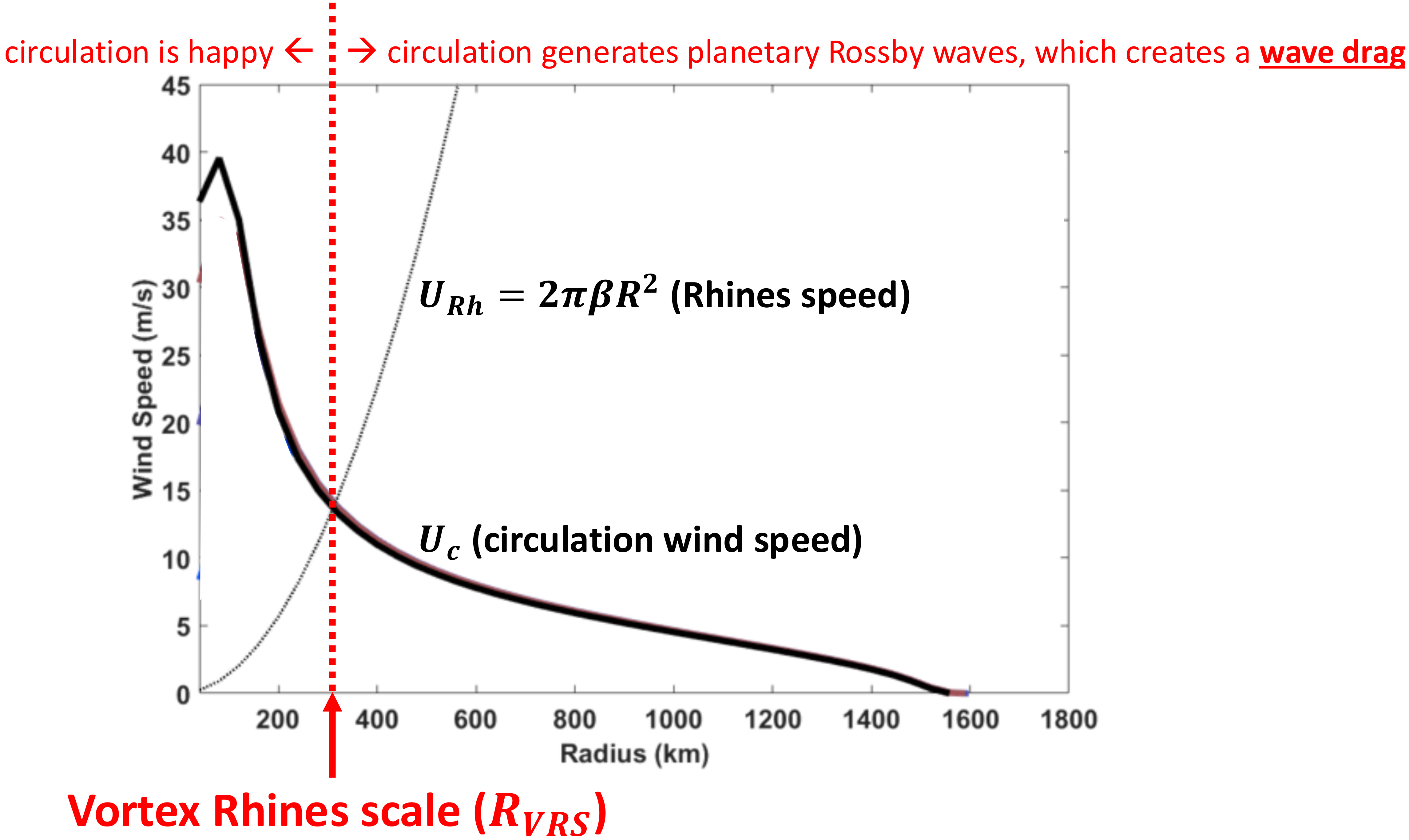
Rhines scale

Variation with radius depends on $U_c(r)$

$$U_{Rh} = 2\pi\beta R^2$$

Rhines speed

Fixed dependence on radius



circulation is happy ← → circulation generates planetary Rossby waves, which creates a wave drag
$U_{Rh} = 2\pi\beta R^2$ (Rhines speed)
U_c (circulation wind speed)
Wind Speed (m/s)
45
40
35
30
25
20
15
10
5
0
200
400
600
800
1000
1200
1400
1600
1800
Radius (km)
Vortex Rhines scale (R_{VRS})

Non-divergent barotropic beta plane model

(James Penn)

initialized with a physical model for axisymmetric TC wind field

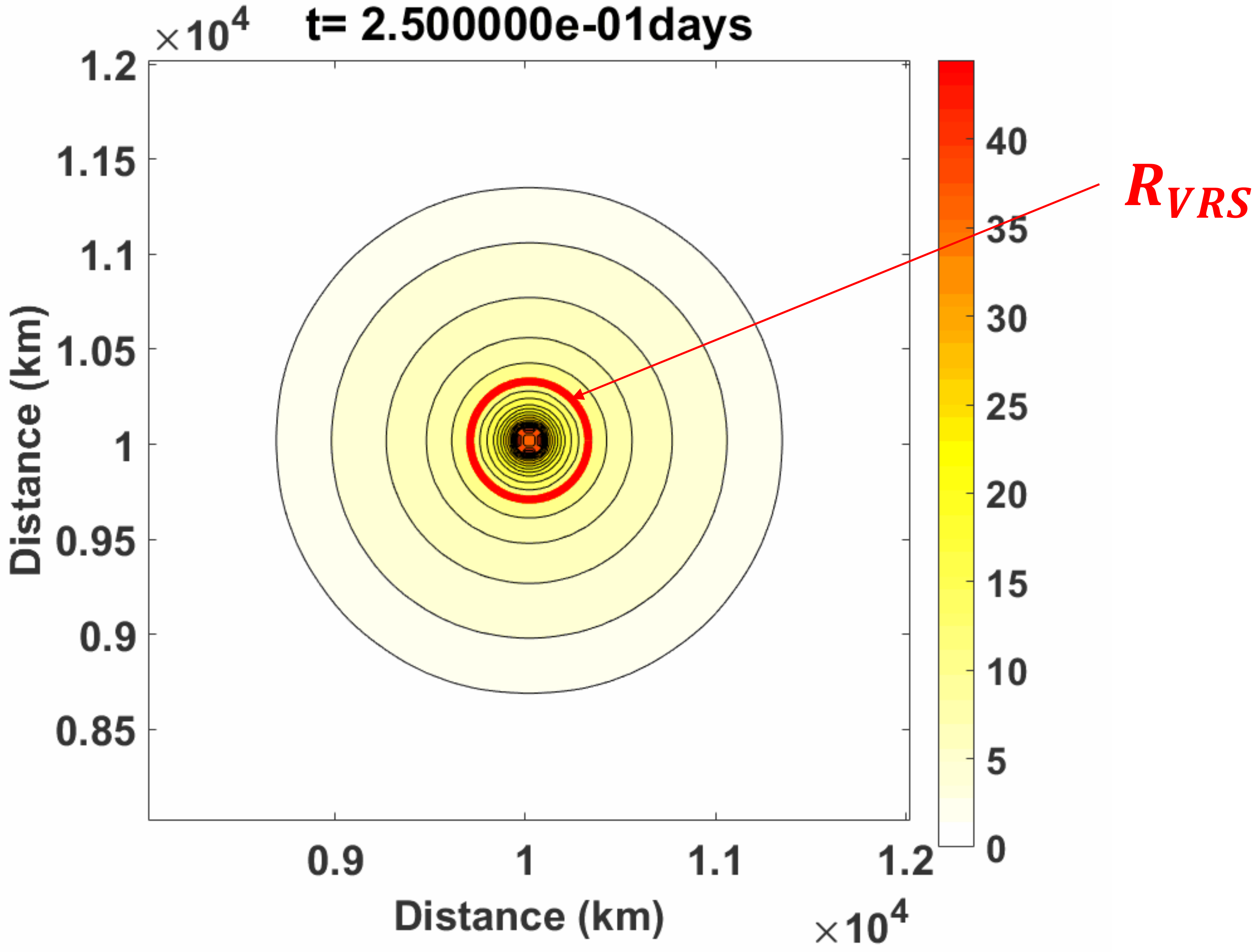
(Chavas et al. 2015)

The storm <u>outer</u> wind field shrinks outside of the "vortex Rhines scale"

The vortex **radiates Rossby waves.**

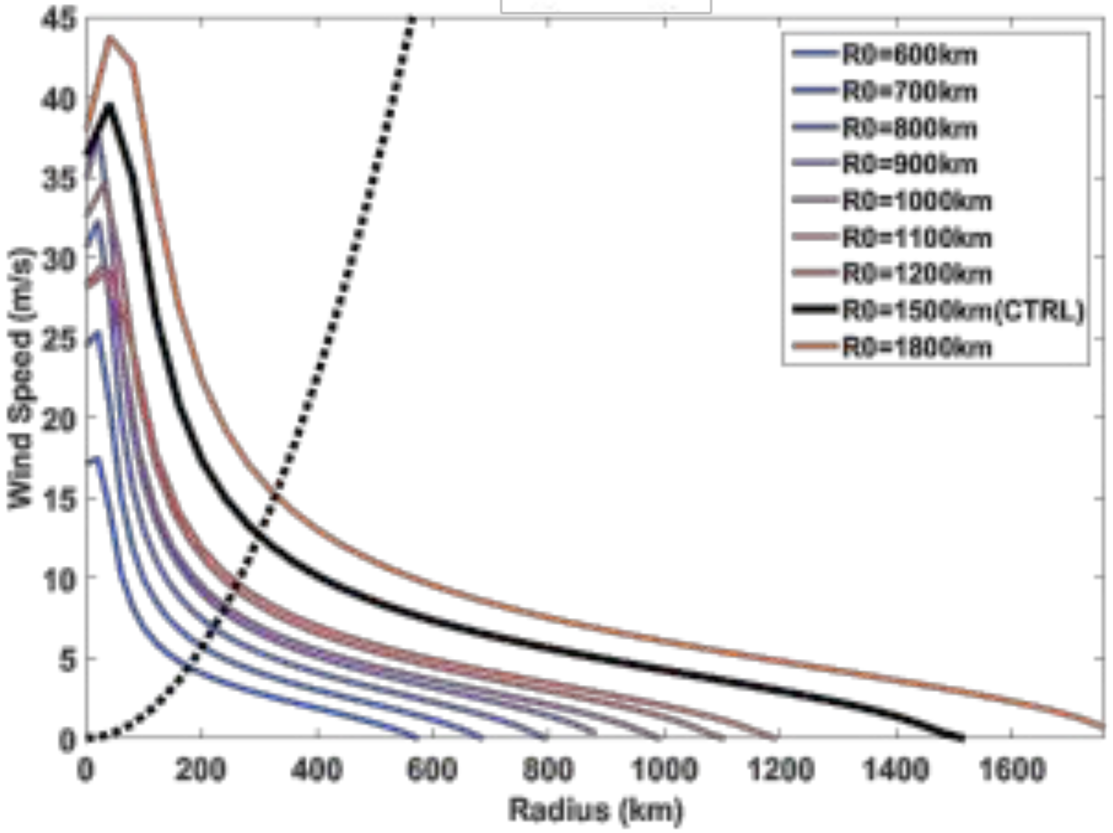
These waves **transfer kinetic energy from the vortex** into the environment

a "wave drag"

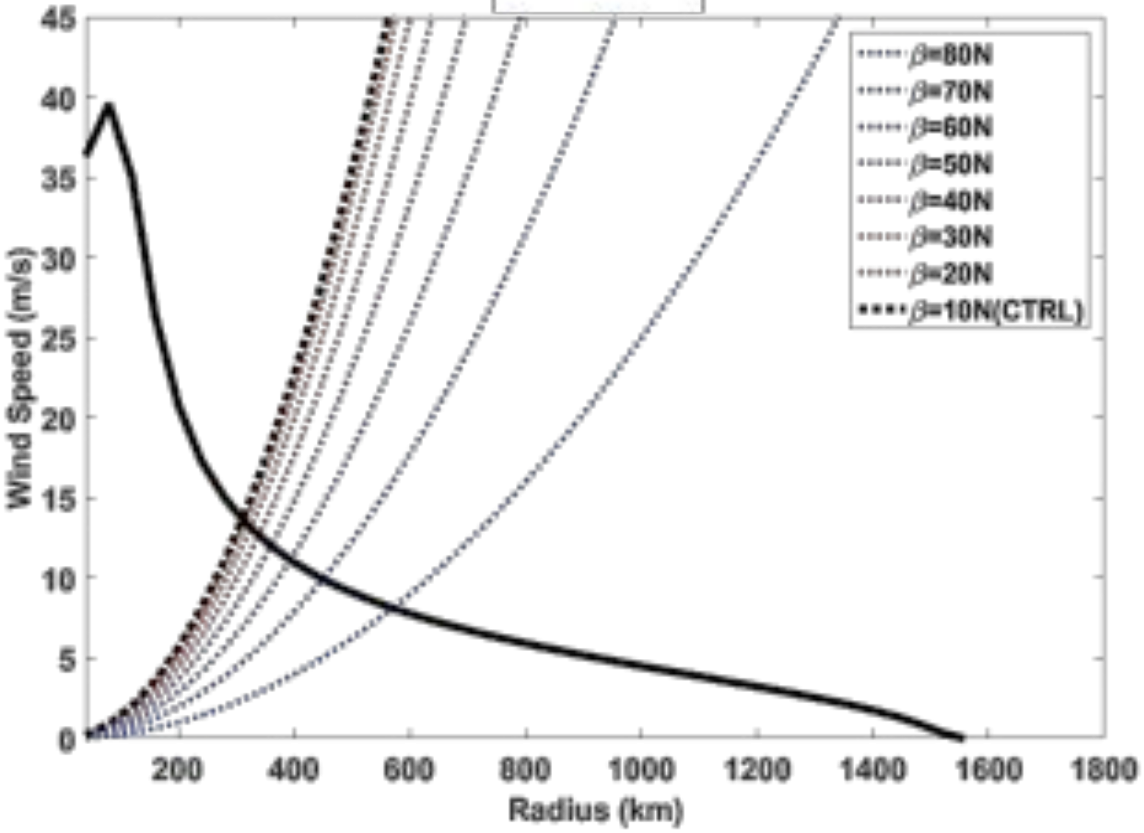


Experiments

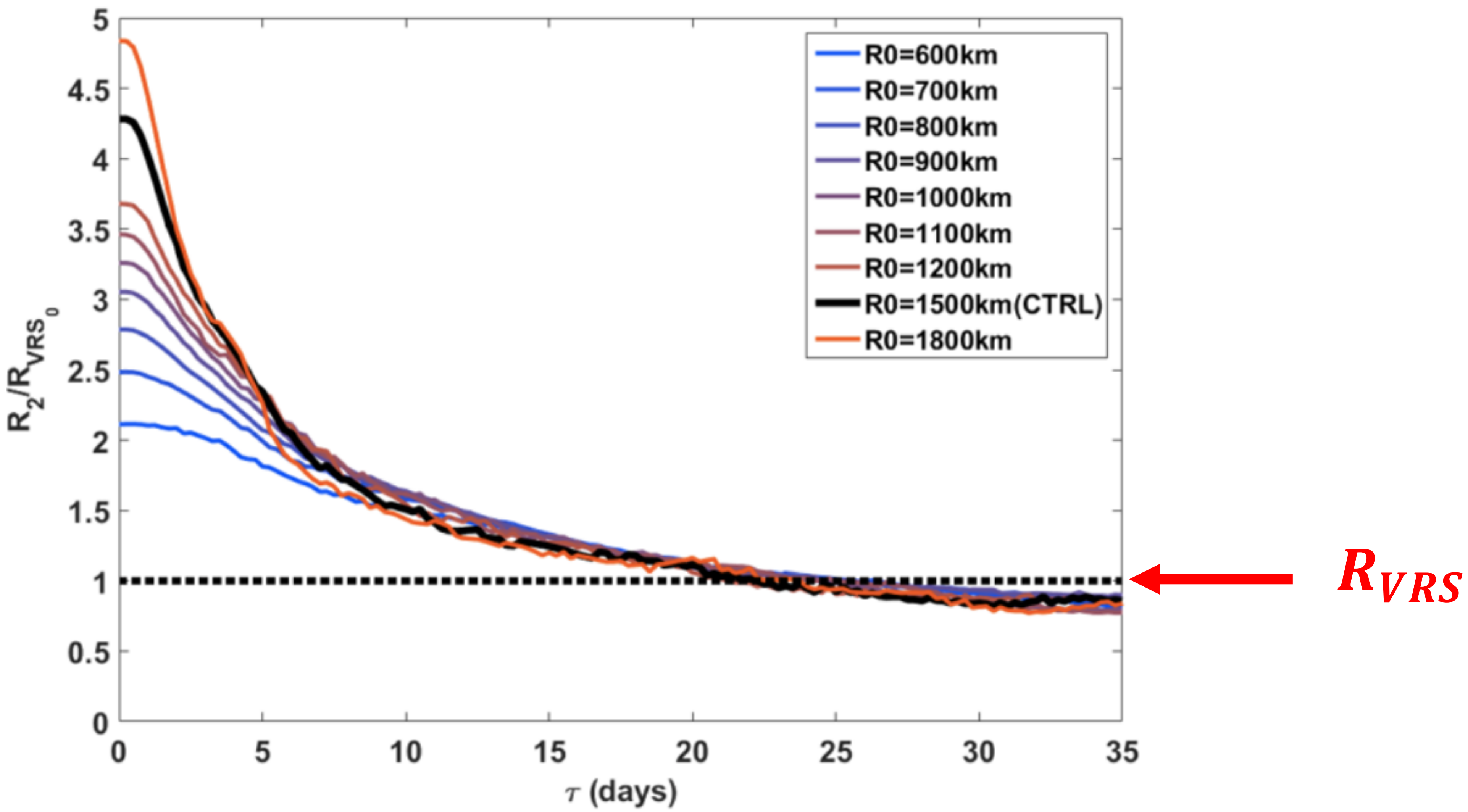
Varying initial storm size



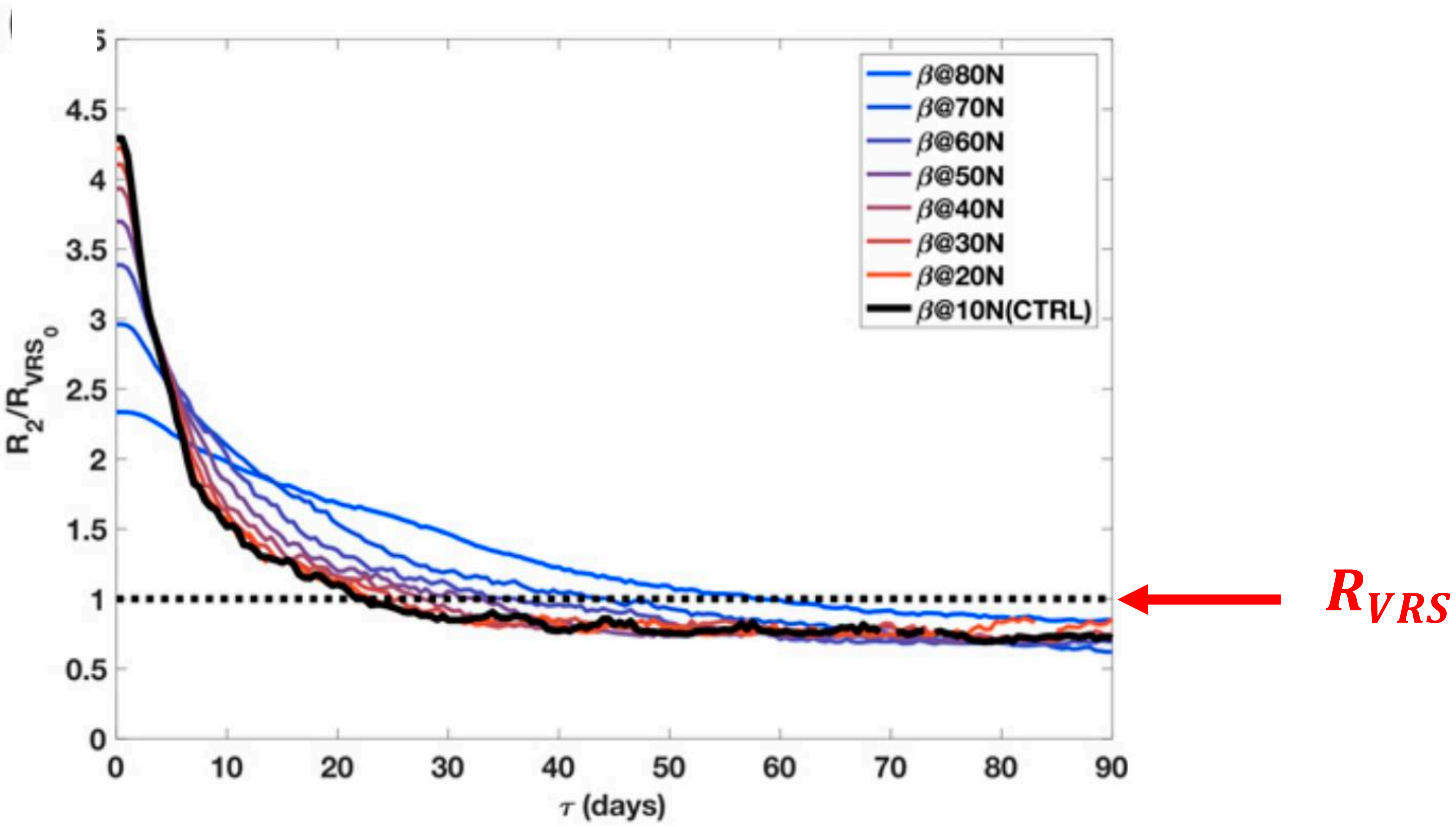
Varying β



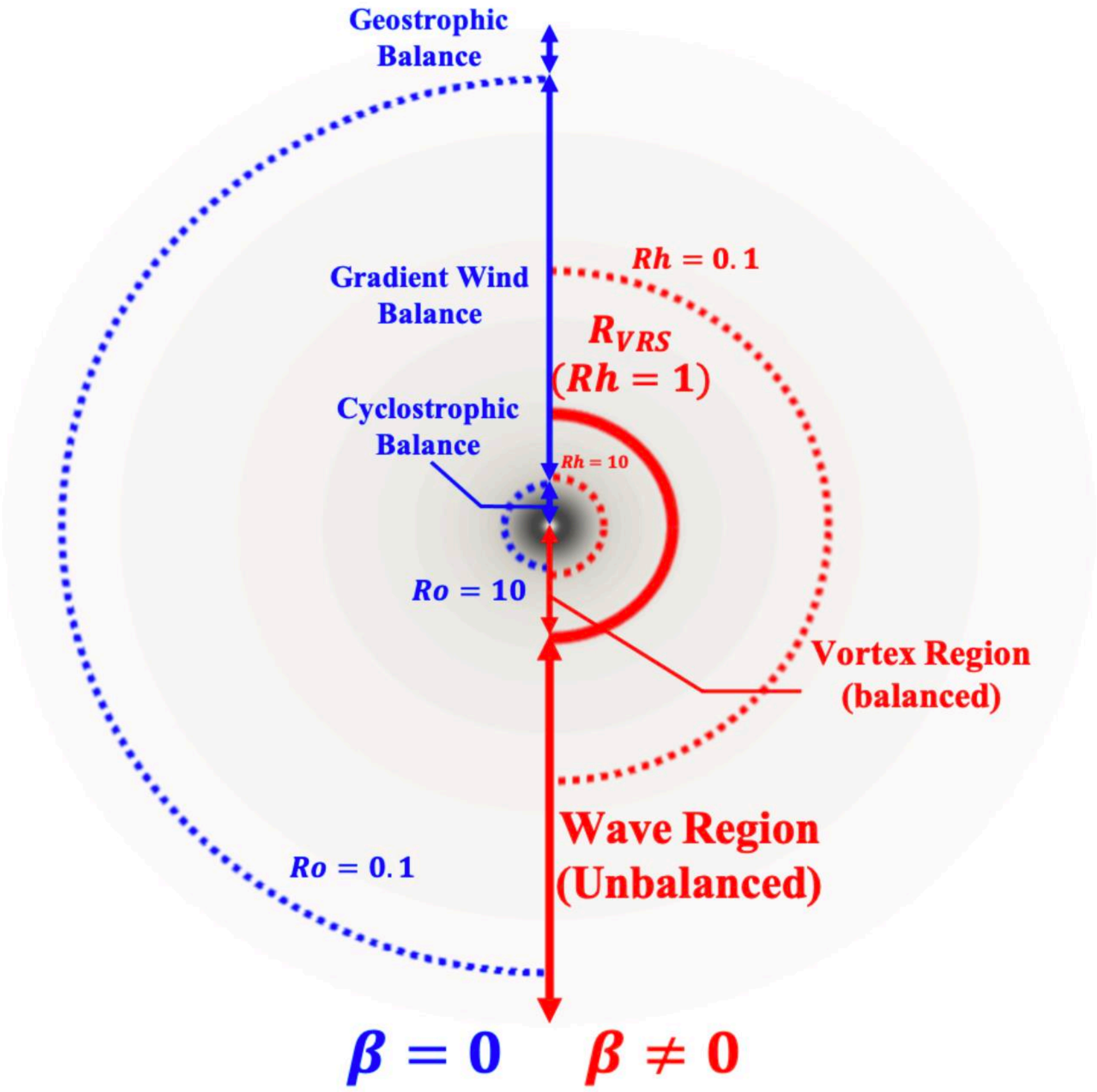
Larger vortices shrink faster toward their vortex Rhines scale



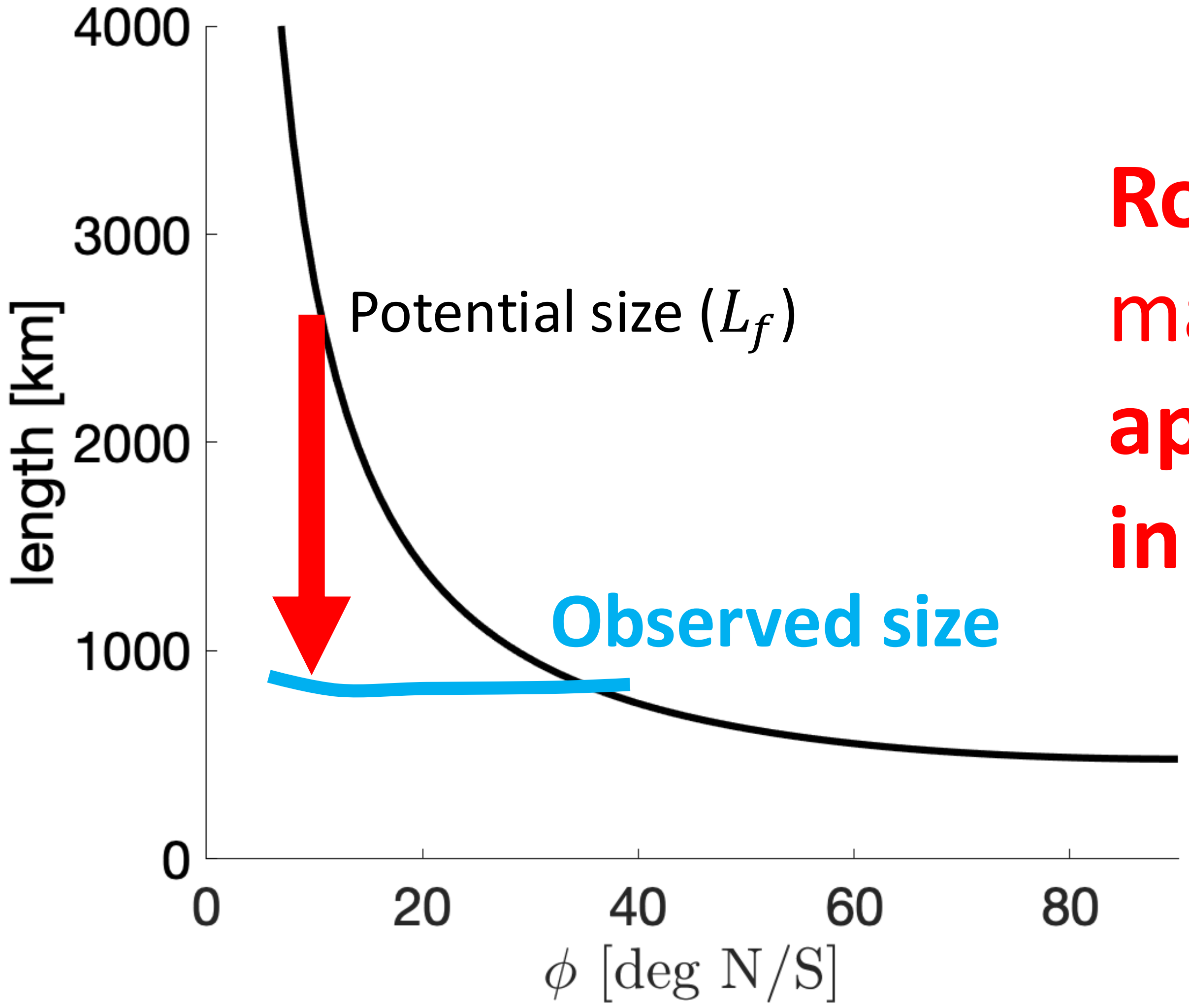
Vortices shrink faster for larger β



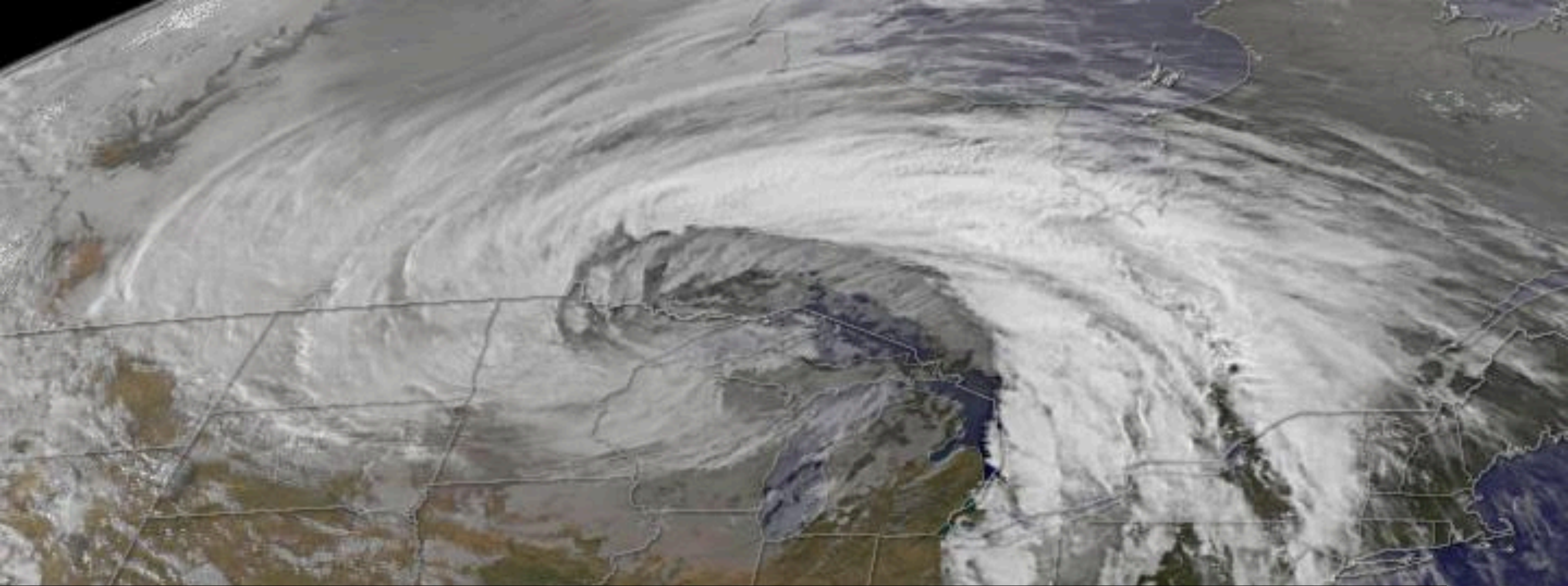
R_{VRS}



Geostrophic Balance
Gradient Wind Balance
Cyclostrophic Balance
$Rh = 0.1$
R_{VRS} $(Rh = 1)$
$Rh = 10$
$Ro = 10$
Vortex Region (balanced)
Wave Region (Unbalanced)
$Ro = 0.1$
$\beta = 0$
$\beta \neq 0$



Rossby wave drag (Rhines effect) makes it **difficult for a storm to approach its potential size in the tropics**



In baroclinic turbulence theory, the Rhines scale “cuts off the inverse energy cascade” = an **upper bound on extratropical cyclone size**.

These are the <u>same physics</u>.

→ **Why are extratropical cyclones are larger than tropical cyclones?**

Because the **Rhines scale is larger at mid-high latitudes.**

Research questions

1. What sets tropical cyclone size on Earth?

$\sim L_\beta$ Rhines scale

2. Why the Rhines scale?

Rossby wave drag weakens the outer circulation

Research questions

1. What sets tropical cyclone size on Earth?

$\sim L_\beta$ Rhines scale

2. Why the Rhines scale?

Rossby wave drag weakens the outer circulation

***3.* Will size change in the future?**

Response to warming

The Rhines scaling does not depend on temperature.

So we might expect that storm size may <u>not</u> change strongly with warming.

Future model projections show outer size remains nearly constant with mean warming

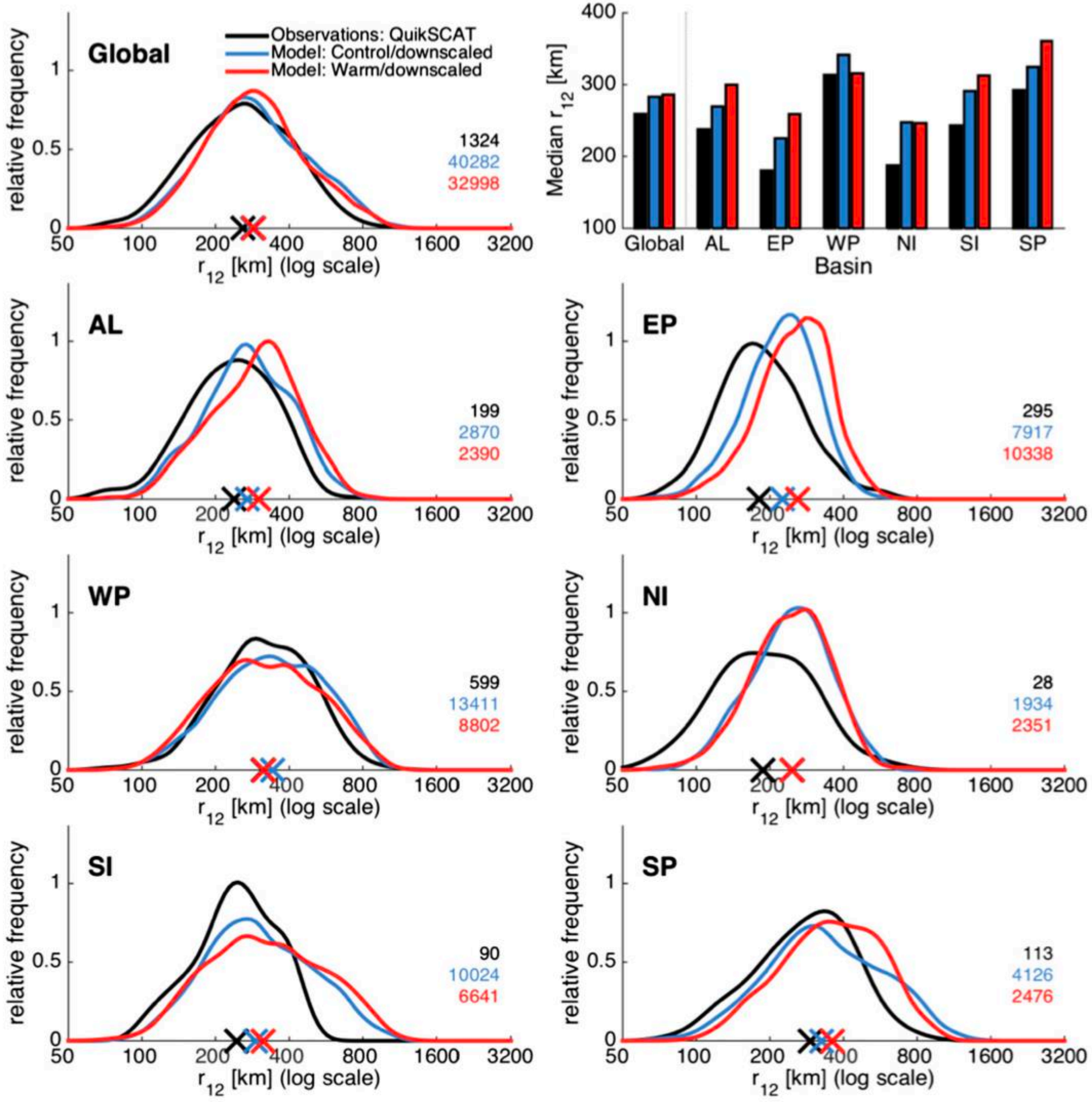


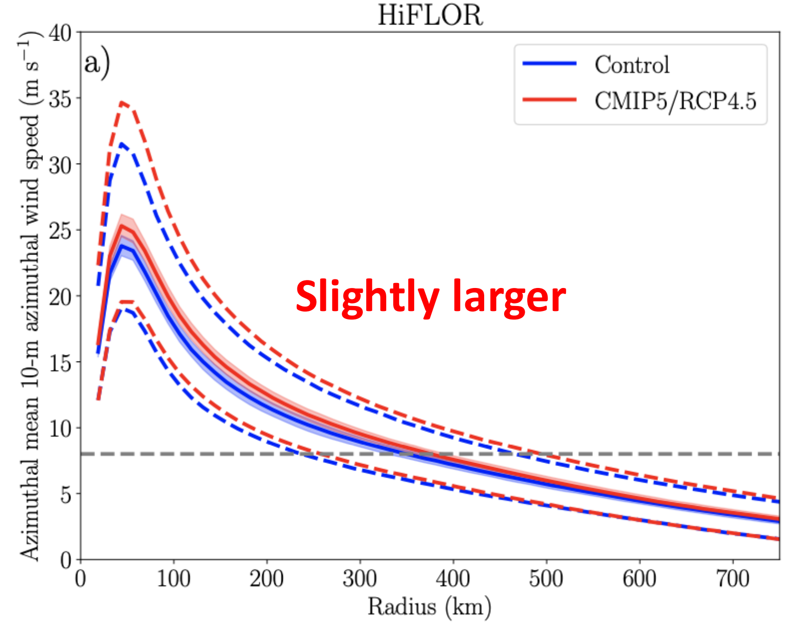
FIG. 5. Relative frequency of tropical cyclone size, globally and for various tropical cyclone basins (AL = North

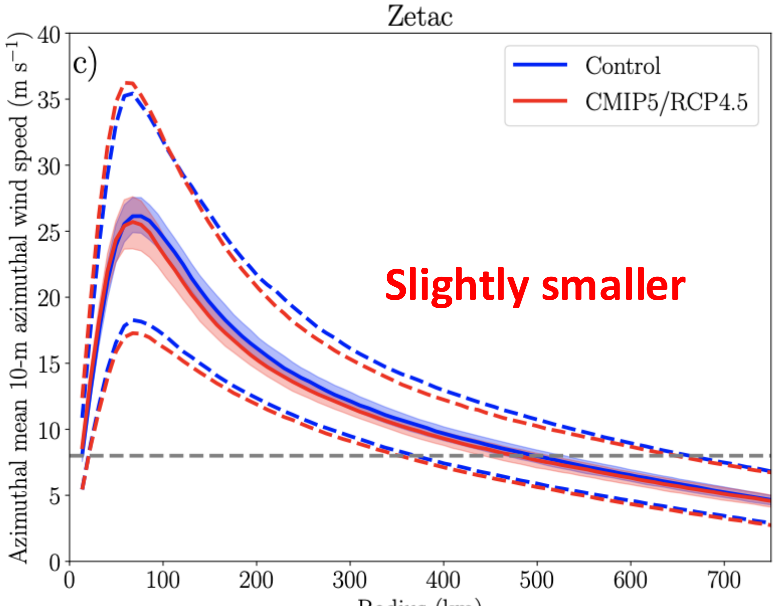
Global downscaled GCM

Knutson et al. (2015), *J. Clim.*

Global Projections of Intense Tropical Cyclone Activity for the Late Twenty-First Century from Dynamical Downscaling of CMIP5/RCP4.5 Scenarios

Future model projections show outer size remains nearly constant with mean warming



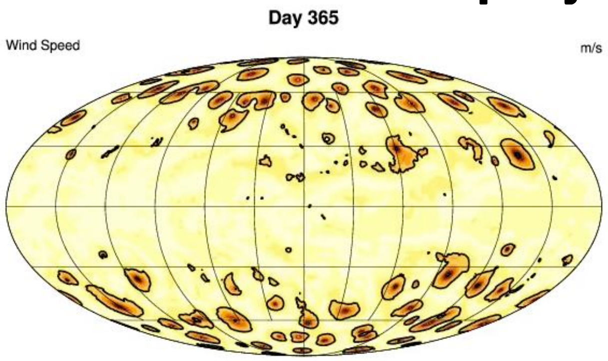


North Atlantic downscaled GCM

Schenkel et al. (2023), J. Clim.
North Atlantic tropical cyclone outer size and structure remain unchanged by the late 21st century.

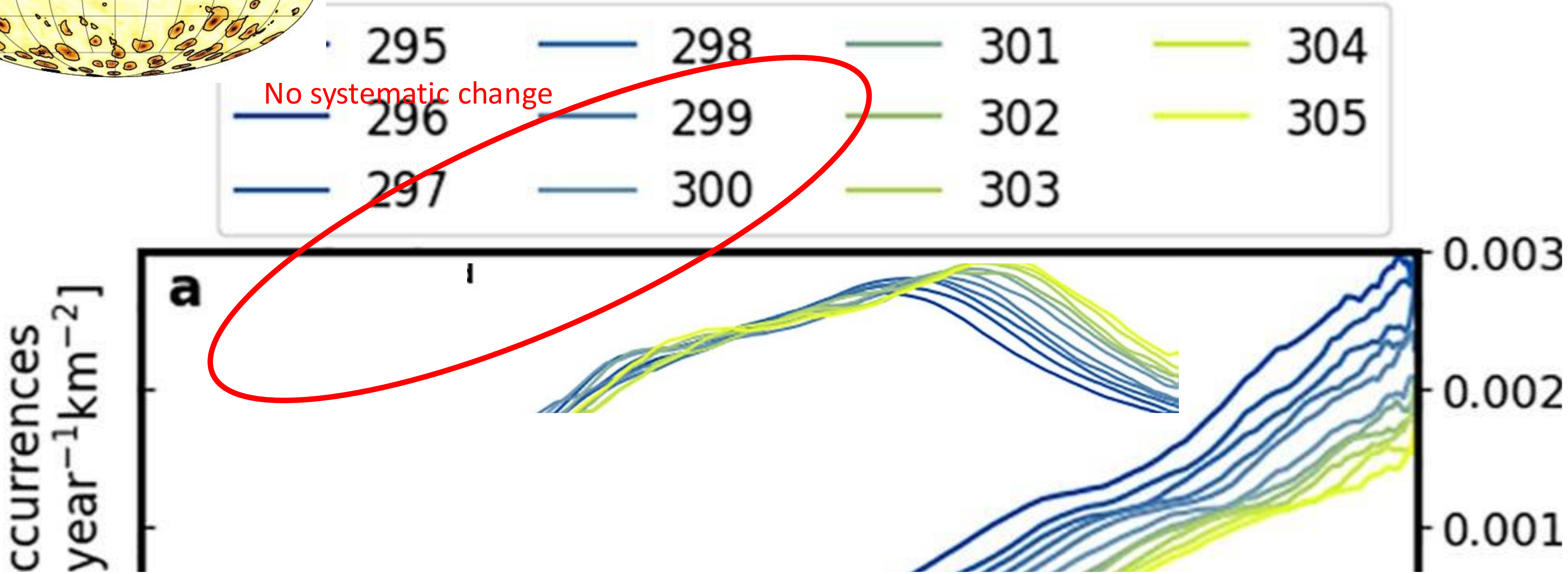
Important: the structure of the wind field remains nearly constant too

Future model projections show outer size remains nearly constant with mean warming



Aquaplanet with constant global SST

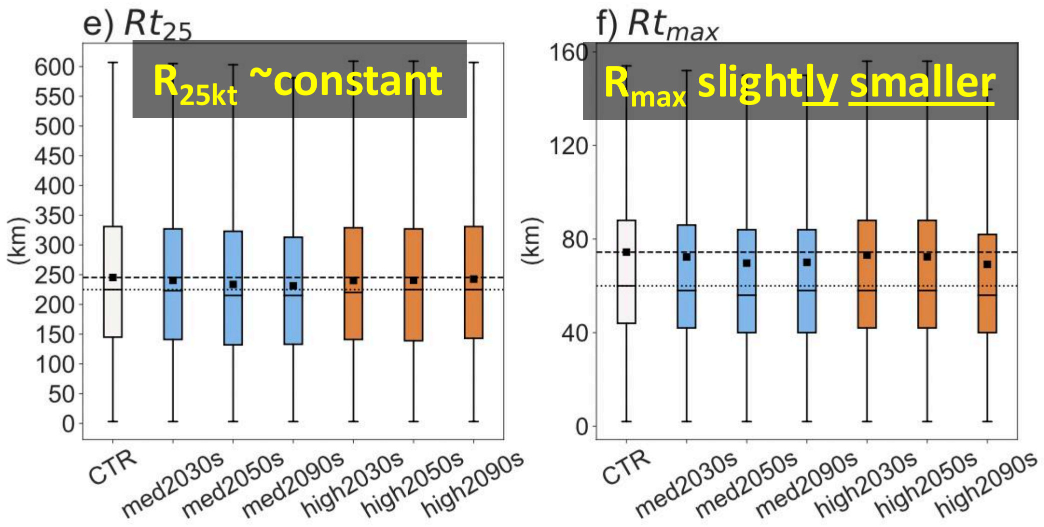
Stansfield and Reed (2021), JAMES

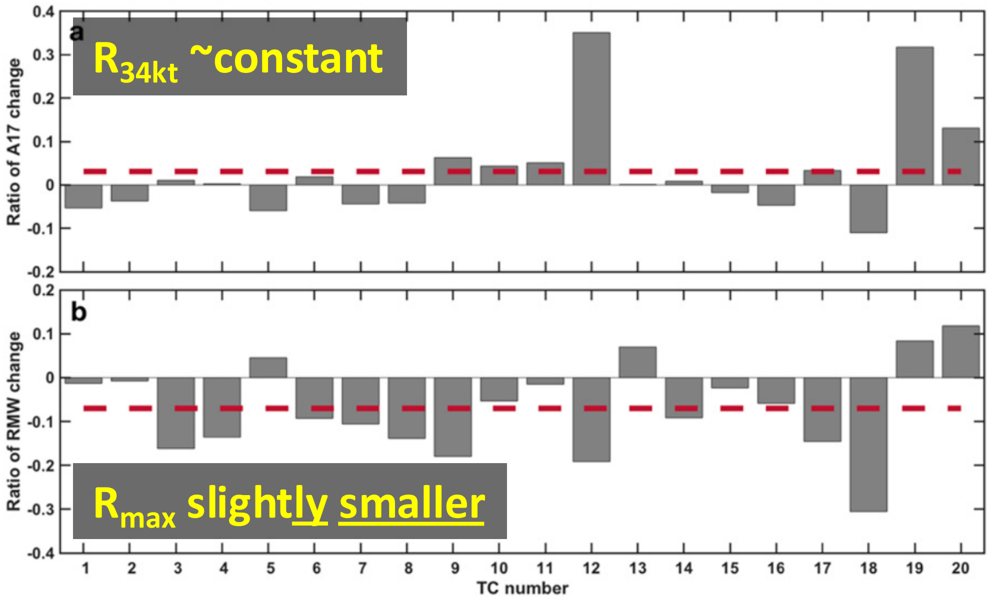


Stansfield and Reed (2021)

Tropical Cyclone Precipitation Response to Surface Warming in Aquaplanet Simulations With Uniform Thermal Forcing

Future model projections show outer size remains nearly constant with mean warming





Pseudo-global warming (PGW) WRF simulation

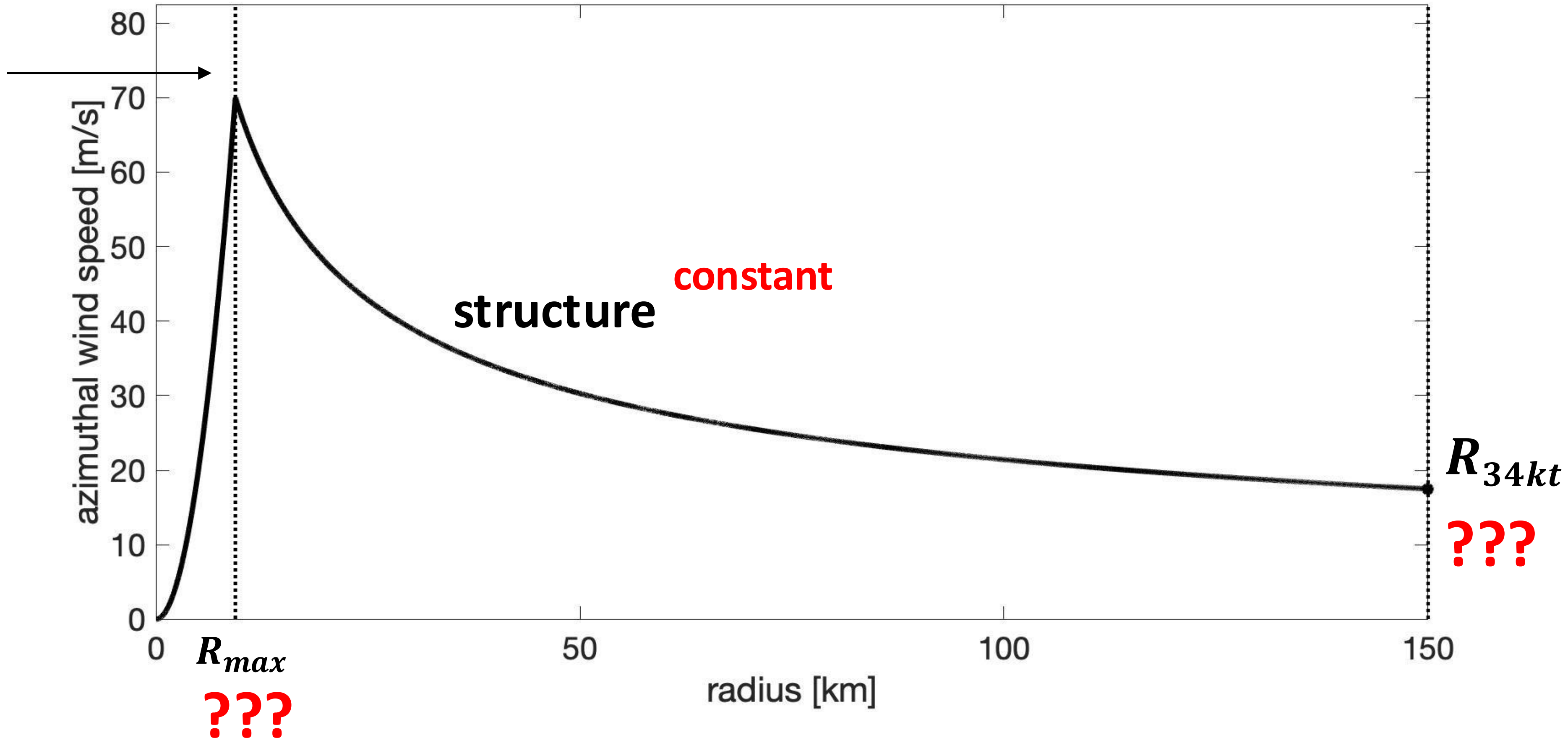
Tran et al. (2022) Earth's Future
Future Changes in Tropical Cyclone Exposure and Impacts in Southeast Asia From CMIP6 Pseudo-Global Warming Simulation

Chen et al. (2022) J. Clim.
Future Thermodynamic Impacts of Global Warming on Landfalling Typhoons and Their Induced Storm Surges to the Pearl River Delta Region as Inferred from High-Resolution Regional Models

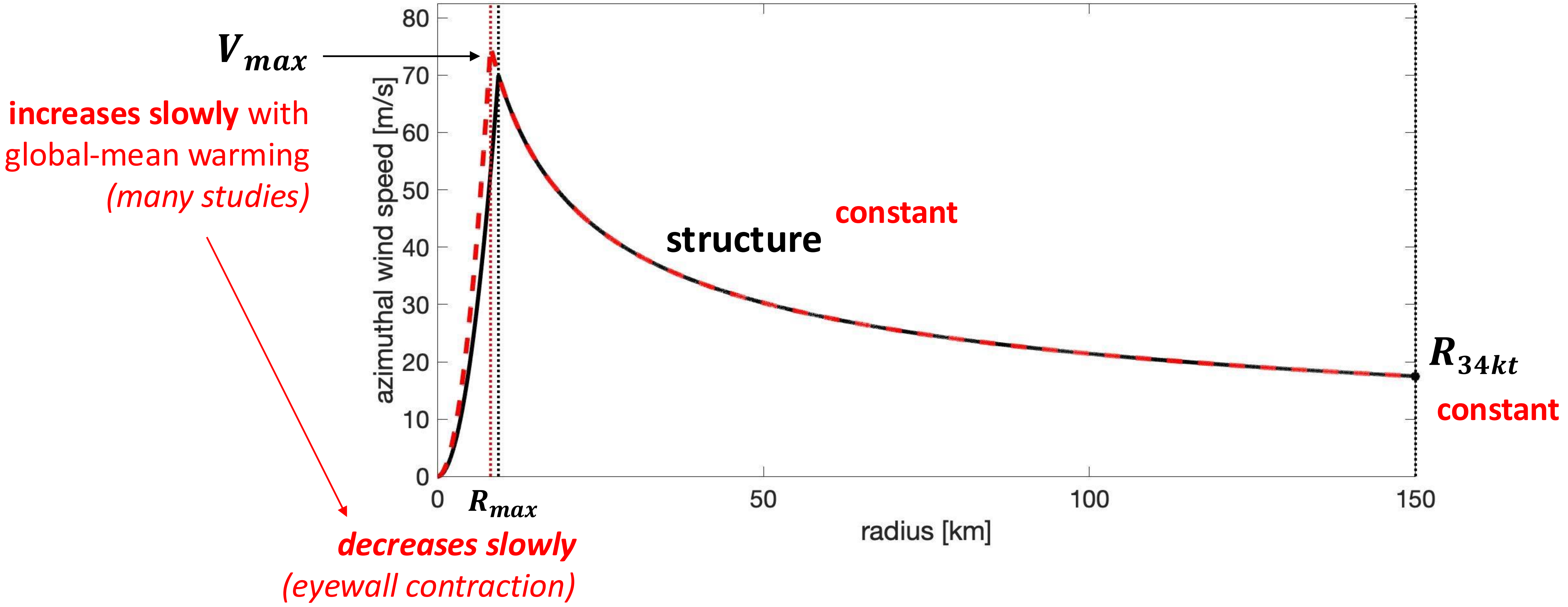
Theory predicts response to global-mean warming in models

V_{max}

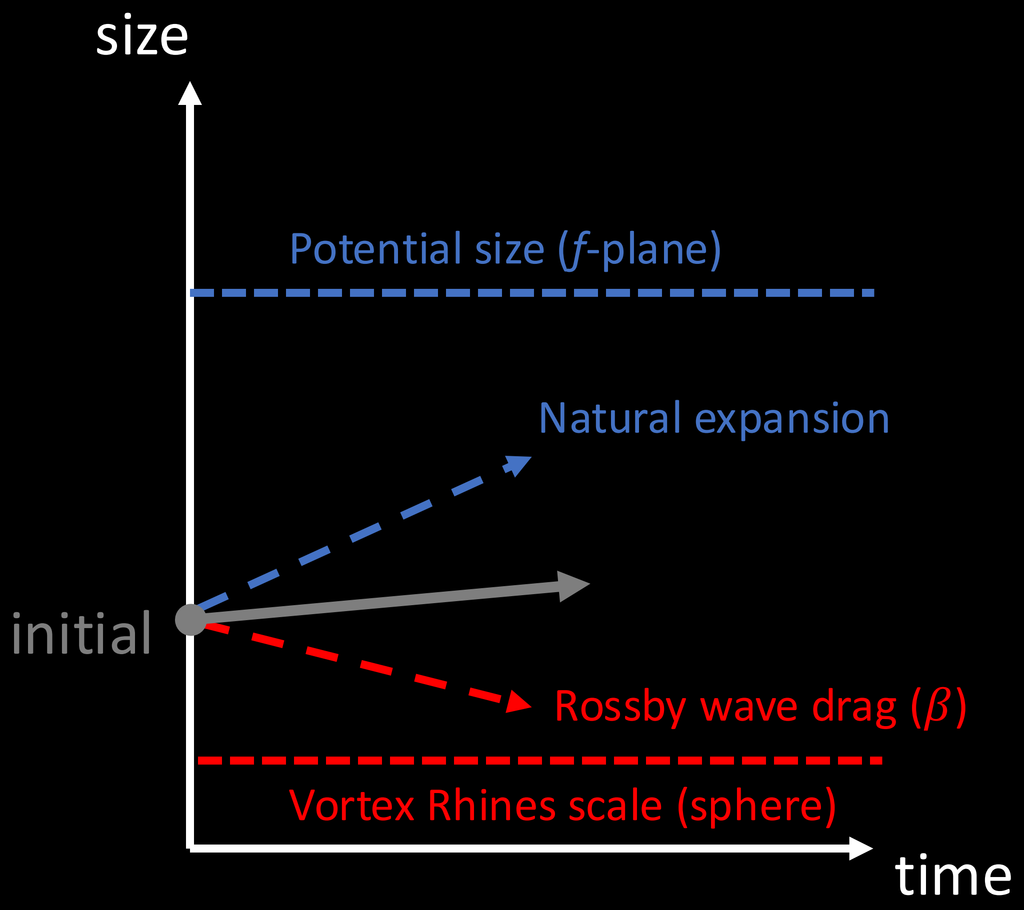
increases slowly with global-mean warming *(many studies)*

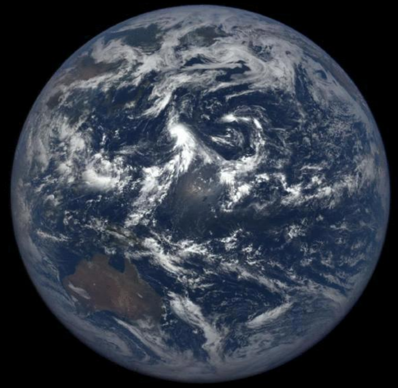


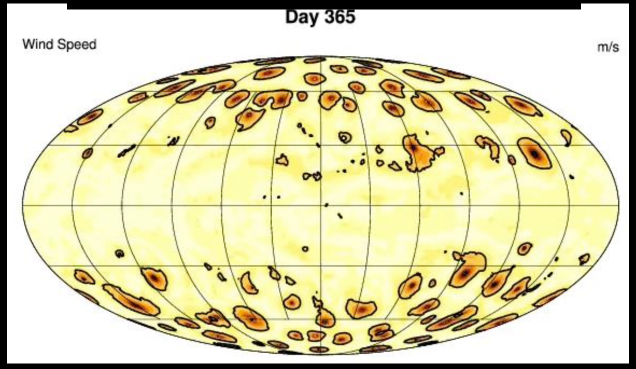
Theory predicts response to global-mean warming in models

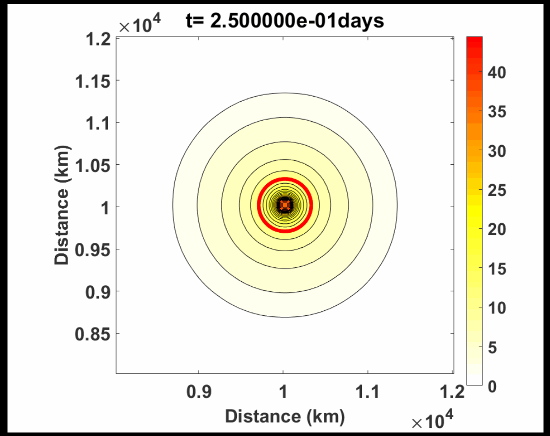


Tropical cyclone size in the tropics/subtropics









This work explains the **statistical** behavior of observed TC size.

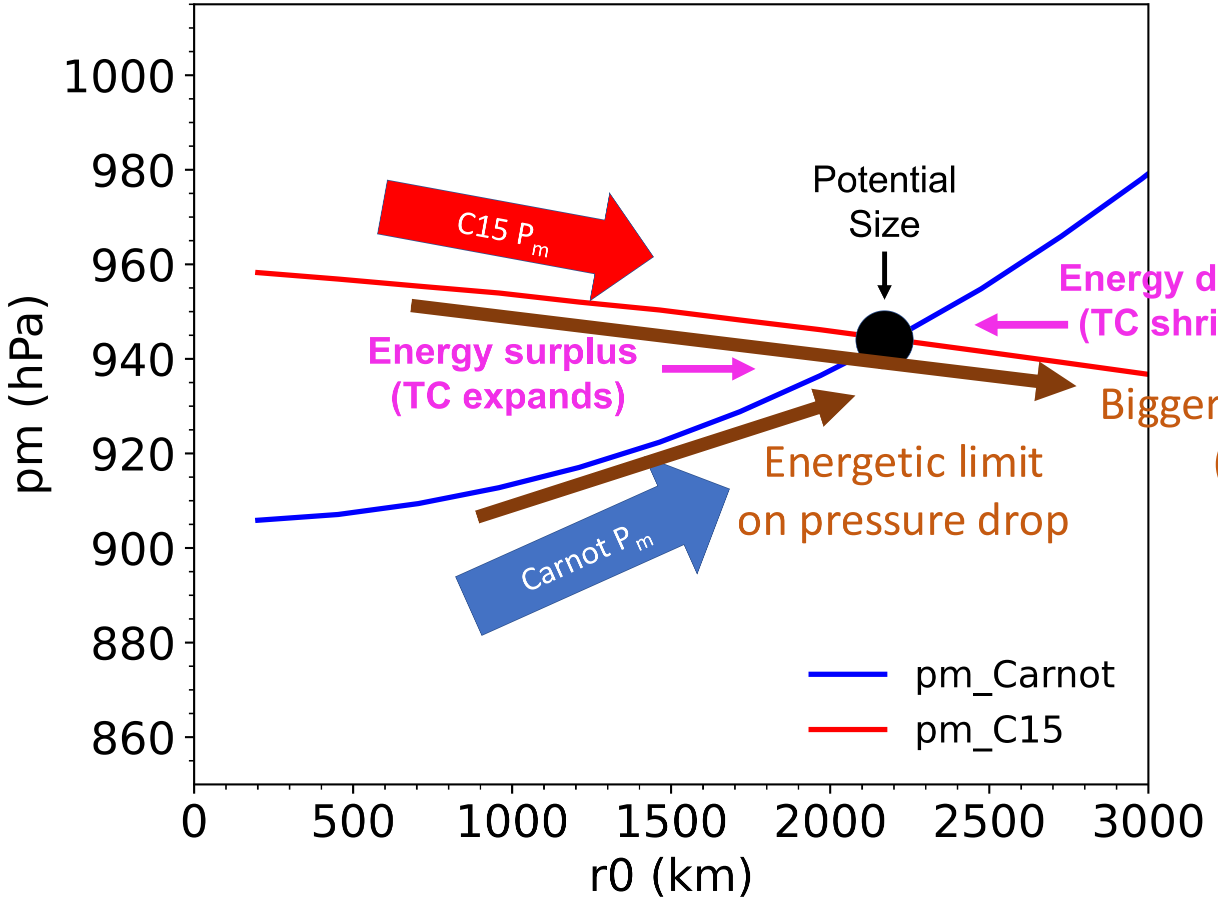
Later: a physical theory for the expansion of an **individual TC**?

First though: wind field → hazards and P_{min}

Break for questions!

EXTRA

Tropical cyclone potential size set by energetic and dynamic constraints



Bigger storm = larger pressure drop
(gradient wind balance)

$$r_a \sim V_{\text{Carnot}}/f$$

$$V^2_{\text{Carnot}} = (\eta \epsilon_C L_v - R_v T_s) q^*_{va}$$

Wang et al (2022). Tropical cyclone potential size, J. Atmos. Sci.

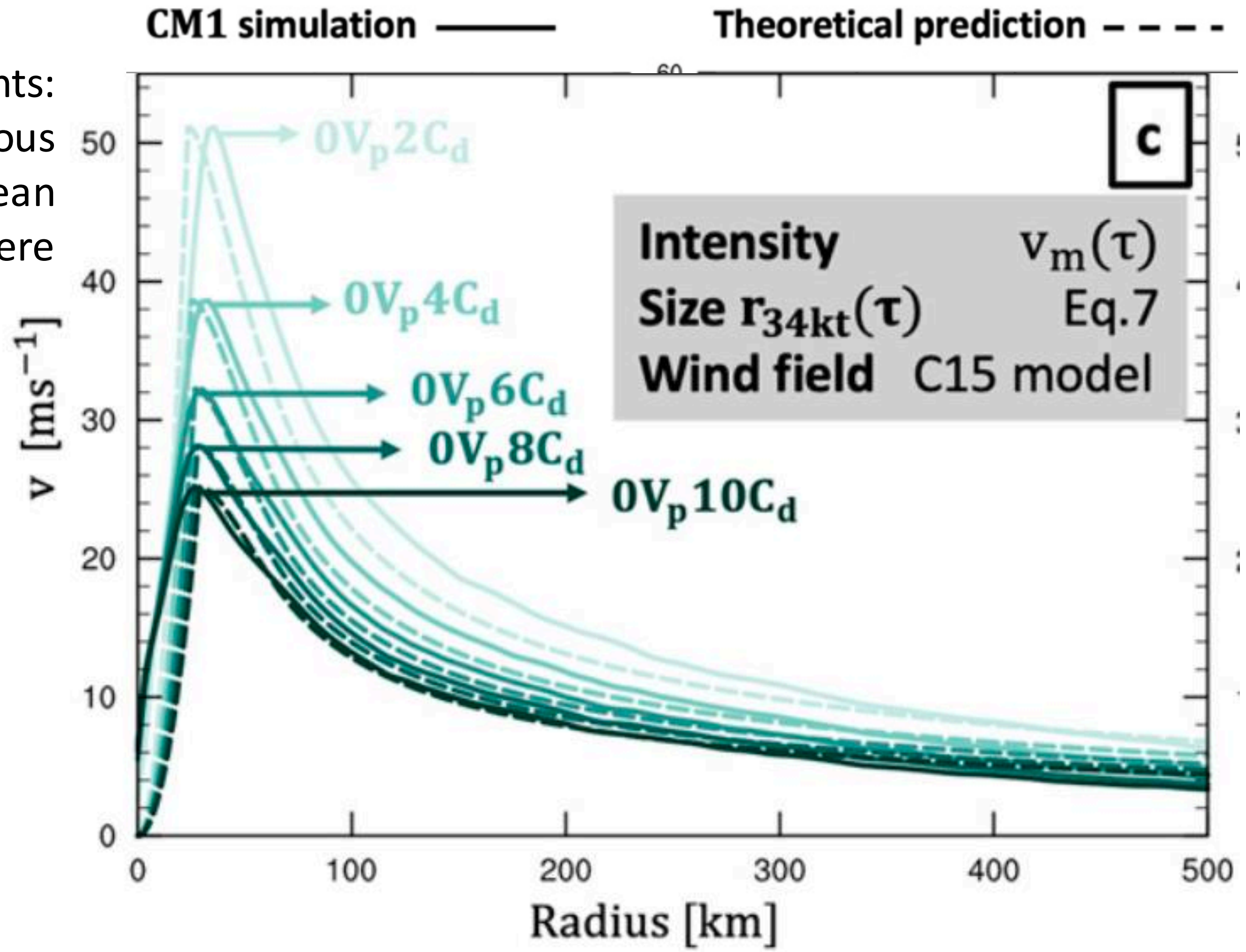
Landfall

Over land, potential size (~v_p/f) is ≈ 0

so size decreases with intensity

structural model still works well

Experiments: instantaneous change from ocean to land everywhere

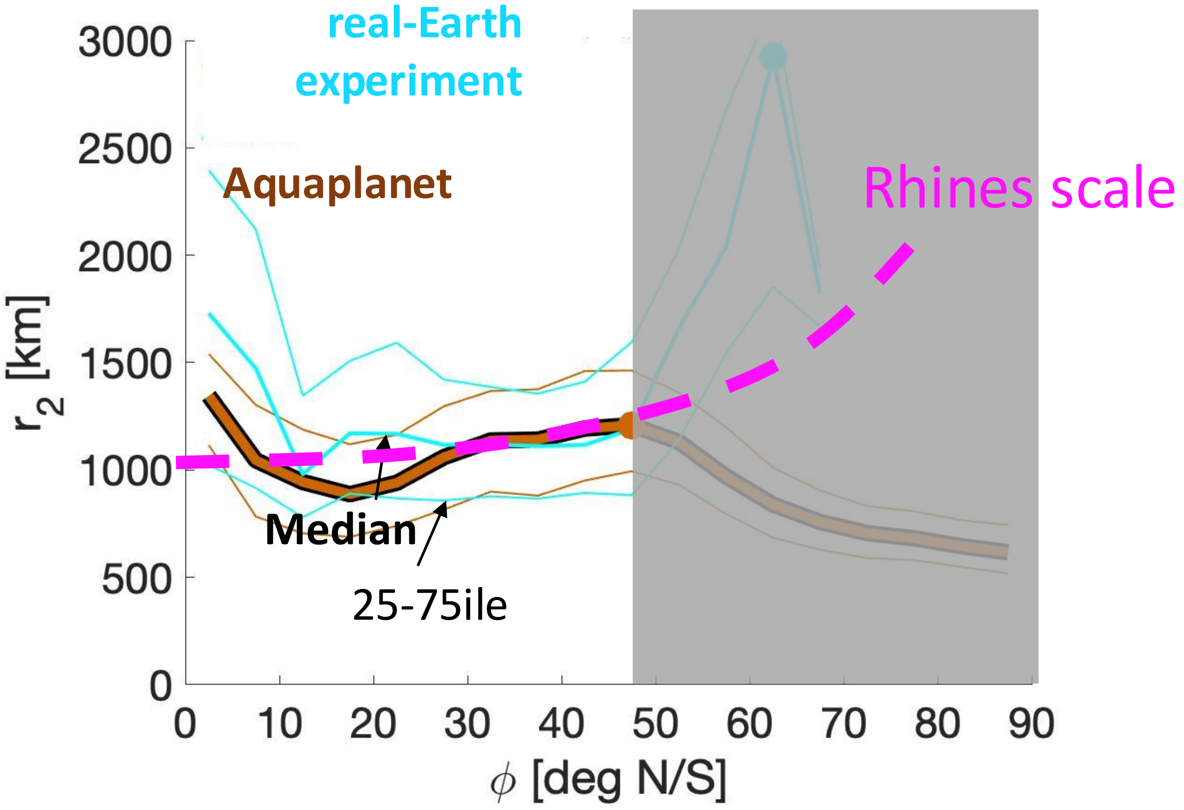


Can give decent representation of **azimuthal-mean** wind field evolution after landfall!

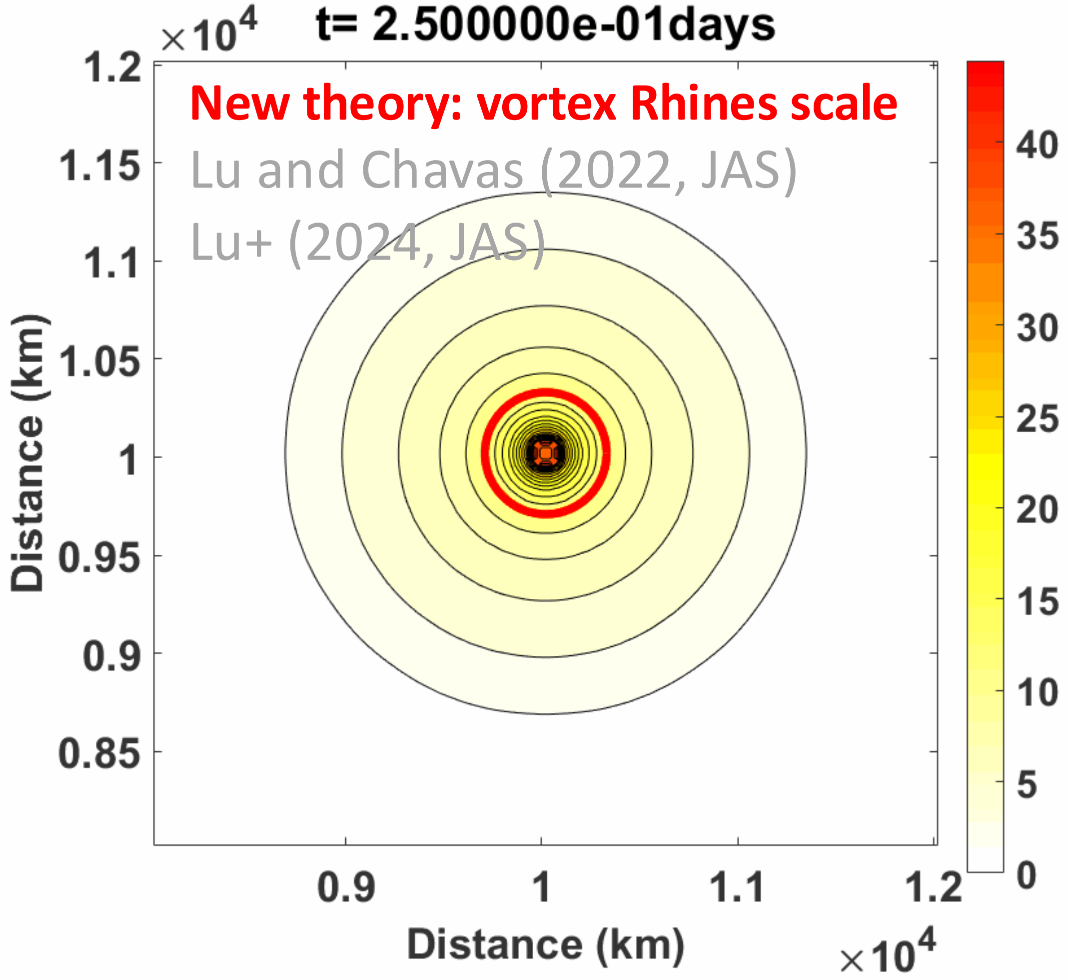
But **asymmetries** become *very large* after landfall Hlywiak and Nolan (2021, 2022) – 3D simulations

Chen and Chavas (2023) JAS

Tropical cyclone size is set by the Rhines scale

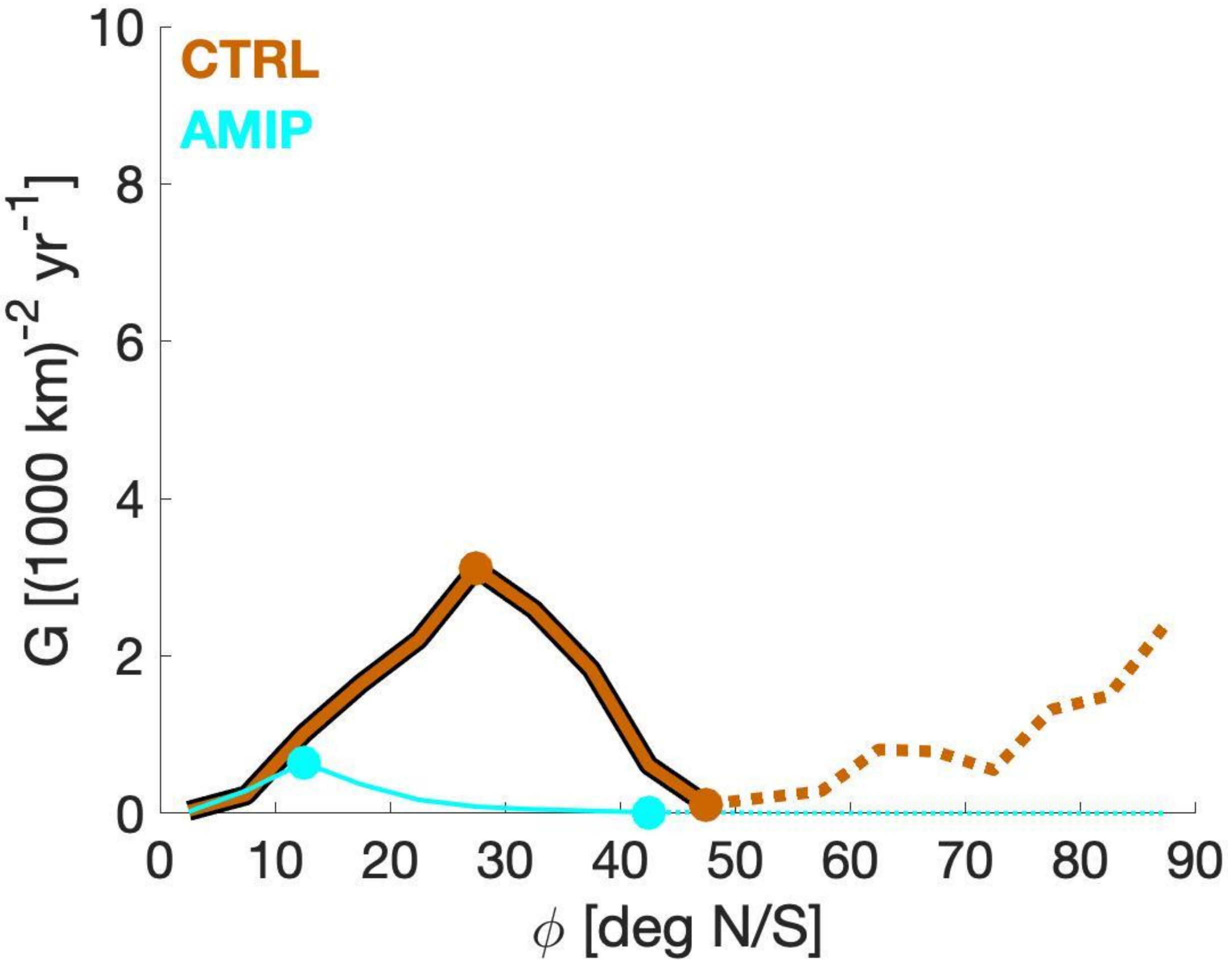


Chavas and Reed (2019), J. Atmos. Sci

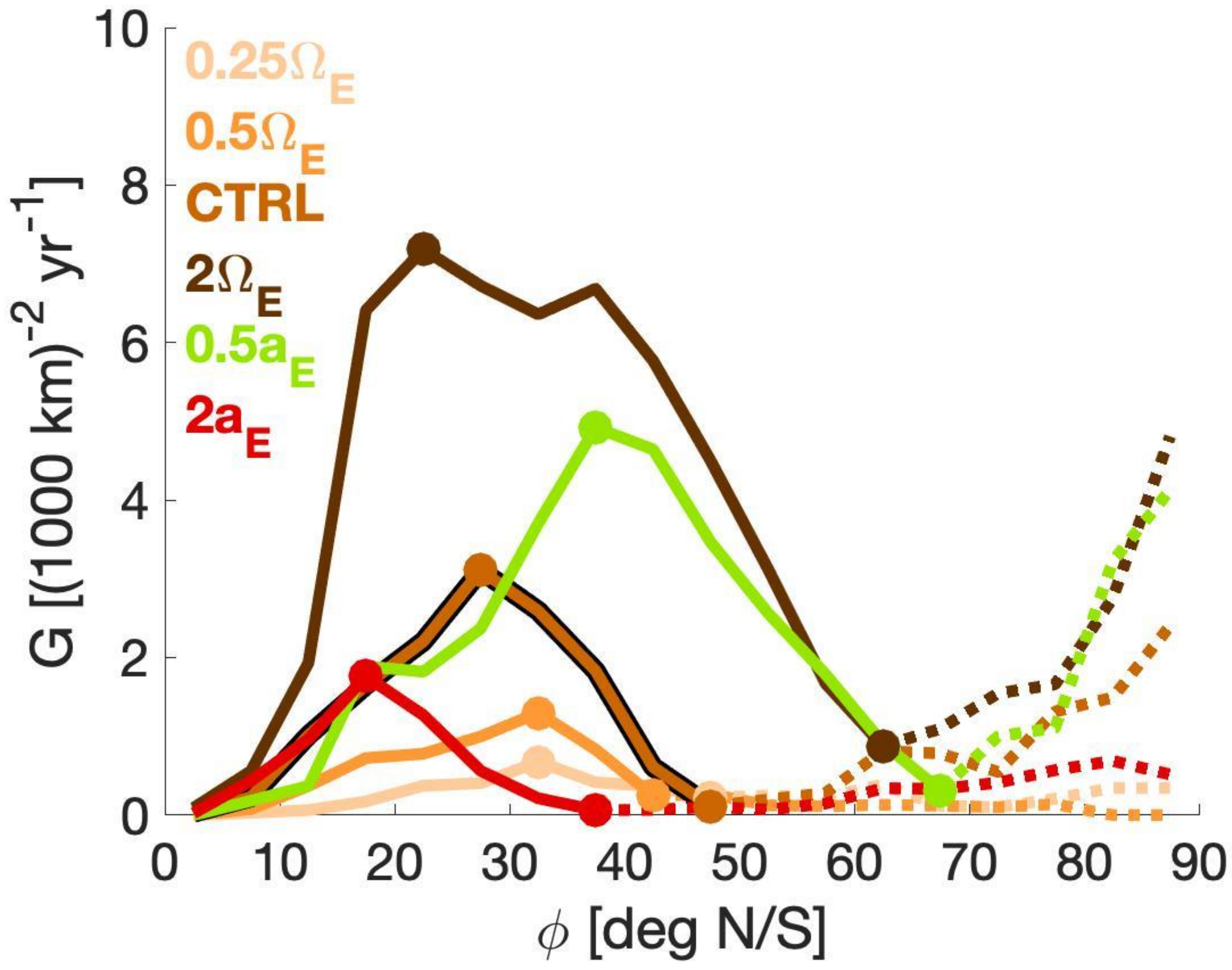


Complete theory for size dynamics:
Wang+ (2022, JAS)
Wang and Chavas (2024, JAS)

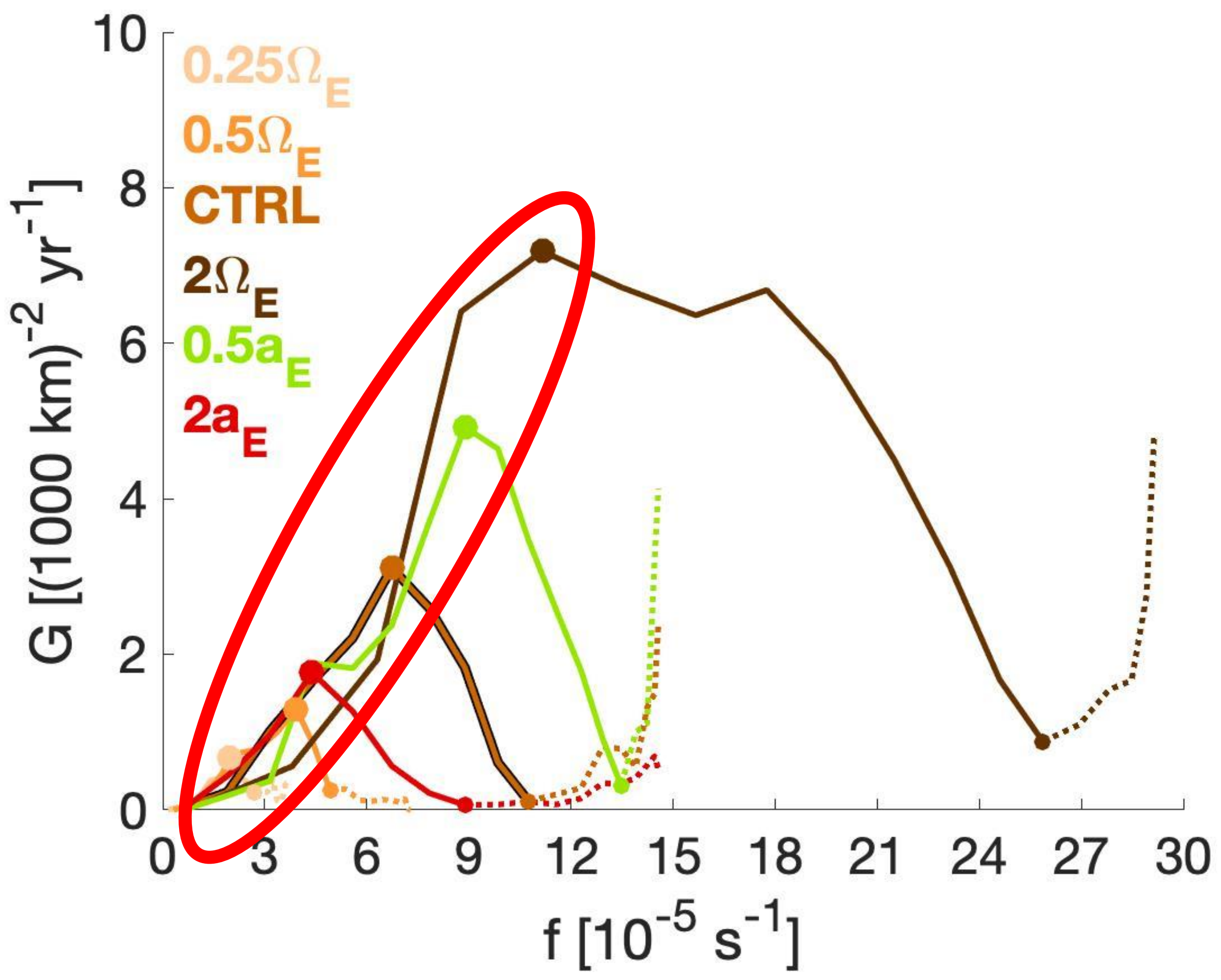
Observations: Chavas et al. (2016)



CTRL
AMIP
G [(1000 km)^-2 yr^-1]
0
2
4
6
8
10
0
10
20
30
40
50
60
70
80
90
ϕ [deg N/S]

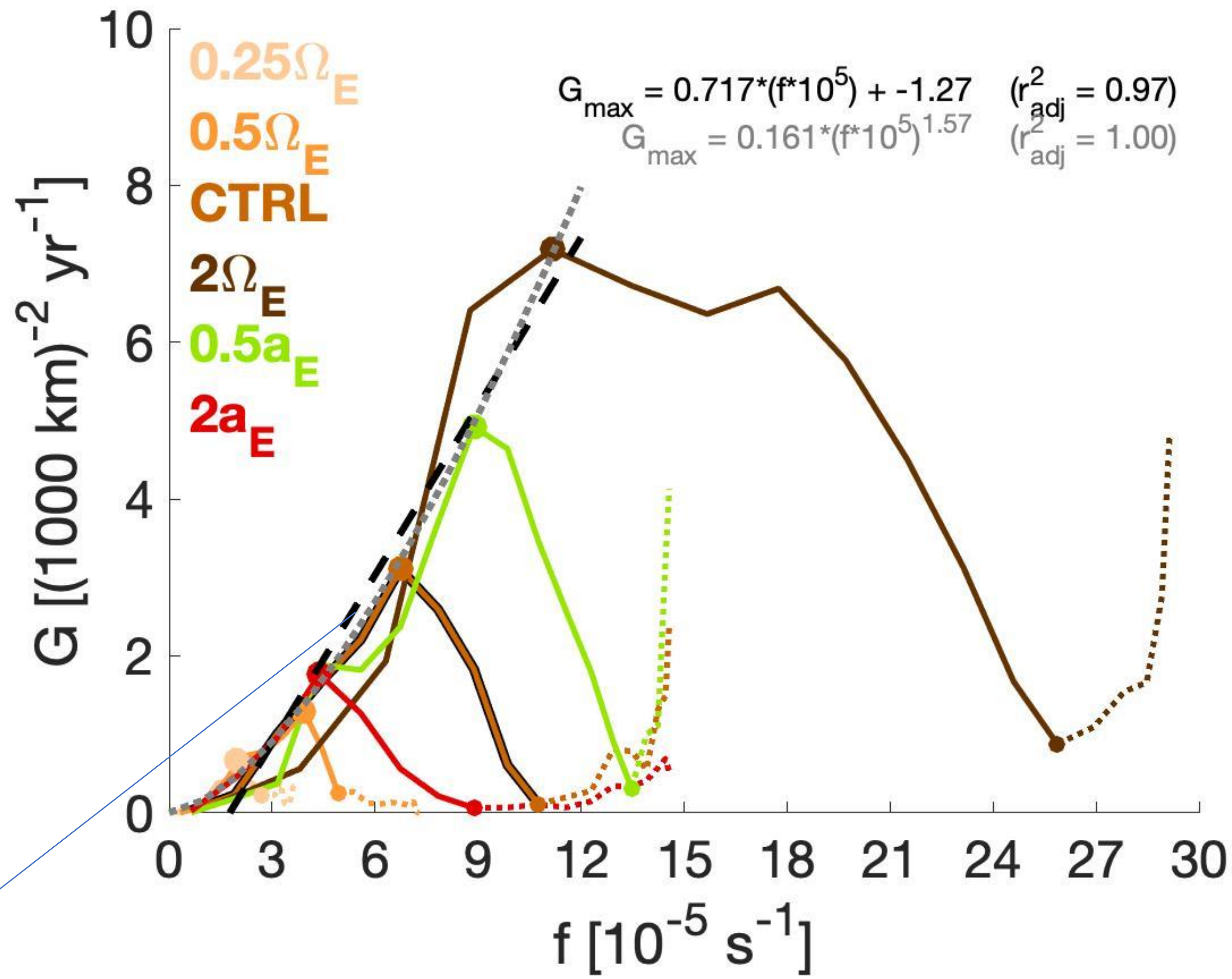


0.25Ω_E
0.5Ω_E
CTRL
2Ω_E
0.5a_E
2a_E
G [(1000 km)^-2 yr^-1]
0
2
4
6
8
10
0
10
20
30
40
50
60
70
80
90
φ [deg N/S]



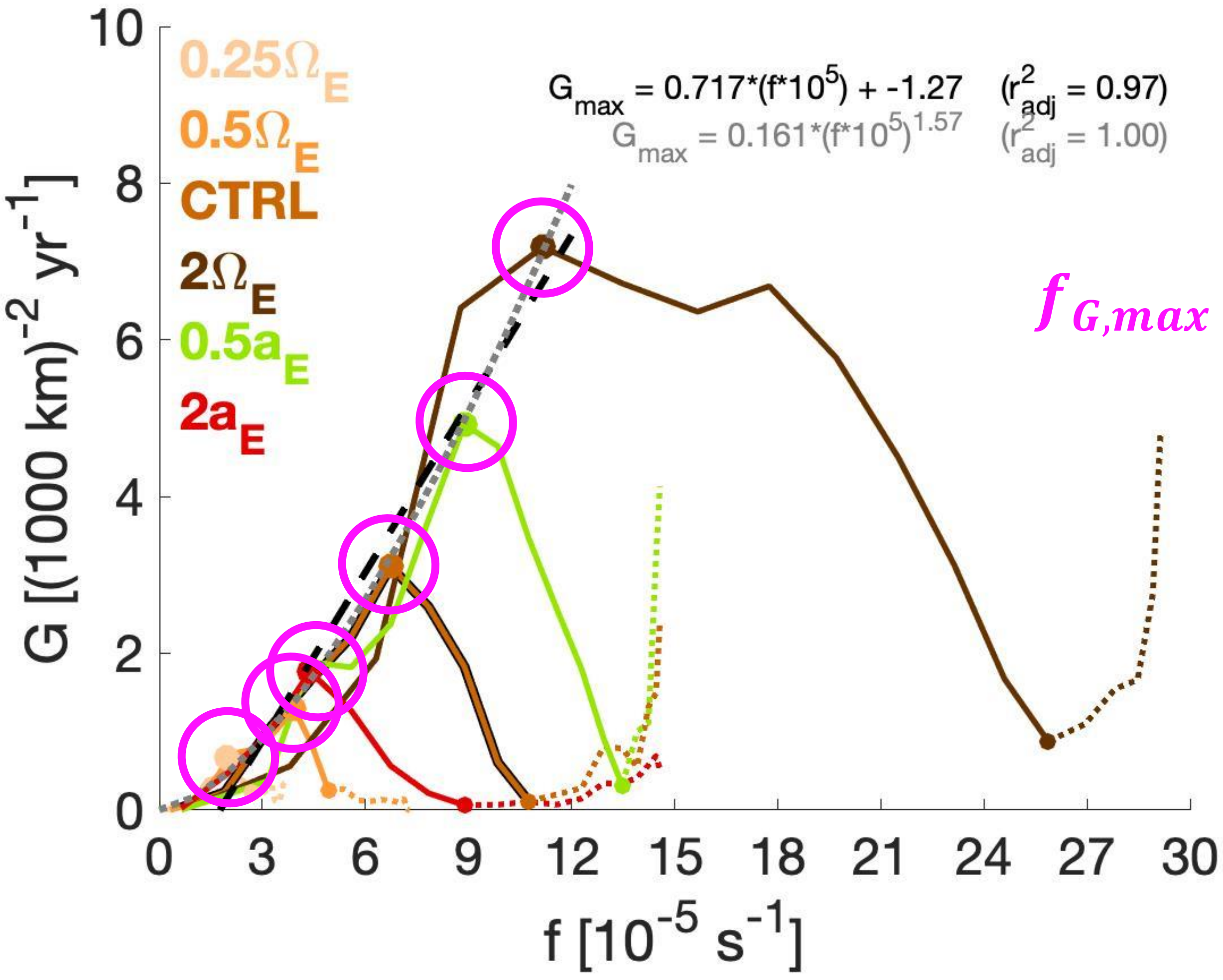
0.25Ω_E
0.5Ω_E
CTRL
2Ω_E
0.5a_E
2a_E
G [(1000 km)$^{-2}$ yr^{-1}]
f [10^{-5} s^{-1}]
0
2
4
6
8
10
0
3
6
9
12
15
18
21
24
27
30

Genesis rate increases linearly with the Coriolis parameter in the low/mid latitudes.



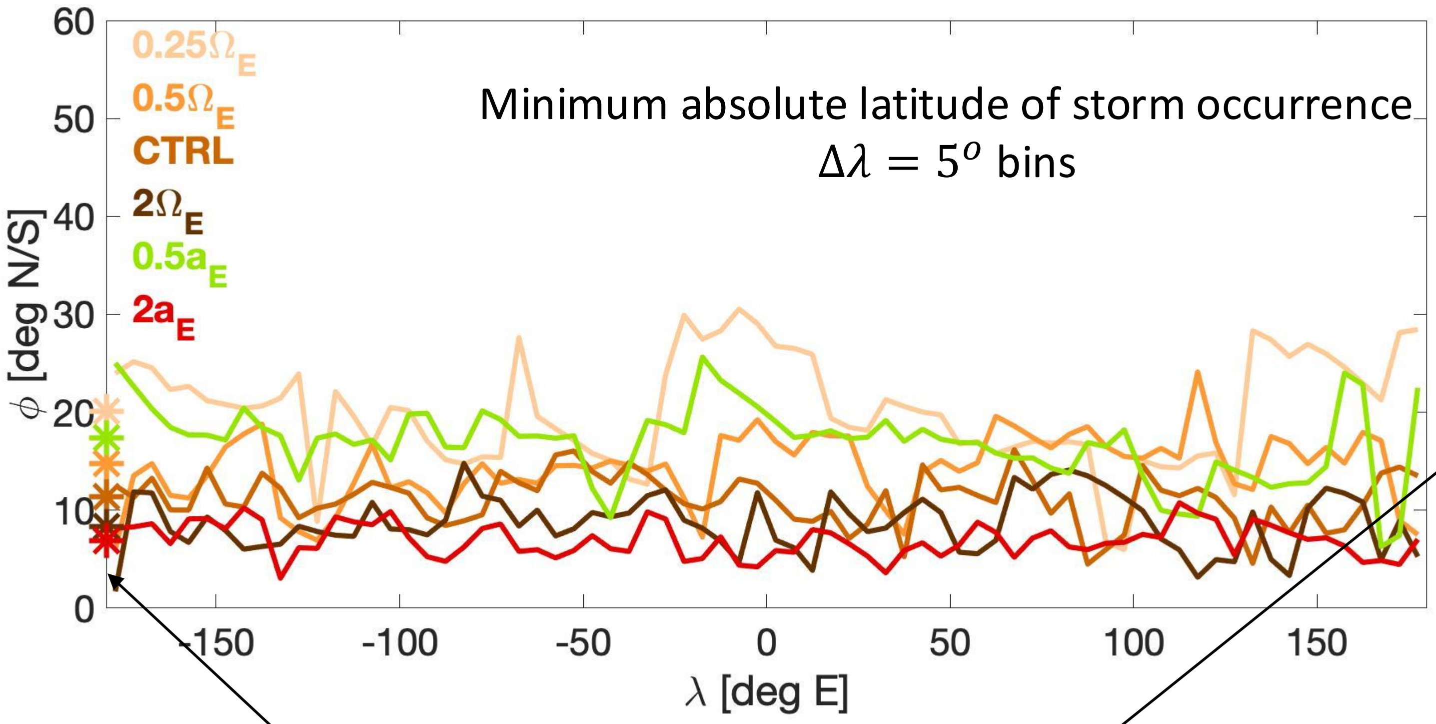
Slope ≈ $0.7\ yr^{-1}(1000\ km)^{-2}(10^{-5}\ s^{-1})^{-1}$

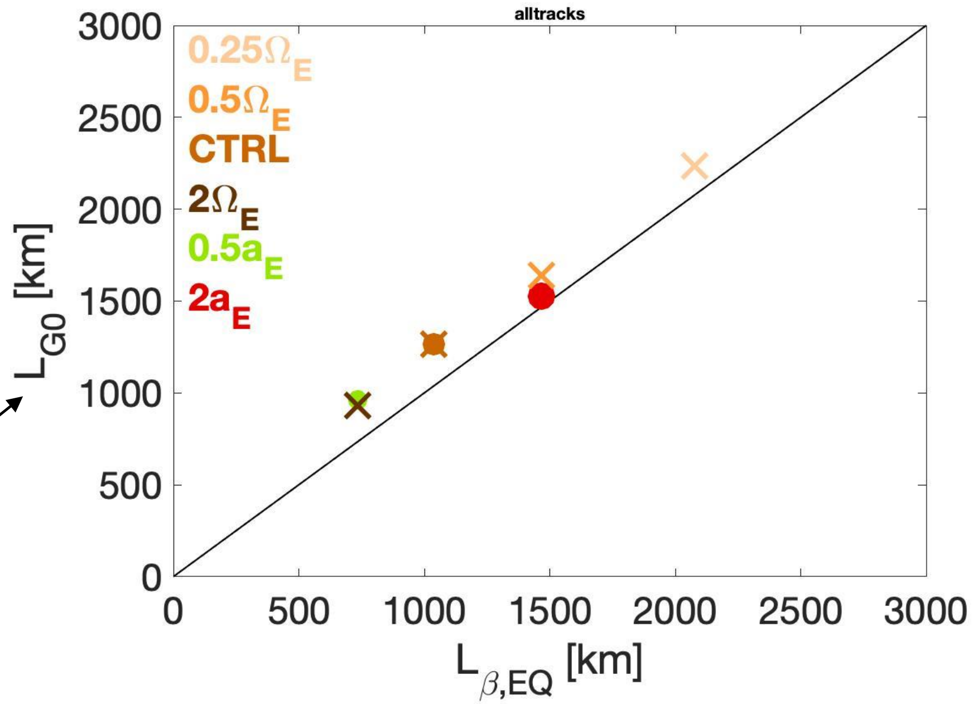
Genesis rate increases linearly with the Coriolis parameter in the low/mid latitudes.



$f_{G,max}$ follows $f(\phi_c)$

Minimum genesis distance from the equator follows the equatorial deformation/Rhines scale.





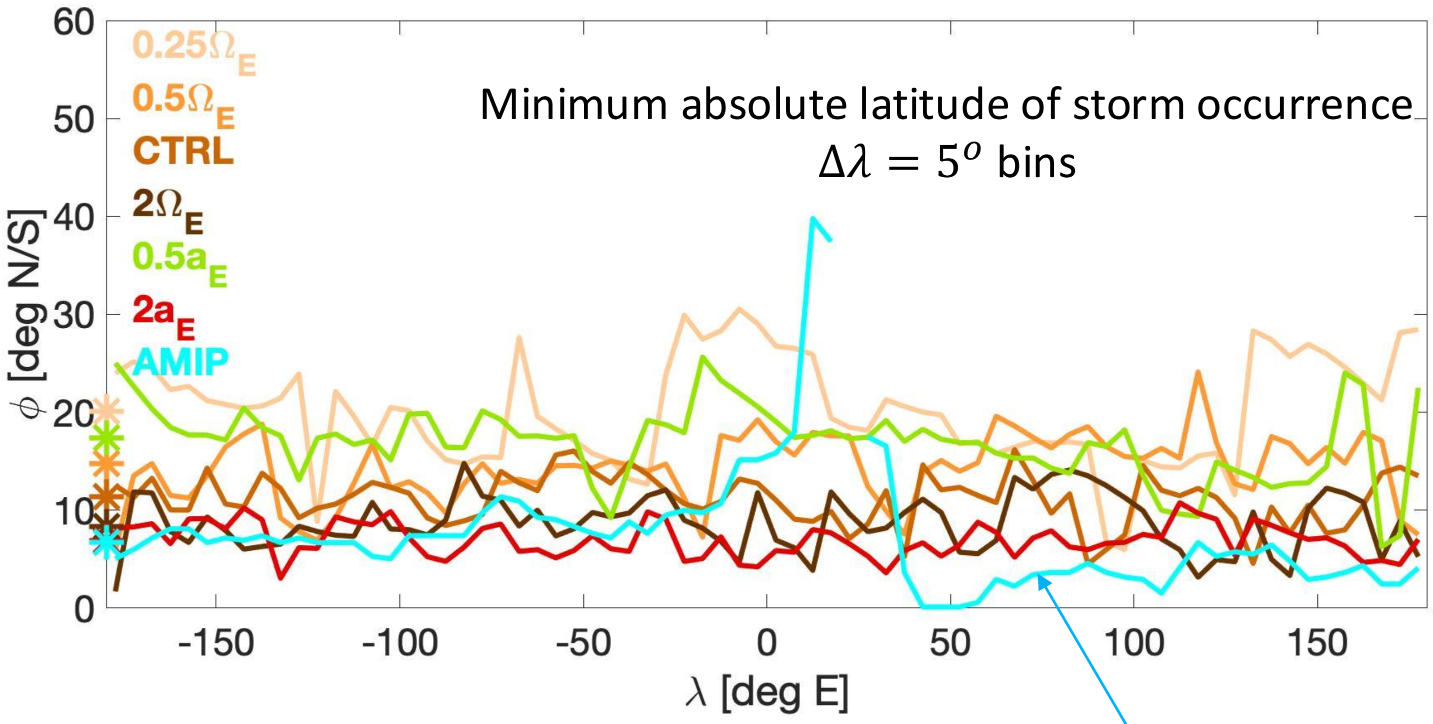
ϕ_{G0} = Median latitude of each curve

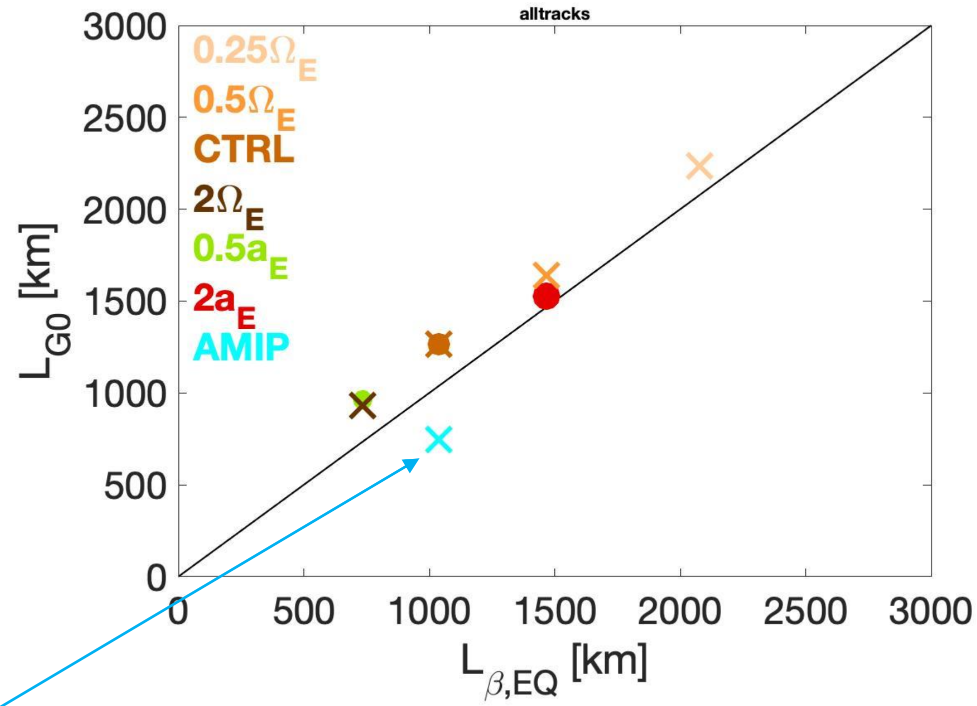
$$L_{\beta,\mathrm{EQ}} = \sqrt{\frac{U_\beta^*}{\frac{2\Omega}{a}}}.$$

Rhines/deformation scale at equator

<u>Not</u> a threshold value of *f*

Minimum genesis distance from the equator follows the equatorial deformation/Rhines scale.





Real world: *relative* vorticity is non-negligible (esp Maritime Continent)

$$L_{\beta,\mathrm{EQ}} = \sqrt{\frac{U_\beta^*}{\frac{2\Omega}{a}}}.$$

Rhines/deformation scale at equator

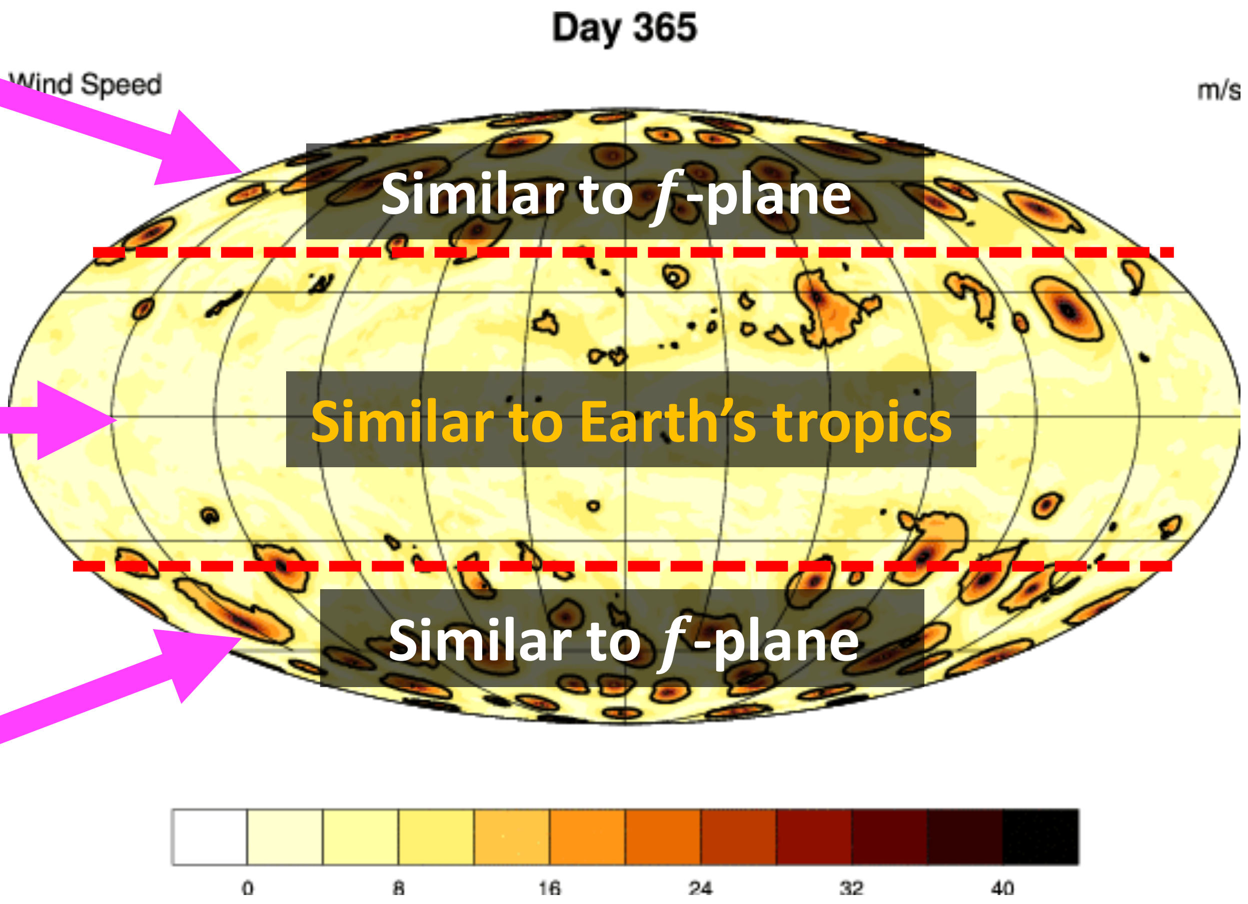
Implicates storm size: most of the storm circulation must lie on one side of equator.

But on (present day) Earth, hurricanes are thermodynamically suppressed here

Rossby waves not important.
Vortices dominate.

Rossby waves significant.
Mix of waves and vortices.

Rossby waves not important.
Vortices dominate.



Chavas and Reed (2019), J. Atmos. Sci