

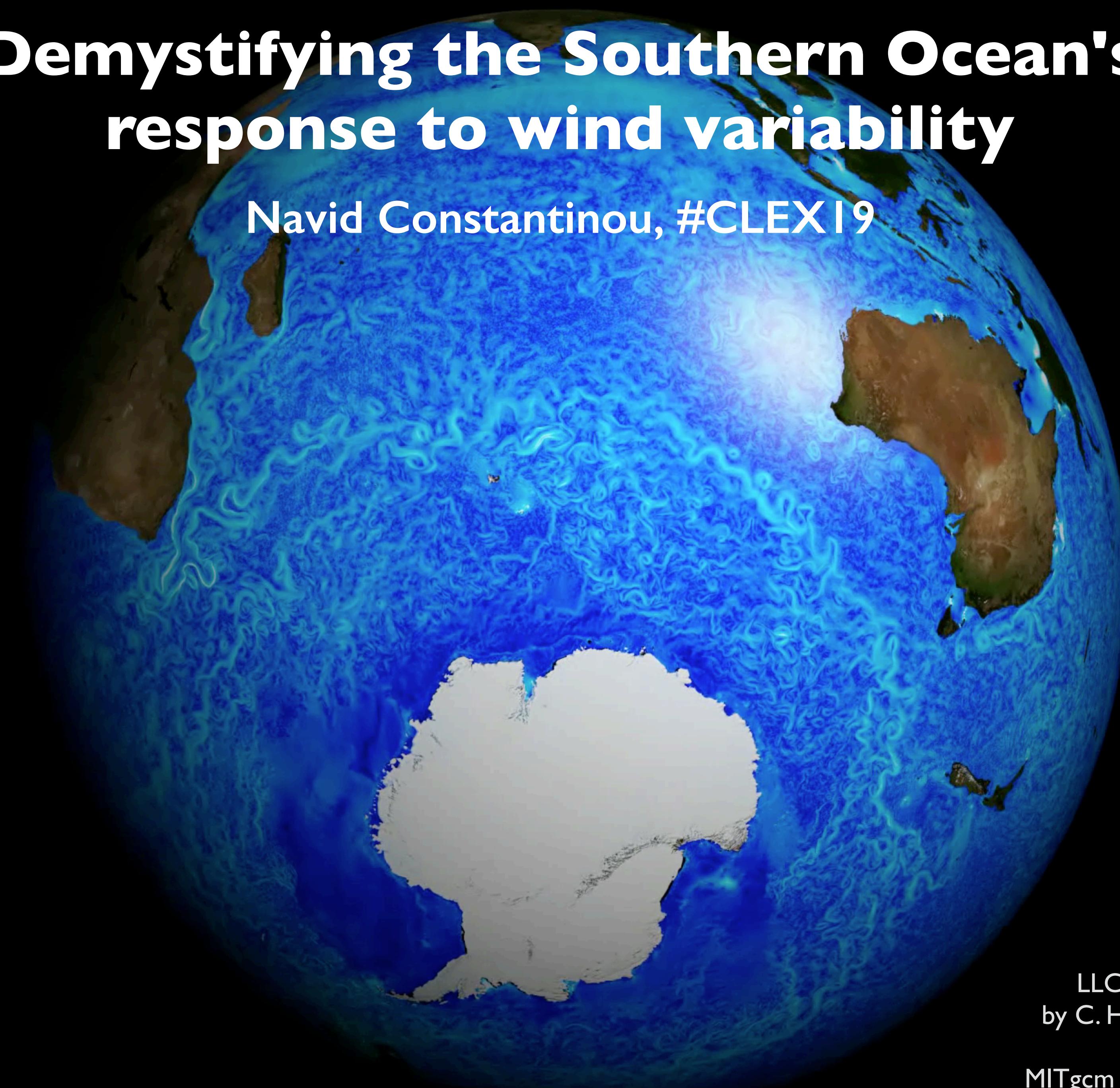


Australian National
University

the
**Antarctic
Circumpolar
Current**

Demystifying the Southern Ocean's response to wind variability

Navid Constantinou, #CLEX19



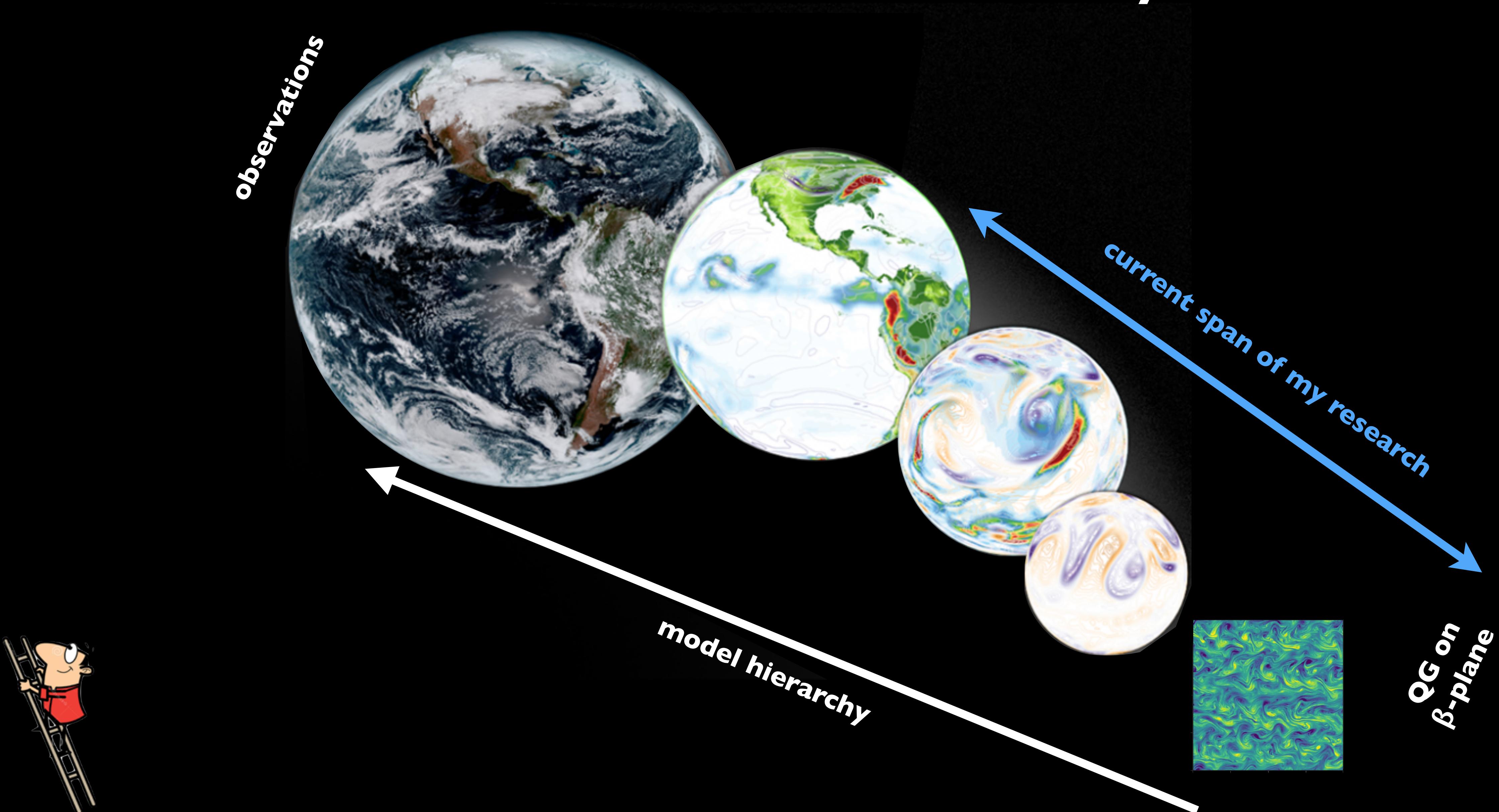
animation
not done
w/ ACCESS-OM2 model

in the spirit of
inclusion and diversity

*"no ocean model
left behind"*

LLC4320 sea surface speed animation
by C. Henze and D. Menemenlis (NASA/JPL)
1/48th degree, 90 vertical levels
MITgcm spun up from ECCO v4 state estimate

build intuition through climate-model hierarchy



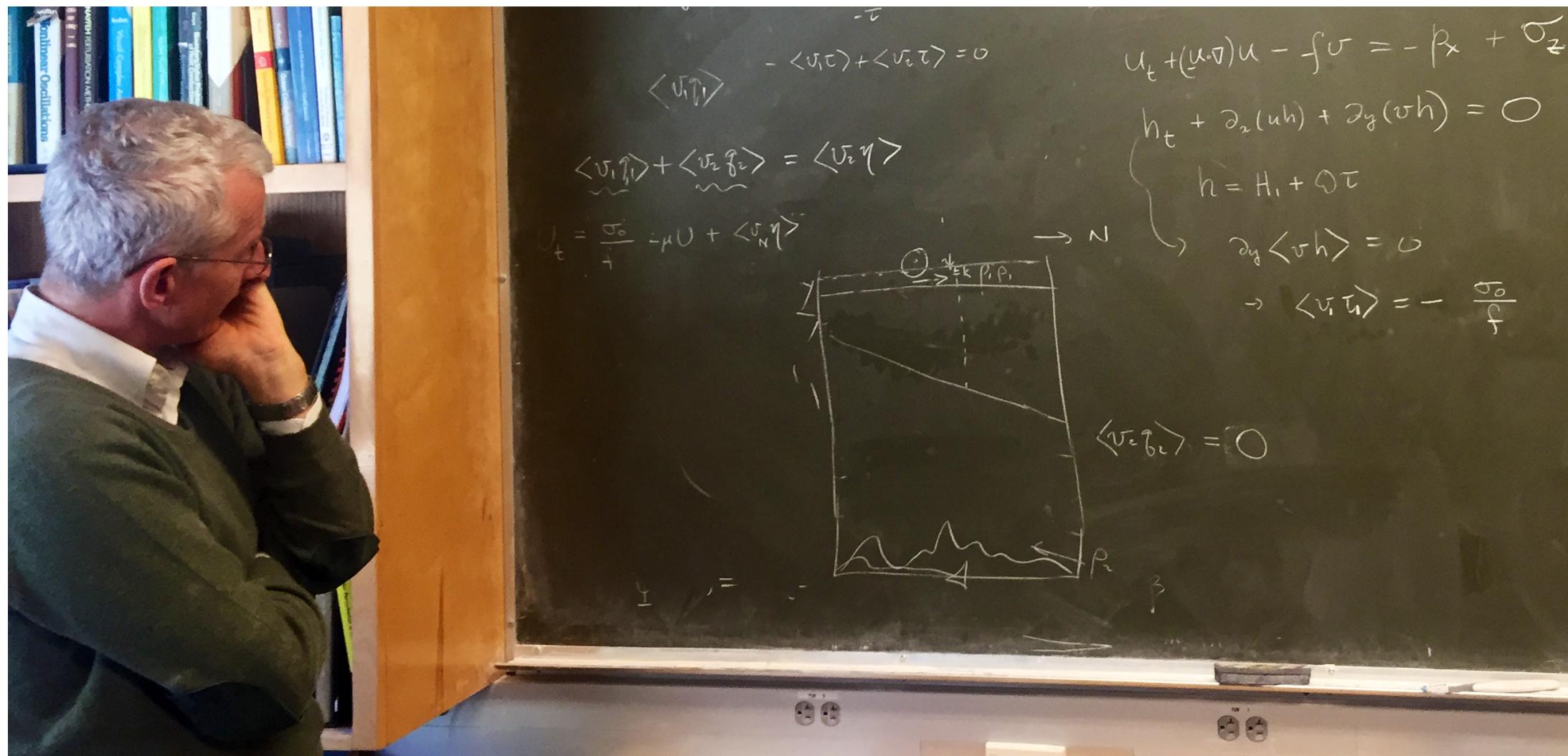
A dichotomy

theory

study dynamical laws
(differential equations)
and the consequences they imply

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = \dots$$

$$\Gamma(x) = \int_0^{\infty} t^{x-1} e^t dt$$



a typical meeting with Bill Young @ Scripps/UCSD

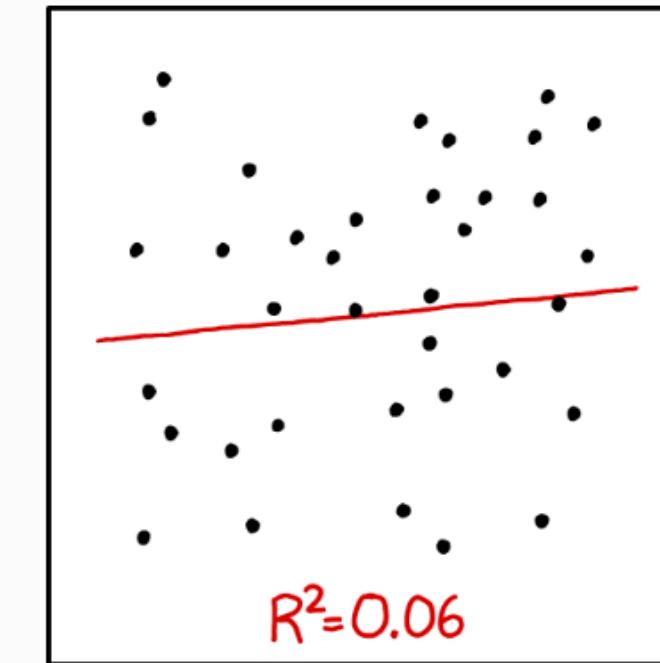
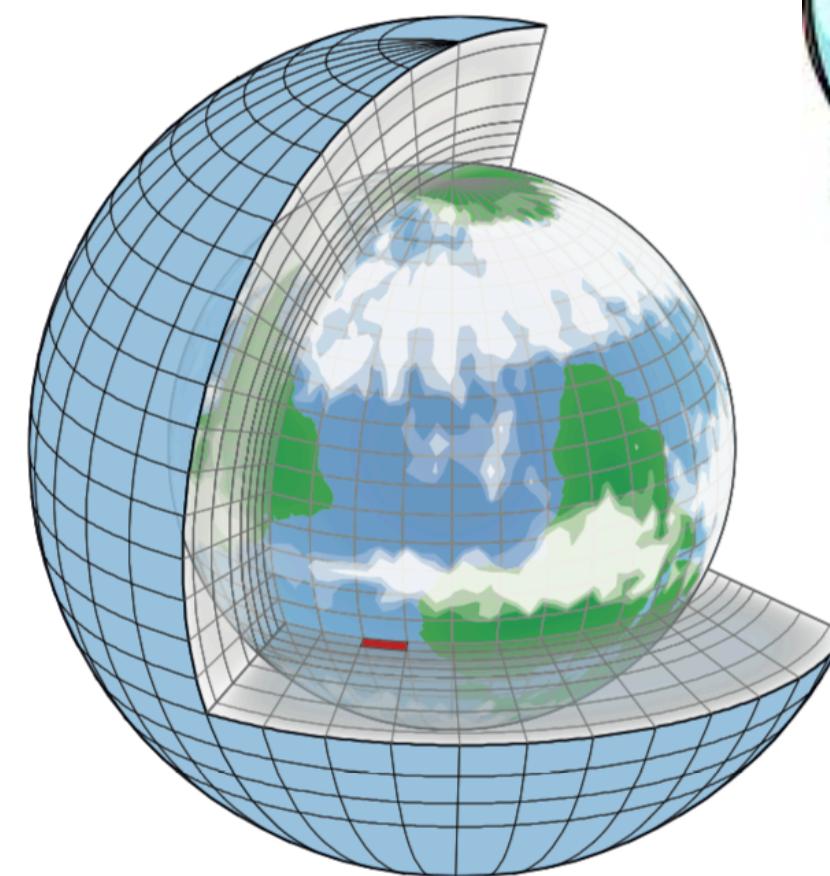
(yes, we still use chalk...)

realistic

simple

climate science

"statistical investigations"
look for patterns/correlations
in obs or climate model output

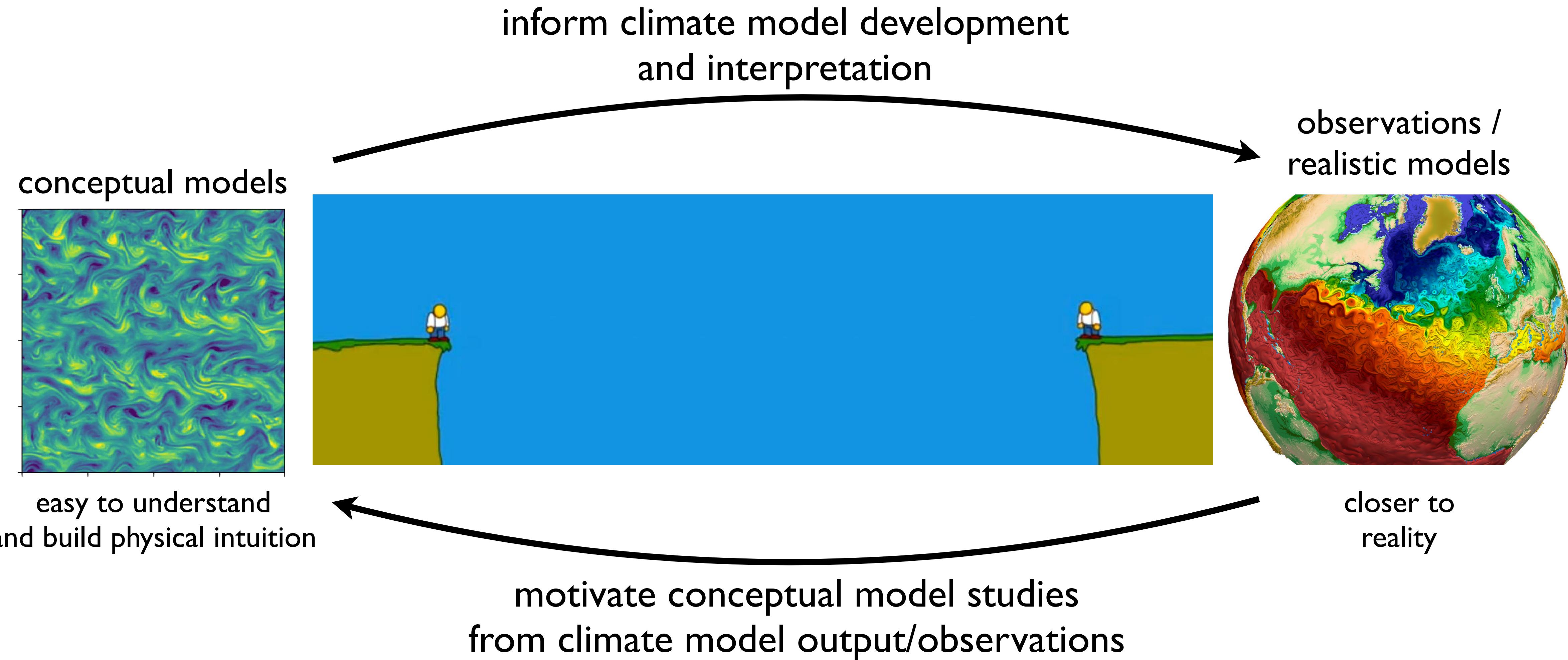


I DON'T TRUST LINEAR REGRESSIONS WHEN IT'S HARDER
TO GUESS THE DIRECTION OF THE CORRELATION FROM THE
SCATTER PLOT THAN TO FIND NEW CONSTELLATIONS ON IT.

reality

Goal: narrow the gap between theory and simulation

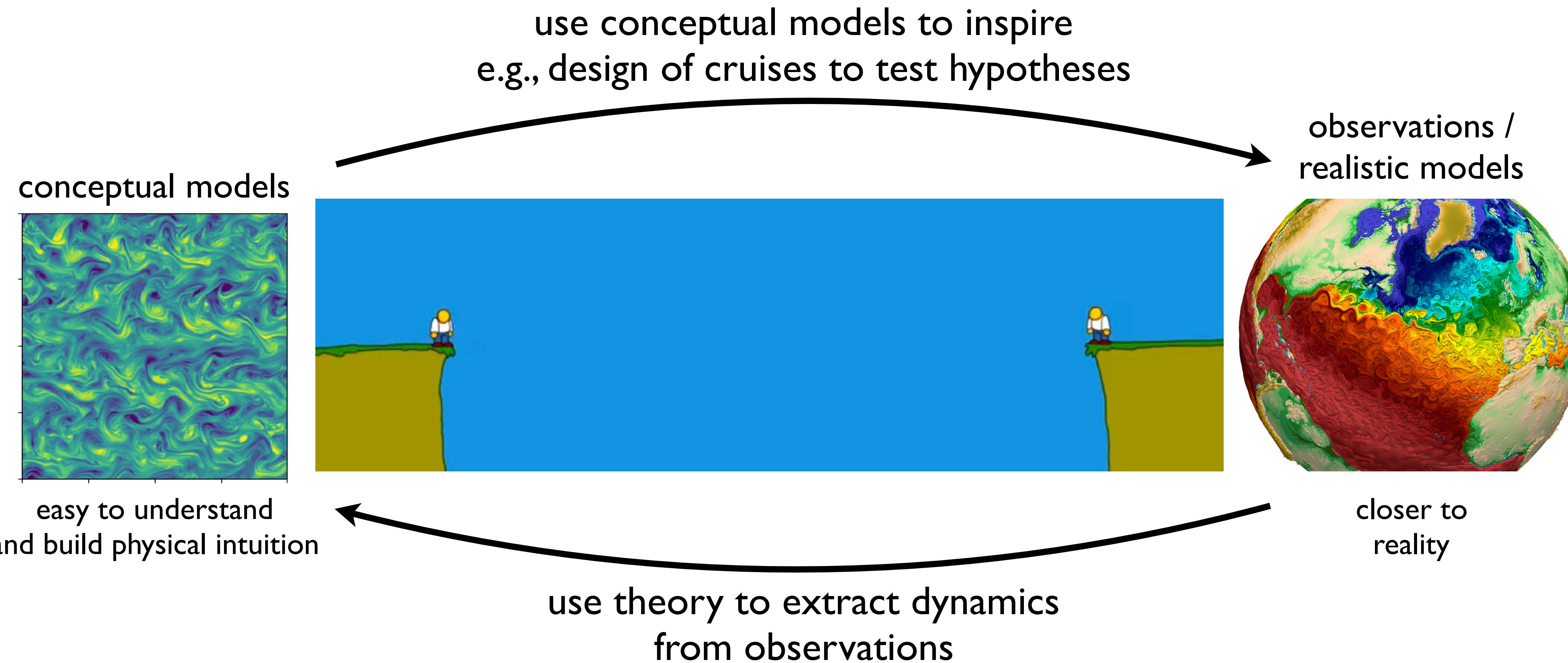
[Held 2005, BAMS]



reality

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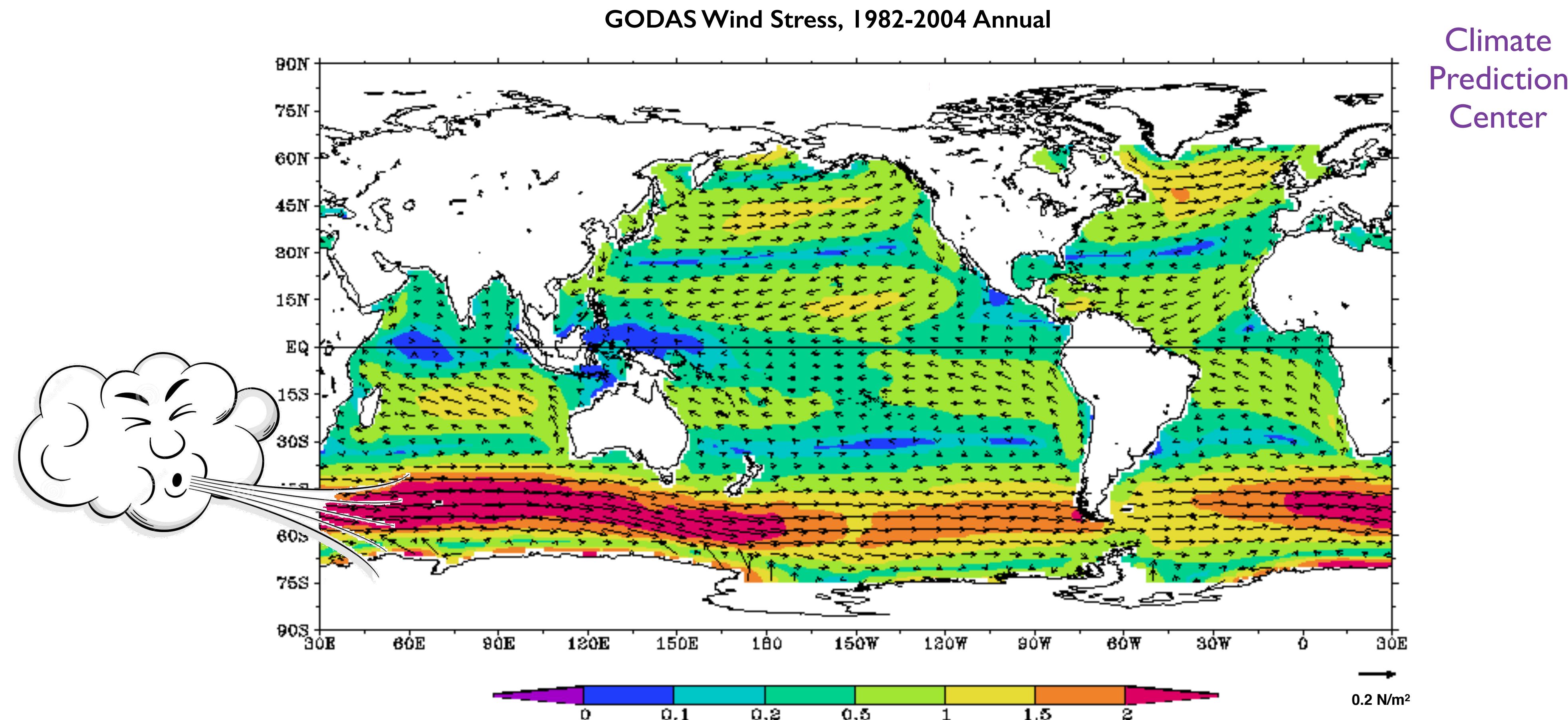
[Held 2005, BAMS]



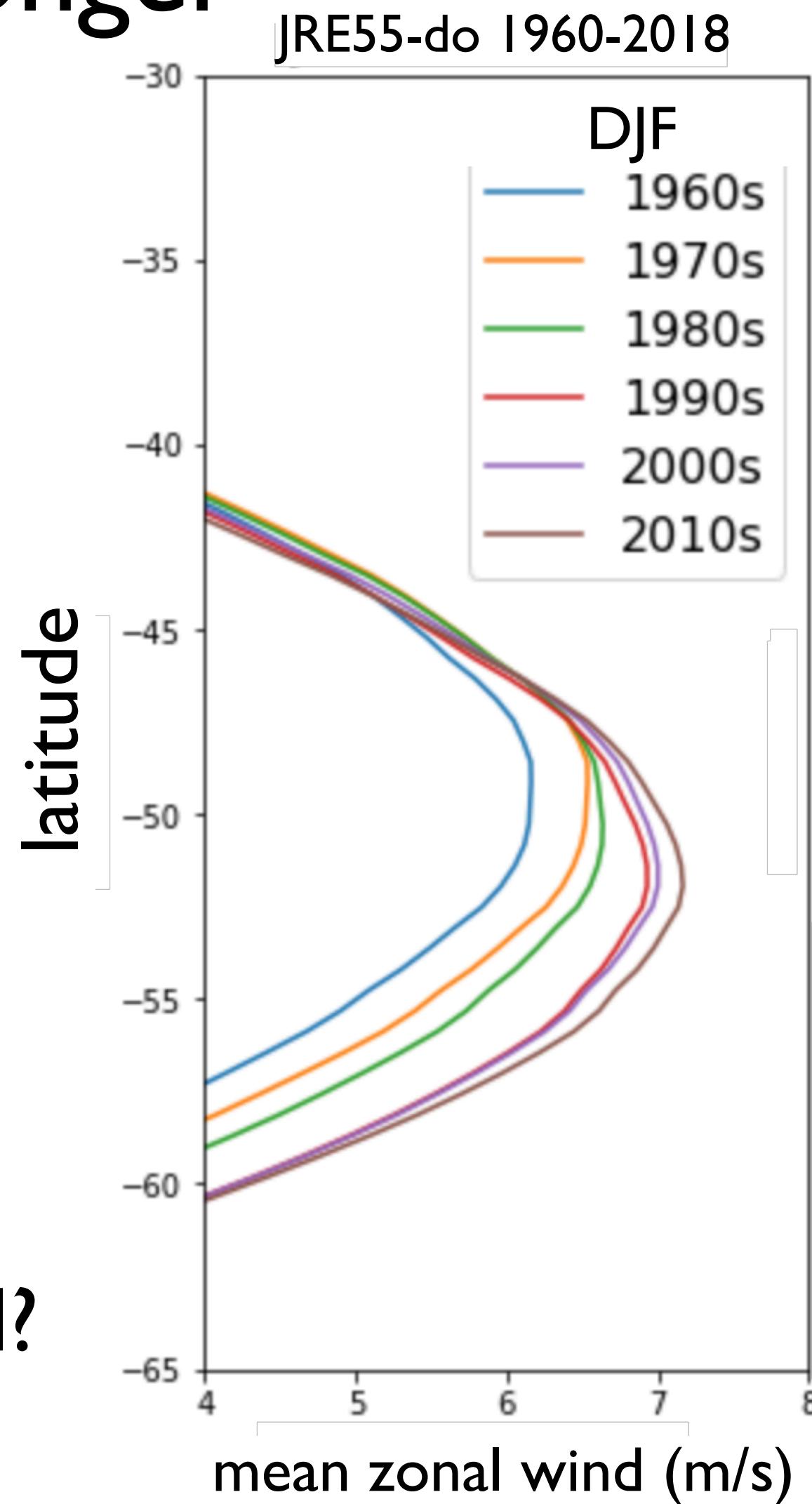
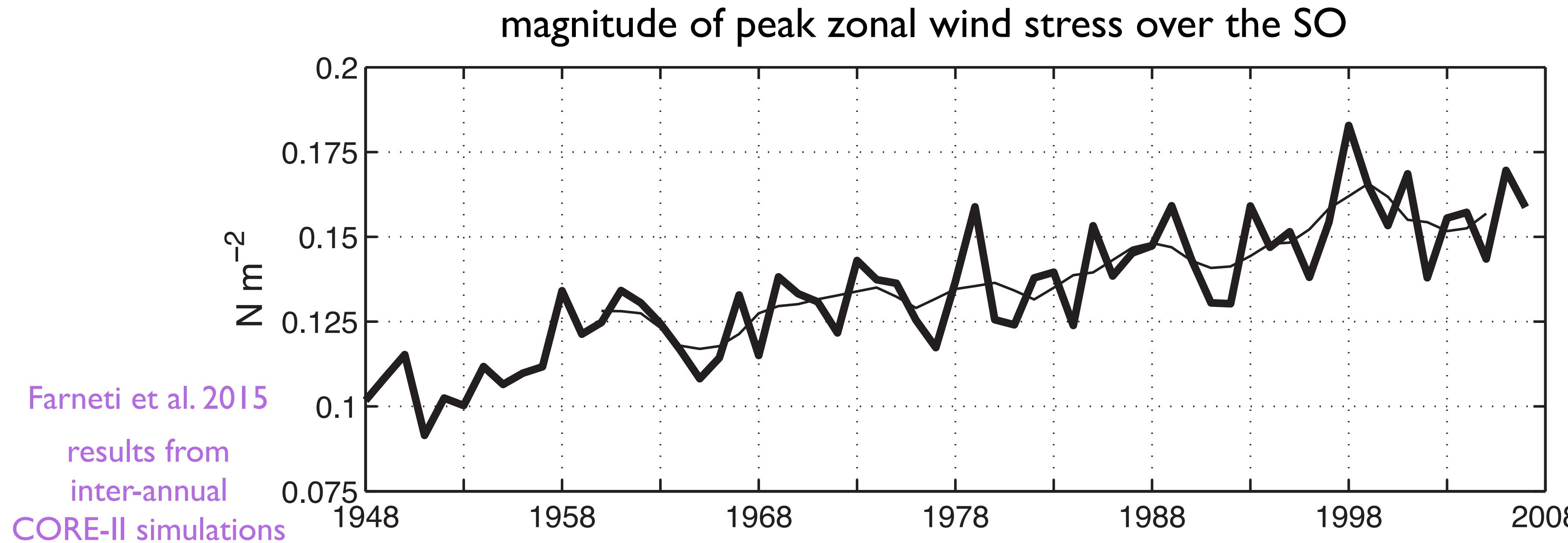
I'll give an example:

Response of Southern Ocean to winds increase.

winds (mainly) drive the Antarctic Circumpolar Current



winds over Southern Ocean are getting stronger



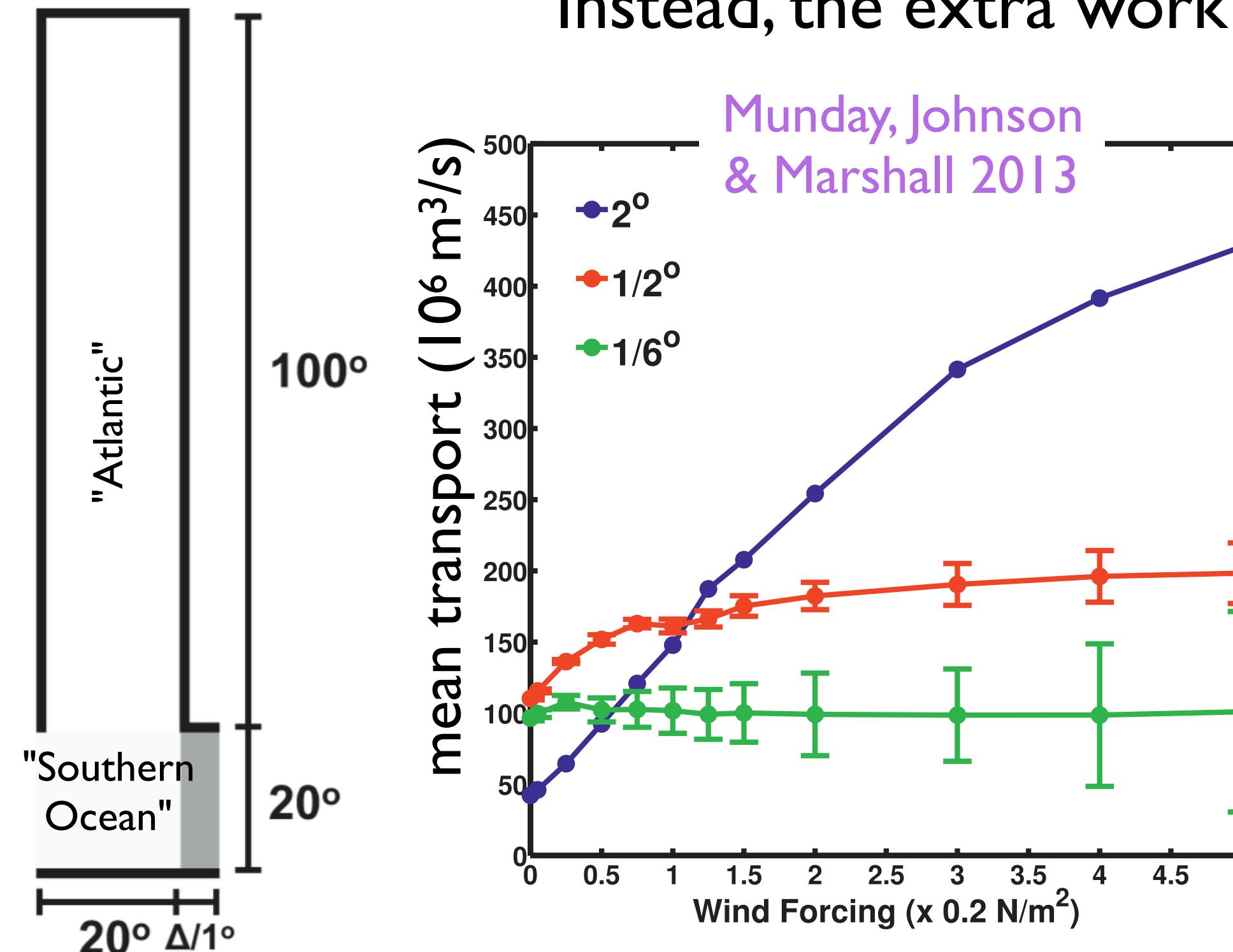
how will the Antarctic Circumpolar Current respond?

does doubling the winds imply double ACC the transport?
not always — “eddy saturation”

what's eddy saturation?

When the total time-mean mass transport of a current
is *relatively insensitive* to wind stress strength.

Instead, the extra work done by increasing wind goes to *mesoscale eddies*.



transport =
a "measure" of the strength of the current;
how much water the current carries per sec

Eddy saturation is seen in
eddy-resolving "ocean models".
(some hints also in obs.)

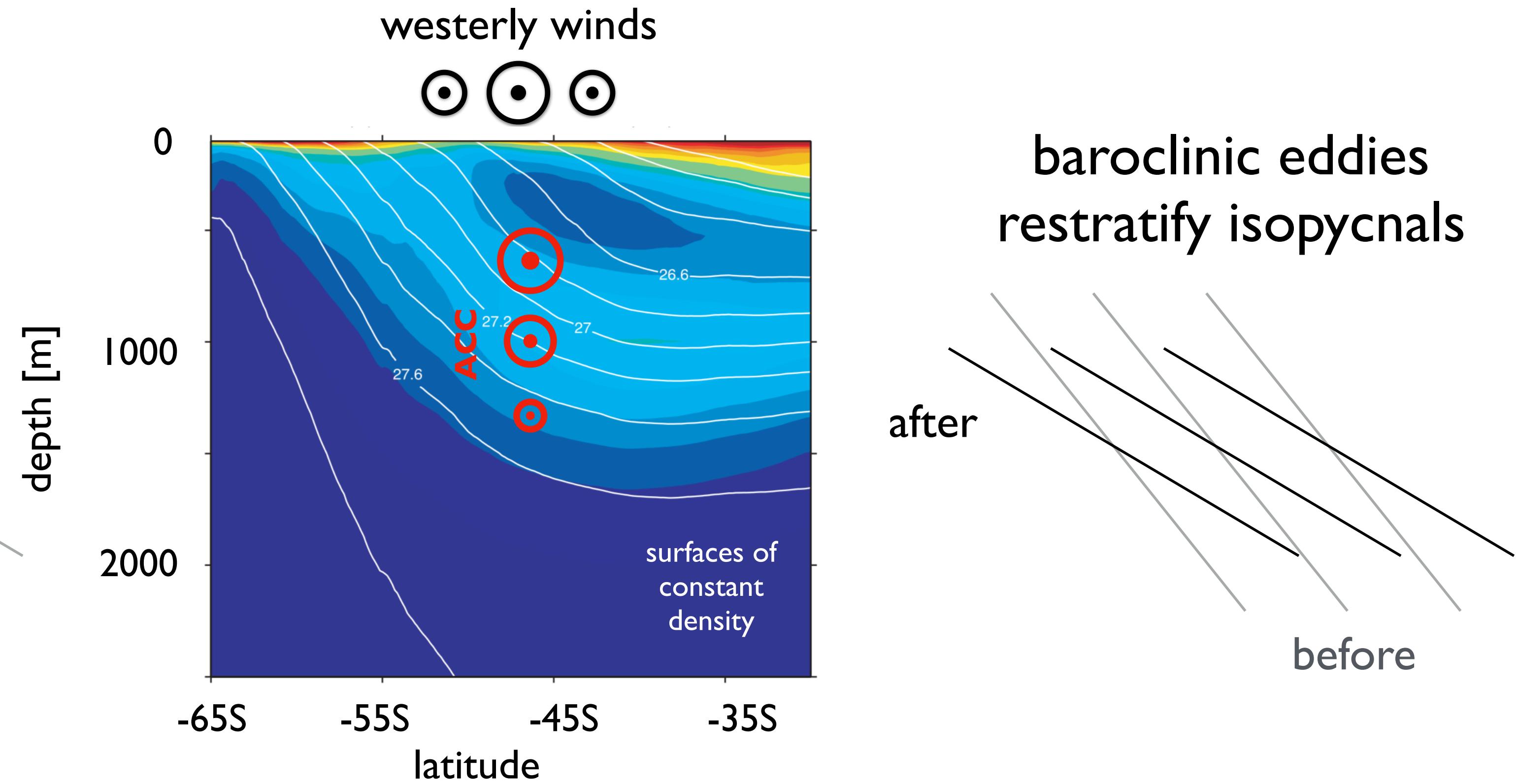
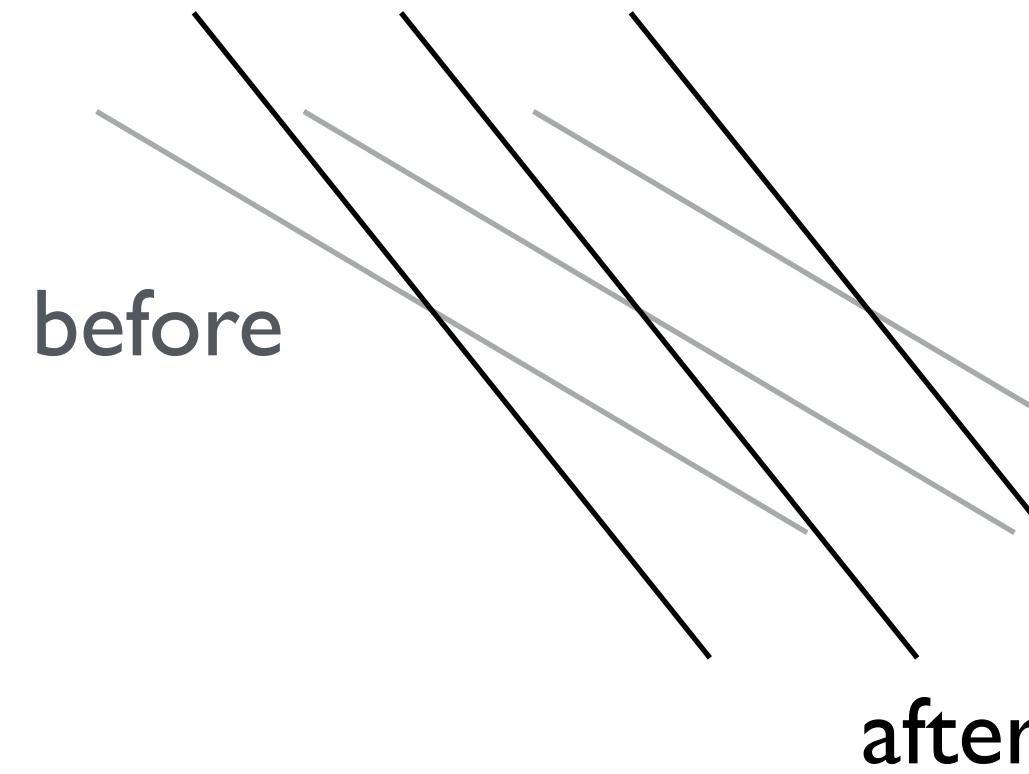
higher
resolution

→ eddy saturation
"emerges"

[Other examples: Hallberg & Gnanadesikan 2001, Tansley & Marshall 2001, Hallberg & Gnanadesikan 2006, Hogg et al. 2008, Nadeau & Straub 2009, 2012, Farneti et al. 2010, Meredith et al. 2012, Morisson & Hogg 2013, Abernathey & Cessi 2014, Farneti et al. 2015, Nadeau & Ferrari 2015, Marshall et al. 2017.]

the textbook explanation: how eddies lead to eddy saturation?

wind increase
slopes the isopycnals

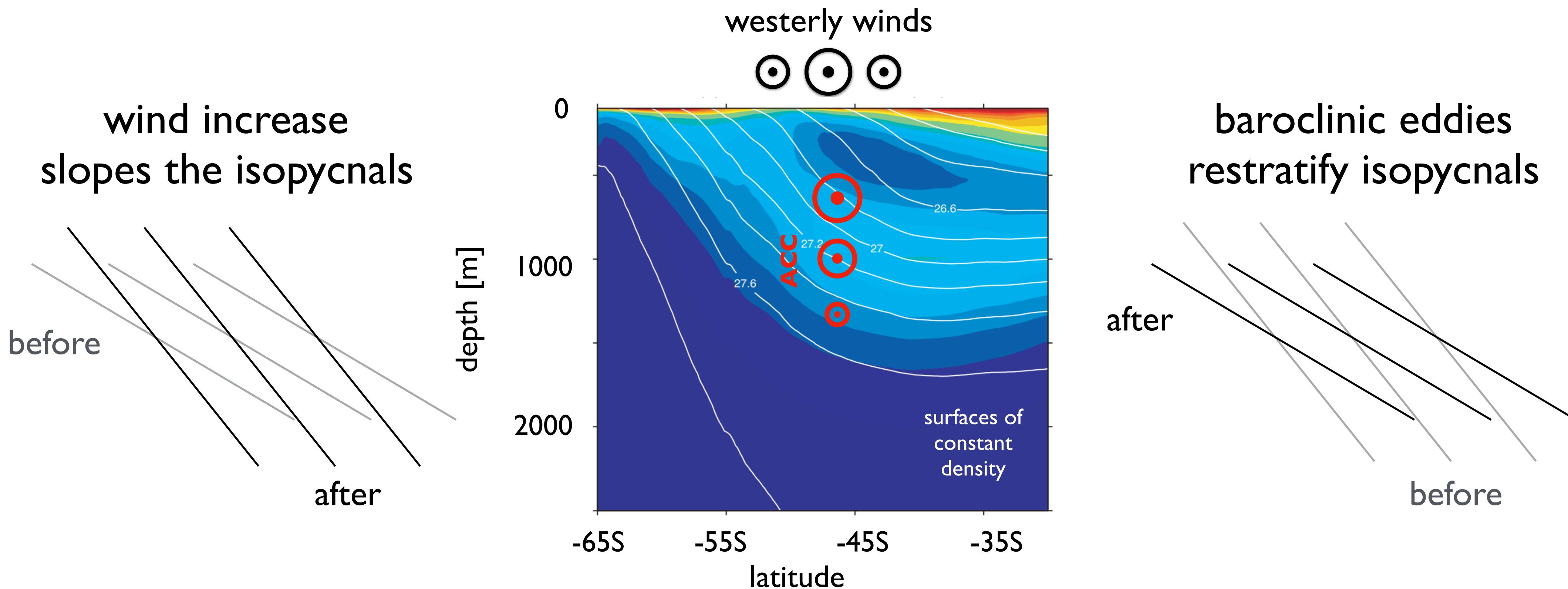


baroclinic eddies
restratify isopycnals

A diagram illustrating the effect of baroclinic eddies on isopycnals. It shows two sets of black lines representing density contours (isopycnals) in a cross-section. The right set, labeled 'before', shows straight, parallel isopycnals. The left set, labeled 'after', shows isopycnals that are tilted and curved, indicating they have been 'restratified' by the eddies. A vertical grey line on the right serves as a reference.

remember
jets & fronts
Amelie's talk

the textbook explanation: how eddies lead to eddy saturation?

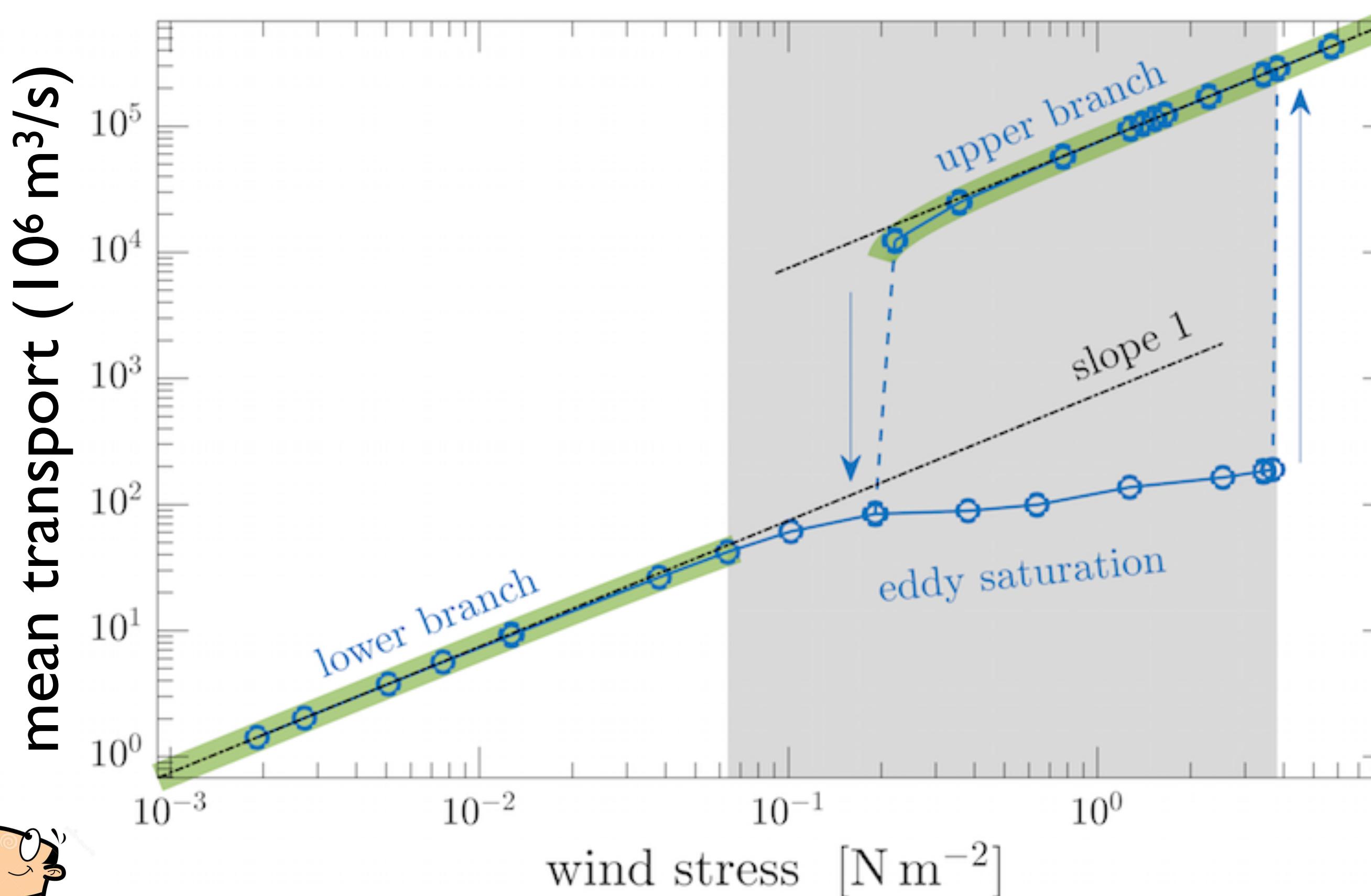


This explanation crucially *relies on density varying with depth.*

(gfd-jargon: **baroclinic**)

Role of bathymetry?

however, simple unstratified models reveal a new possible mechanism



Eddy saturation can occur
without any baroclinicity
in a model with
constant density with depth
and bathymetry.

(gfd-jargon: **barotropic**)



role of bathymetry I

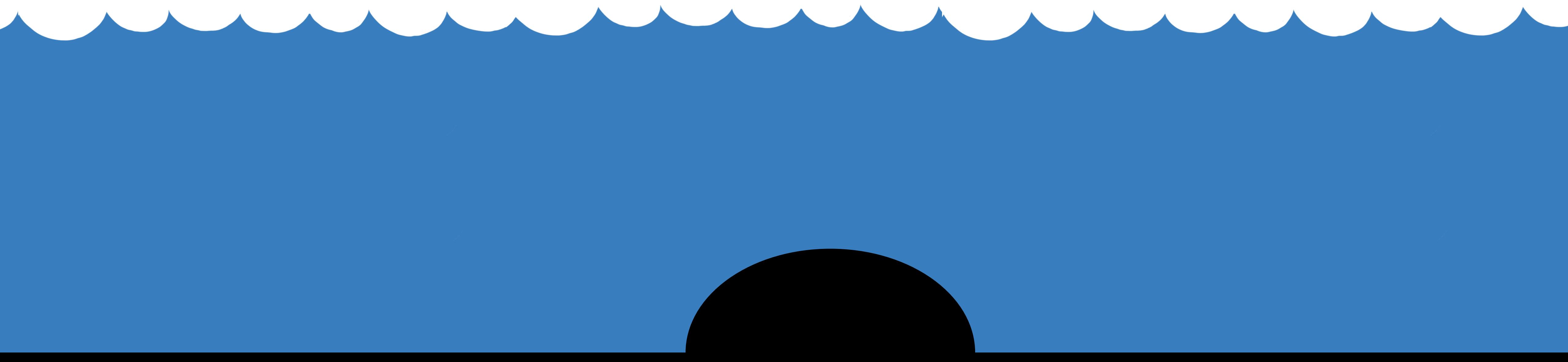
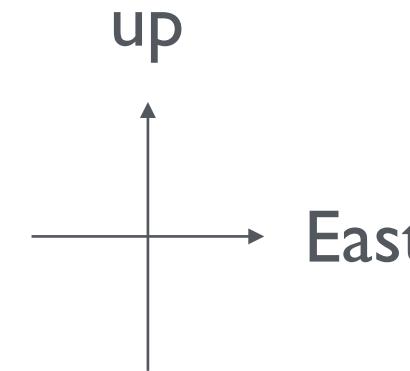
Momentum balance in the Southern Ocean is
"applied at the bottom [...] where ridges lie."



W.H. Munk
1917 - Feb 2019

Munk & Palmen (1951)

topographic form stress



role of bathymetry I

Momentum balance in the Southern Ocean is
"applied at the bottom [...] where ridges lie."



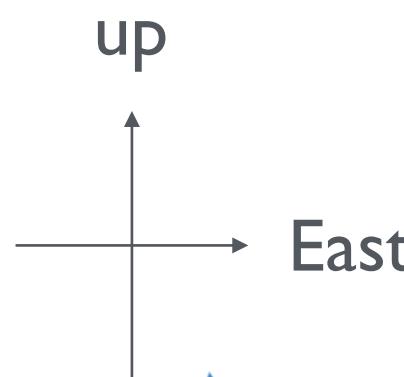
W.H. Munk
1917 - Feb 2019

Munk & Palmen (1951)

topographic form stress

wind stress

τ



U

pressure
gradient
force

$$F_p = \frac{\Delta p}{\text{ridge width}}$$

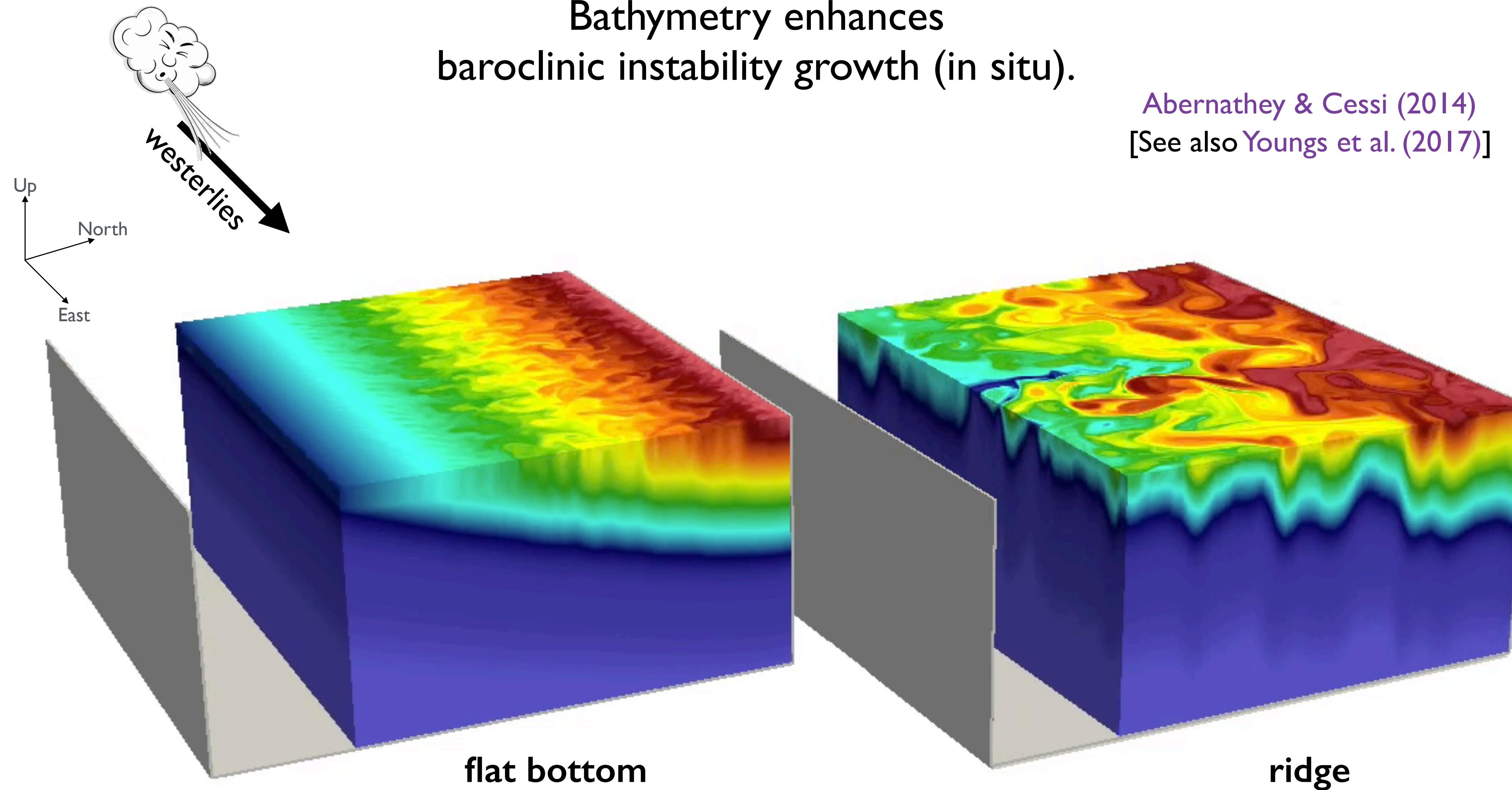
p_+

p_-

role of bathymetry II

Bathymetry enhances
baroclinic instability growth (in situ).

Abernathy & Cessi (2014)
[See also Youngs et al. (2017)]



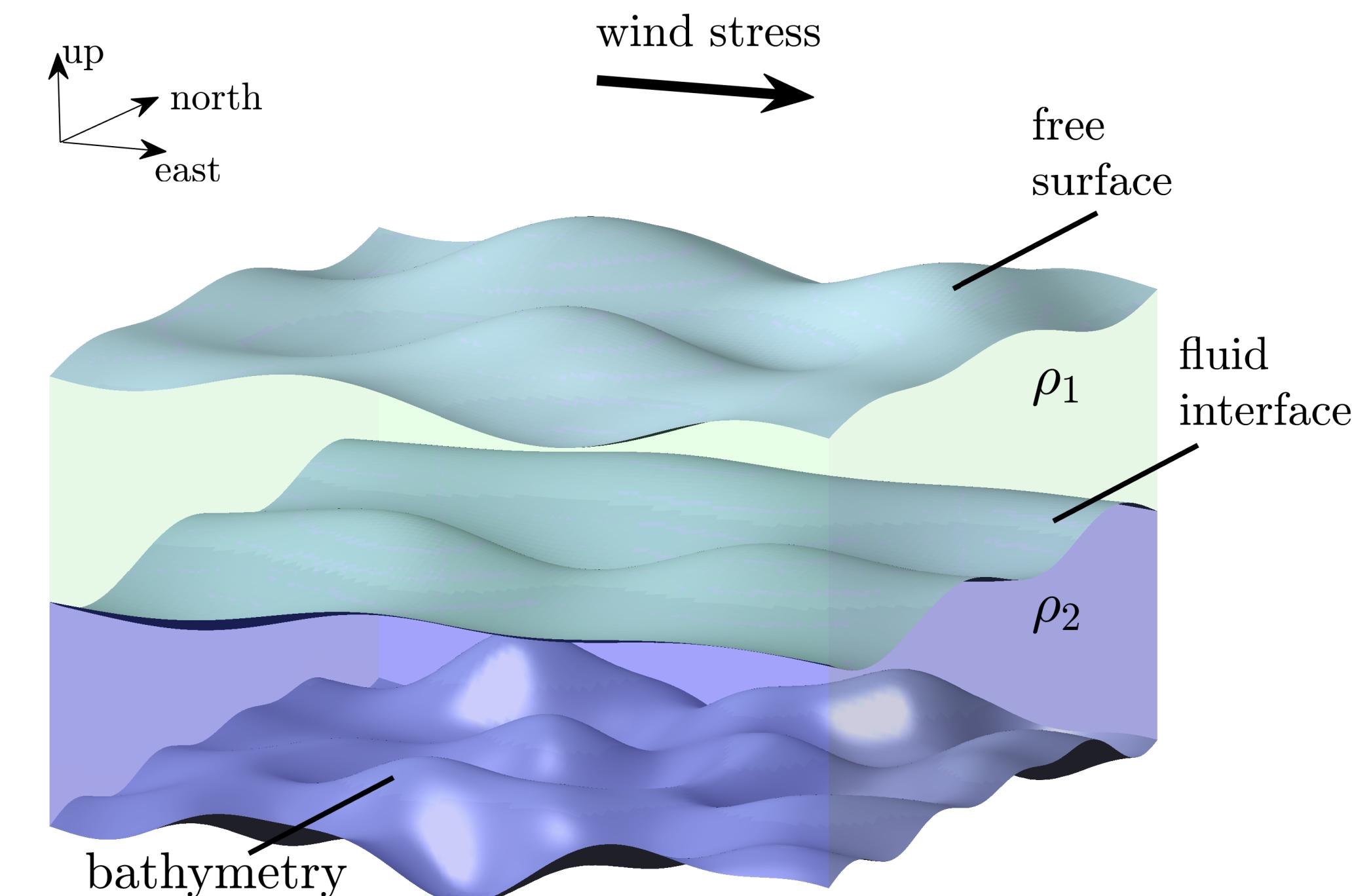
<http://vimeo.com/55486114>

equilibration ~100 yr
isosurfaces of potential temperature
colors from 0 °C to 8 °C

what's the plan

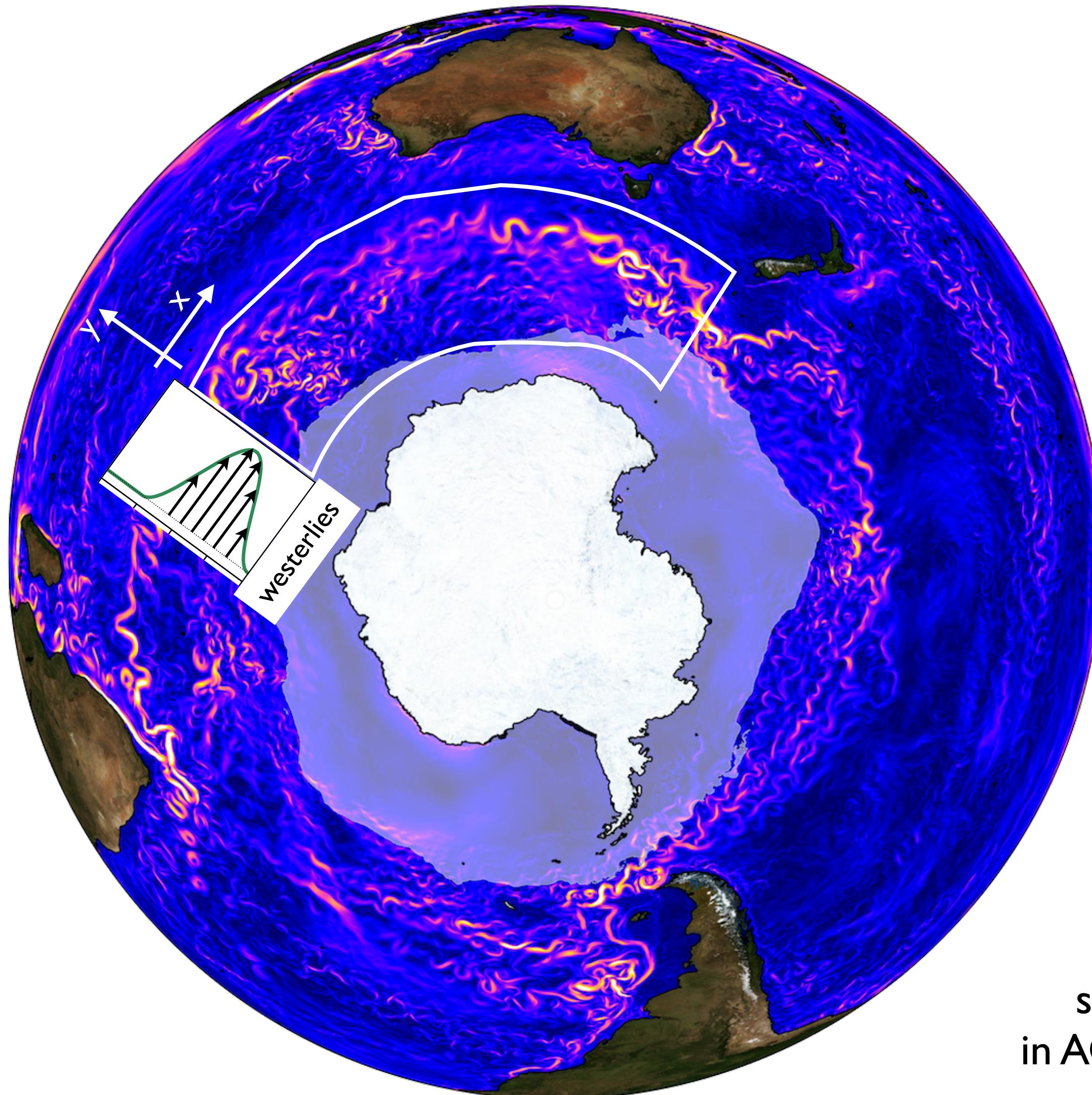
Assess the relative role of
barotropic versus **baroclinic** dynamics
in establishing "eddy saturated" ocean states.

Use a model
with varying
number of fluid layers.



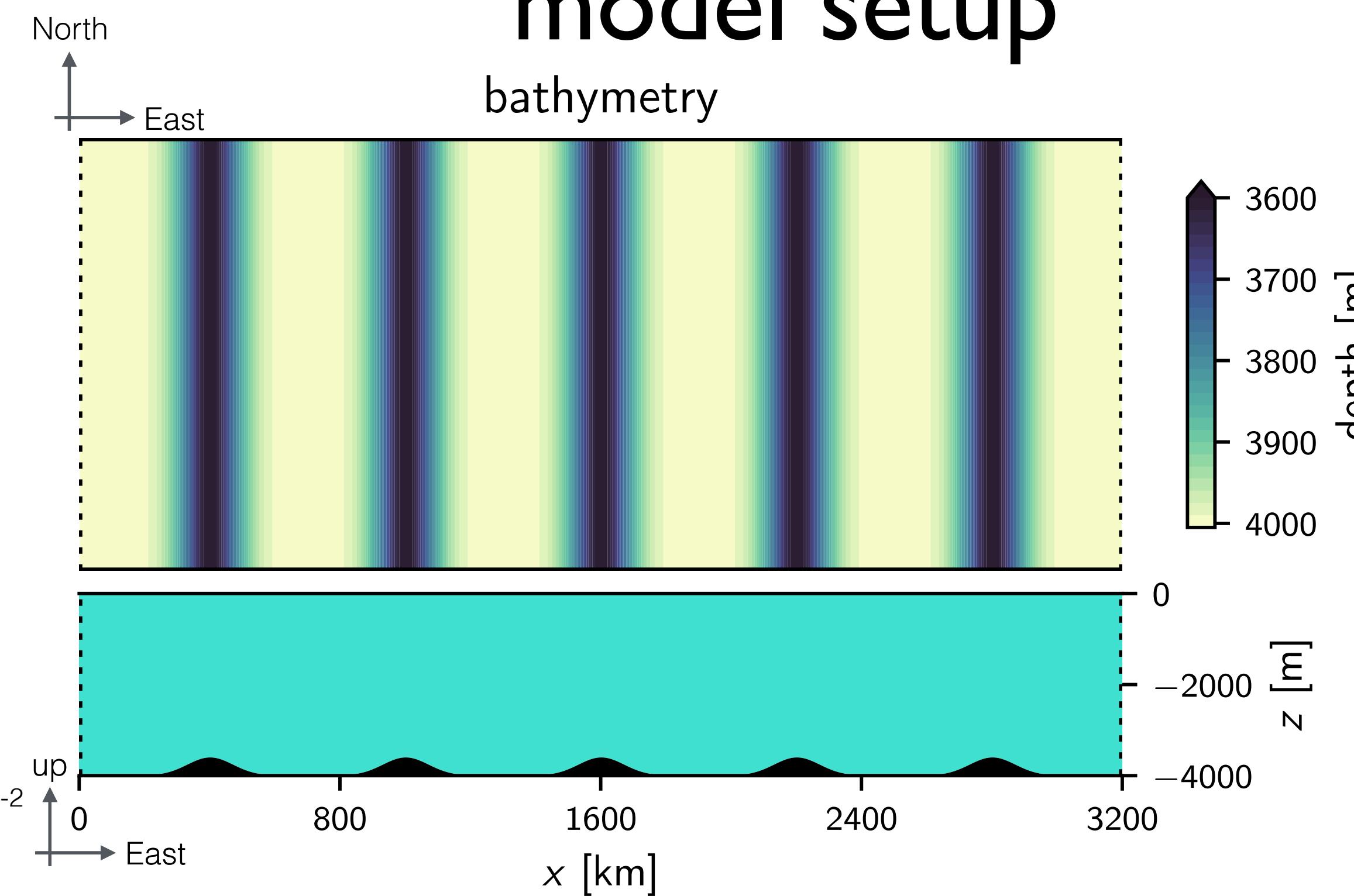
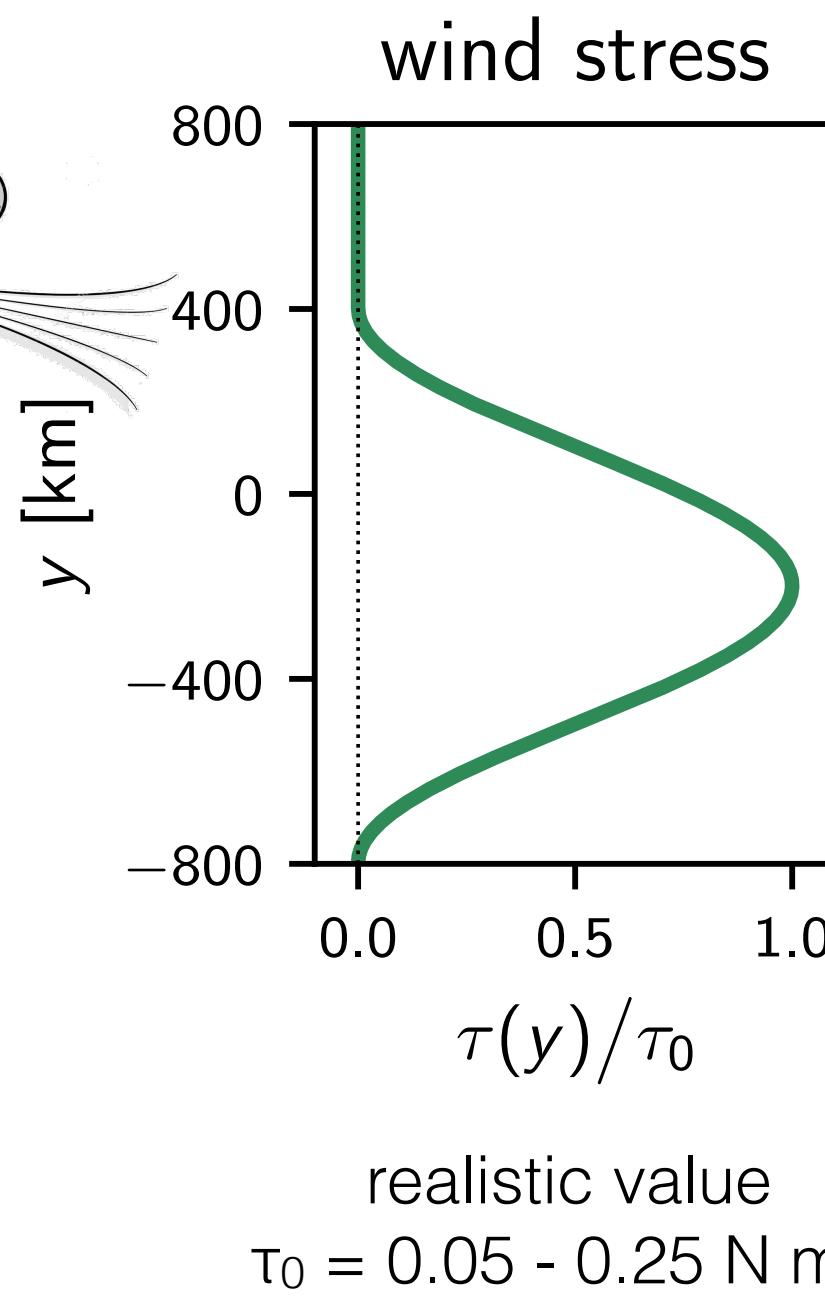


the "spherical-cow"-version of the Southern Ocean



sea-surface speed
in ACCESS-OM2 model
at 0.1° resolution

model setup



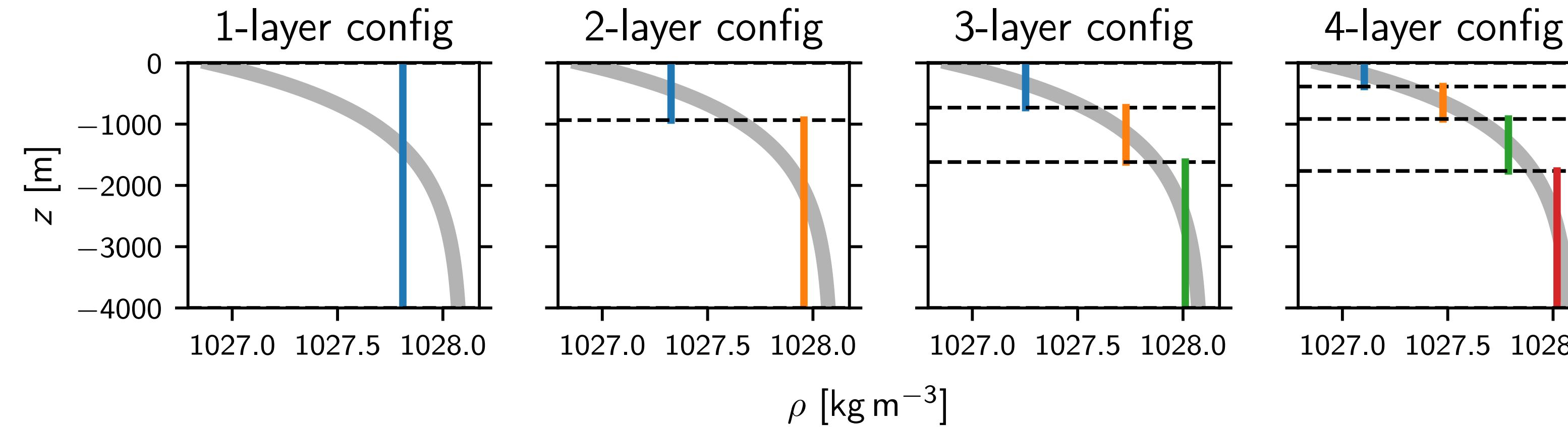
GFDL's MOM6 model
 isopycnal coordinates/Boussinesq

Southern Ocean parameter values

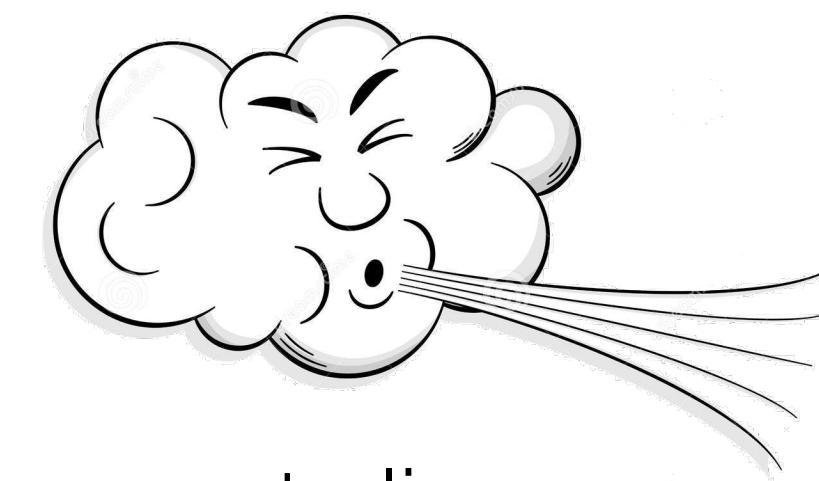
no diapycnal motions
 no buoyancy forcing

(some oceanographic-jargon;
 important is what's in **bold**)

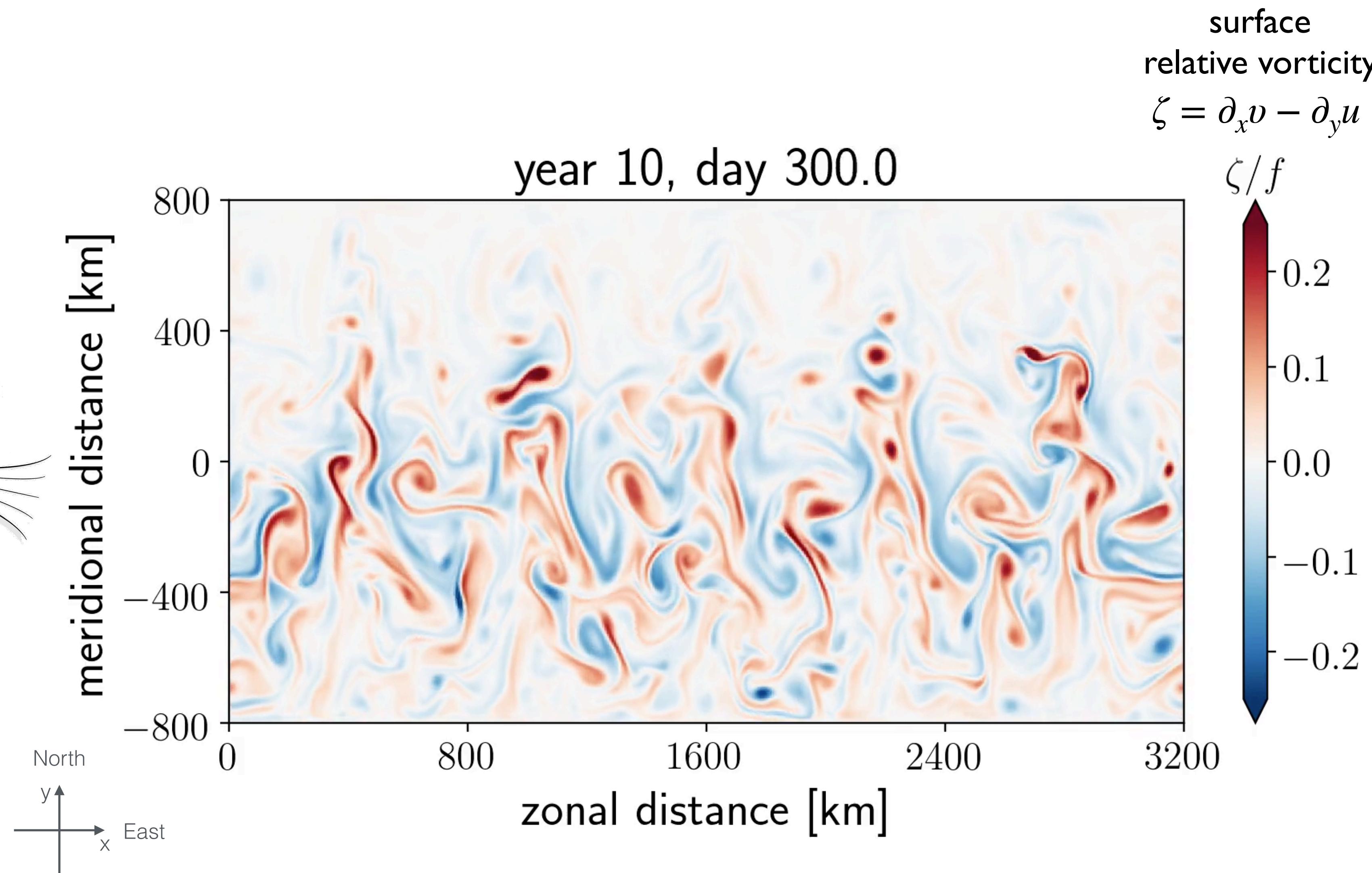
layered approximations



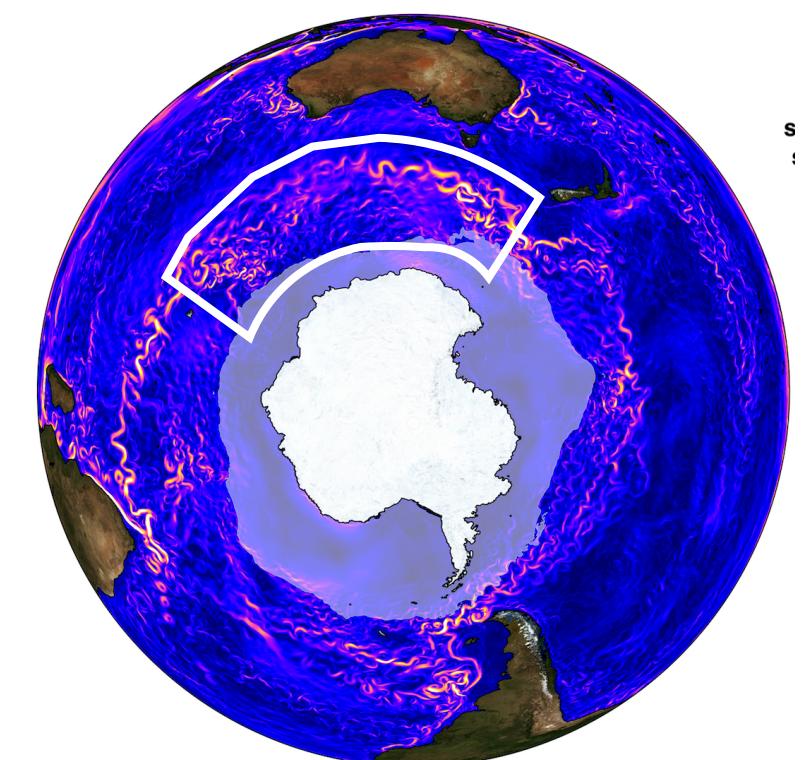
the "spherical-cow"-version of the ACC



westerlies
 $\tau_0=0.2 \text{ N/m}^2$

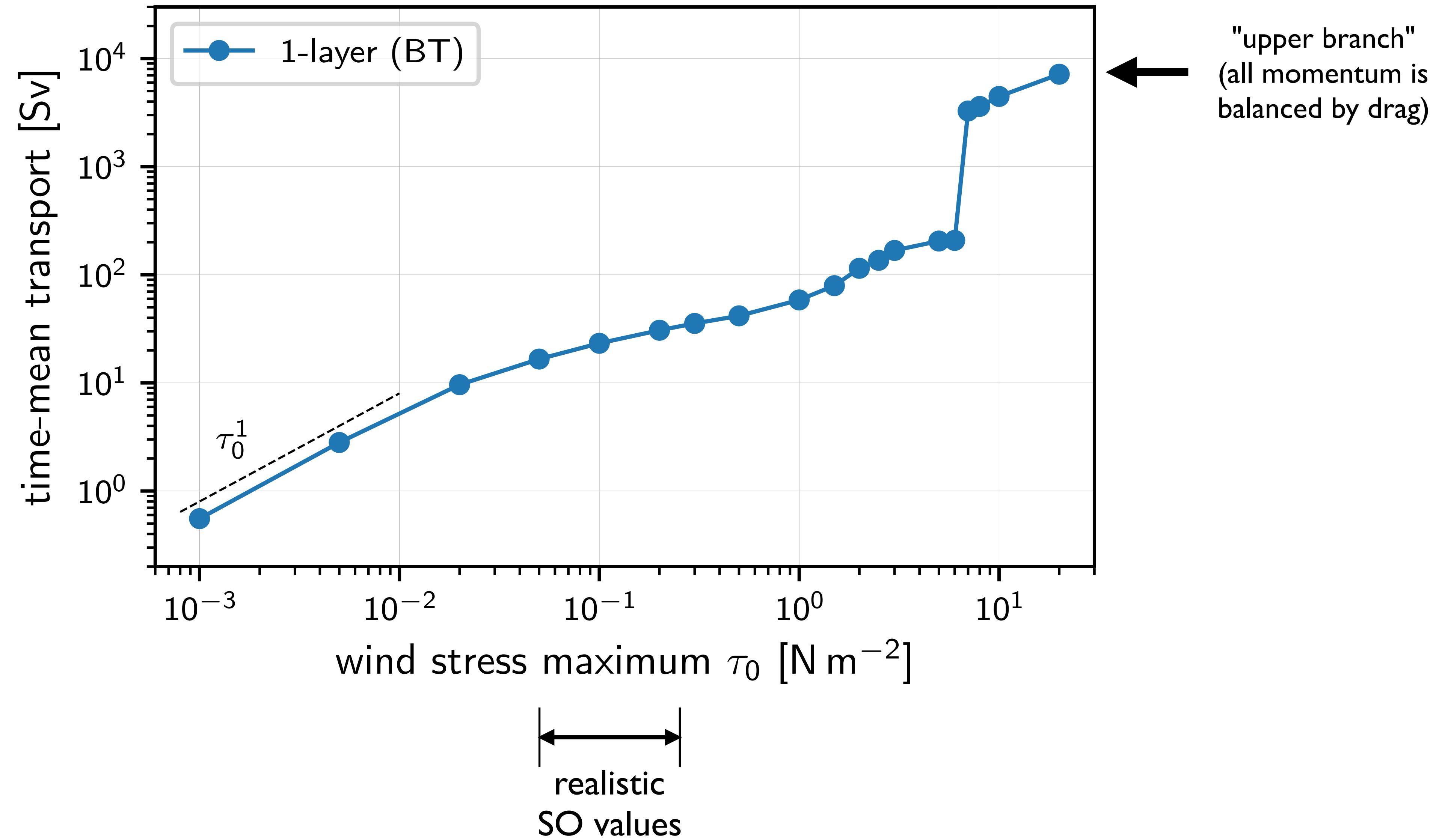


note the standing meander
(remember Amelie's talk on Tue)

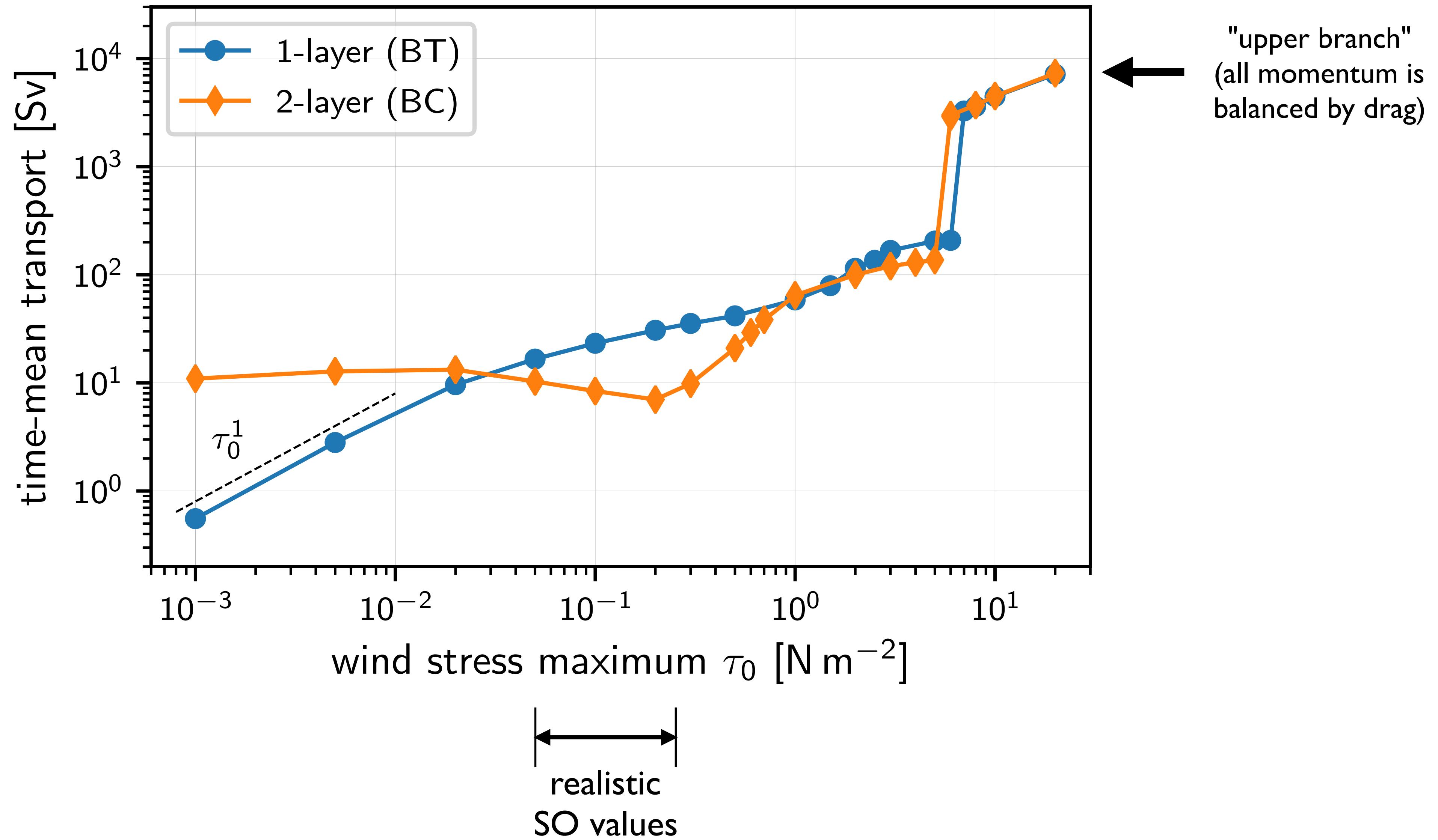


vary the wind stress amplitude T_0
and see how the time-mean zonal transport changes

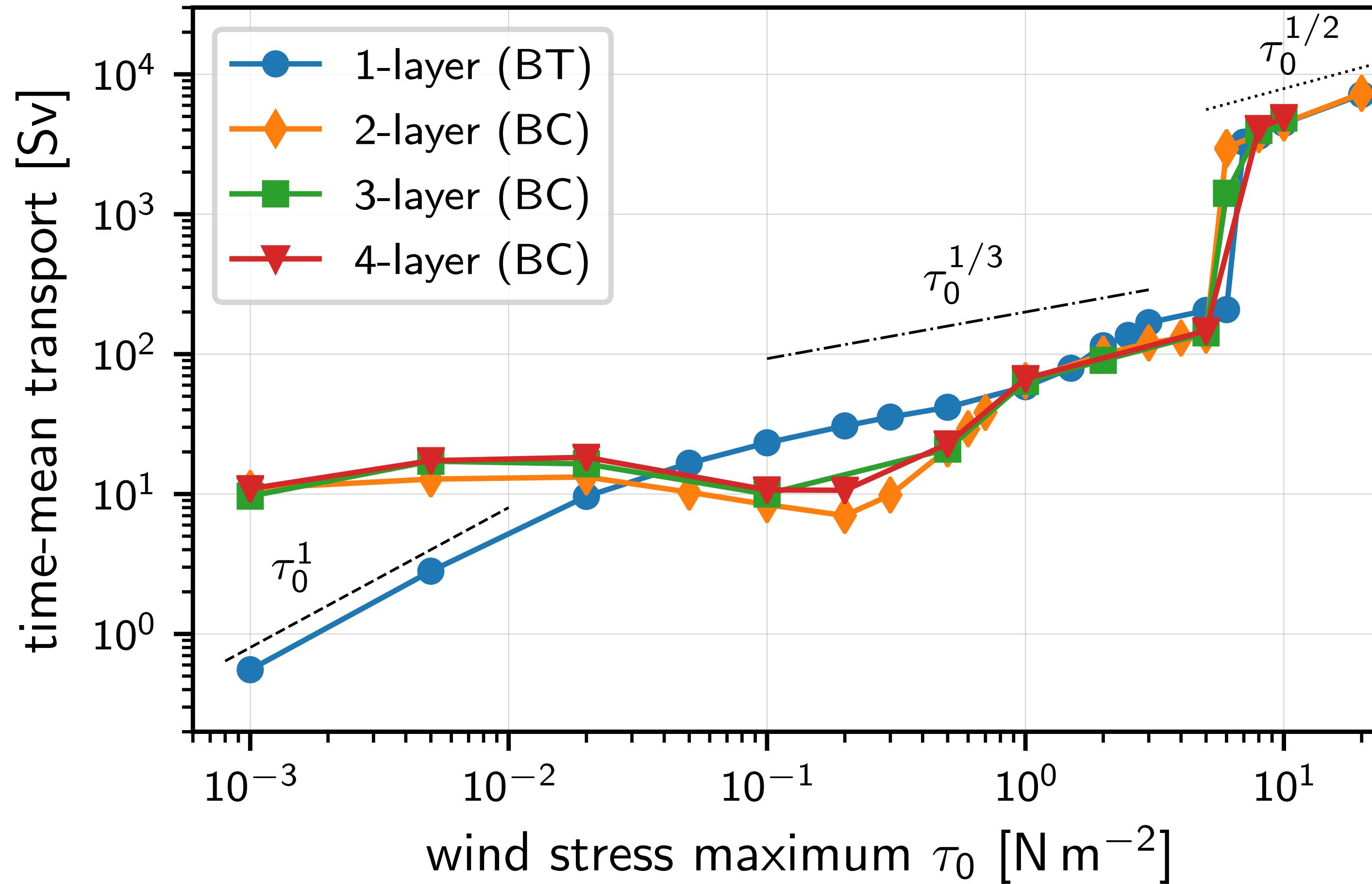
mean ACC transport Vs wind stress



mean ACC transport Vs wind stress

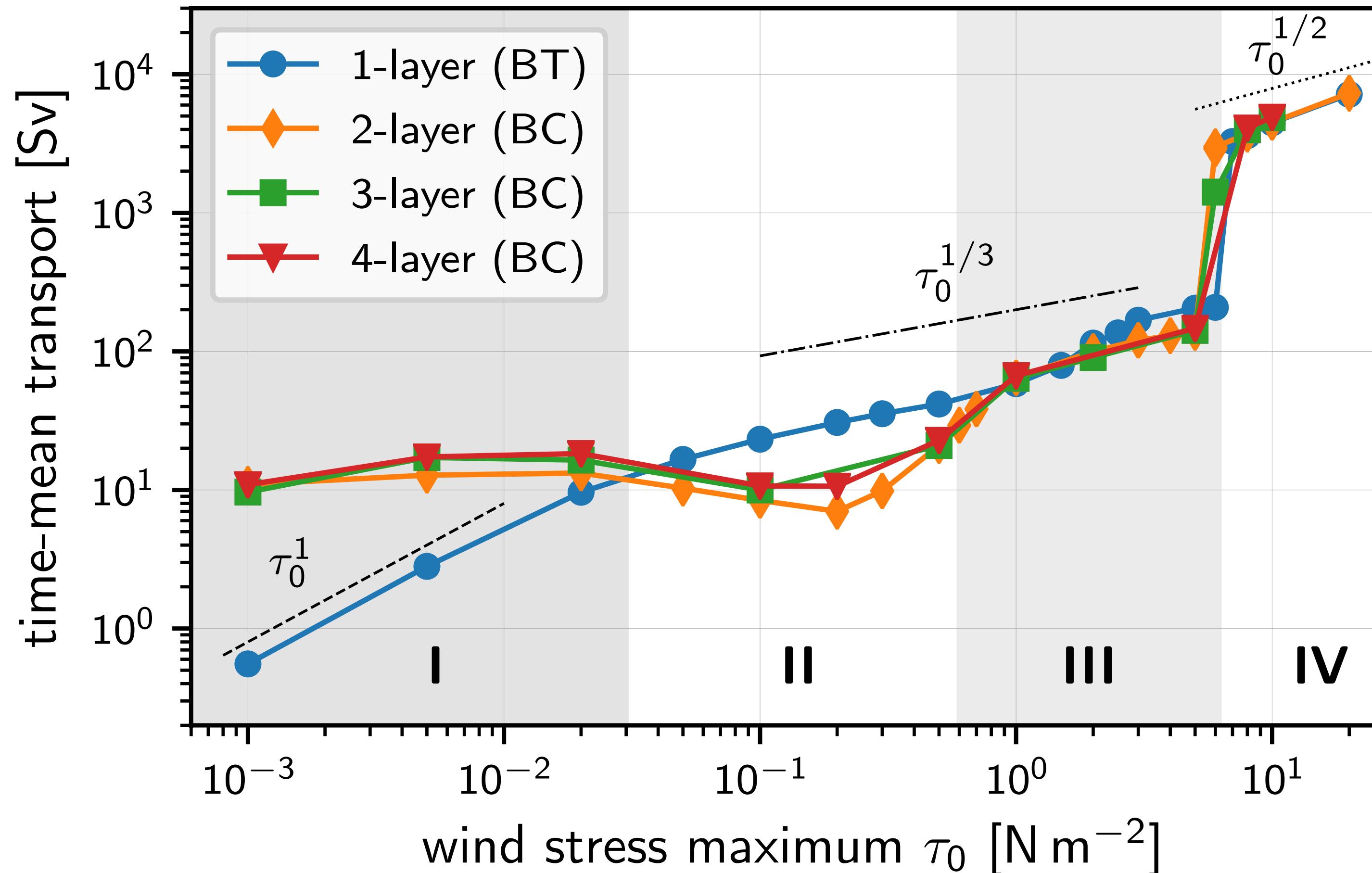


mean ACC transport Vs wind stress



>3-layer configurations are the same as 2-layers
(as far as the mean zonal transport is concerned)

mean ACC transport Vs wind stress



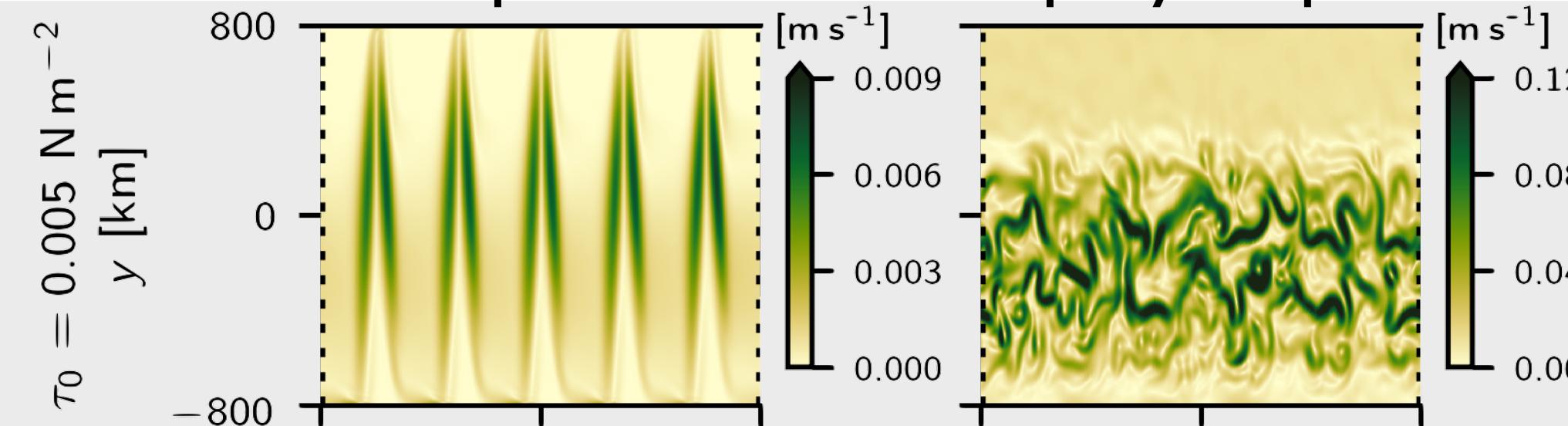
realistic
SO values

four
distinct
flow
regimes

how does the flow look like in the four flow regimes?

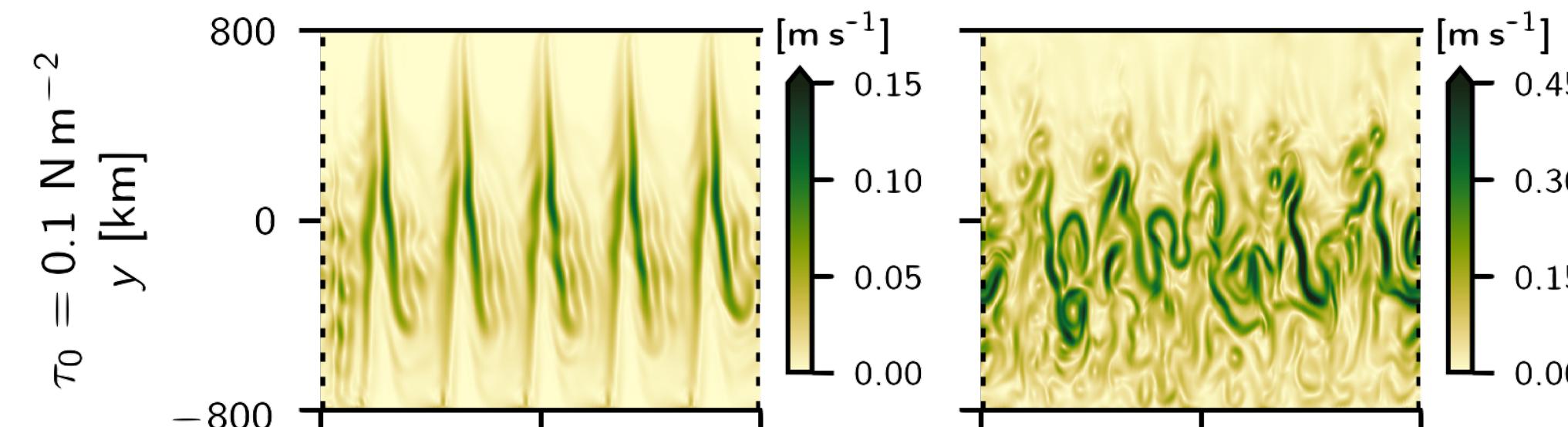
yeap, this slide
is too much

I-layer config
speed



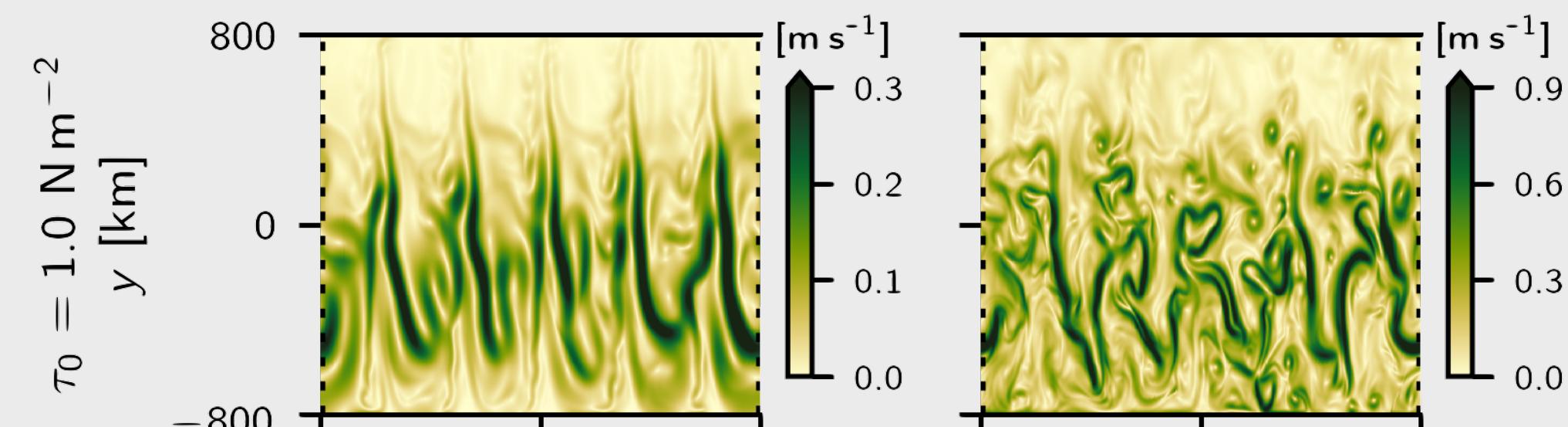
II

II-layer config
speed



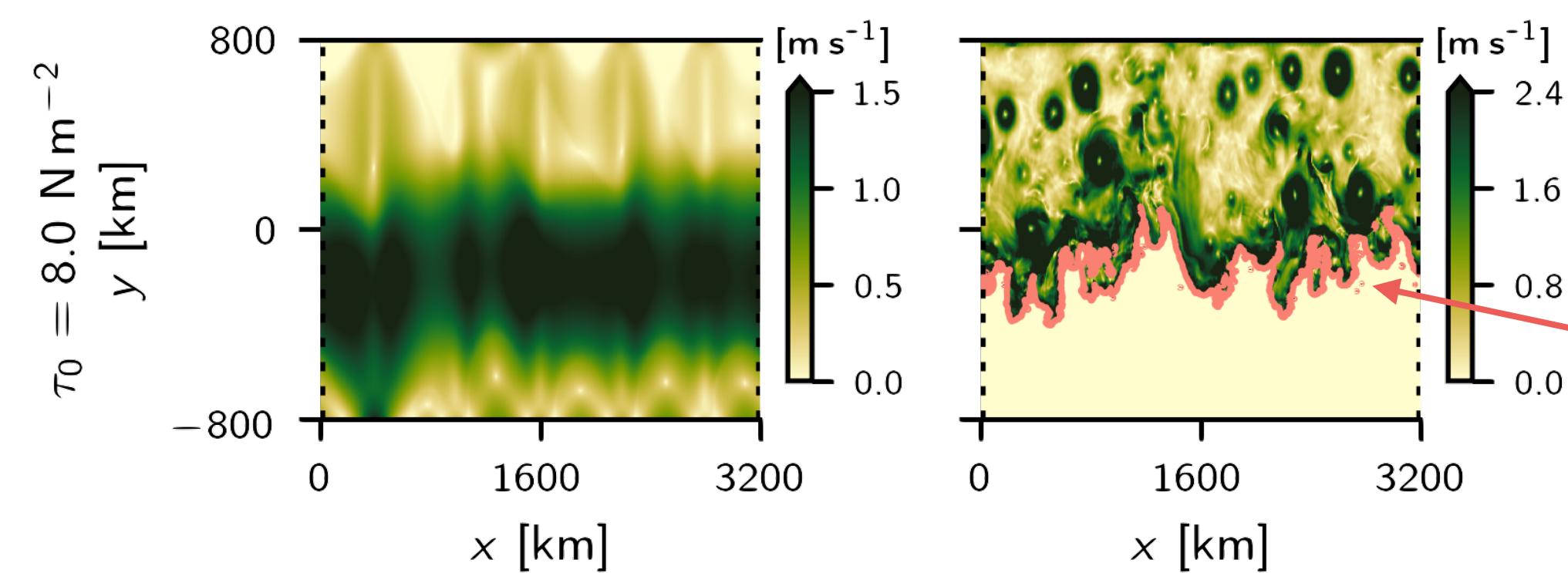
III

III-layer config
speed



IV

IV-layer config
speed



BT: weak steady flow following f/h contours

BC: multiple jets + eddies
"homogeneous BC turbulence"-regime

BT: transients develop;
flow steered by f/h

BC: one jet with signature of bathymetry
appears in top-layer flow

BT: transients develop;
flow steered by f/h

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appears in top-layer flow

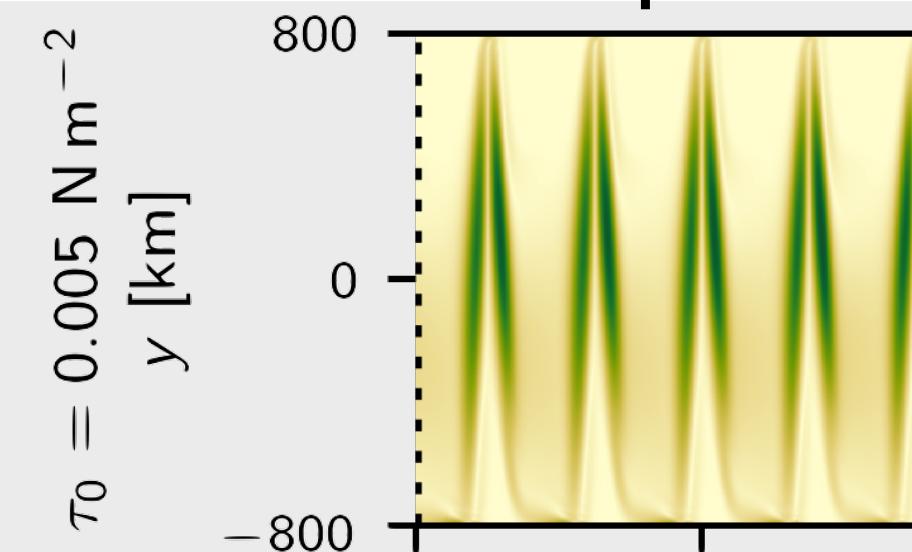
BT: a strong jet develops

BC: bottom layer outcrops;
strong jet seen in depth-averaged flow

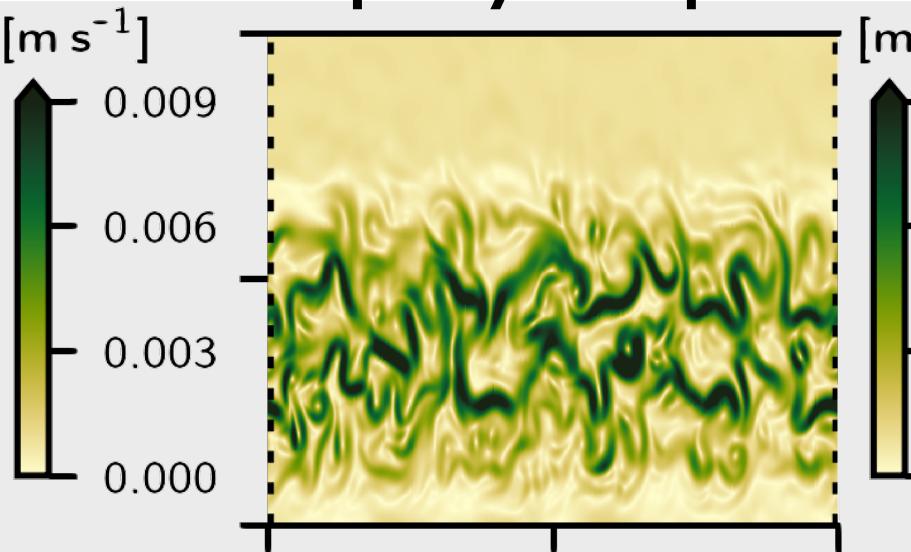
bottom layer
outcrops

yeap, this slide
is too much

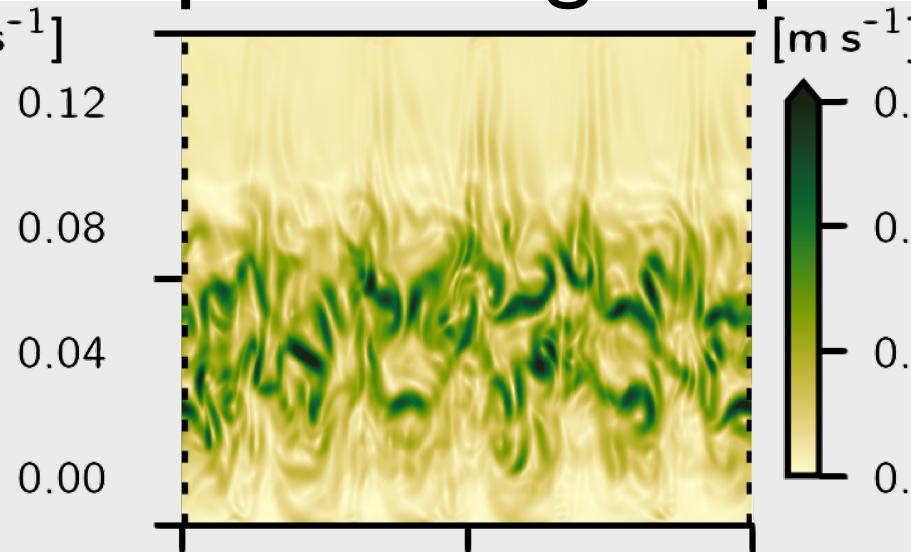
I-layer config
speed



2-layer config
top-layer speed

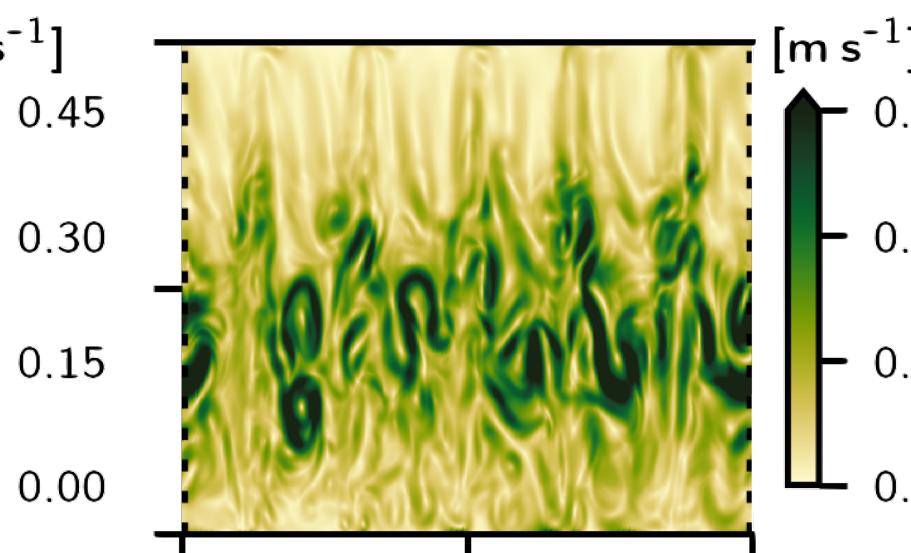
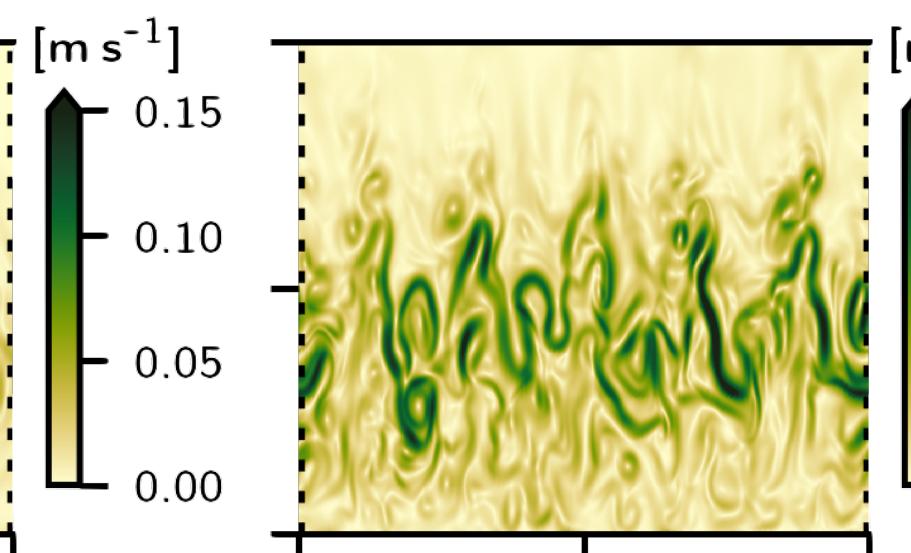
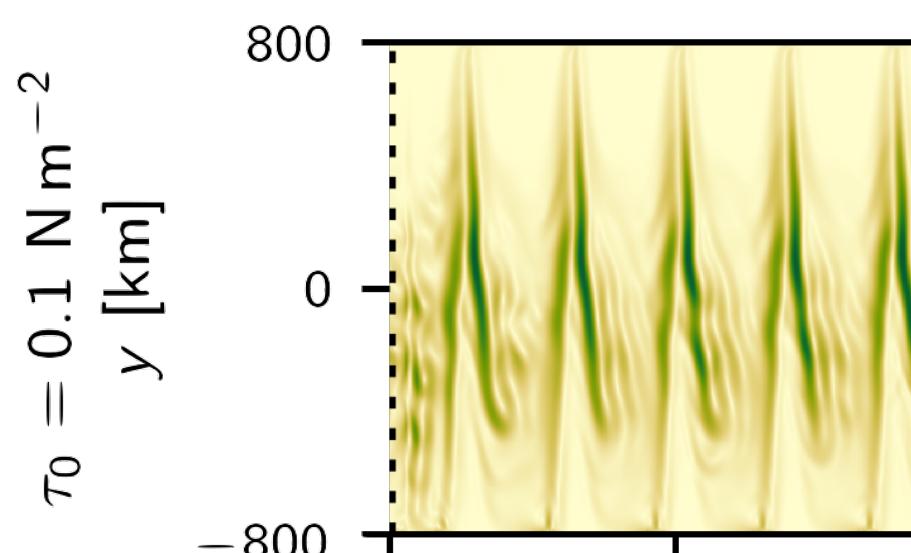


2-layer config
depth-averaged speed



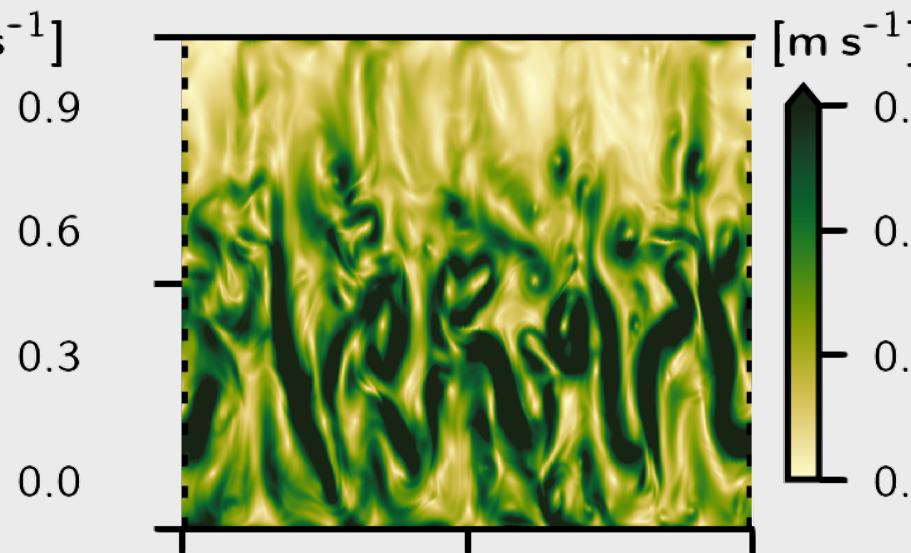
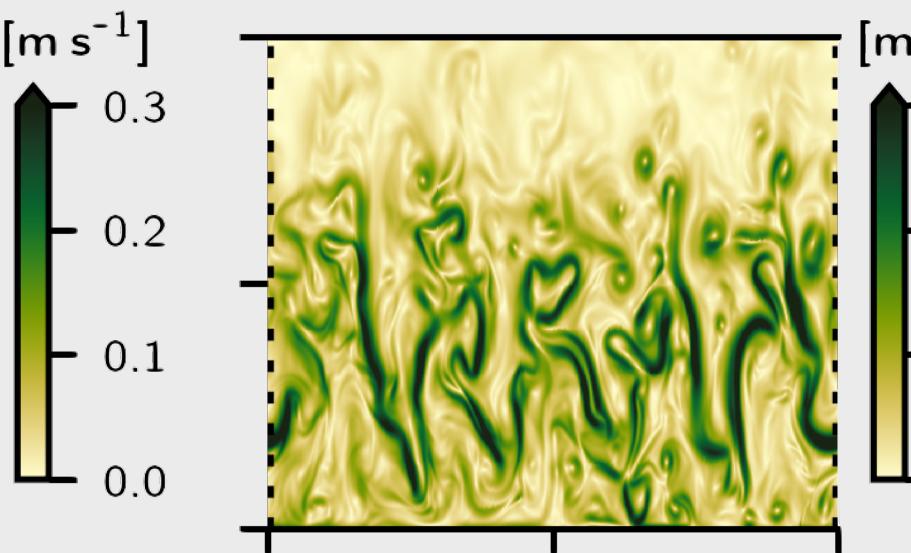
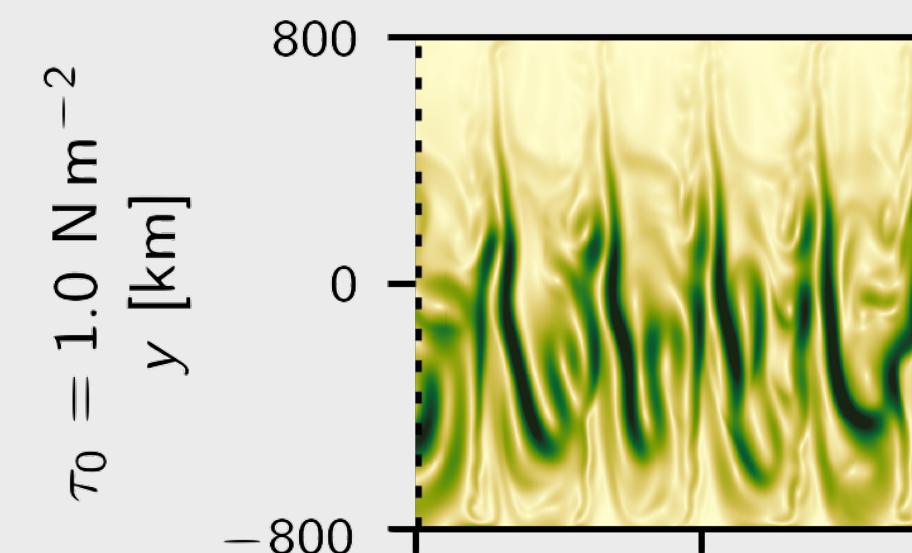
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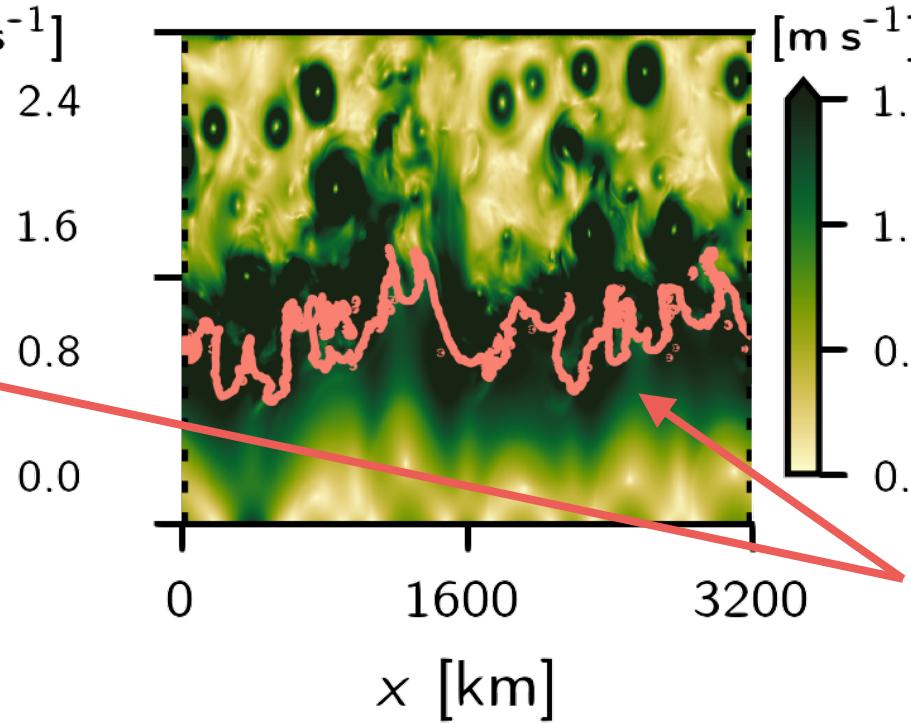
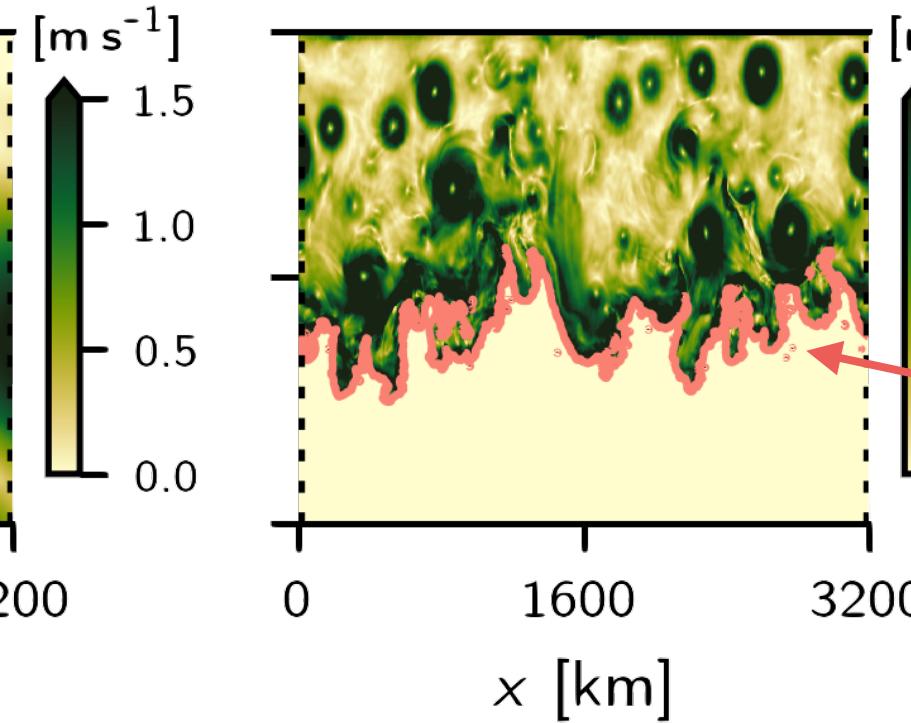
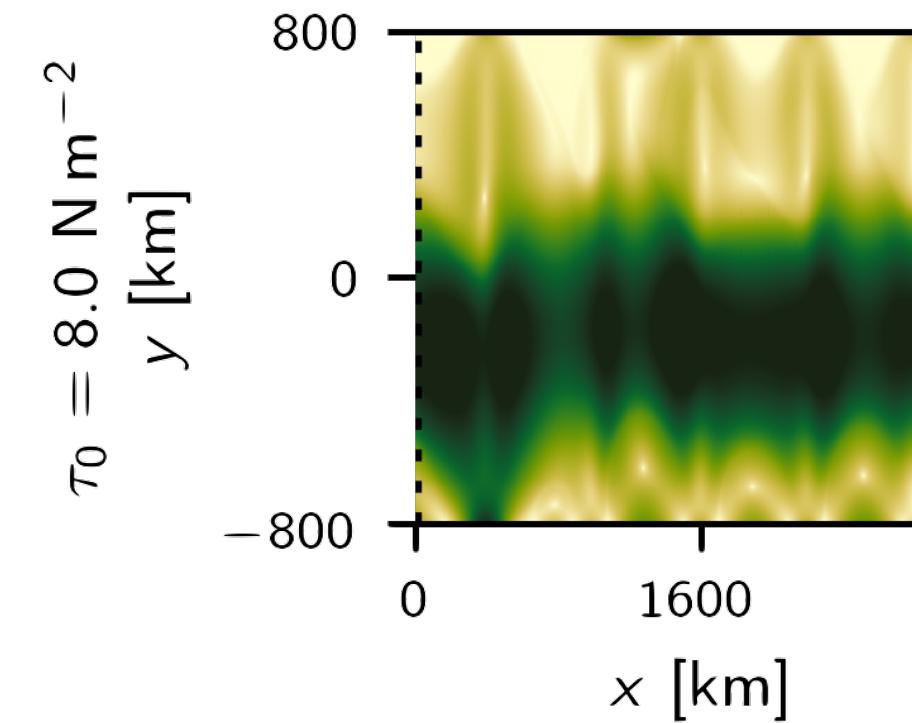
BT:
transients develop;
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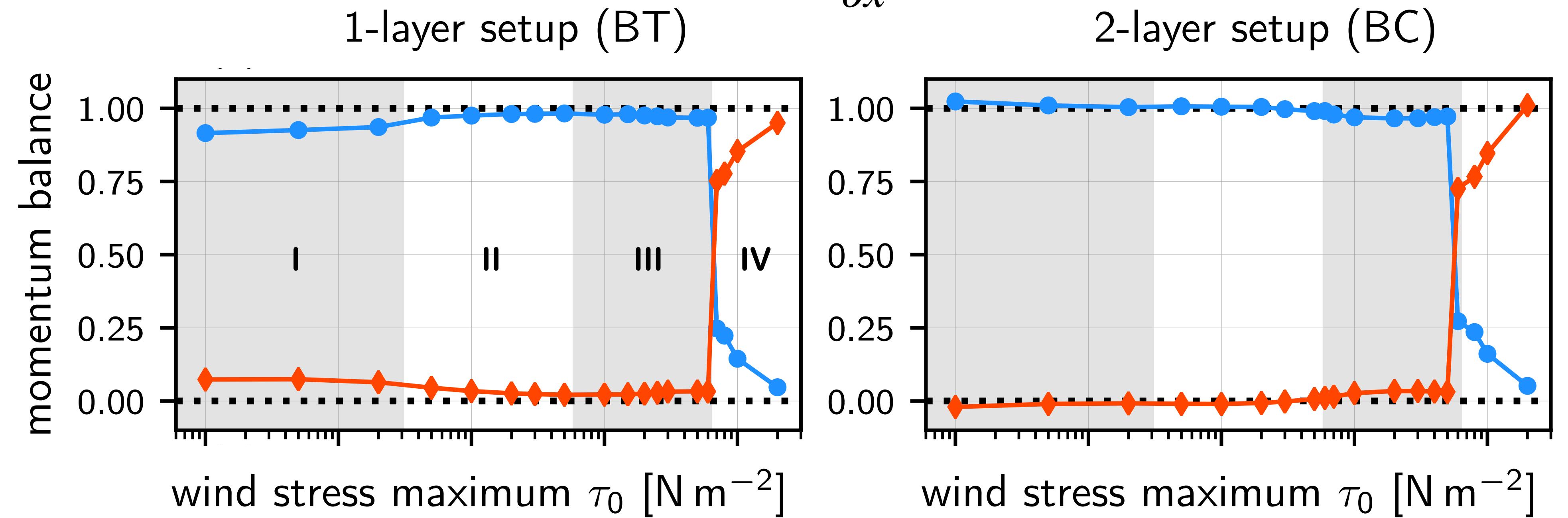
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strong jet seen in depth-averaged flow

bottom layer
outcrops

depth-integrated time-mean zonal momentum balance

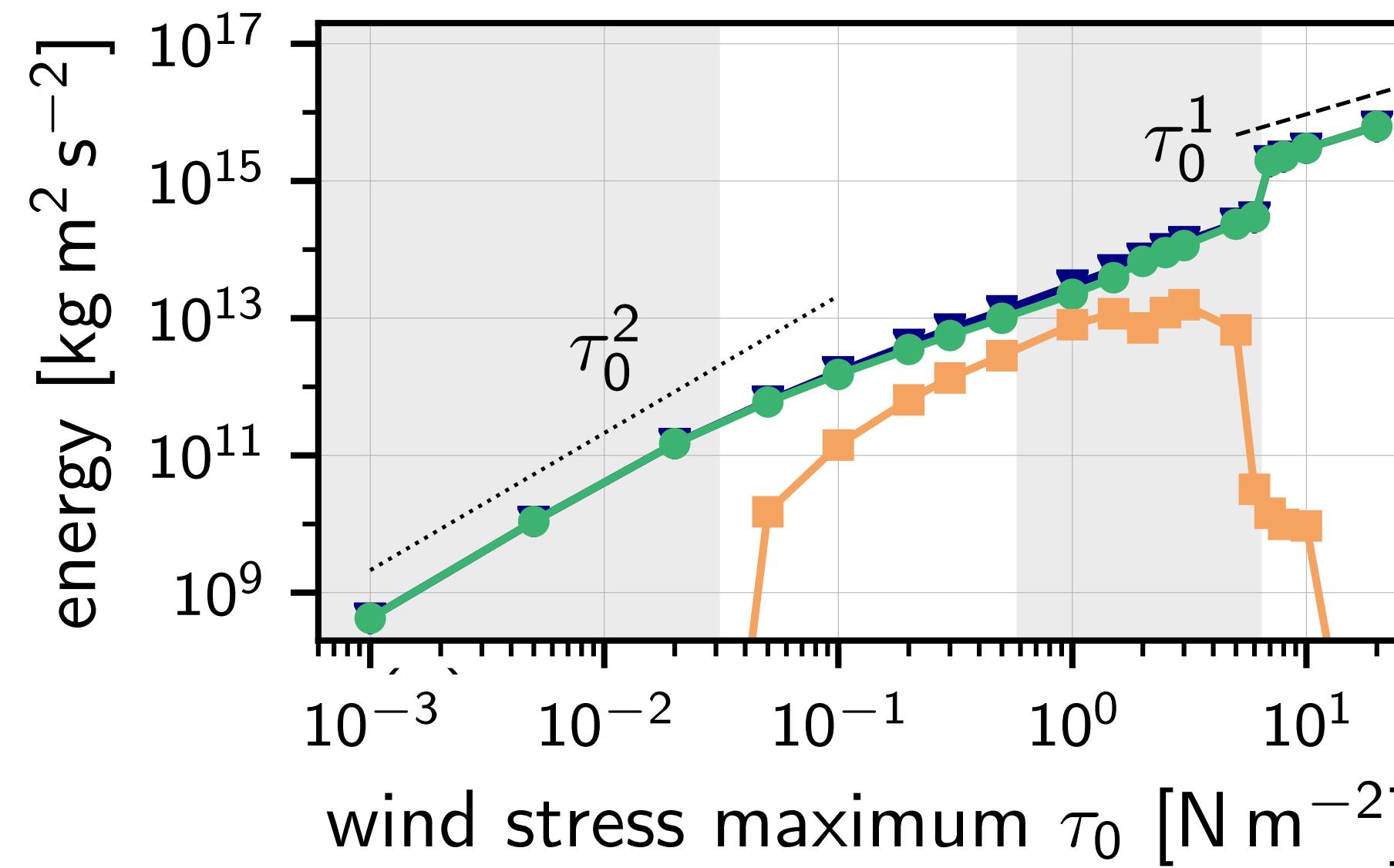
$$\begin{array}{ccc} \text{wind} & = & \text{topographic} \\ \text{stress} & & \text{form stress} \\ (\text{WS}) & & (\text{TFS}) \\ & & \propto p_{\text{bot}} \frac{\partial h_{\text{bot}}}{\partial x} \\ & & + \\ & & \text{bottom drag} \\ & & (\text{BD}) \end{array}$$



Almost all momentum is balanced by topographic form stress
(except when flow transitions to "upper branch").

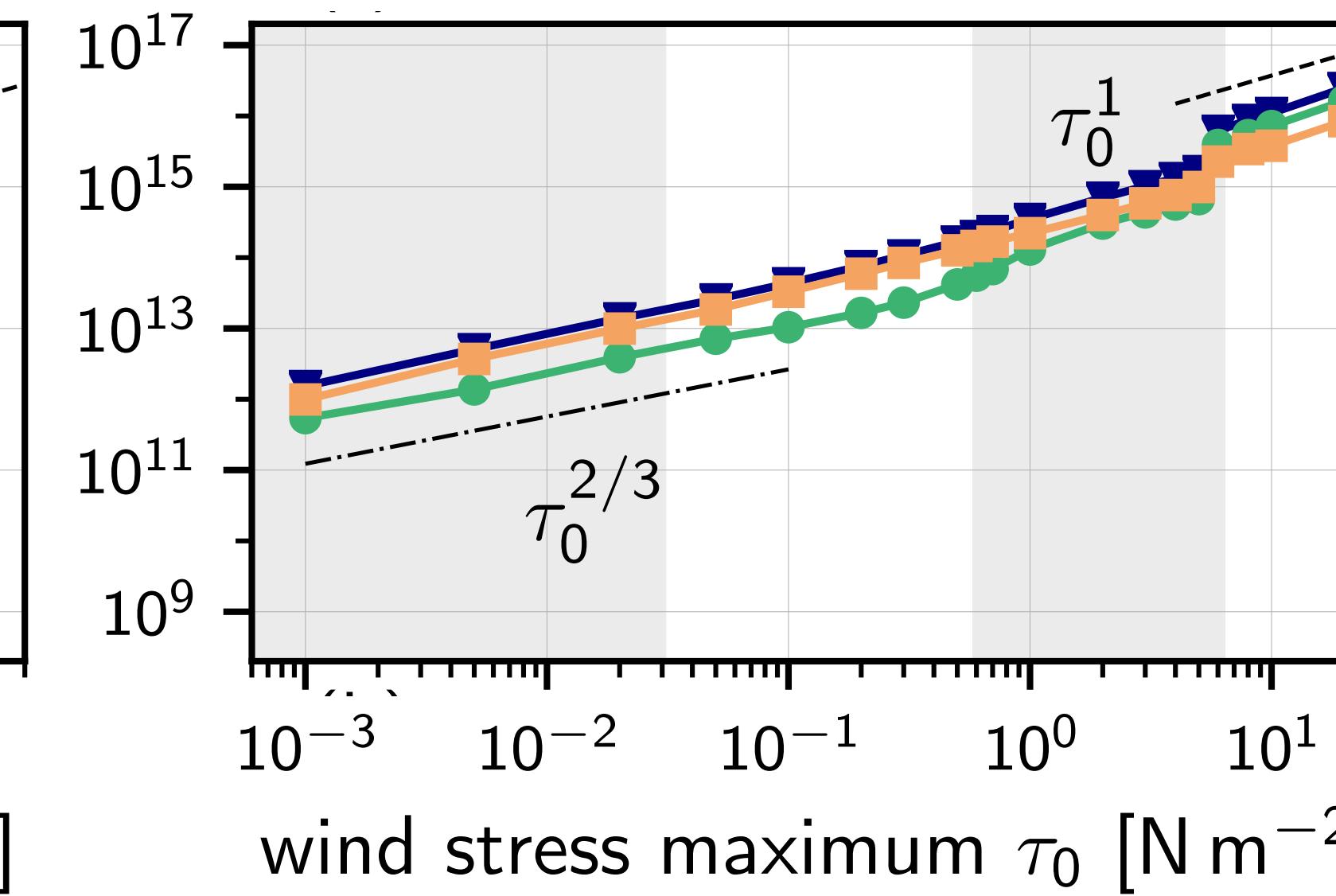
standing-transient kinetic energy decomposition

1-layer setup (BT)



BT config
has transients
only in II & III

2-layer setup (BC)



total kinetic energy
standing kinetic energy
transient kinetic energy

standing flow
dominates
in BT config;

transient flow
dominates in BC

Despite the great differences in flow fields,
both **BT** and **BC** configs show same mean zonal transport for regimes III & IV.

standing-transient contribution to TFS

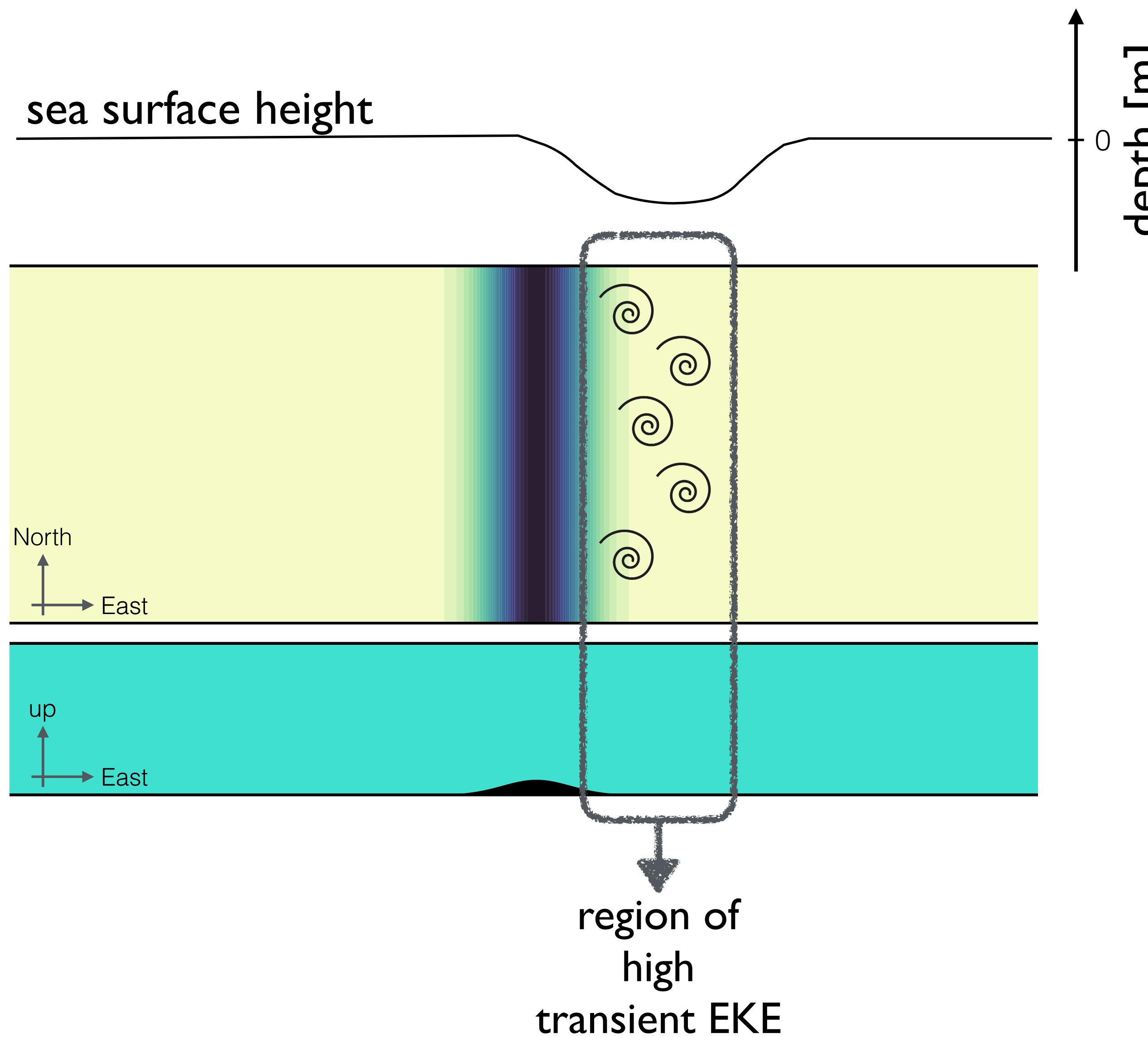
$\langle \rangle$: horizontal average
 $\overline{}$: time average

$$\langle \overline{p_{\text{bot}} \partial_x h_{\text{bot}}} \rangle = \langle \overline{p_{\text{bot}}} \partial_x h_{\text{bot}} \rangle$$

only standing flow contributes to
time-mean topographic form stress

how transients affect
topographic form stress?

how transients lead to time-mean topographic form stress?



transient eddies appear downstream of topography

have an asymmetric signature on SSH

induce asymmetric time-mean pressure upstream & downstream the ridge

topographic form stress
 $\langle \bar{p}_{\text{bot}} \partial_x h_{\text{bot}} \rangle$

[Same phenomenology as that described by Youngs et al. 2017]

take home message

when transient eddies exist (both in **barotropic** or **baroclinic** configs)
the mean zonal transport becomes eddy saturated
[transport is much less sensitive to wind stress increase]

proposal:

eddy saturation occurs due to
transient eddies shaping the standing flow
to produce topographic form stress that balances the wind stress
(regardless of the process from which transient eddies originate)

our results show that the (oftentimes ignored) barotropic flow-component
plays an important role in setting up the ACC transport
[in agreement with recent obs. evidence, e.g., Thompson & Naveira Garabato 2014,
Peña-Molino et al. 2014, Donohue et al. 2016 (cDrake exp)]

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what's next?

check what holds in a global ocean model?

use SAMx perturbation experiments?

another way of changing wind forcing?

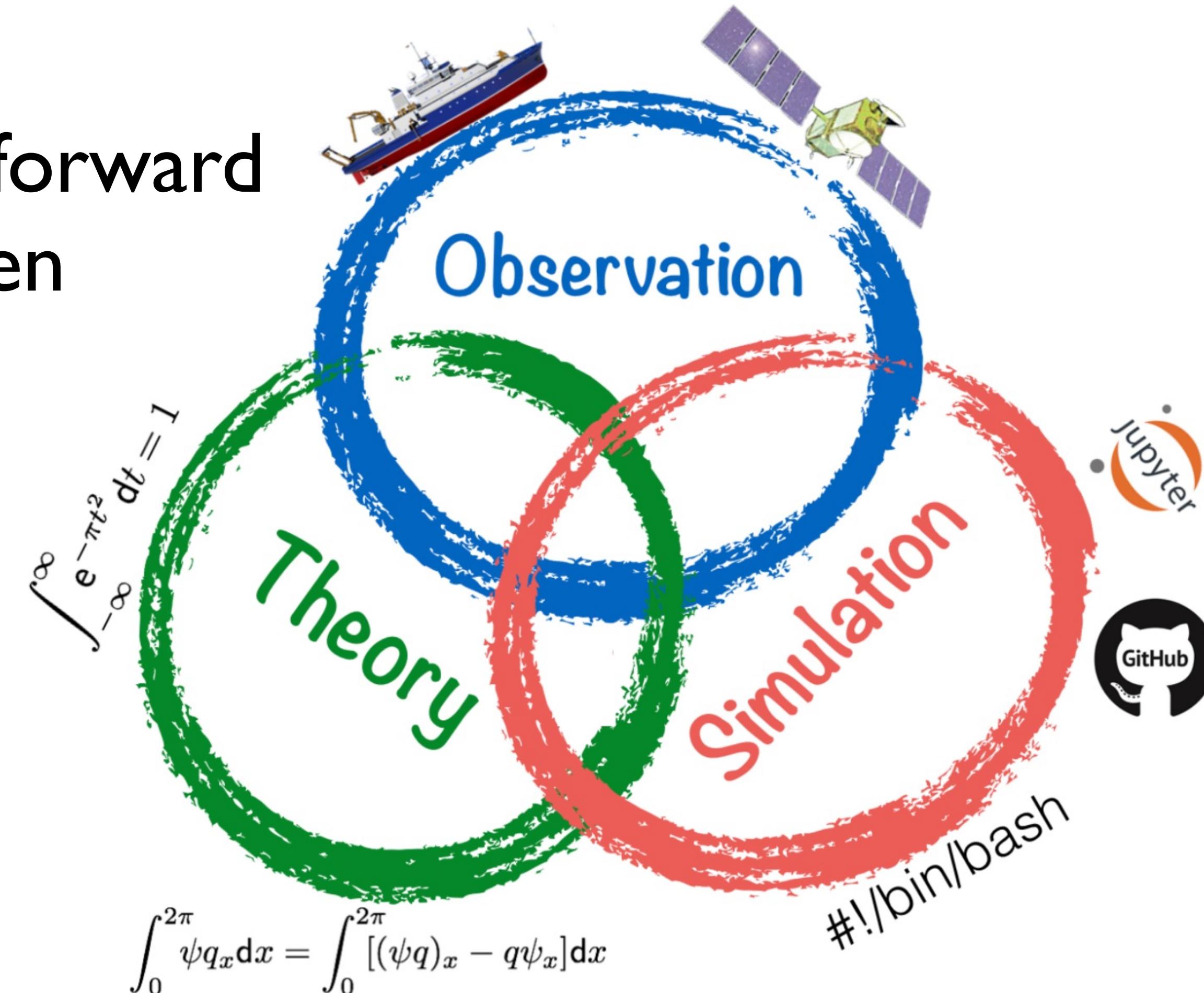


but really, if you only want to take **one** thing back home

(e.g., airline luggage restrictions)

the proper way forward
comes when

[schematic by
CB Rocha]



let's try to reduce this gap

work together
in unison