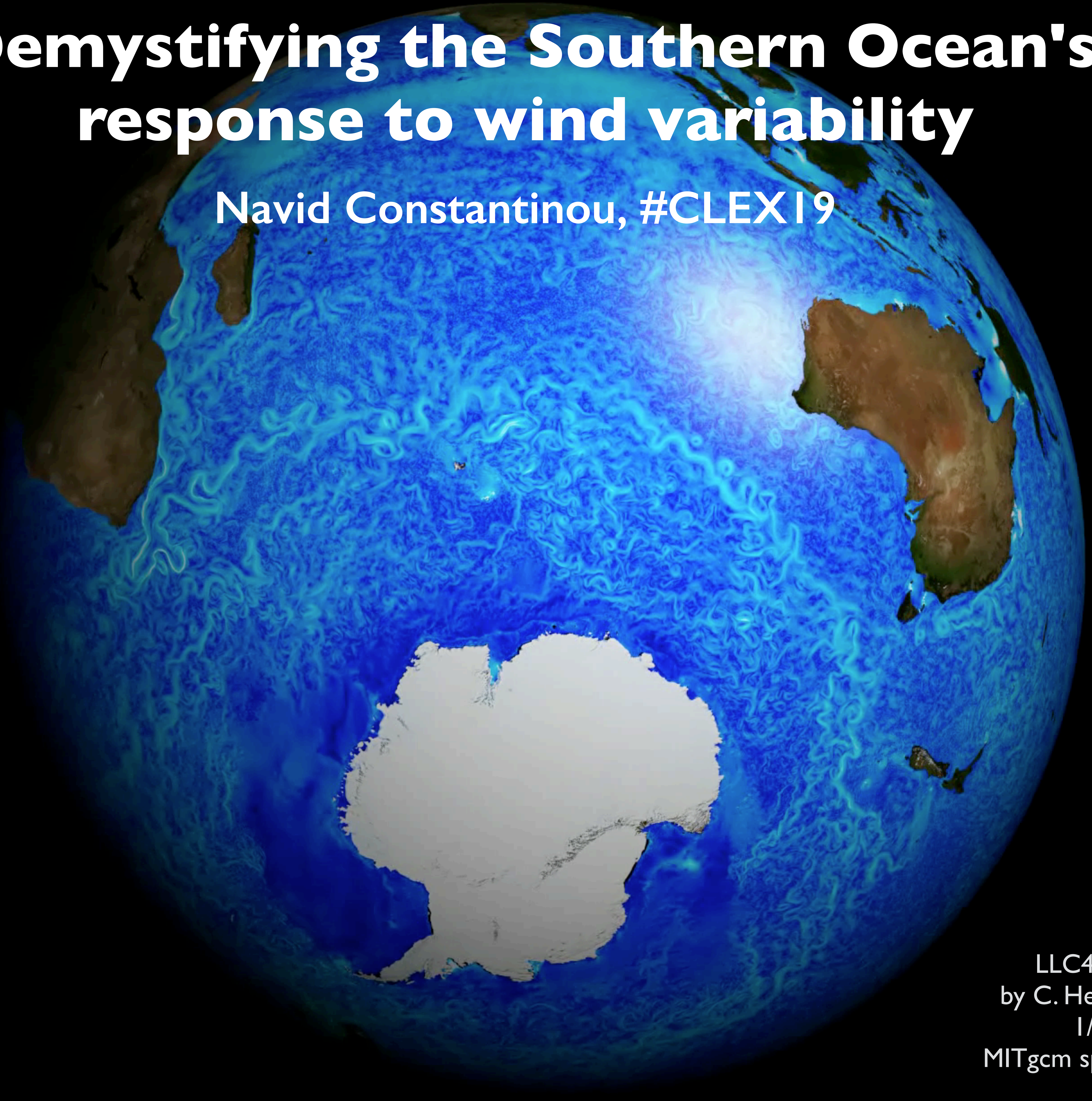
Demystifying the Southern Ocean's response to wind variability

Australian National University

Navid Constantinou, #CLEX19



the
Antarctic
Circumpolar
Current

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

"If anybody fully understands what he [Navid] does please come explain to me."

Andy Pitman
Tue, Nov 19th

(photo taken earlier than Tue)

"I never studied ocean dynamics;
I was most interested studying the land,
where our food comes from."

(slightly paraphrased)

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Tue, Nov 19th

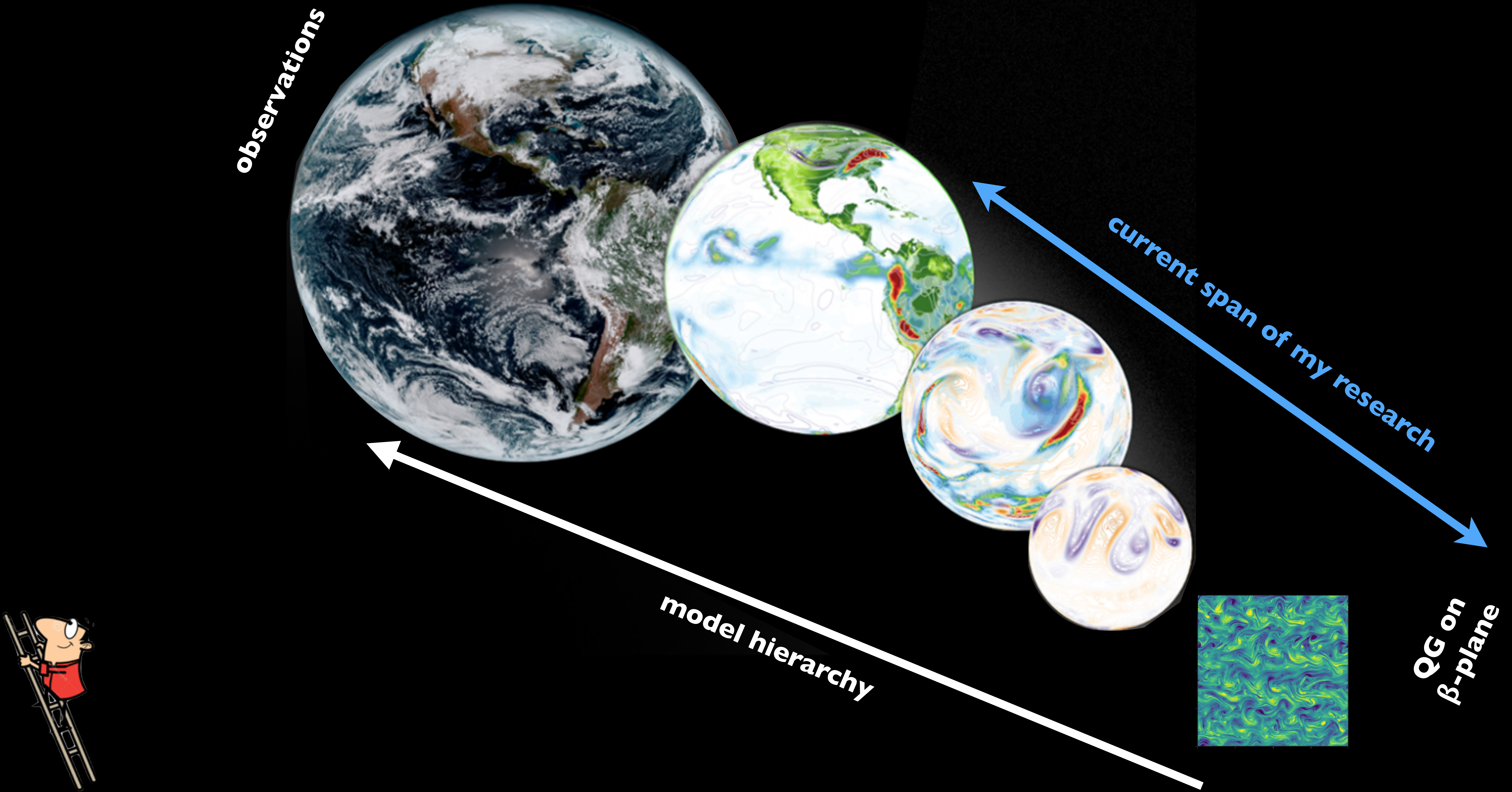
(photo taken earlier than Tue)

"How inappropriate to call this planet
Earth, when clearly it is Ocean."

Arthur C. Clark

NASA JPL

build intuition through
climate-model hierarchy

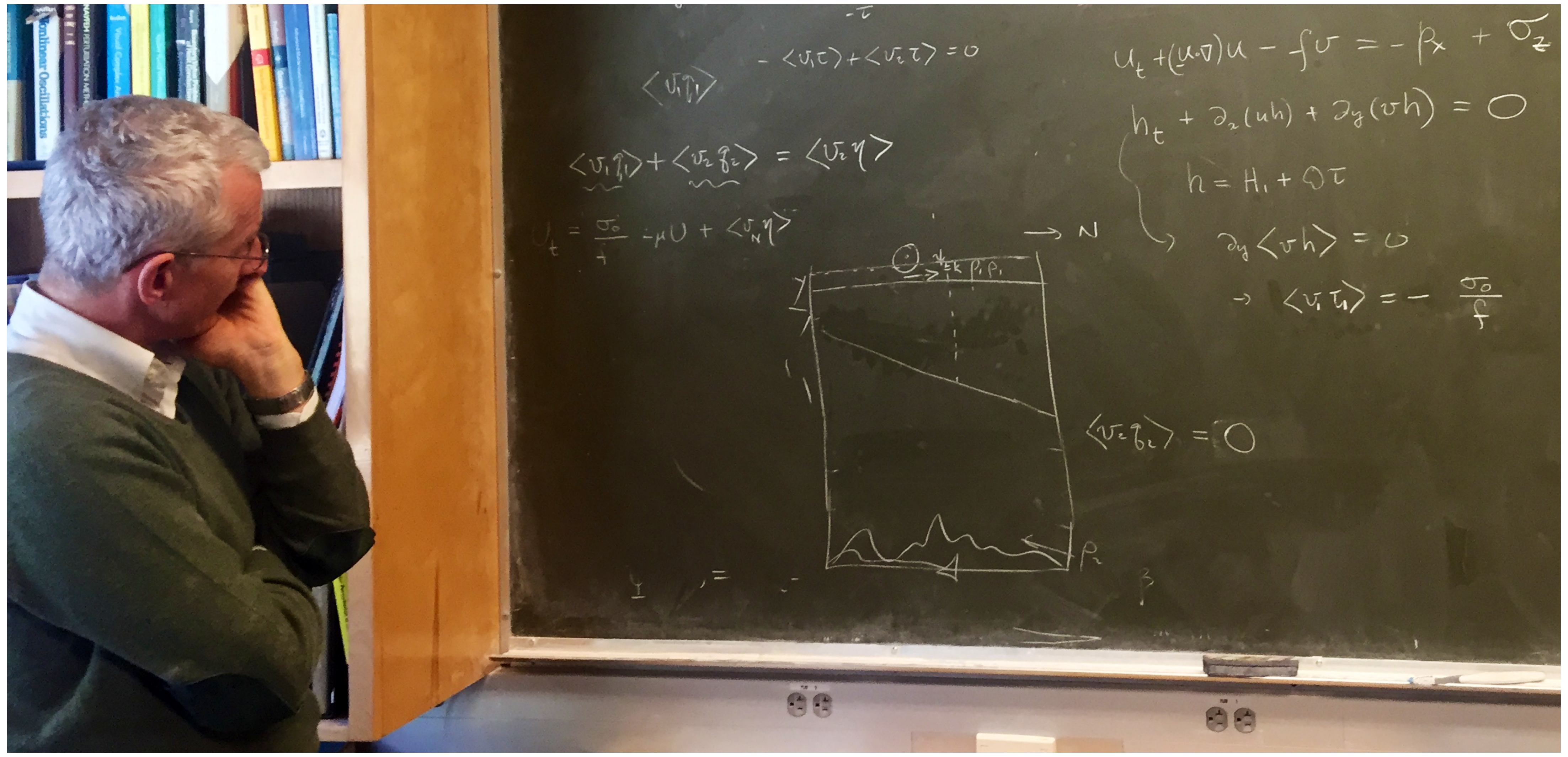


A dichotomy

theory

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

$$\rho\Big(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u}\cdot\nabla \boldsymbol{u}\Big) = \dots \qquad \Gamma(x) = \int_0^\infty t^{x-1} e^t \, \mathrm{d}t$$

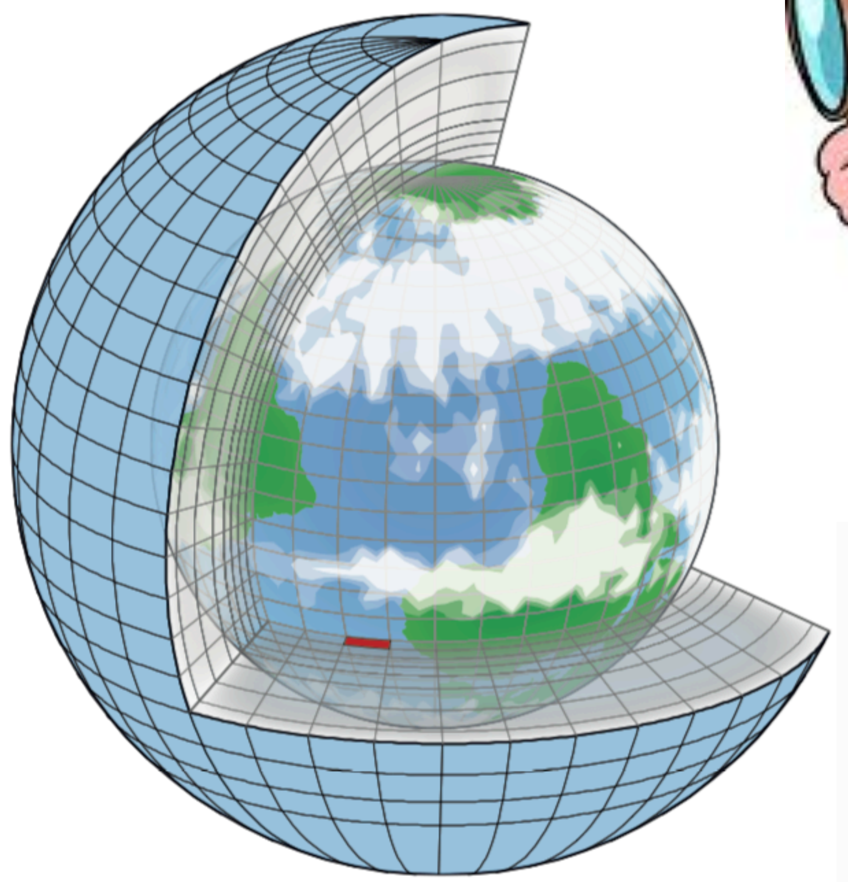


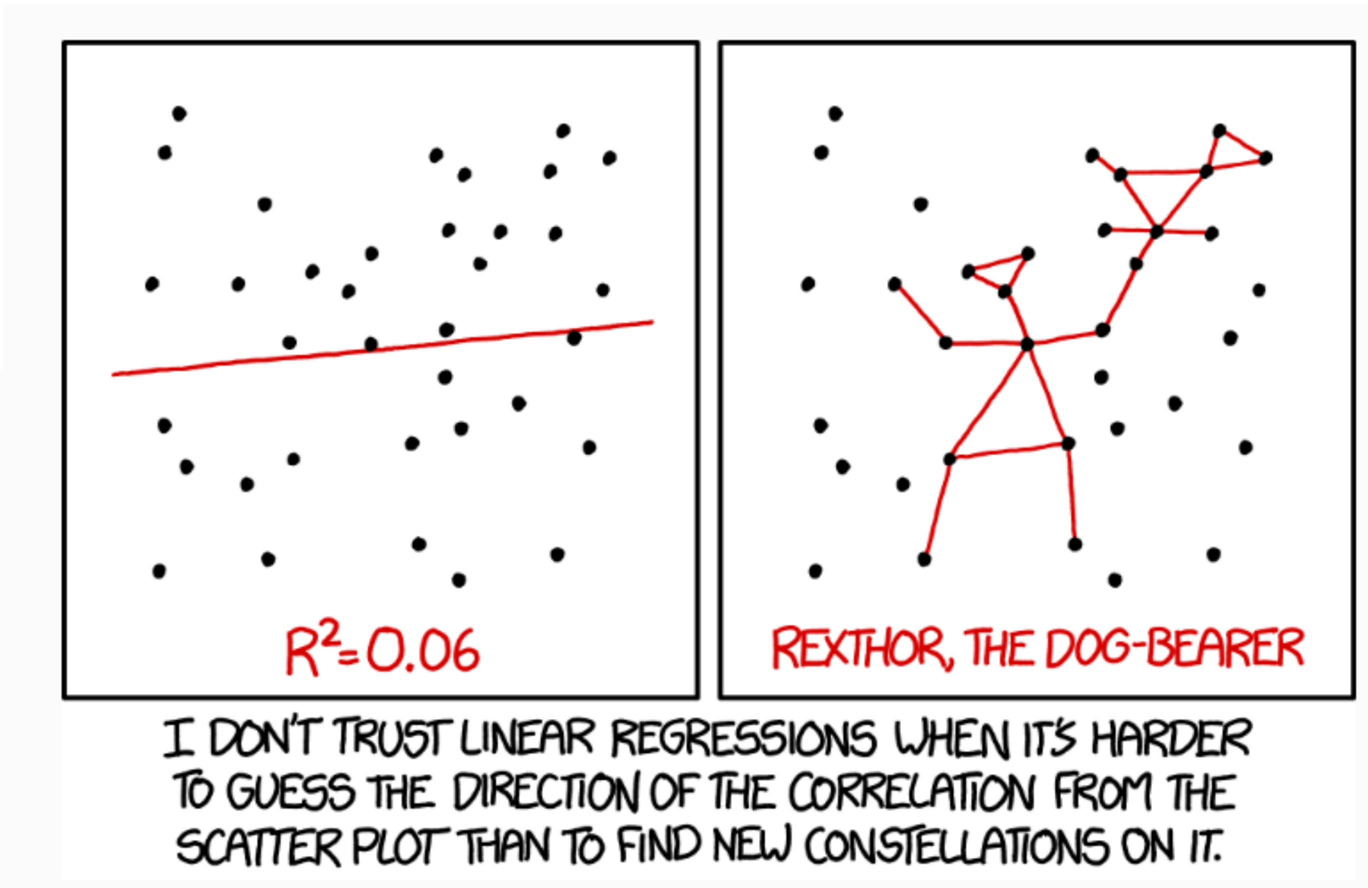
a typical meeting with Bill Young @ Scripps/UCSD

(yes, we still use chalk...)

climate science

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





A dichotomy

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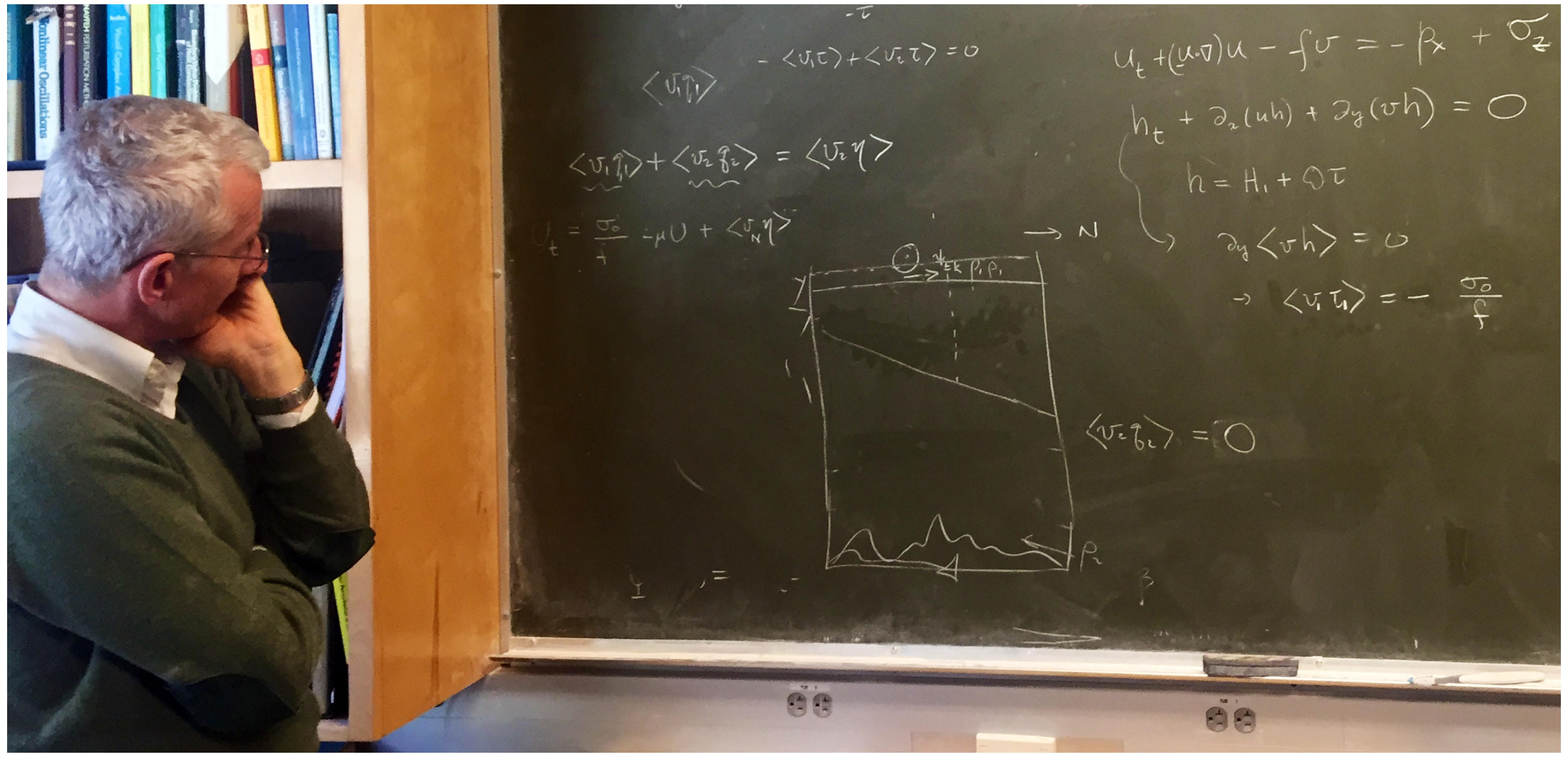
$$\rho\left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u}\cdot\nabla\boldsymbol{u}\right) = \ldots \qquad \Gamma(x) = \int_0^\infty t^{x-1}e^t\,\mathrm{d}t$$



a typical meeting with Bill Young @ Scripps/UCSD

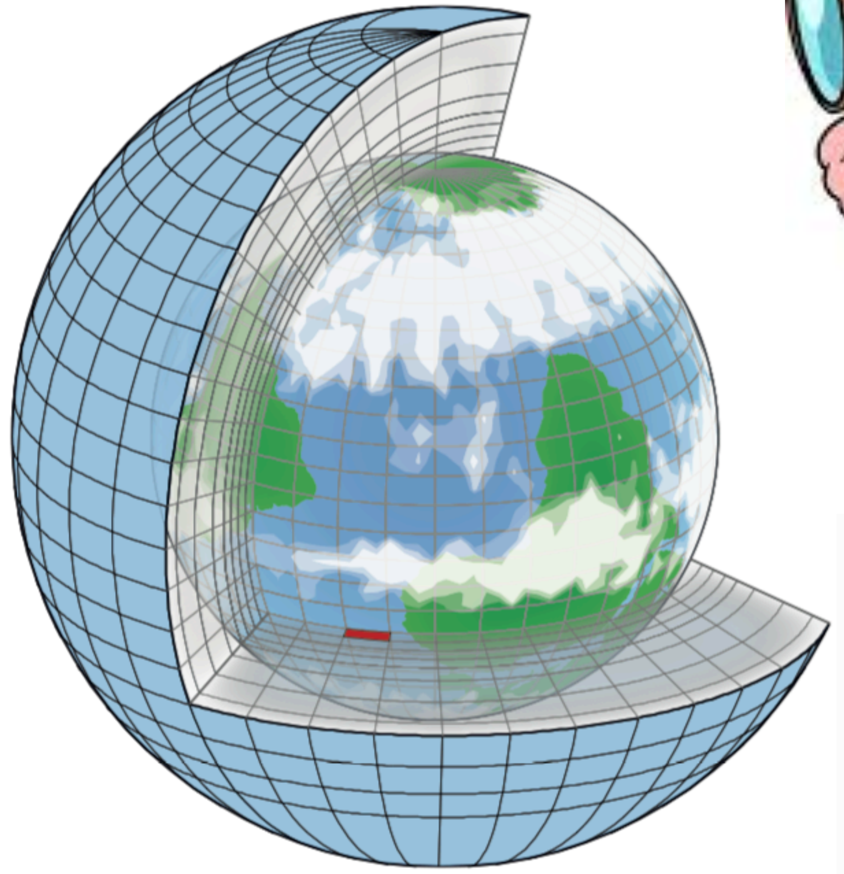
(yes, we still use chalk...)

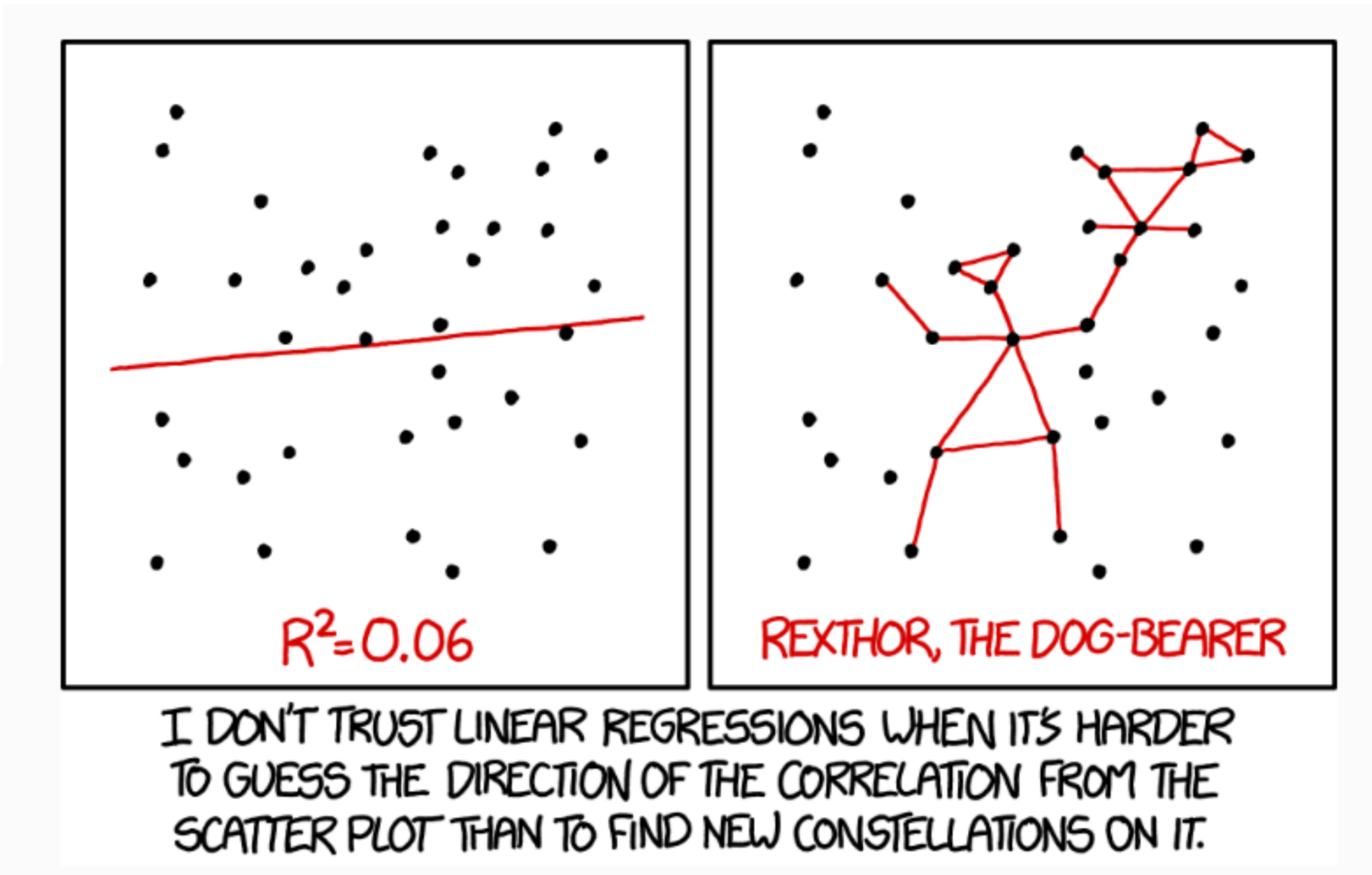
realistic

simple

climate science

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



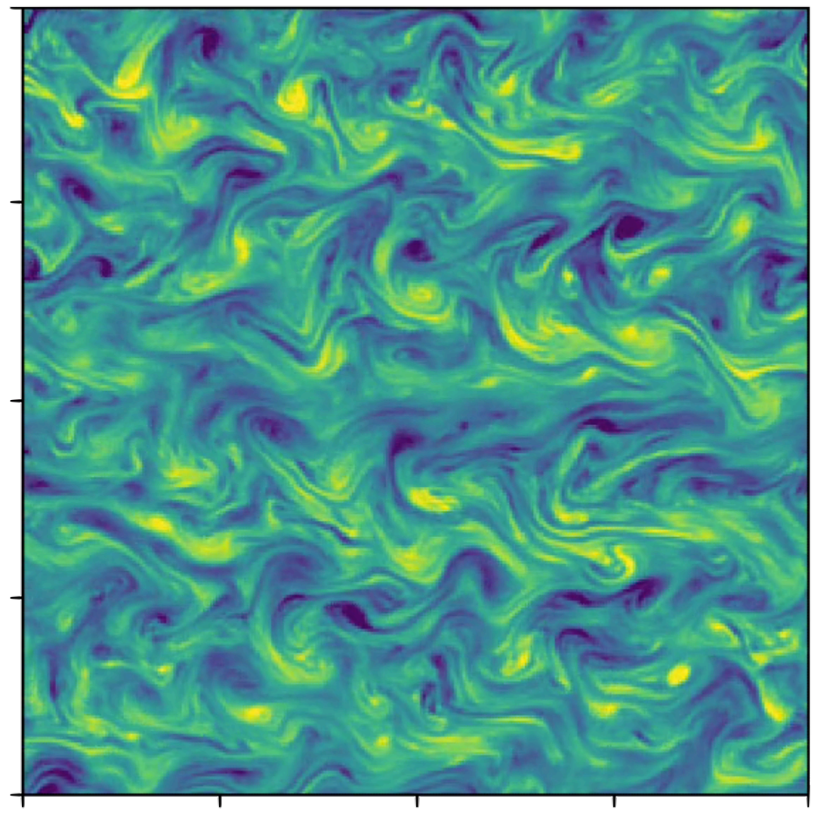


Goal: narrow the gap between theory and ~~simulation~~ *reality*

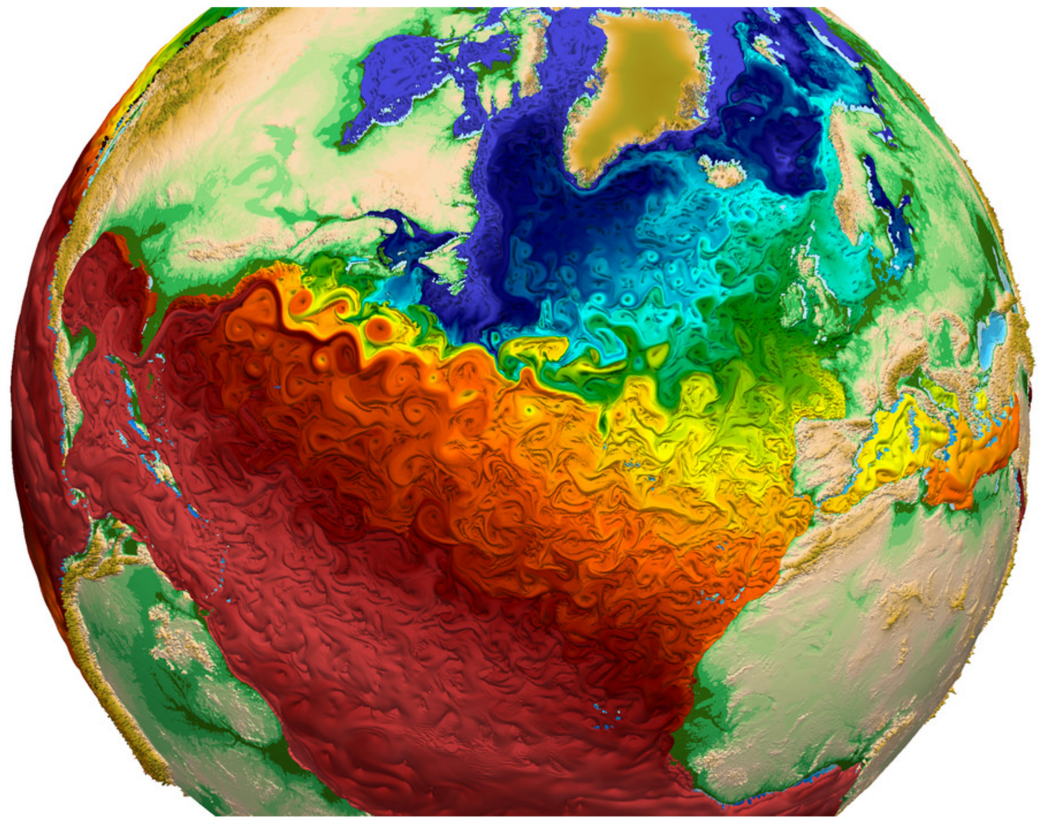
[Held 2005, BAMS]

inform climate model development
and interpretation

conceptual models



observations /
realistic models



easy to understand
and build physical intuition

closer to
reality

motivate conceptual model studies
from climate model output/observations

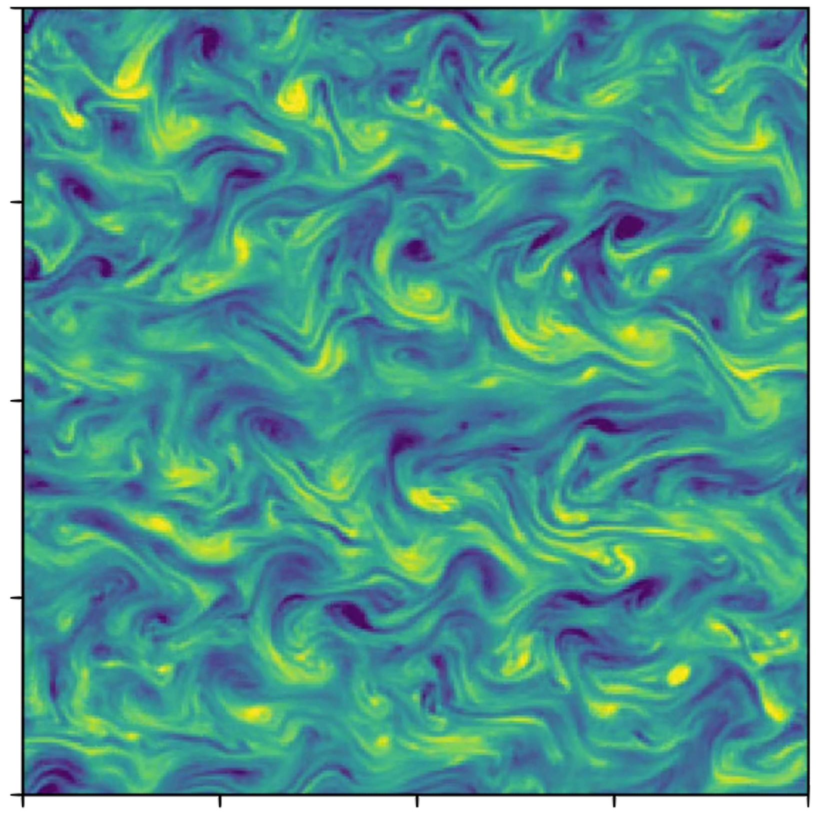
reality

Goal: narrow the gap between theory and ~~simulation~~

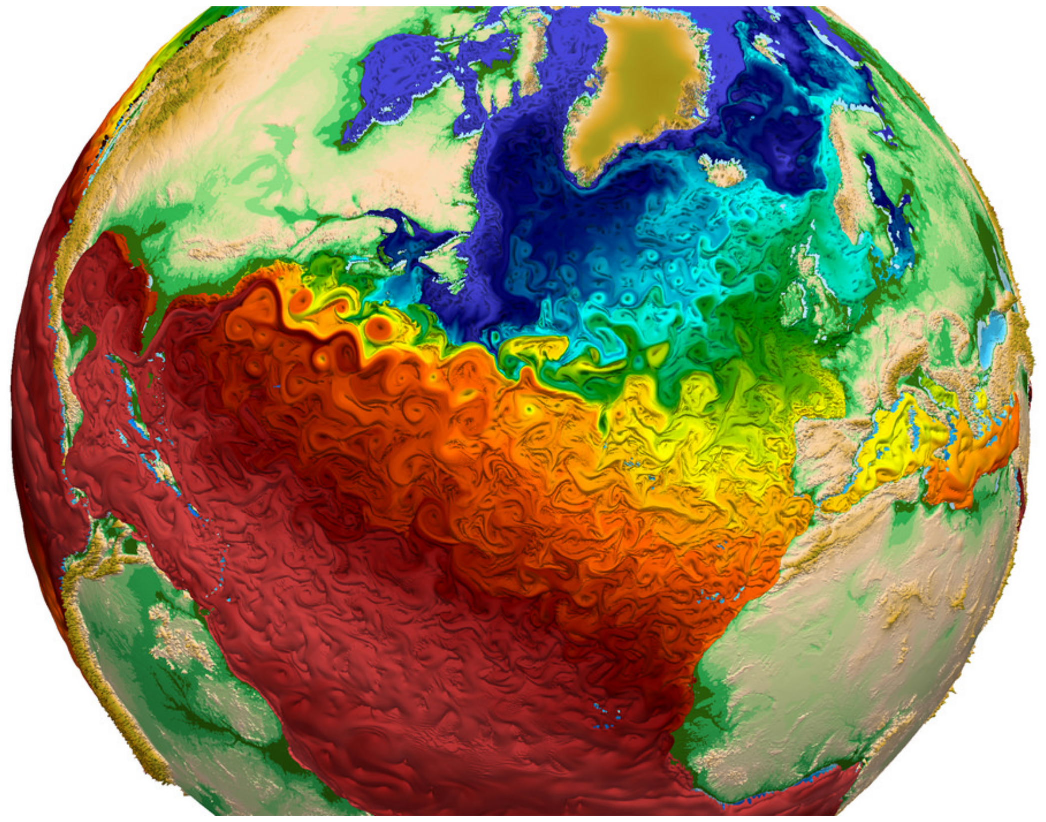
[Held 2005, BAMS]

use conceptual models to inspire
e.g., design of cruises to test hypotheses

conceptual models



observations /
realistic models



easy to understand
and build physical intuition

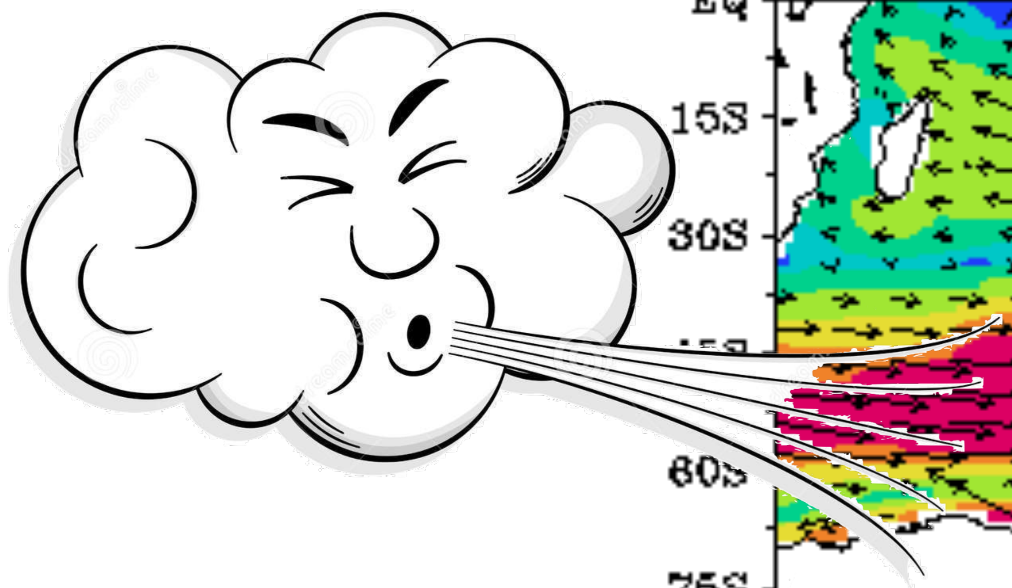
closer to
reality

use theory to extract dynamics
from observations

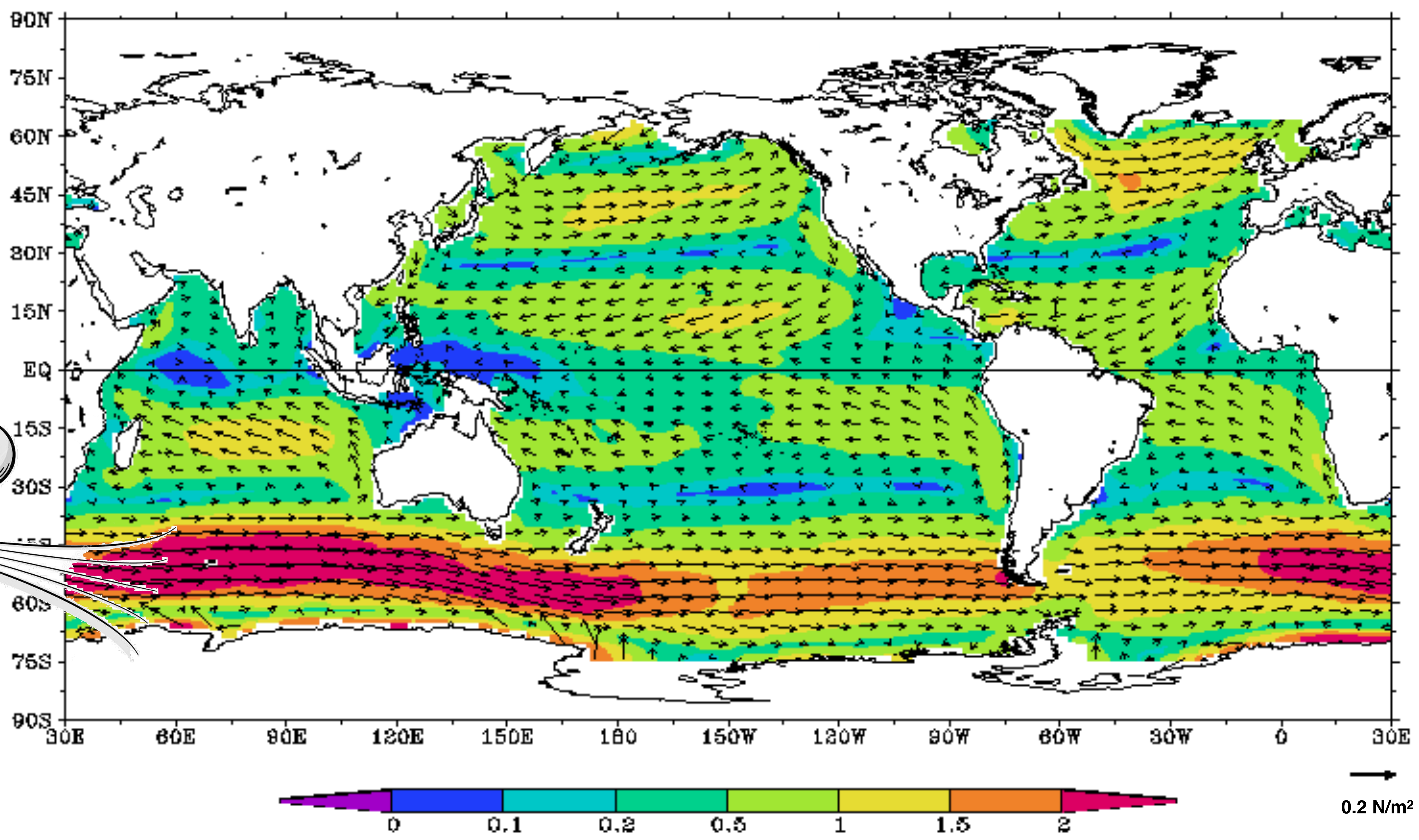
I'll give an example:

Response of Southern Ocean to winds increase.

winds (mainly) drive the Antarctic Circumpolar Current



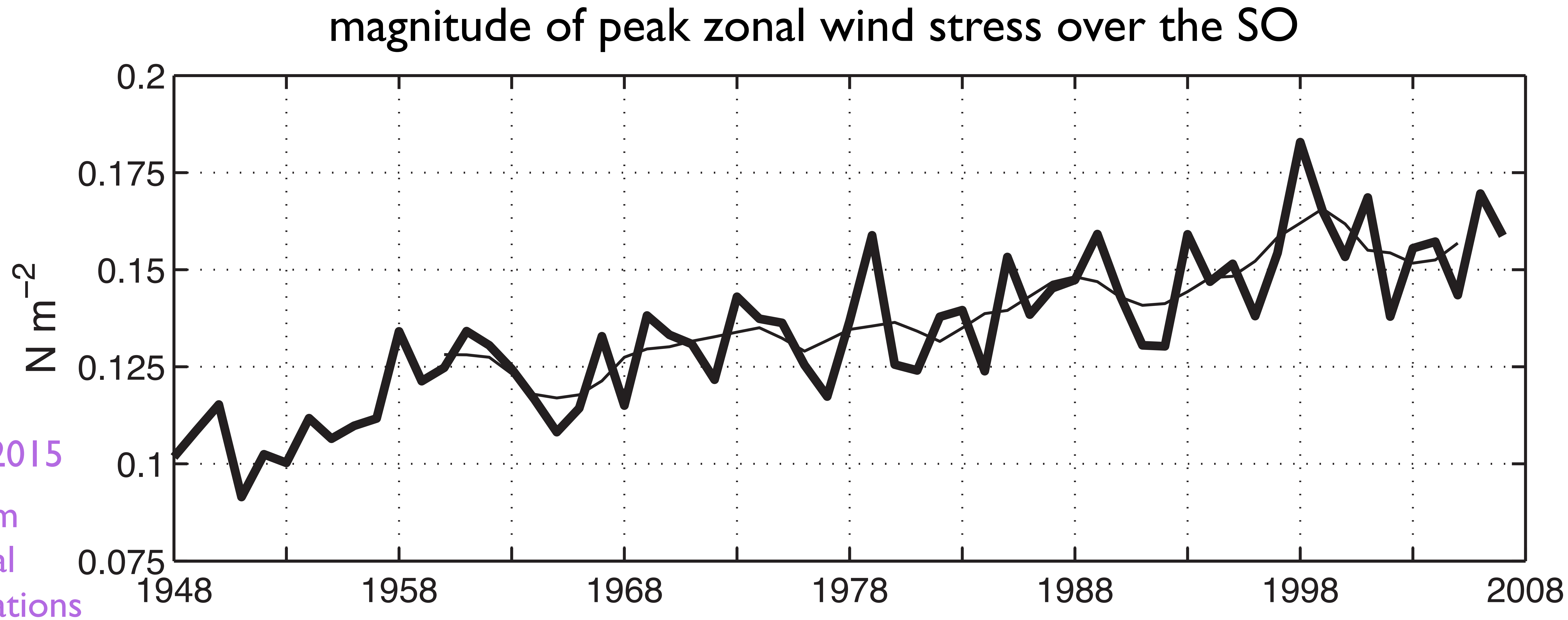
GODAS Wind Stress, 1982-2004 Annual



Climate Prediction Center

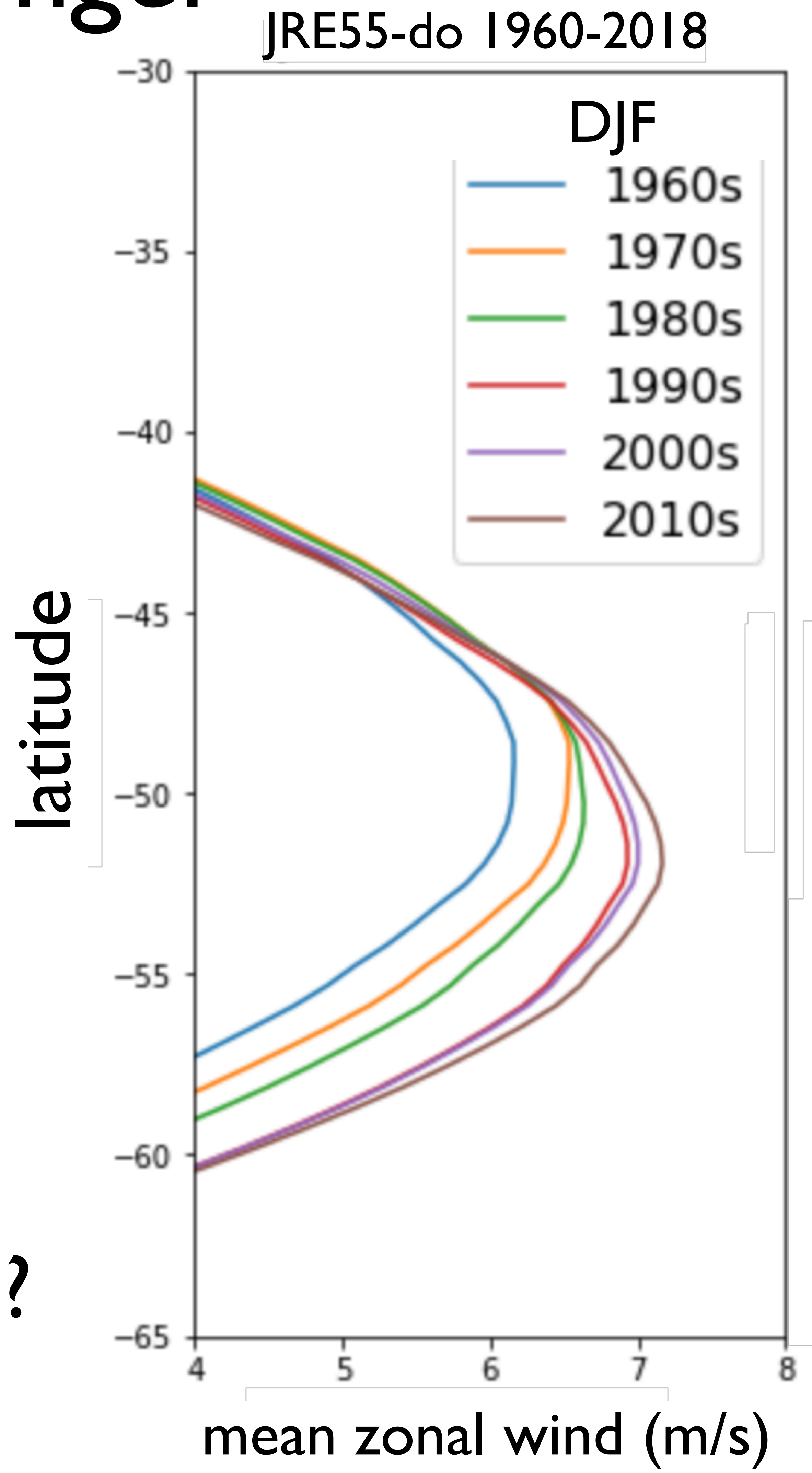
strong westerly winds blow over the Southern Ocean transferring momentum through wind stress at the surface

winds over Southern Ocean are getting stronger



Farneti et al. 2015

results from inter-annual CORE-II simulations



how will the Antarctic Circumpolar Current respond?

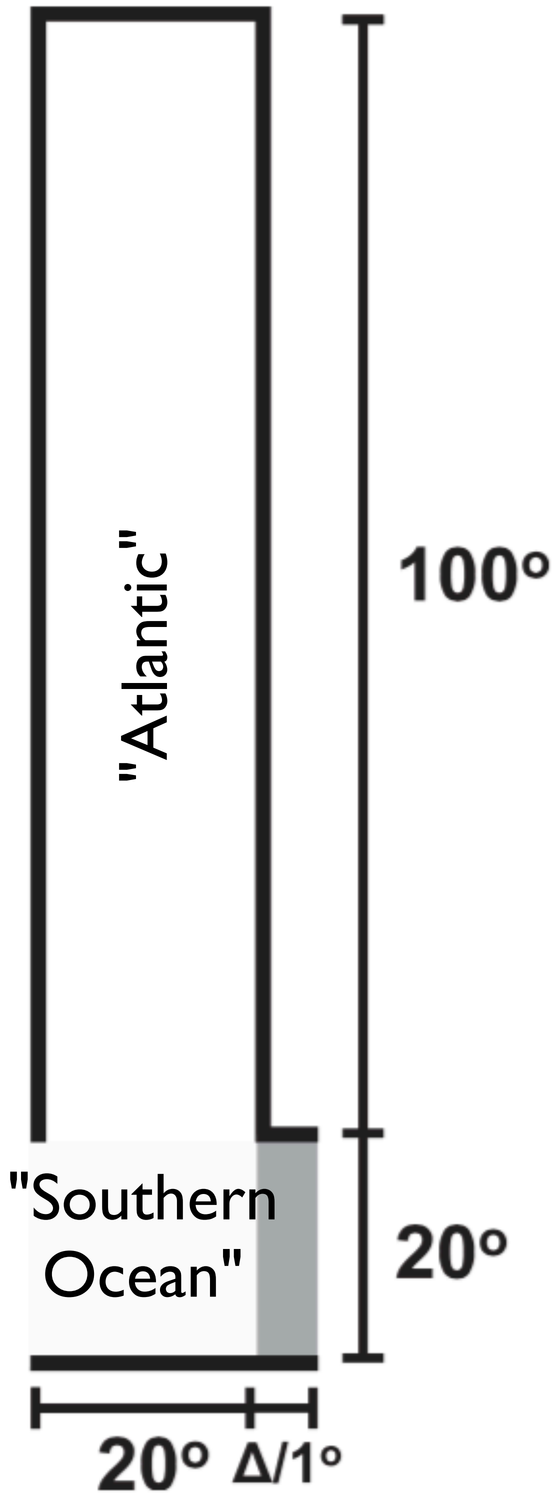
does doubling the winds imply double ACC the transport?

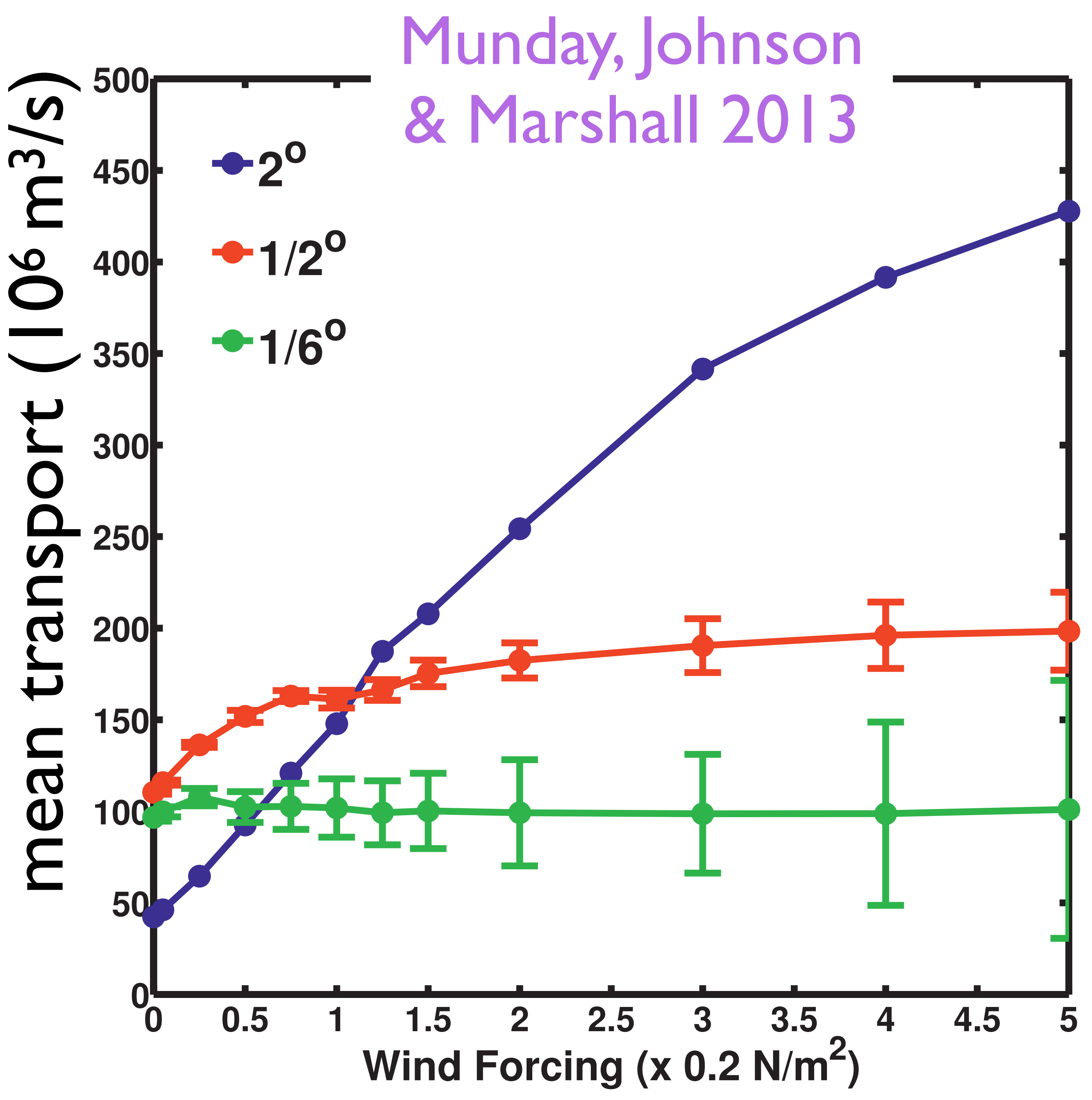
not always — “eddy saturation”

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

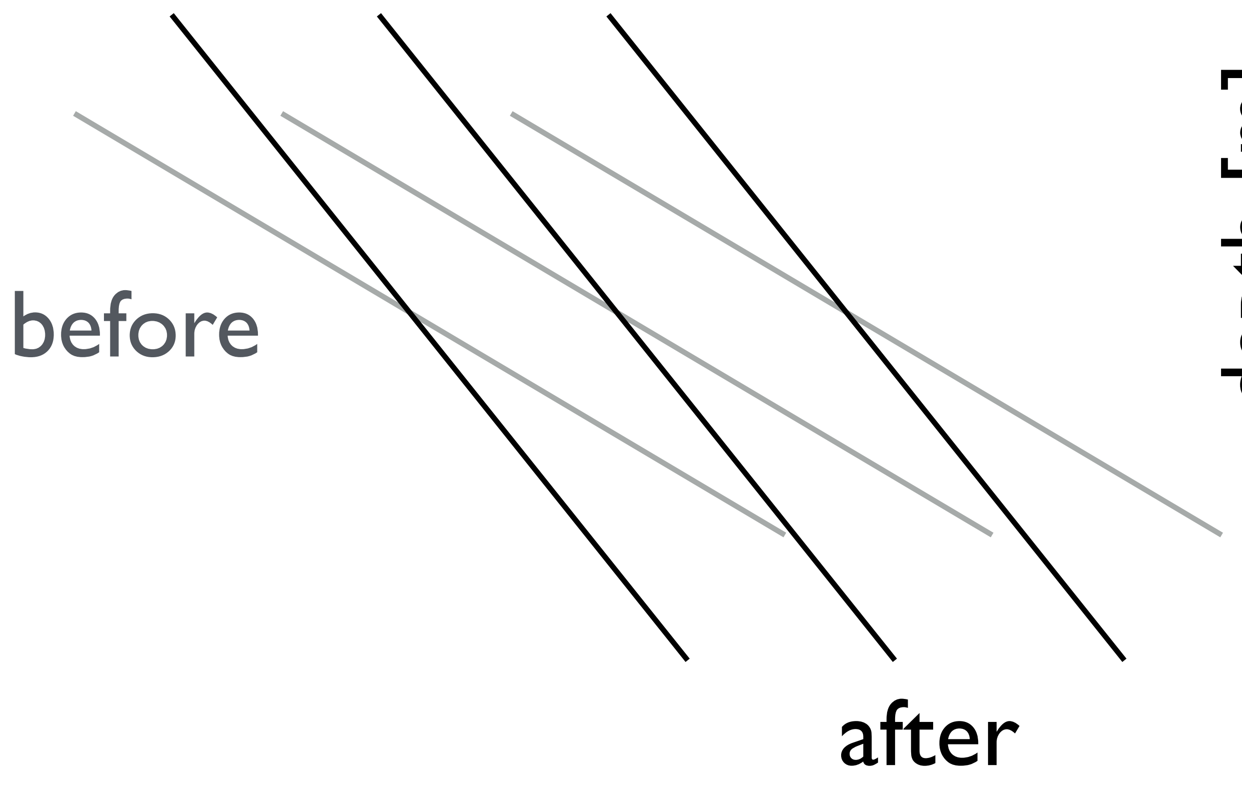
Eddy saturation is seen in
eddy-resolving "ocean models".
(some hints also in obs.)

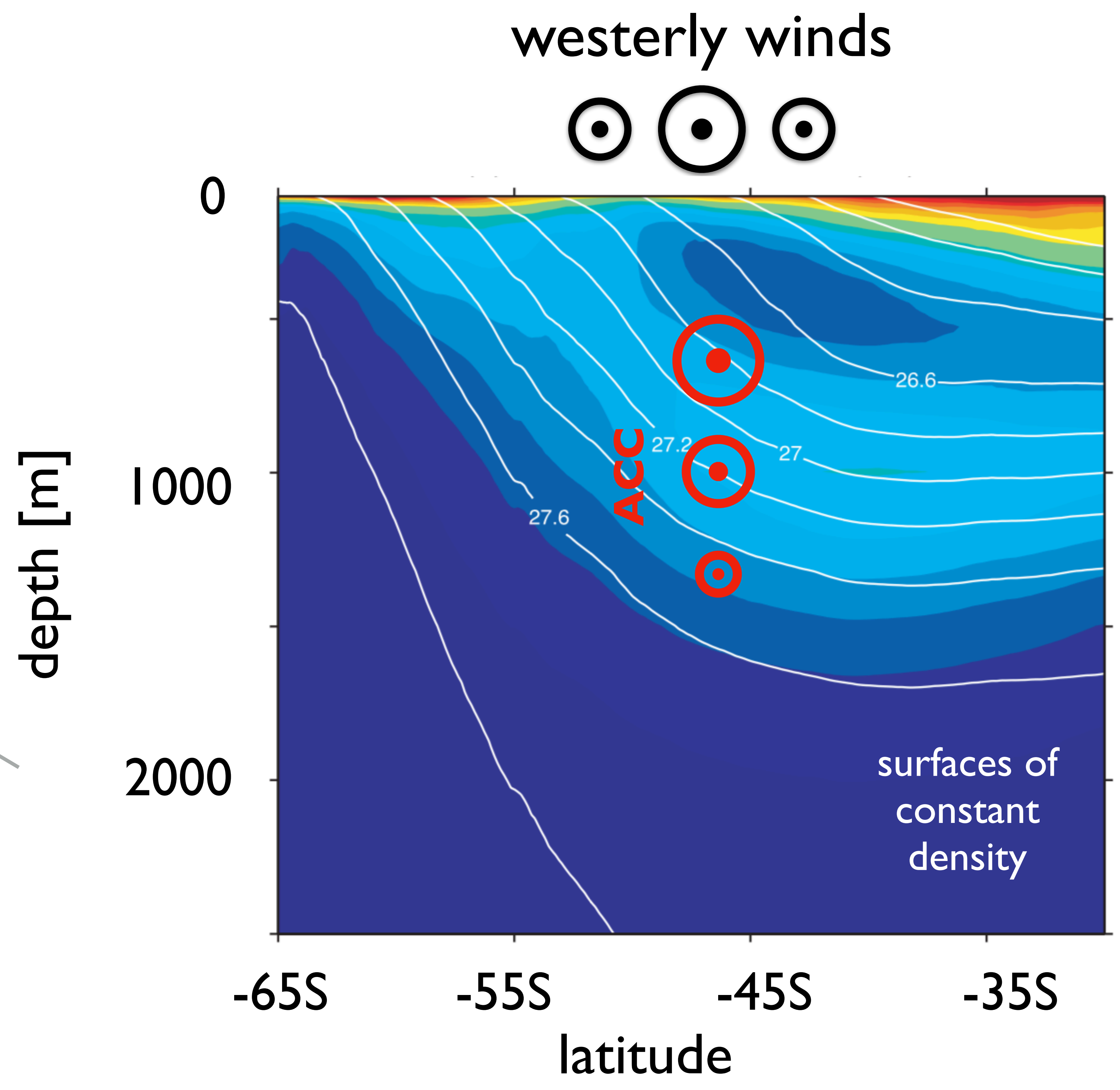
higher resolution → eddy saturation "emerges"

[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.]

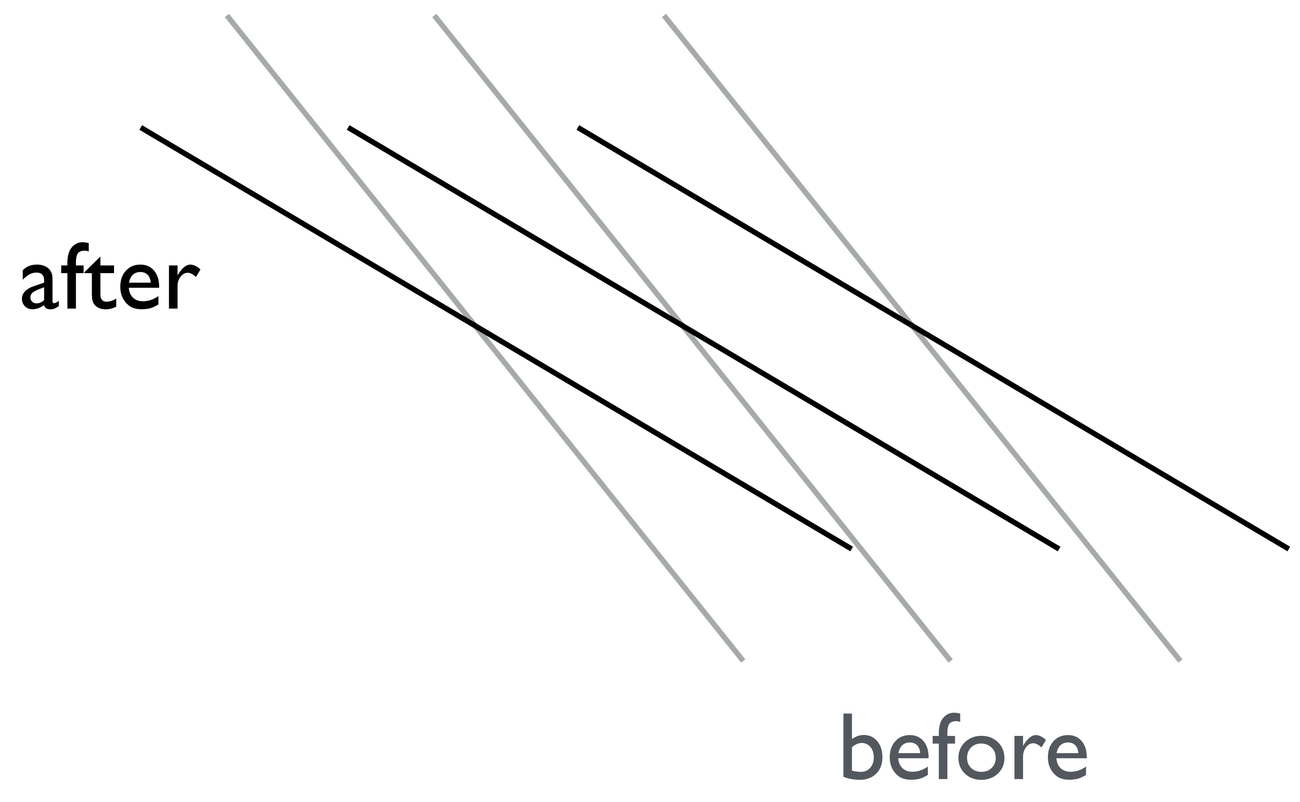
the textbook explanation:
how eddies lead to eddy saturation?

wind increase
slopes the isopycnals





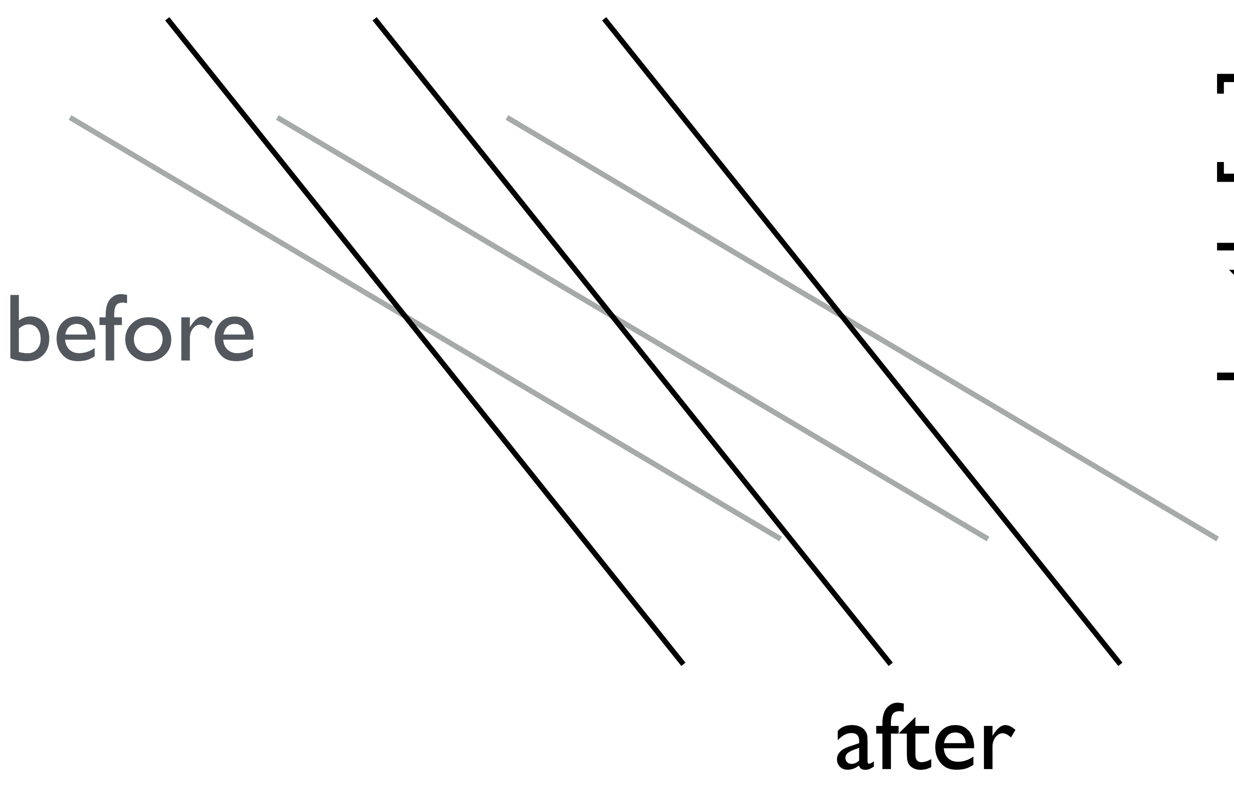
baroclinic eddies
restratify isopycnals

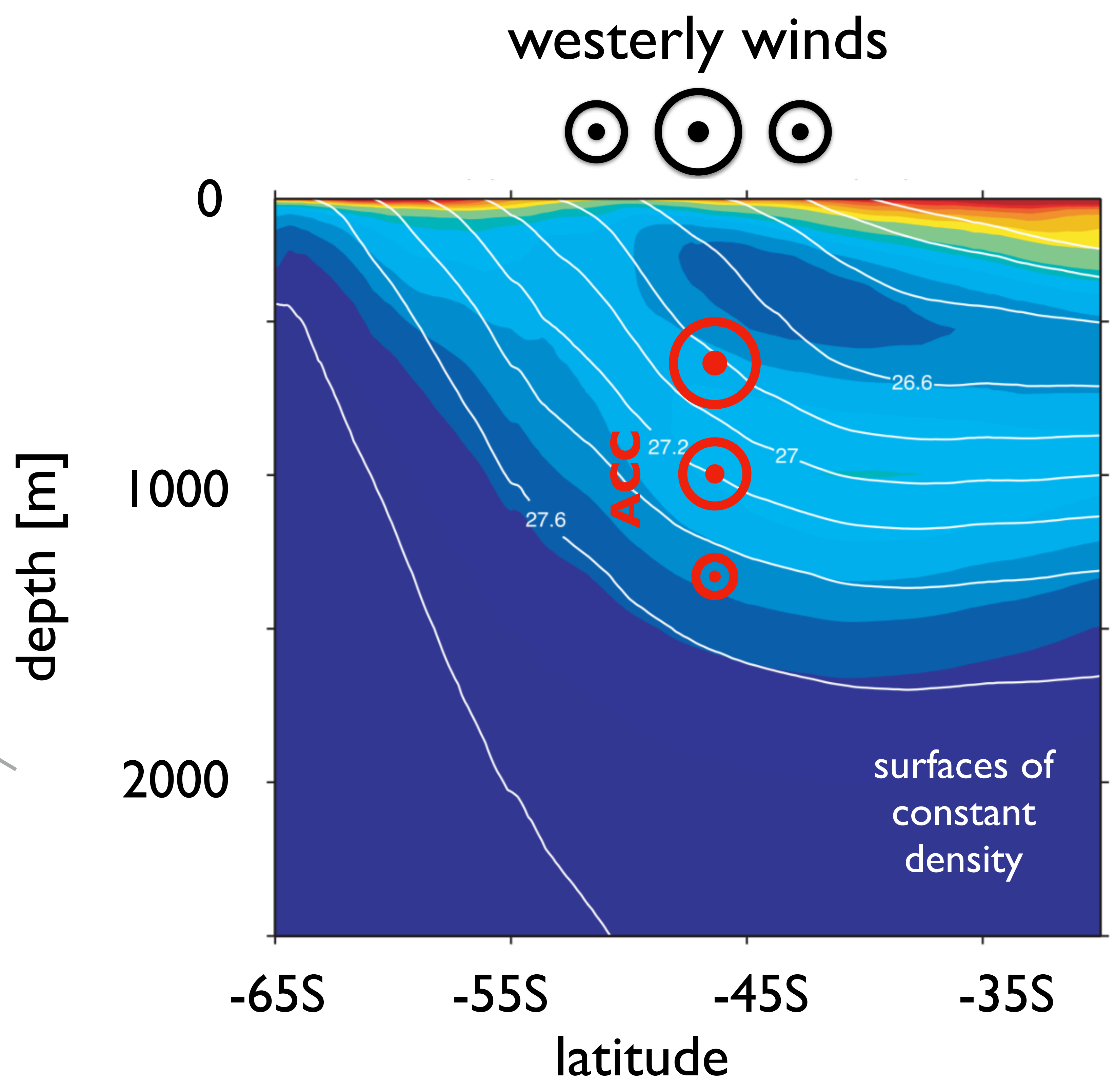


remember
jets & fronts
Amelie's talk

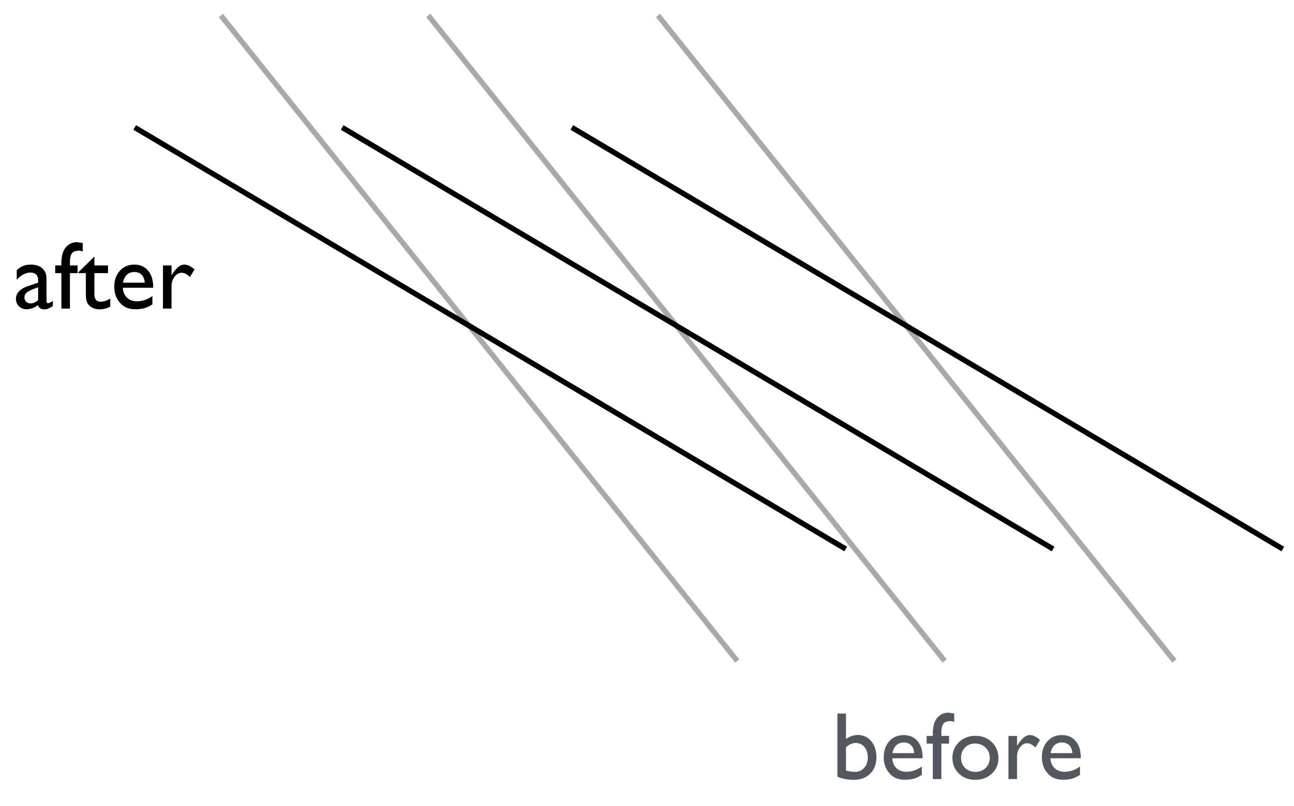
the textbook explanation:
how eddies lead to eddy saturation?

wind increase
slopes the isopycnals





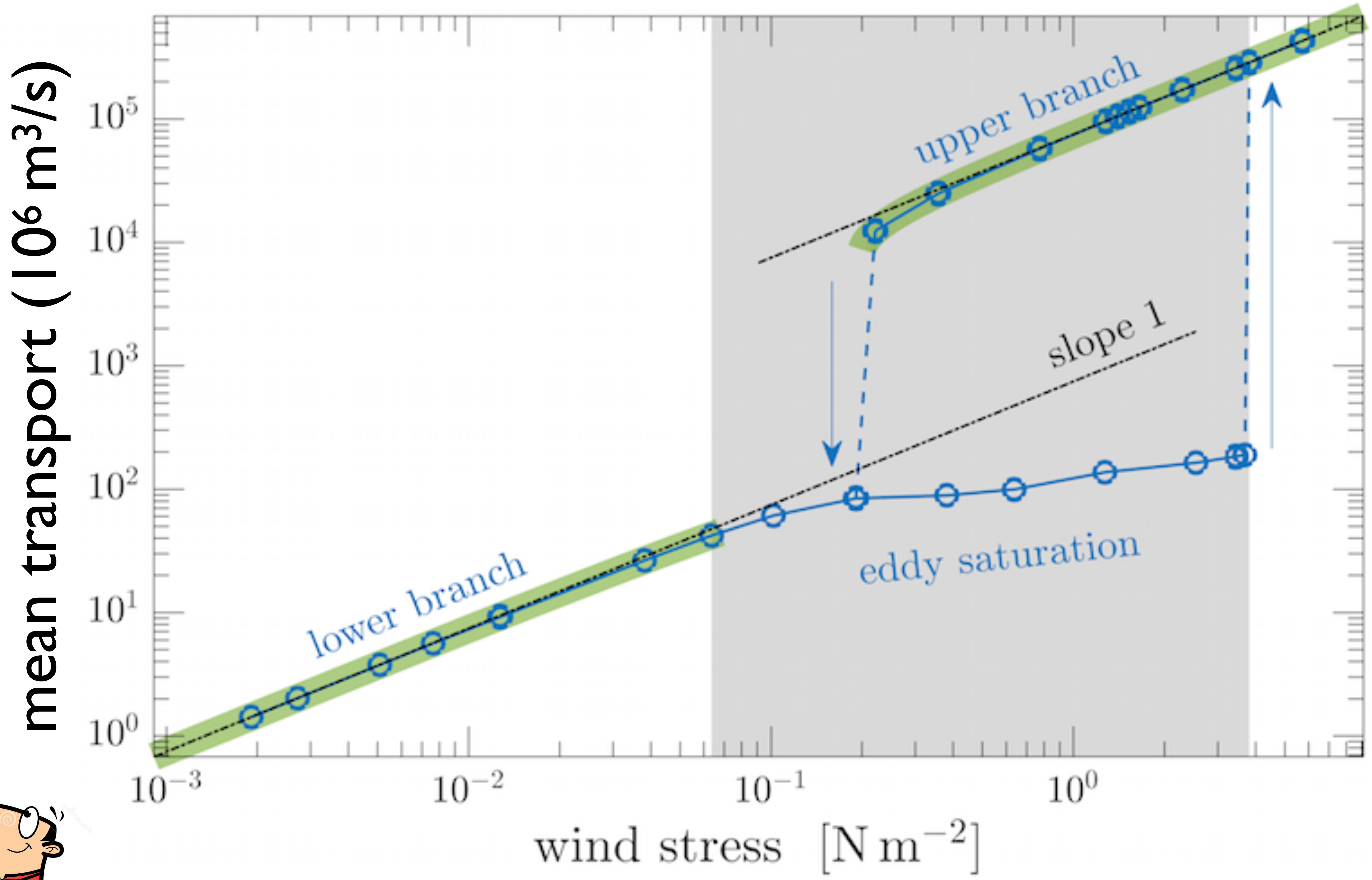
baroclinic eddies
restratify isopycnals



This explanation crucially ***relies on density varying with depth***.
(gfd-jargon: **baroclinic**)

Role of bathymetry?

however, simple unstratified models reveal a new possible mechanism



Constantinou & Young 2017
Constantinou 2018

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

(gfd-jargon: **barotropic**)

role of bathymetry I

W.H. Munk
1917 - Feb 2019

Munk & Palmen (1951)

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

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)

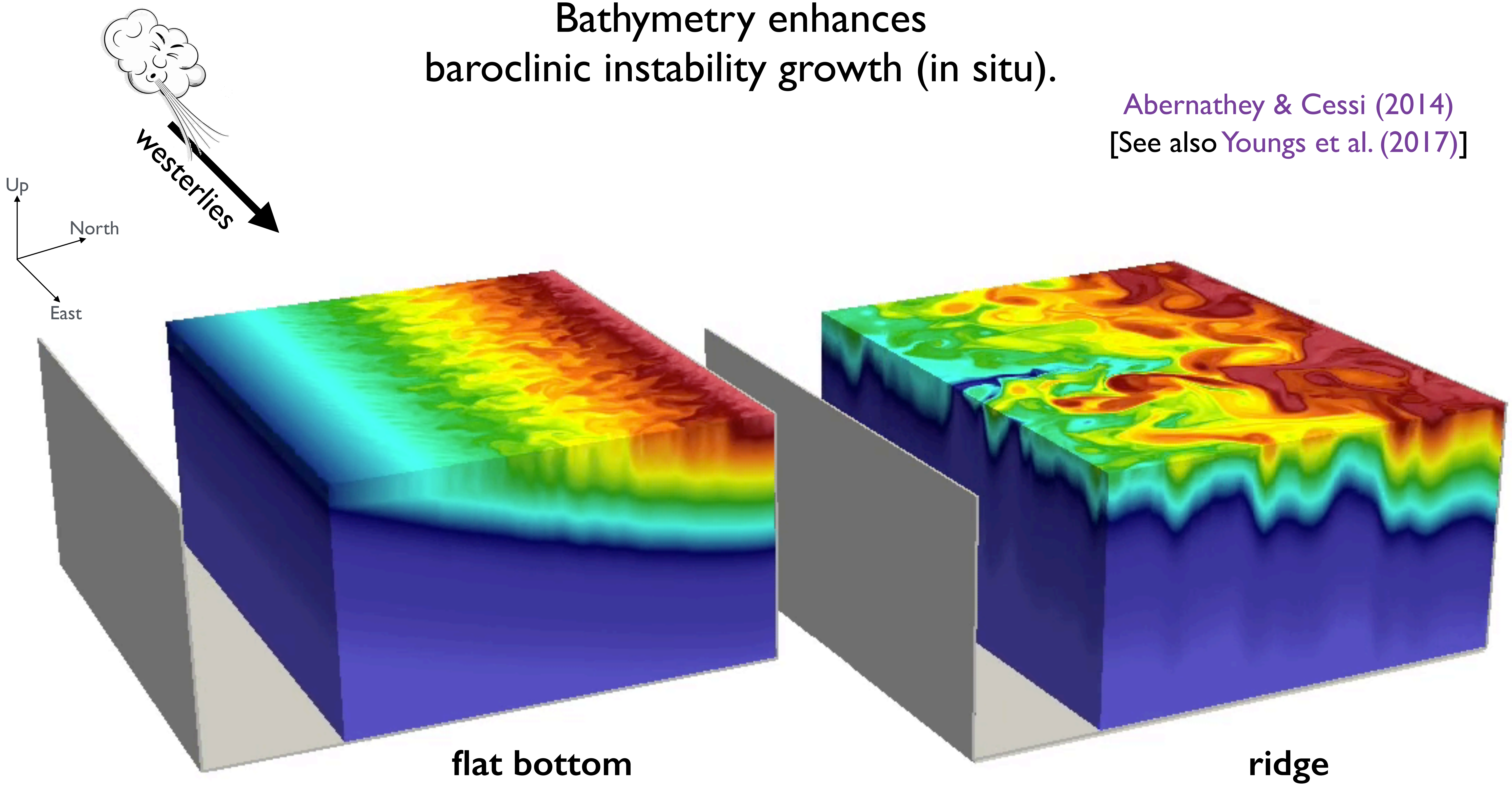
topographic form stress

wind stress

role of bathymetry II

Bathymetry enhances
baroclinic instability growth (in situ).

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



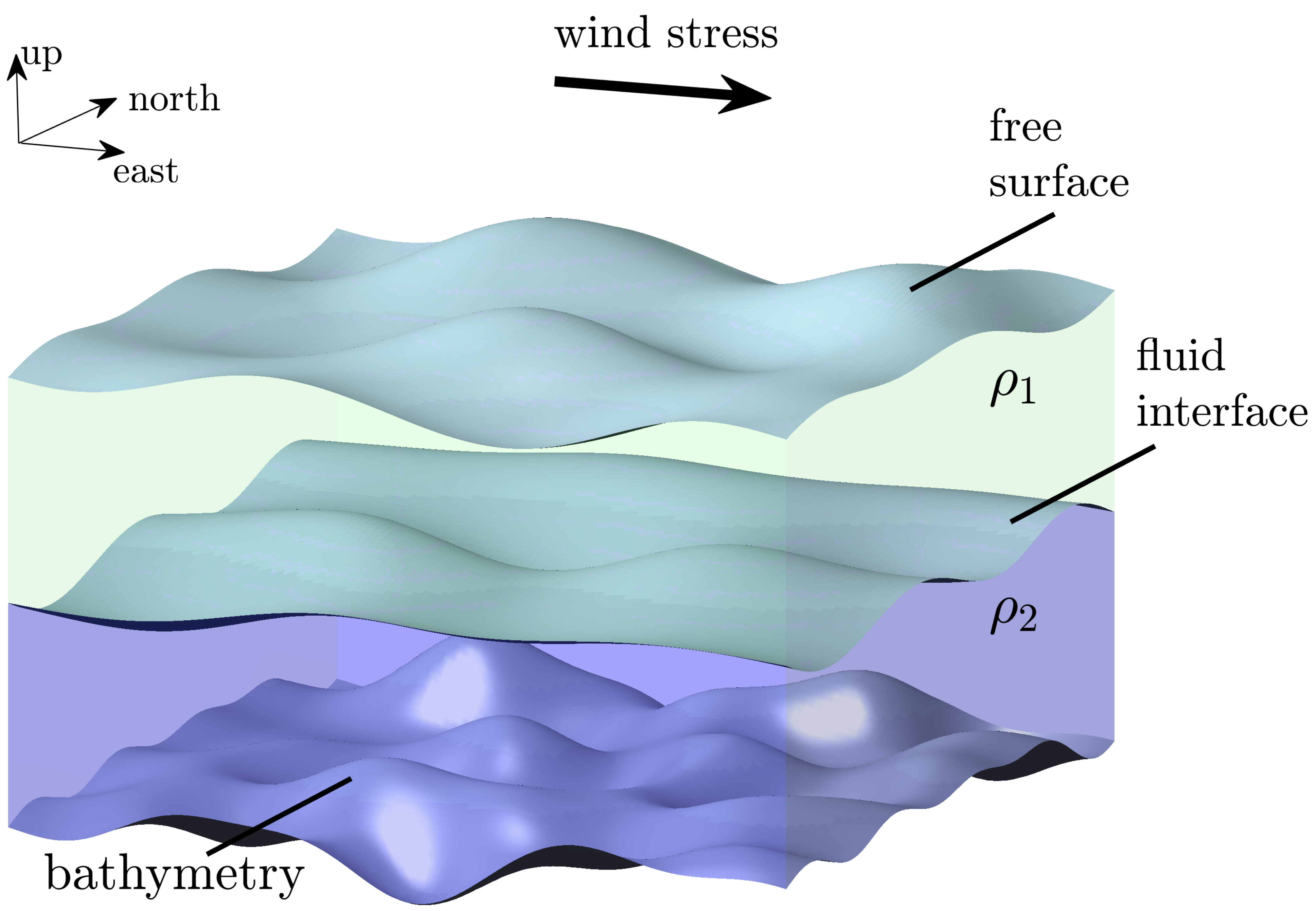
http://vimeo.com/55486114

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

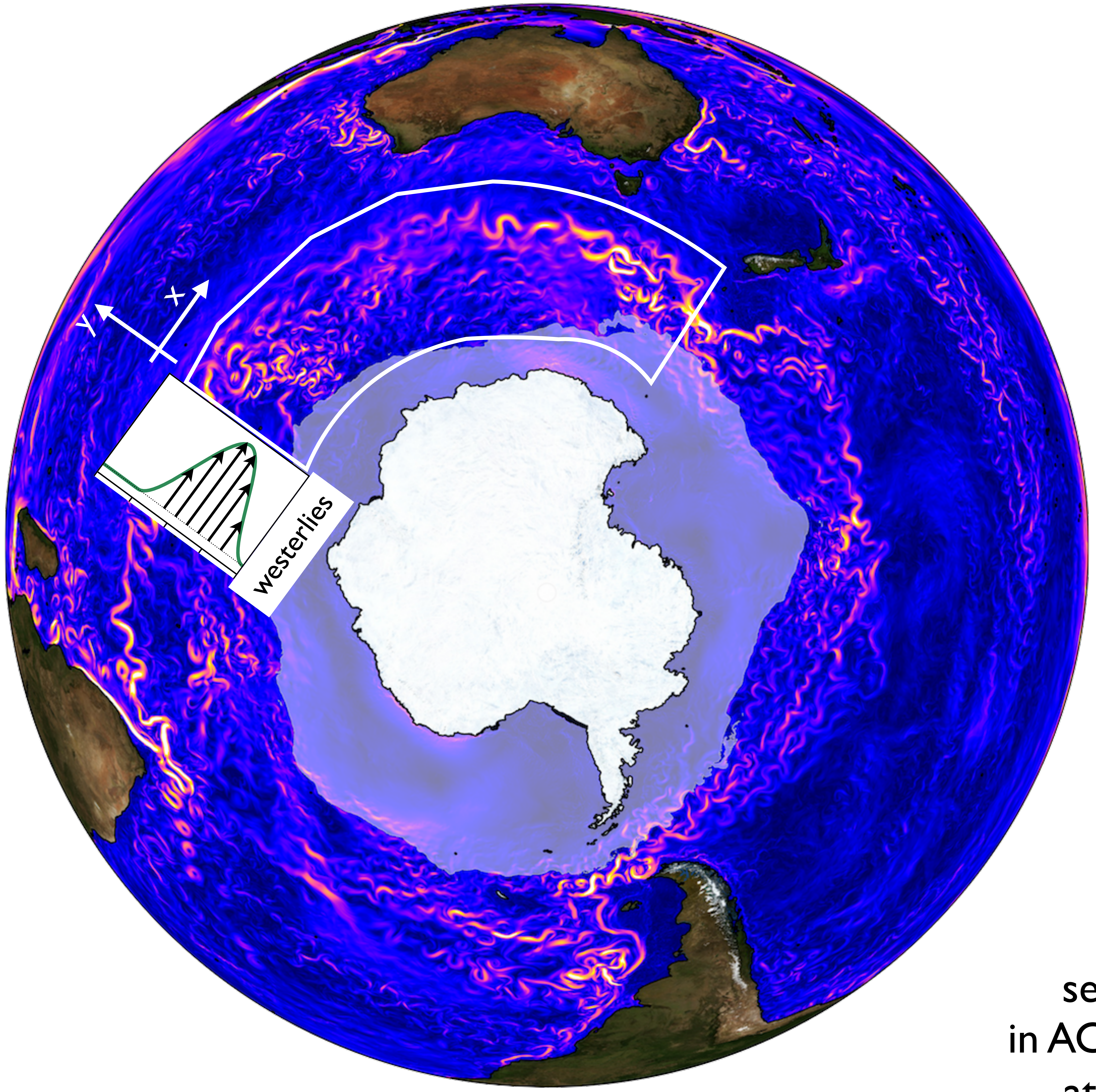
what's the plan

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

Use a model
with varying
number of fluid layers.

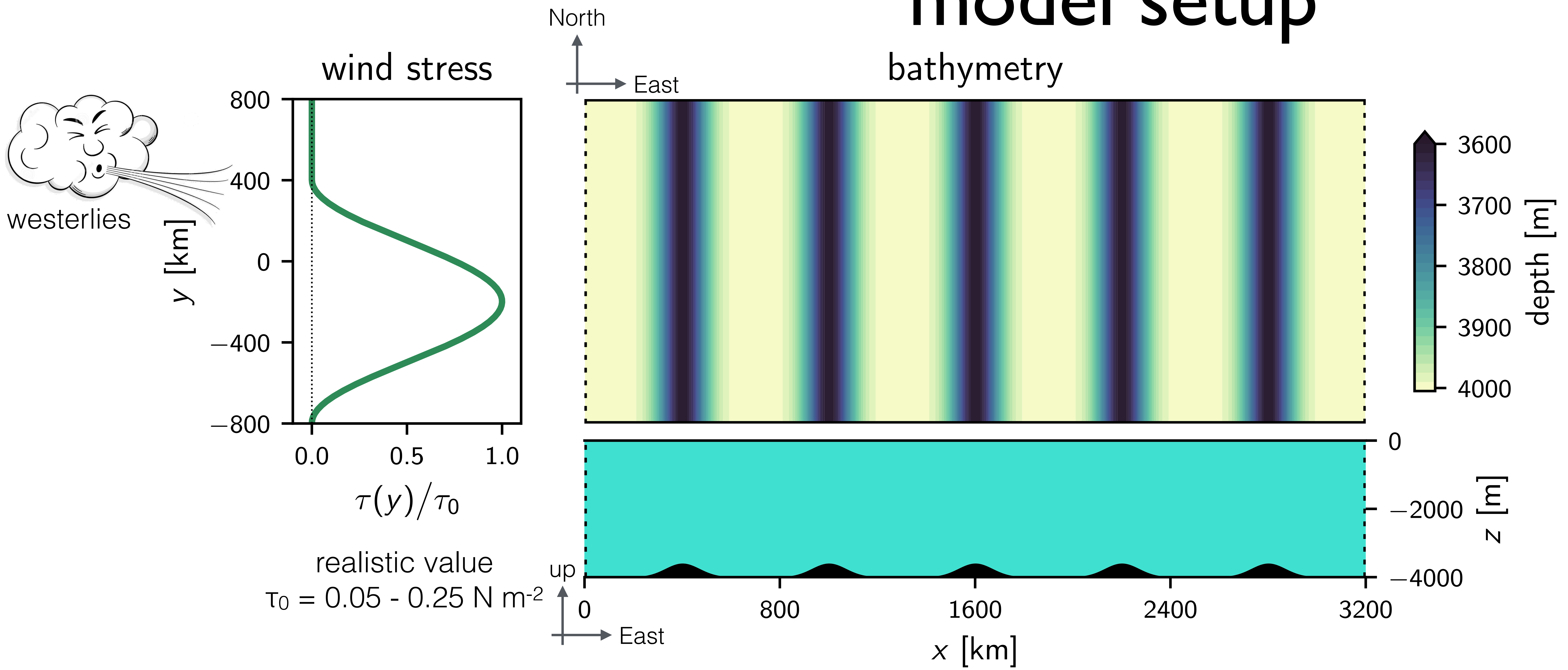


the "spherical-cow"-version of the Southern Ocean



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

model setup

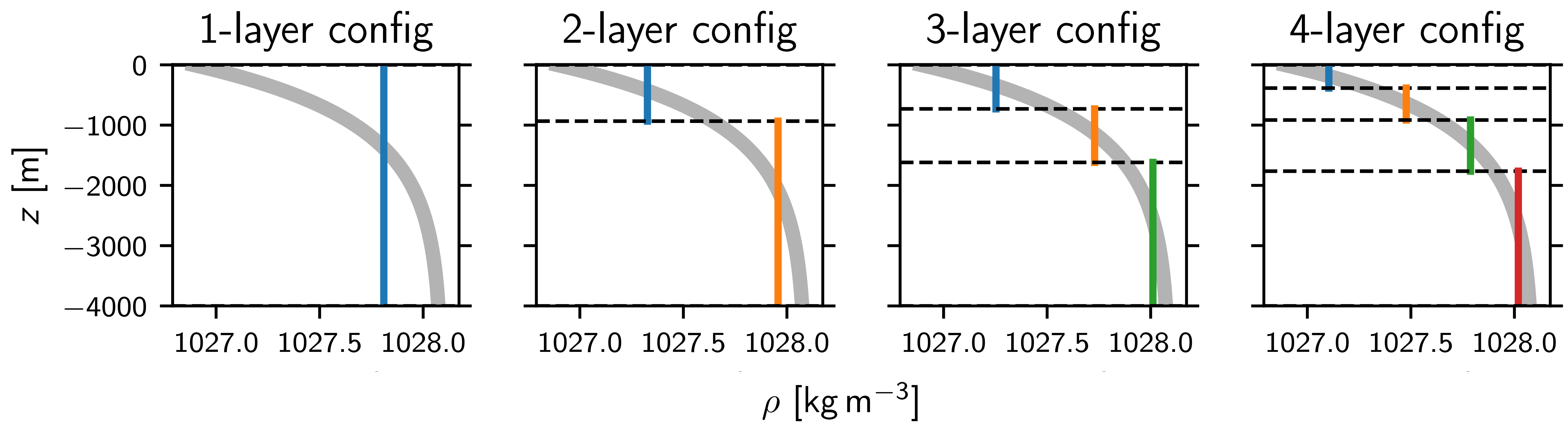


GFDL's MOM6 model
isopycnal coordinates/Boussinesq

Southern Ocean parameter values

no diapycnal motions
no buoyancy forcing

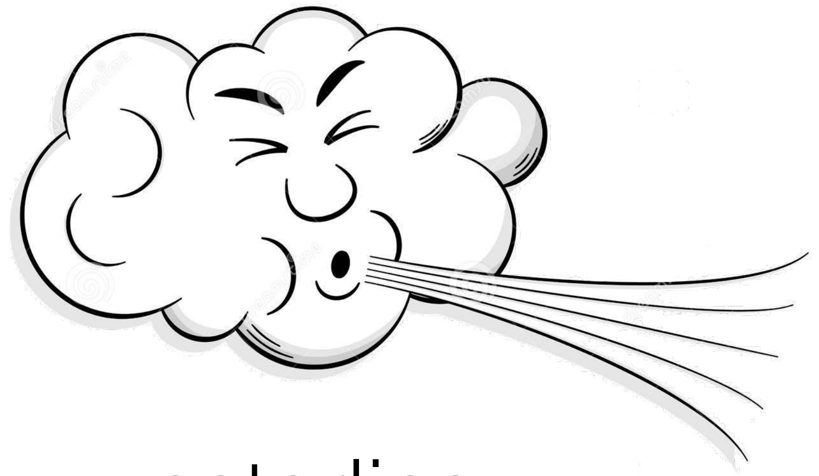
(some oceanographic-jargon; important is what's in **bold**)



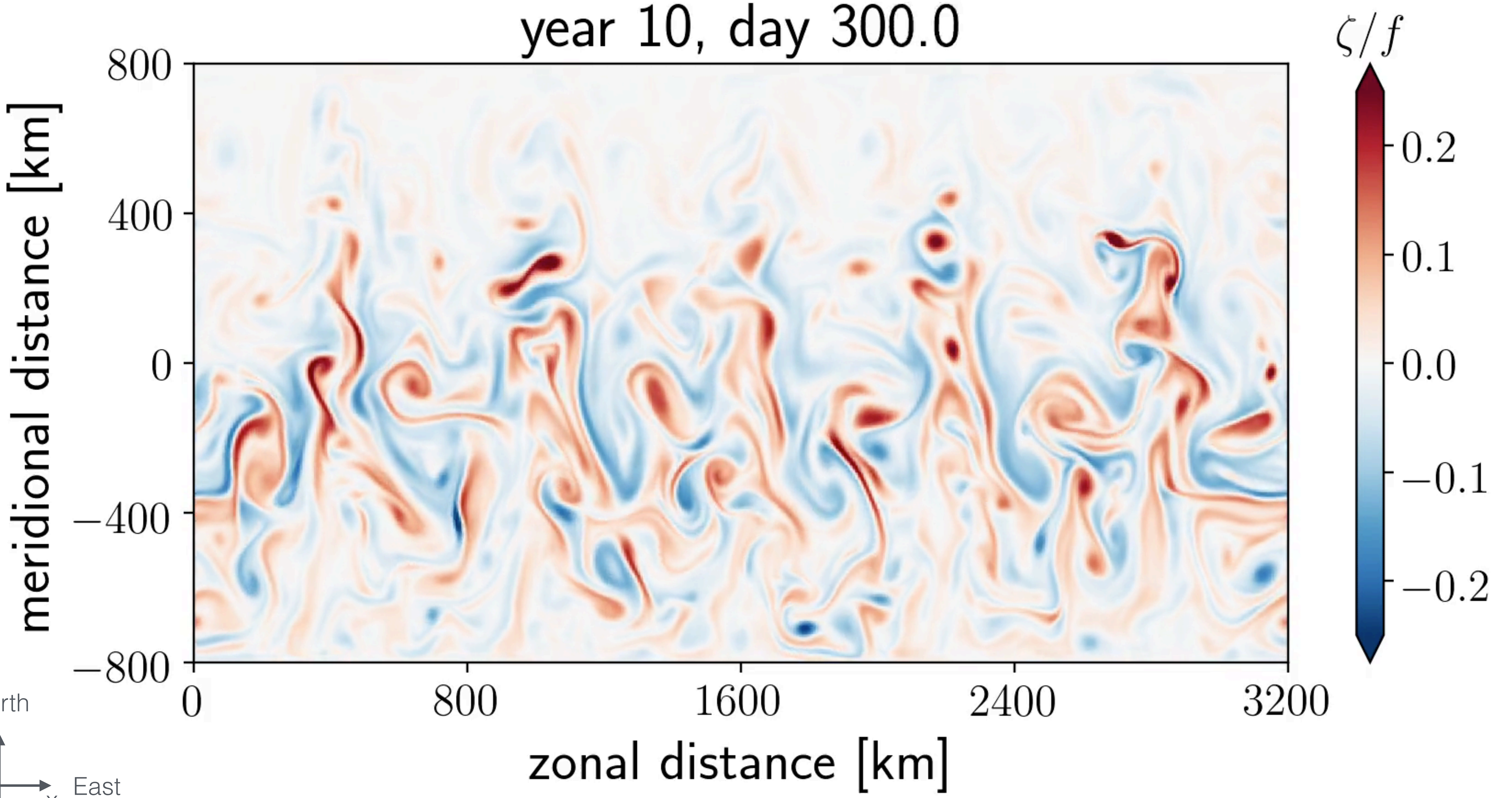
layered approximations

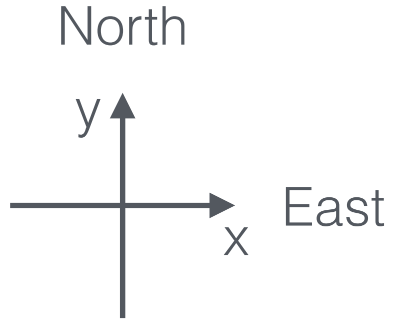
the "spherical-cow"-version of the ACC

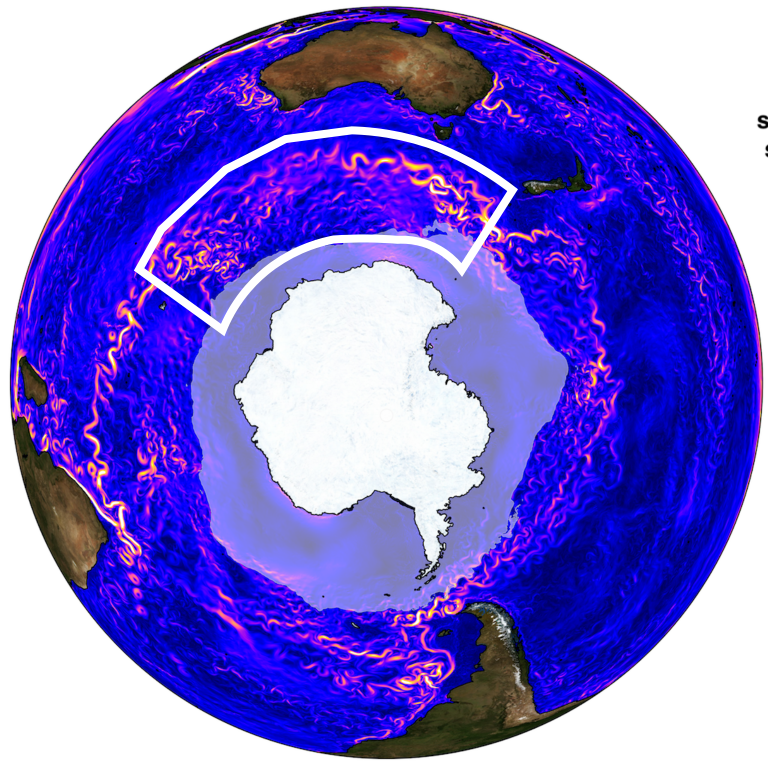
surface
relative vorticity
$\zeta = \partial_x v - \partial_y u$



westerlies
τ_0=0.2 N/m^2



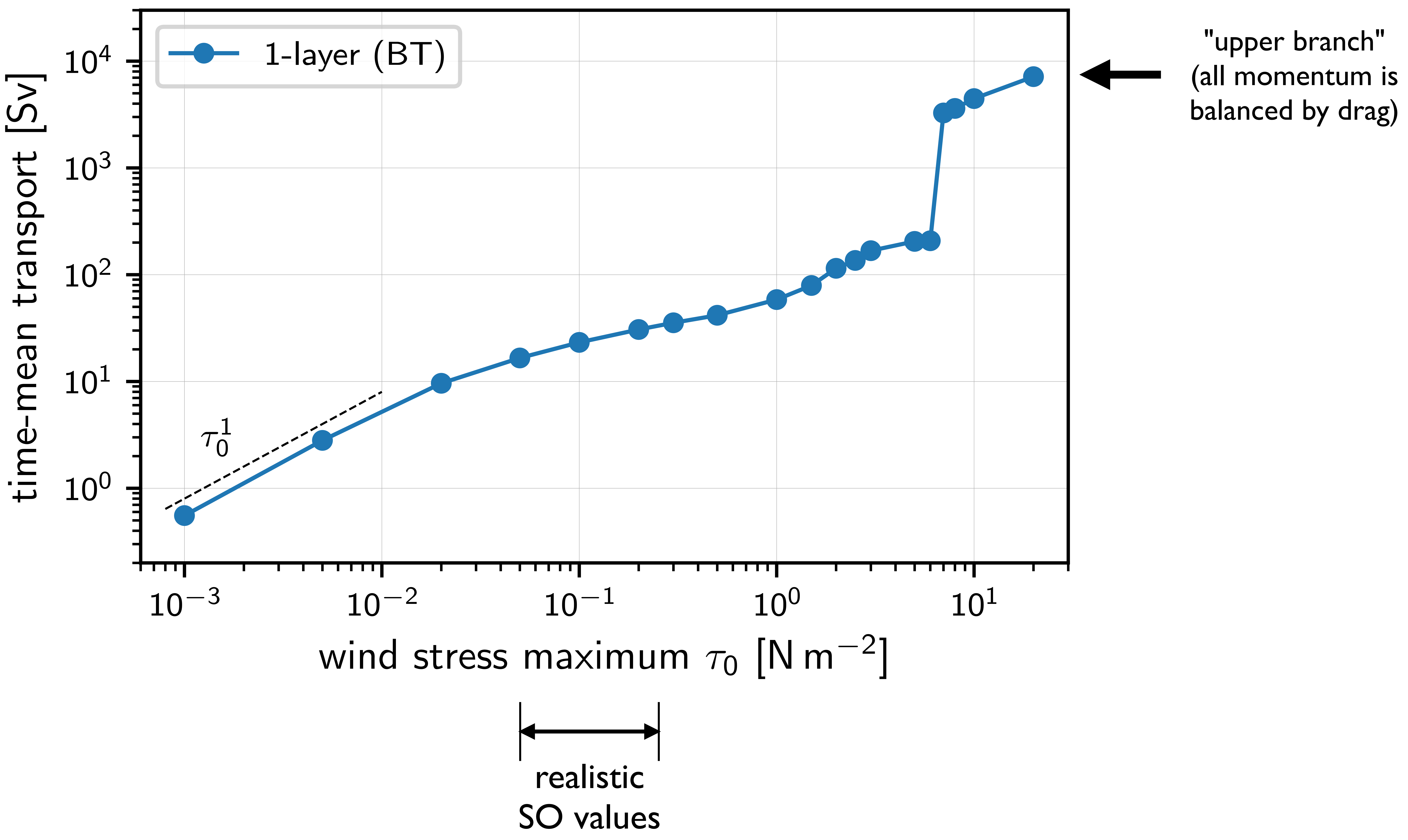




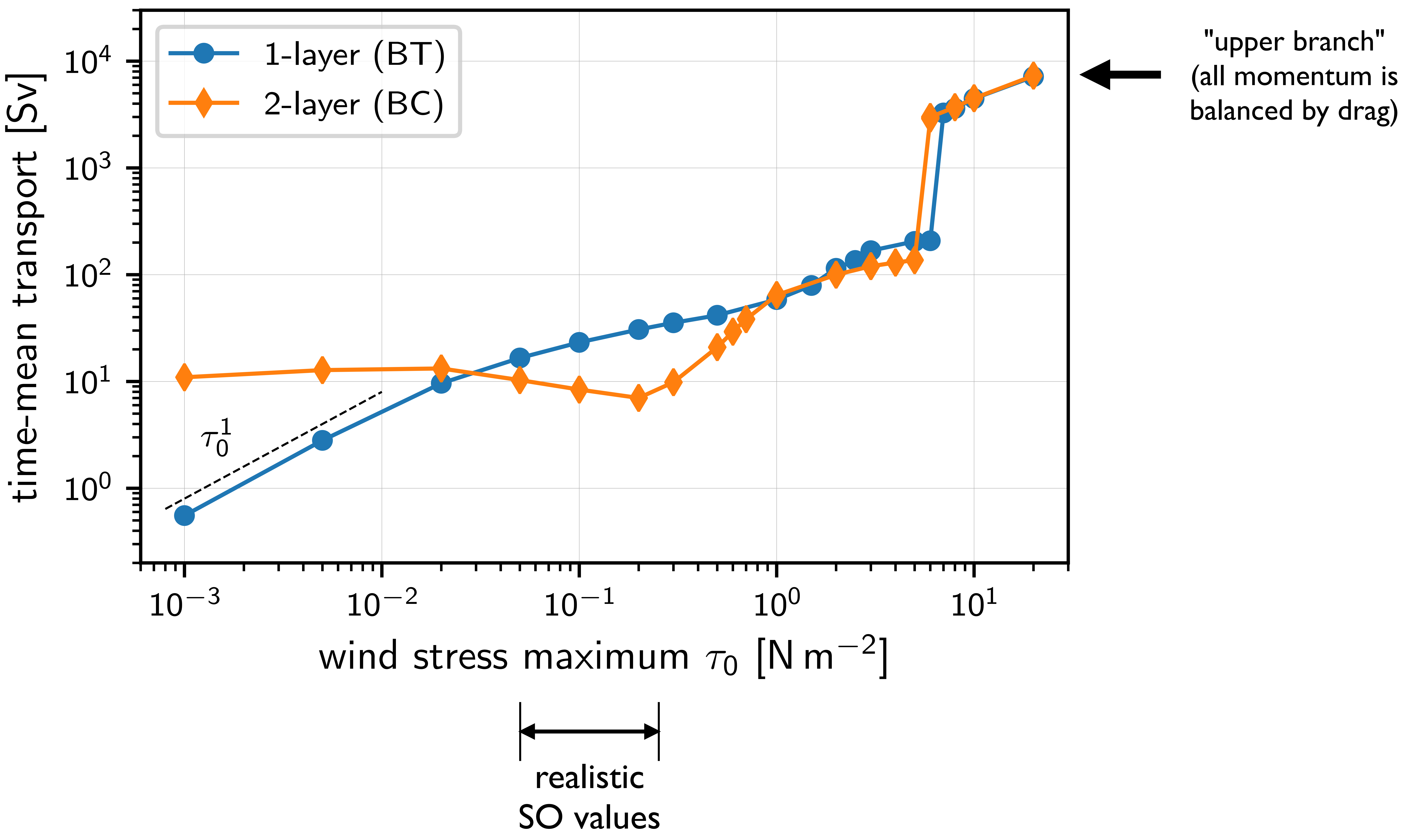
note the standing meander
(remember Amelie's talk on Tue)

vary the wind stress amplitude τ_0
and see how the time-mean zonal transport changes

mean ACC transport Vs wind stress



mean ACC transport Vs wind stress



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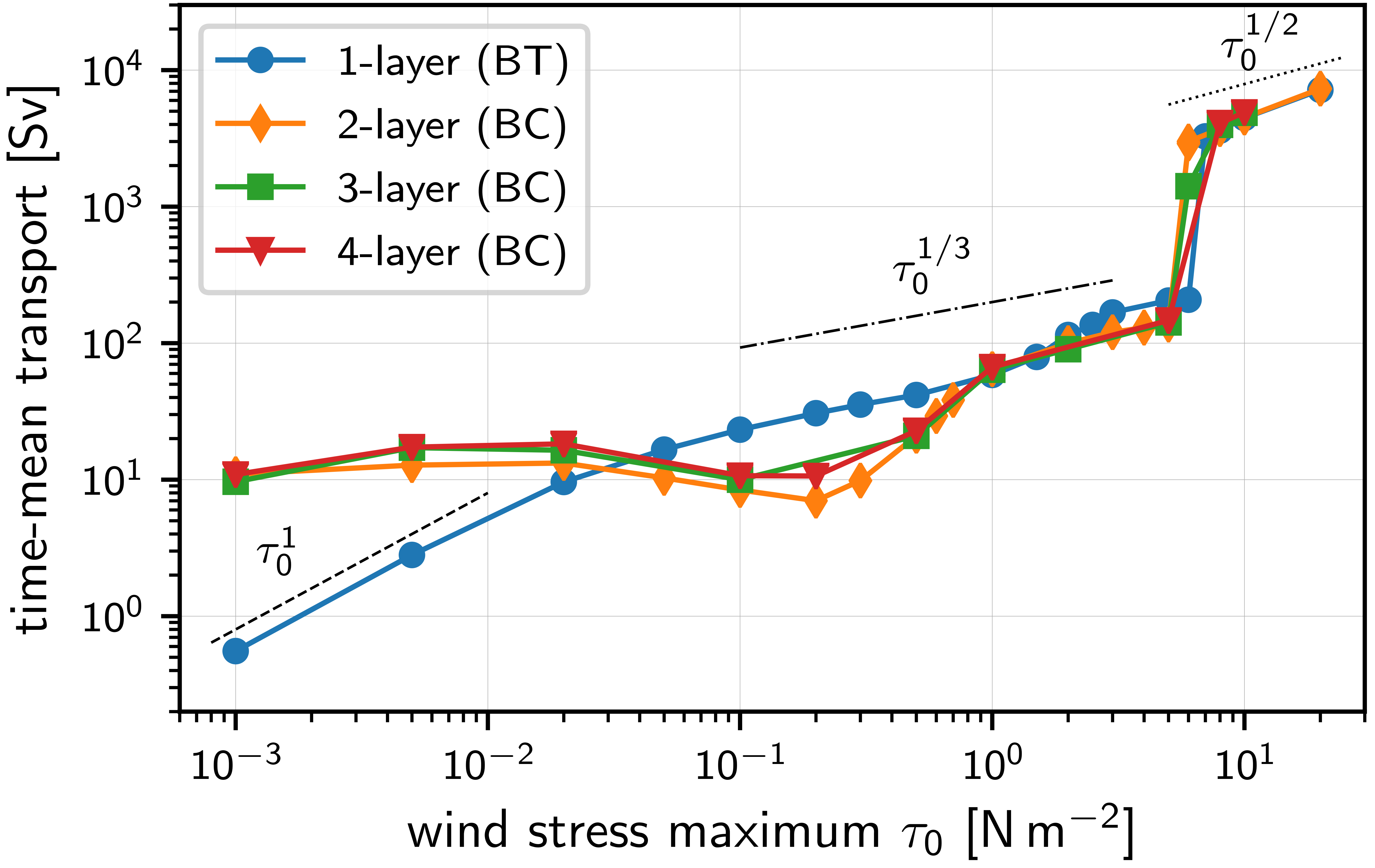
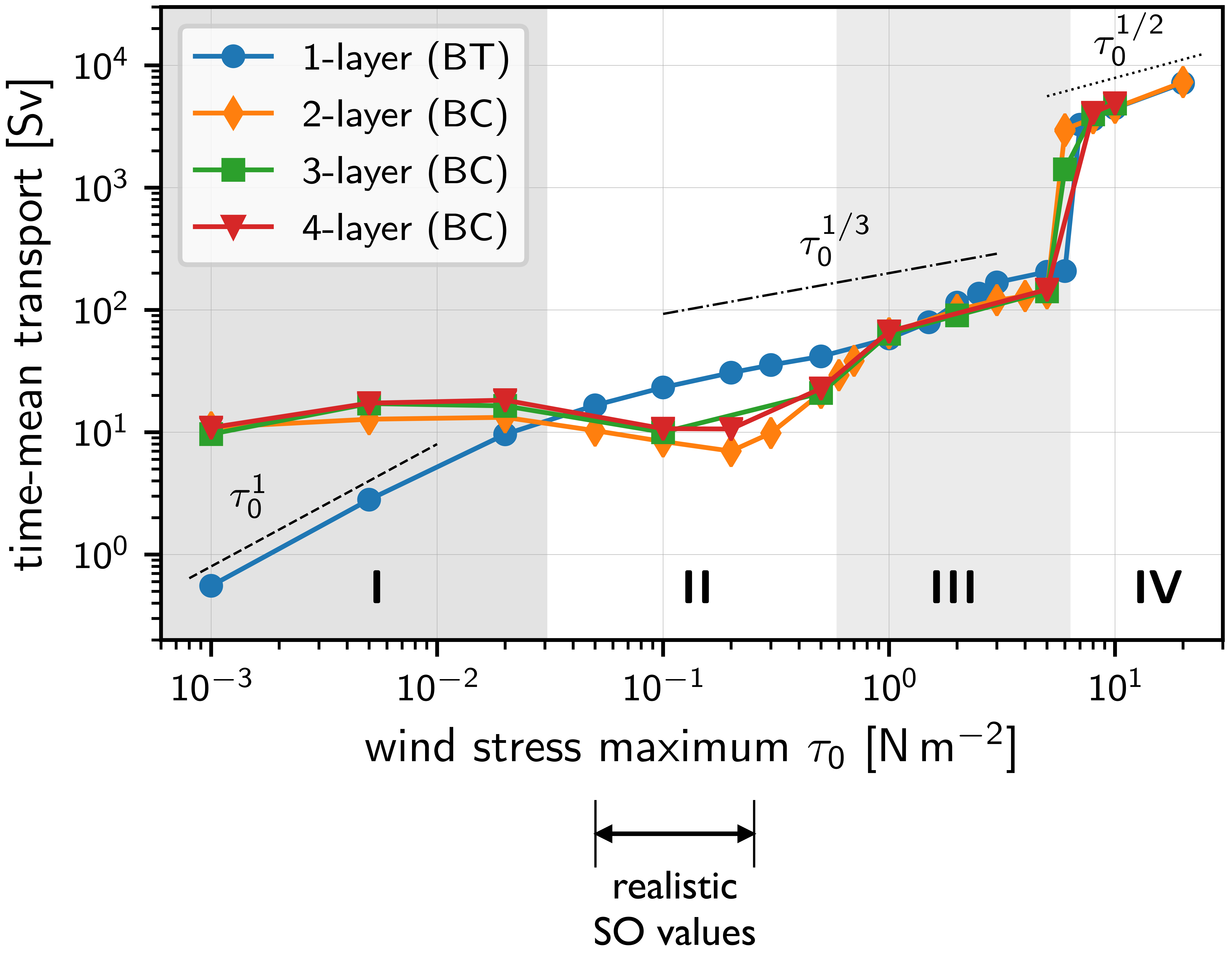


>3-layer configurations are the same as 2-layers

(as fas as the mean zonal transport is concerned)

mean ACC transport Vs wind stress



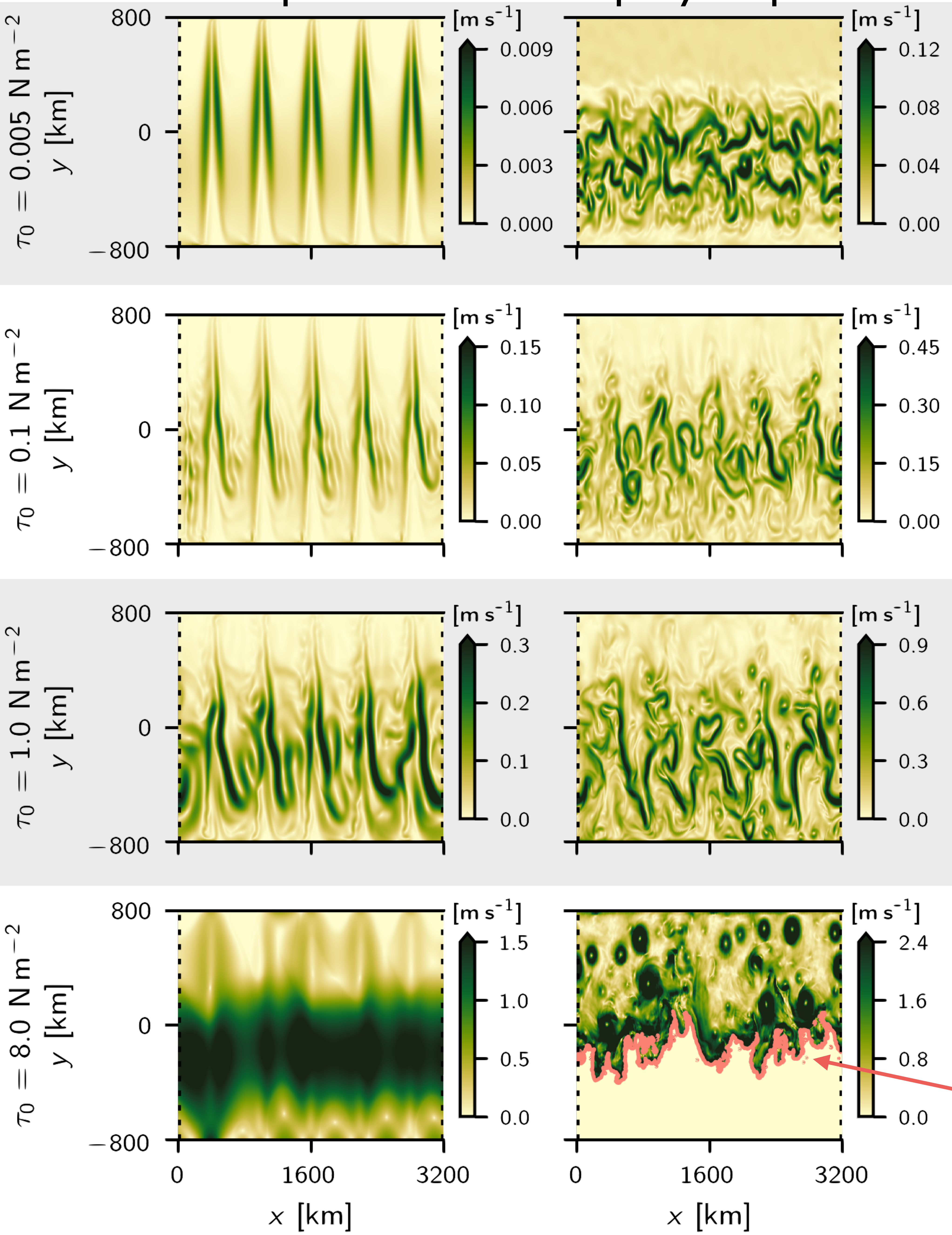
four
distinct
flow
regimes

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

yeap, this slide is too much

1-layer config speed

2-layer config top-layer speed



I

BT: weak steady flow following *f*/*h* contours

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

II

BT: transients develop; flow steered by *f*/*h*

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

III

BT: transients develop; flow steered by *f*/*h*

BC: signature of bathymetry appears in top-layer flow

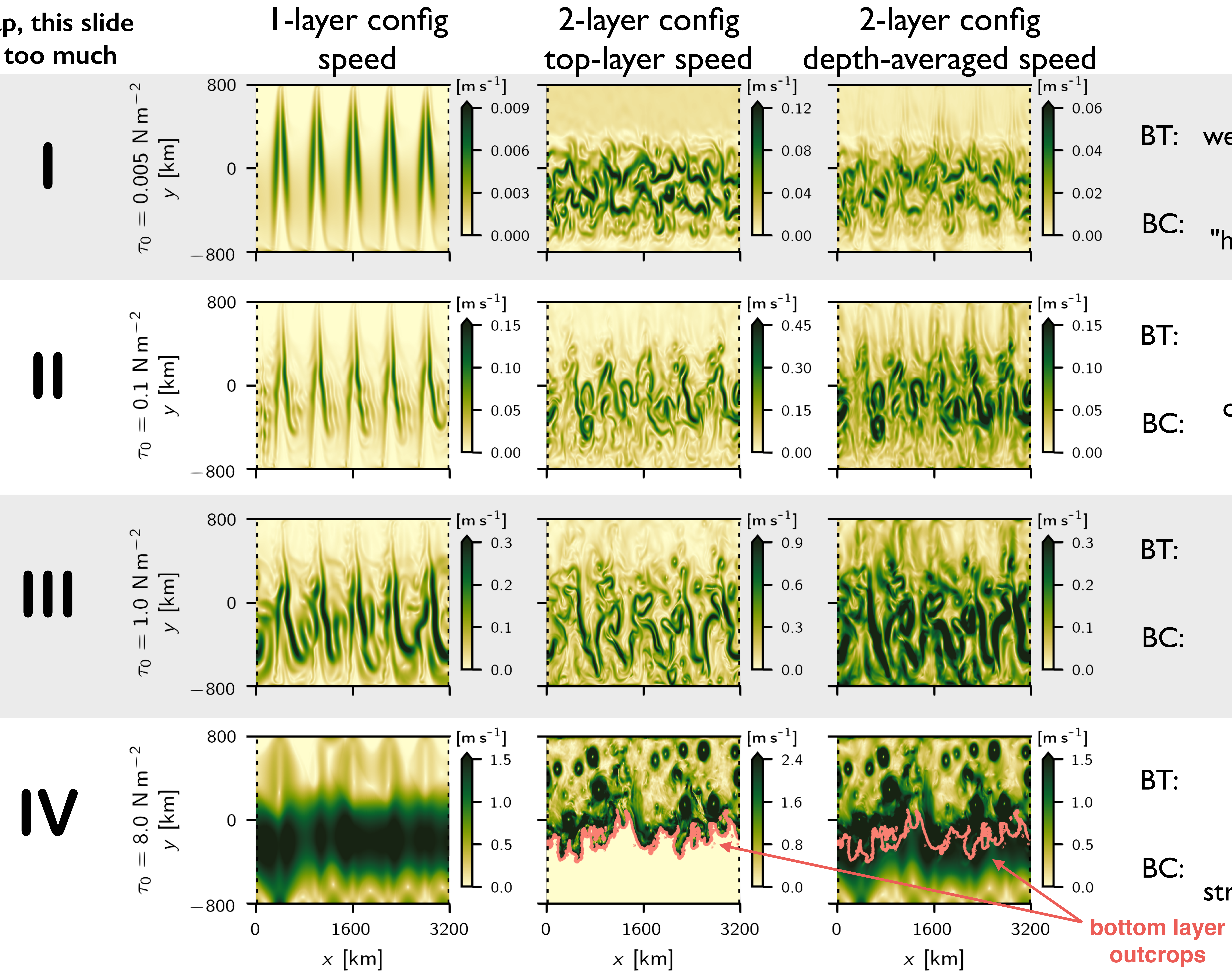
IV

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



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BC: signature of bathymetry appears in top-layer flow

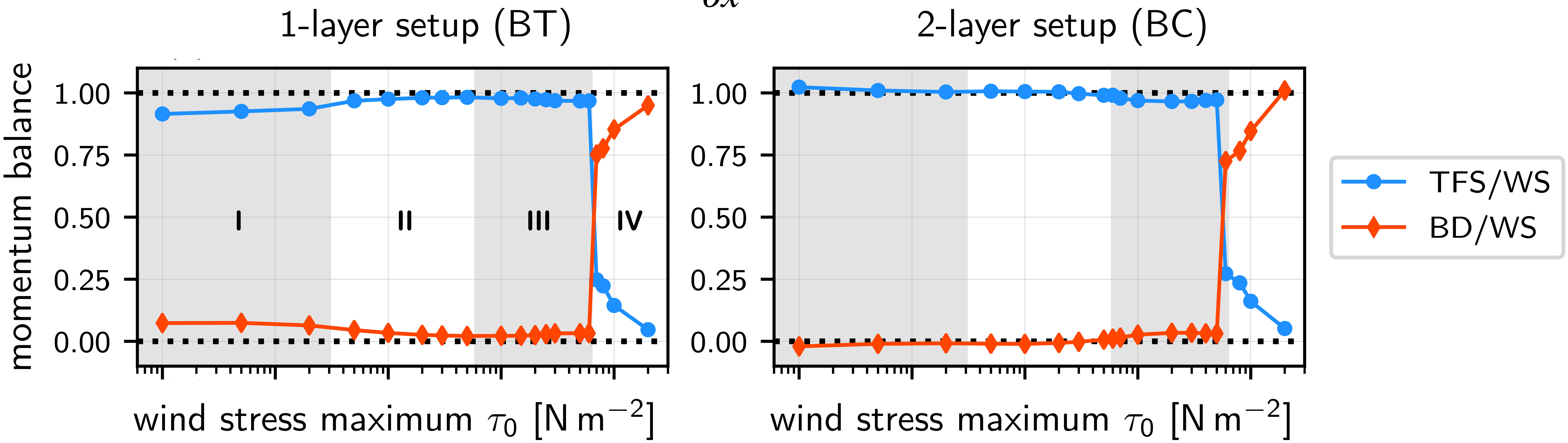
BT: a strong jet develops

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

depth-integrated time-mean zonal momentum balance

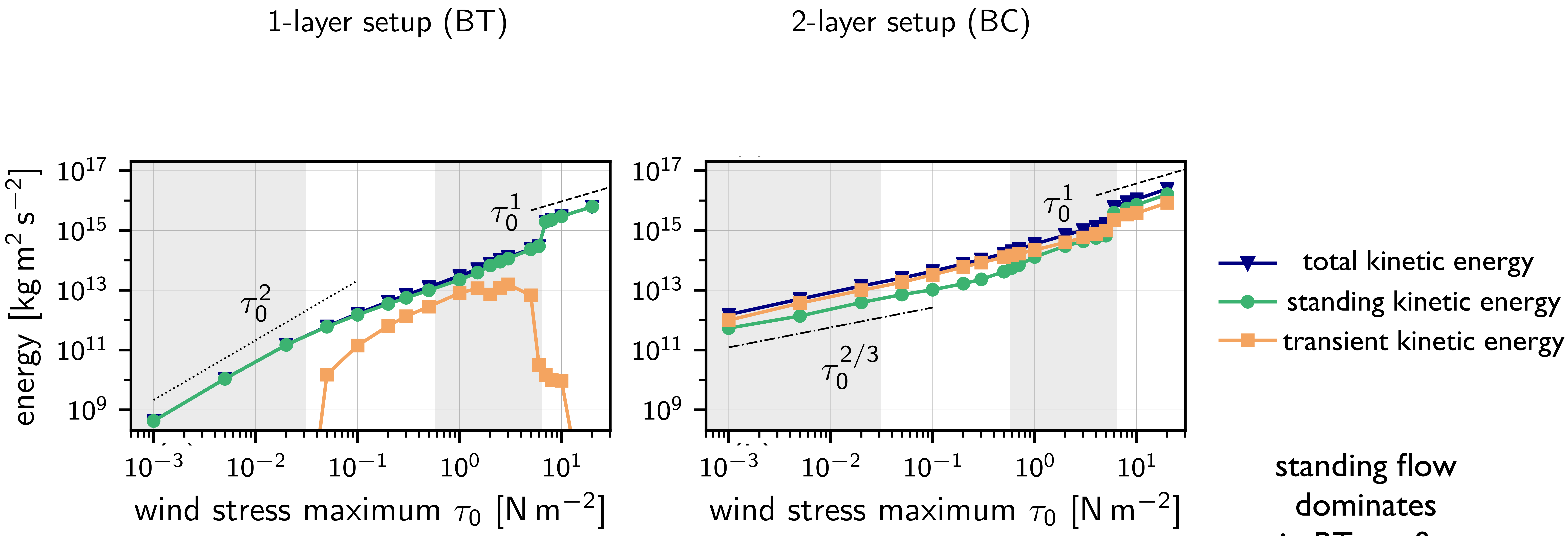
wind stress (WS) = topographic form stress (TFS) + bottom drag (BD)

$$\text{TFS} \propto p_{\text{bot}} \frac{\partial h_{\text{bot}}}{\partial x}$$



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

standing–transient kinetic energy decomposition



BT config
has transients
only in II & III

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

$\langle \quad \rangle$: horizontal average

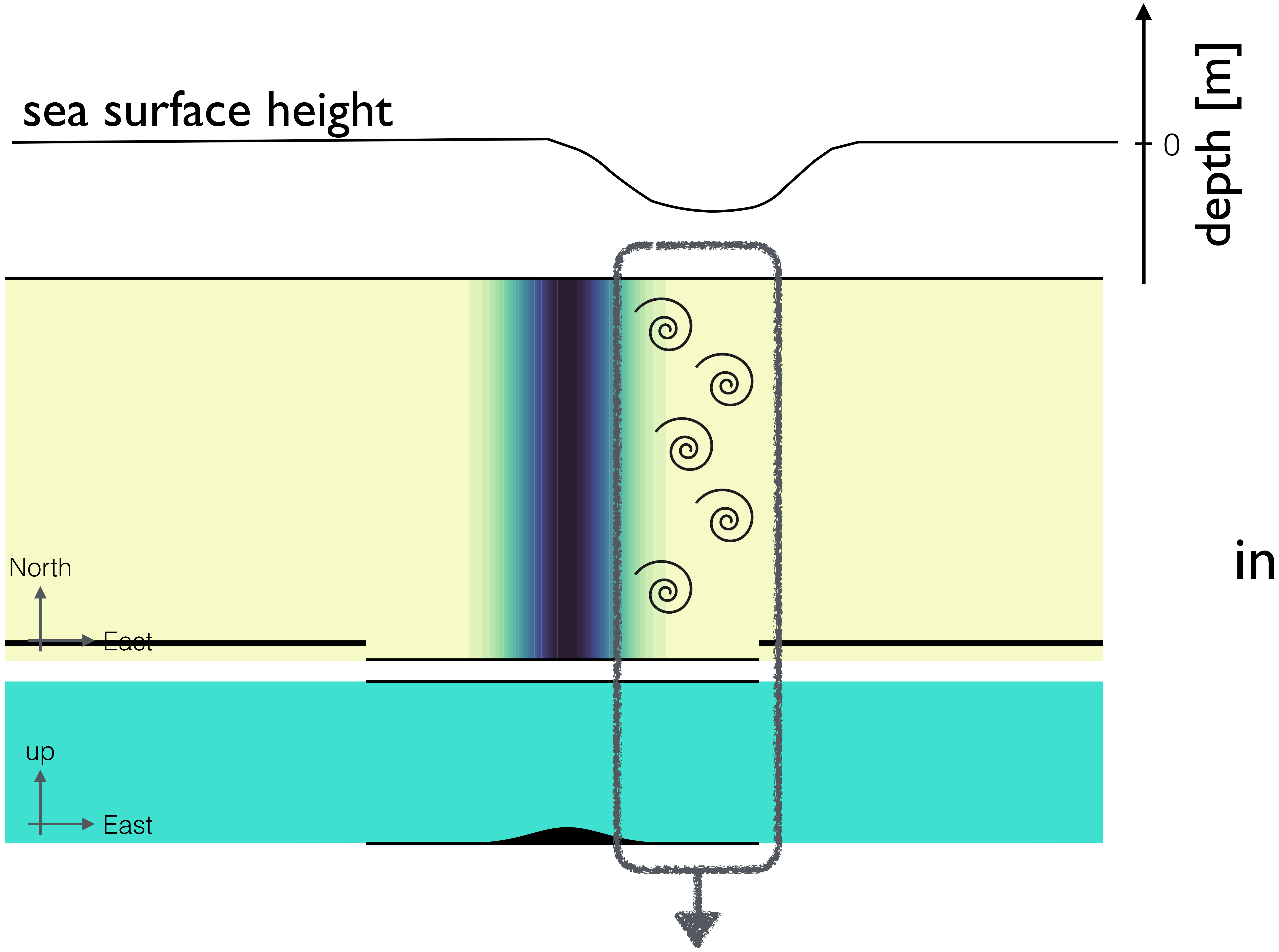
$\overline{\quad}$: time average

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

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

$$\langle \overline{p_{\mathrm{bot}}}\, \partial_x h_{\mathrm{bot}} \rangle$$

[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?

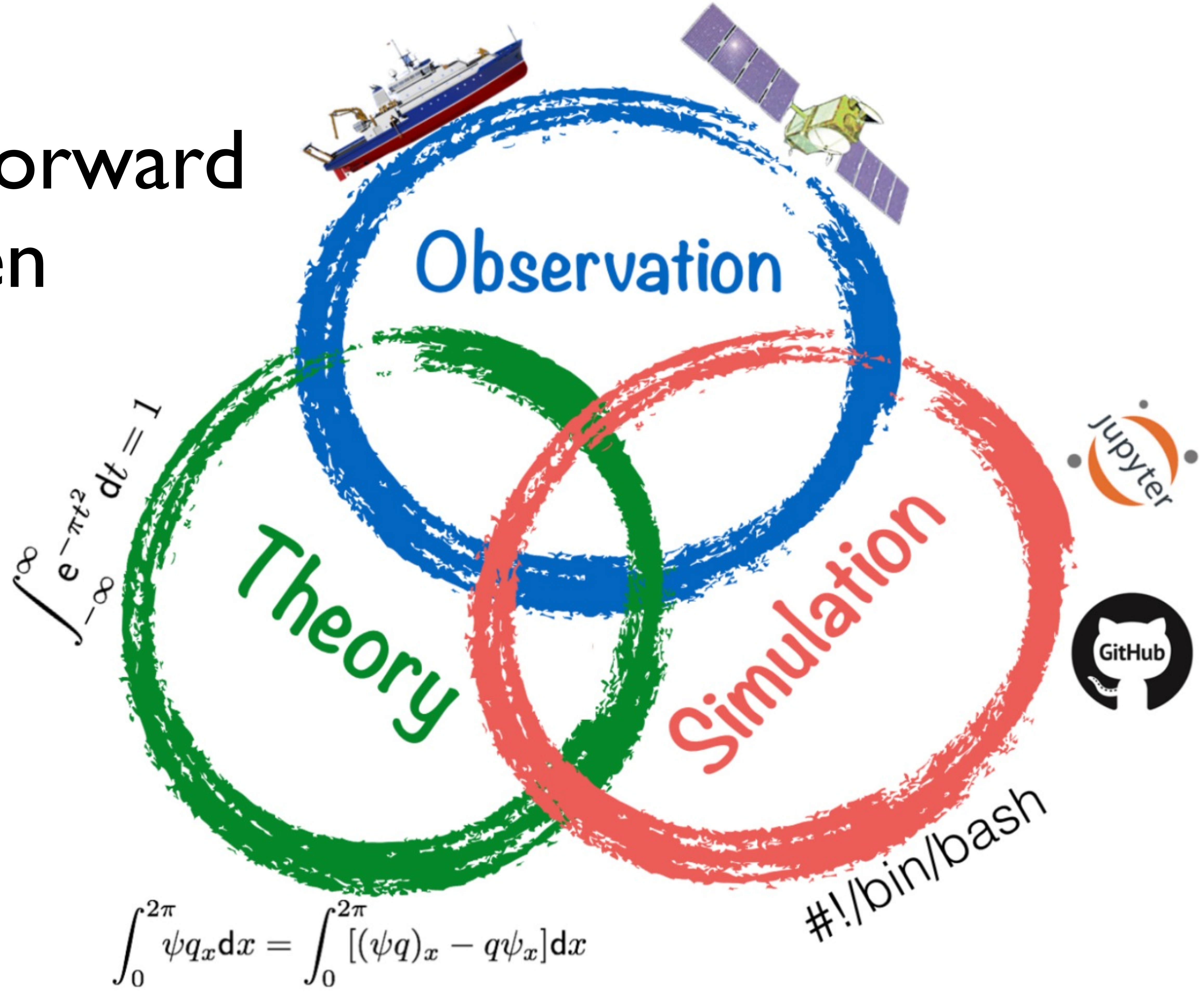
use SAMx perturbation experiments?

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]

work together in unison

let's try to reduce this gap