Barotropic versus Baroclinic eddy saturation: implications to Southern Ocean dynamics

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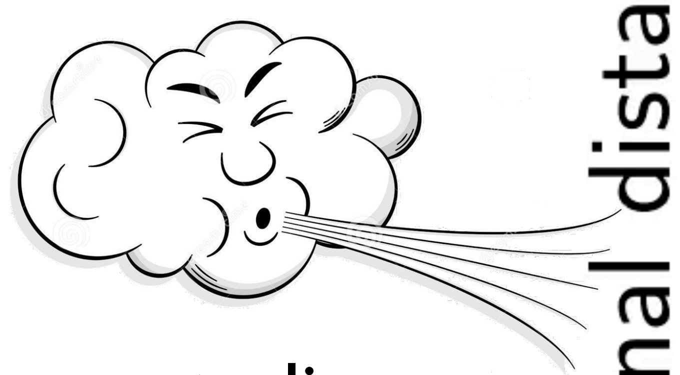
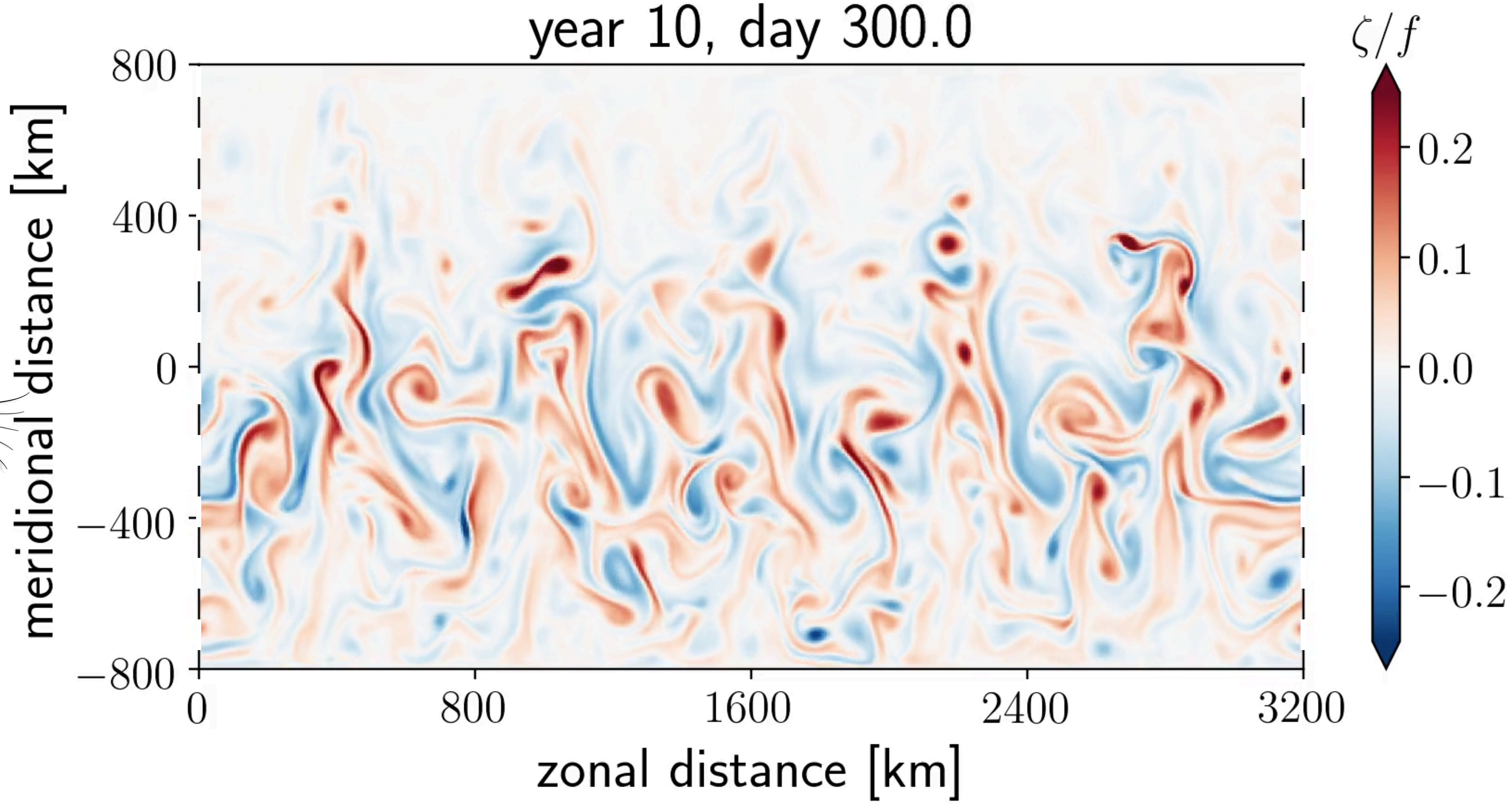
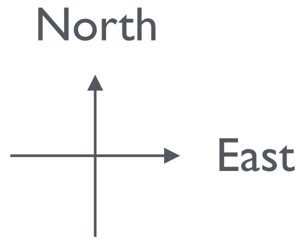
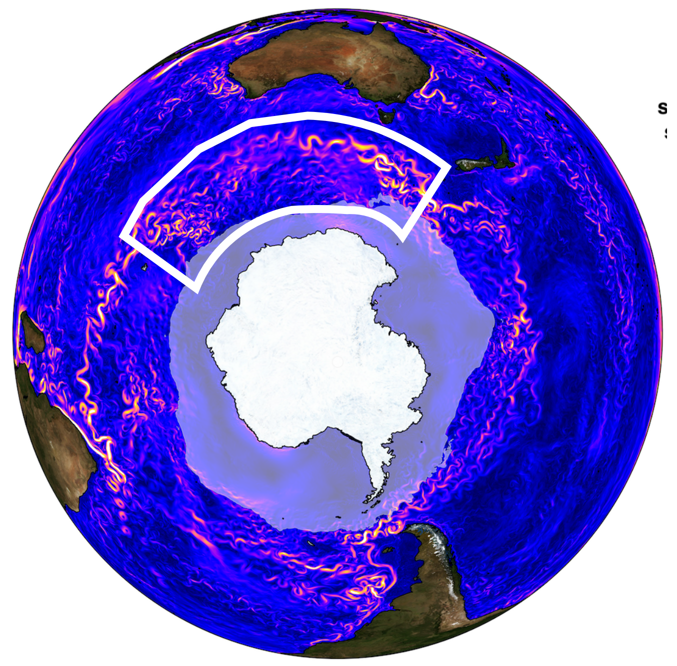


westerlies



top-layer
relative vorticity
$\zeta = \partial_x v - \partial_y u$



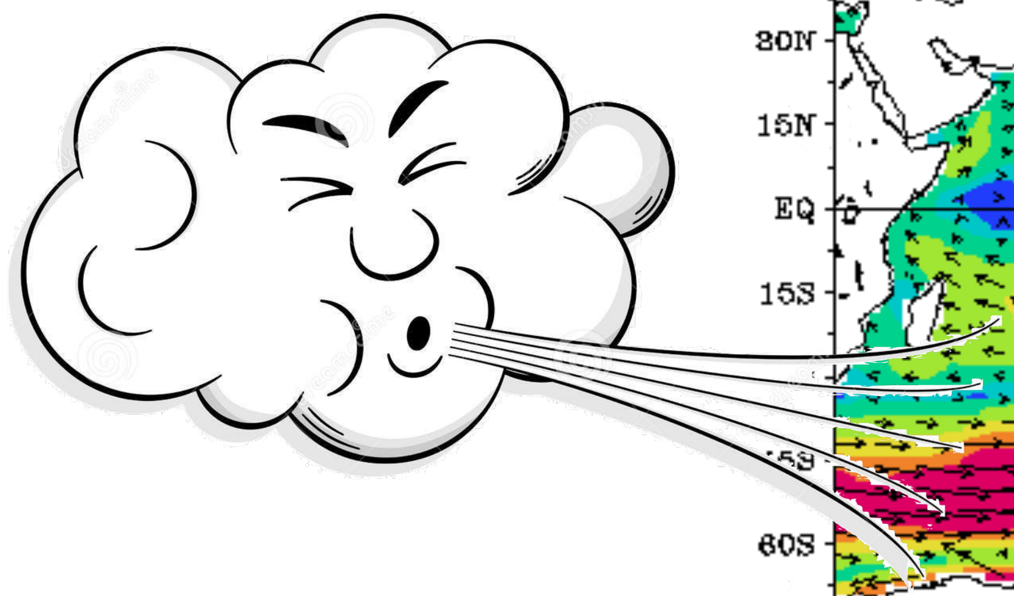


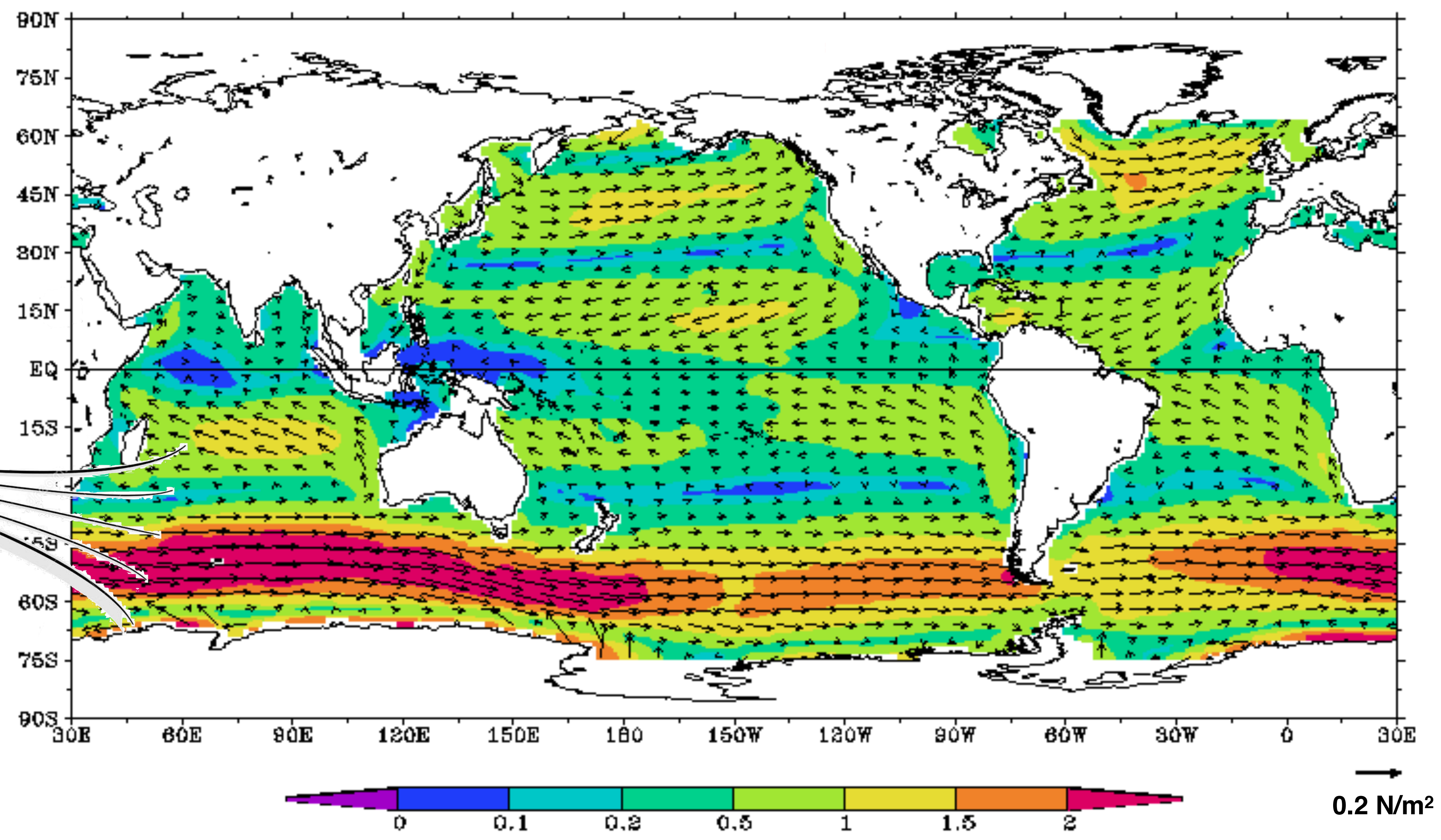
GFD Summer Program
Walsh Cottage — July 9th, 2019

what drives the Antarctic Circumpolar Current?

Climate Prediction Center

GODAS Wind Stress, 1982-2004 Annual

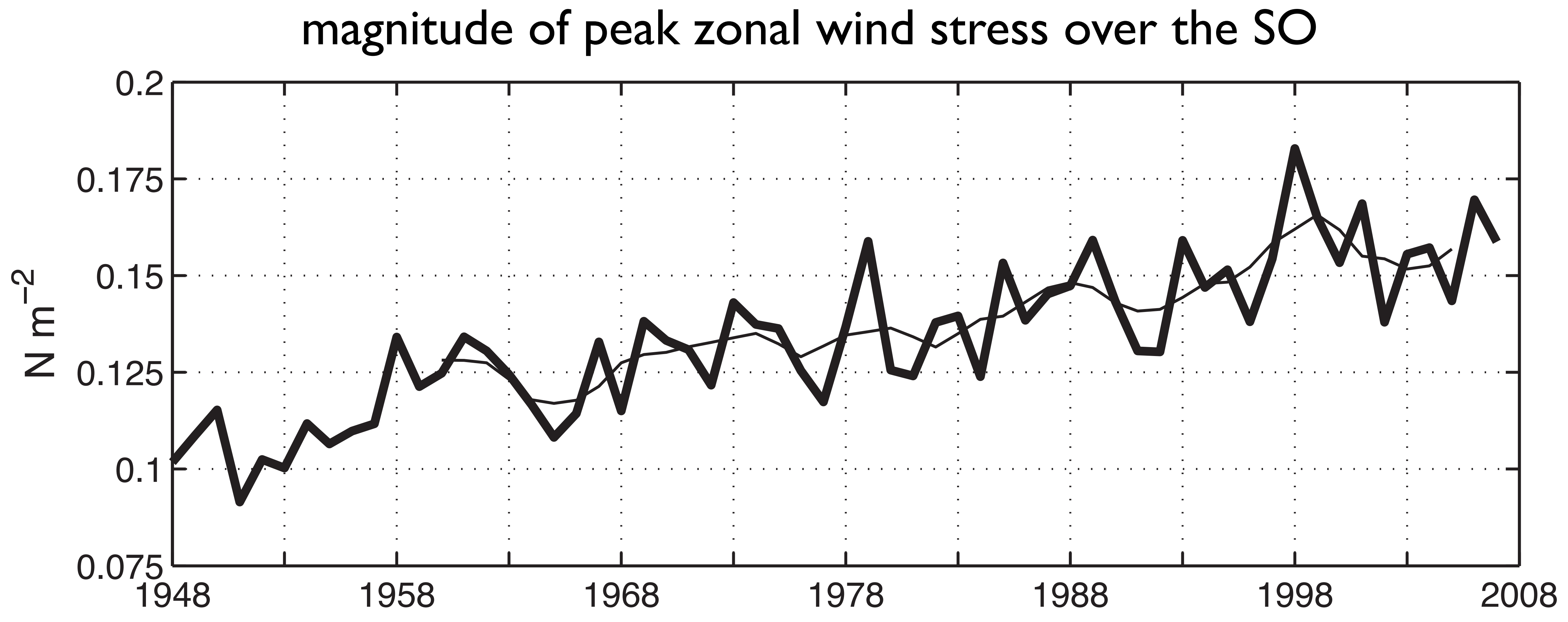




strong westerly winds blow over the Southern Ocean transferring momentum through wind stress at the surface

how is this momentum balanced?

winds over the Southern Ocean are getting stronger



Farneti et al. 2015
results from
inter-annual
CORE-II simulations

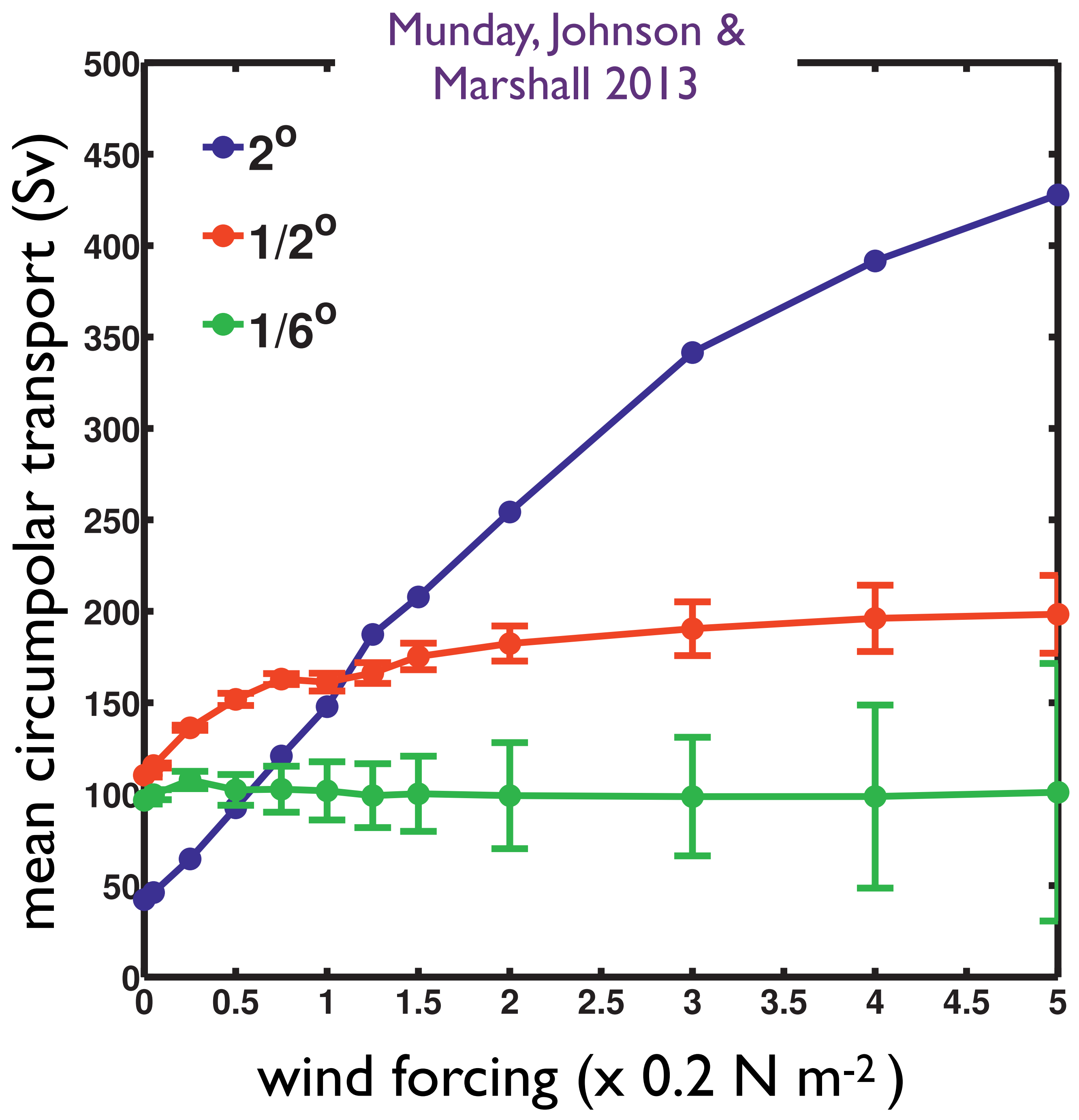
how will the Antarctic Circumpolar Current (ACC) respond?

does doubling the winds imply double ACC the transport?

not always — "eddy saturation"

but first, what is "eddy saturation"?

The *insensitivity* of the total ACC volume transport to wind stress increase.



higher resolution → eddy saturation "occurs"

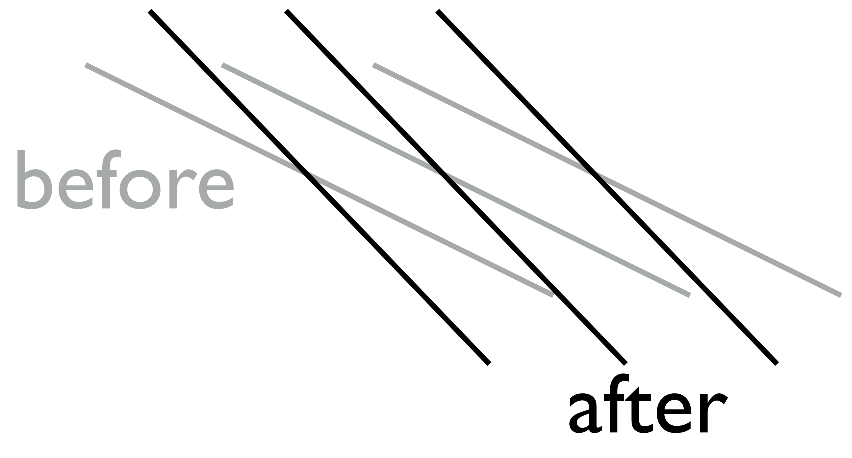
Eddy saturation was theoretically predicted by Straub (1993) with an *entirely* baroclinic argument.

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

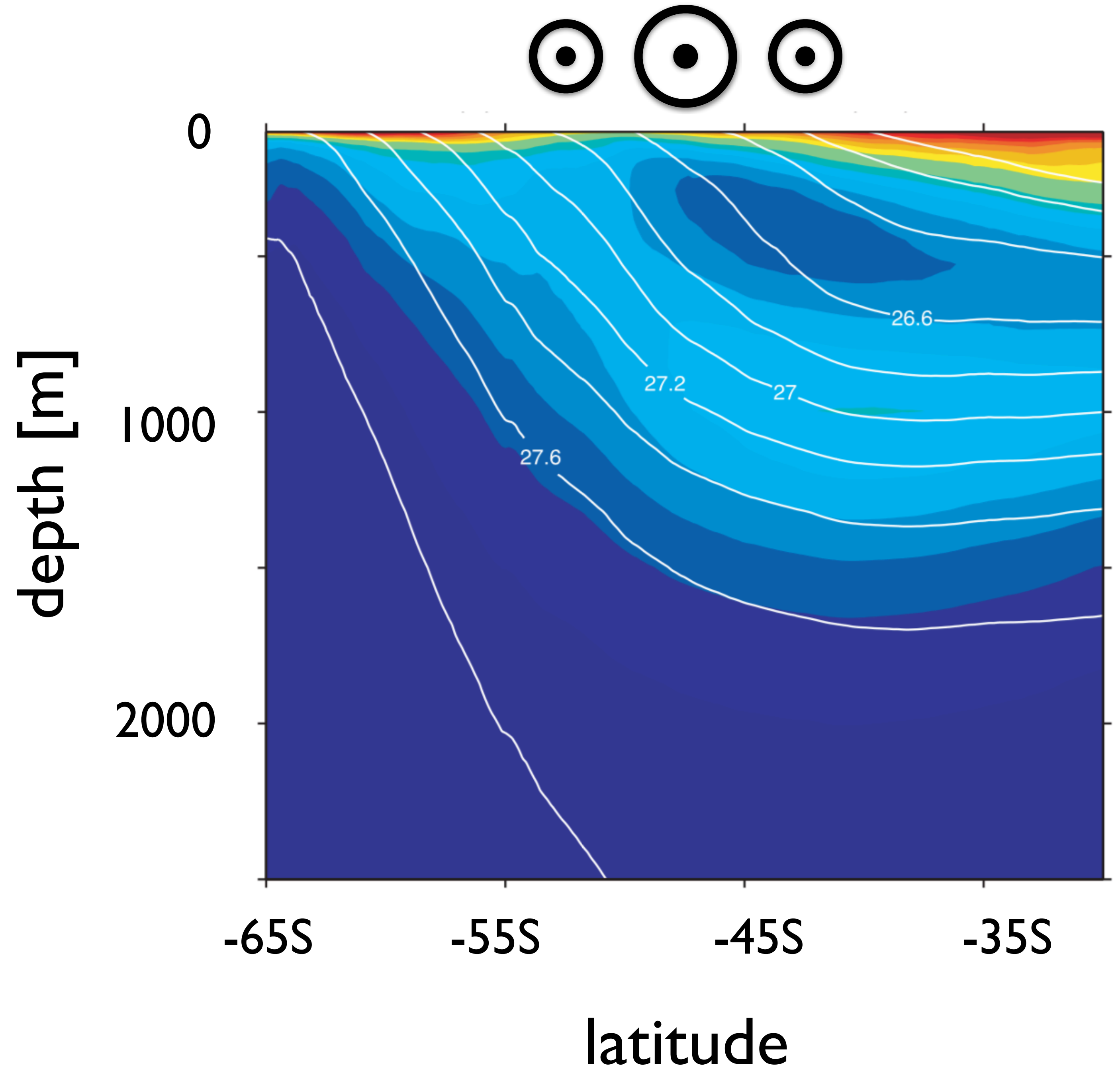
[Other examples: Hallberg & Gnanadesikan 2001, Tansley & Marshall 2001, Hallberg & Gnanadesikan 2006, Hogg et al. 2008, Nadeau & Straub 2009, 2012, Farneti et al. 2010, Meredith et al. 2012, Morisson & Hogg 2013, Abernathey & Cessi 2014, Farneti et al. 2015, Nadeau & Ferrari 2015, Marshall et al. 2017.]

how baroclinic eddies lead to eddy saturation?

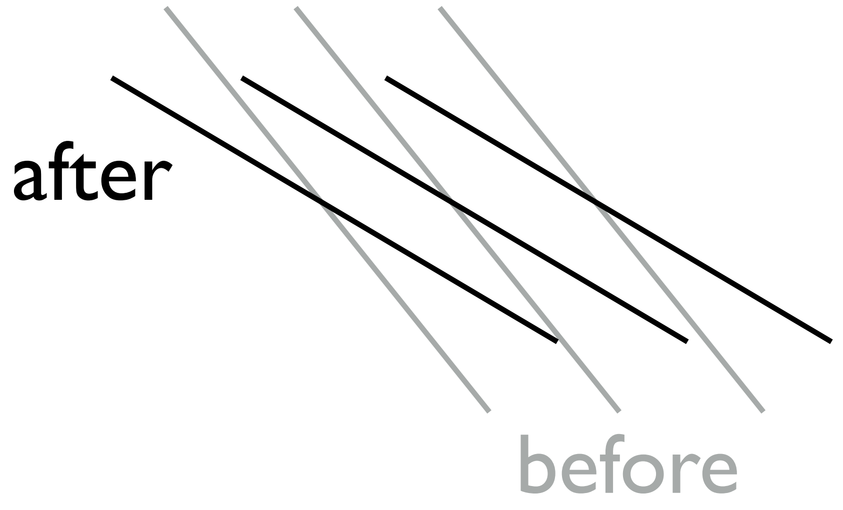
wind increase
slopes the isopycnals



westerly winds



baroclinic eddies
restratify isopycnals



role of bathymetry?

role of bathymetry I

Momentum balance in the Southern Ocean is
"applied at the bottom [...] where ridges lie." Munk & Palmen (1951)

topographic form stress

role of bathymetry I

Momentum balance in the Southern Ocean is
"applied at the bottom [...] where ridges lie." Munk & Palmen (1951)

topographic form stress

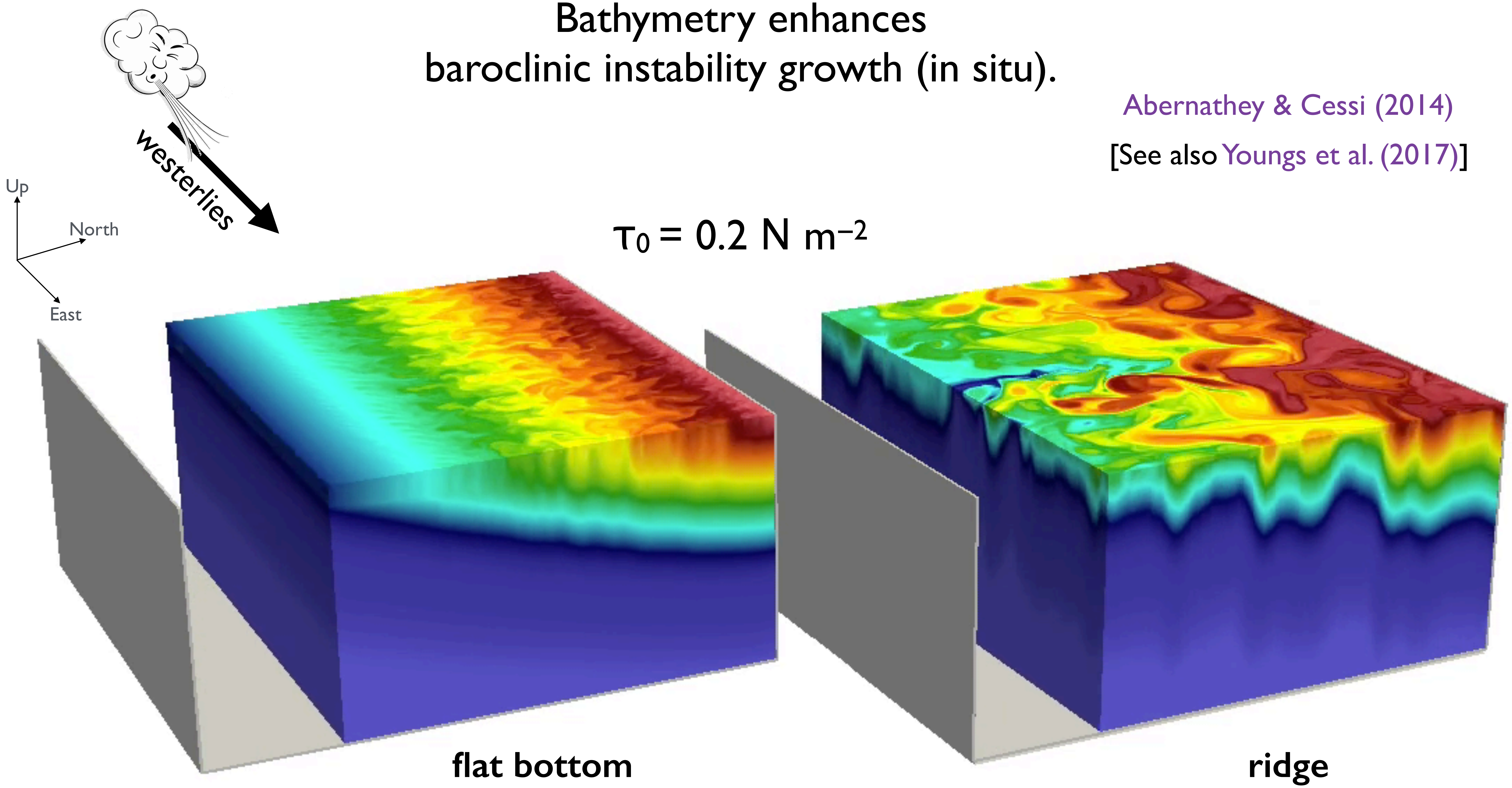
role of bathymetry II

Bathymetry enhances
baroclinic instability growth (in situ).

Abernathey & Cessi (2014)

[See also Youngs et al. (2017)]

$\tau_0 = 0.2\ \mathrm{N\ m^{-2}}$



flat bottom **ridge**

http://vimeo.com/55486114

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

the "thermal-wind" zonal transport

baroclinic interpretation of eddy saturation $\longleftrightarrow$ thermal-wind component dominates ACC trasport

[thermal-wind transport refers to transport inferred from hydrography assuming zero flow at the bottom]

cDrake experiment measured
time-mean bottom flows $\mathcal{O}(10\mathrm{cm\ s^{-1}})$

Donohue et al. 2016

bottom-flow contribution to ACC transport ~25%

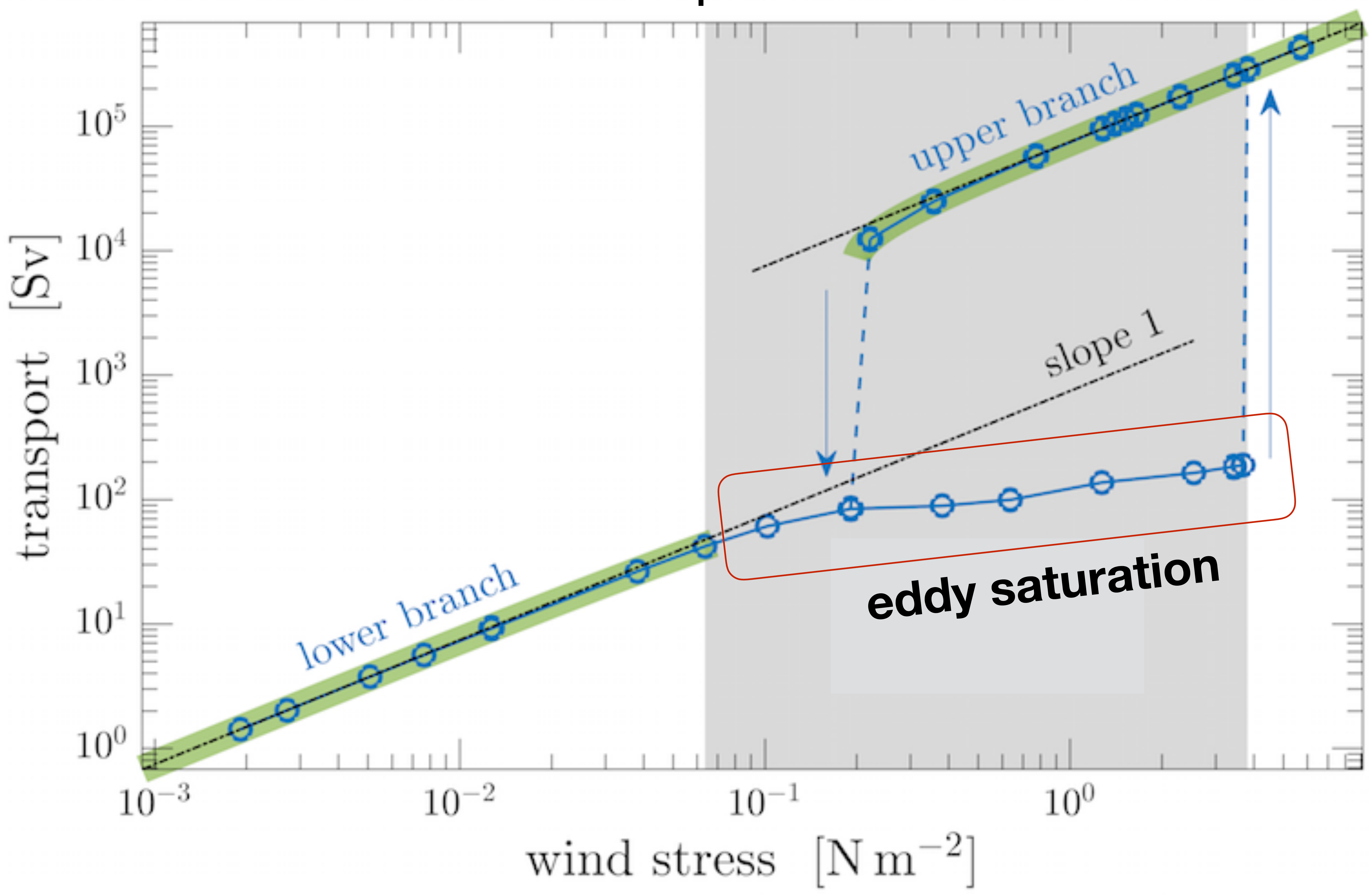
a surprise

Eddy saturation can occur
without baroclinicity
in a homogeneous QG barotropic
model with bathymetry.

Surprising!

All previous arguments
relied on baroclinic instability
for producing transient eddies.

Southern Ocean-parameter values

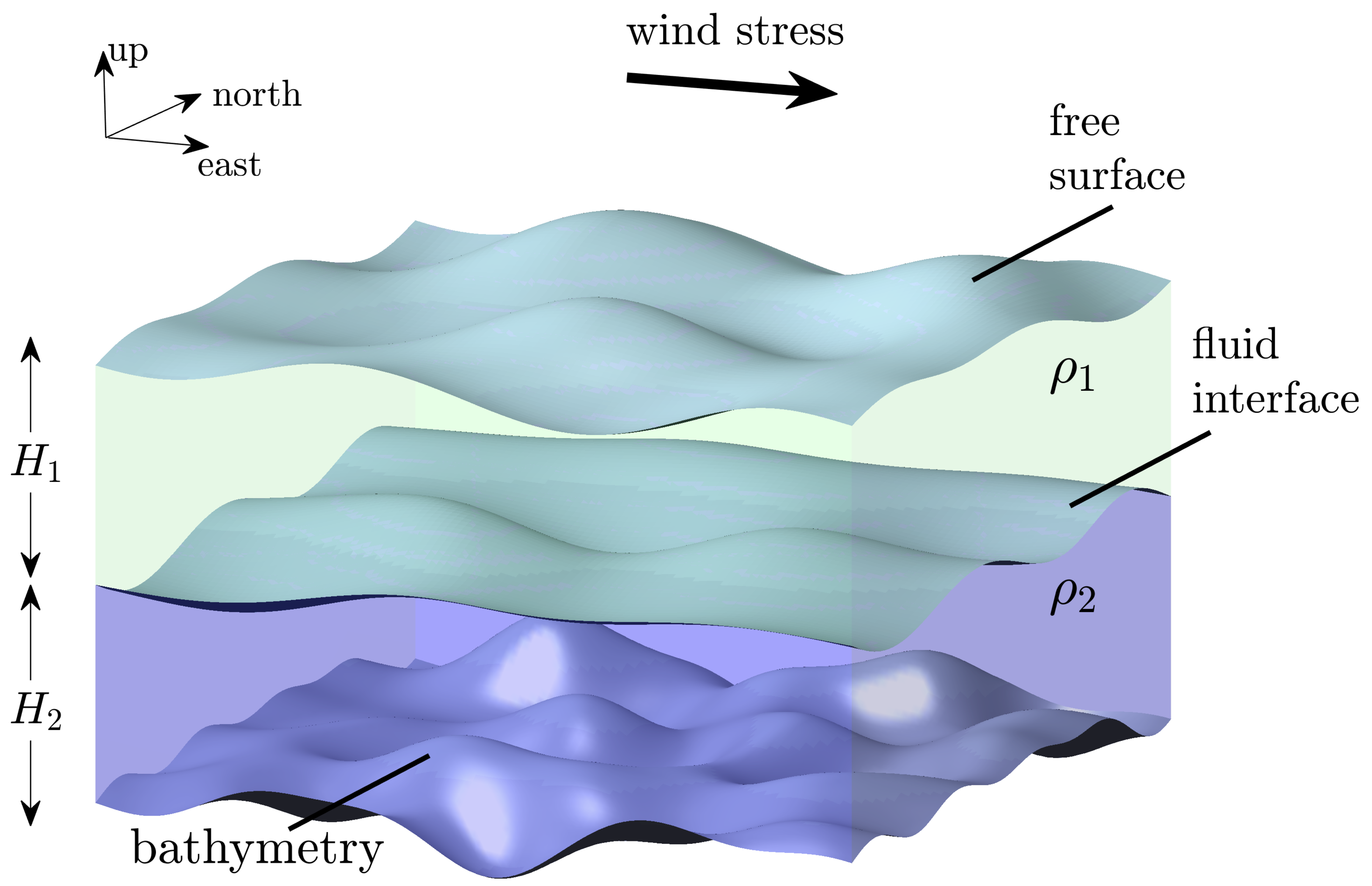


Constantinou & Young 2017, Constantinou 2018

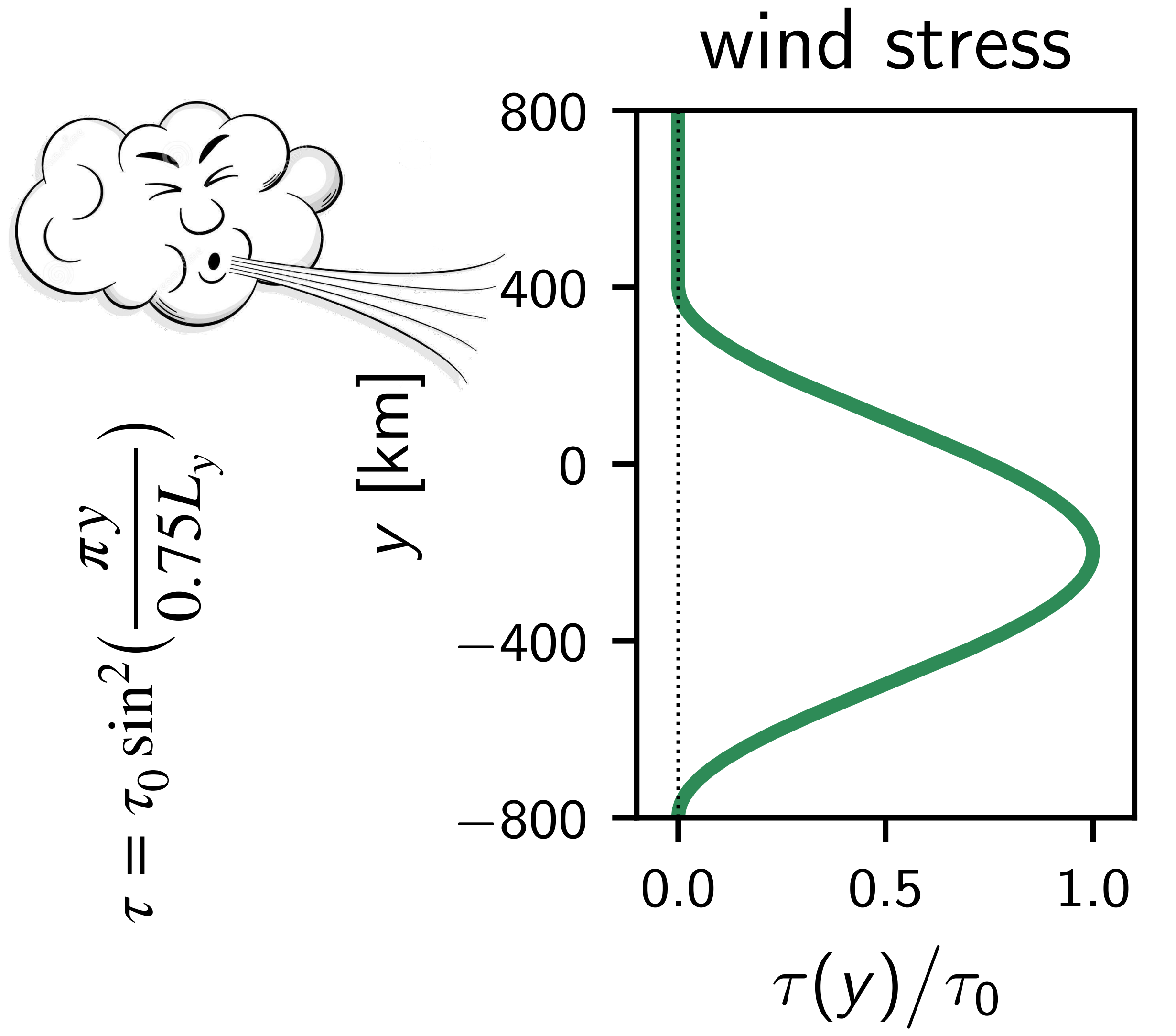
what's the plan for today

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

Use an isopycnal layered model
with varying number of fluid layers.

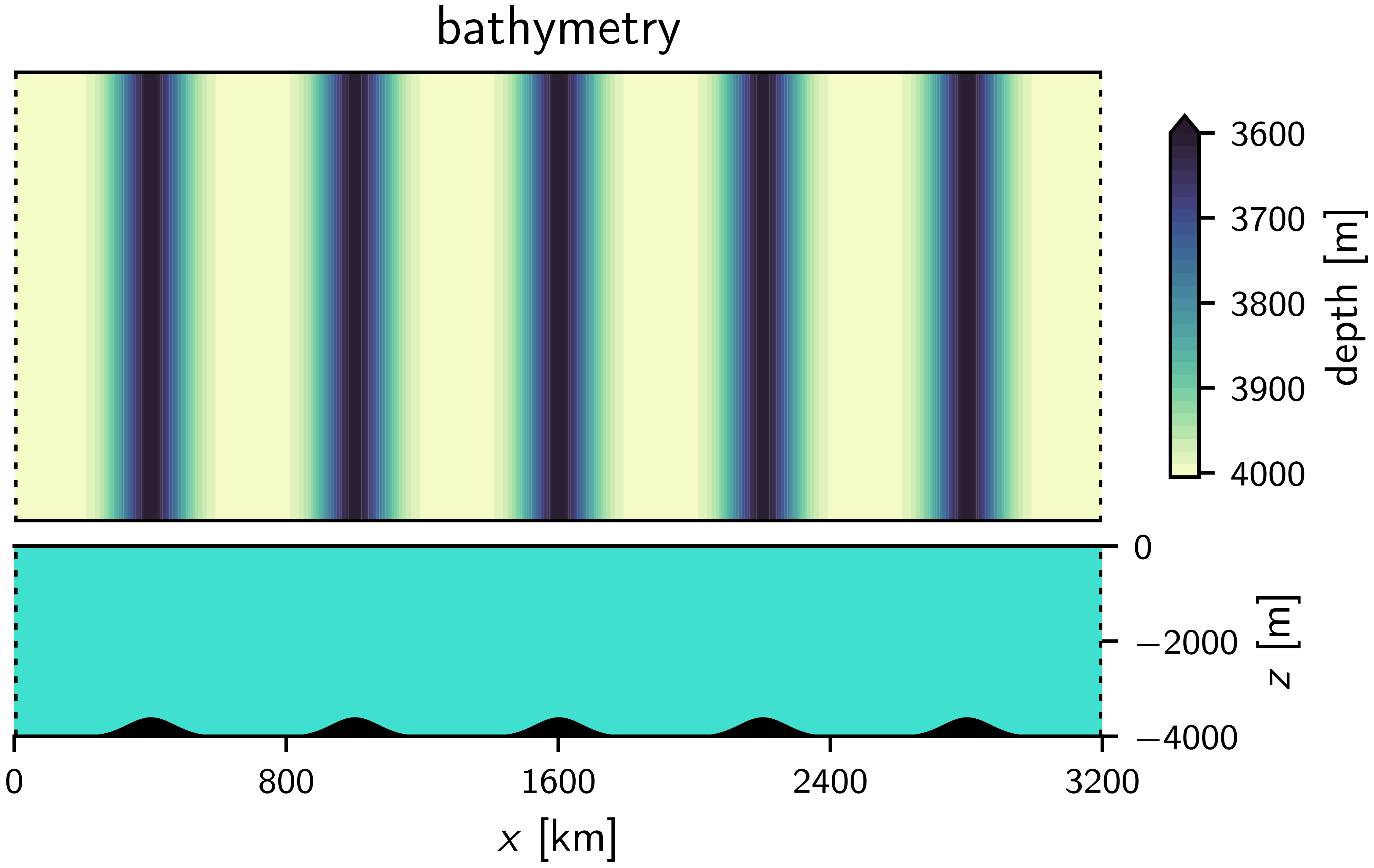


model setup



$\tau = \tau_0 \sin^2\left(\frac{\pi y}{0.75 L_y}\right)$

realistic value
τ_0 = 0.05 - 0.25 N m^{-2}



GFDL's MOM6
primitive equations
in isopycnal coordinates
Boussinesq approximation

β-plane $f = f_0 + \beta y$
zonally re-entrant
1st deformation radius ≈ 19 km
(2nd deformation radius ≈ 10 km)
free surface
free-slip walls
quadratic bottom drag
grid spacing 4 km

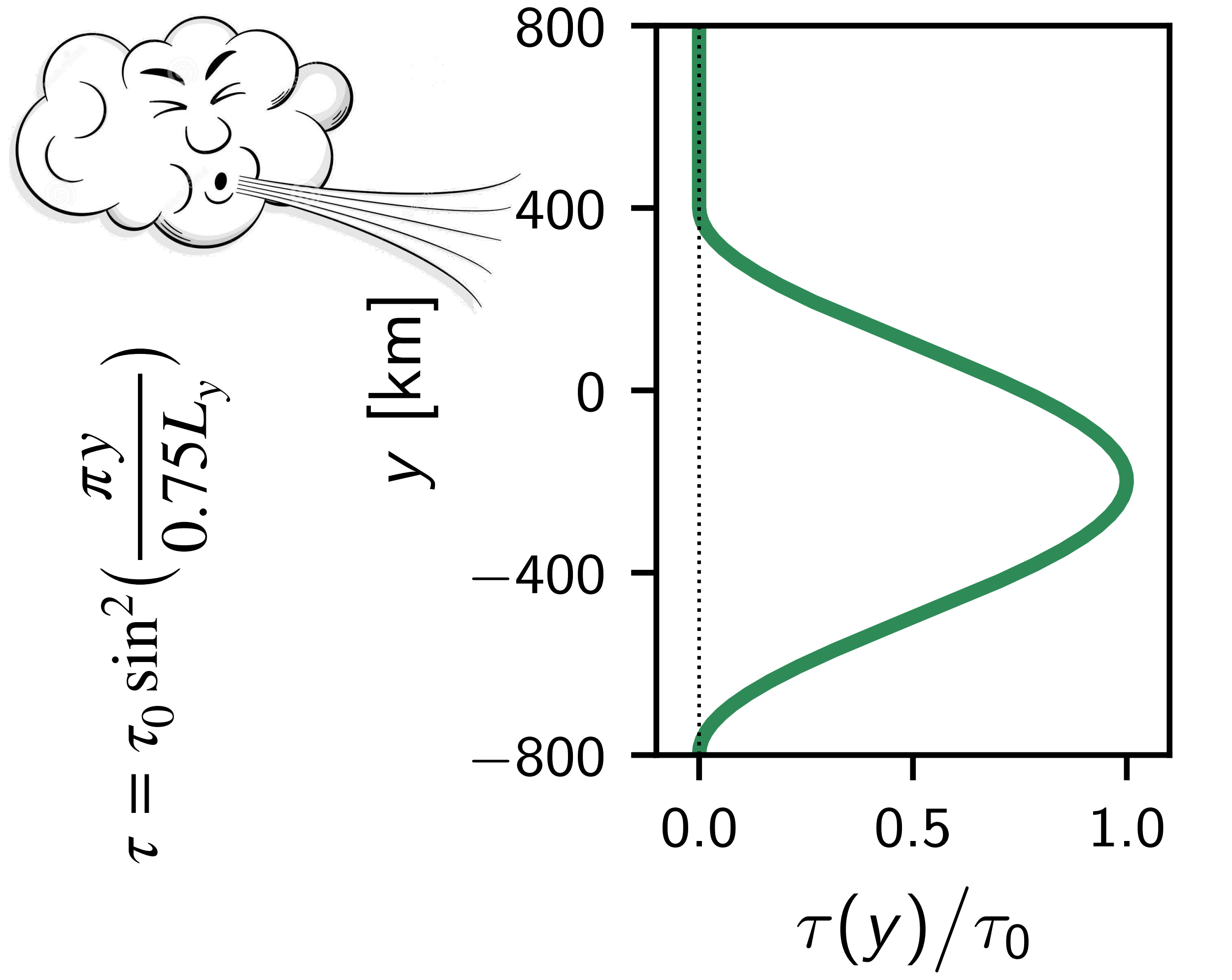
bathymetry:
Gaussian ridges
400 m tall, half-width 165 km

no buoyancy forcing

no diapycnal motions

f/h contours are not fully blocked

model setup



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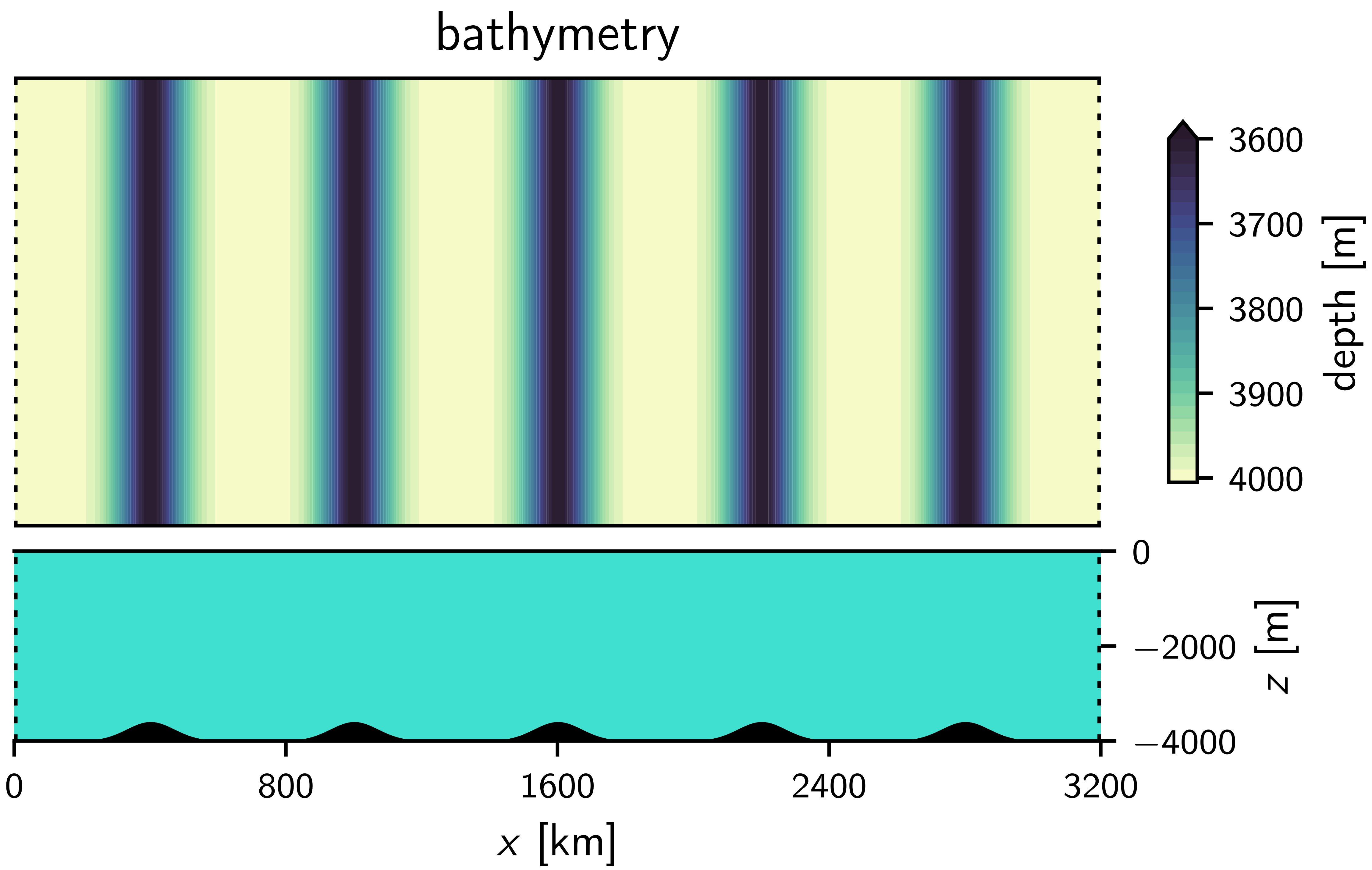

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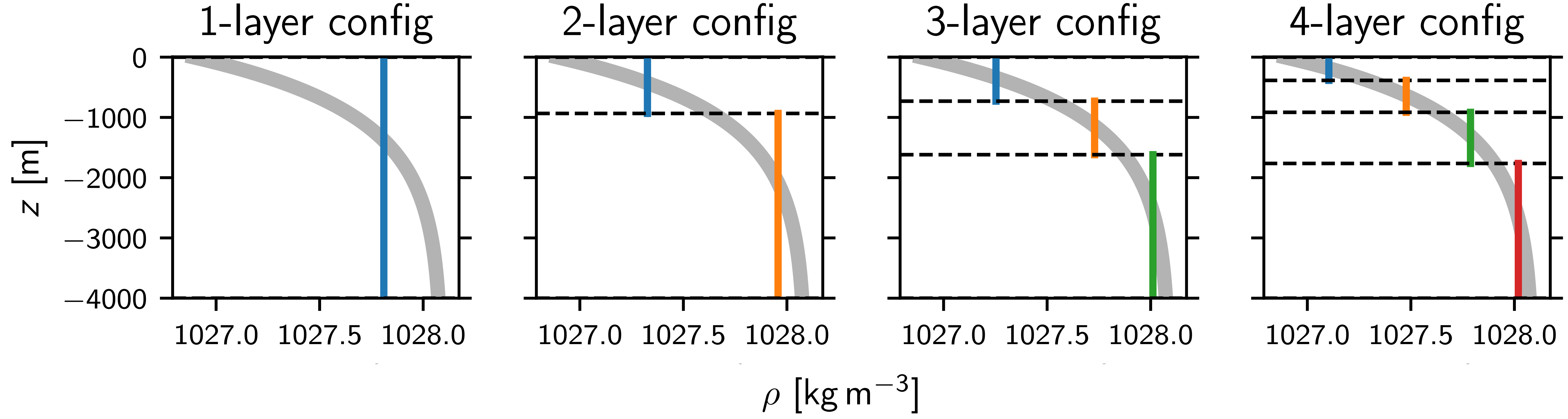
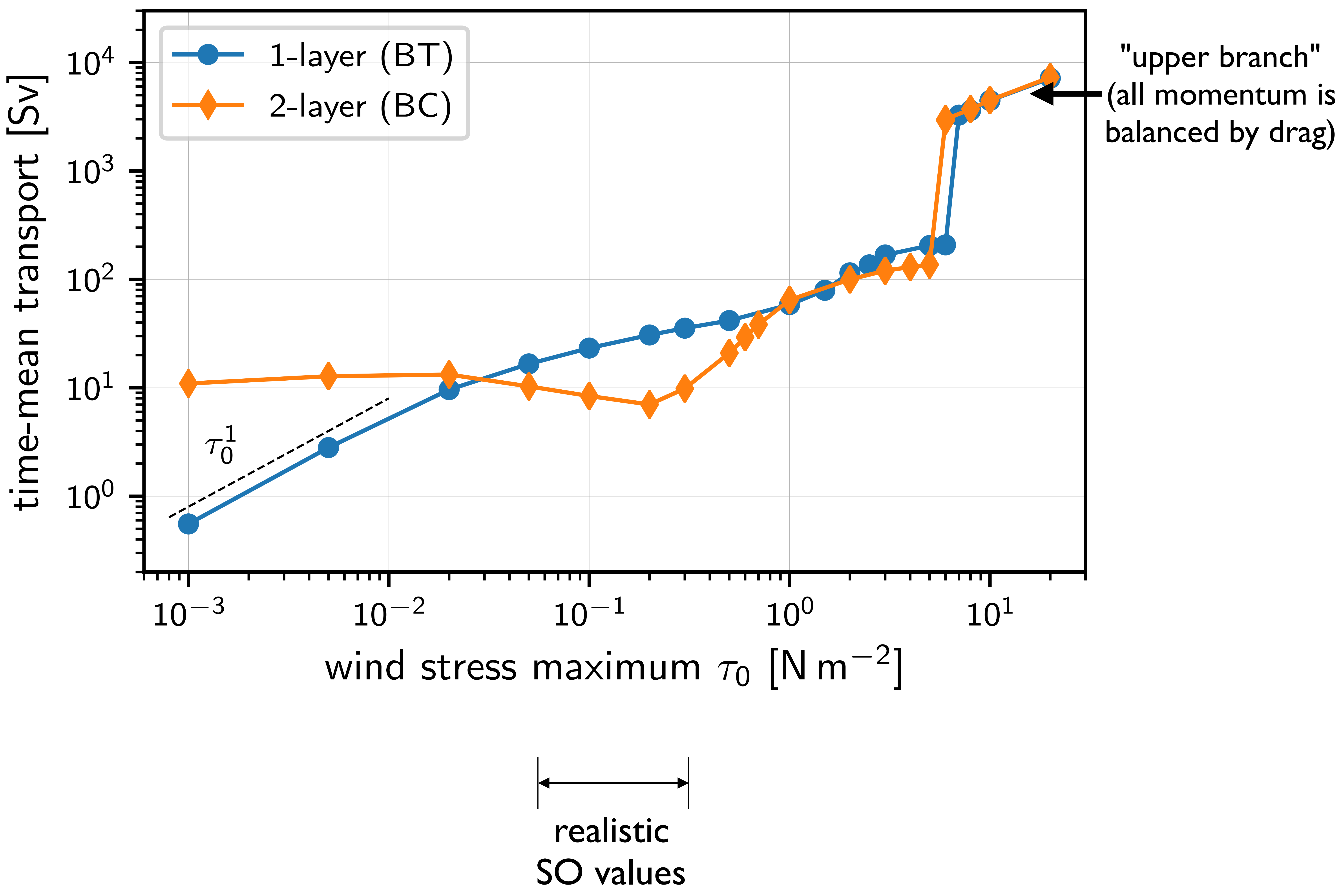


exponential density profile
$$\rho = \rho_0 + \Delta\rho\,(1 - e^{z/d})$$
$\Delta\rho$ =1.2 kg m^{-3}, d=1 km

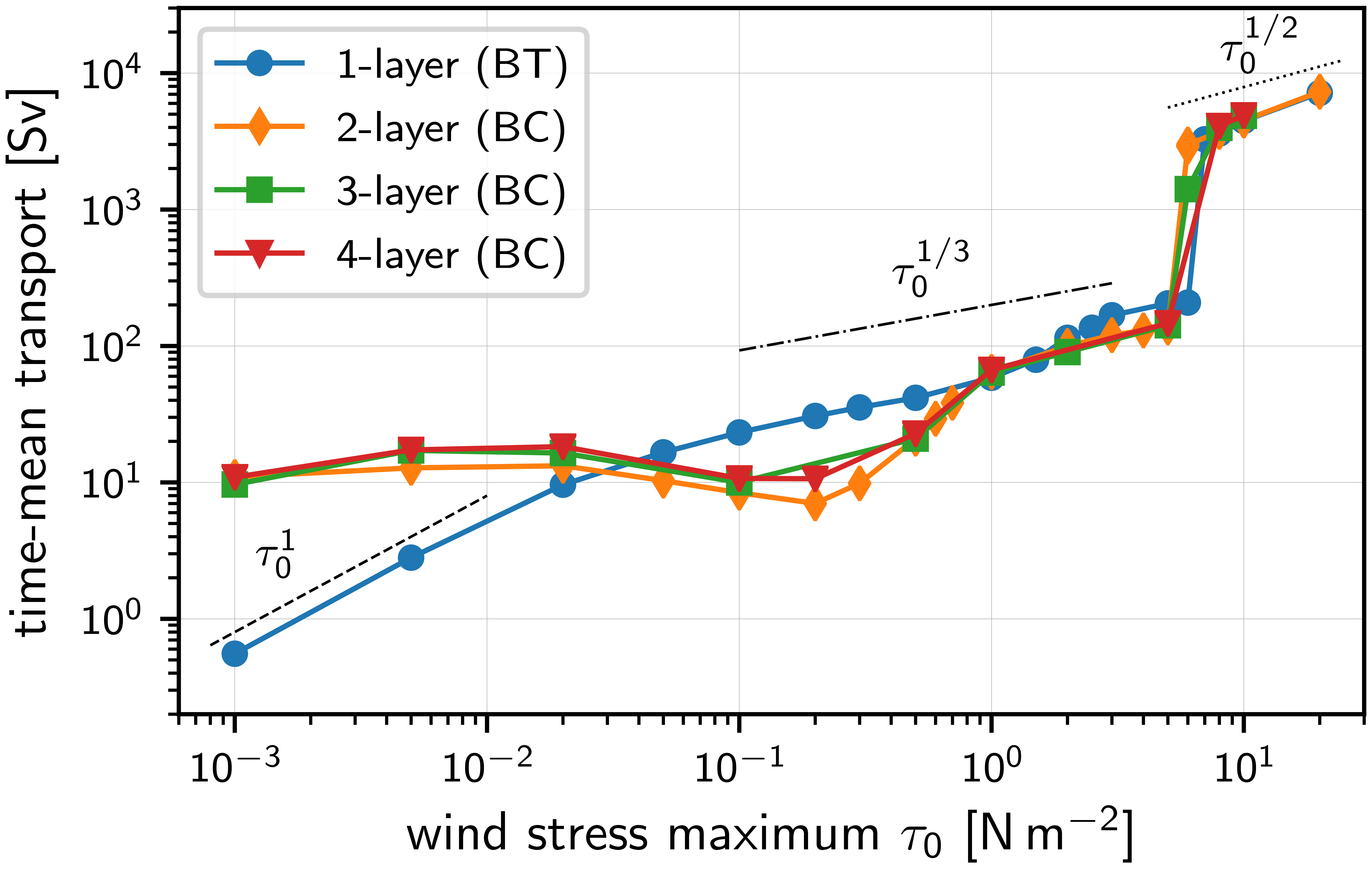
← layered approximations

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

mean zonal transport versus wind stress



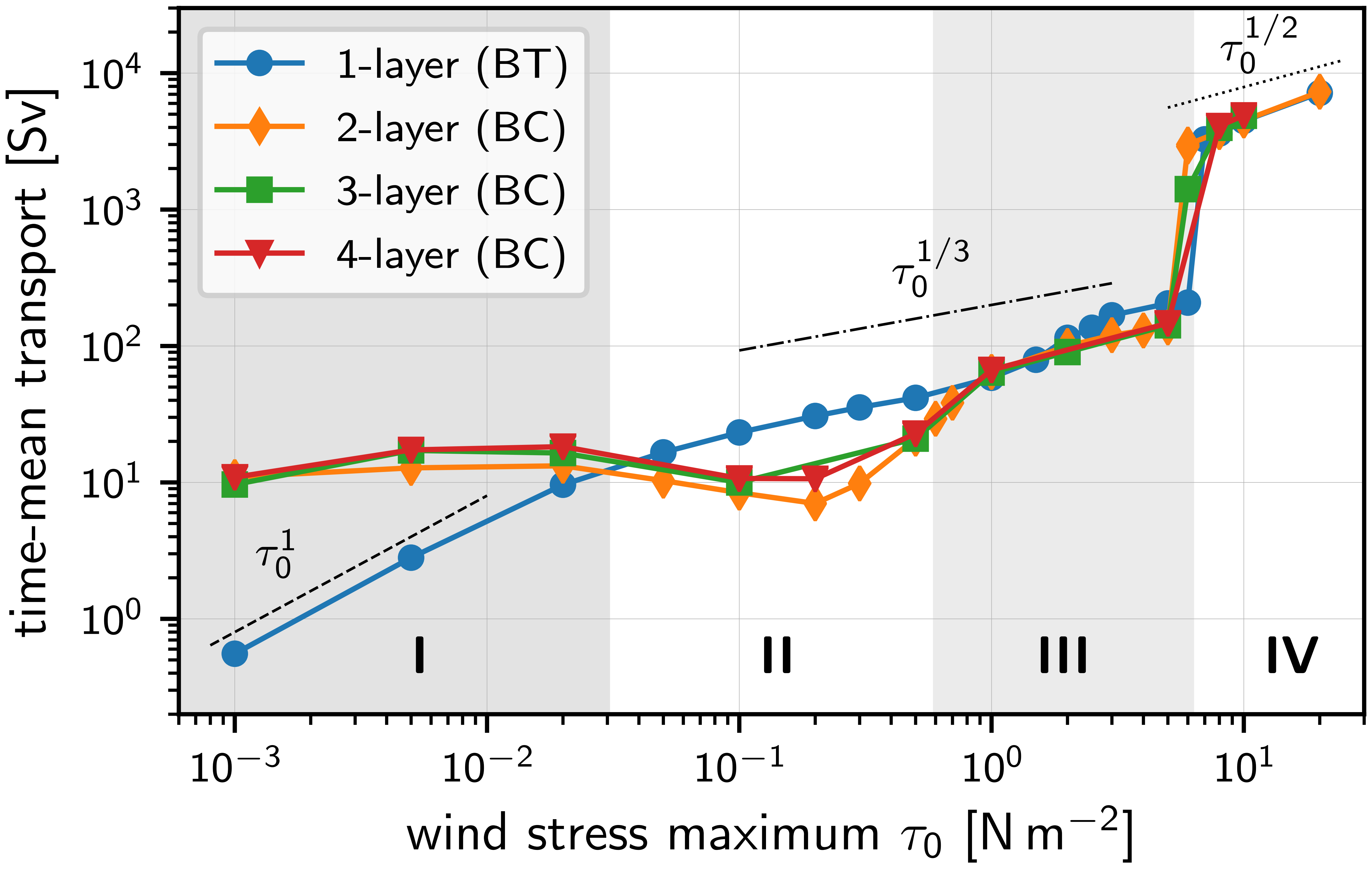
mean zonal transport versus wind stress



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

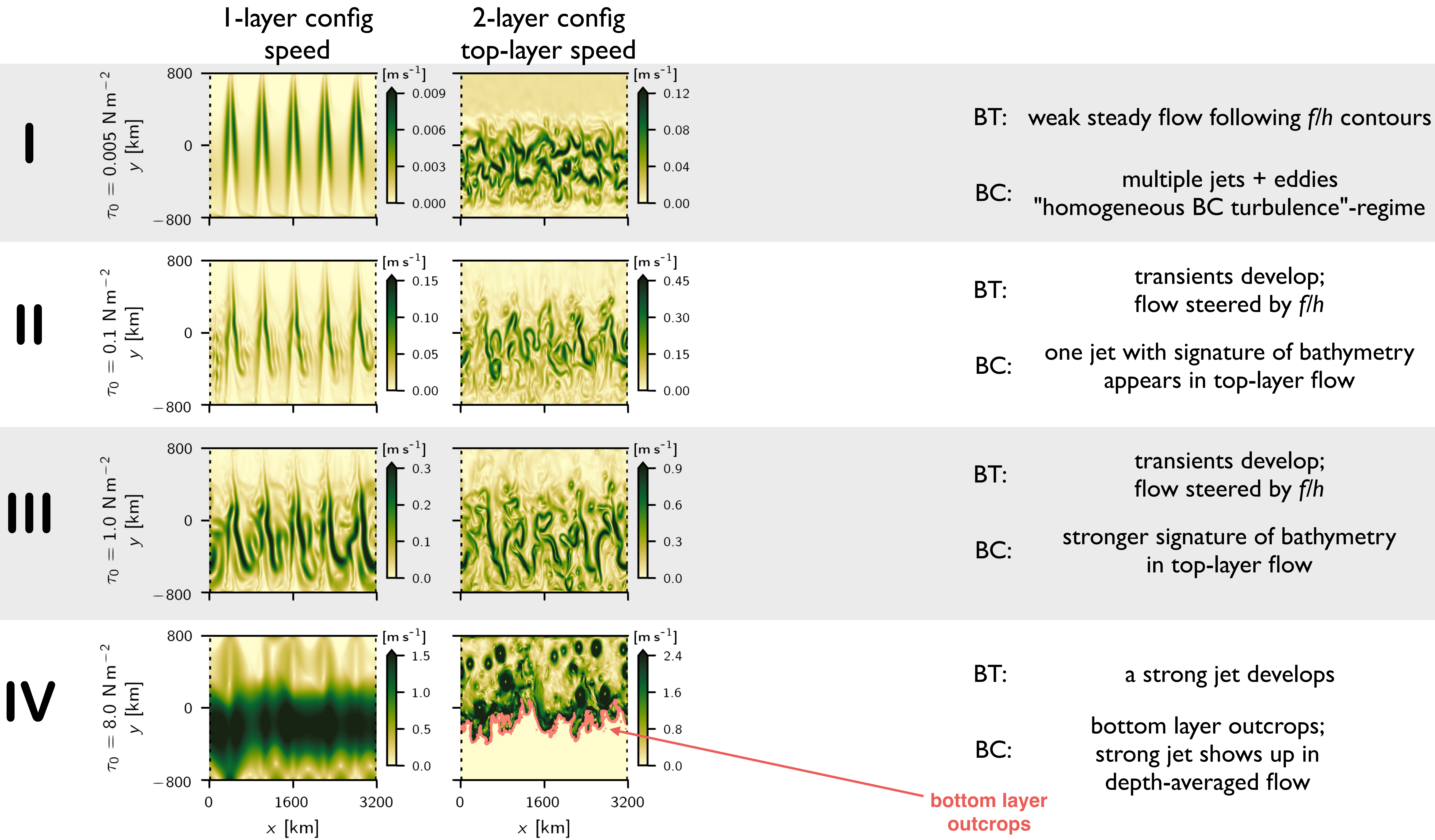
(as fas as the mean zonal transport is concerned)

mean zonal transport versus wind stress



four distinct flow regimes

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



1-layer config
speed
2-layer config
top-layer speed
I
$\tau_0 = 0.005$ N m^{-2}
y [km]
800
0
−800
[m s^{-1}]
0.009
0.006
0.003
0.000
[m s^{-1}]
0.12
0.08
0.04
0.00
BT: weak steady flow following f/h contours
BC: multiple jets + eddies
"homogeneous BC turbulence"-regime
II
$\tau_0 = 0.1$ N m^{-2}
y [km]
800
0
−800
[m s^{-1}]
0.15
0.10
0.05
0.00
[m s^{-1}]
0.45
0.30
0.15
0.00
BT: transients develop;
flow steered by f/h
BC: one jet with signature of bathymetry
appears in top-layer flow
III
$\tau_0 = 1.0$ N m^{-2}
y [km]
800
0
−800
[m s^{-1}]
0.3
0.2
0.1
0.0
[m s^{-1}]
0.9
0.6
0.3
0.0
BT: transients develop;
flow steered by f/h
BC: stronger signature of bathymetry
in top-layer flow
IV
$\tau_0 = 8.0$ N m^{-2}
y [km]
800
0
−800
[m s^{-1}]
1.5
1.0
0.5
0.0
[m s^{-1}]
2.4
1.6
0.8
0.0
0
1600
3200
x [km]
0
1600
3200
x [km]
BT: a strong jet develops
BC: bottom layer outcrops;
strong jet shows up in
depth-averaged flow
bottom layer
outcrops

1-layer config speed
2-layer config top-layer speed
2-layer config depth-averaged speed
I
II
III
IV
$\tau_0 = 0.005$ N m^{-2}
$\tau_0 = 0.1$ N m^{-2}
$\tau_0 = 1.0$ N m^{-2}
$\tau_0 = 8.0$ N m^{-2}
y [km]
x [km]
[m s^{-1}]
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
BC: stronger signature of bathymetry in top-layer flow
BT: a strong jet develops
BC: bottom layer outcrops; strong jet shows up in depth-averaged flow
bottom layer outcrops

depth-integrated zonal momentum balance

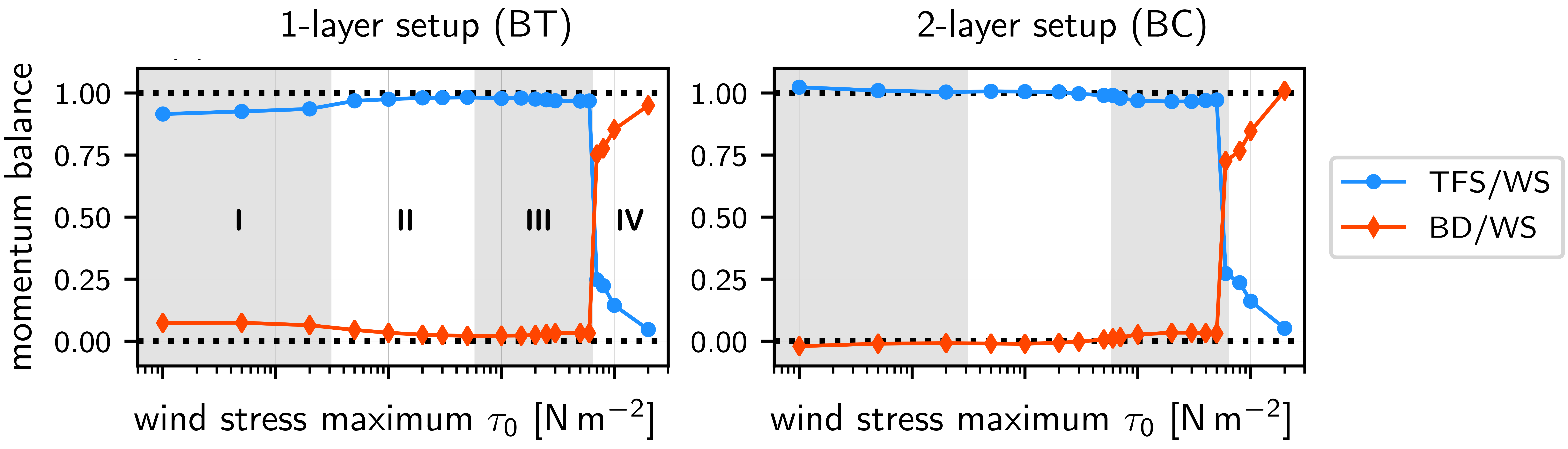
$\langle\ \rangle$: layer average
$\overline{}$: time average

$$\langle \tau \rangle = \langle\, \overline{p_{\text{bot}}\, \partial_x h_{\text{bot}}}\, \rangle + \langle\, \rho_{\text{m}} c_D\, \overline{u_{\text{bot}} \,|\, \mathbf{u}_{\text{bot}} \,|}\, \rangle$$

wind stress (WS) | topographic form stress (TFS) | bottom drag (BD)

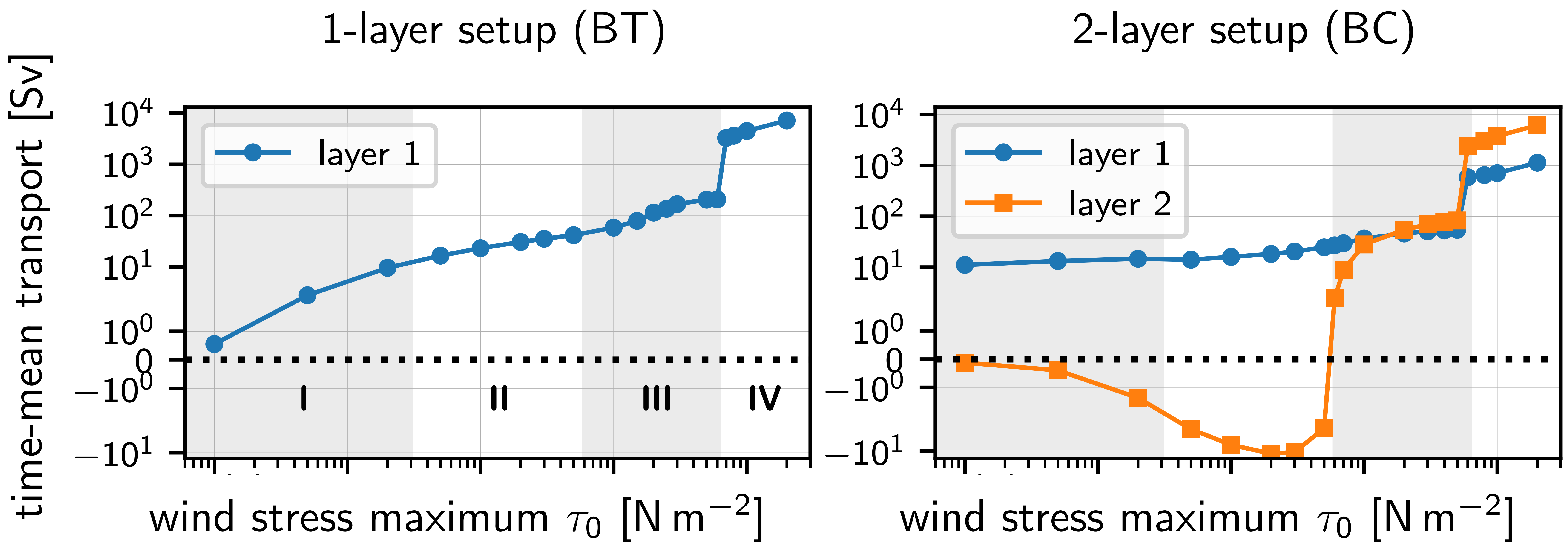
$$\langle \overline{p_{\text{bot}}\, \partial_x h_{\text{bot}}} \rangle = \langle \overline{p_{\text{bot}}}\, \partial_x h_{\text{bot}} \rangle$$

only time-mean flow contributes to TFS



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

layer-wise transport decomposition



[Westward bottom-layer flows also in 3-layer and 4-layer configs.]

Similar bottom-layer westward flows were found by Treguier & McWilliams (1990) and Stevens & Ivchenko (1997).

Obs. evidence in certain regions of the SO (Cunningham & Barker 1996).

Westward flows are not robust.
Flip to eastward, e.g., for:

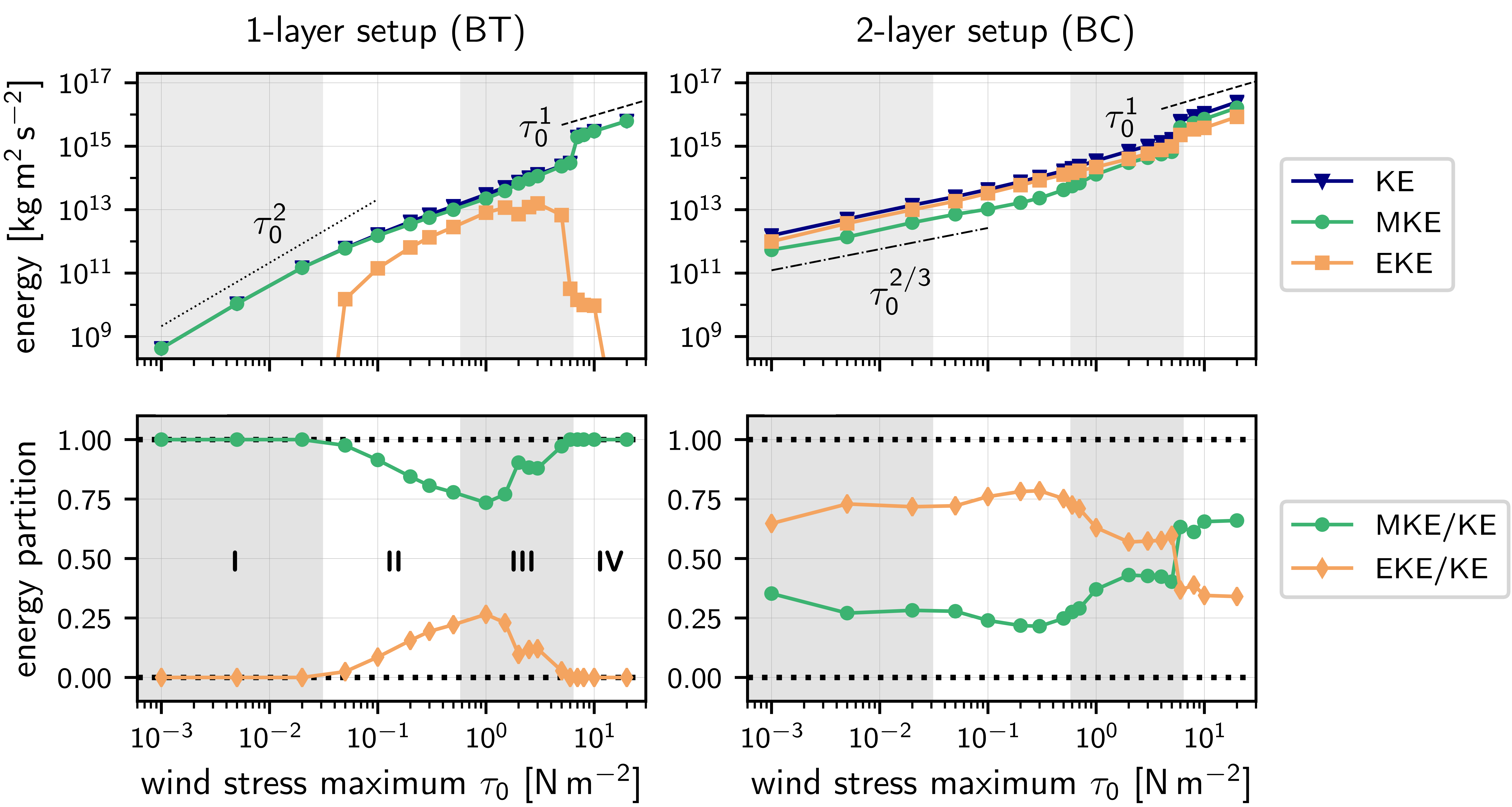
- β=0 [Neptune effect? (Holloway 1987)]
- single-ridge bathymetry

standing–transient kinetic energy decomposition

BT config
has transients
only in **II** & **III**

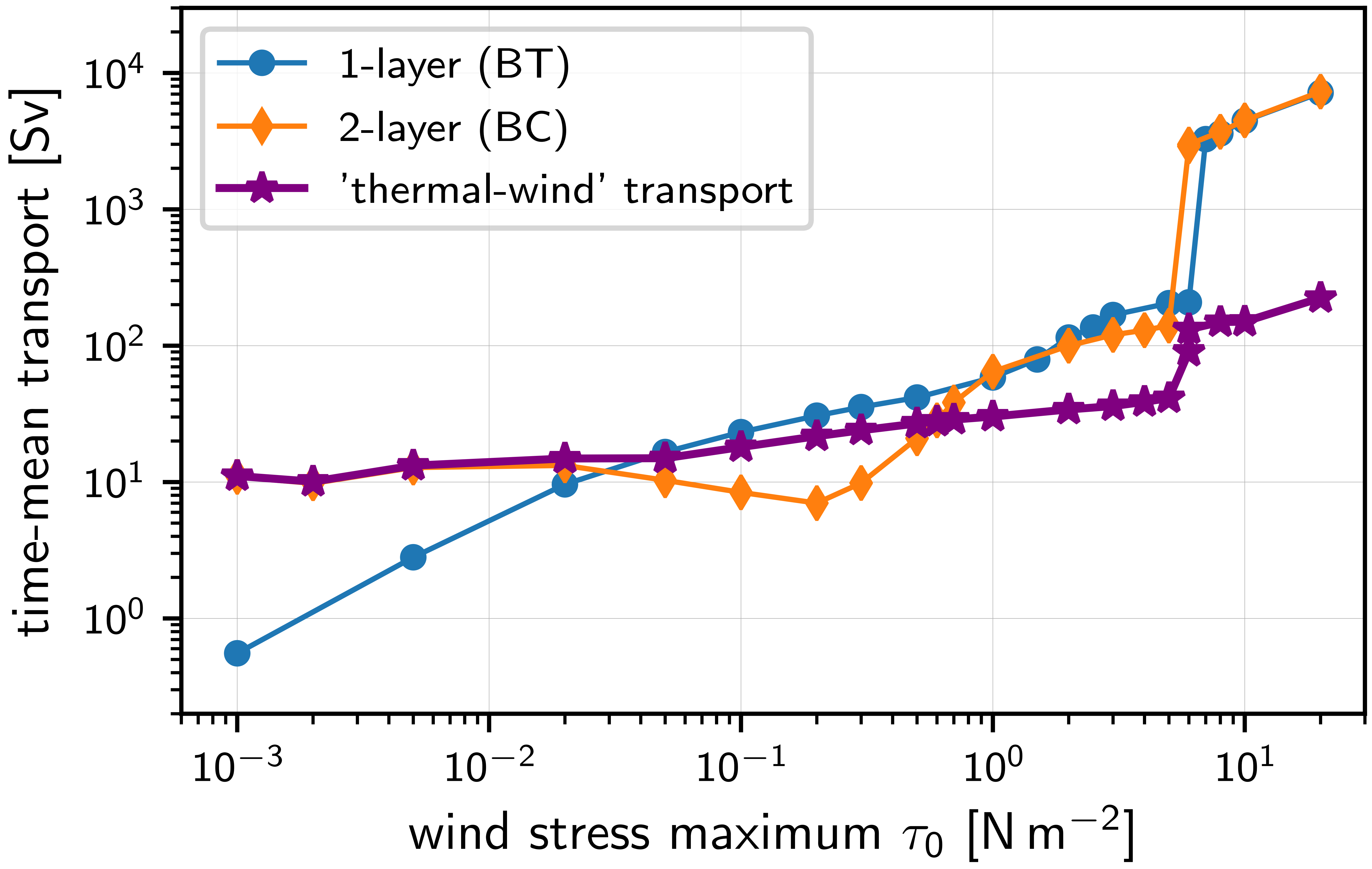
standing flow
dominates
in BT config;

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**.

"thermal-wind"-transport $= \langle \overline{h_1(u_1 - u_2)} \rangle L_y$



"thermal-wind"-transport $= \langle \overline{h_1(u_1 - u_2)} \rangle L_y$

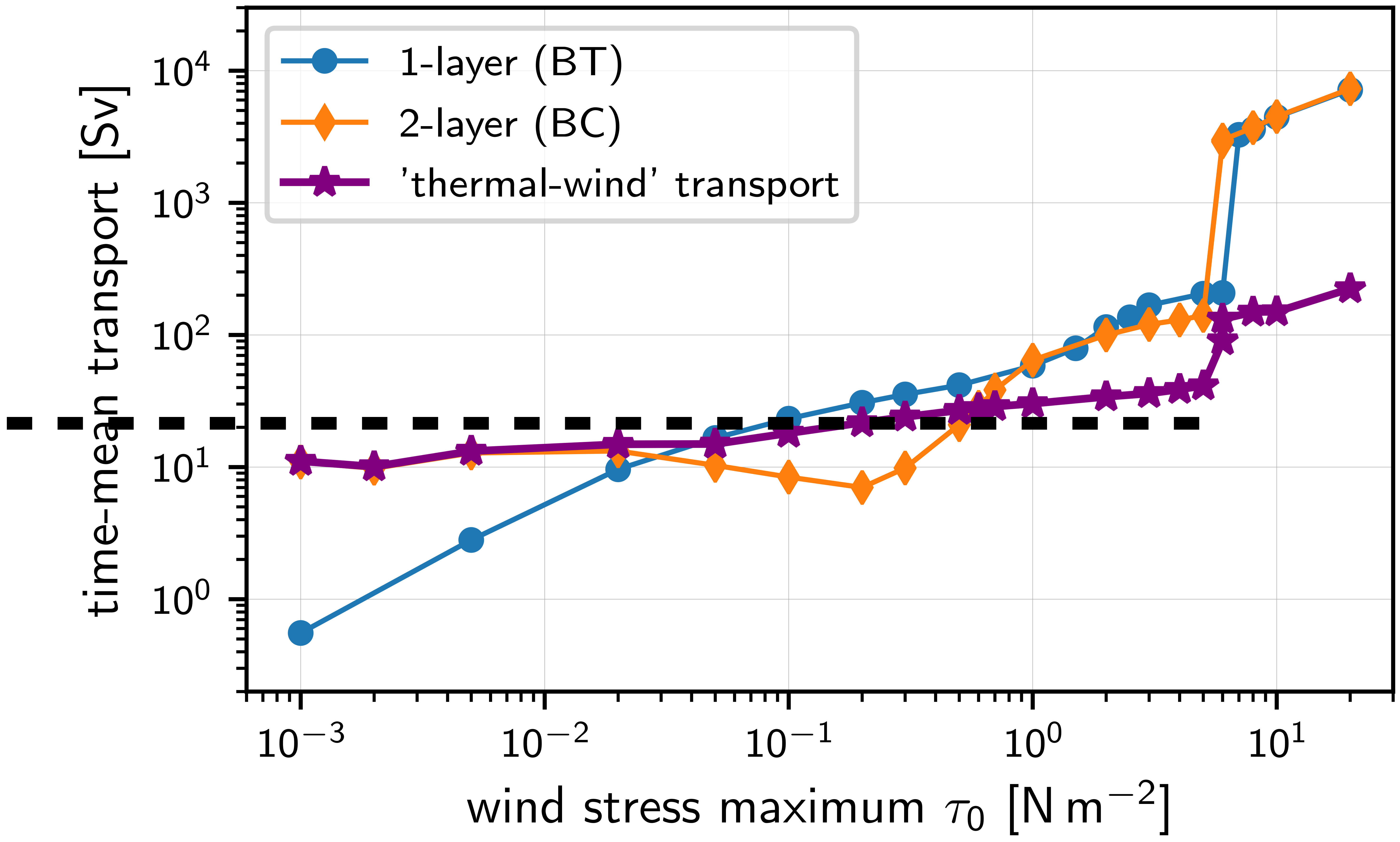
prediction by
Marshall et al. 2017

$$T_{\text{thermal wind}} = \lambda \frac{N}{|f|} \frac{H^2 L_y}{2\alpha_2} \approx 20\,\text{Sv}$$

$$N = \frac{1}{H}\int_{-H}^{0} \left(-\frac{g}{\rho_m}\frac{\partial\rho}{\partial z}\right)^{1/2} \mathrm{d}z$$

$\lambda = 1/(6\text{ months})$

$\alpha_2 = 0.61$



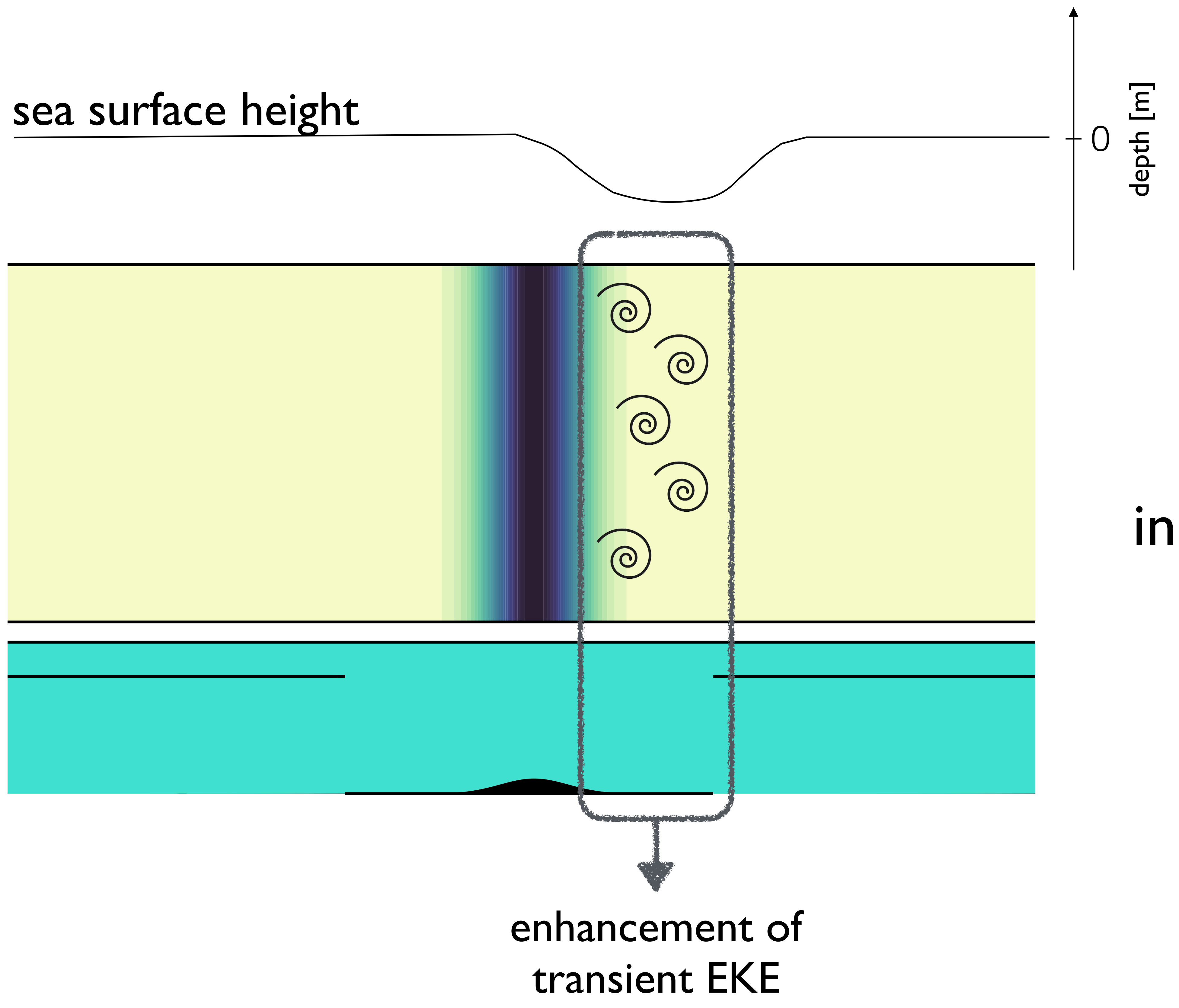
Coincidence? Probably....
A test would be to vary N and see how the Marhall's prediction performs....
LP Nadeau finds $T_{\text{thermal wind}} \propto N^{3/2}$ (AOFD '19).

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

only standing flow contributes to
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

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

[As also described by Youngs et al. 2017.]

take home messages

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) bottom 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)]

thank you

Constantinou and Hogg (2019). Eddy saturation of the Southern Ocean:
a baroclinic versus barotropic perspective. (in review, arXiv:1906.08442)