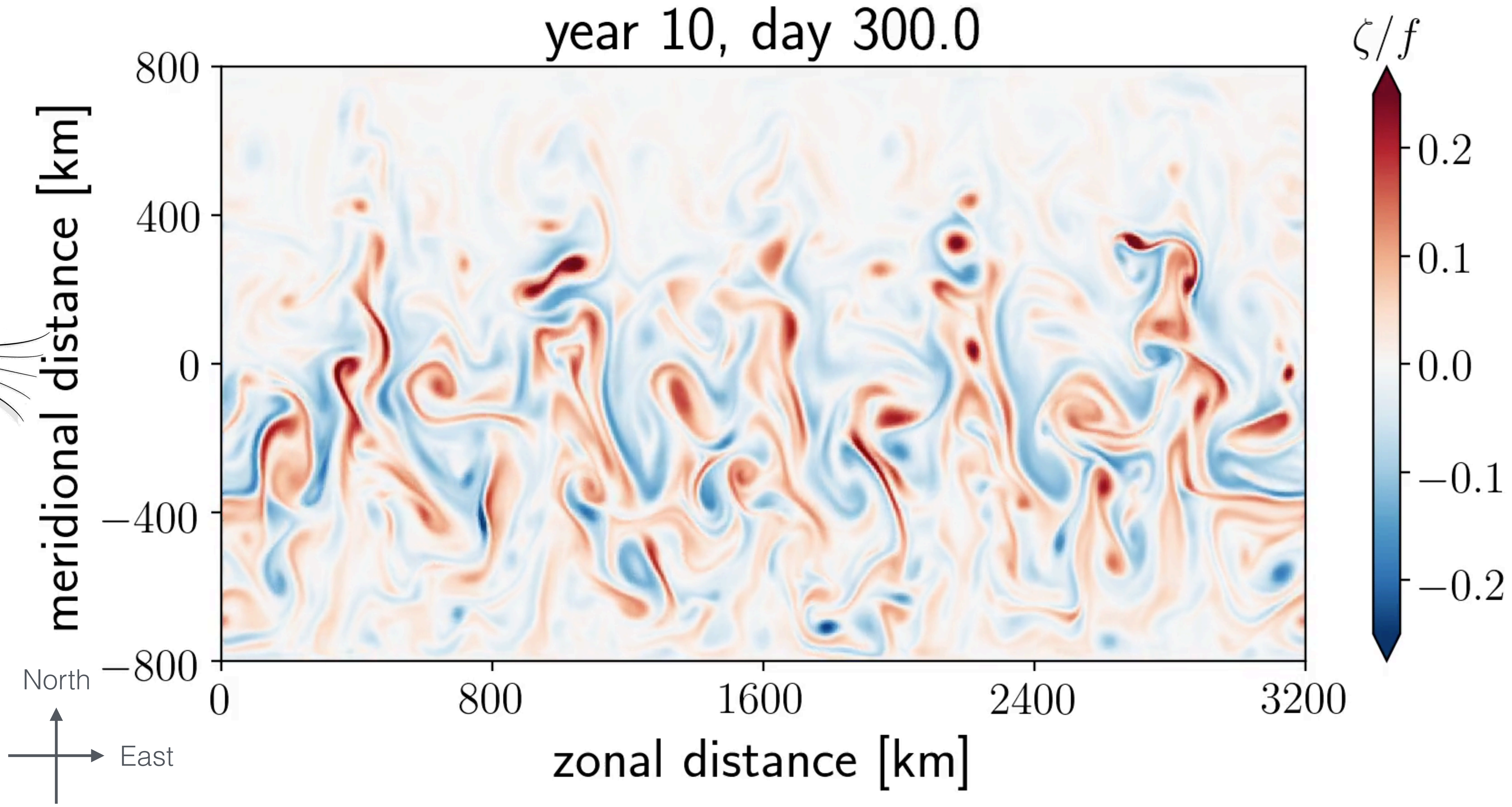
Barotropic versus Baroclinic eddy saturation: implications to Southern Ocean dynamics

Australian National University

Navid Constantinou & Andy Hogg

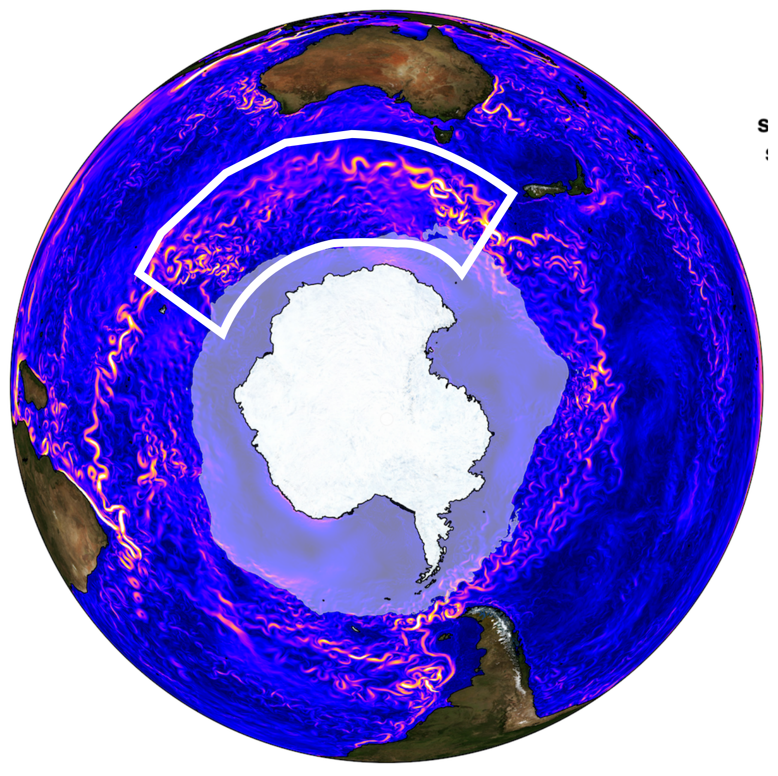
ARC Centre of Excellence for Climate Extremes

westerlies



top-layer relative vorticity

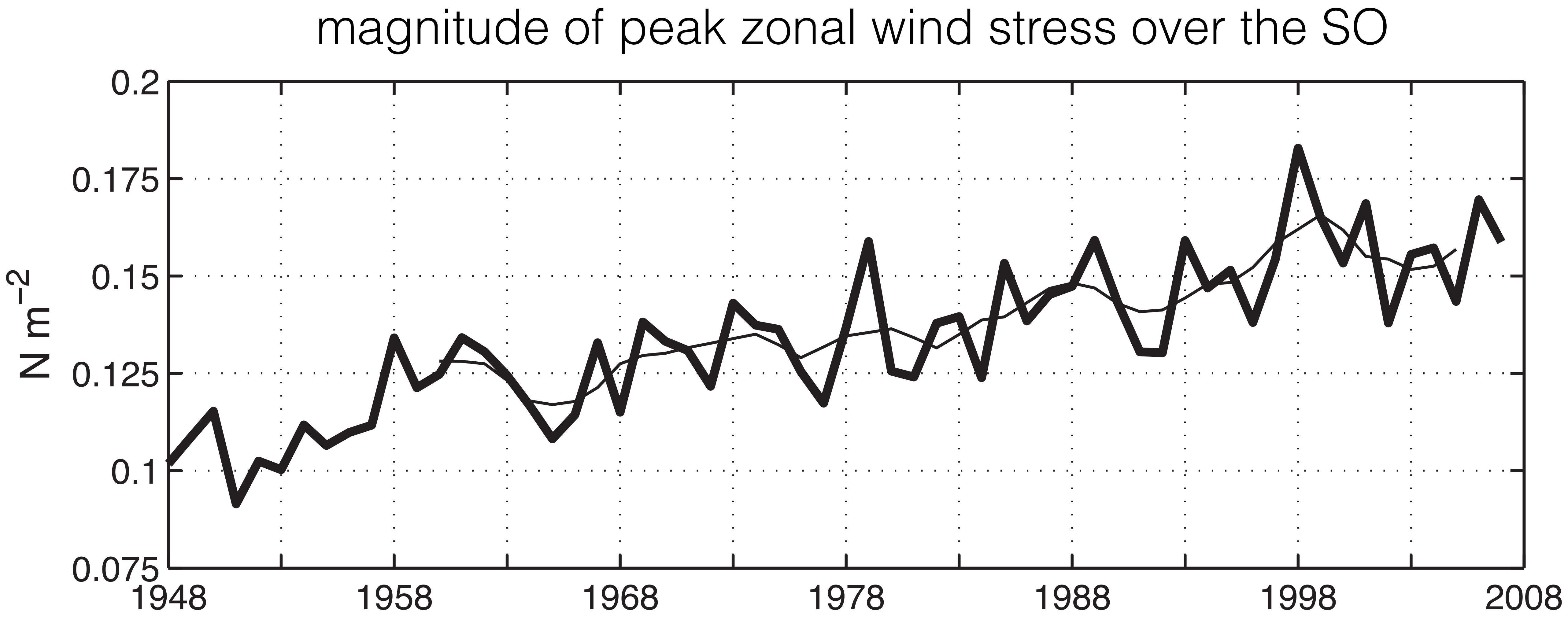
$\zeta = \partial_x v - \partial_y u$



22nd AOFD Conference

Portland ME, June 25th, 2019

winds over Southern Ocean are getting stronger



Farneti et al. 2015

results from
inter-annual
CORE-II simulations

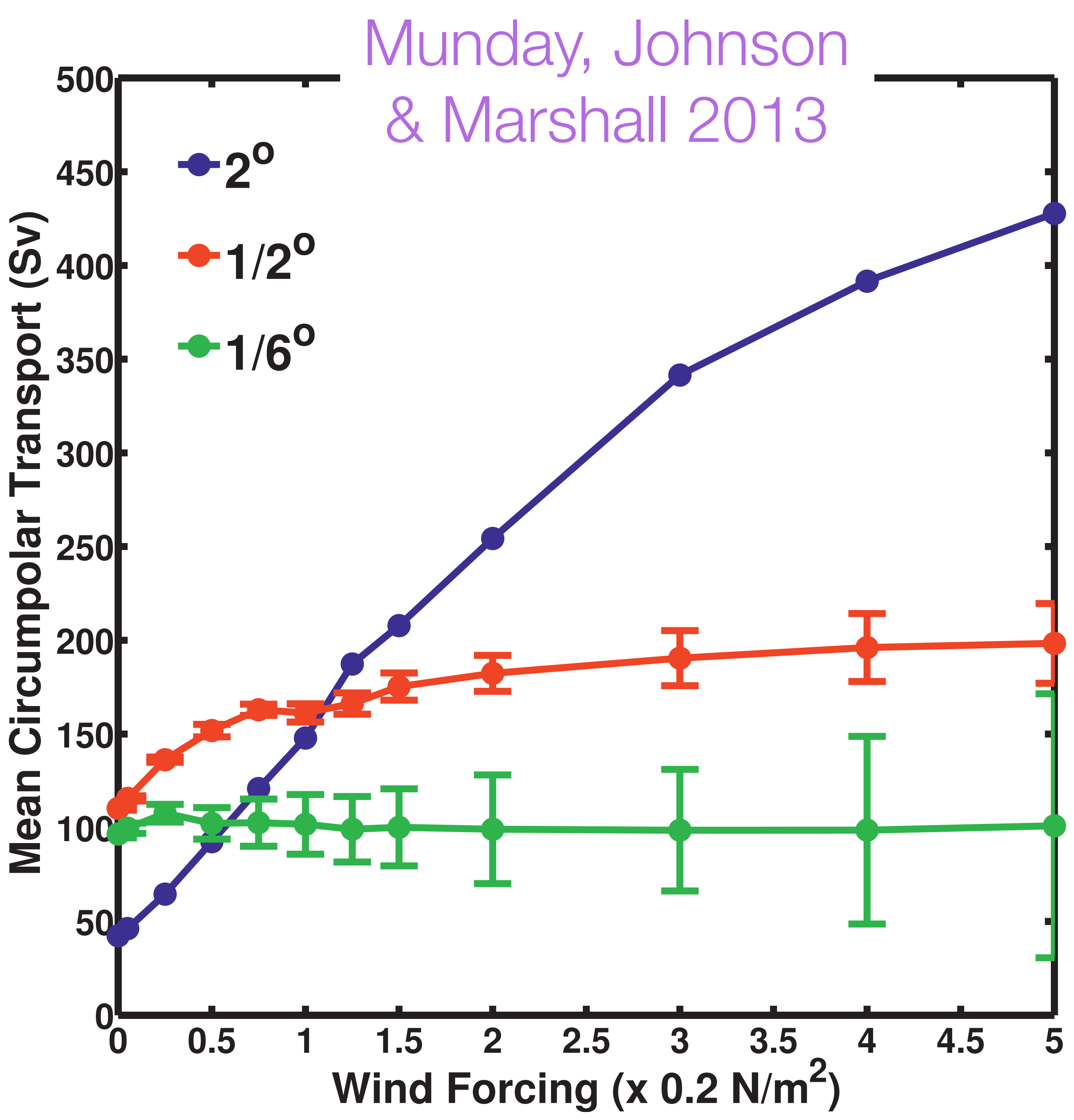
how will the Antarctic Circumpolar Current (ACC) respond?

does doubling the winds imply double ACC the transport?

not always — “eddy saturation”

what's eddy saturation?

The *insensitivity* of the time-mean ACC volume transport to wind stress increase.



higher resolution → eddy saturation "occurs"

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

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

[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.]

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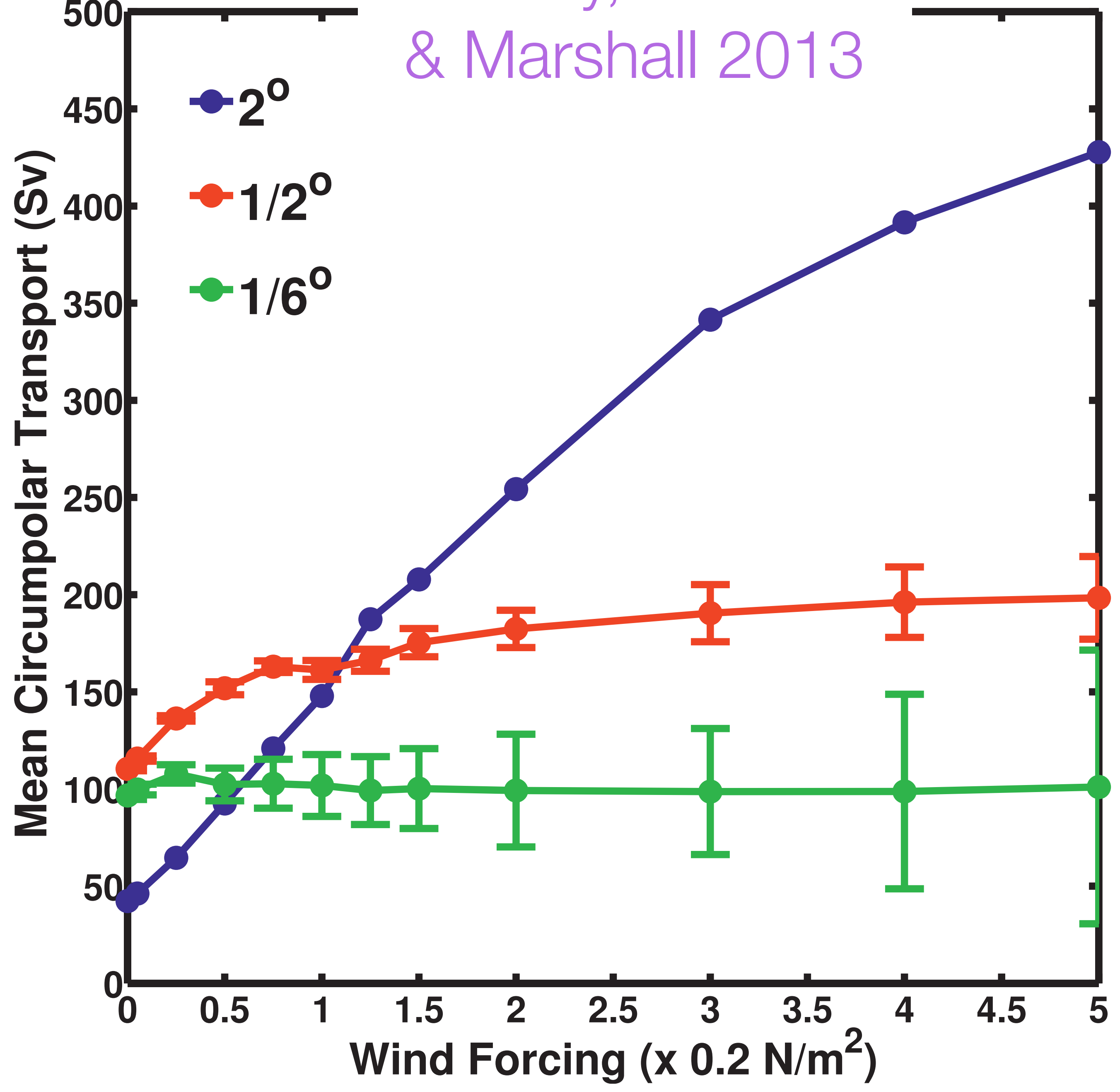
Munday, Johnson & Marshall 2013



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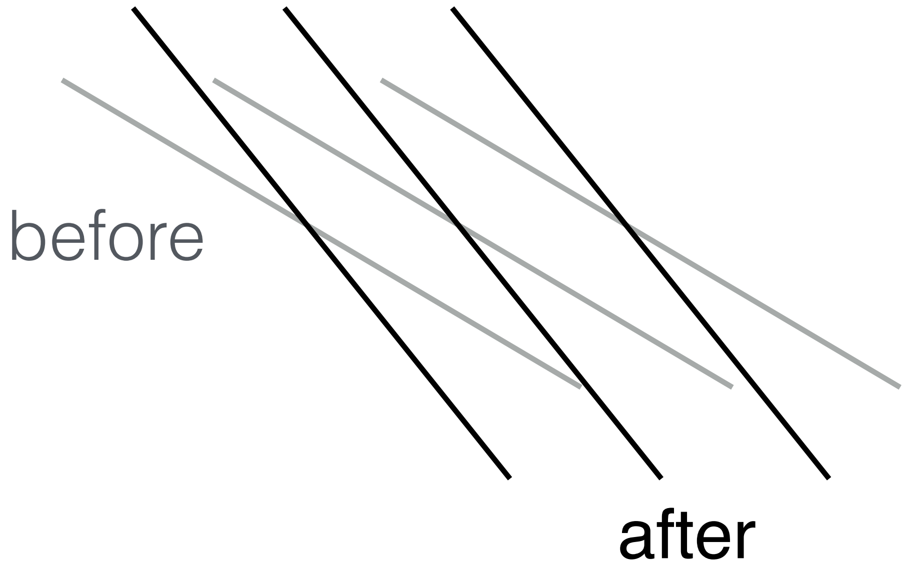
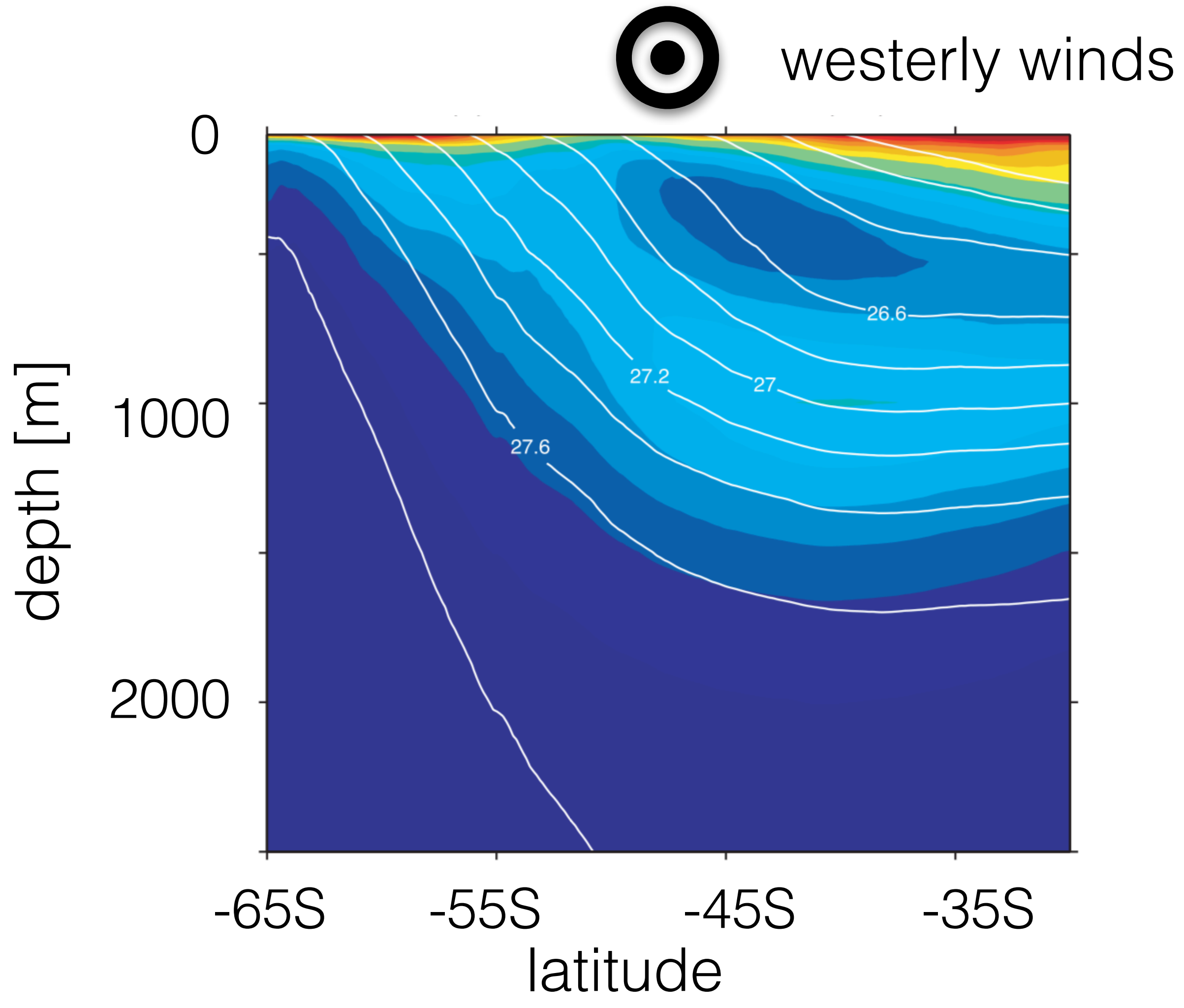
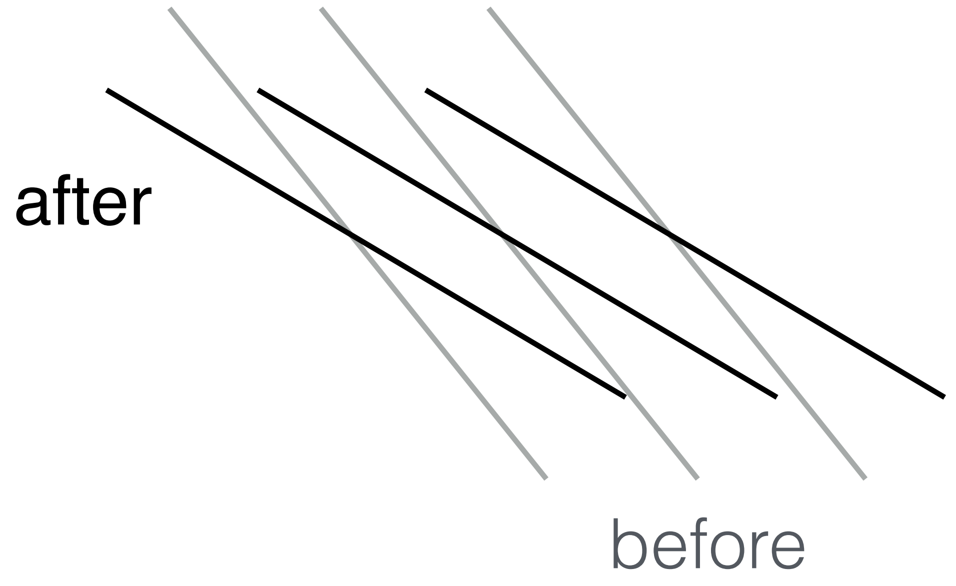
wind increase
slopes the isopycnals





baroclinic eddies
restratify isopycnals



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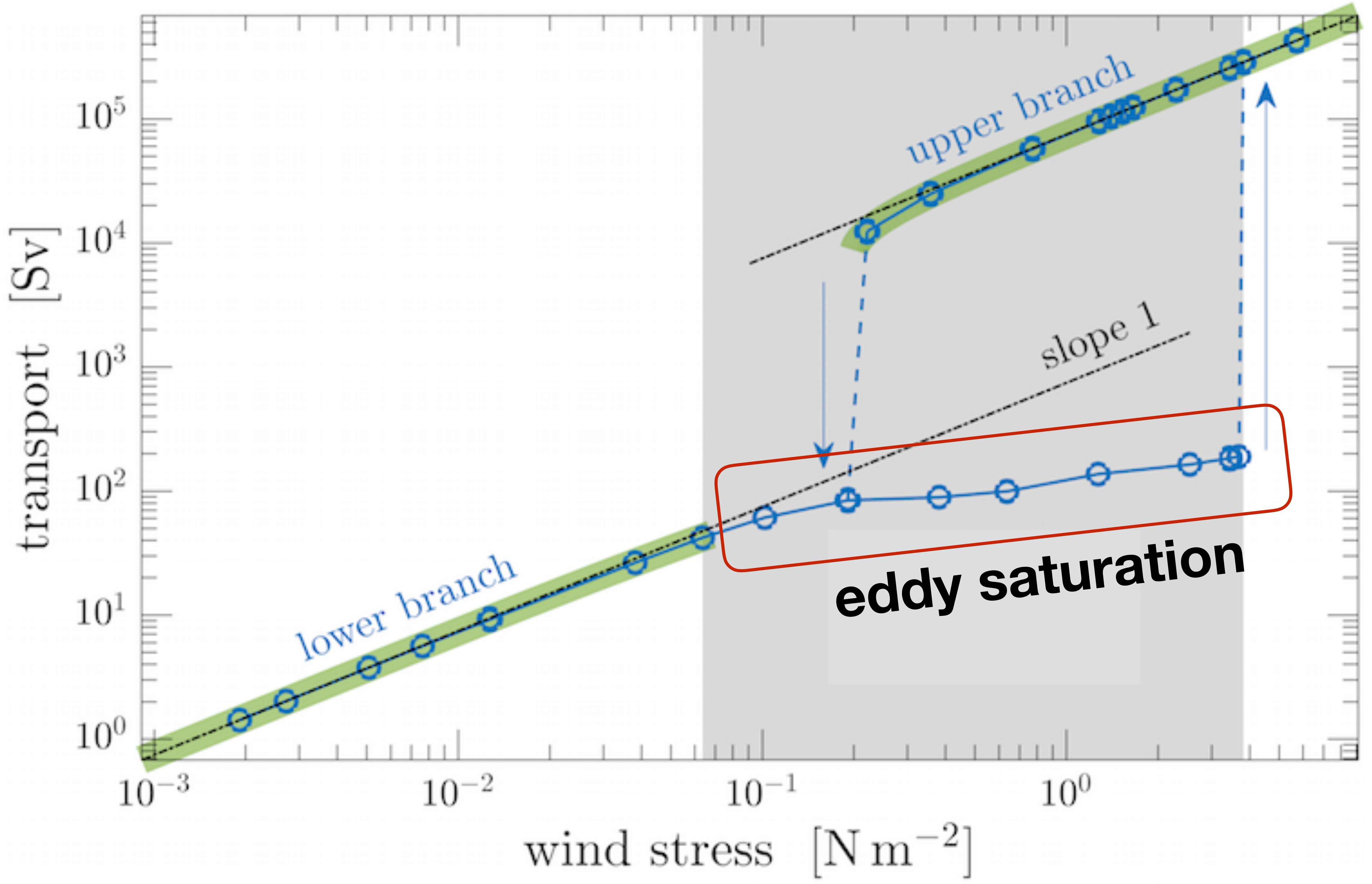
in the previous episode

[back in 2017, in a Portland far far away]

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.



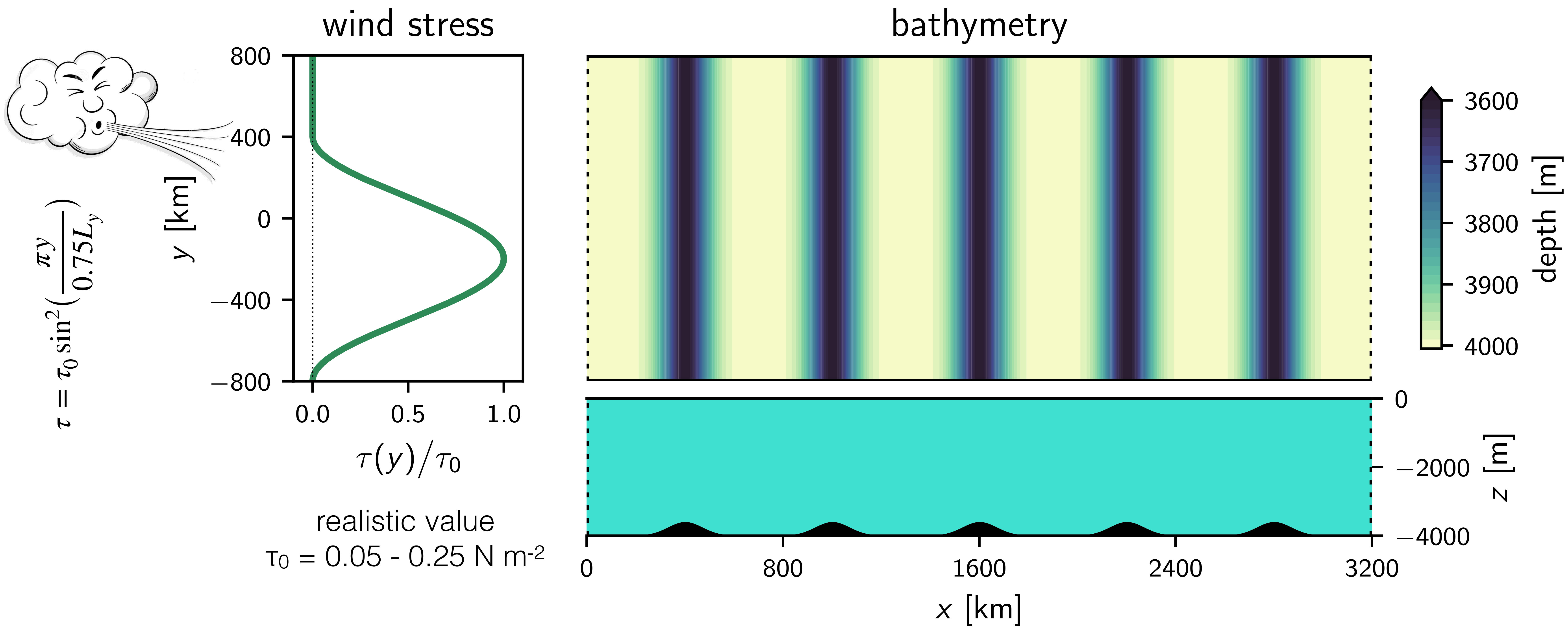
Constantinou & Young 2017, Constantinou 2018

what's the plan

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

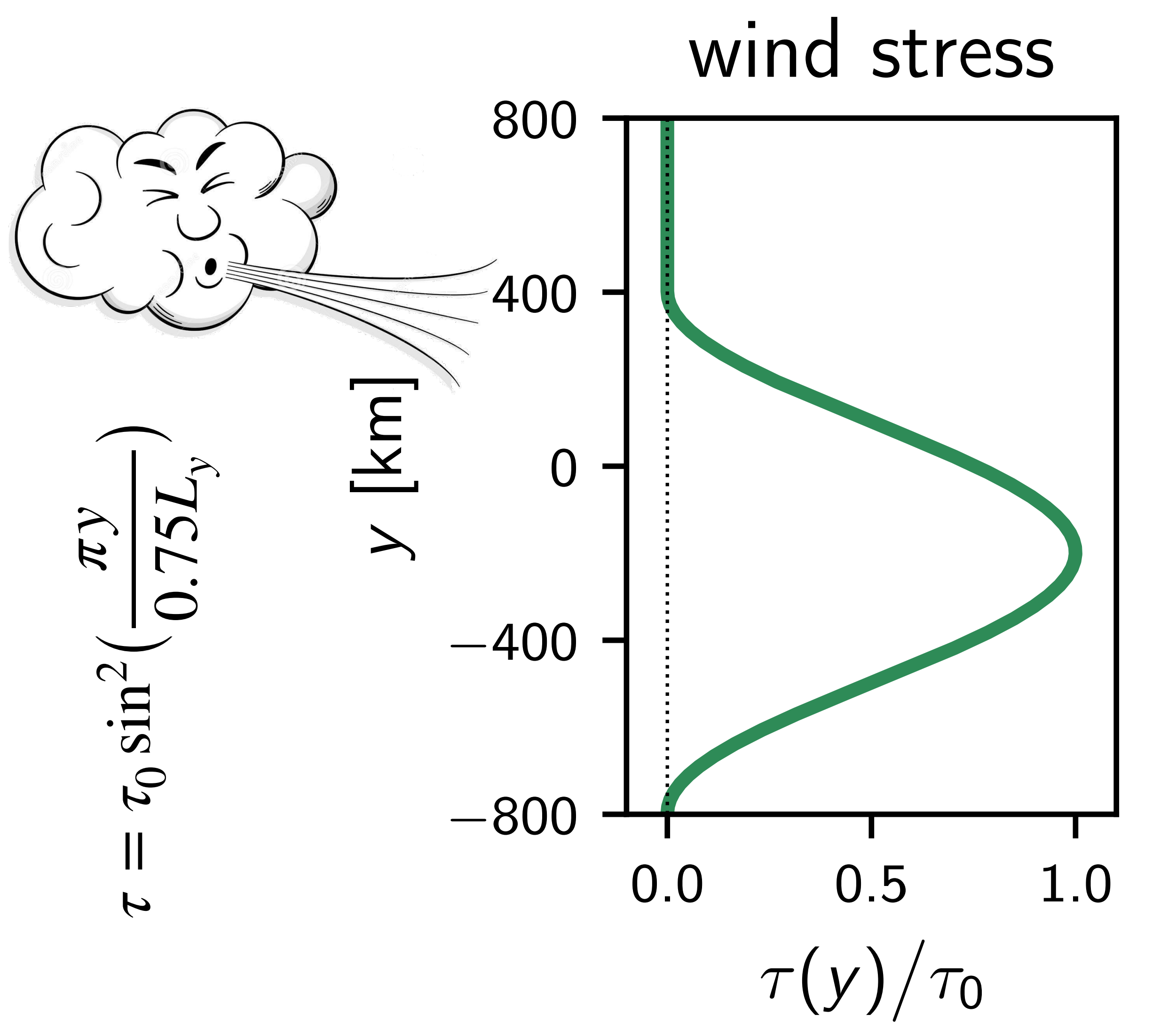


GFDL's MOM6
primitive equations
in isopycnal coordinates
Boussinesq approximation

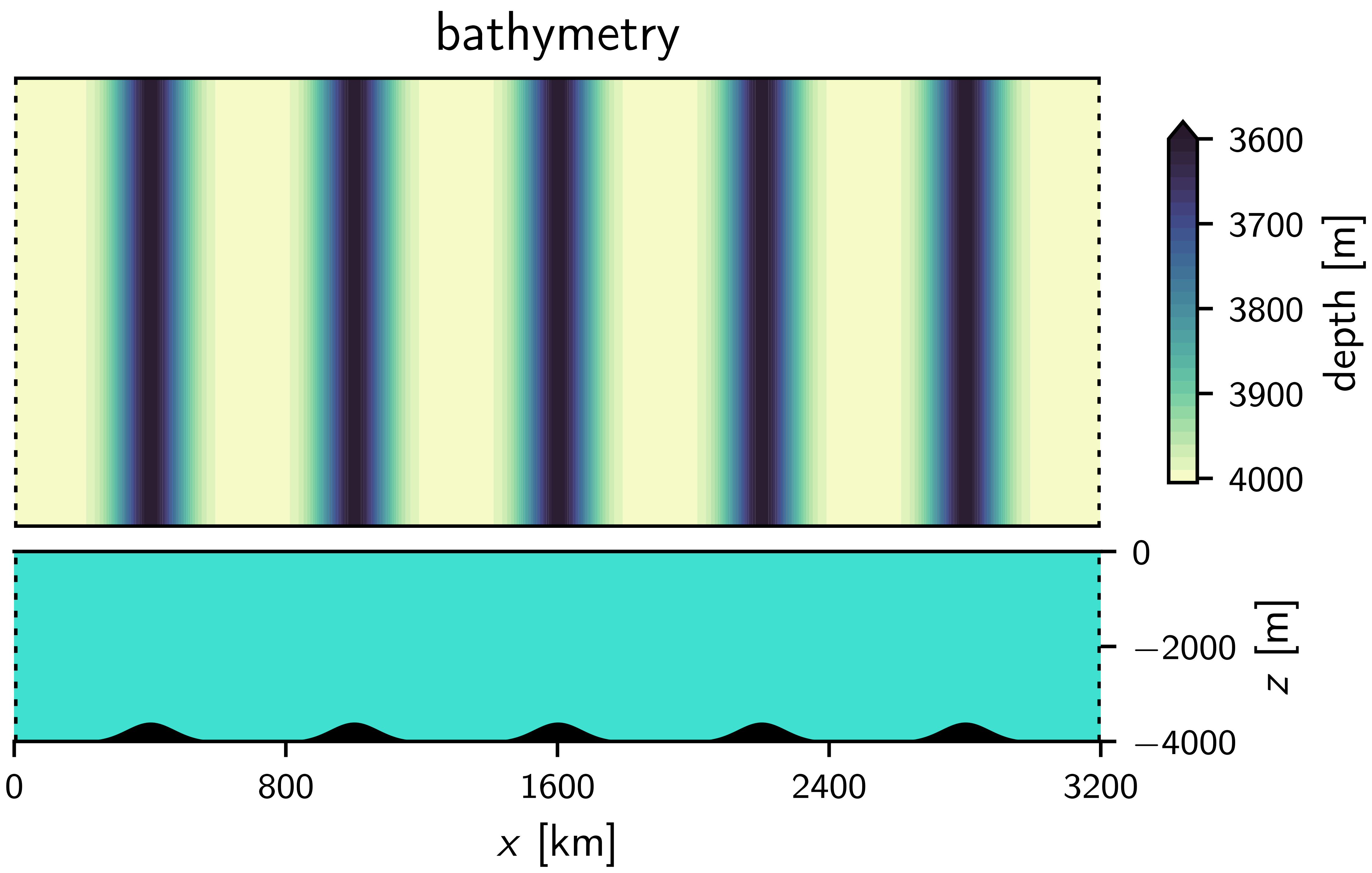
β-plane $\quad f = f_0 + \beta y$
1st deformation radius ≈19 km
zonally re-entrant
free surface
free-slip walls
quadratic bottom drag
grid spacing 4 km

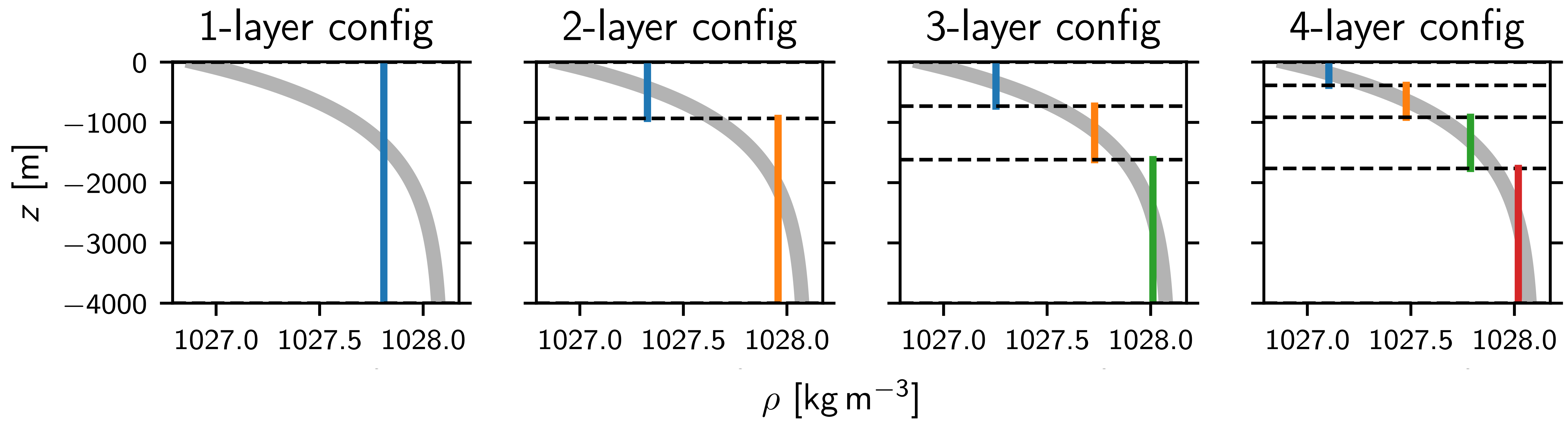
bathymetry:
Gaussian ridges
400 m tall, half-width 165 km

model setup



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





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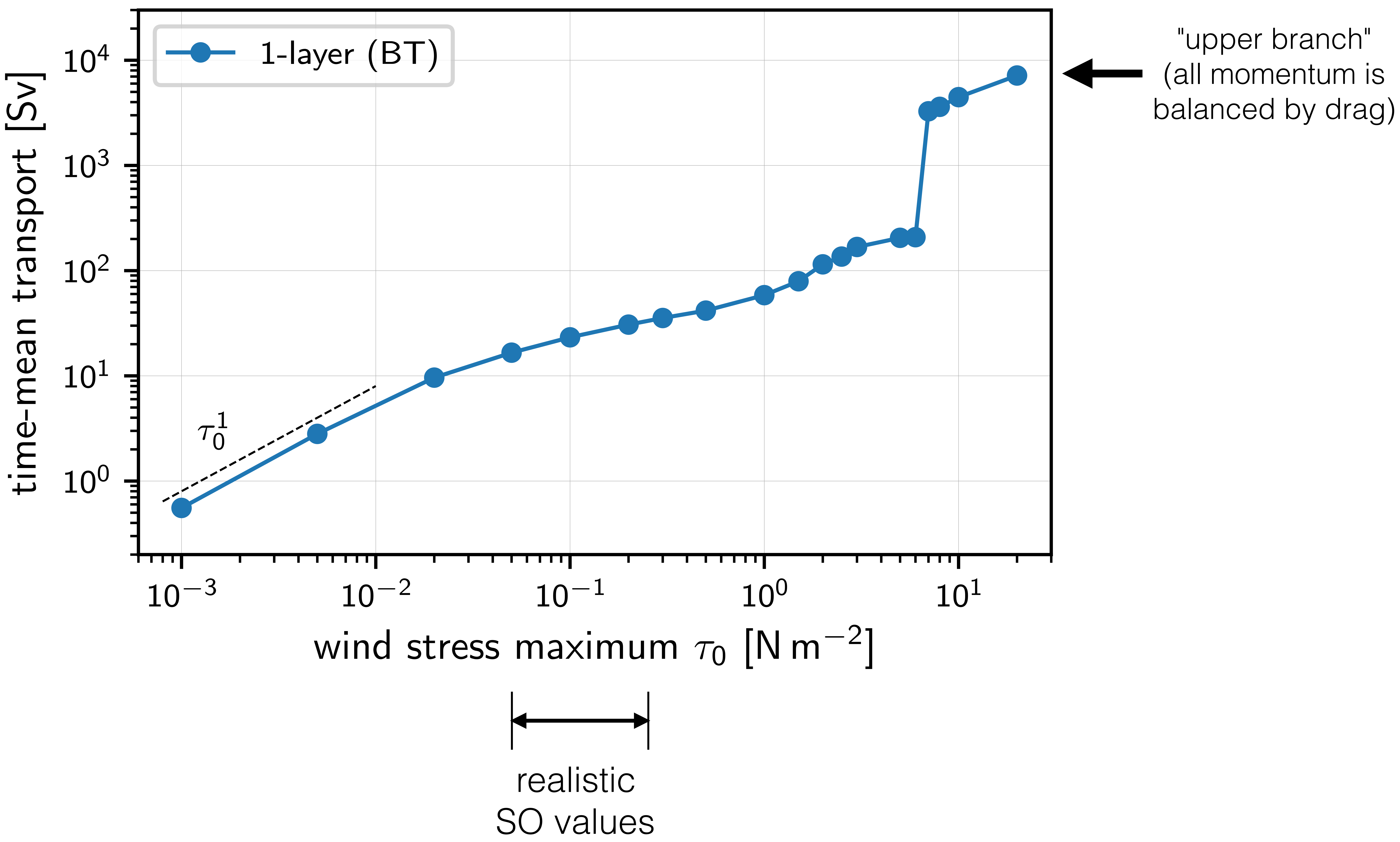
exponential density profile
$$\rho = \rho_0 + \Delta\rho\,(1 - e^{z/d})$$
$\Delta\rho$ =1.2 kg m^{-3}, d=1 km

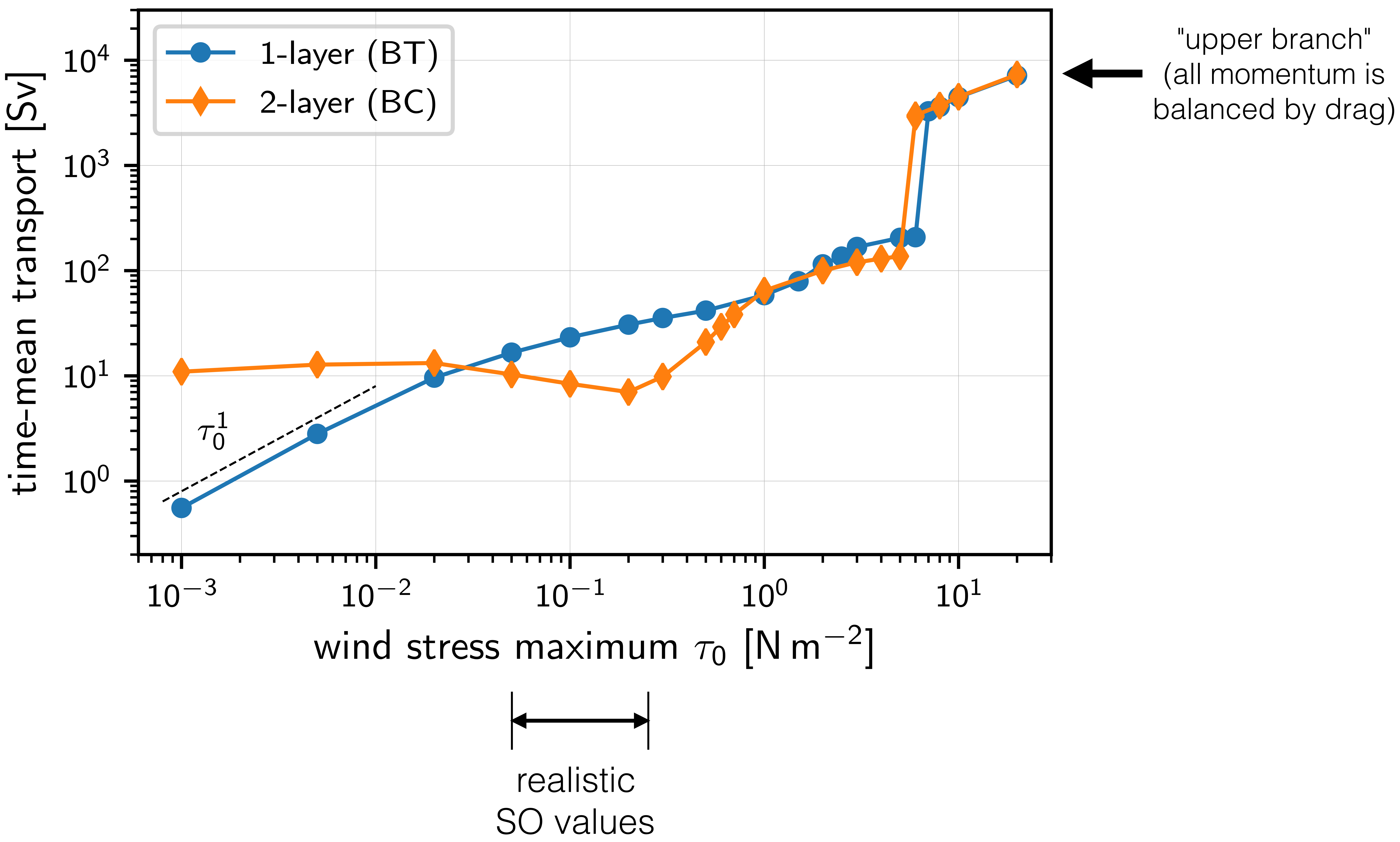
← layered approximations

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

mean zonal transport Vs wind stress



mean zonal transport Vs wind stress



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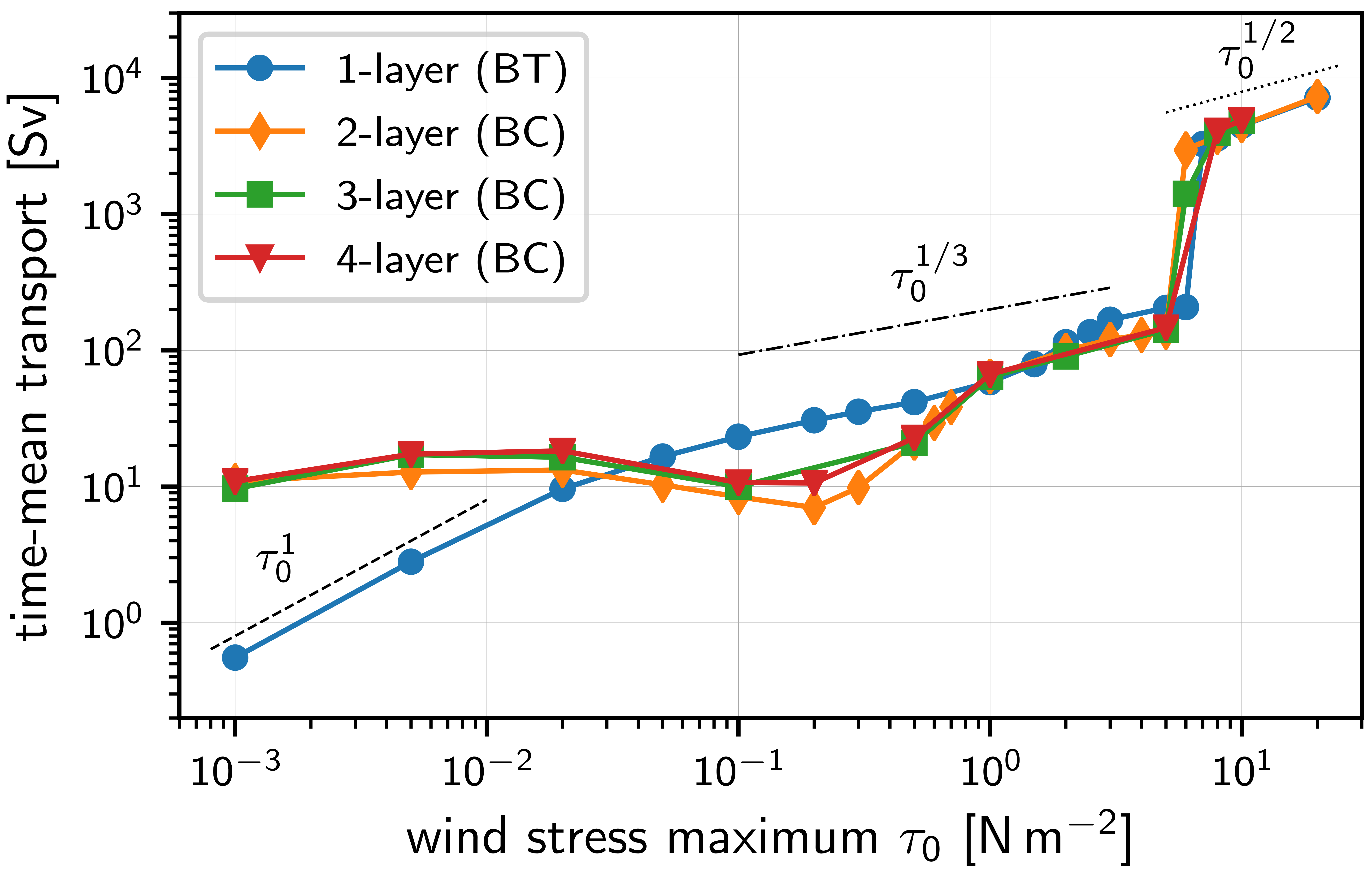
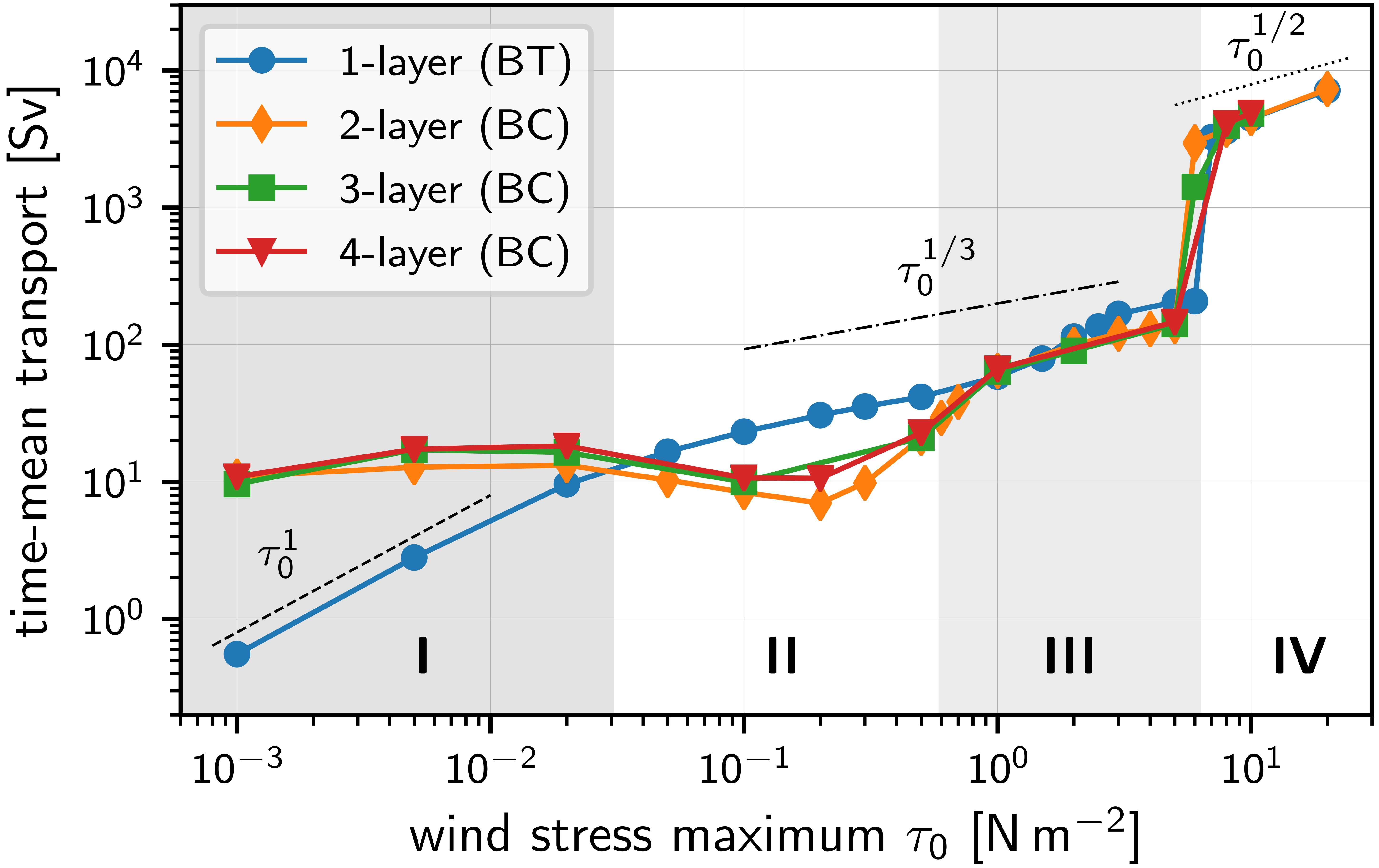


>3-layer configurations are the same as 2-layers
(as fas as the mean zonal transport is concerned)

mean zonal transport Vs 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}
II
$\tau_0 = 0.1$ N m^{-2}
III
$\tau_0 = 1.0$ N m^{-2}
IV
$\tau_0 = 8.0$ 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: signature of bathymetry appears in top-layer flow
BT: a strong jet develops
BC: bottom layer outcrops; strong jet seen 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}
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bottom layer outcrops

depth-integrated zonal momentum balance

$\langle\ \rangle$: layer average

$\overline{}$: time average

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

wind stress (WS)

topographic form stress (TFS)

bottom drag (BD)

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

only standing flow contributes to TFS

depth-integrated zonal momentum balance

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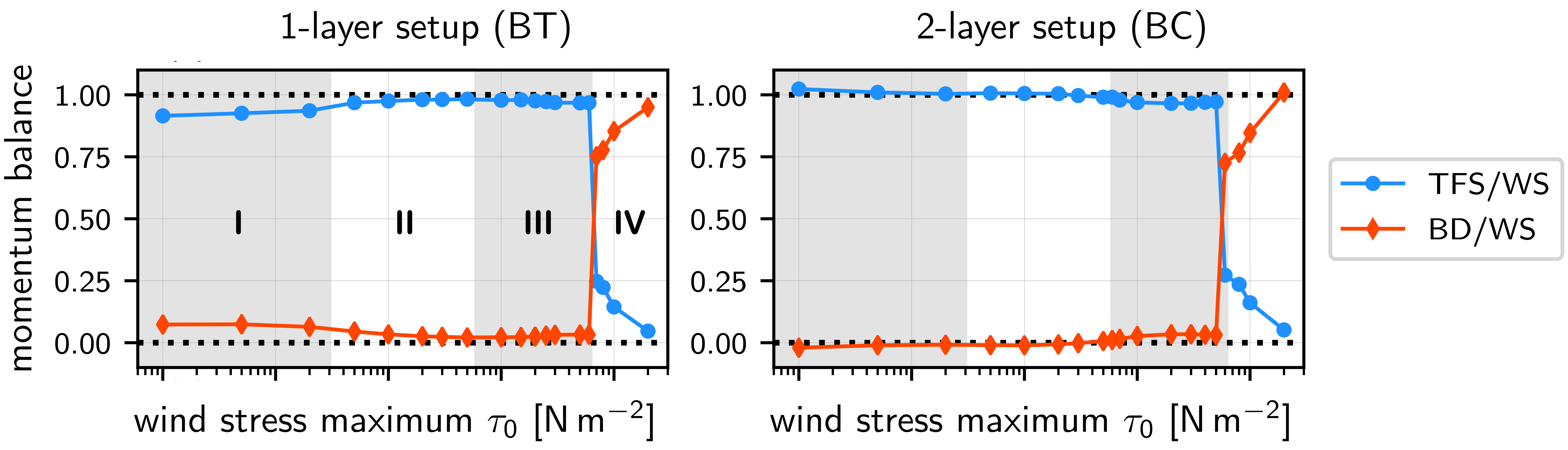
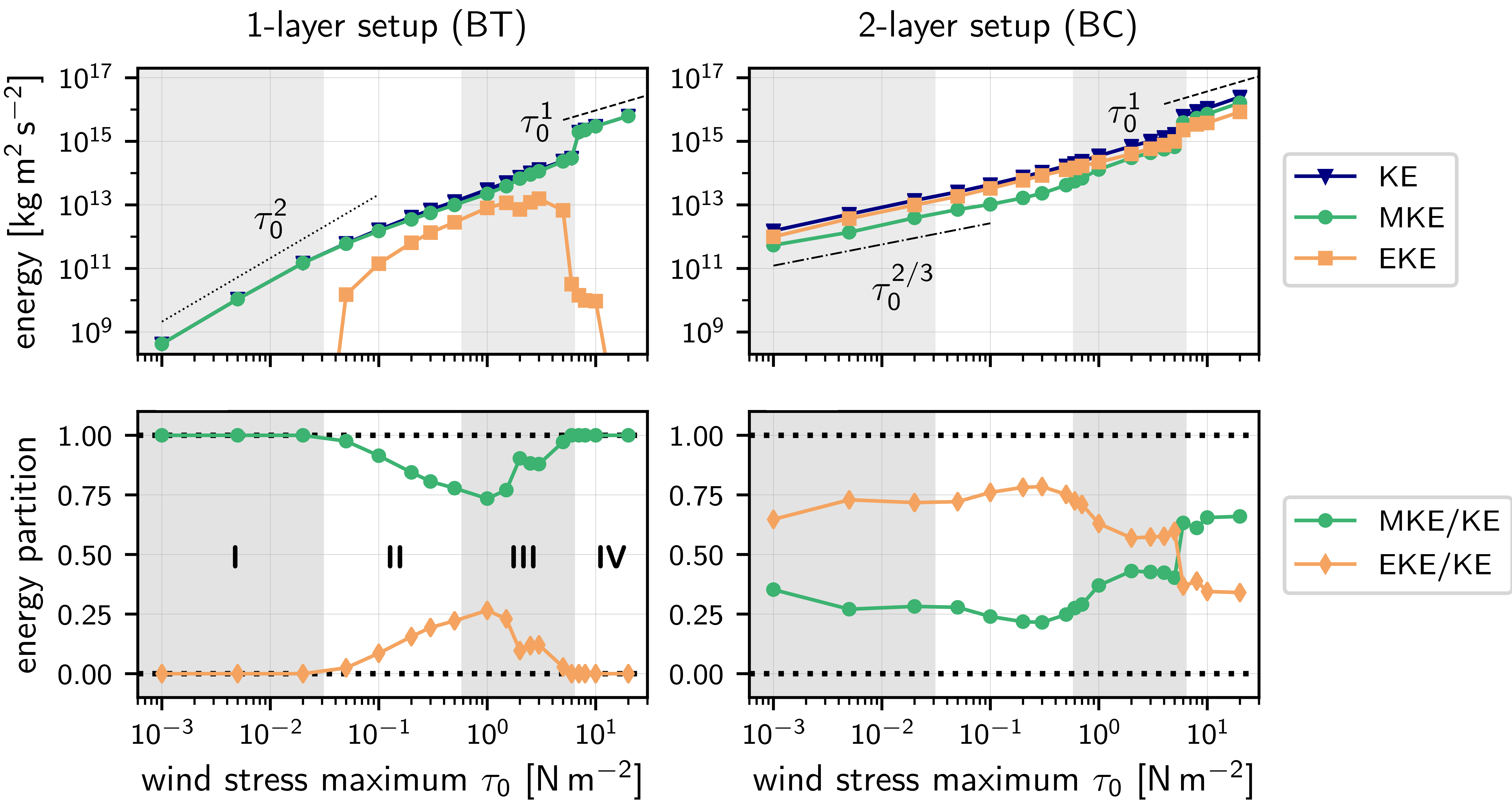


Almost *all* momentum is balanced by topographic form stress (except when flow transitions to "upper branch").

standing–transient kinetic energy decomposition

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



standing flow
dominates
in BT config;

transient flow
dominates in BC

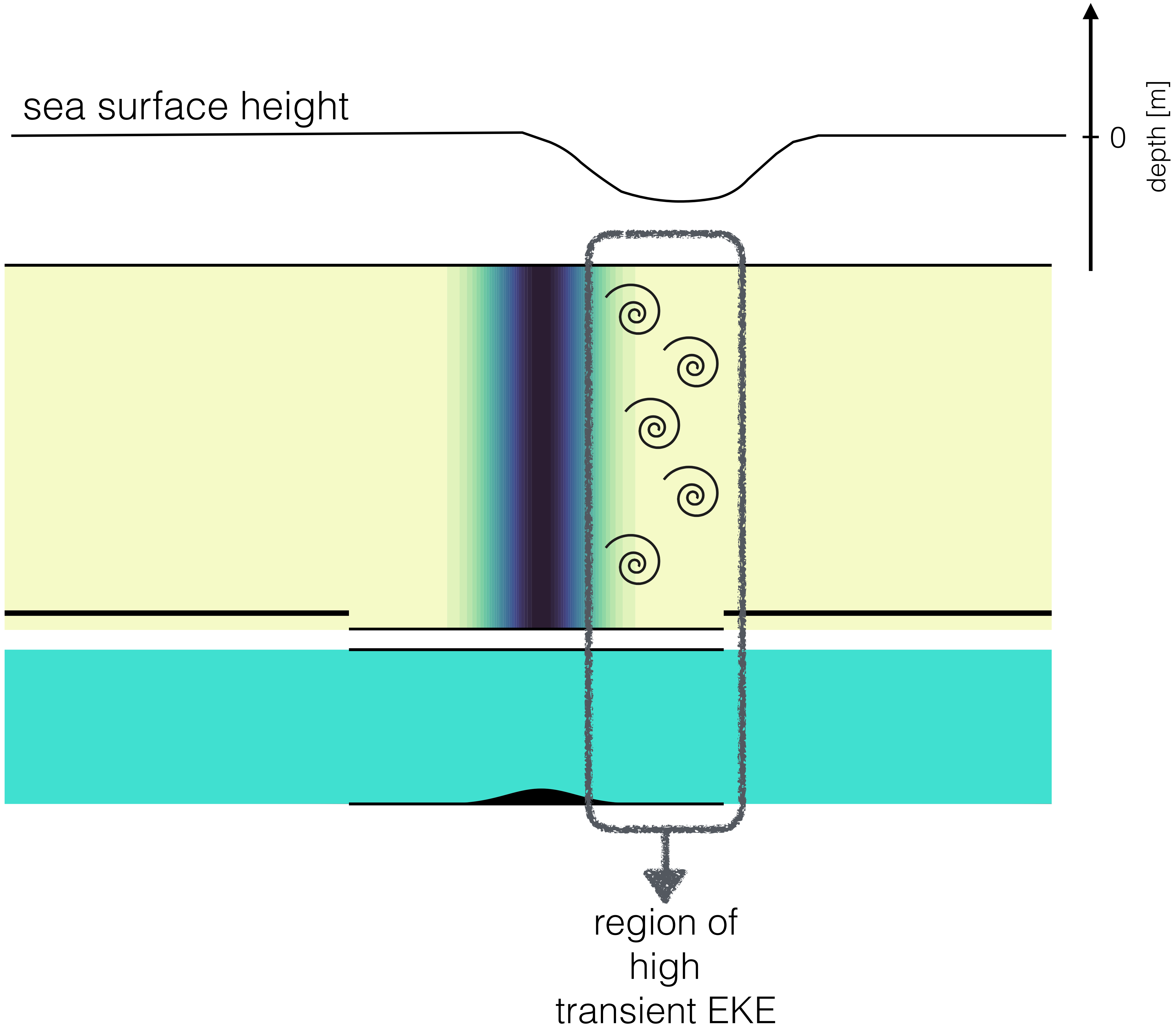
Despite the great differences in flow fields,
both **BT** and **BC** configs show *same* mean zonal transport for regimes **III** & **IV**.

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

only standing flow contributes to
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 & dowsteam the ridge

↓

topographic form stress

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

[Same process as 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) 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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thank you

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

extra slides

mean zonal transport Vs wind stress

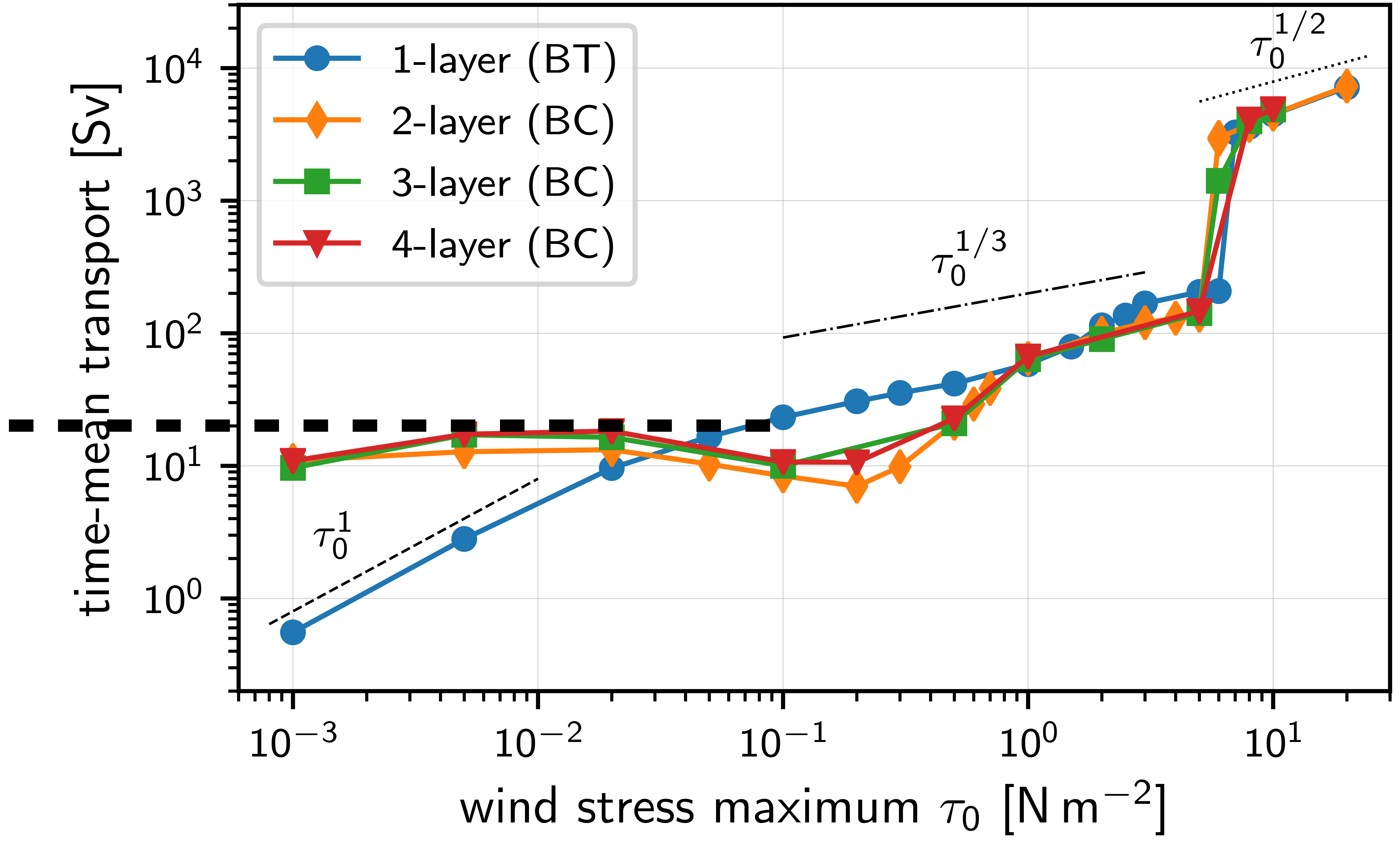
$$T = \lambda \frac{N}{|f|}\frac{H^2 L_y}{2\alpha_2} \approx 20\,\mathrm{Sv}$$

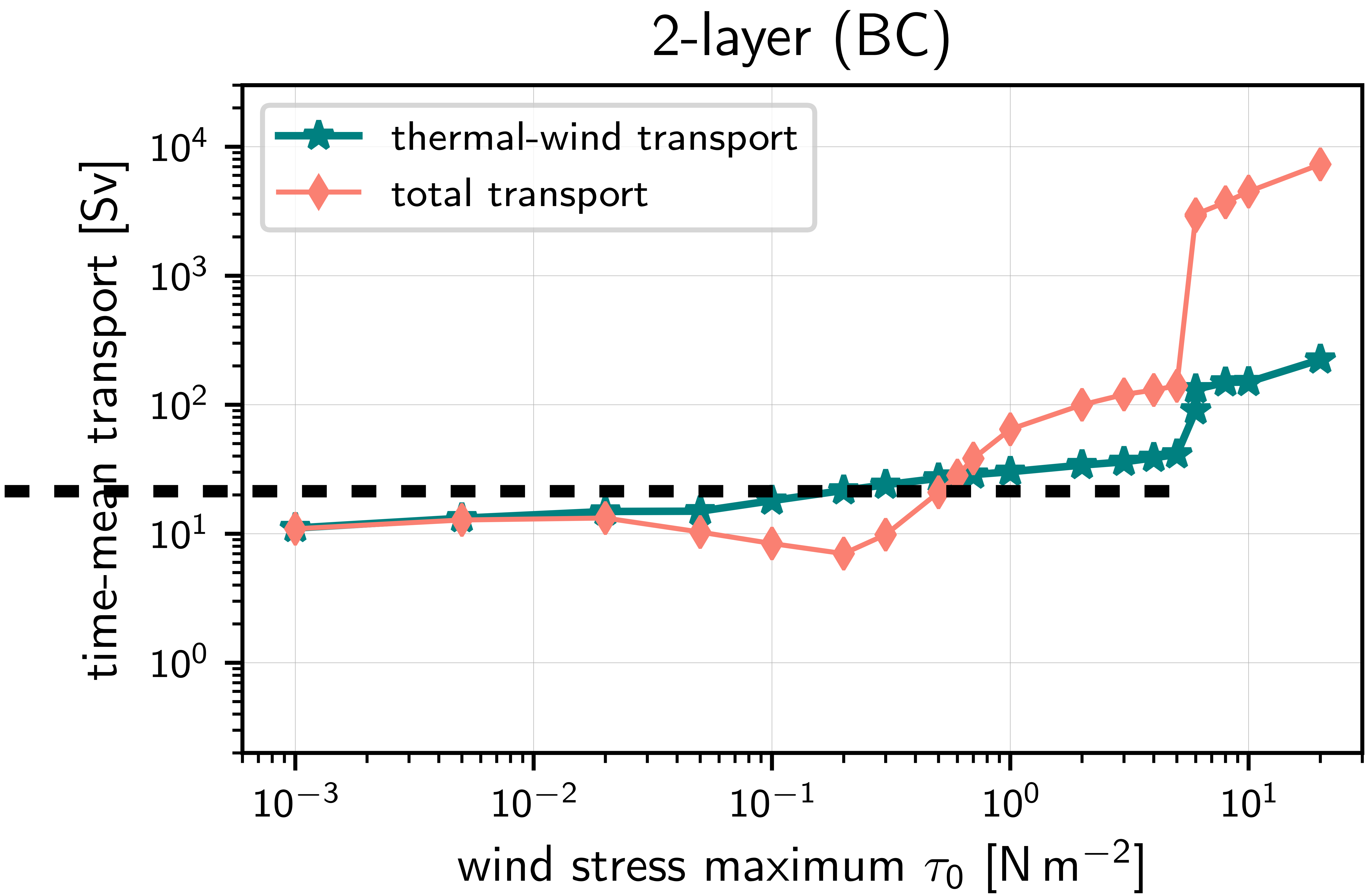
Marshall et al. 2017

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

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

$\alpha_2 = 0.61$





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