Eddy saturation of the Southern Ocean: a baroclinic versus barotropic perspective

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Abstract

"Eddy saturation" is the regime in which the total time-mean volume transport of an oceanic current is relatively insensitive to the wind stress forcing and is often invoked as a dynamical description of Southern Ocean circulation. We revisit the problem of eddy saturation using a primitive-equations model in an idealized channel setup with bathymetry. We apply only mechanical wind stress forcing; there is no diapycnal mixing or surface buoyancy forcing. Our main aim is to assess the relative importance of two mechanisms for producing eddy saturated states: (i) the commonly invoked baroclinic mechanism that involves the competition of sloping isopycnals and restratification by production of baroclinic eddies, and (ii) the barotropic mechanism, that involves production of eddies through lateral shear instabilities or through the interaction of the barotropic current with bathymetric features. Our results suggest that the barotropic flow-component plays a crucial role in determining the total volume transport.

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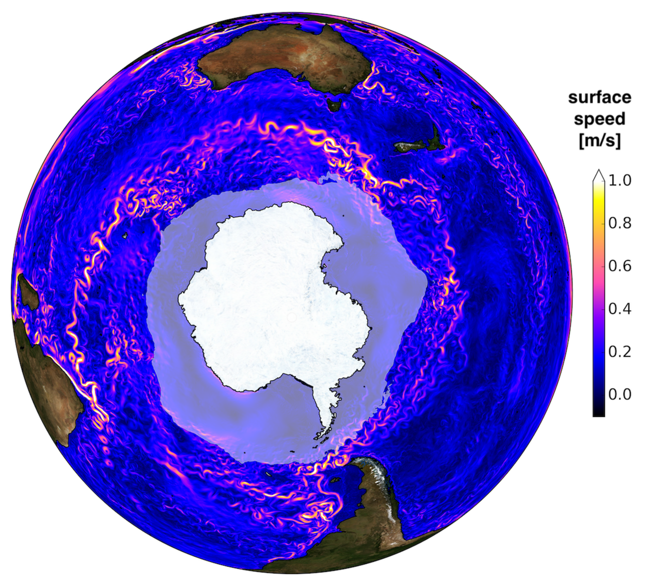
How does the Antarctic Circumpolar Current respond to the increasing winds over the Southern Ocean?

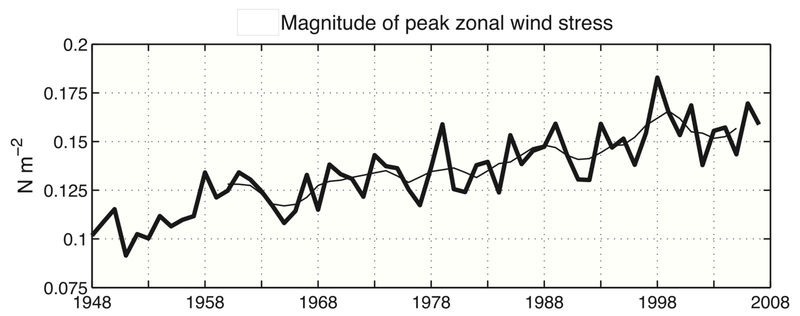
Motivation

The Antarctic Circumpolar Current (ACC) is an important driver of the global climate.



[ACCESS-OM2-010 sea surface speed, COSIMA Consortium]

Westerlies over the Southern Ocean that drive the ACC are getting stronger:



[Farneti et al. 2015]

How will the ACC respond to increasing winds?

"Eddy saturation"

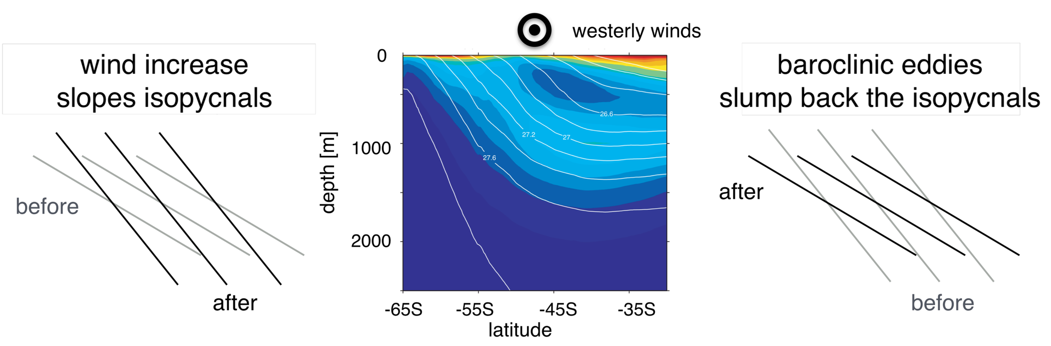
Many models (idealized & realistic) find that:

wind strength increases → ACC remains (almost) insensitive.

Excess momentum from the winds goes into eddies: **"eddy saturation"**

Textbook interpretation based on baroclinic instability

Depth-Latitude section of the Southern Ocean



[Meredith et al. 2012]

Eddies tap the excess energy due wind increase → ACC stays the same

Barotropic Eddy Saturation

Recently, it was shown that **barotropic** (depth-independent) flow **above bathymetry** can **also** show eddy saturation.

[Constantinou & Young 2017, Constantinou 2018]

This challenges the current paradigm...

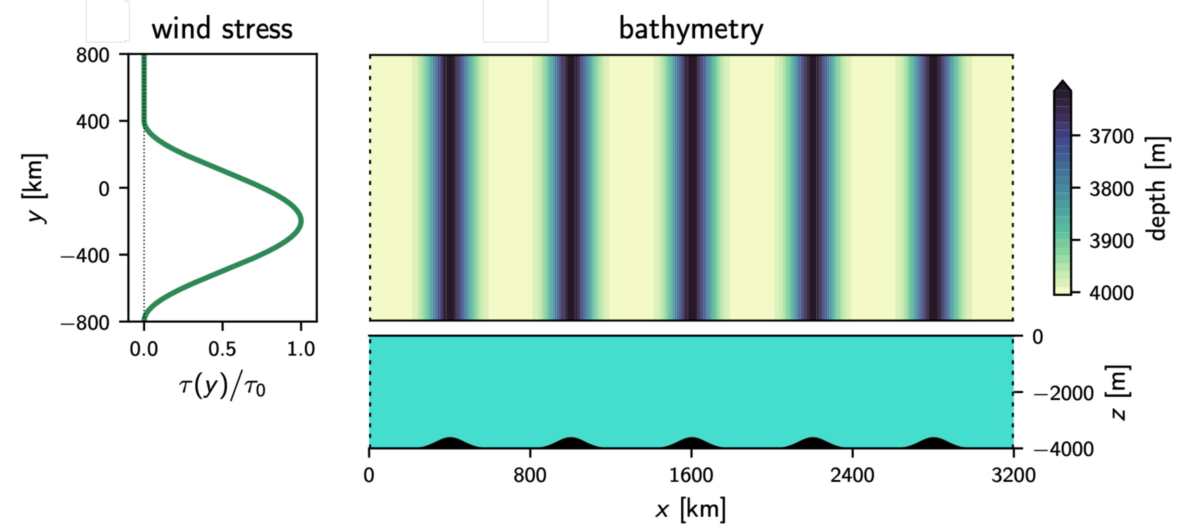
Objectives

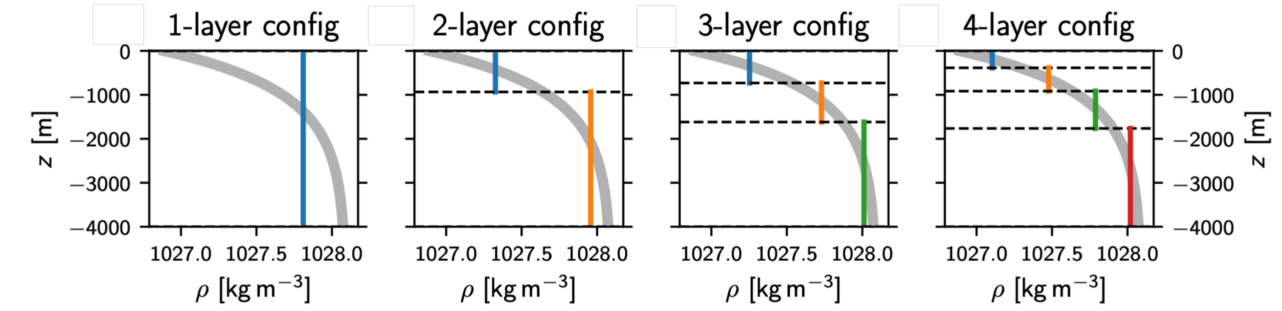
Demystify the physics behind eddy saturation:

- Establish whether barotropic flows show eddy saturation in a primitive-equation model.
- Assess the relative importance of barotropic and baroclinic processes in the observed eddy-saturated states.

Model

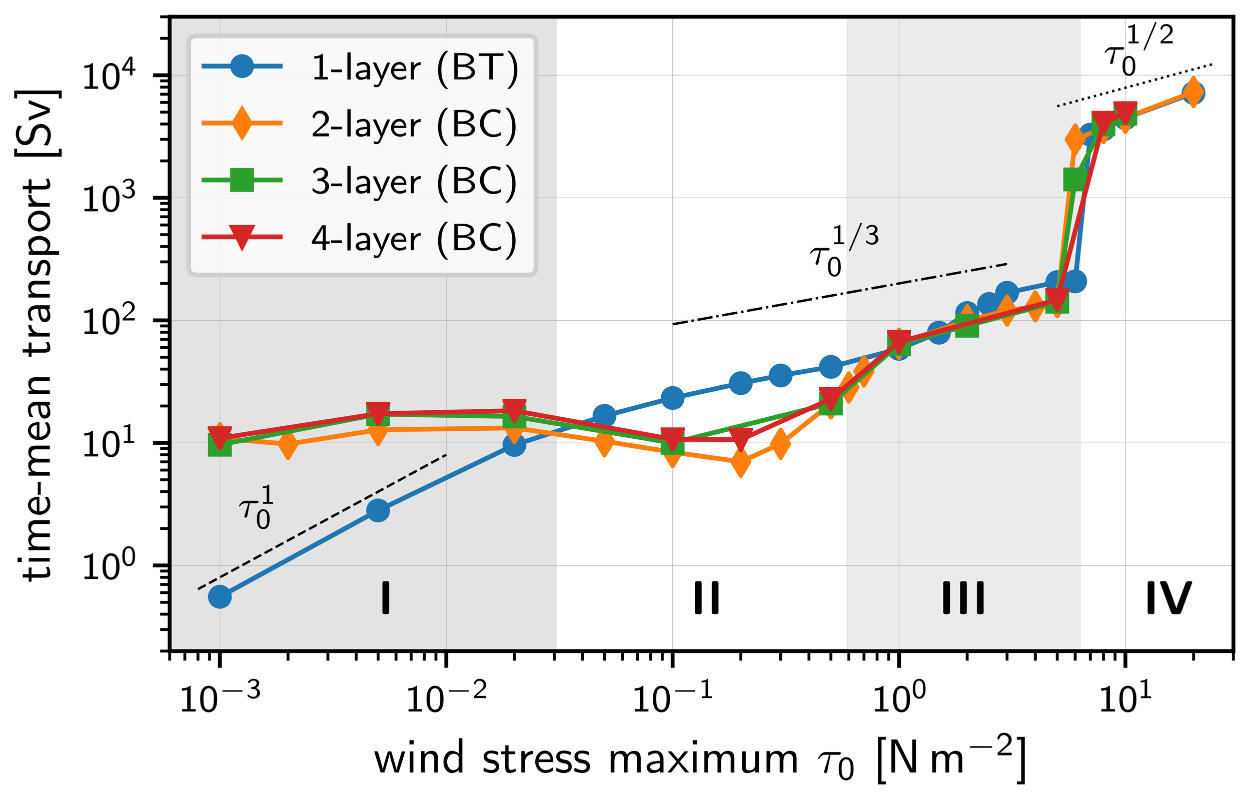
- Idealized re-entrant channel with 'bumpy' bottom
- $L_x = 3200\,\mathrm{km}$, $L_y = 1600\,\mathrm{km}$, and $H = 4\,\mathrm{km}$
- Beta-plane with Southern Ocean parameters
- Modest stratification (few fluid layers of constant ρ)
- 1st Rossby radius of deformation: 15.7 km (for ≥2 layers)
- Modular Ocean Model v6 (MOM6) in isopycnal mode





[wind stress, bathymetry, layered approximation of the stratification]

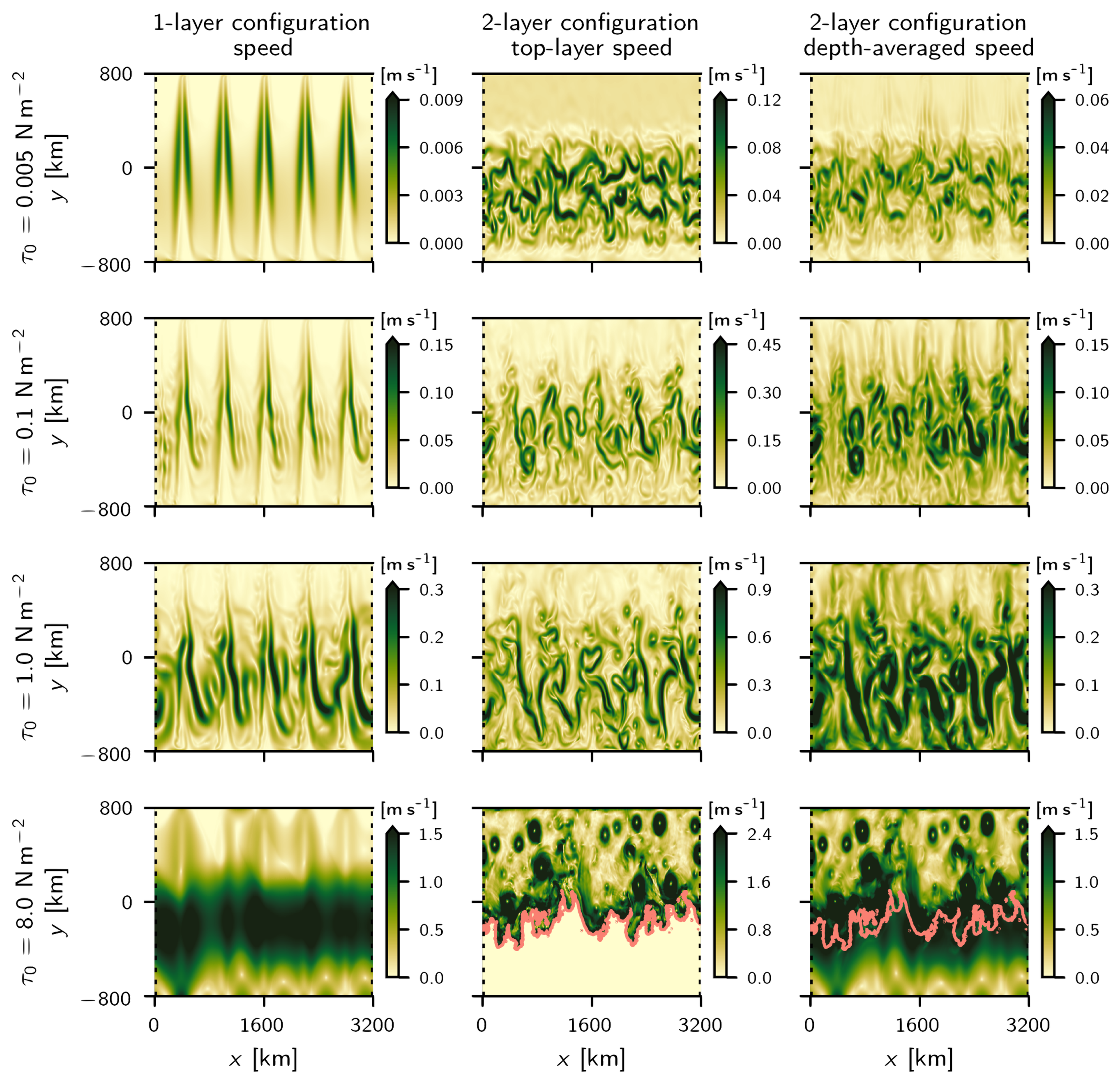
How transport scales with wind stress?



- Four distinct flow regimes.
- Baroclinic cases (# layers ≥ 2) show an eddy saturation regime.
- The single-layer case (barotropic) shows insensitivity to wind stress (transport grows only about 10-fold over 100-fold wind stress increase)

What does the flow look like?

Top-view snapshots for 1-layer (BT) and 2-layer (BC) configs:

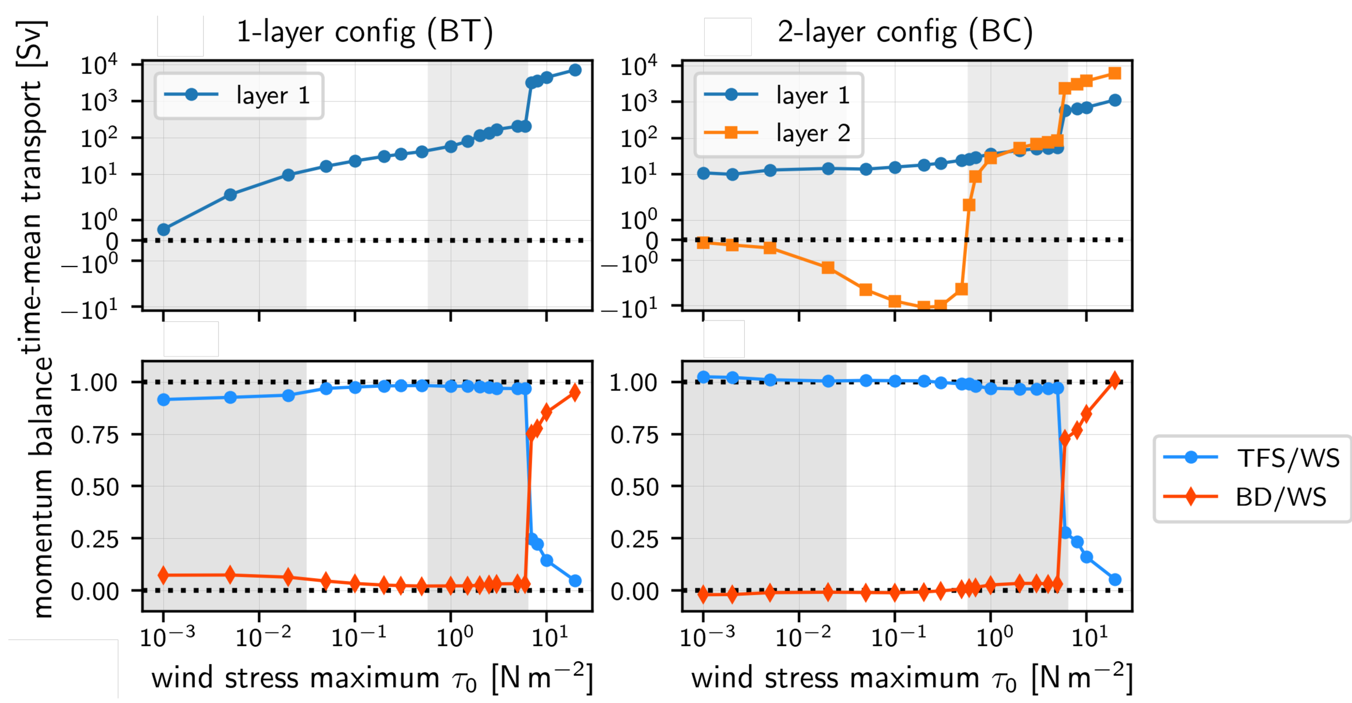


The 1-layer fluid configuration shows eddies. These eddies do not arise from baroclinic instability.

What balances the wind stress?

Depth-integrated, layer-wise average zonal momentum balance:

$$\underbrace{\langle \tau \rangle}_{\text{wind stress (WS)}} = \underbrace{\langle \overline{p_{\text{bot}}\, \partial_x h_{\text{bot}}} \rangle}_{\text{form stress (TFS)}} + \underbrace{\langle \rho_{\text{m}} c_D |\boldsymbol{u}_n| u_n \rangle}_{\text{bottom drag (BD)}}$$



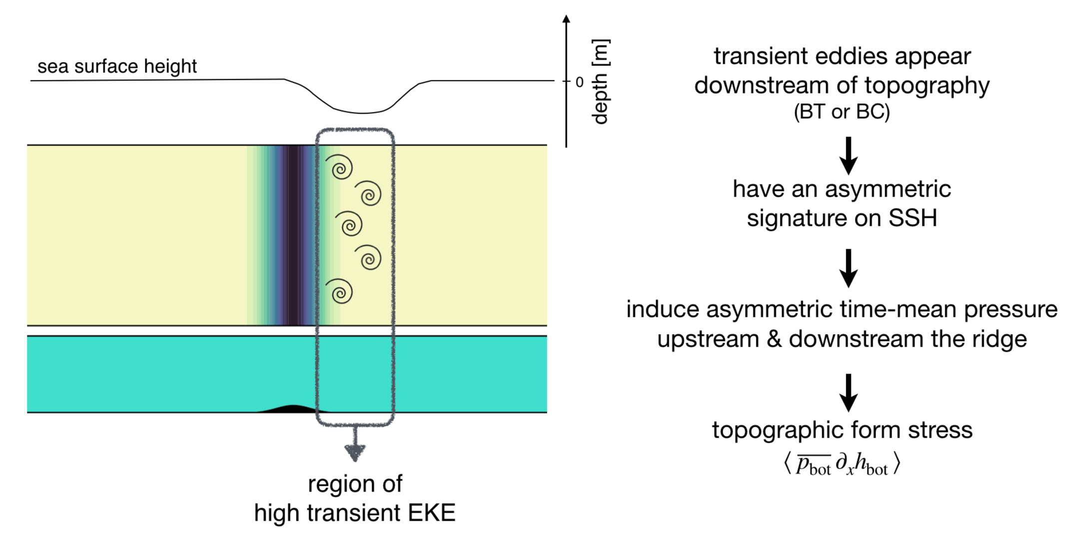
- Most of the momentum is balanced by topographic form stress.
- Flow shows a transition to a regime (IV) with high transport and in which the momentum balance changes.

(Consistent with Constantinou & Young 2017, Constantinou 2018)

How transient eddies affect mean momentum balance?

Transient eddies affect the momentum balance.

But transient eddies do not appear in TFS: $\langle \overline{p_{\text{bot}}\, \partial_x h_{\text{bot}}} \rangle = \langle \overline{p_{\text{bot}}}\, \partial_x h_{\text{bot}} \rangle$



Conclusions

- There exists a barotropic contribution to eddy saturation (e.g., for 0.05 < wind stress < 1.00).
- Barotropic eddy saturation relies on eddy production due to bathymetric features or lateral shear instabilities.
- This highlights the role of topographically-induced eddies.
- At high wind stress values there is a structural bifurcation to a strong zonal flow that does not "see" the topography.

Proposal

Eddy saturation results from the feedbacks between transient eddies and the mean flow that create topographic form stress and, in turn, balances the momentum input from wind stress.

This occurs *regardless* of the process from which the transient eddies originate.

References

Constantinou & Hogg (2019) Eddy saturation of the Southern Ocean: a baroclinic versus barotropic perspective. *GRL*, **46**, 12202–12212.

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Constantinou & Young (2017) Beta-plane turbulence above monoscale topography. *JFM*, **827**, 415-447.