Barotropic versus Baroclinic eddy saturation

Navid Constantinou[1] and Andrew M. Hogg[1]

[1]Australian National University

November 25, 2022

Abstract

Wind is an important driver of large-scale ocean currents, imparting momentum into the ocean at the sea surface. In particular, strong westerly winds help to drive the Antarctic Circumpolar Current, which of key importance for the global climate system. Over the past decades observations established that the strength of the westerlies over the Southern Ocean has increased as a result of climate change forcing. This increase is consistent with global climate model simulations. The future climate state depends strongly on how will the Antarctic Circumpolar Current respond to this strengthening. Eddy saturation is a theoretical regime where the transport of the current remains insensitive to the strengthening of the westerlies. Instead, the strengthening of the westerlies energizes transient eddies. Both satellite observations and numerical simulations suggest that the Antarctic Circumpolar Current is close to the eddy saturated limit. Traditionally eddy saturation has been attributed to baroclinic processes, but recent work suggests that barotropic processes that involve, e.g., standing meanders of the Antarctic Circumpolar Current, can also be responsible for producing eddy-saturated states. Here, we discus the different physical entities of the“usual” baroclinic eddy saturation as well as the recent notion of barotropic eddy saturation. We assess the relative importance of barotropic and baroclinic processes in producing eddy-saturated states using numerical simulations of primitive equations in an idealized setup. Lastly, we discuss potential implications these processes have on global ocean modeling.

Barotropic versus Baroclinic Eddy Saturation

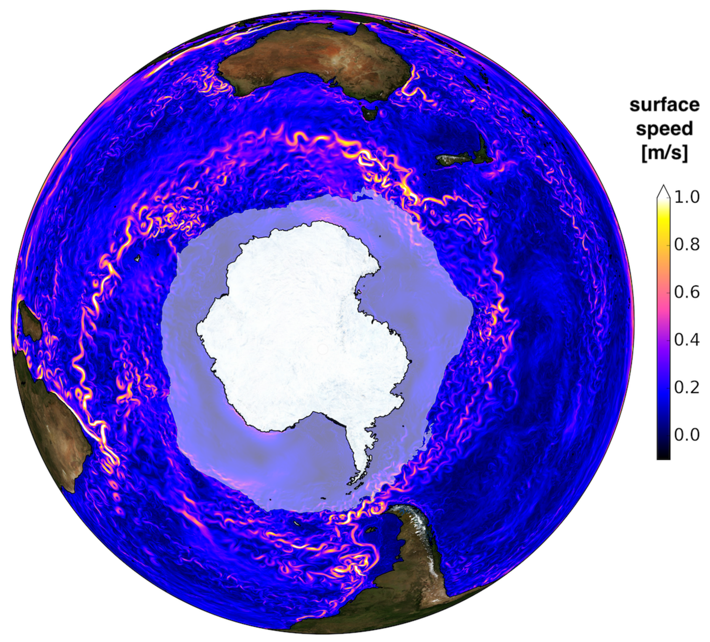
Navid C. Constantinou Andy McC. Hogg

Research School of Earth Sciences, Australian National University

How does the ACC respond to the increasing winds over the Southern Ocean?

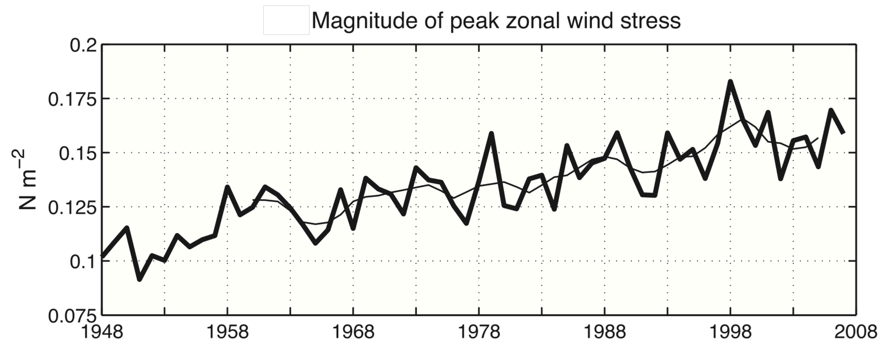
Motivation

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:

as the wind strength increases,
the ACC remains (almost) insensitive.

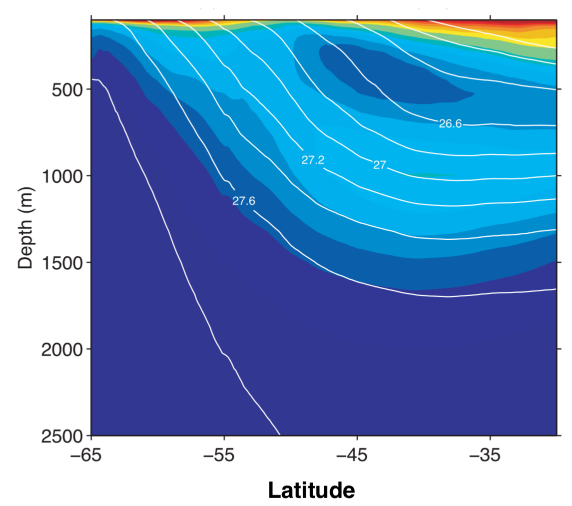
All excess momentum from the wind goes into eddies:

→ **"eddy saturation"**

Traditionally, a flow is "eddy saturated" if the volume zonal transport shows (substantially) less than linear increase with wind stress strength.

The "textbook" explanation is that:

increasing winds → isopycnals slope more → more available potential energy → more eddies produced by baroclinic instability → **the mean flow (ACC) stays the same**



[Meredith et al. 2012]

Barotropic Eddy Saturation

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

[Constantinou & Young 2017, Constantinou 2018]

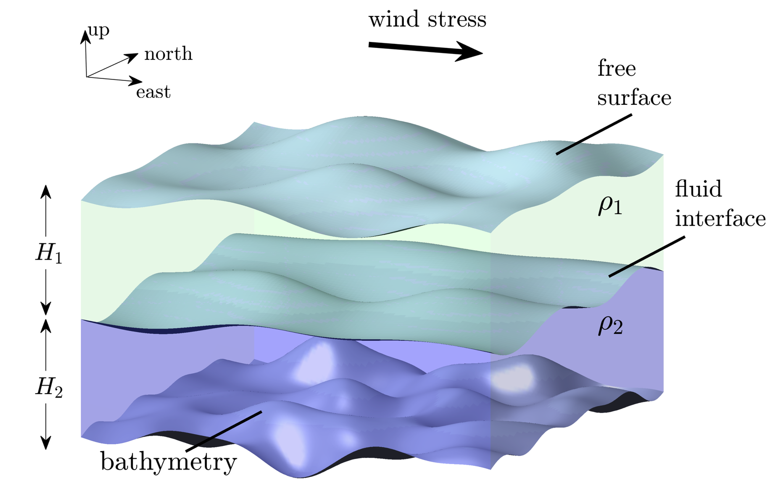
This challenges the current paradigm...

Objectives

Demystify the physics behind eddy saturation:

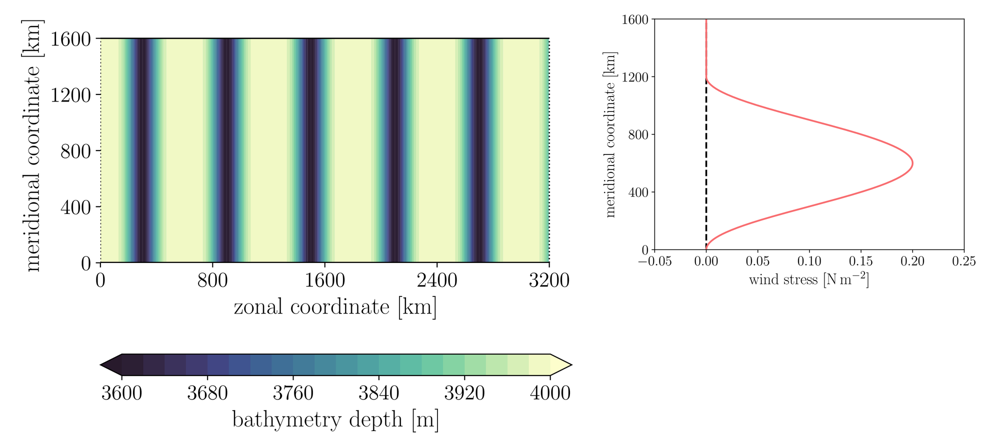
- Establish whether barotropic flows show eddy saturation in a primitive-equation model.
- Assess the relative importance of barotropic and baroclinic processes in the observed eddy-saturated states.

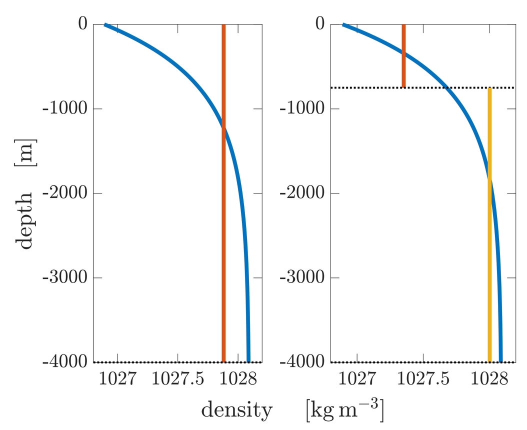
Model



[an example configuration with a two-layer fluid]

- Idealized re-entrant channel with 'bumpy' bottom
- $L_x = 3200\,\text{km}$, $L_y = 1600\,\text{km}$, and $H = 4\,\text{km}$
- 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

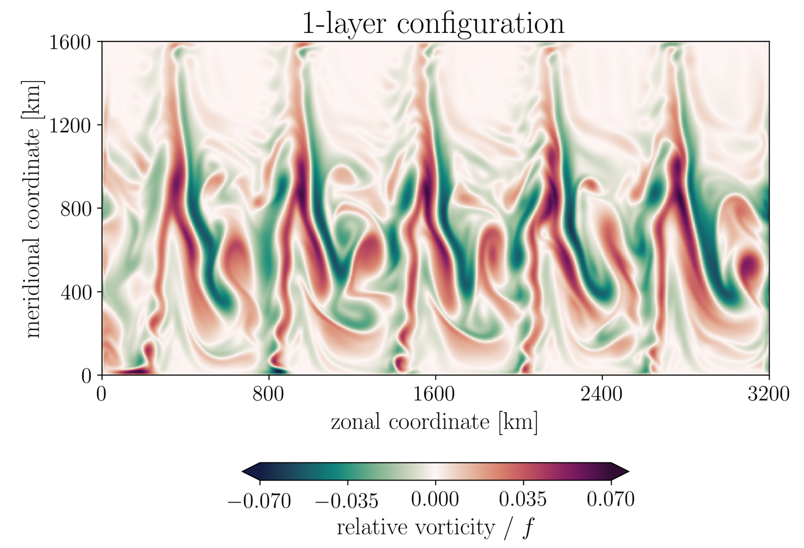


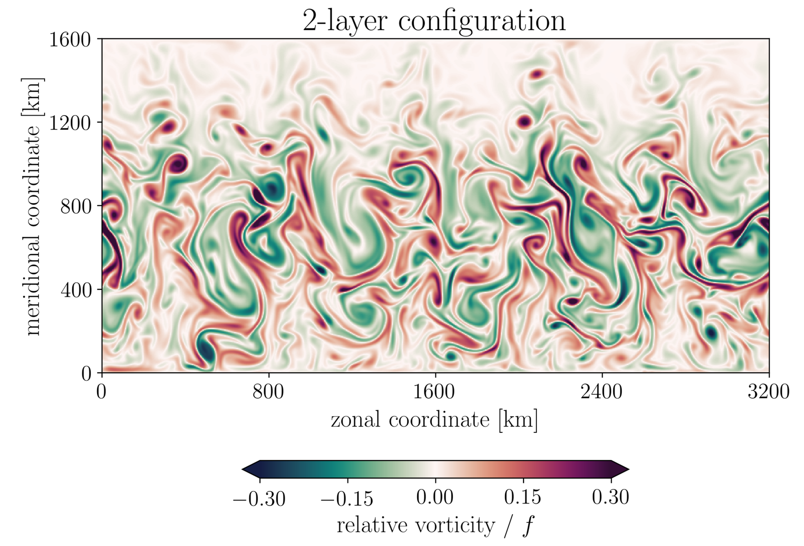


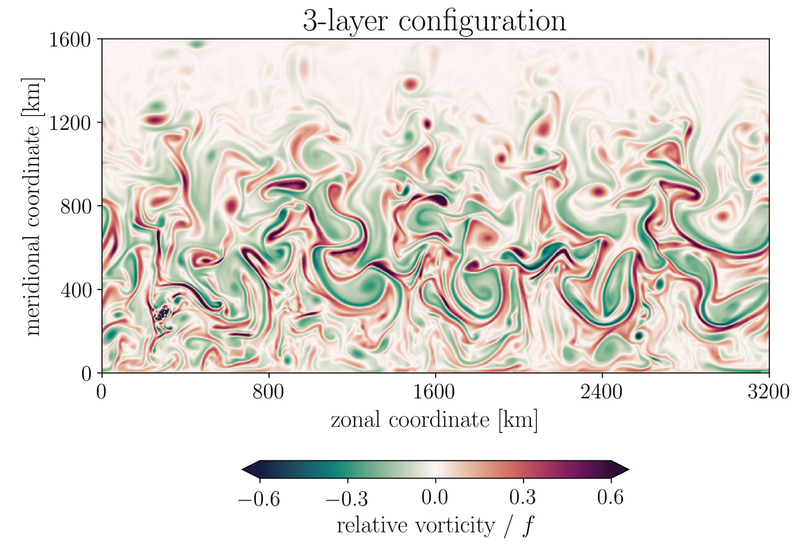
[bathymetry, wind stress, 1- and 2-layer stratification discretizations]

What does the flow looks like?

Vorticity in the top-fluid layer for wind stress peak $0.5\,\text{N}\,\text{m}^{-2}$:

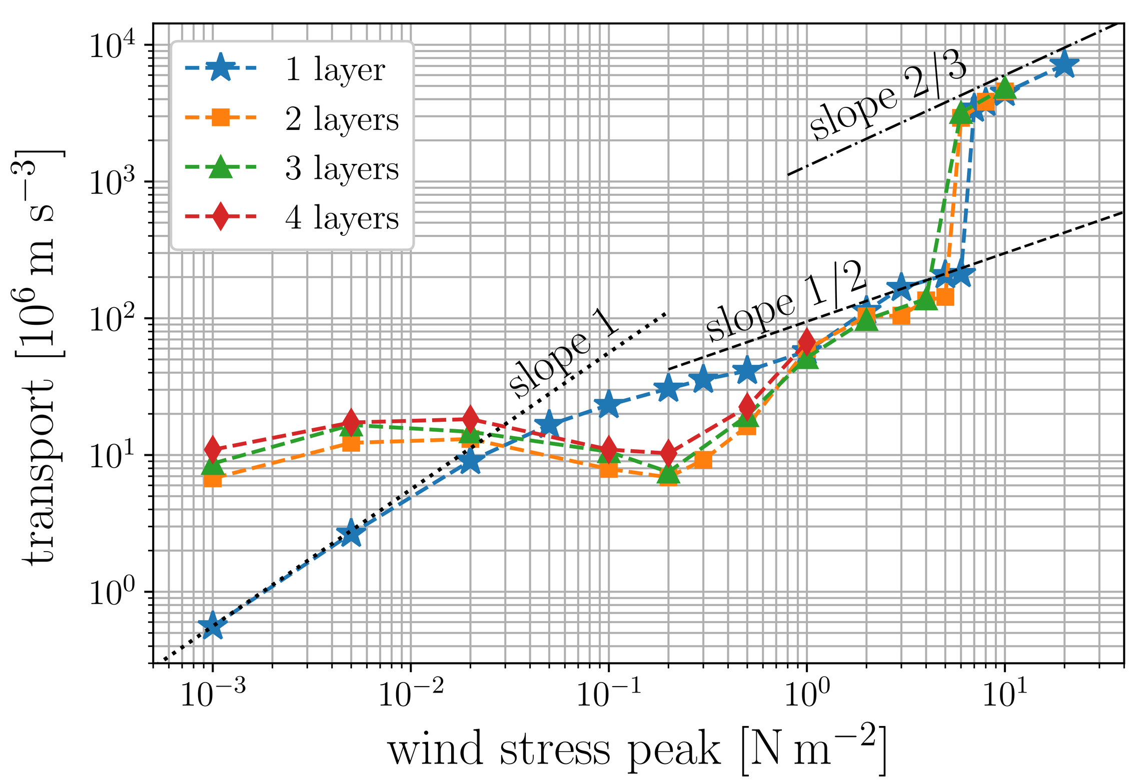






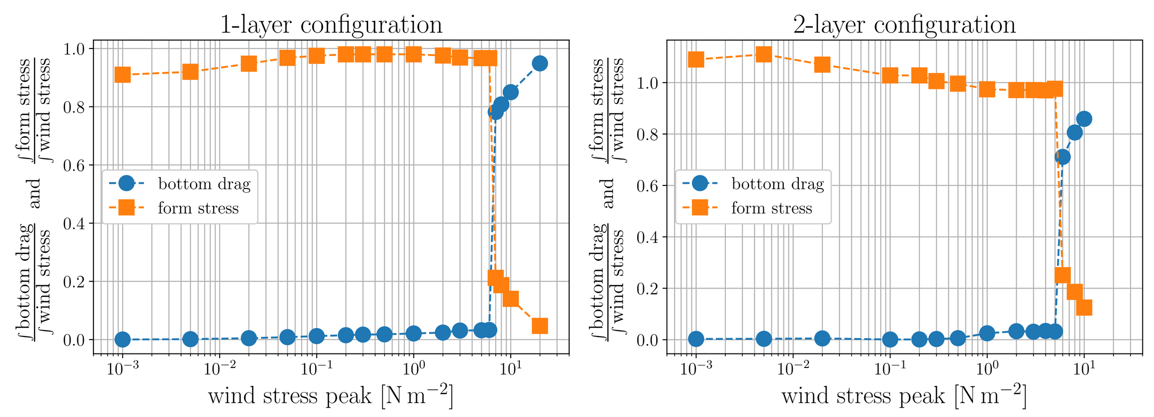
The 1-layer fluid configuration shows eddies. These eddies do not result from baroclinic instability.

How transport varies with wind stress?

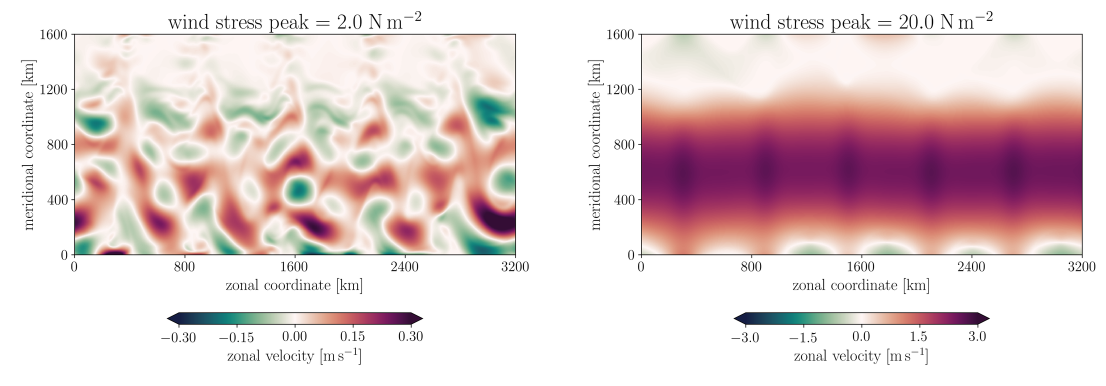


- Baroclinic cases (# layers ≥ 2) show an eddy saturation regime.
- The single-layer case (barotropic) shows insensitivity to wind stress (transport grows only about 10-fold over 100-fold wind stress increase)

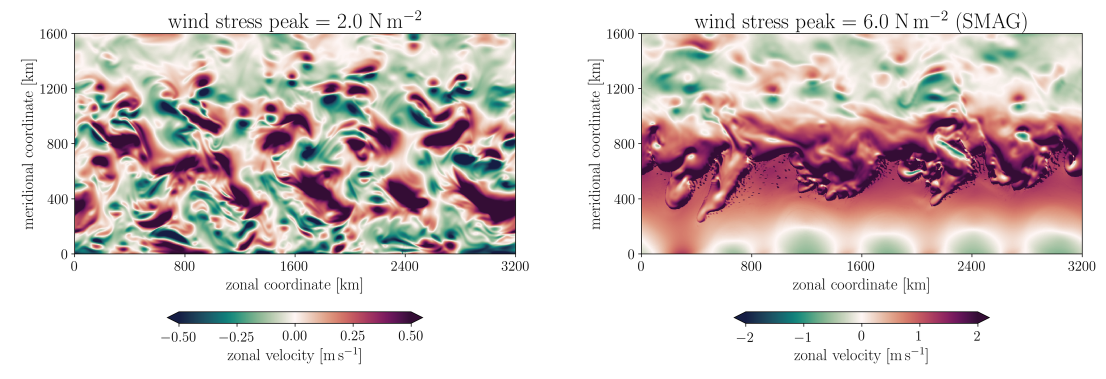
What balances the wind stress?



- Most of the momentum is balanced by bottom form stress.
- The flow shows a transition to a regime with high transport and in which the momentum balance changes. (Consistent with Constantinou & Young 2017, Constantinou 2018)



[zonal flow structure for 1-layer setup]



[top-layer zonal flow structure for 2-layer setup]

Conclusions

- There exists a barotropic contribution to eddy saturation (e.g., for 0.05 < wind stress < 1.00).
- The barotropic eddy saturation relies on eddy production due to bathymetric features.
- 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.

References

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

Constantinou (2018) A barotropic model for eddy saturation. *J. Phys. Oceanogr.*, **48 (2)**, 397-411.

Contact Information

www.navidconstantinou.com
navid.constantinou@anu.edu.au