Impact of Wind Stress Curl on the Eddy Saturation of the Antarctic Circumpolar Current from a Barotropic Perspective

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I. Introduction

- The strength of zonal transport of the Antarctic Circumpolar Current (ACC) is almost independent of the variations in westerly winds over the Southern Ocean; this phenomenon is called **eddy saturation**.
- The eddy saturation has been studied in both barotropic and baroclinic contexts in the presence of topography, yet many aspects of its dynamics remain elusive. ([?, ?, ?, ?, ?, ?, ?, ?, ?, ?])
- How does **the introduction of wind stress curl** affect the existence and characteristics of the eddy saturation regime found in barotropic QG model under constant wind stress?

Main Take Away

→Zonal transport depends on wind curl if the wind stress forcing has a negative component locally $\tau_{local} < 0$. If τ is always positive, zonal transport does not depend on τ_{curl}.
→The source of this asymmetric behavior is eddy momentum flux created by nonlocal instabilities (that generate Rossby waves).

II. Barotropic QG Model

- Solved using DEDALUS [?] where $L = 775$ km, $H = 4$ km, $h_{rms} = 200$ m [?] in a **doubly periodic 2D domain** with size $2\pi L \times 2\pi L$, and 512×512 grid.
  (1) Monochromatic topography **(2)** Single ridge topography

$$\eta = \sqrt{2}\eta_{\rm rms}\cos\left(\frac{14x}{L}\right) \qquad \eta = 2\sqrt{2}\eta_{\rm rms}\exp\left(-\frac{x^2}{2\,(L/14)^2}\right).$$

- The vorticity and momnetum equations are given below where **the total streamfunction is** $-Uy + \psi'$.
  $\langle\rangle$ is the domain mean and the $\overline{}$ is the time mean over the steady-state solution:

$$\partial_t\nabla^2\psi' + J\left(\psi' - Uy, \nabla^2\psi' + \eta + \beta y\right) = -\underbrace{D\nabla^2\psi'}_{\text{Ekman drag + hyperviscosity}} - \underbrace{\frac{\tau_y}{\rho_0 H}}_{\text{wind curl}} \qquad (1)$$

$$\partial_t U = \underbrace{\frac{\tau_{const}}{\rho_0 H}}_{\text{wind forcing}} - \underbrace{\mu U}_{\text{bottom drag}} + \underbrace{\langle\overline{\psi'_x\eta}\rangle}_{\text{topographical form stress}} \qquad (2)$$

- The wind profile contains a component τ_{const} that is constant over the domain, and a second component τ_{curl} that varies over y.

$$\tau_w^x = \tau_{const} - \tau_{curl}\cos\left(\frac{2\pi y}{L_y}\right) \qquad (3)$$

- The eddy kinetic energy is decomposed into the total eddy kinetic energy (EKE) and standing eddy kinetic energy (sEKE).

$$\text{EKE} = \frac{1}{2}\langle\overline{|\nabla\psi|^2}\rangle \qquad \text{sEKE} = \frac{1}{2}\left\langle|\nabla\bar{\psi}|^2\right\rangle$$

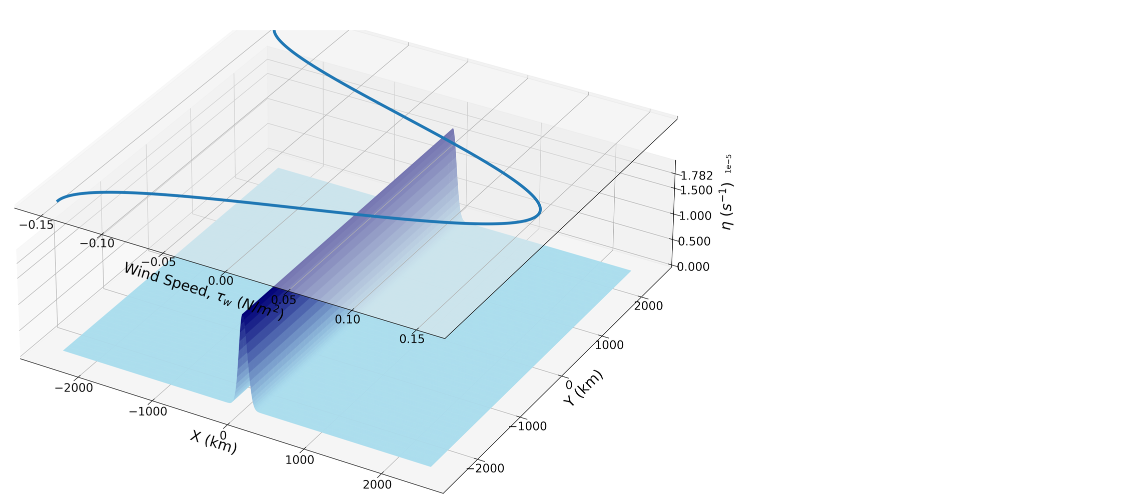

Figure 1. Single ridge topography and wind forcing example where $\tau_{const} = 0$ and $\tau_{curl} = 0.14\ N/m^2$.

III. Eddy Saturation with Uniform Wind

We validate our method against Constantinou (2018) [?] for a uniform wind profile where $\tau_{curl} = 0$ and τ_{const} is changing in magnitude.

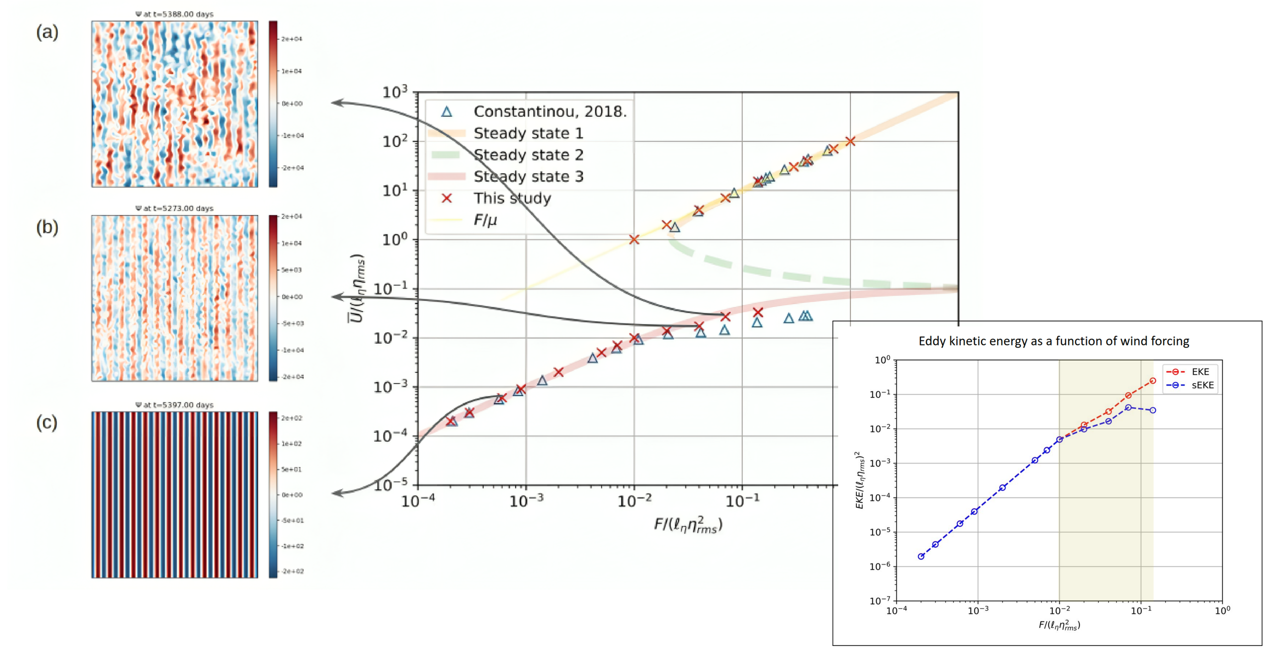

Figure 2. (Left) The time-mean large-scale domain averaged zonal nondimensional flow U as a function of nondimensional mean forcing. The highlighted lines show the analytical steady-state solutions. [?] (Right corner) The nondimensional EKE and sEKE as a function of the nondimensional wind forcing.

- Lower branch region (shown in 2c) before the eddy saturation regime is dominated by the **form stress and wind forcing** terms and shows laminar characteristics.
- In the eddy saturation region (shown in 2a and 2b), EKE increases, while the mean zonal transport and sEKE stay nearly constant.
- Higher branch region is dominated by **bottom drag and wind forcing** and exhibits laminar characteristics.

Research Questions

→Does the eddy saturation depend on wind variation across the domain (i.e. wind curl)?
→What are the underlying dynamics for nonlocal sources of momentum?

IV. Sensitivity of the Volume Transport and Eddies to the Wind Curl with Zero Mean Wind Forcing

How does transport change where $\tau_{constant} = 0$ and τ_{curl} is changing in magnitude?

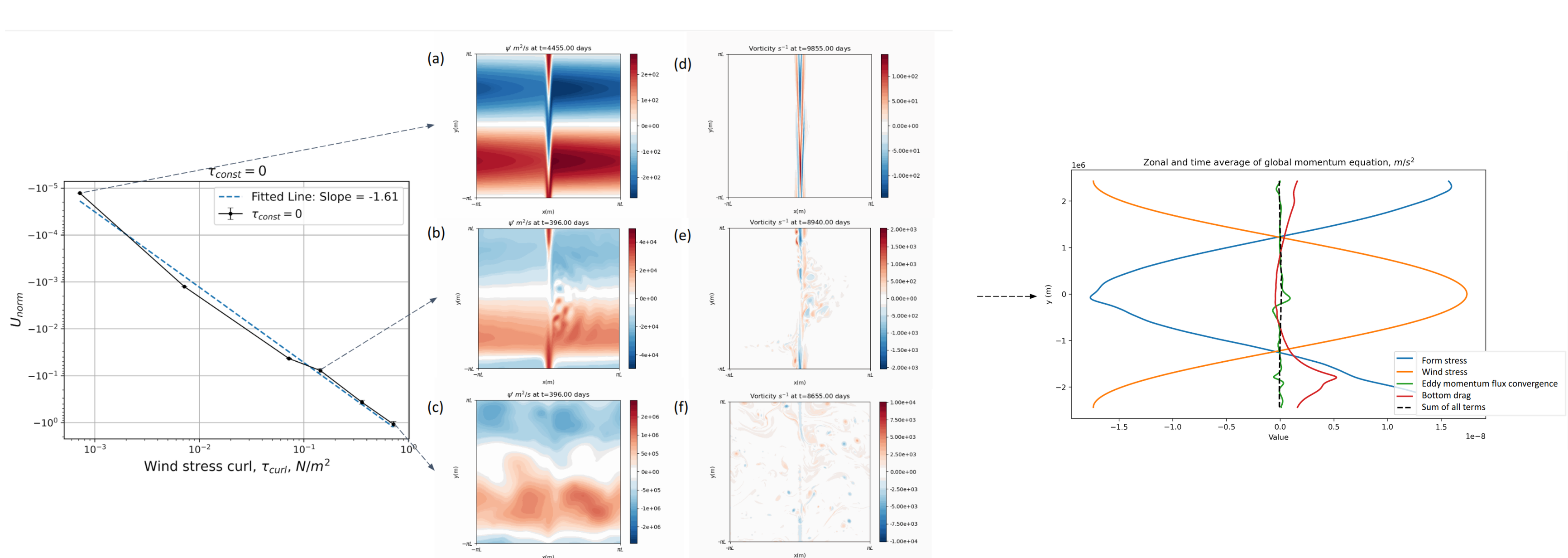

Figure 3. (Left) The mean zonal transport where $\tau_{constant} = 0$, for varying τ_{curl} values. (Right) The momentum budget for $\tau_{curl} = 0.14N/m^2$

The nonlinear term eddy momentum flux convergence creates an asymmetry through nonlocal dynamics and form stress term in the momentum equation. Westward transport increases with increasing τ_{curl} for zero mean wind forcing.

V. Sensitivity of the Volume Transport to the Wind Stress Curl

Can we make local assumptions of zonal flow from uniform wind solutions for different ranges of wind stress values?

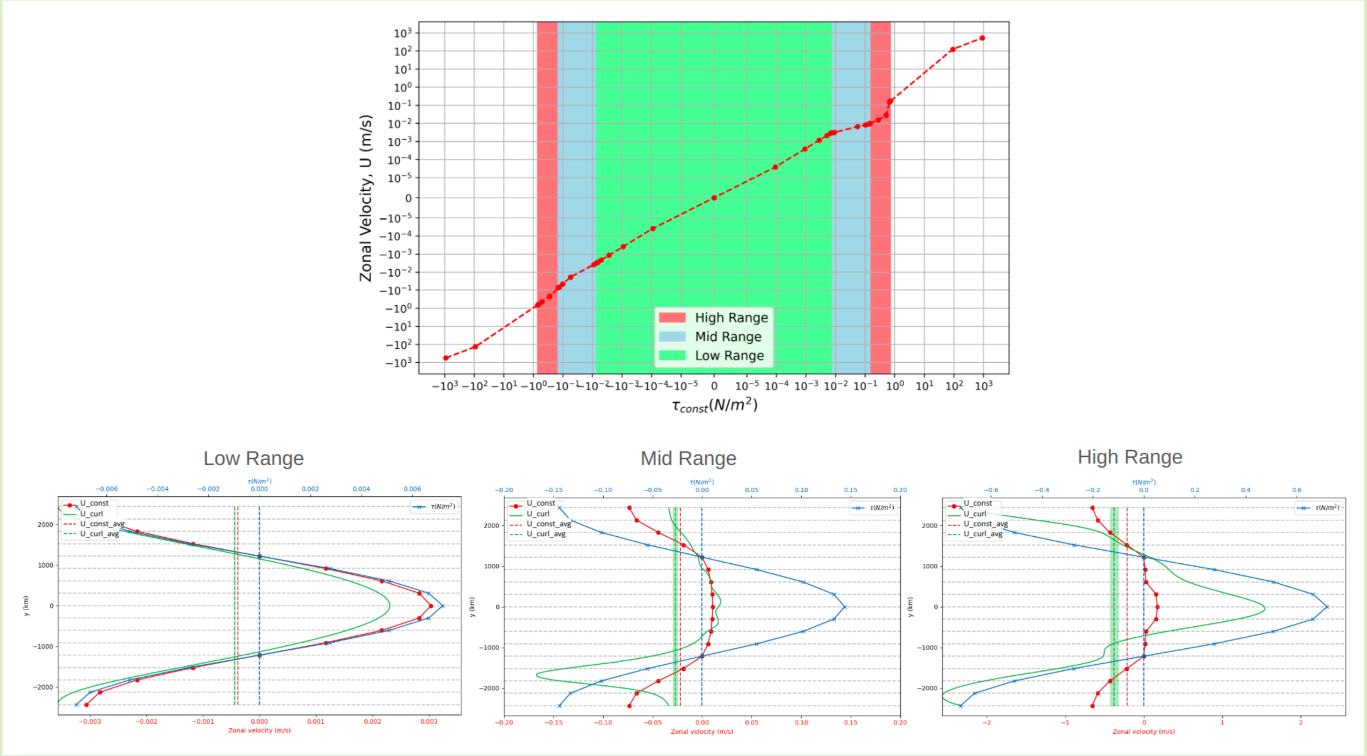

Figure 4. (Top) Zonal velocity as a function of τ_{const}, where $\tau_{curl} = 0$. (Below) Reconstruction of zonal flow from uniform wind simulations for low-range, mid-range, and high-range shown in the plot above.

- For a single ridge and uniform wind: the zonal velocity is larger for $\tau < 0$ than $\tau > 0$ for values larger than a limit τ_{linear}.
- For low τ, the zonal flow, U derived from $\tau_{constant}$ (given in red) is close to the zonal flow with wind curl (given in green). The solution is (almost) linear around $\tau = 0$.
- For mid-range τ values, the zonal flow diverges from the localized solution where $\tau < 0$. The zonal assumption coincides with wind curl experiments for $\tau > 0$.
- For high-range τ, the local assumption is highly asymmetric due to a rapid increase in $\tau > 0$. The zonal assumption diverges from wind curl experiments for all τ.
- Overall, the zonal assumption doesn't hold for flows with the transient flow, where eddy saturation typically occurs.

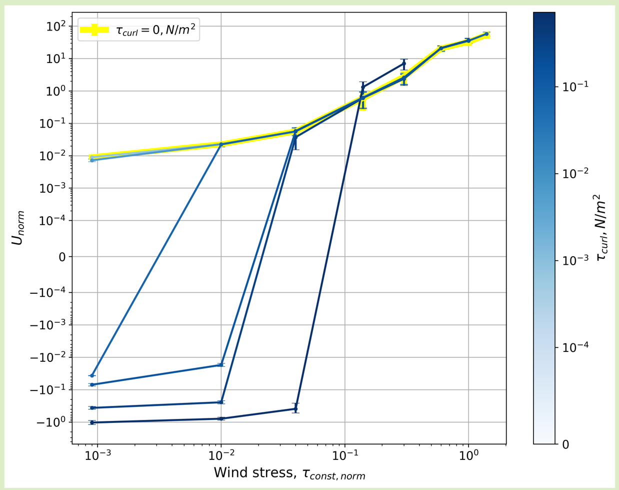

Figure 5. The zonal flow is shown as a function of wind stress where the wind stress curl changes are given in the color bar.

- Negative transport for low values of τ_{const} established through boundary layer instabilities in a system where a transition from negative to positive values of wind stress exists.
- **Convergence to zero curl limit for** $\tau_{constant}/\tau_{curl}$ **>1**

VI. Current & Future Work

- Analytical solutions for different stable and unstable regimes depending on the (1) wind profile and (2) topography with a focus on the eddy saturation regime.
- Critical boundary layer instabilities as a source of nonlocalized momentum.
- Generation of Rossby waves where $\tau_{local} > 0$ at the center of the domain east of the ridge as a source of vorticity.
- Further experiments with various topography and wind profiles.

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