Sensitivity of eddy-permitting ocean simulations to the vertical structure of energy backscatter parameterization

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Motivation

- **Eddy-permitting ocean models**, with resolution $0.1^{\circ} - 0.5^{\circ}$, often exhibit weaker and more surface-intensified eddy kinetic energy than higher-resolution models and observations.
- The **kinetic energy backscatter** parameterization (e.g., Jansen and Held, 2014, Jansen et al., 2019) was introduced to enhance the energy of mesoscale eddies in eddy-permitting models.
- The **vertical structure** of backscatter remains unconstrained, which can significantly impact large-scale dynamics (Yankovsky et al., 2024)

Goal of This Study

- Examine the sensitivity of large-scale circulations to the vertical structure of eddy momentum forcing
- Provide guidance on constraining the vertical structure of backscatter parameterization

Approach

- An idealized configuration of **MOM6**, *Neverworld2*, is used to test the backscatter parameterization
- **Setup:** Double-hemisphere domain; isopycnal coordinate with 15 layers; forced by zonally uniform zonal wind stress; no buoyancy forcing; adiabatic and hydrostatic
- Momentum equation in vector invariant form:

$$\partial_t \mathbf{u}_n + \frac{f+\zeta_n}{h_n}\hat{\mathbf{z}}\times(h_n\mathbf{u}_n) + \nabla K_n = -\nabla M_n + \mathbf{F}_n^v - \nabla\cdot[\nu_4\nabla(\nabla^2\mathbf{u}_n)] + \nabla\cdot(\nu_2\nabla\mathbf{u}_n)$$

Biharmonic damping

Backscatter (ν_2 is negative)

- A subgrid EKE (**MEKE**) equation:

$$\partial_t \mathrm{MEKE} = \dot{e}_{Bhvisc} - \dot{e}_{backscatter} - \dot{e}_{diss} - \dot{e}_{adv}$$

- Backscatter counteracts the biharmonic viscosity term by injecting the dissipated energy back to the model at larger scales
- The antiviscosity, ν_2, is formulated following Jansen et al. (2019),

$$\nu_2(x,y,z) = -c_0\sqrt{2\mathrm{MEKE}(x,y,z)}L_{mix}(x,y)$$

where c_0 is a constant, L_{mix} is the mixing length

- MEKE equation is solved for either a **2D** field or a **3D** field (Juricke et al., 2019). For the 2D case, ν_2 is prescribed with a vertical mode structure
- Different vertical structure of backscatter is tested:
  (1) 2D MEKE + barotropic (BT) mode
  (2) 2D MEKE + equivalent barotropic (EBT) mode
  (3) 2D MEKE + surface quasigeostrophic (SQG) mode
  (4) 3D MEKE
- The formulation of SQG vertical structure is given by Zhang et al. (2024):

$$\Phi_{sqg}(z,\Delta) \approx e^{2k_g z_s}$$

where $z_s = \int_z^0 \frac{N}{|f|}dz$, and $k_g = \max\left(k_{Rh}, \frac{c}{\Delta}\right)$,
Δ is the grid spacing, k_{Rh} is the inverse of Rhines scale, and c is a tuning parameter

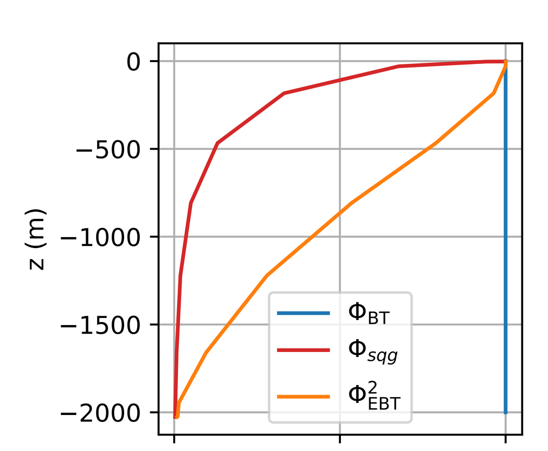

Figure 1. Vertical structure of the barotropic (blue), square of equivalent barotropic (orange), and SQG mode (red) at a location in the Southern Ocean of the model

Reference

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Juricke, S., Danilov, S., Kutsenko, A. and Oliver, M., 2019. Ocean kinetic energy backscatter parametrizations on unstructured grids: Impact on mesoscale turbulence in a channel. Ocean Modelling, 138, pp.51-67.
Yankovsky, E., Bachman, S., Smith, K.S. and Zanna, L., 2024. Vertical structure and energetic constraints for a backscatter parameterization of ocean mesoscale eddies. Journal of Advances in Modeling Earth Systems, 16(7), p.e2023MS004093.
Zhang, W., Griffies, S.M., Hallberg, R.W., Kuo, Y.H. and Wolfe, C.L., 2024. The role of surface potential vorticity in the vertical structure of mesoscale eddies in wind-driven ocean circulations. Journal of Physical Oceanography, 54(6), pp.1243-1266.

Response to the Backscatter Parameterization

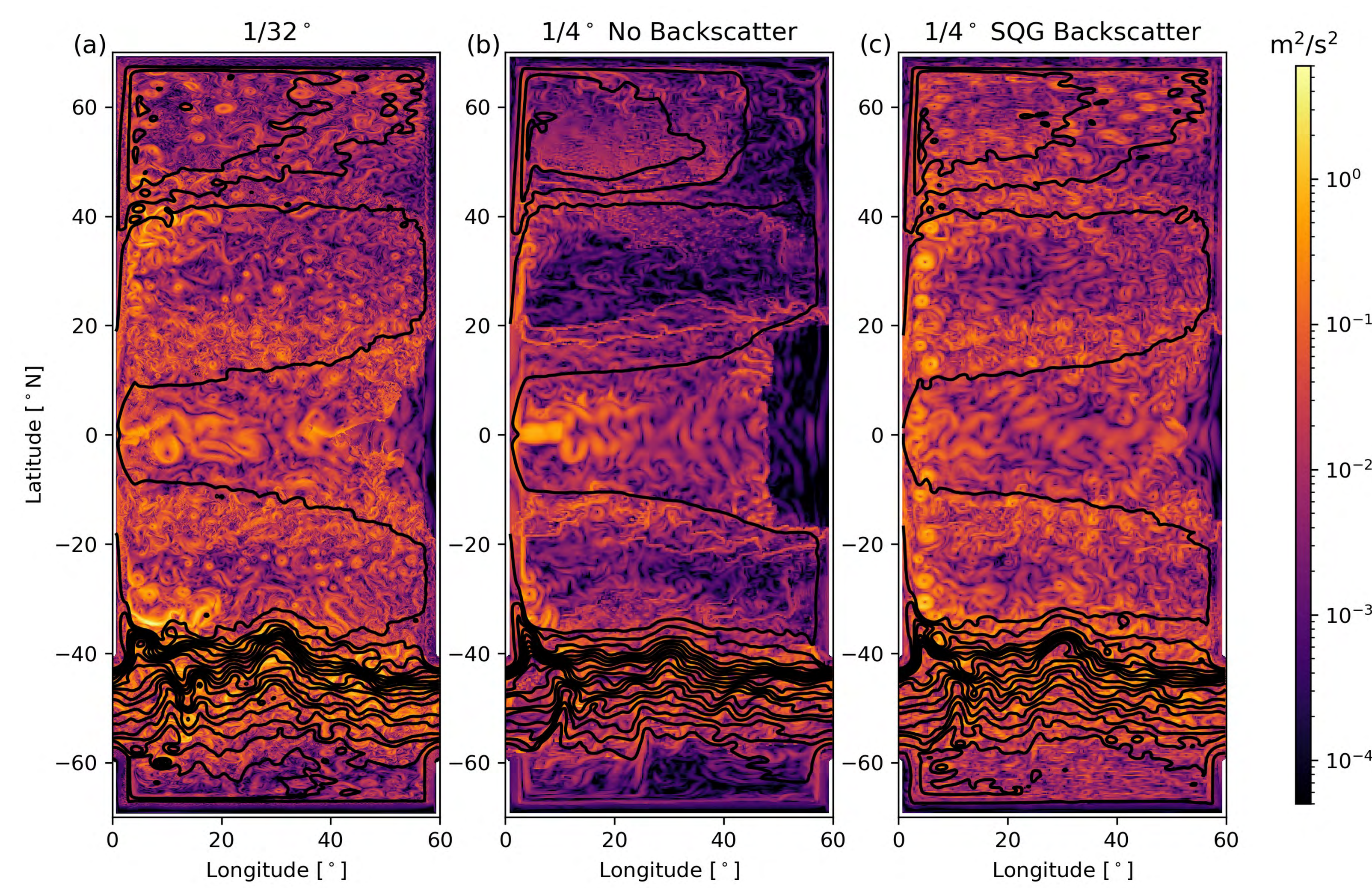

Figure 2. Surface kinetic energy snapshot in (a) 1/32° simulation (b) 1/4° simulation without the backscatter, and (c) 1/4° simulation with the backscatter using an SQG structure. Black lines are 500-day mean sea surface height contours.

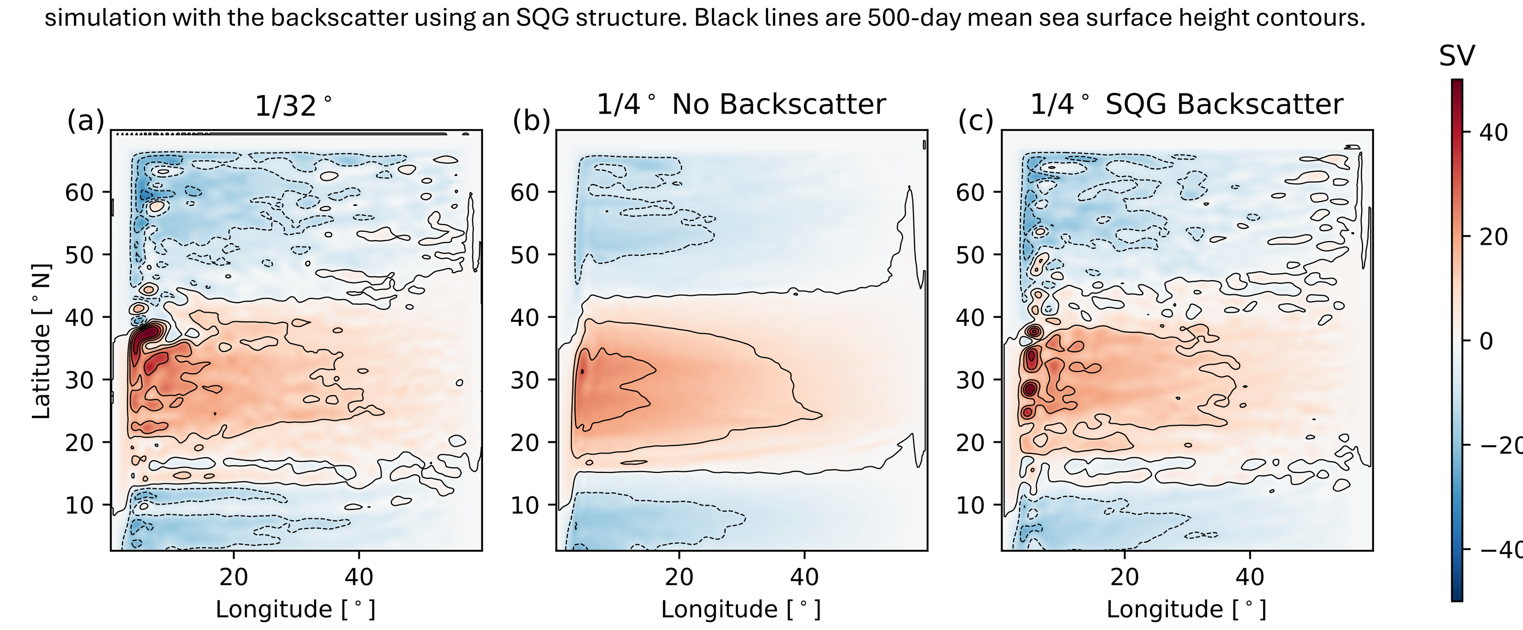

Figure 3. As figure 2 but for the 500-day mean barotropic streamfunction of gyres in the North Hemisphere.

- Kinetic energy and gyre transport are improved by the backscatter parameterization for all vertical structures
- **Mean available potential energy** (APE) is computed as

$$\mathrm{APE} = \frac{1}{2}g'(\bar{\eta} - \eta_{ref})^2$$

where η is the isopycnal interface height and η_{ref} is the initialized interface height

- APE measures the **baroclinicity** of mean flow
- BT and EBT backscatters lead to too weak mean APE in the **Southern Ocean**
- **SQG and 3D backscatters** improves the mean APE that matches the high-resolution simulation

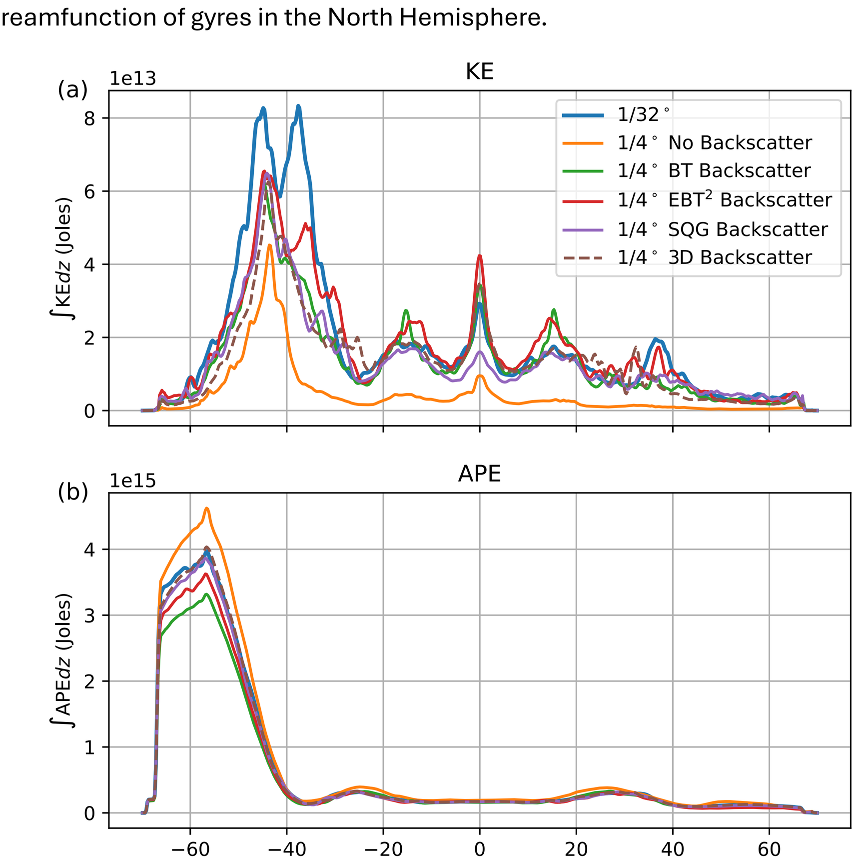

Figure 4. Zonally averaged vertical integral of (a) kinetic energy and (b) mean available potential energy. Blue, orange, green, red and purple lines are for the 1/32° simulation, 1/4° simulation without backscatter, 1/4° simulation with the BT, EBT, and SQG backscatters, respectively. Grey dashed line indicates the 1/4° simulation with backscatter informed by 3D MEKE.

Energetics in the Southern Ocean

Isopycnal Structure

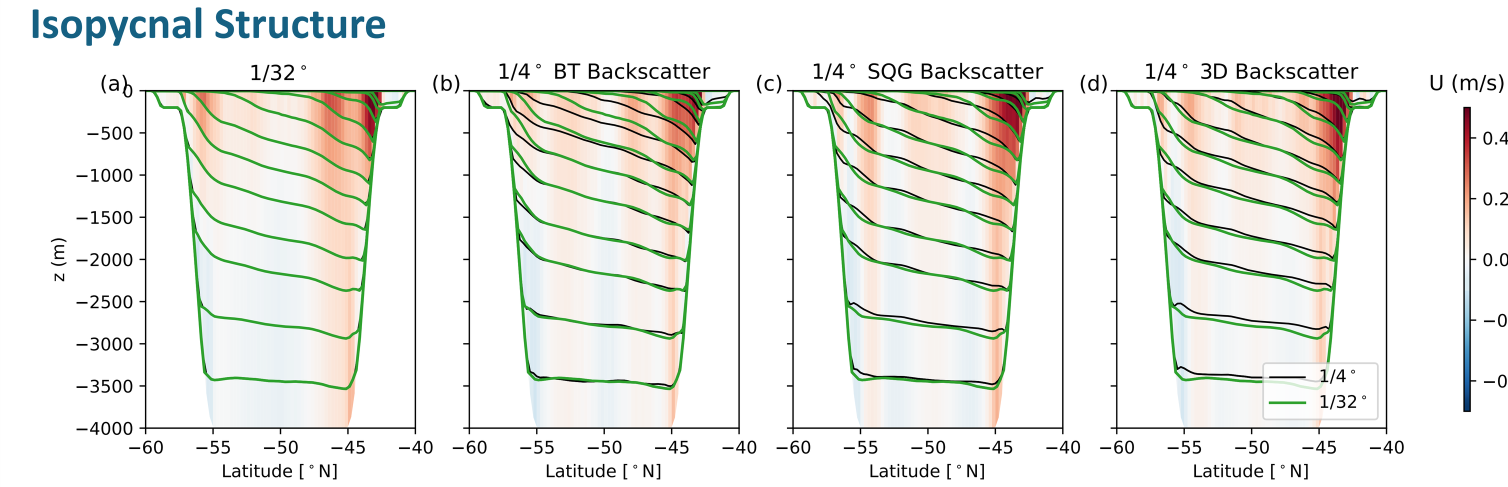

Figure 5. Isopycnal structure in a meridional section of Southern Ocean in (a) 1/32° simulation, (b) –(d) 1/4° simulations with the BT, SQG, and 3D backscatter, respectively. Green and black lines are isopycnals in the 1/32° and 1/4° simulations, respectively. Color shading indicates the mean zonal velocity.

- Backscatter with deep vertical structure (BT and EBT^2) leads to flatter isopycnals (i.e., reduced baroclinicity) in the upper ocean
- A more surface-intensified vertical structure (SQG and 3D) leads to better isopycnal structure

Energy Contribution by Backscatter

Energy tendency due to horizontal viscous stress in spectral space:

$$\hat{\mathbf{u}}^* \cdot \hat{\mathbf{F}}_h$$

$$\mathbf{F}_n^h = -\nabla\cdot[\nu_4\nabla(\nabla^2\mathbf{u}_n)] + \nabla\cdot(\nu_2\nabla\mathbf{u}_n)$$

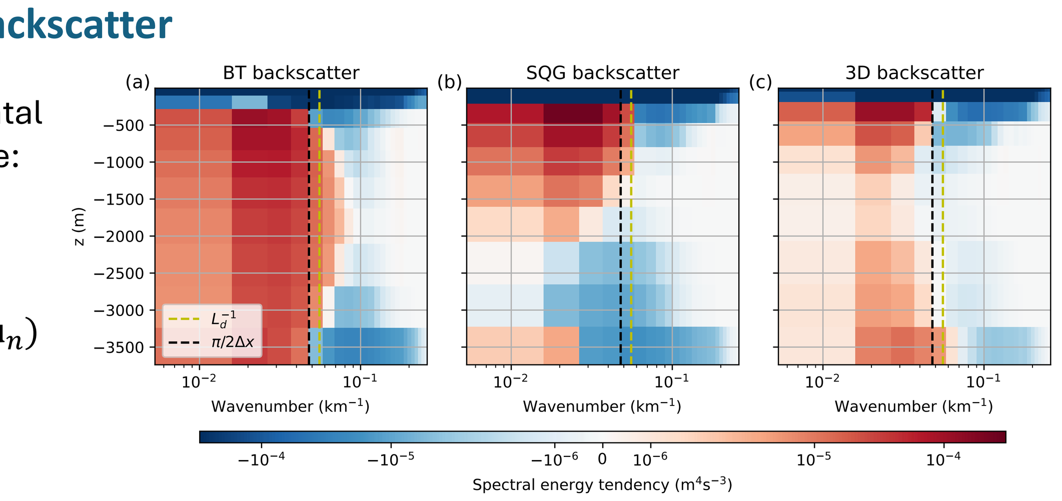

Figure 6. Energy tendency due to horizontal viscous stress as a function of horizontal wavenumber and depth in Southern Ocean. Red and blue indicate energy source and sink, respectively. (a)-(c) 1/4° simulation with the BT, SQG, and 3D backscatter, respectively. Black dashed line indicates the wavenumber of 4Δx wave. Yellow dashed line indicates the inverse of Rossby deformation radius.

- Biharmonic viscosity dissipates energy at scale smaller than 4Δx (~70 km); backscatter injects energy at scales around 200 km
- Forcing is vertically uniform in the BT backscatter case, leading to more barotropic eddies
- SQG and 3D backscatters enhance surface-intensified eddies at about 200 km

Eddy Rectification Effect

KE spectral flux:

$$\Pi = \int_k^{\infty} \mathrm{Re}[\hat{\mathbf{u}}^* \cdot \widehat{\mathbf{u}\cdot\nabla\mathbf{u}}]dk$$

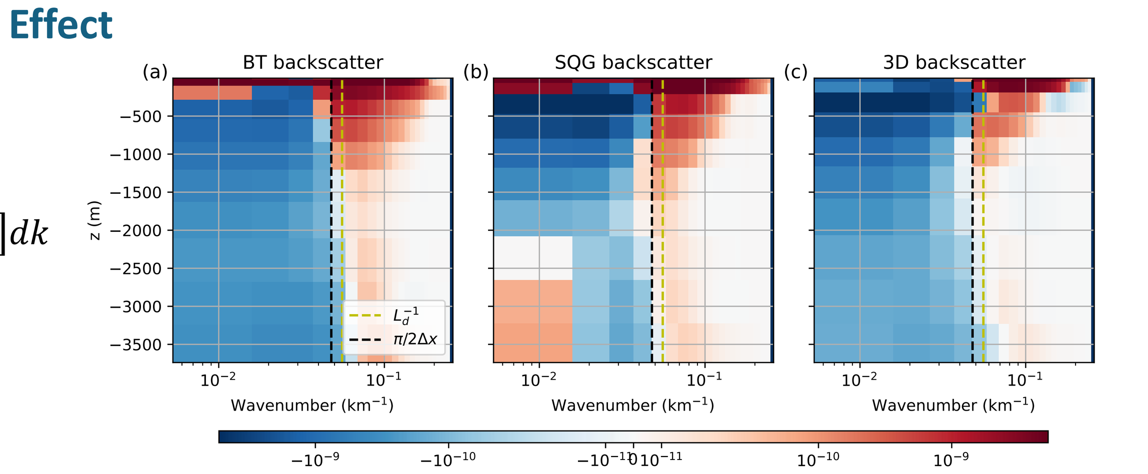

Figure 7. As figure 6 but for the kinetic energy spectral flux. Blue and red indicate inverse and forward energy cascades, respectively.

- Eddies enhance by backscatter rectifies the large-scale circulations through inverse energy cascade
- Spurious barotropic eddies reduce the baroclinicity of mean flow

Conclusion

- Energy backscatter can shape the vertical structure of resolved eddies, which further modulate the large-scale circulation structure
- A more surface-intensified vertical structure like SQG mode leads to better large-scale isopycnal structure by reasonably representing the momentum fluxes of surface-intensified eddies