Impacts of Lee Waves on the Southern Ocean circulation and its sensitivity to Wind Stress

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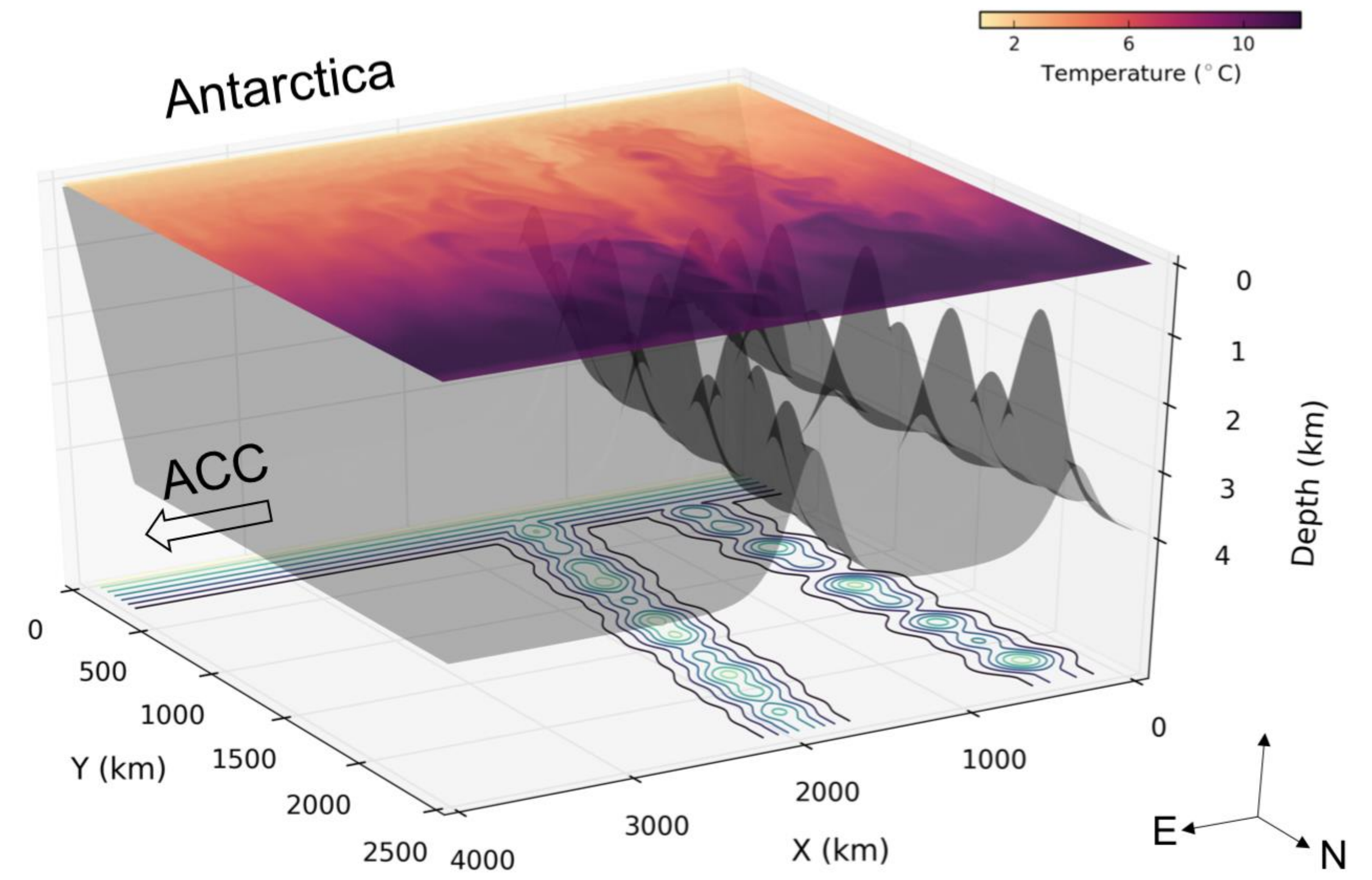
1. Introduction

- Lee waves are generated primarily by *transient eddies* flowing over rough small-scale bottom topography in the Southern Ocean (Yang et al, 2018).
- Lee waves apply a *wave drag* to and extract energy from transient eddies. This energy is used to power *turbulent mixing* in the ocean interior (e.g. Nikurashin and Ferrari, 2013).
- The sensitivity of the Antarctic Circumpolar Current (ACC) and Meridional Overturning Circulation (MOC) to wind is regulated by transient eddies (e.g. Marshall et al, 2017) and hence might be dependent on lee waves.



2. Model Configuration

An idealized periodic channel model of the Southern Ocean with the following configuration:

- Modular Ocean Model, version 6 (MOM6)
- 4000km × 2500km × 4km domain
- 10km horizontal resolution
- 5m to 100m stretched vertical grid, 72 layers
- Steady idealized surface wind forcing
- Restoring temperature surface b.c.
- Enhance diffusivity northern b.c.

We carry out 2 sets of 3 wind experiments, with and without lee wave drag and mixing parameterization (*Full* and *Reference* below).

Goal: Implement an energetically-consistent lee wave drag and mixing parameterization into an eddy-resolving ocean model to study the impacts of lee waves on the Southern Ocean circulation and its sensitivity to wind stress.

3. Lee wave parameterization

We parameterize both *lee wave drag*, as a stress in the momentum equations, and *lee wave-driven mixing*, as a diapycnal diffusivity in the tracer equations.

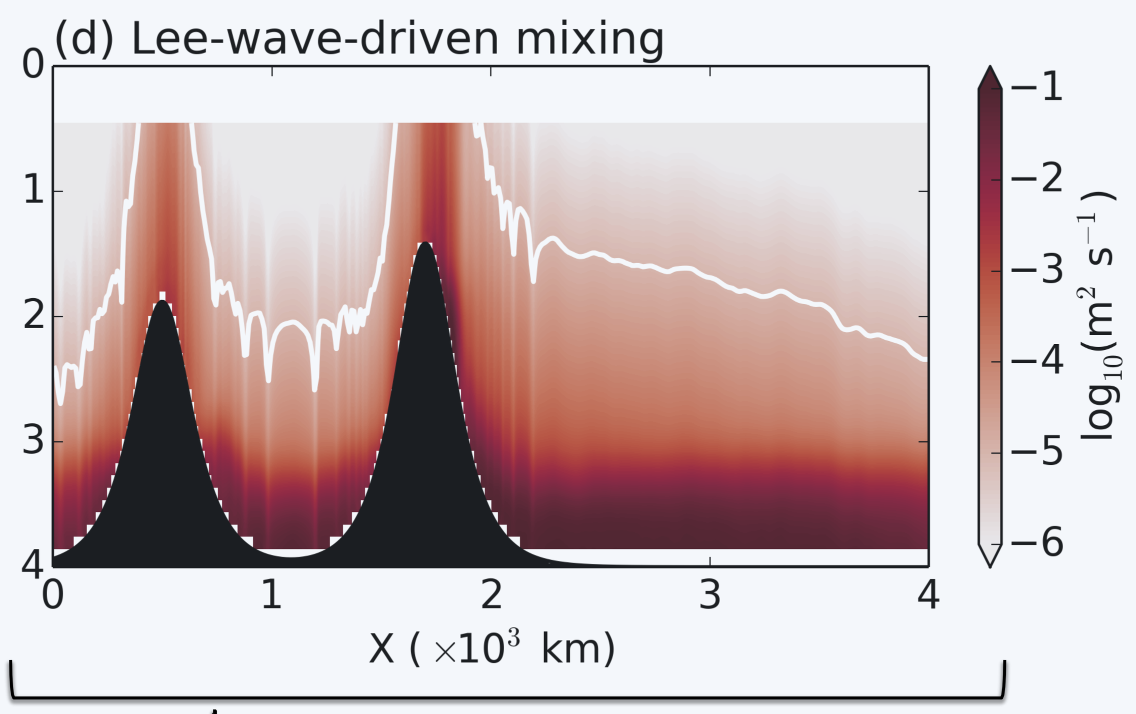
1) Lee wave drag is parameterized based on a linear theory (e.g. Gill, 1975),

$$\overrightarrow{\tau_{lw}} = -\rho_0 \cdot \gamma_{lw} \cdot \overrightarrow{\mathbf{u_b}} \cdot F(z)$$

where $\overrightarrow{u_b}$ is bottom flow, $F(z)$ is a vertical exponential profile representing wave breaking (e.g. Melet et al, 2014), and γ_{lw} is the lee wave drag coefficient,

$$\gamma_{lw} = 0.5 N_b h^2 k$$

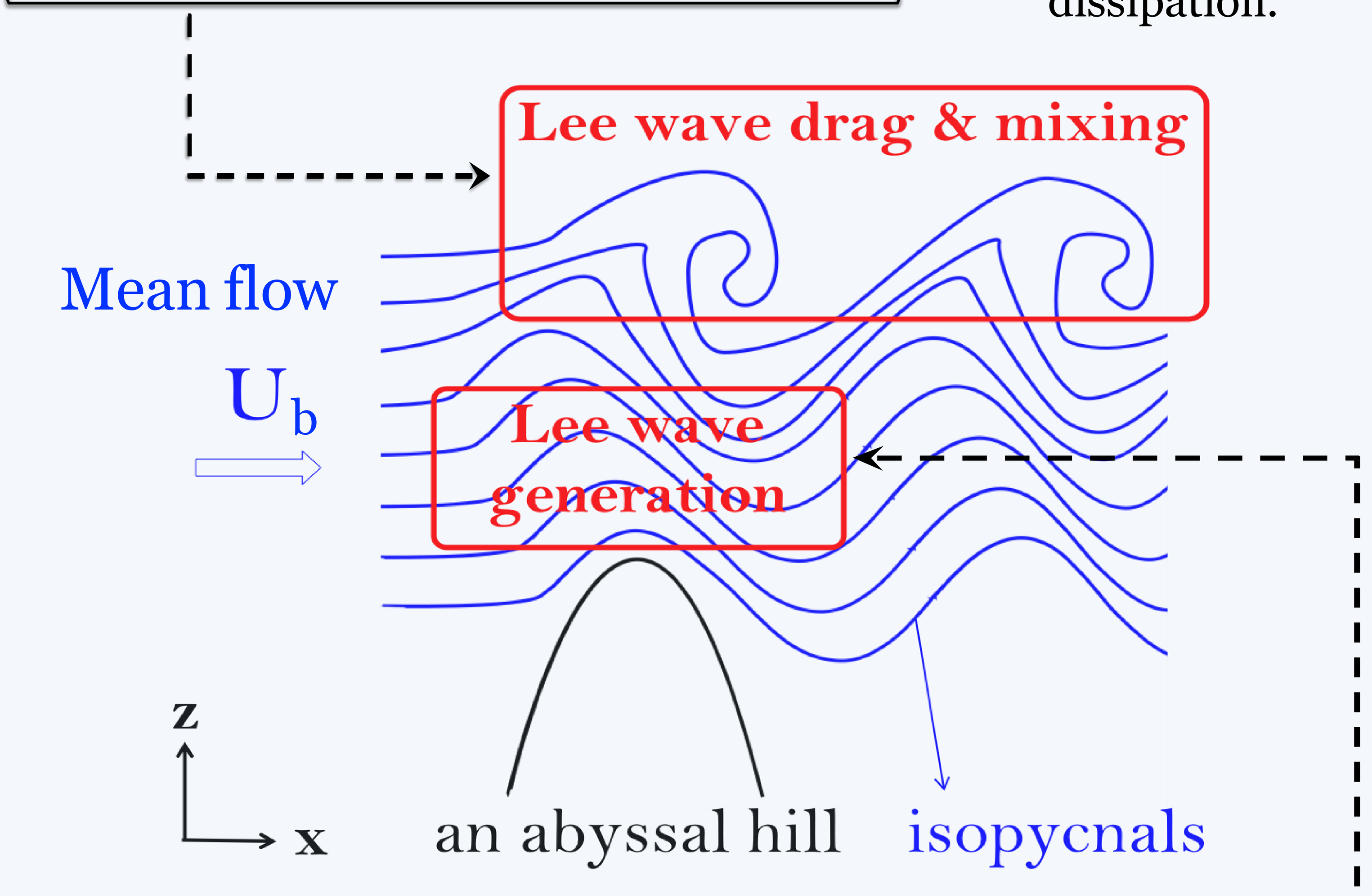
where N_b is bottom stratification and h and k are characteristic amplitude and horizontal wavelength of abyssal hill topography, prescribed in this study.



2) Lee wave-driven mixing is parameterized using Osborn (1980) relation,

$$\kappa_v^{lw} = \Gamma \frac{\varepsilon_{lw}}{N^2}$$

where Γ is the mixing efficiency (0.2) and ε_{lw} is lee wave energy dissipation.

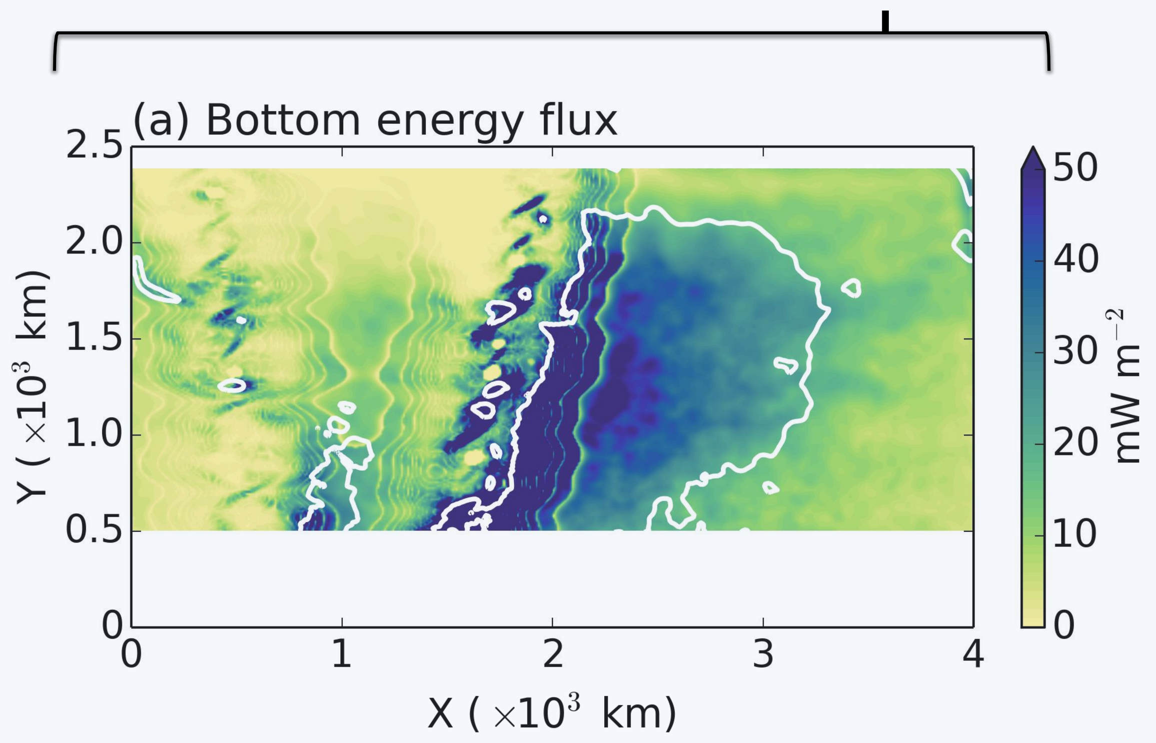


3) Lee wave energy dissipation is computed as the work done by wave drag on bottom flow,

$$\varepsilon_{lw} = \overrightarrow{\mathbf{u_b}} \cdot \left(-\frac{1}{\rho_0} \frac{\partial \overrightarrow{\tau_{lw}}}{\partial z} \right),$$

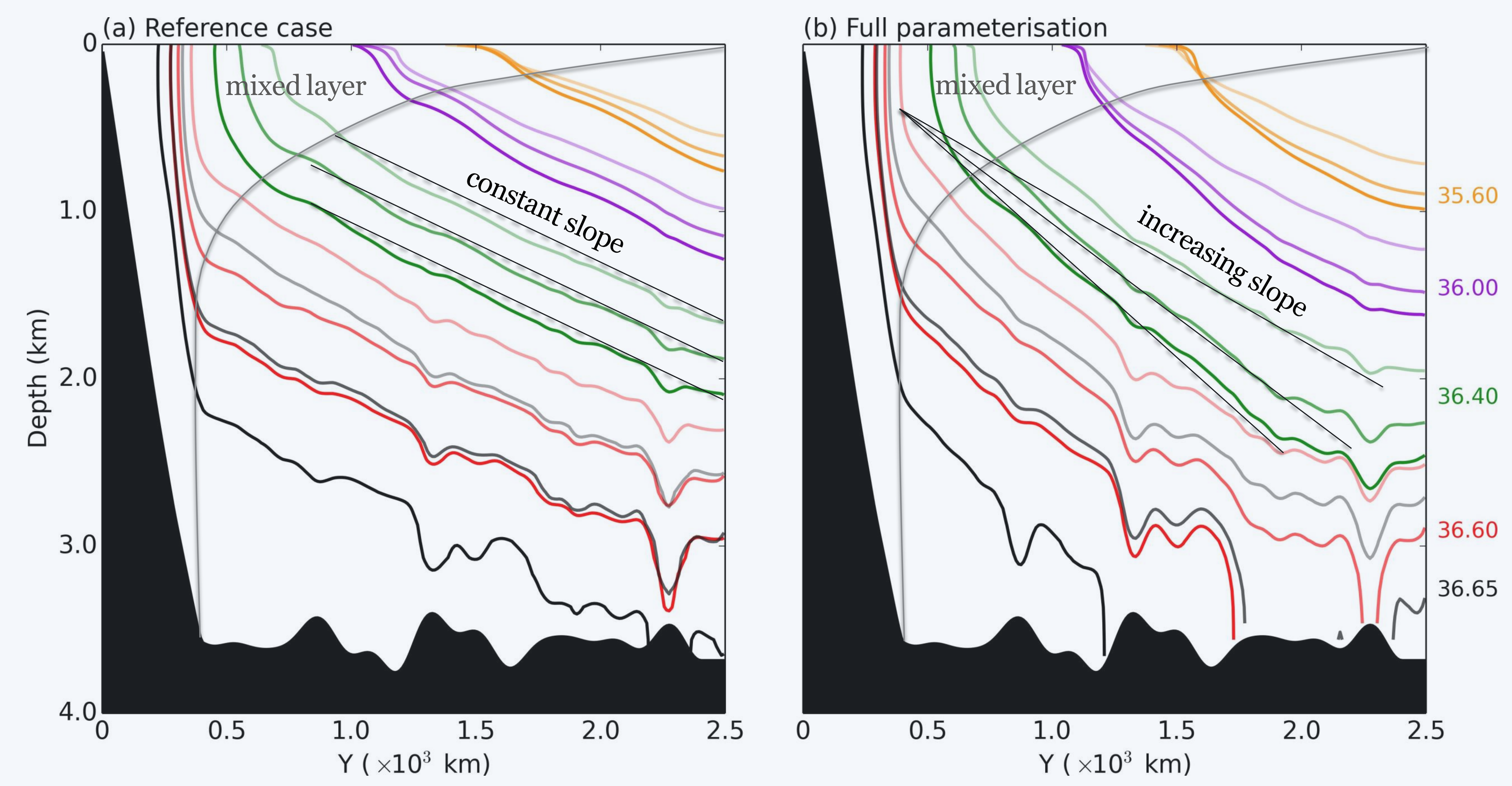
corresponding to the total energy dissipation of

$$E = \int \rho_0 \varepsilon_{lw} dz = -\overrightarrow{\mathbf{u_b}} \cdot \overrightarrow{\tau_{lw}}.$$

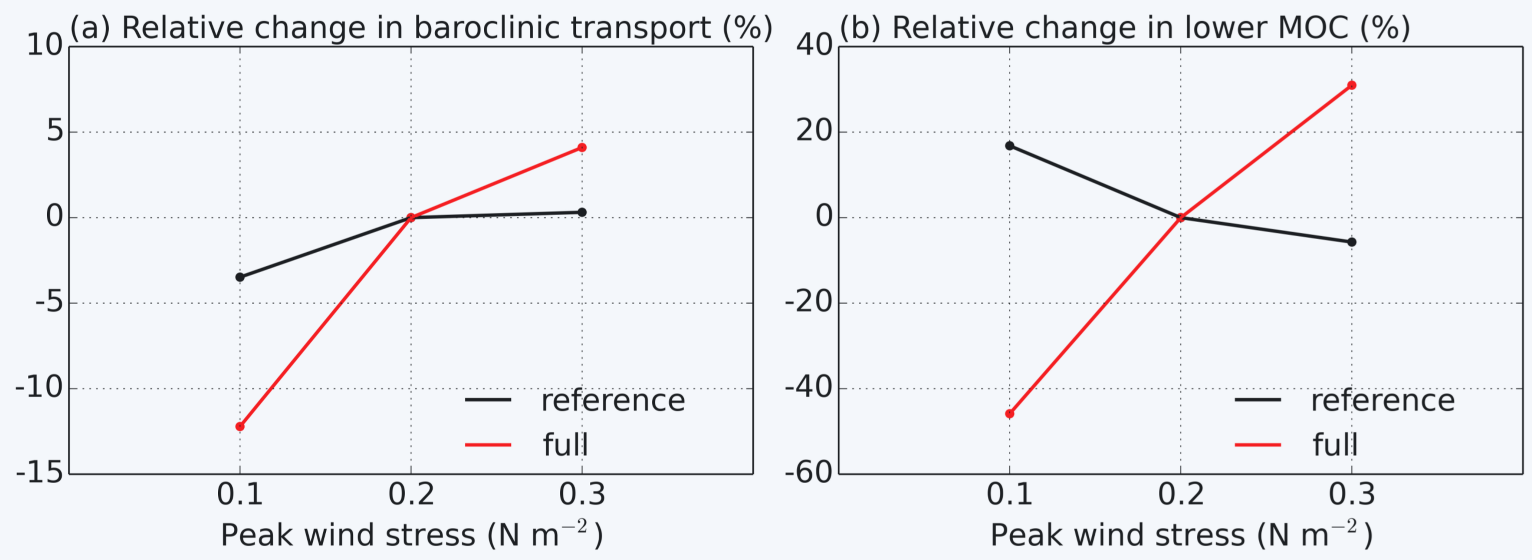


4. The ACC sensitivity to wind

In response to wind, isopycnals are pushed deeper into the ocean interior, increasing the bottom stratification, in both sets of runs and hence also increasing lee wave drag in the *Full*. Increasing wave drag leads to isopycnal slope *increase* with wind in the *Full*, while it remains *constant* in the *Reference*.

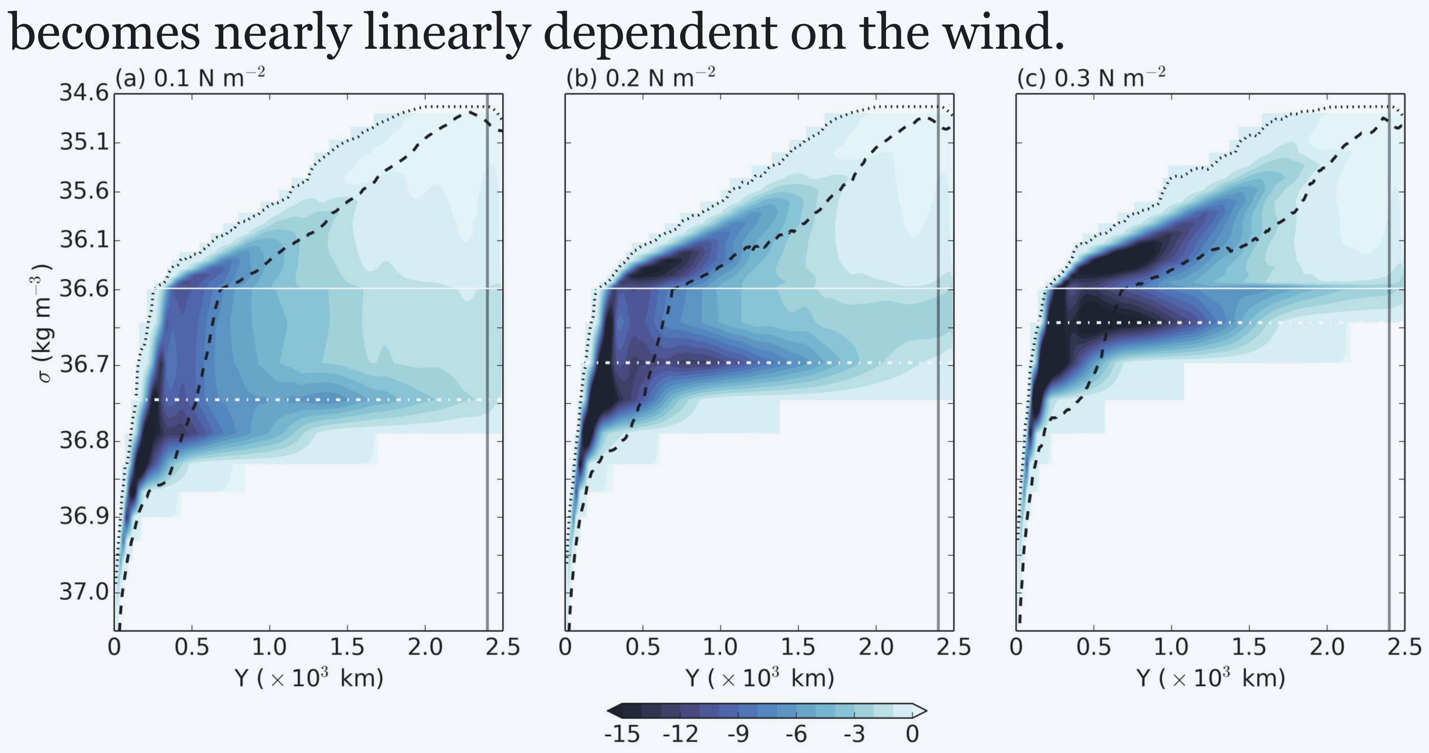


The isopycnal slope increase corresponds to the ACC transport increase and hence sensitivity to wind in the *Full*. This response is consistent with the ACC response to bottom drag theory of Marshall et al (2017).



5. The MOC sensitivity to wind

In the *Reference* without lee waves, there is little sensitivity of the MOC to wind, because diapycnal mixing is fixed and isopycnal slopes are nearly constant. In the *Full* with lee waves, diapycnal mixing scales with the bottom eddy kinetic energy and hence increases linearly with wind. As a result, the MOC becomes nearly linearly dependent on the wind.



6. Summary

- The effects of lee wave drag and lee-wave-driven mixing are interdependent.
- Lee waves modify the *eddy saturation* (insensitivity to wind) of the ACC by applying wave drag that scales with stratification (and hence with wind).
- Lee waves make the lower MOC sensitive to wind by re-routing the dissipated EKE, increasing with wind, into diapycnal mixing.