The impact of lee waves on the Southern Ocean circulation and its response to wind stress

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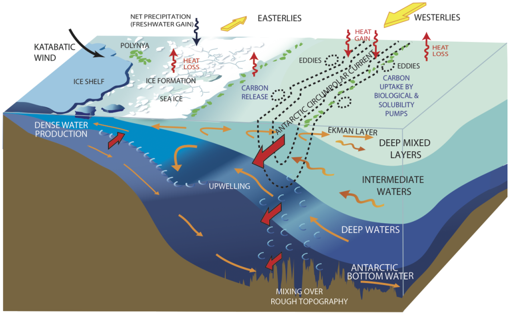
Southern Ocean in global ocean and climate

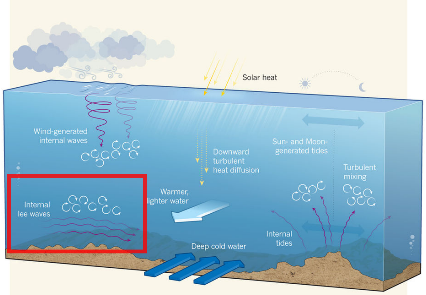
- The circumpolar flow permits the inter-basin exchange of heat, carbon, and nutrients;
- The overturning circulation regulates the exchange of heat and carbon between the deep ocean and atmosphere.
- Energetic eddy field redistributes heat, tracers, and momentum in the Antarctic Circumpolar Current (ACC), and regulates the response of the ACC and the overturning circulation to changing westerly wind.



Rintoul et al. (2001), Olbers et al. (2004), Böning et al. (2008), Rintoul and Naveira Garabato (2013), Frölicher et al. (2015), Rintoul (2018), Gruber et al. (2019)

Potential impact of lee waves

Transient eddies → Lee waves → Turbulent mixing



MacKinnon (2013)

e.g., Nikurashin and Ferrari (2013), Trossman et al. (2013, 2016), Melet et al. (2014), Meyer et al. (2015), de Lavergne et al. (2016), Marshall et al. (2017), Yang et al. (2018)

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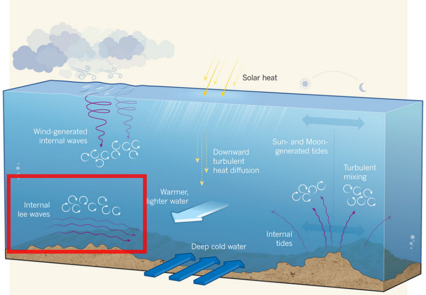
↓ ACC ↓ MOC



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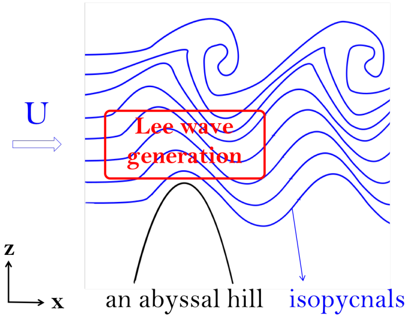
Current lee waves parameterizations

Transient eddies → Lee waves → Turbulent mixing



Modified from Fig. 1 in Yang et al. (2018)

- Lee wave generation: the drag effect leading to energy and momentum loss of the resolved flow (parameterised in Trossman et al., 2013; 2016).

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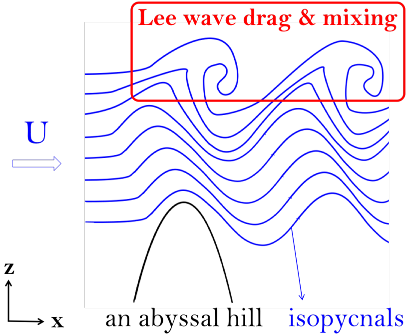

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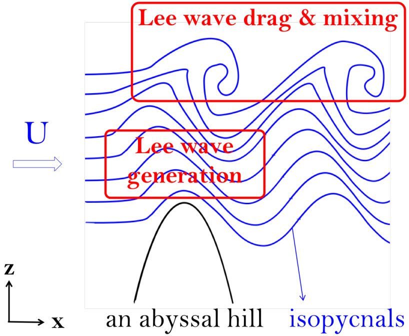

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- Lee wave breaking: the mixing effect on tracers (parameterised in Melet et al., 2014; Broadbridge et al., 2016) and the momentum transfer back to the mean flow.
- **Goal**: Implement a **full** lee wave parameterisation, i.e., both the lee wave **drag and mixing effect**, into an eddy-resolving configuration and use it to study the impact of lee waves on the Southern Ocean circulation and its sensitivity to wind stress.

Full lee wave parameterisation

- **Lee wave drag**

$$\boldsymbol{\tau}_{\mathrm{LW}} = -\rho_0 \gamma_{\mathrm{LW}} \mathbf{u_b} \cdot F(z)$$

  - Lee wave linear theory (Bell, 1975)
  - F(z): vertical profile, wave radiation and breaking (St Laurent et al., 2002; Melet et al., 2014)

- **Lee wave drag coefficient**

$$\gamma_{\mathrm{LW}} = 0.5 \mathrm{N_b} \mathrm{h}_0^2 \mathrm{k}$$

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- **Turbulent energy dissipation rate**

$$\epsilon^{\mathrm{LW}} = \mathbf{u_b} \cdot \left(-\frac{1}{\rho_0} \frac{\partial}{\partial z} \boldsymbol{\tau}_{\mathrm{LW}}\right)$$

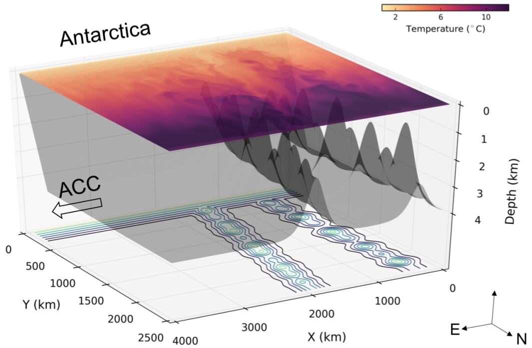
This is an **energetically consistent** parameterisation where the lee-wave-driven mixing is sustained by the energy extracted from the resolved flows.

Model Configuration

- Modular Ocean Model, version 6 (MOM6)
- 10 km horizontal resolution
- 5 m to 100 m stretched vertical grid, 72 layers
- Steady surface wind forcing
- Surface temperature restoring b.c.
- Diffusive northern sponge layer (100 km thick)

Experiments:

- a **reference** experiment (no lee waves);
- a lee wave **full** parameterisation experiment;



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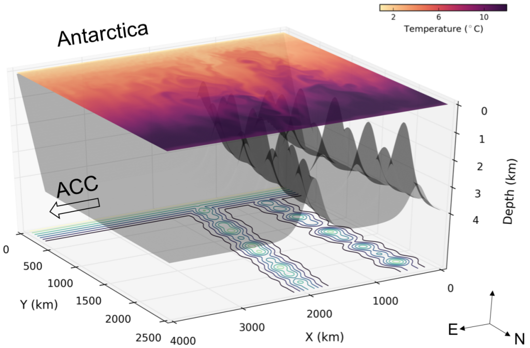
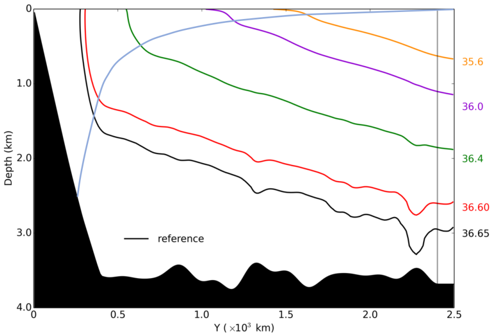


Experiments:

- a **reference** experiment (no lee waves);
- a lee wave **full** parameterisation experiment;
- a lee wave **drag only** experiment;
- a lee-wave-driven **mixing only** experiment.

Mean state: isopycnal slope



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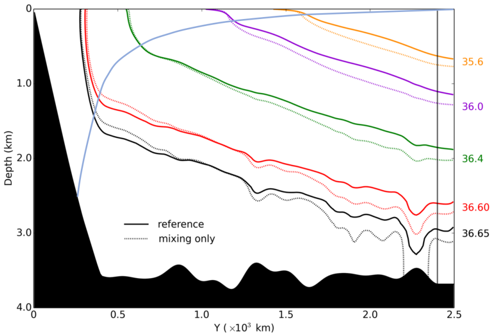

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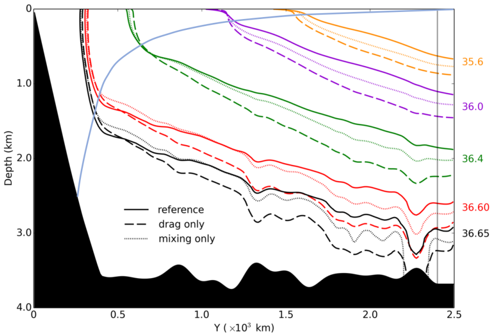

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- Lee wave **drag** also leads to the steepening of isopycnals through the **adiabatic** processes, i.e., the adjustment of the baroclinic shear of the ACC to the increase in eddy energy dissipation (Marshall et al., 2017).

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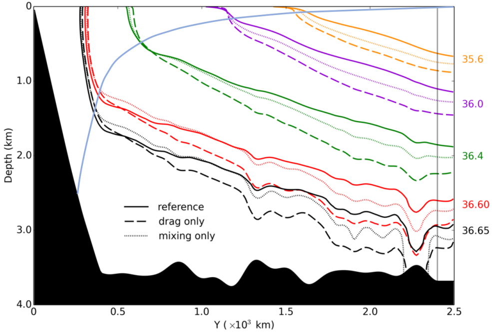

Lee wave drag
↓
More eddy energy dissipation
↓
Need more eddy energy generation to balance
↓
Stronger vertical shear
↓
Steeper isopycnals

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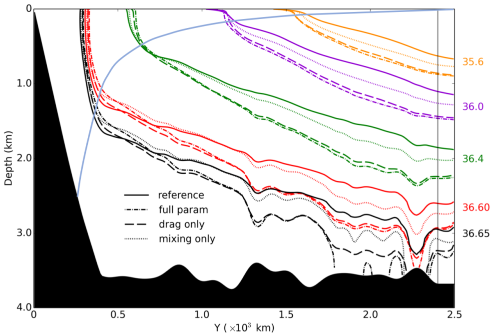

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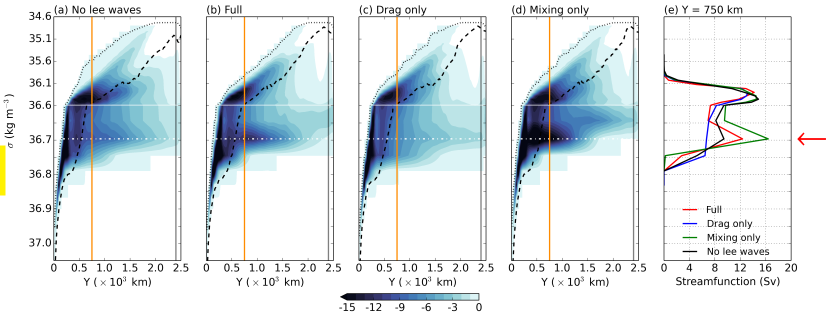
Mean state: ACC transport

Reference	Mixing only	Drag only	Full parameterisation
144 Sv	168 Sv	202 Sv	207 Sv
	+24 Sv (+17%)	+58 Sv (+40%)	+63 Sv (+44%)

- Consistent with the steepening of isopycnals, the baroclinic transport **increases** in all lee wave parameterisation experiments.
- The increase in the baroclinic transport is dominated by the parameterisation of **lee wave drag**.
- The increase of the baroclinic transport in the full parameterisation experiment is **smaller** than the sum of the increase in the drag only case and that in the mixing only case.

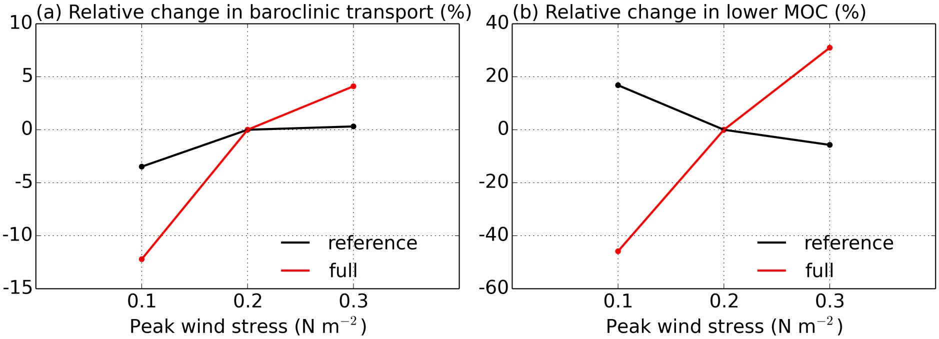
Mean state: overturning circulation

$$\Psi_{\text{res}} \sim \frac{\kappa}{s_\rho}$$



- Lee-wave-driven mixing strengthens the lower overturning circulation by 7 Sv (+75%).
- Lee wave drag weakens the lower overturning circulation by 2.7 Sv (-29%), through increasing the isopycnal slope (e.g., Ito and Marshall, 2008).
- The full parameterisation leads to an increase of 3 Sv (+32%) in the lower overturning circulation.

Wind sensitivity



- The baroclinic ACC transport is more sensitive to wind stress in the presence of lee waves primarily due to the dependence of lee wave **drag coefficient** on wind through bottom stratification.
- Lee waves reverse the sensitivity of lower overturning circulation to wind stress due to the dependence of lee-wave-driven **mixing** on wind through the eddy field.

Summary

- The full parameterisation of lee waves increases the baroclinic ACC transport by over **40% (60 Sv)** due to their effect on isopycnal slope via **eddies**.
- The parameterisation of lee wave drag weakens the lower overturning circulation, which **counter-acts** the mixing effect.
- The full parameterisation of lee waves modifies the eddy saturation of the ACC and makes it **more sensitive** to wind stress.
- The full parameterisation of lee waves **reverse** the sensitivity of the lower overturning circulation to wind stress due to the dependence of lee-wave-driven mixing on wind through eddies.

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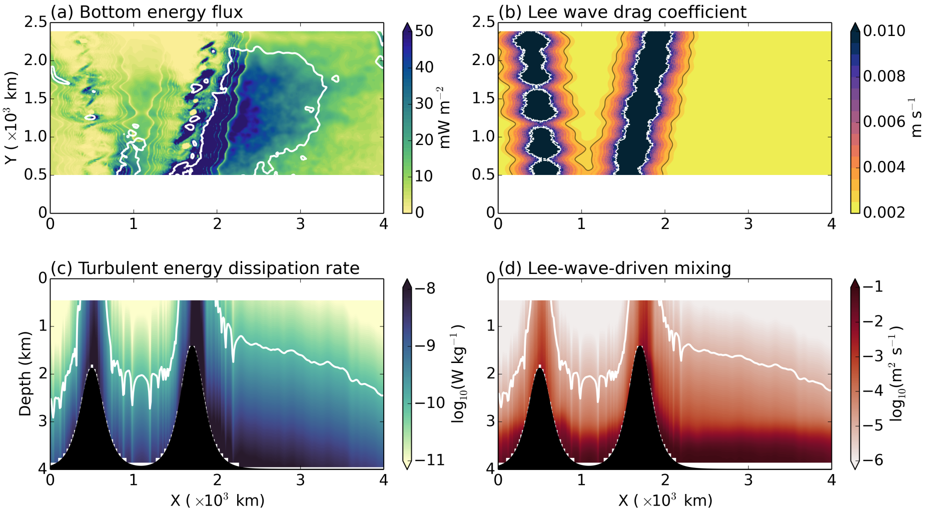
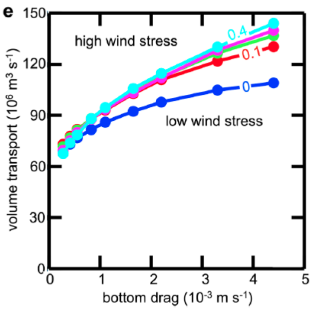
Lee wave characteristics



Marshall et al. (2017)'s theory: Linear drag



Marshall et al. (2017), Fig. 2e

- Eddy energy source

$$\alpha_1 \frac{|f|}{N} \frac{\partial \overline{u}}{\partial z} \int_{-H}^{0} E dz$$

- Eddy energy sink

$$\lambda \int_{-H}^{0} E dz$$

- Eddy energy balance

$$\alpha_1 \frac{|f|}{N} \frac{\partial \overline{u}}{\partial z} = \lambda$$

- (Baroclinic) Volume transport

$$\mathbf{T} = \lambda \frac{N}{|f|} \frac{H^2 L}{2\alpha_1}$$

Lower overturning circulation

- Transformed Eulerian-mean theory

$$\Psi_{\text{res}} = \overline{\Psi} + \Psi^* \longrightarrow \begin{cases} \text{Wind-driven Ekman overturning} : \overline{\Psi} = -\frac{\tau_{\text{w}}^x}{\rho_0 f} \\ \text{Eddy-induced overturning} : \Psi^* = K s_\rho \\ \text{Residual overturning} : \Psi_{\text{res}} = \frac{\kappa}{s_\rho} \end{cases}$$

- Residual overturning circulation
  - Buoyancy advection-diffusion equation: $J_{\text{y, z}}(\Psi_{\text{res}}, \overline{b}) = \frac{\partial}{\partial z}(\kappa \frac{\partial \overline{b}}{\partial z})$
  - Assuming $|\overline{b}_{\text{z}}| \gg |\overline{b}_{\text{y}}|$: $\frac{\partial \Psi_{\text{res}}}{\partial y}\frac{\partial \overline{b}}{\partial z} = \frac{\partial}{\partial z}(\kappa \frac{\partial \overline{b}}{\partial z})$
  - Using characteristic scales: $\Psi_{\text{res}} = \frac{\kappa}{h/l} = \frac{\kappa}{s_\rho}$

$$-\frac{\tau_{\text{w}}^x}{\rho_0 f} + K s_\rho = \frac{\kappa}{s_\rho}$$

Gent and McWilliams, 1990; Marshall and Radko, 2003; Ito and Marshall, 2008; Nikurashin and Vallis, 2011