# Isopycnal Mixing and Ventilation Controlled by Winds

↬Ryan Abernathey[1] & David Ferreira[2]

1 ↠ Columbia University / Lamont Doherty Earth Observatory
2 ↠ University of Reading

## 1 Mesoscale Fluxes

Mesoscale turbulence transports stuff (e.g. heat, salt, disolved chemicals, etc.) through the ocean in significant quantities. The scales of mesoscale eddy transport (~10 km - 200 km) are generally not resolved by climate models. The fluxes must therefore be parameterized through subgrid schemes.

The mesoscale flux of a tracer c is parameterized through two distinct components:

$$\boldsymbol{F}_c = \overline{\boldsymbol{u}'c'} = \boldsymbol{u}^*\overline{c} - K_{redi}\nabla_n c$$

**Eddy-induced advection** represents the fundamentally advective (variance conserving) part of the eddy flux. Related to the "skew flux" and the "bolus correlation." Part of the meridional overturning circulation. Proper representation of this component is crucial for accurate simulations, and many studies have shown its importance for a wide range of climate problems, particularly in the Southern Ocean.

Parameterized through the Gent-McWilliams scheme:

$$\Psi^* = -K_{gm} s$$

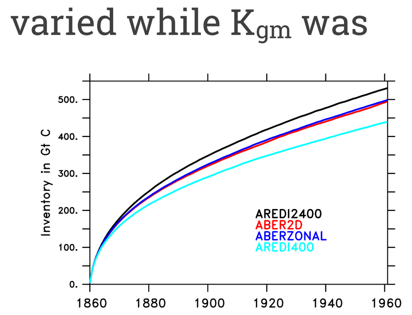
streamfunction — coefficient — isopycnal slope

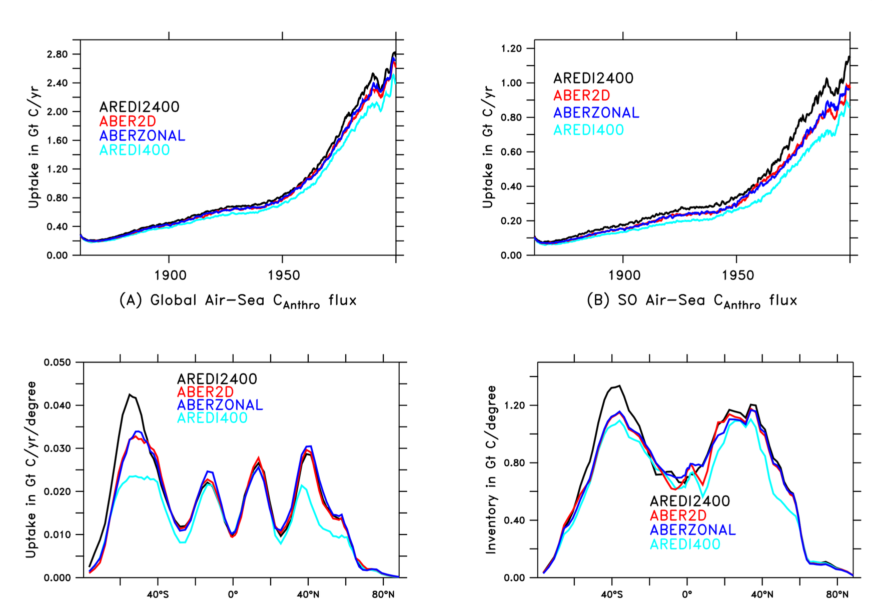
**Isopycnal diffusion** represents the irreversible mixing of tracers by mesoscale eddy stirring. Because of energetic constraints on the mesoscale, the "mixing angle" must be very close to the isopycnal slope. Tracers with no isopycnal gradient (e.g. buoyancy) do not feel any isopycnal diffusion, and consequently this flux has a limited impact on the physical circulation. But isopycnal mixing plays an important role in the ventilation of the ocean interior and the transport of biogeochemical tracers.

## 2 Isopycnal Mixing "Matters"

Significant uncertainty exists regarding the magnitude and spatial pattern of $K_{redi}$. There is convincing evidence (e.g. Smith & Marshall, 2009; Abernathey et al. 2013) that it is not necessarily the same as $K_{gm}$. Gnanadesikan et al. (2015) recently performed climate model experiments (GFDL ESM2Mc) in which $K_{redi}$ was varied while $K_{gm}$ was held fixed.

The results (shown at right) indicate that, even with minimal changes in the MOC, isopycnal mixing significantly impacts the rate of anthropogenic $CO_2$ uptake, especially in the Southern Ocean.



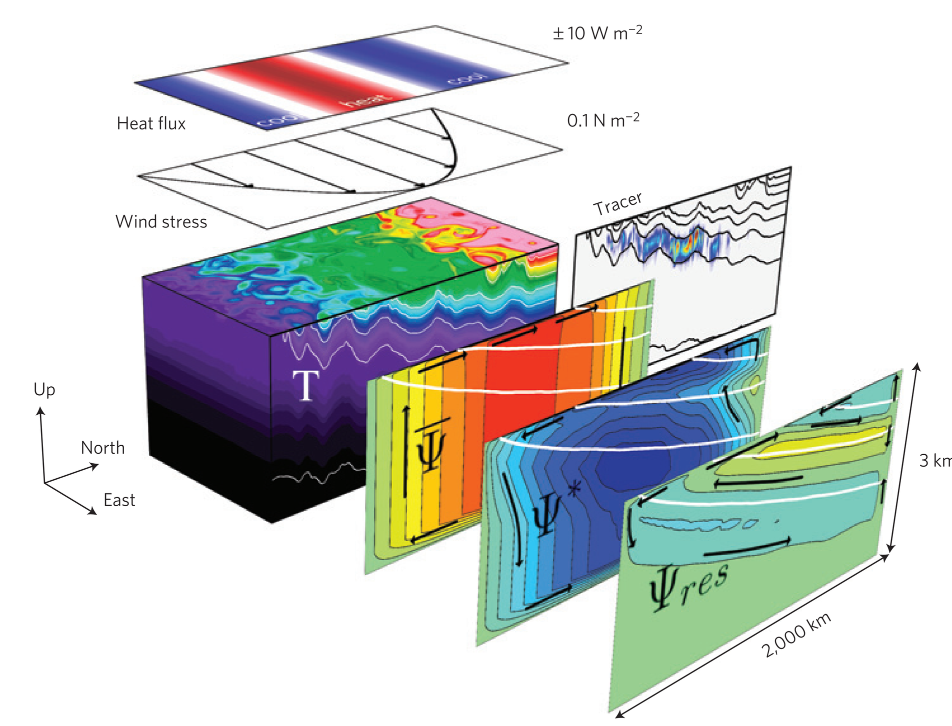



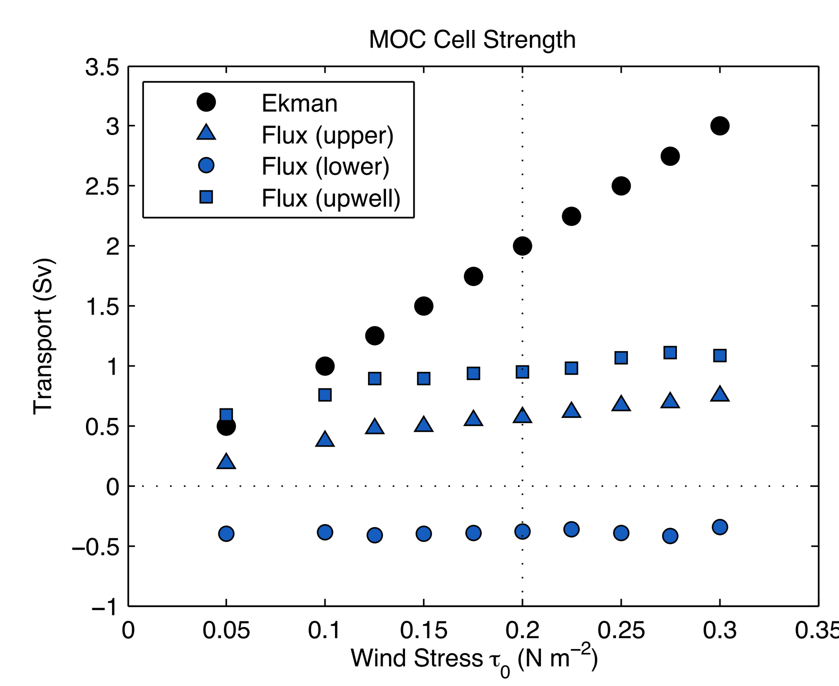

## 3 Eddy Resolving Process Model

To understand how mesoscale fluxes might evolve in a changing climate, we use a high-resolution, idealized process model meant to qualitatively reproduce the Southern Ocean overturning circulation. While simplified, this model explicitly resolves mesoscale turbulence, providing an important guide for parameterization and theoretical analysis.

### Model Configuration

- MITgcm: Primitive equation z-coordinate
- 5 km horizontal resolution
- 40 vertical levels
- Linear, temperature-only equation of state
- Forced by sinusoidal wind jet
- Fixed surface heat flux
- Sponge layer Norther boundary
- Highly conservative second-order-moment advection scheme




stronger winds

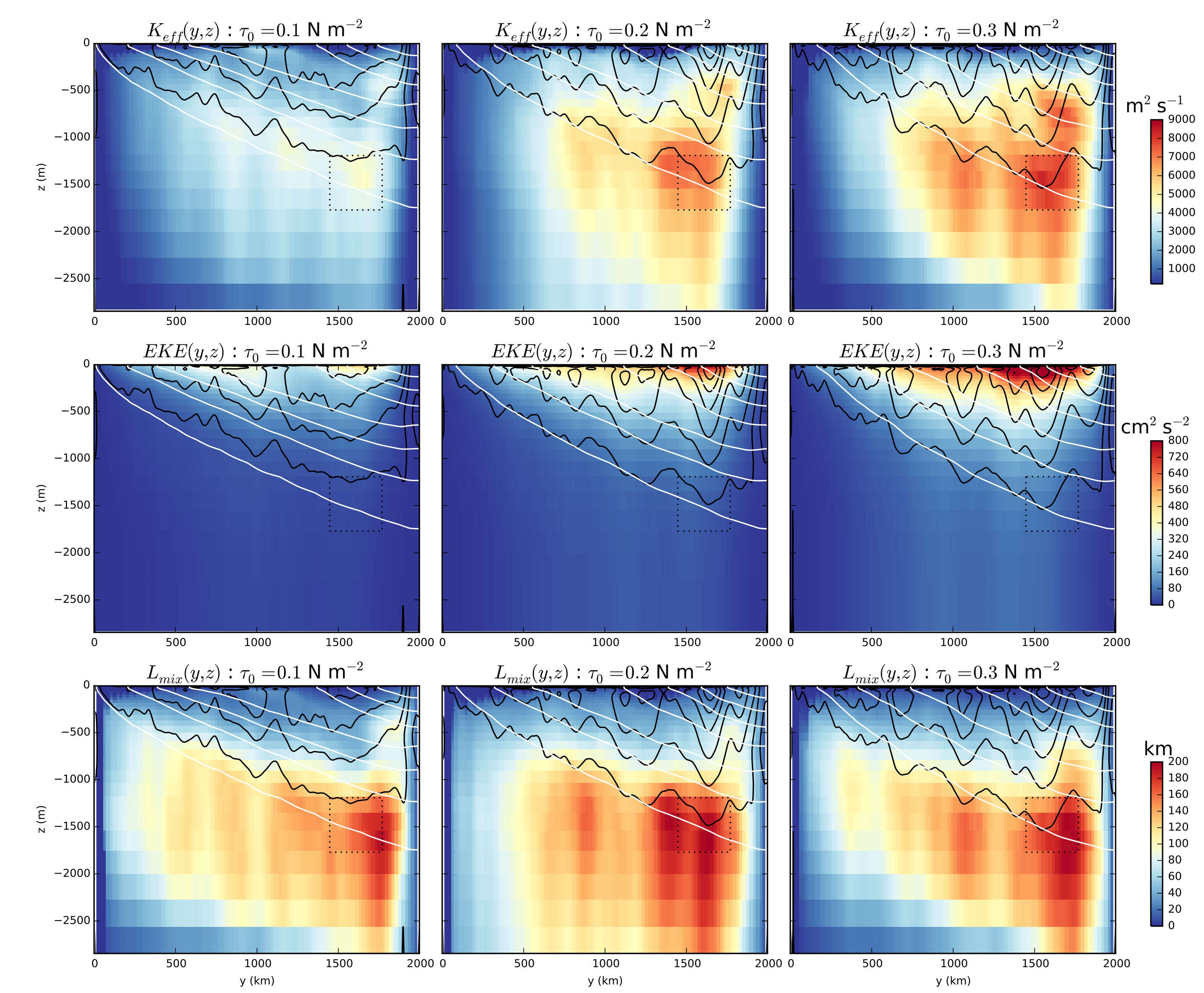
### MOC Eddy Compensation

Prior work showed how the residual MOC in this model has very weak sensitivity to wind strength. This behavior can be explained by a strong cancellation between increased Ekman-driven advection and increased eddy-induced advection.

↬ Requires significant dependence of $K_{GM}$ on winds.

## 4 Mixing Dependence on Winds

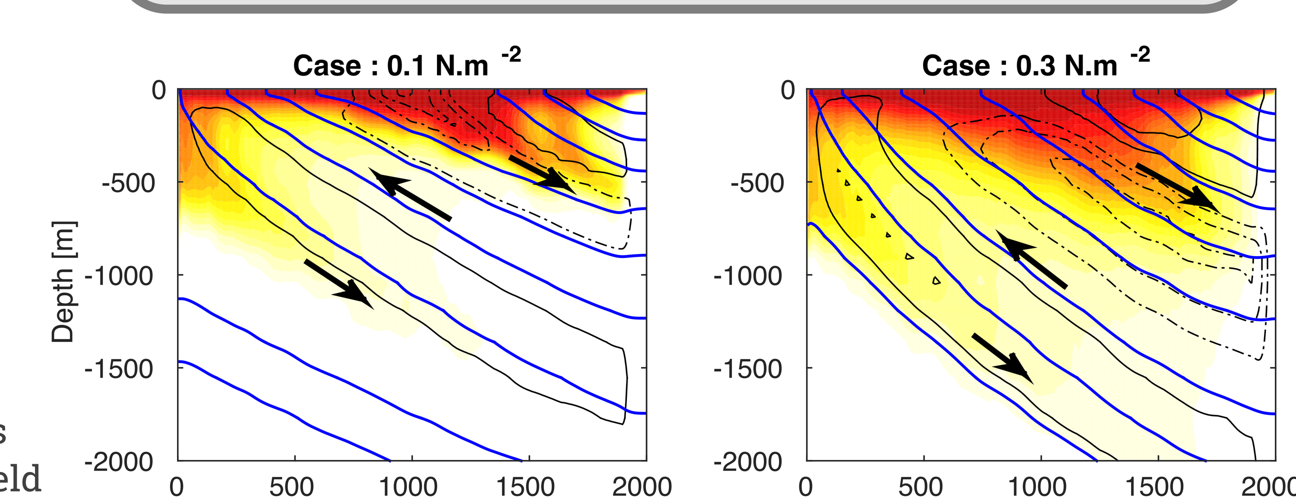
We diagnose isopycnal mixing rates by releasing a passive tracer and applying the method of Nakamura. Results show a strong increase of $K_{redi}$ with stronger winds.




The increase in mixing is due to the linear relationship between EKE and wind work

$$K = \Gamma L_{mix} V_{rms} \qquad V_{rms} \propto \tau_0^{1/2}$$

## 5 Ventilation Tracer




Transient tracer ventilation (analogous to $CO_2$ uptake) is simulated by a passive tracer whose concentration is held fixed at the surface. Although the MOC changes are minimal, substantial differences in ventilation are observed with different wind strength. Stronger winds lead to increased net uptake. **Even for isopycnals on which upwelling increases, transient tracer ventilation increases with winds.**

These results clearly demonstrate that, along with the MOC, changes in isopycnal mixing must be considered in order to understand the Southern Ocean CO2 sink in a changing climate.