# Evolving Southern Ocean overturning in warming climates

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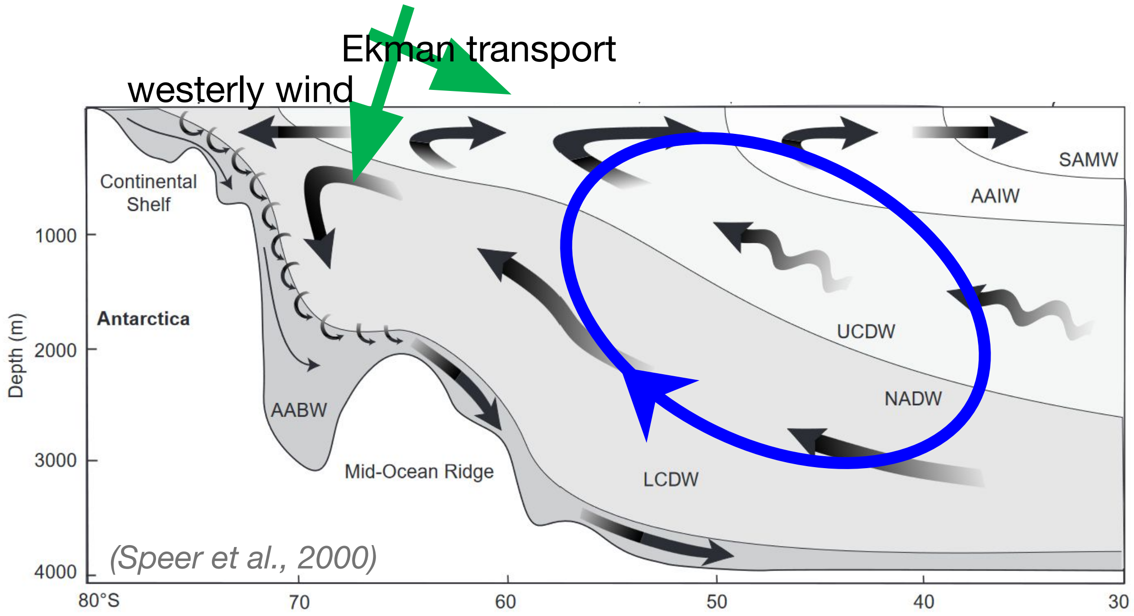
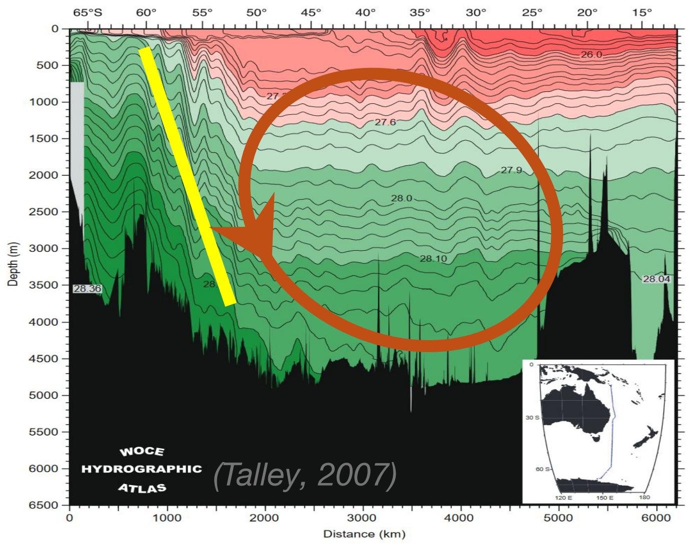
# Southern Ocean meridional overturning circulation (MOC)




Eulerian-mean MOC (Wind-driven MOC)

steepen isopycnals□baroclinic instability




Eddy-induced MOC

**Eddy Compensation:** Eddy-induced MOC act to "compensate" for the Eulerian-mean MOC, regulating the residual overturning circulation. *(e.g., Marshall and Radko 2003; Viebahn and Eden 2010)*

$$\Psi res = \bar{\Psi} + \Psi^*$$

Residual MOC　　Eulerian-mean MOC　　Eddy-induced MOC

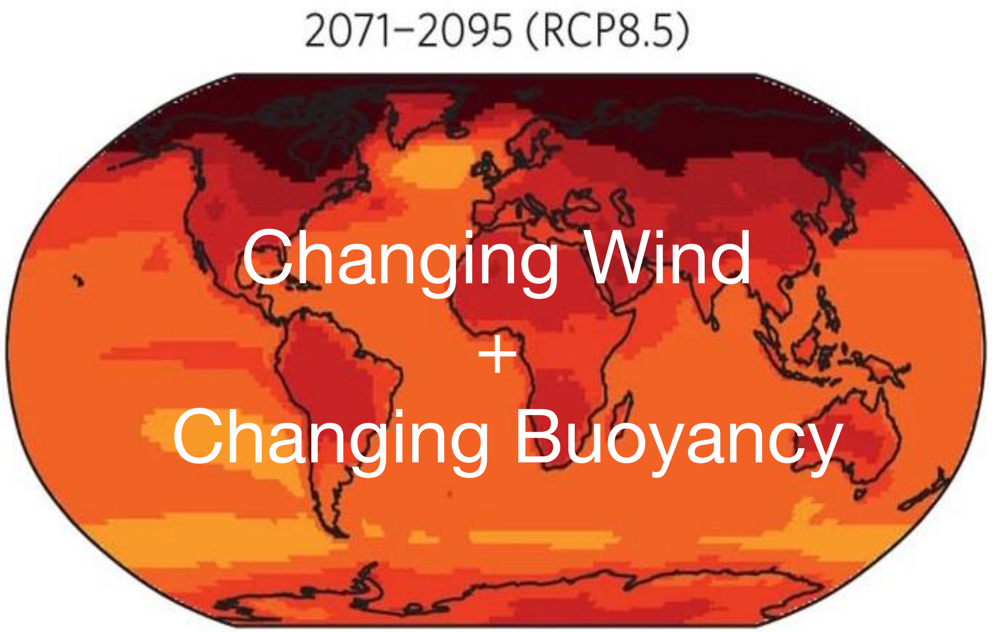
# How will the Southern Ocean MOC respond to warming climates?

$$\Psi res = \bar{\Psi} + \Psi^*$$

Residual MOC — Eulerian-mean MOC — Eddy-induced MOC

1. The eddy-induced MOC can **partially compensate** for changes in the Eulerian-mean MOC induced by **shifts in zonal wind stress** in the Southern Hemisphere.
2. However, the degree of compensation is uncertain and influenced by **surface buoyancy**.

*(Gent et al., 2016; Abernathey et al. 2011; Wolfe & Cessi 2010; Liu et al 2018)*



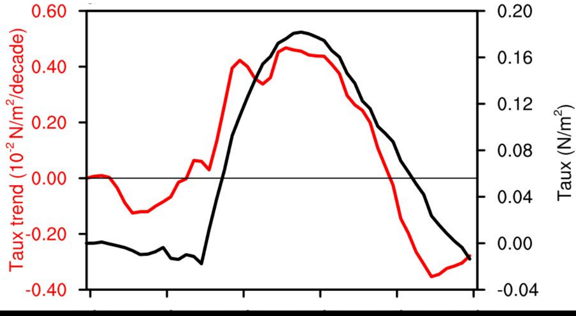

*(Peter et al, 2016)*

**The eddy-induced and Eulerian-mean MOC responses, and the complex interactions and compensation between them, are still uncertain under future climate scenarios**

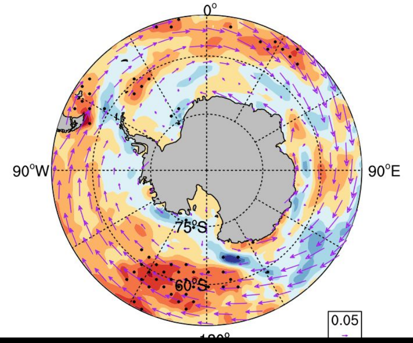
# The Southern Ocean MOC has changed in recent decades

**ECCO v4r4**
**1992-2017**

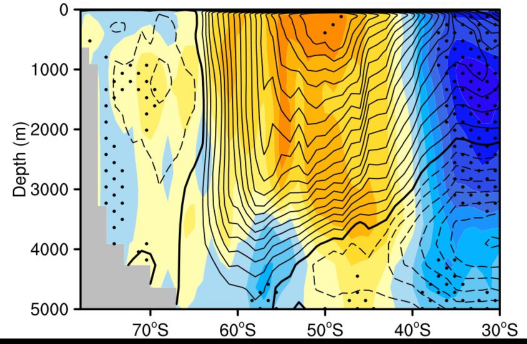
zonal-mean westerly
wind stress trend




westerly wind stress trend

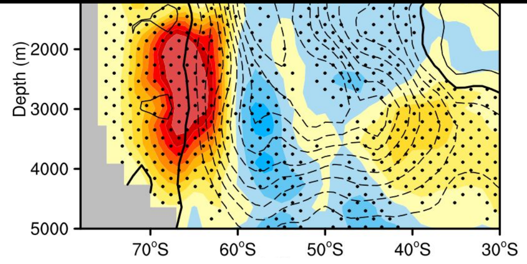



Eulerian-mean MOC



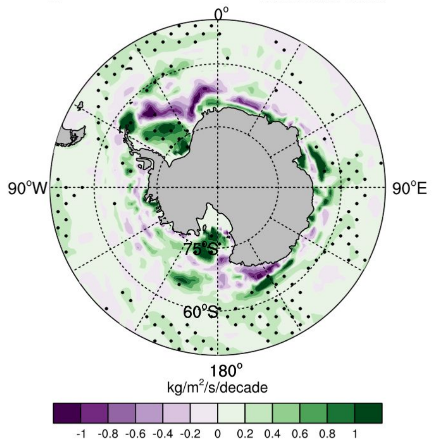

poleward shift
intensification

**A poleward shift and intensification trend has been observed in the Eulerian-mean MOC, while the intensified eddy-induced MOC provides a small compensating effect.**



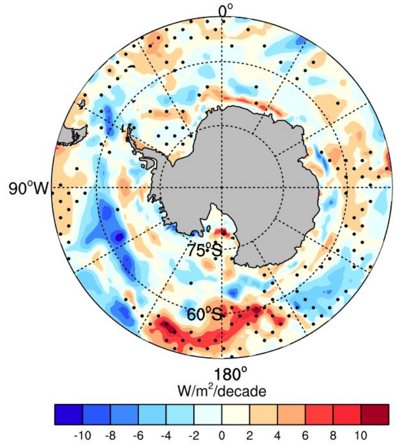

intensified trend
partial compensation

freshwater flux trend



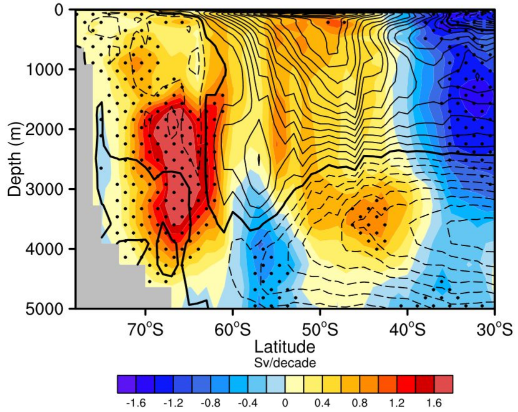

increasing trend

heat flux trend




spatially varying

residual MOC



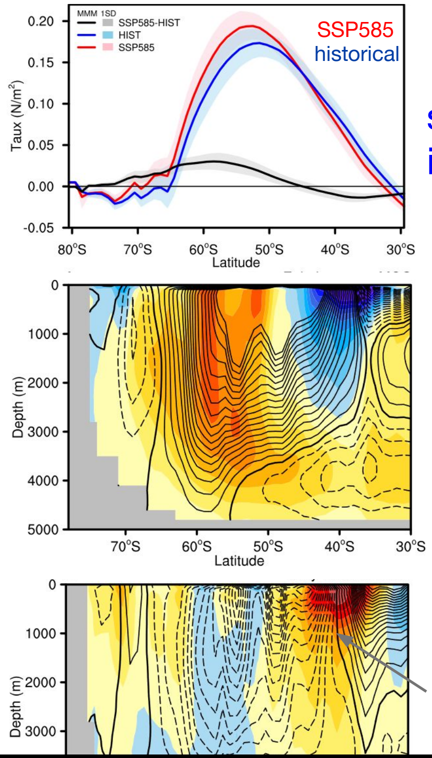
# The Southern Ocean MOC response in past and future warming climates

**CMIP5/CMIP6**

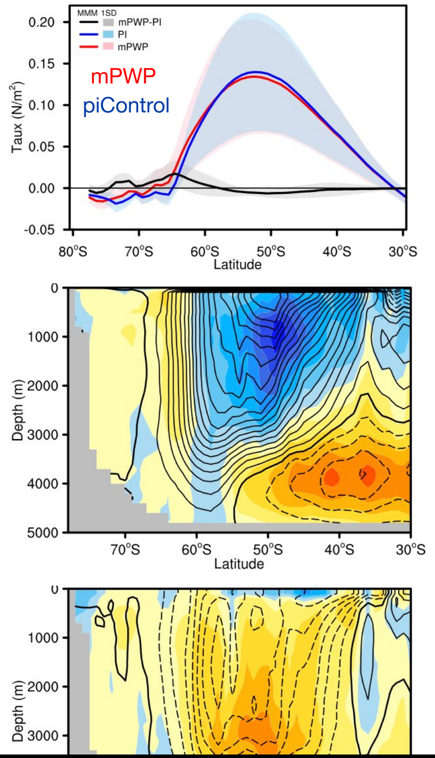
**SSP585 - Historical** (19 models)

**Mid-Pliocene Warming Period (mPWP) - piControl** (6 models)

zonal-mean westerly wind stress




SSP585 - Historical: shift poleward, intensify




mPWP - piControl: shift poleward, weaken

Eulerian-mean MOC

SSP585 - Historical: poleward shift intensification

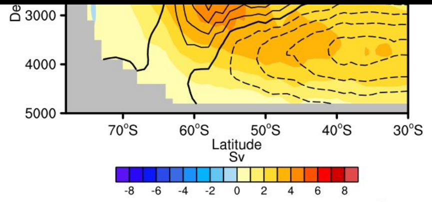
mPWP - piControl: poleward shift weakening

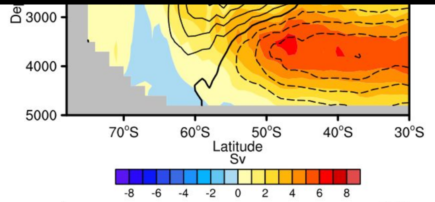
Eddy-induced MOC

SSP585 - Historical: strong compensation

mPWP - piControl: weak compensation

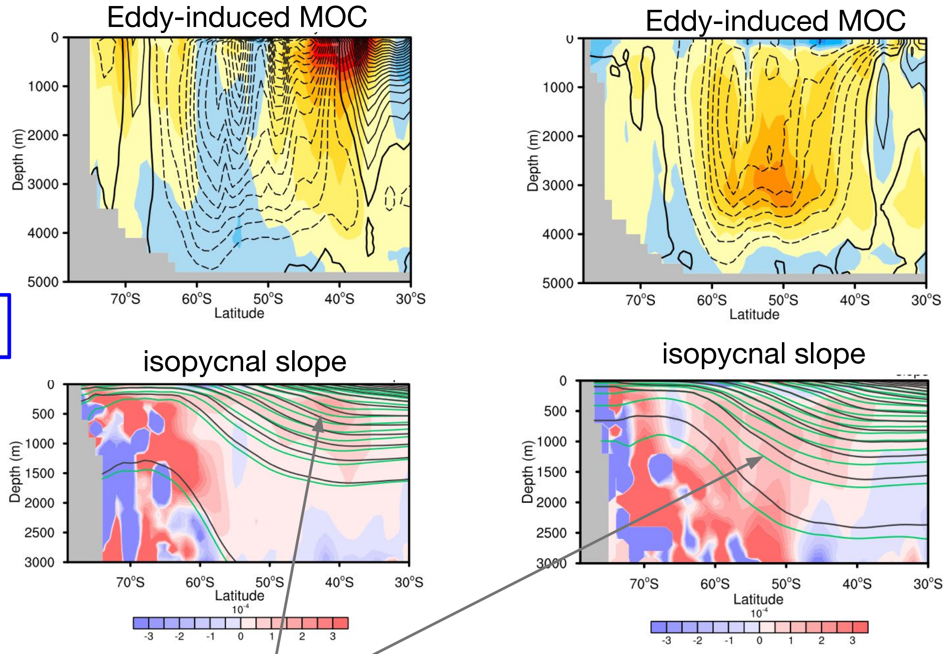
1. **In the future warming climate, the Eulerian-mean MOC undergoes a poleward shift with strong eddy compensation sustaining a uniformly intensified residual overturning.**
2. **The poleward shifting has been confirmed in the past warming but with weaker eddy compensation, leading to a non-uniform intensified residual overturning.**



# How changes in buoyancy forcing affect the Southern Ocean MOC

**SSP585-Historical** (shaded) **mPWP-piControl** (shaded)




$$\Psi^* = K * S_\rho$$

flatten isopycnal slope  weakened eddy-induced MOC

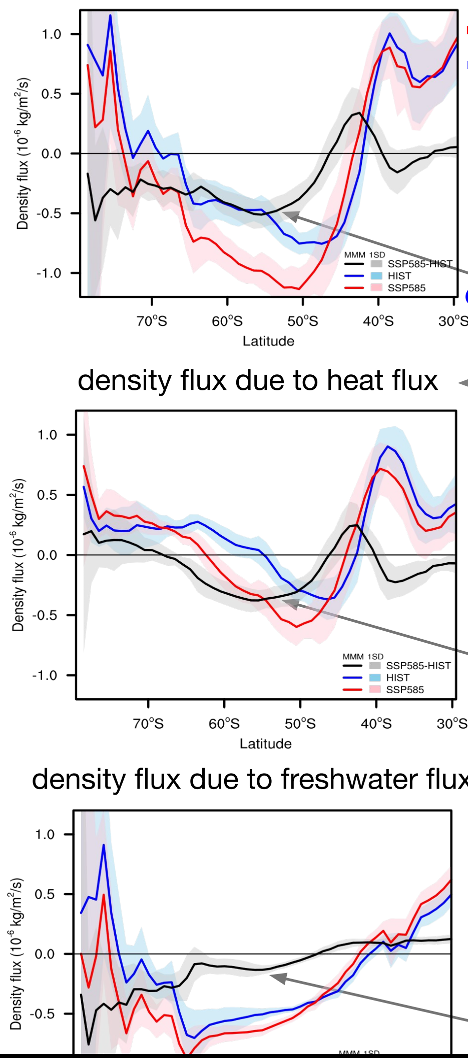
total density flux (heat+freshwater)

SSP585
Historical
SSP585-Historical

$$D_0 = D_{H_0} + D_{F_0} = -\frac{\alpha}{c_p} H_0 + SSS \frac{\rho}{\rho_0} \beta F_0$$

density flux due to heat flux

density flux due to freshwater flux



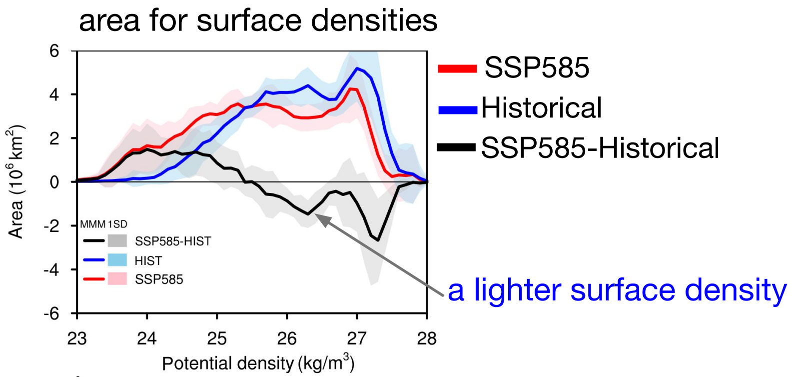

decrease density flux

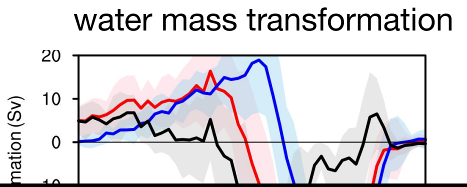
mainly

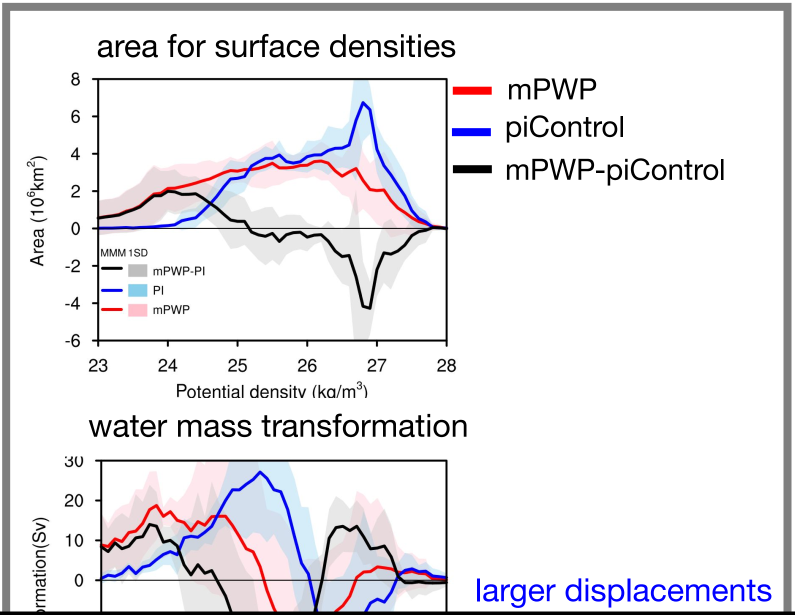
small

**The weakened eddy-induced MOC in both future and past warming climates is driven by a flattened isopycnal slope, primarily caused by increased surface heat flux.**

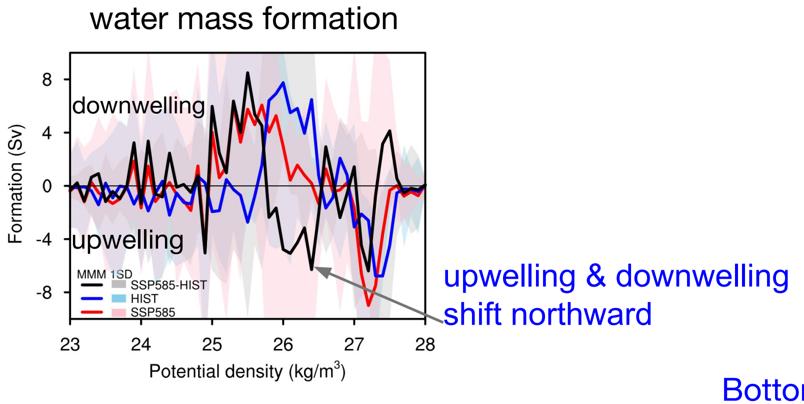
# Water mass formation in the past and future warming climates

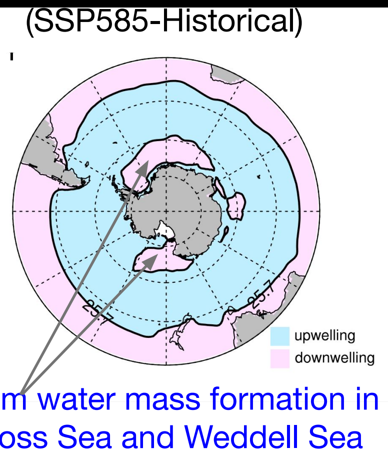


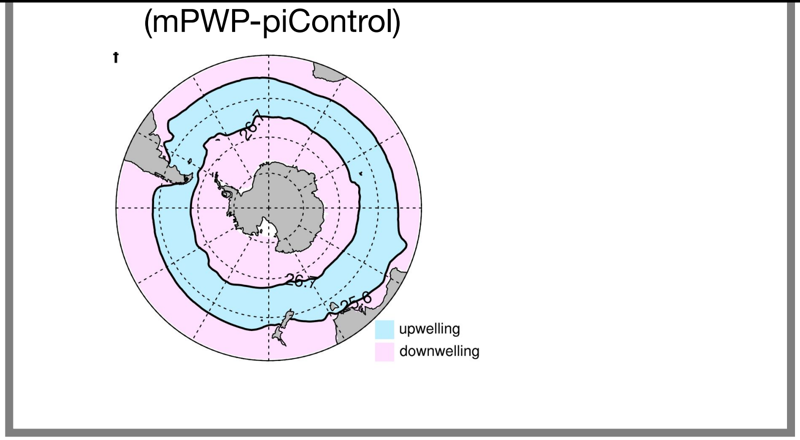




**The associated buoyancy forcing changes have driven northward upwelling around Antarctica, with larger displacements over the past warm period, promoting the bottom water formation in the Ross and Weddell Seas.**



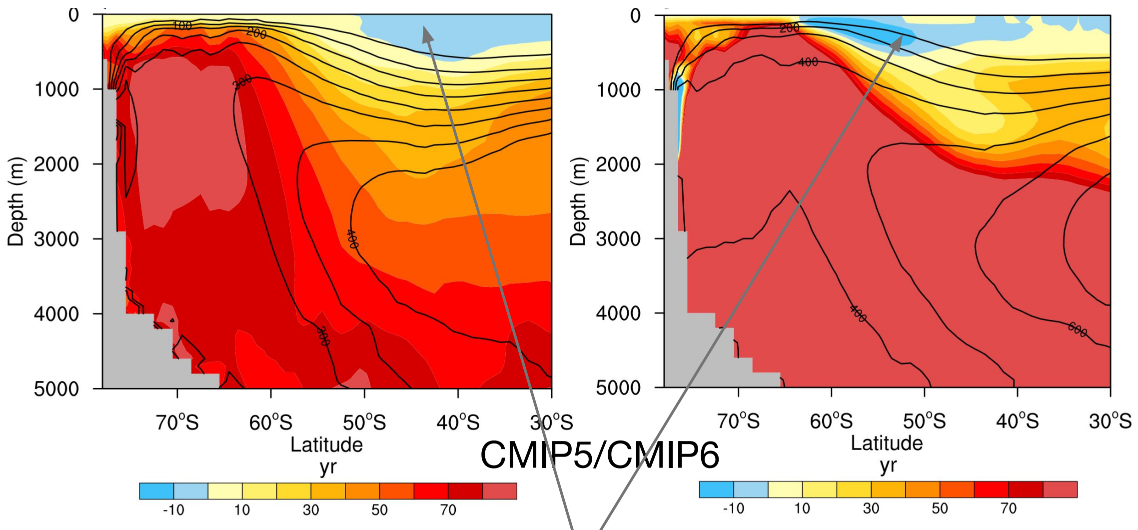



# Response of Southern Ocean Ventilation

Ideal age represents the average time since the water last resided in the surface layer.

ideal age (**SSP585-HIST**) | ideal age (**mPWP-piControl**)




CMIP5/CMIP6

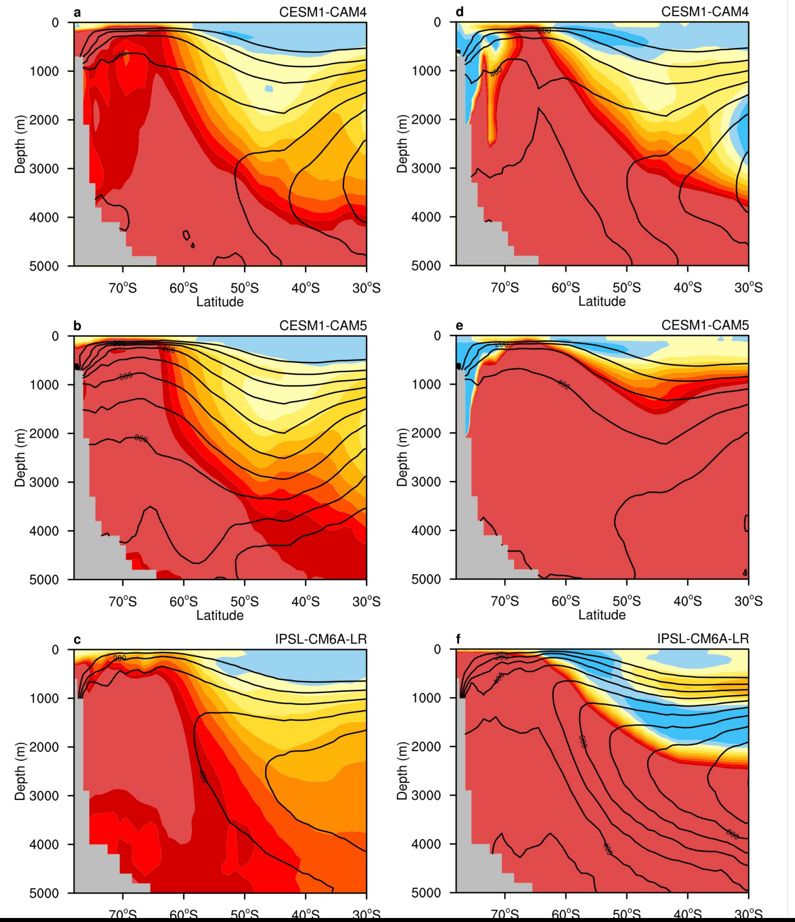
enhanced ventilation

ideal age (**SSP585-HIST**) | ideal age (**mPWP-piControl**)

CESM1-CAM4

CESM1-CAM5

IPSL-CM6A-LR




**Along with MOC changes, ventilation intensifies in the subduction branch, especially during the past warm period.**

# Conclusions

1. Under high-emission scenarios, the Eulerian-mean MOC shifts poleward, with strong eddy compensation sustaining a uniform residual overturning. In the mid-Pliocene, a similar shift occurs but weaker eddy compensation leads to an un-uniform residual response.

2. The associated buoyancy forcing changes have driven northward upwelling around Antarctica, with larger displacements over the past warm period, promoting the bottom water formation in the Ross and Weddell Seas.

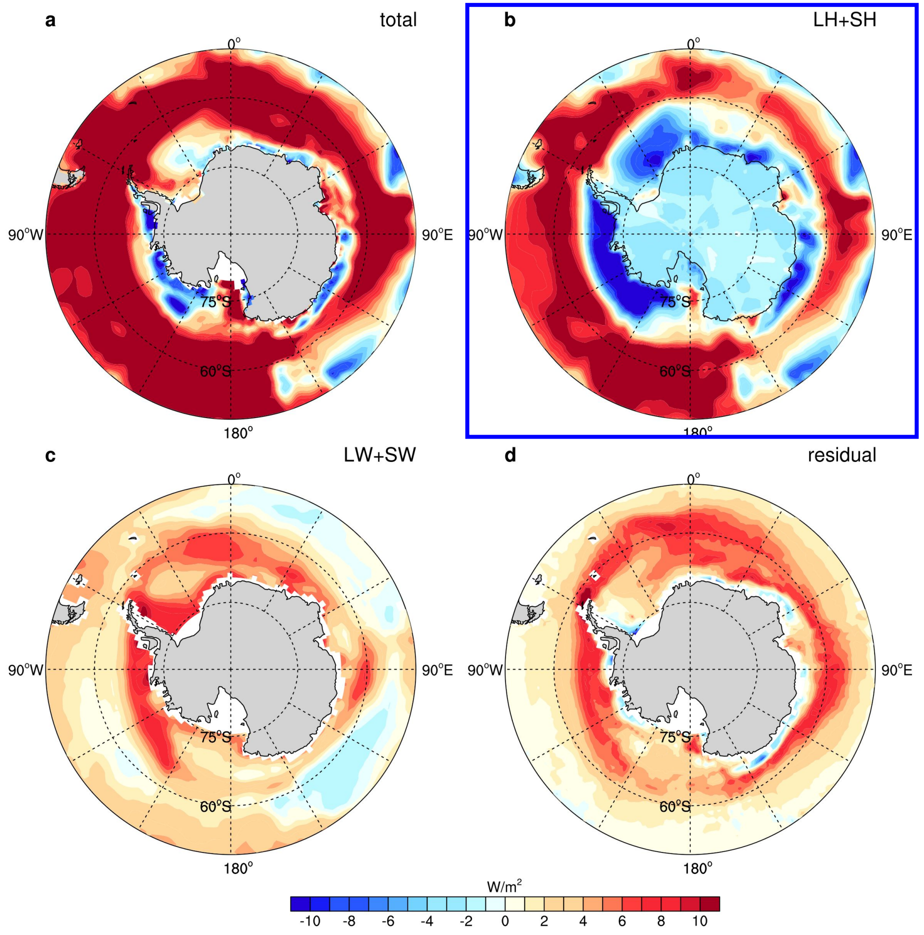
3. Alongside changes in the Southern Ocean MOC, ventilation linked to the subduction branch intensifies, particularly during the past warm period. This intensified ventilation has critical implications for climate feedbacks, impacting ocean heat uptake, carbon storage, and air-sea interactions.

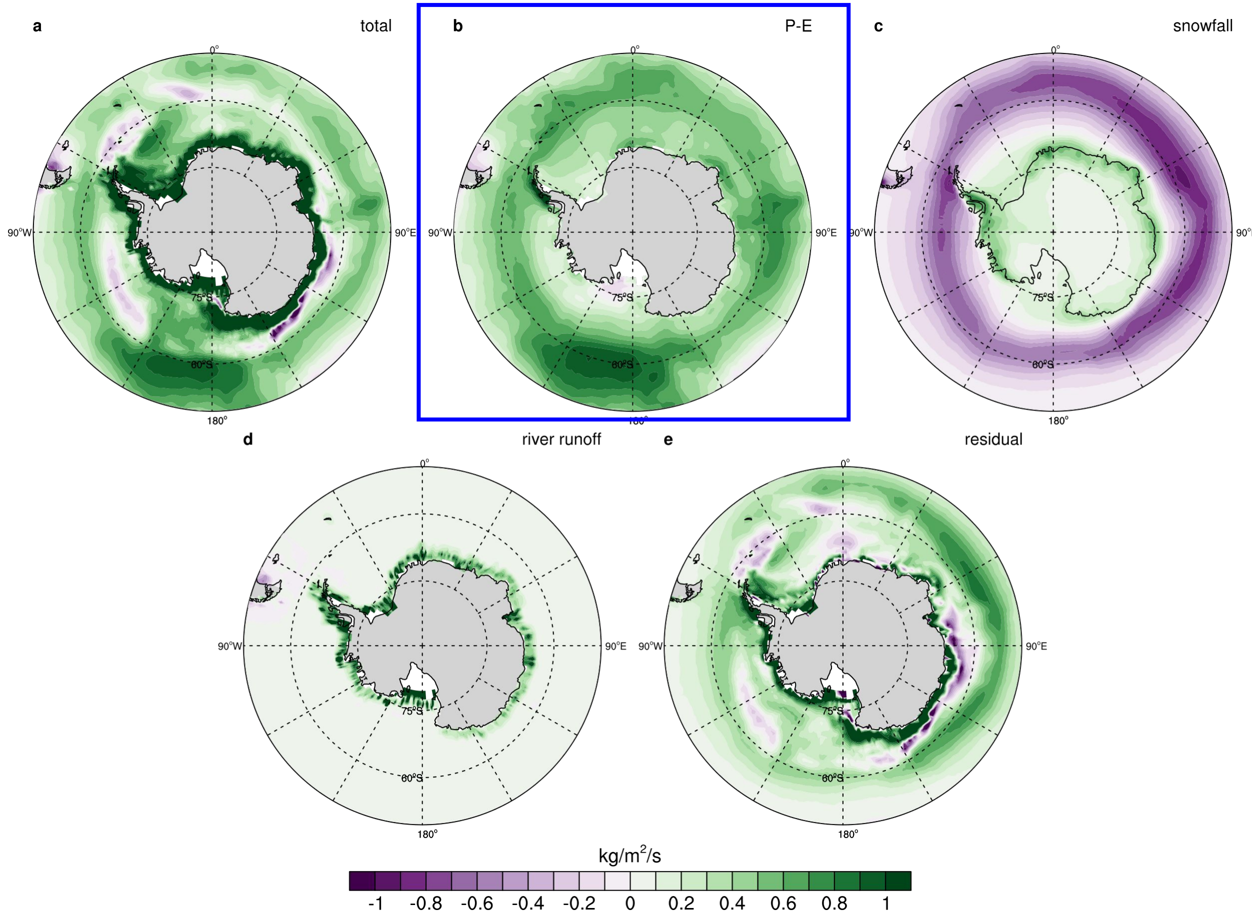
*Zhu T. & Liu W. (2025) Evolving Southern Ocean overturning in warming climates. in review*

The Eulerian-mean MOC ($\bar{\psi}$) is calculated by integrating the Eulerian mean meridional velocity v zonal and vertically:

$$\bar{\psi}(\mathrm{y}, \mathrm{z}) = \oint \int_{z}^{0} \bar{v} dz' dx$$

# The eddy-induced MOC change due to buoyancy forcings



# Response of Southern Ocean Ventilation