

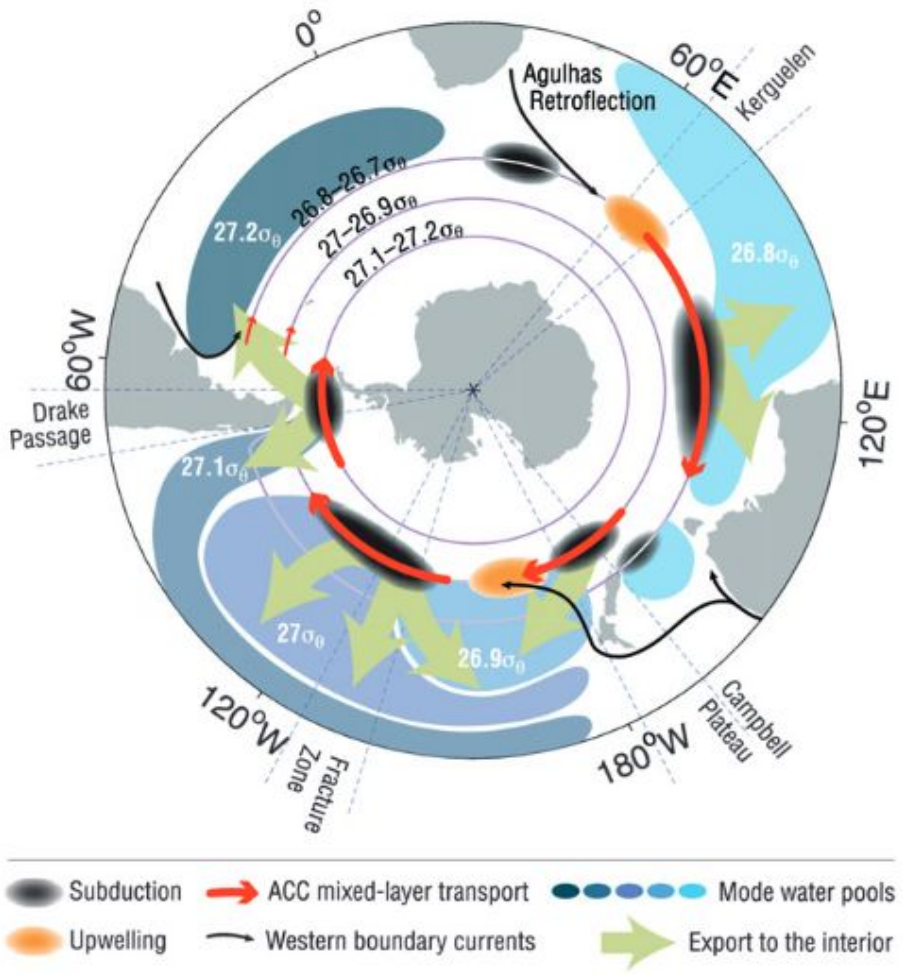
Ocean ventilation in an increasingly stratified Southern Ocean

Lily Dove (she/her)

NOAA C&GC Postdoctoral Fellow, Brown University
Starting August: Assistant Professor, **Georgia Tech**

The Southern Ocean is central to ocean ventilation

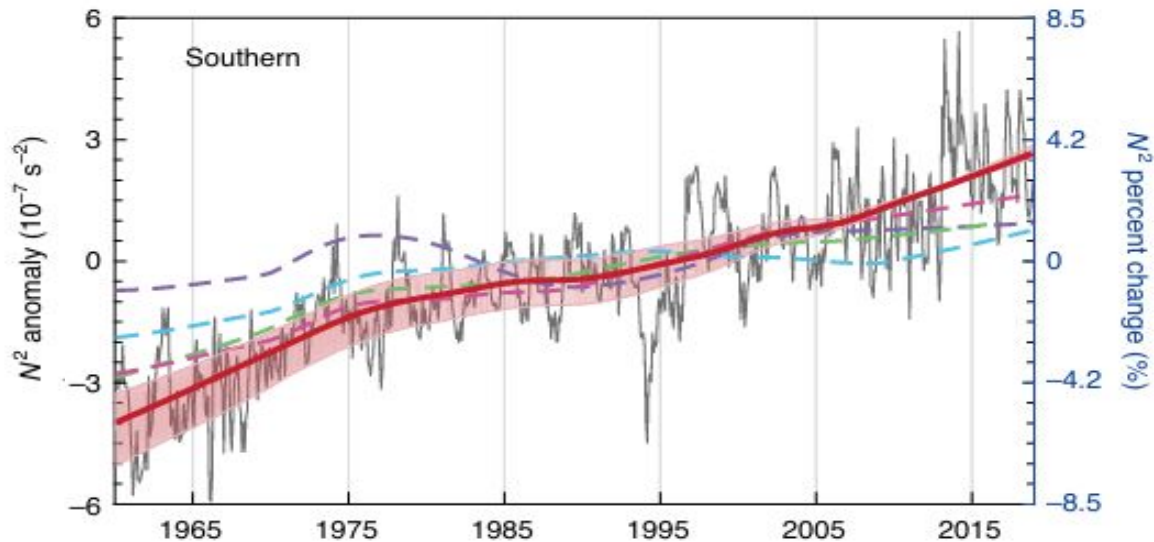
~43% of anthropogenic carbon and ~75% of excess heat uptake by the ocean has entered the ocean south of 30°S.



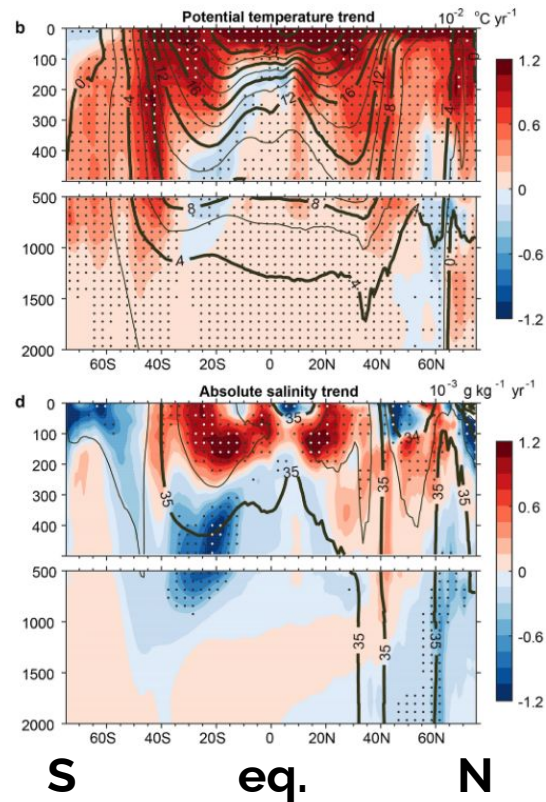
Frölicher et al. (2015)

Sallée et al. (2010)

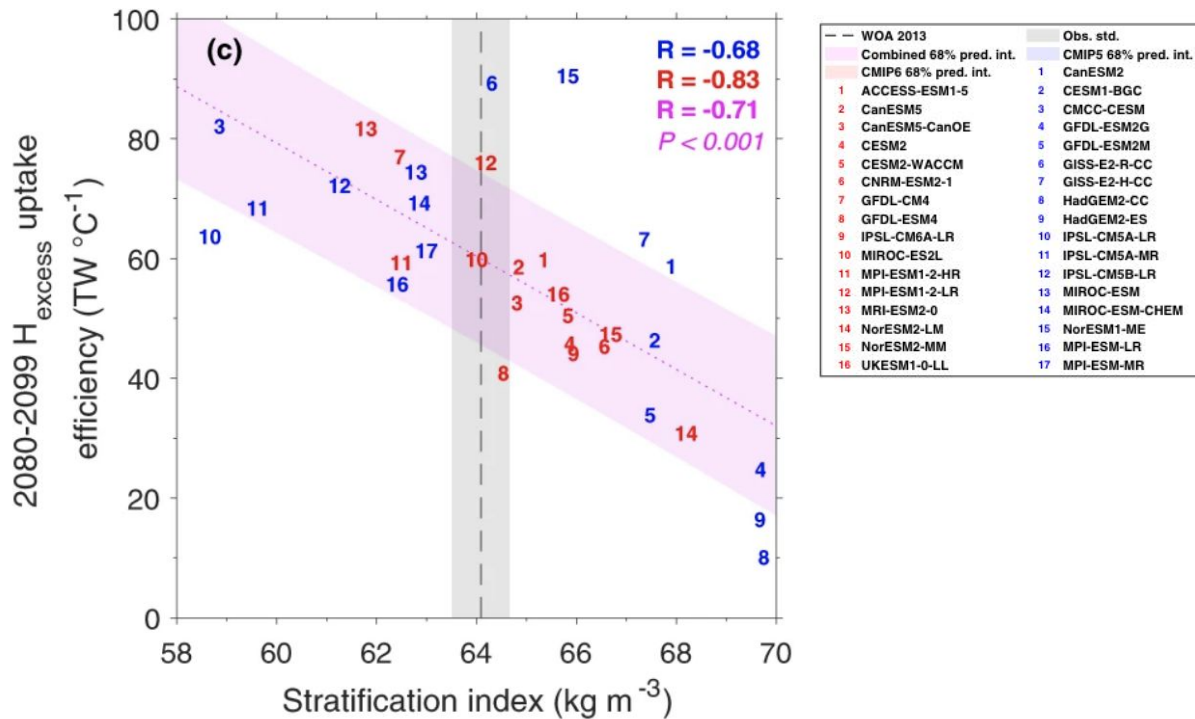
The Southern Ocean is increasingly stratified



Li et al. (2020)

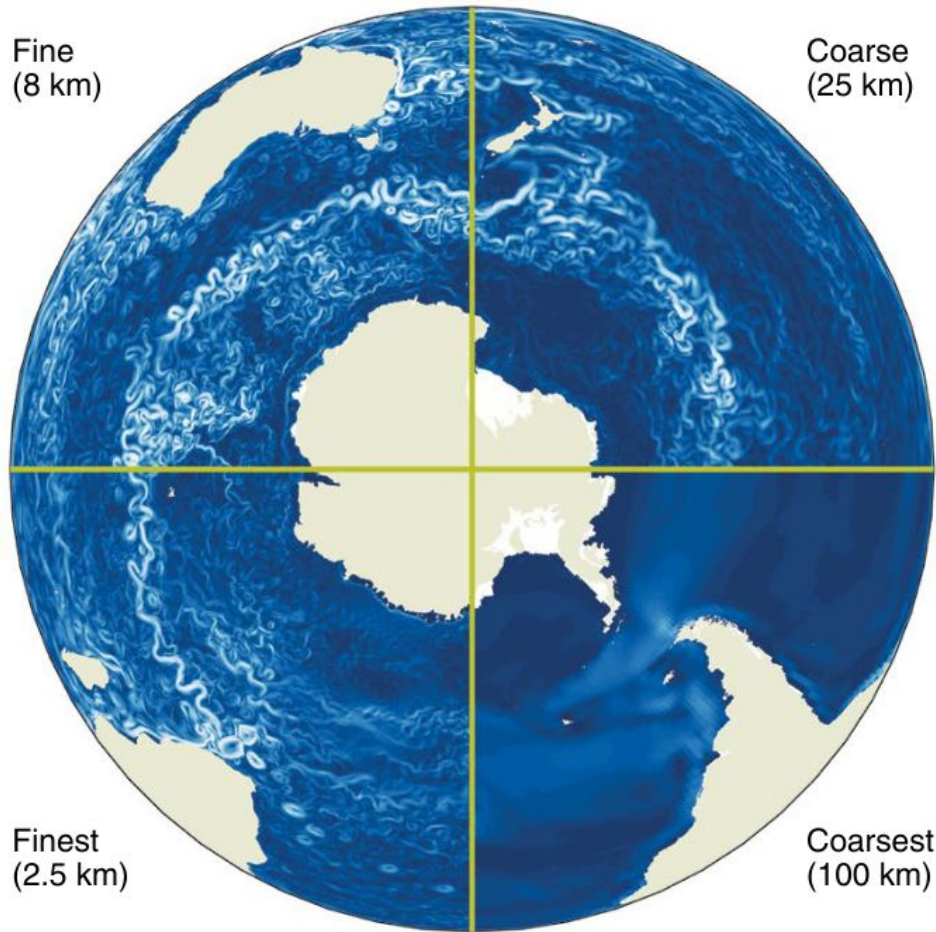


At the basin scale, stratification constrains future heat and carbon uptake



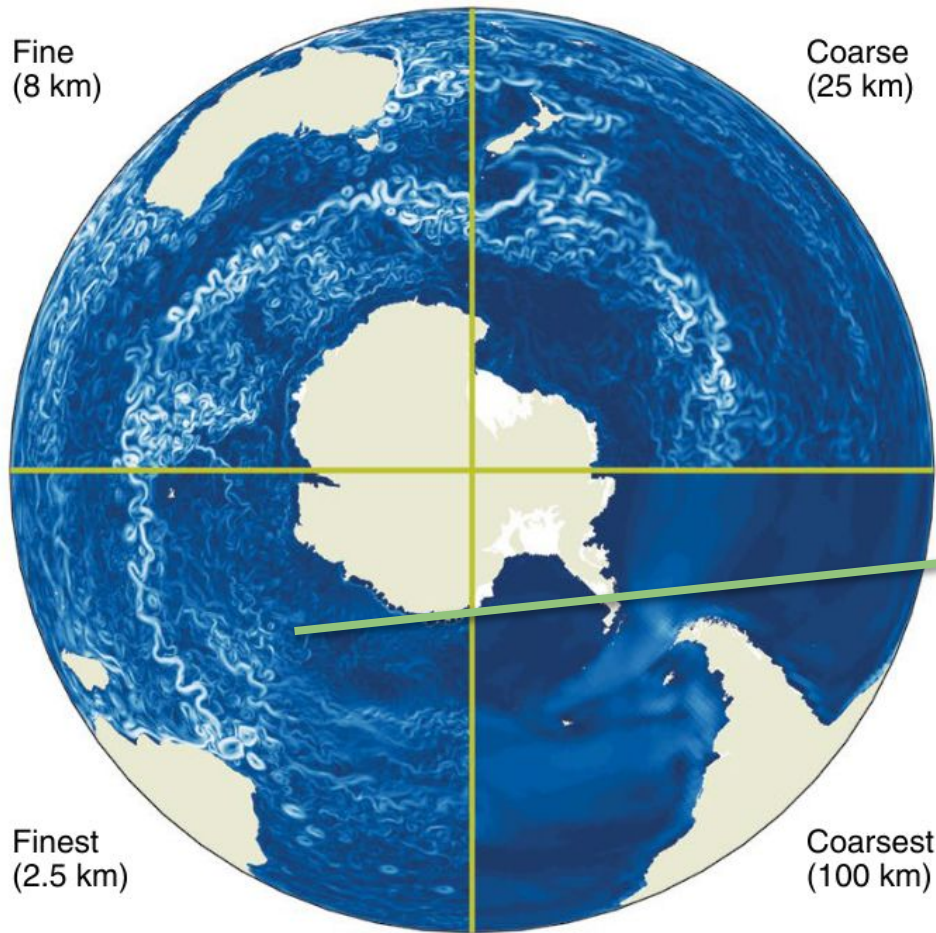
Bourgeois et al. (2022)

See also Newsom et al. (2023)



How do these
basin-wide
changes translate
to the ocean's fine
scale?

Hewitt et al. (2022)



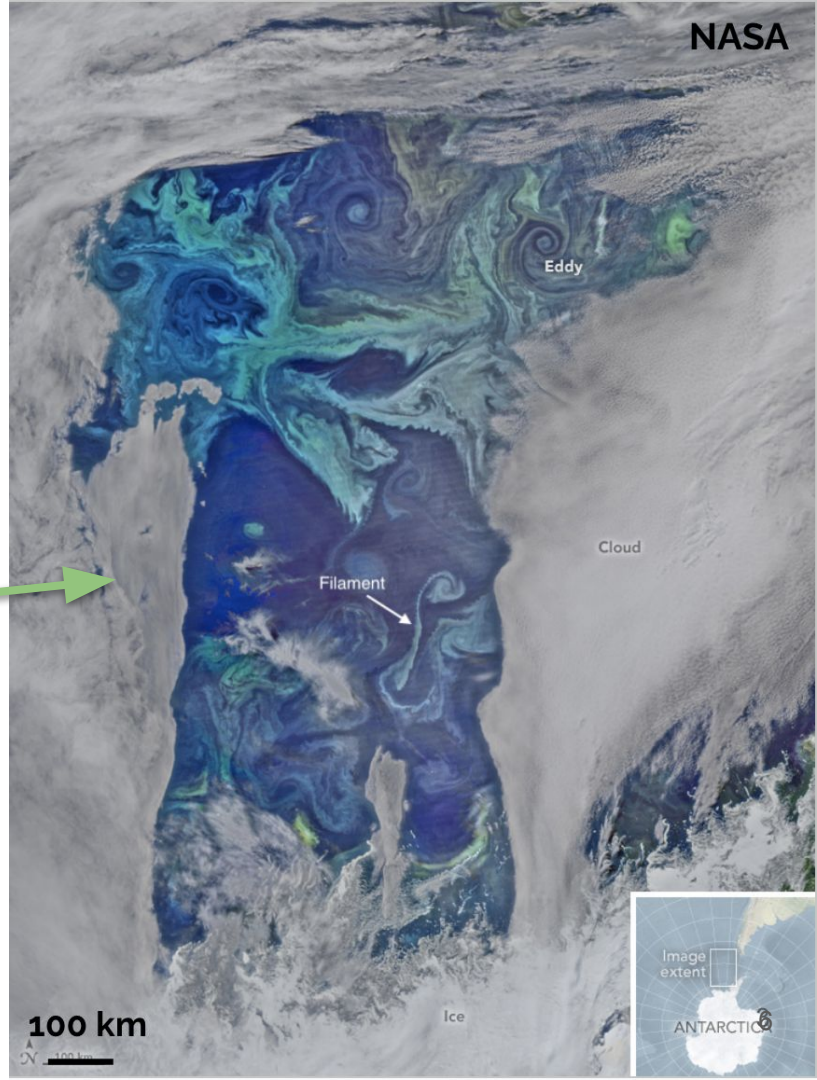
Fine
(8 km)

Coarse
(25 km)

Finest
(2.5 km)

Coarsest
(100 km)

Hewitt et al. (2022)



NASA

Eddy

Cloud

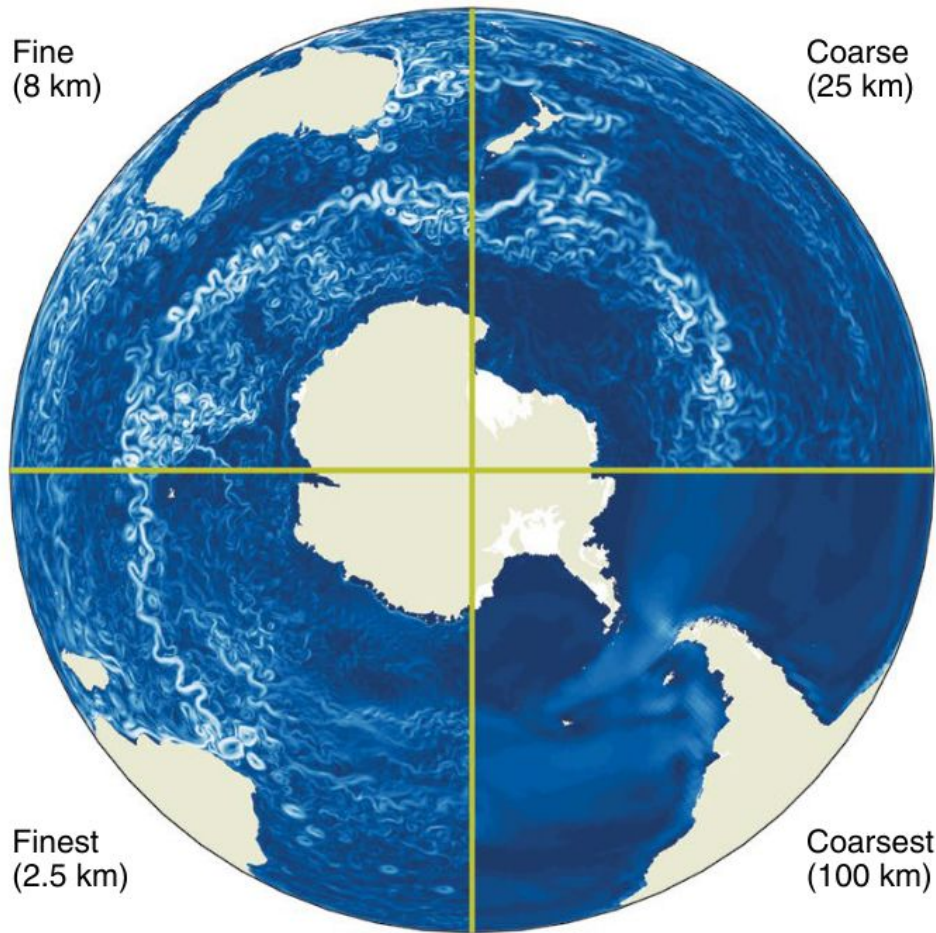
Filament

100 km

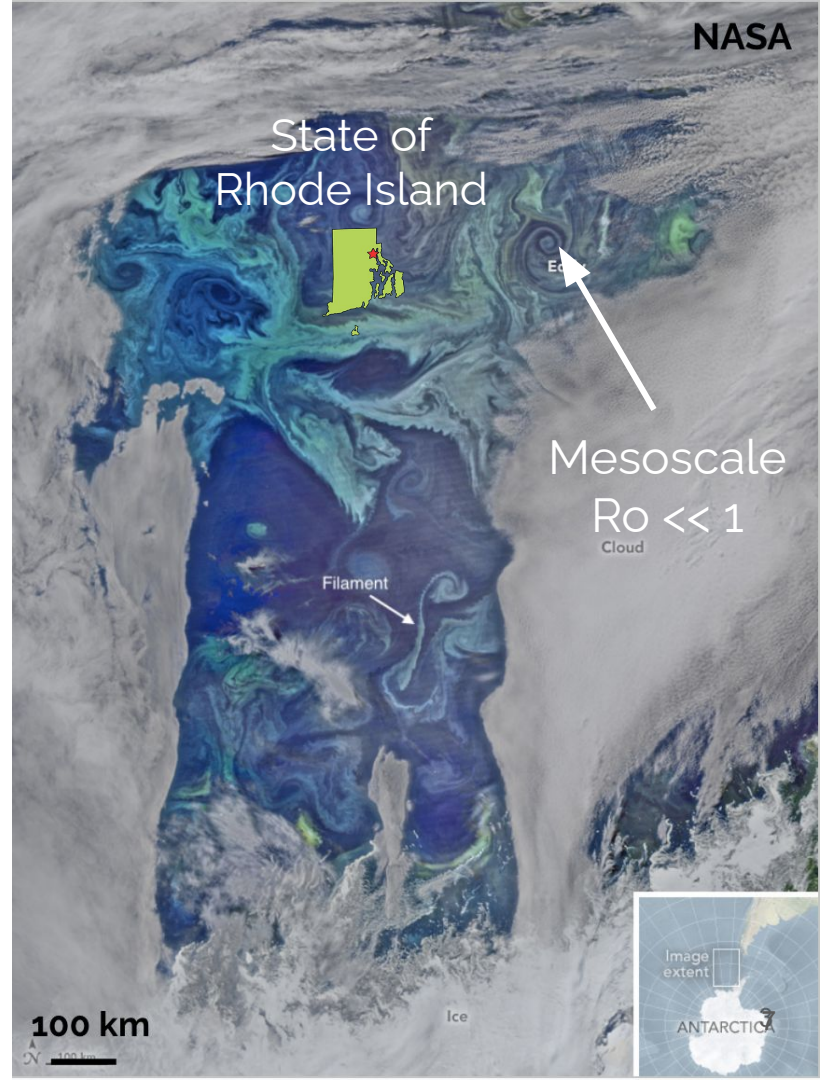
Ice

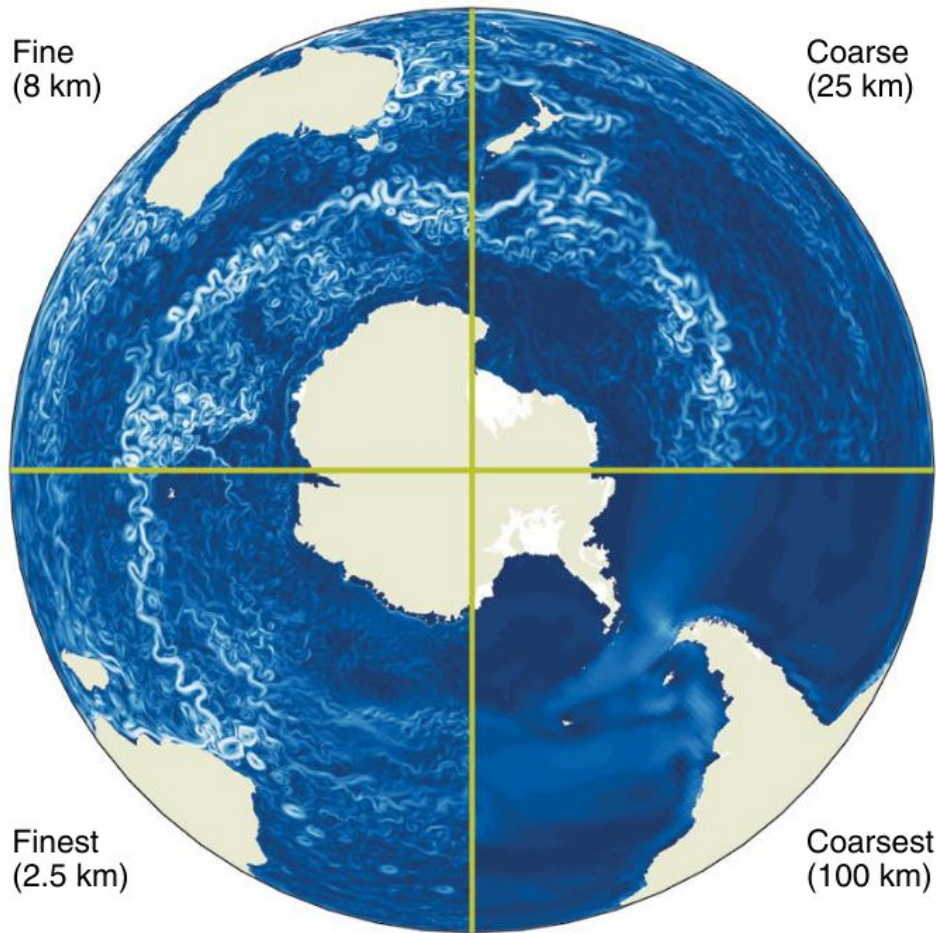
Image
extent

ANTARCTIC

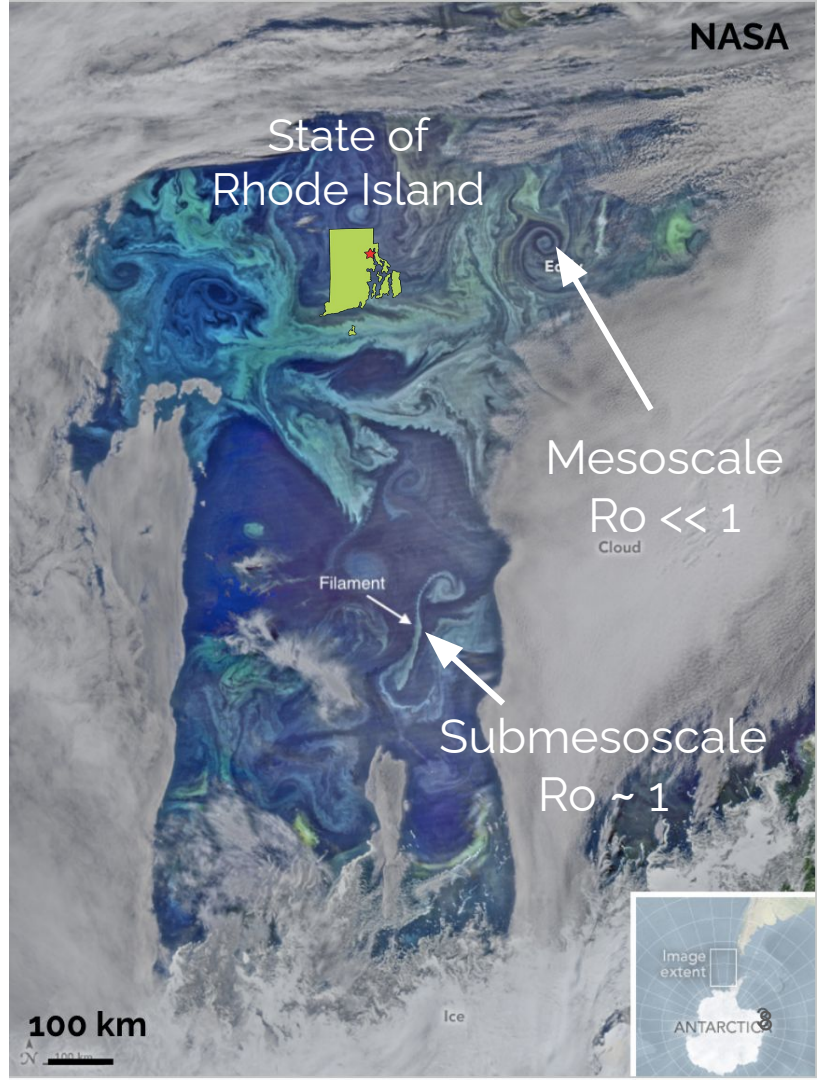


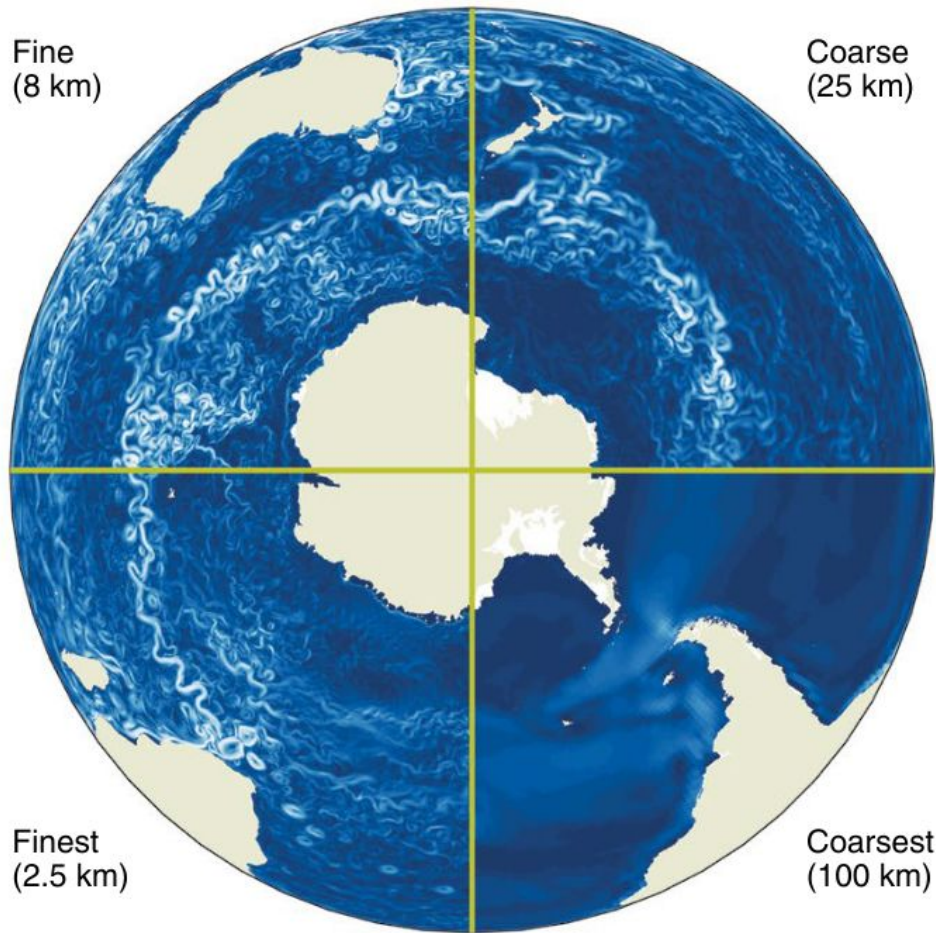
Hewitt et al. (2022)



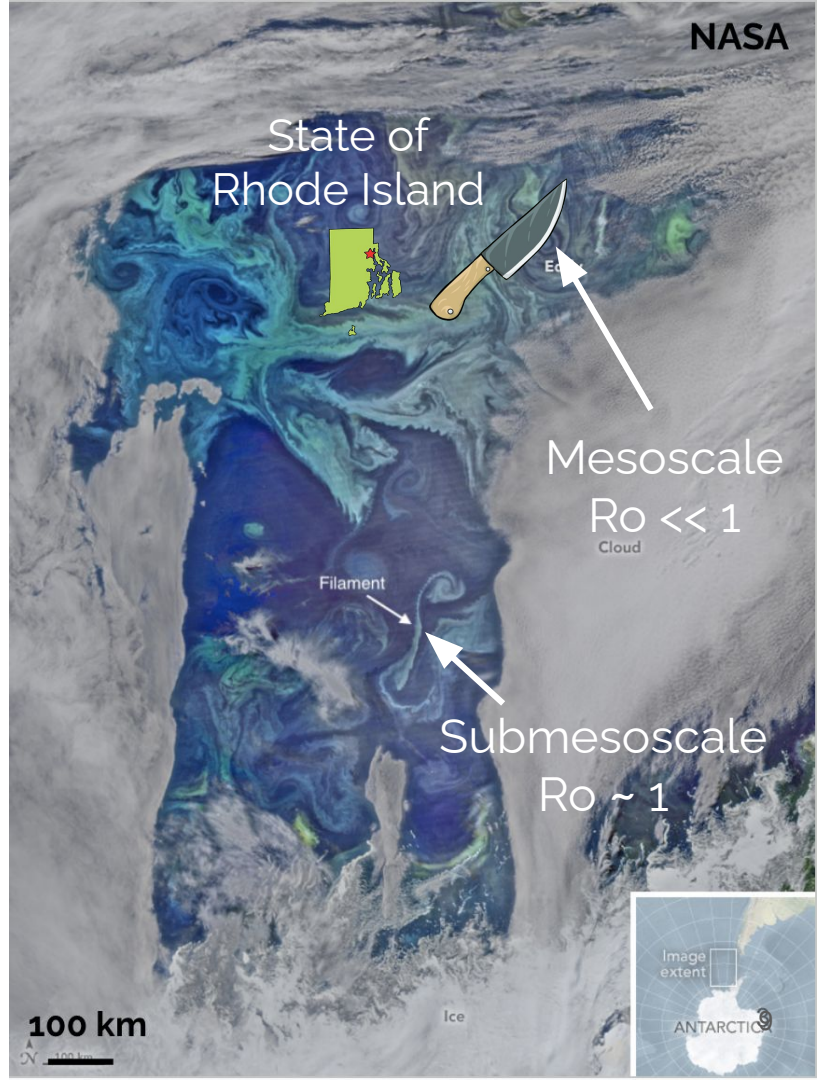


Hewitt et al. (2022)

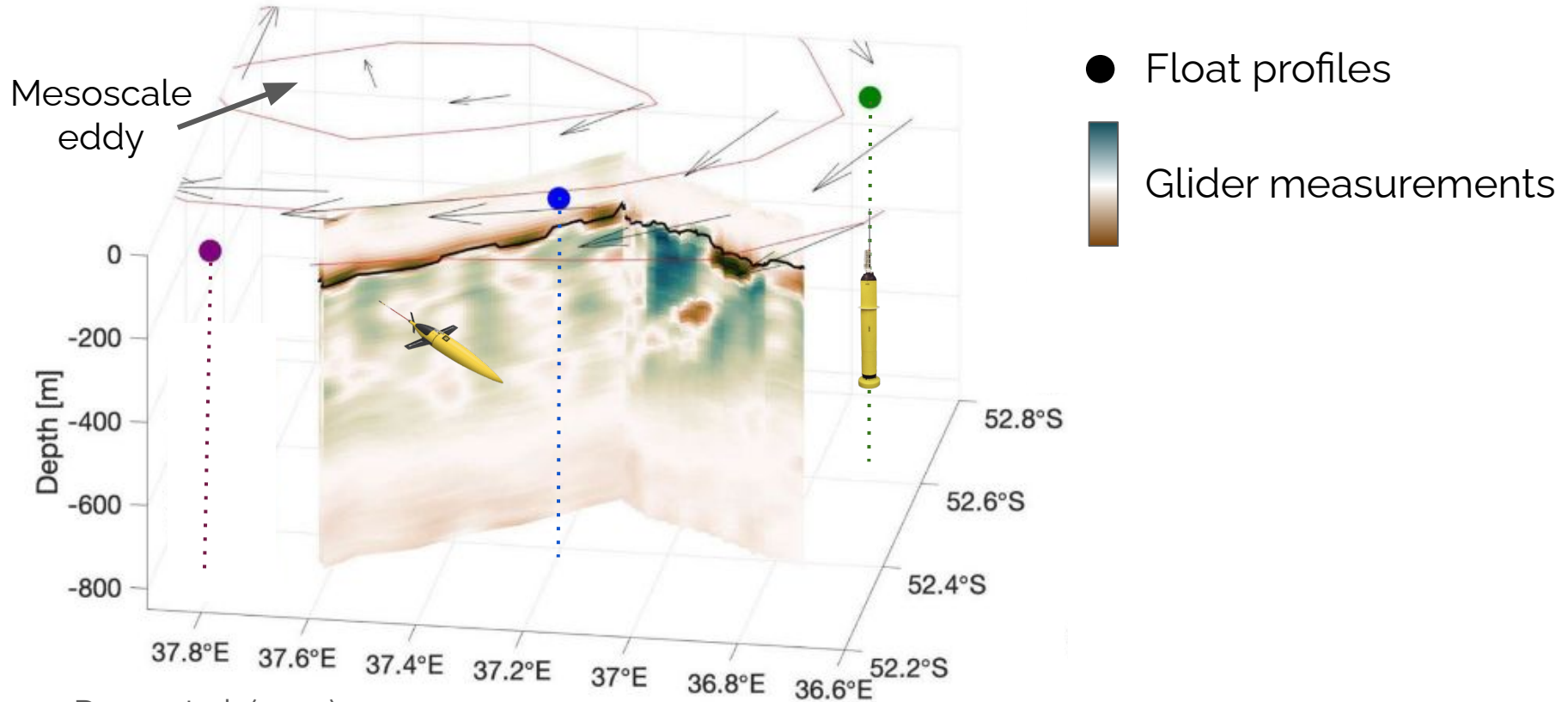




Hewitt et al. (2022)

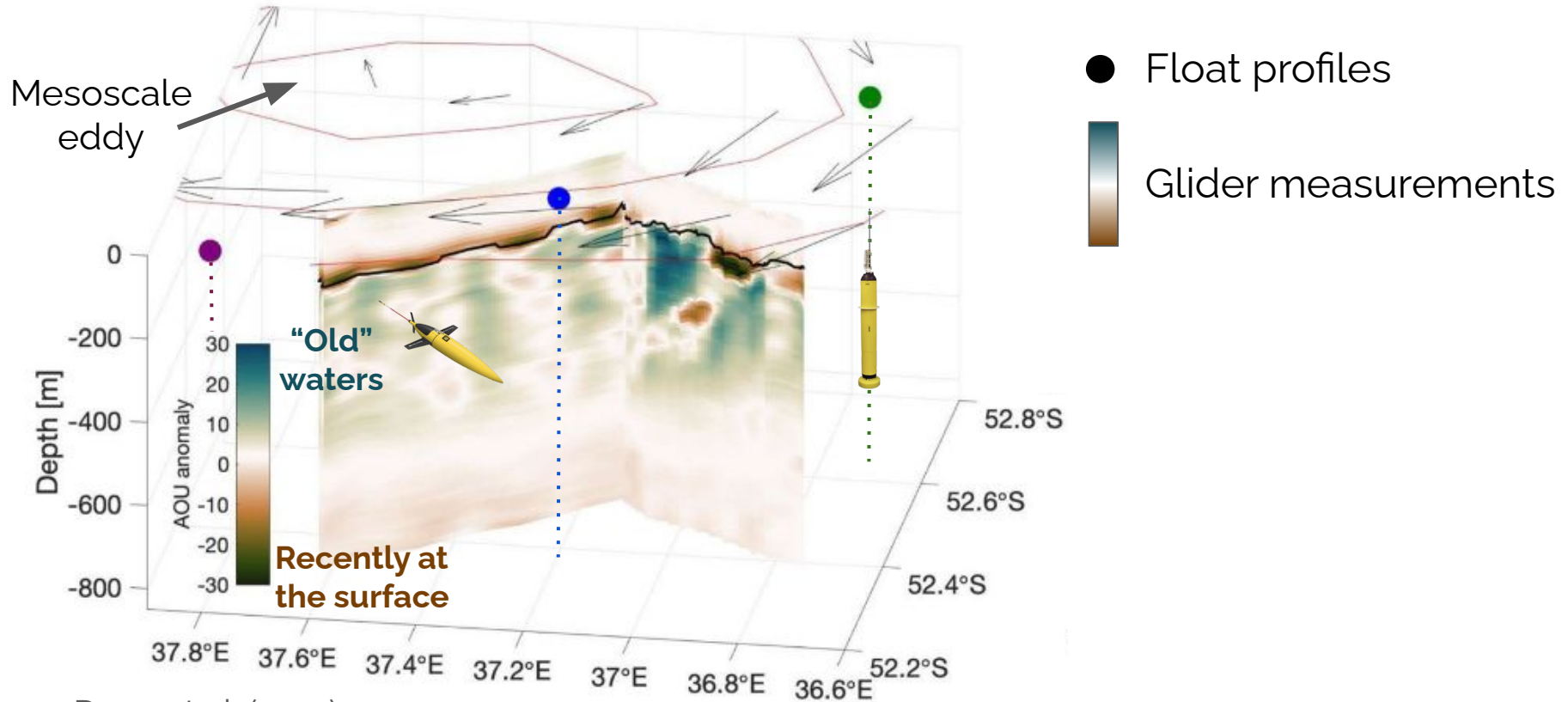


Ventilation at fine scales



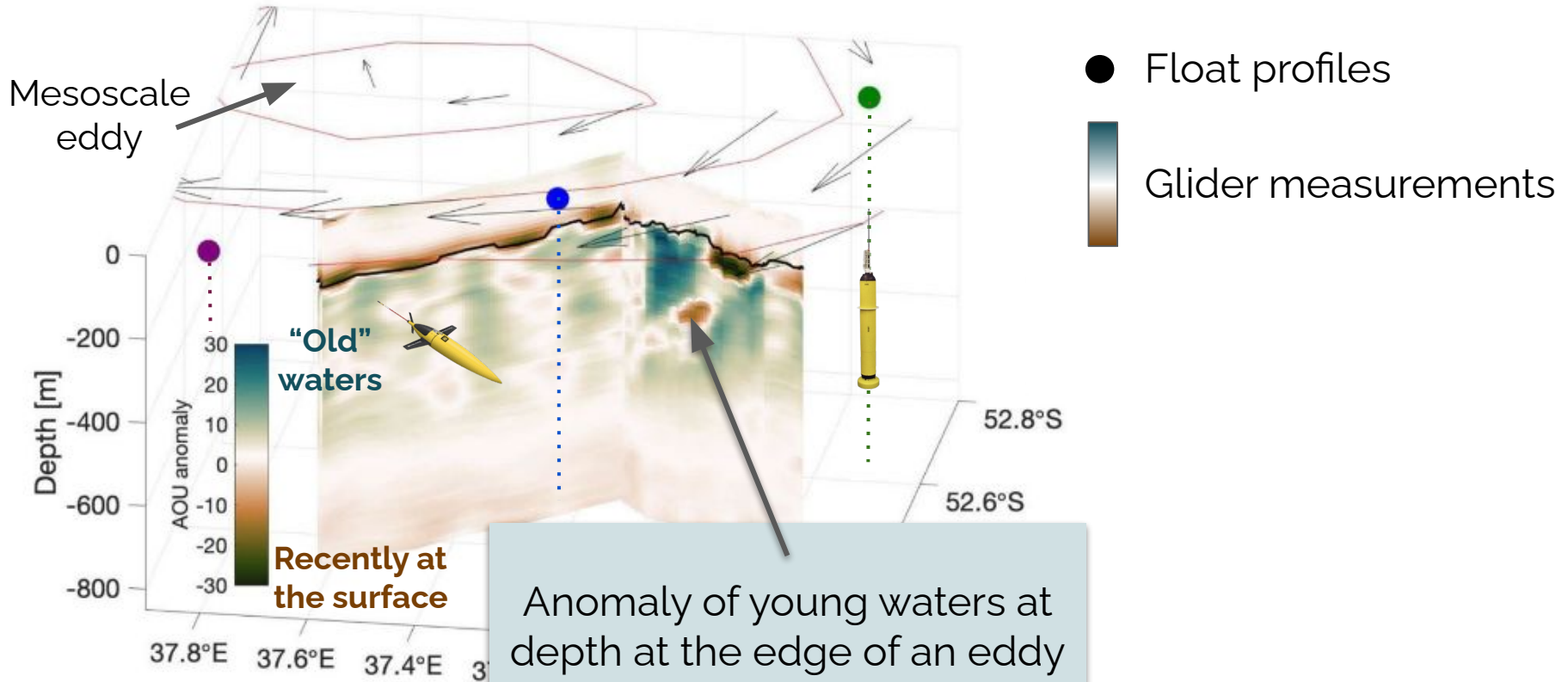
Dove et al. (2021)

Ventilation at fine scales



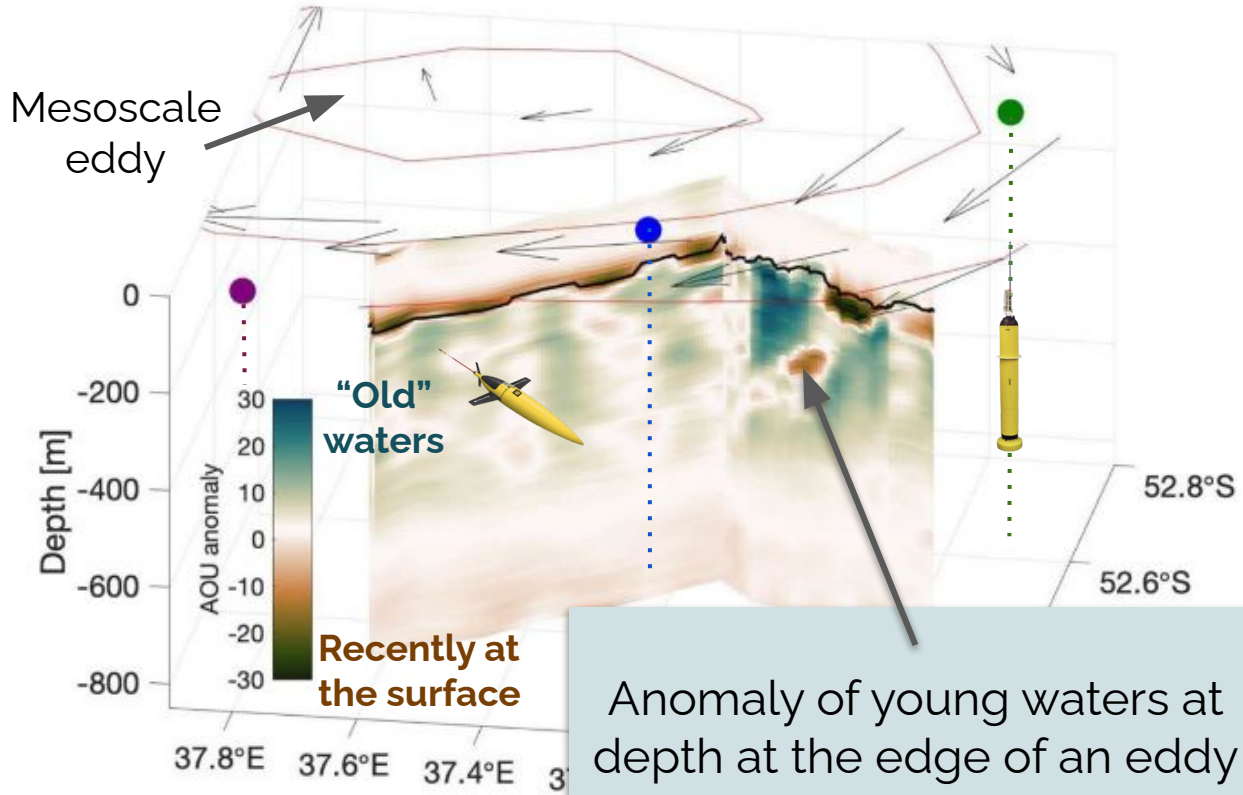
Dove et al. (2021)

Ventilation at fine scales



Dove et al. (2021)

Ventilation at fine scales

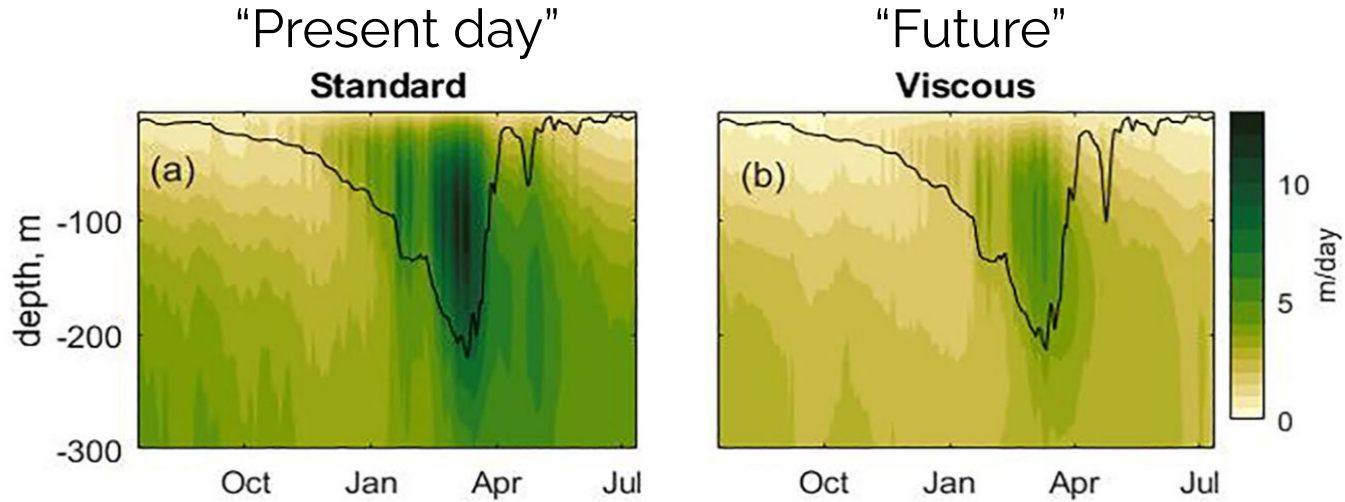


- Float profiles
- █ Glider measurements

Anomaly of young waters at depth at the edge of an eddy

Fine scales may be important for carbon and heat budgets across the Southern Ocean

Previous studies project that fine-scale ventilation decreases in an increasingly stratified world



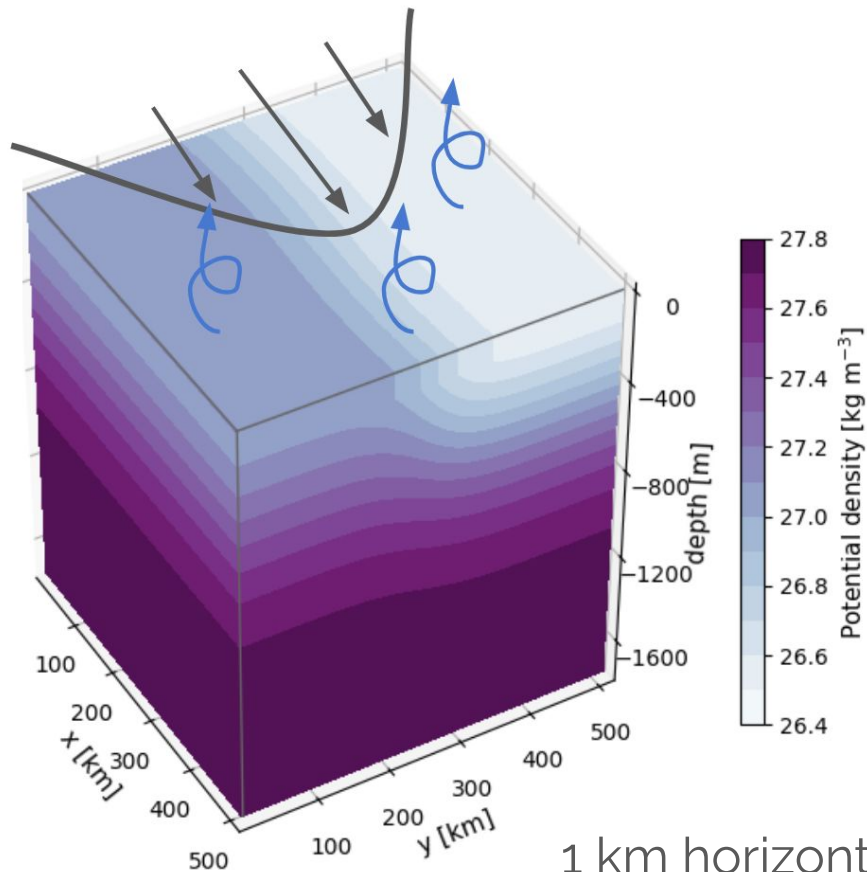
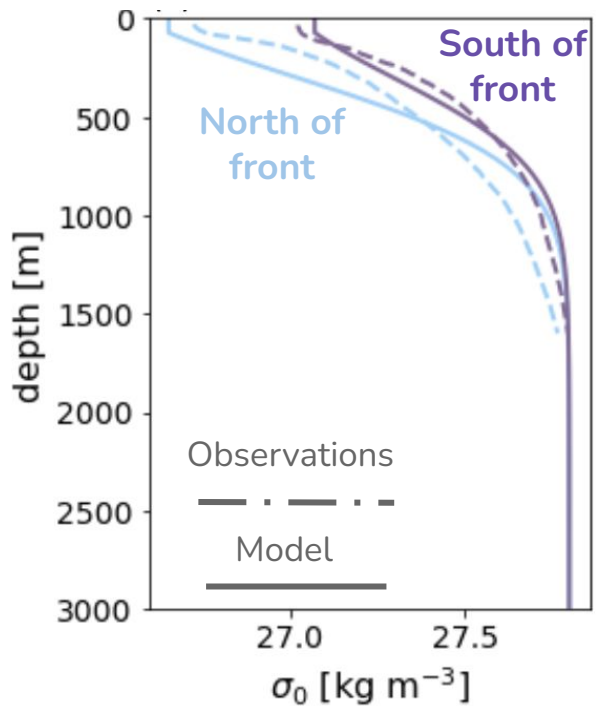
Brett et al. (2023)

See also Richards et al. (2021)

What are the mechanisms by which tracers ventilate at fine scales?

How will changing ocean stratification impact fine-scale ventilation?

Where do we go from here?

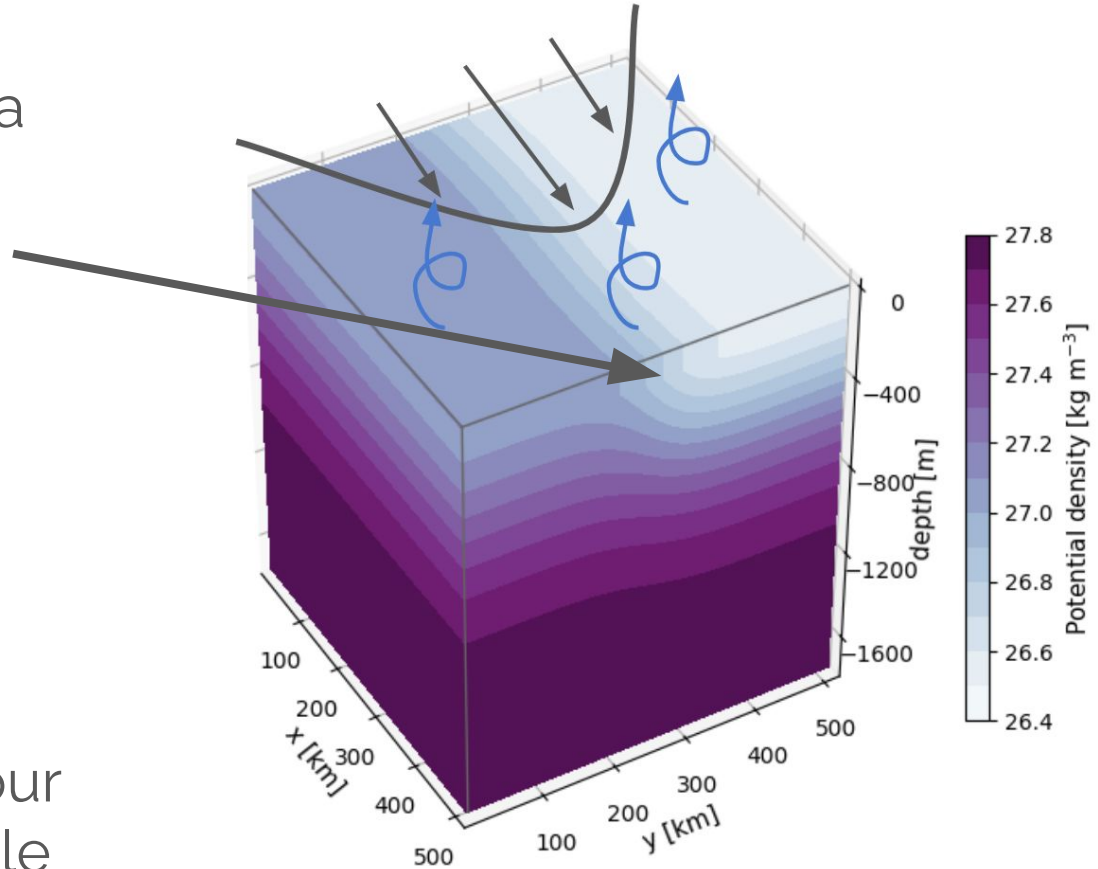


1 km horizontal resolution

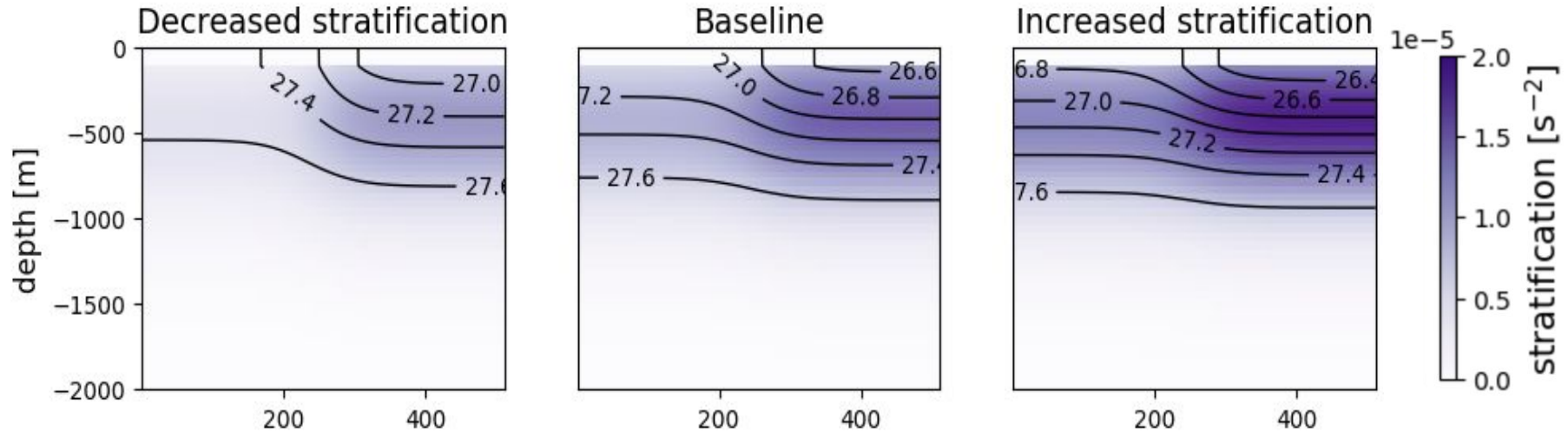
Isopycnal slope is a function of both vertical density gradient (b_z) and lateral buoyancy gradient (b_x)

$$\Gamma = b_x / b_z$$

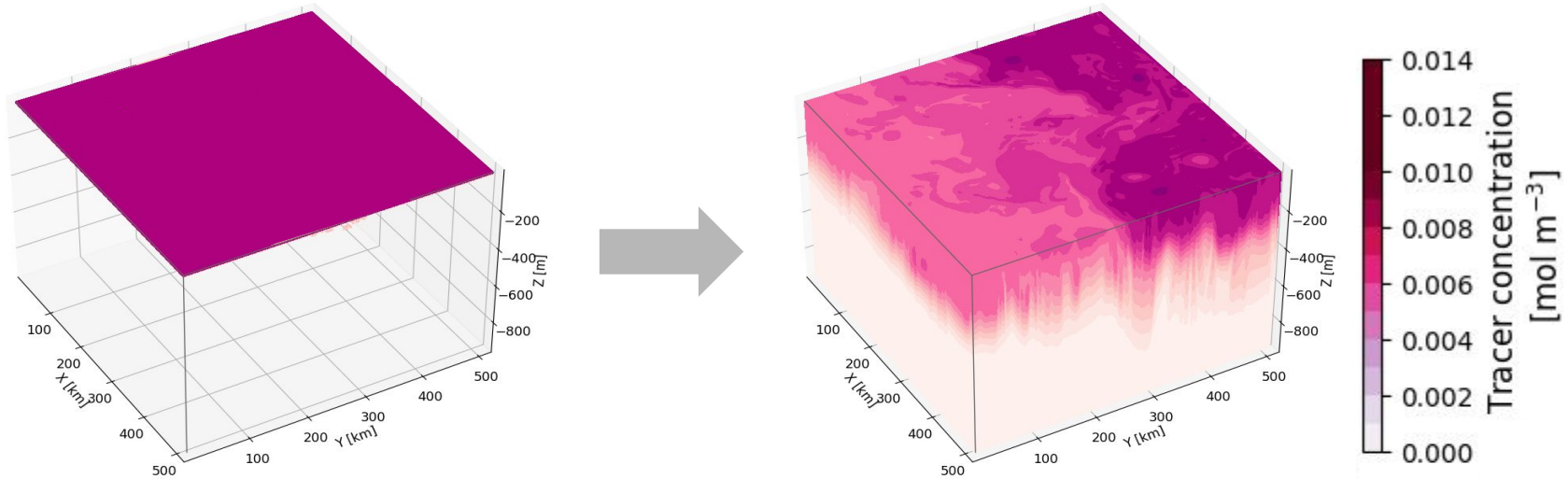
b_z is stratification: our independent variable



We test different stratification regimes to observe changes to ventilation

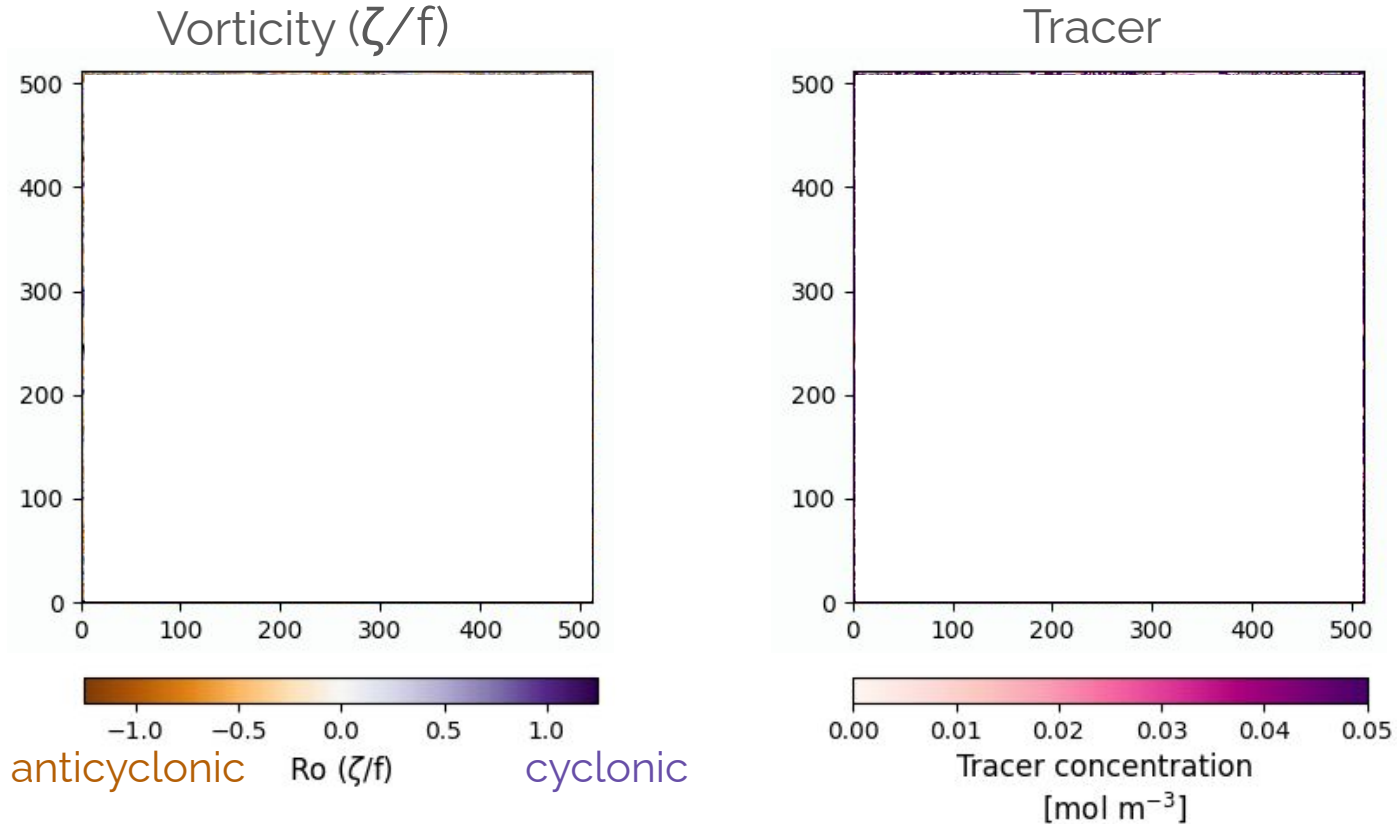


What are the mechanisms by which tracers move from the surface to the interior ocean?

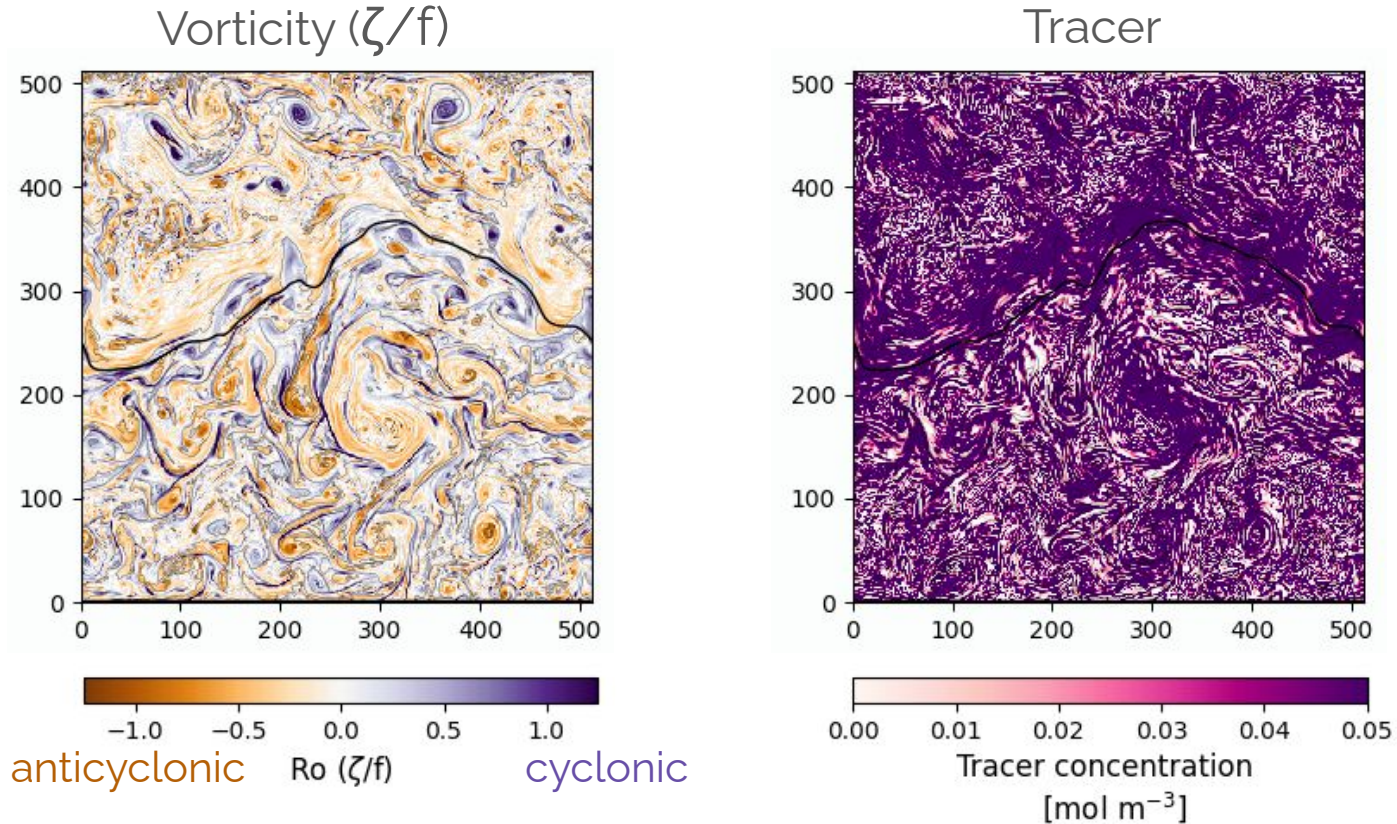


Think of tracers as a “dye” - or pink phytoplankton

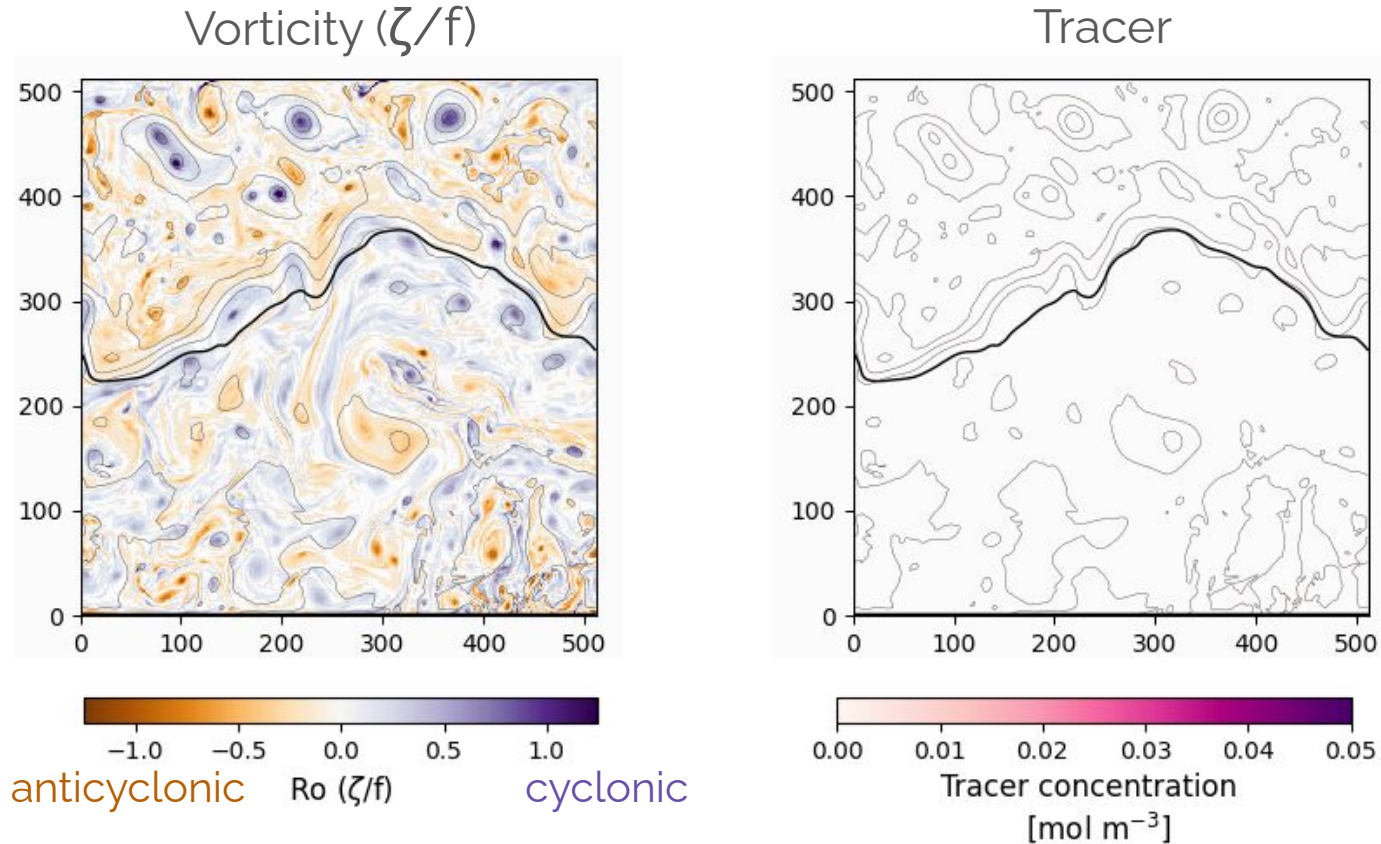
The **surface** (10m) is highly energetic and tracer is rapidly shaped by the small-scale flow

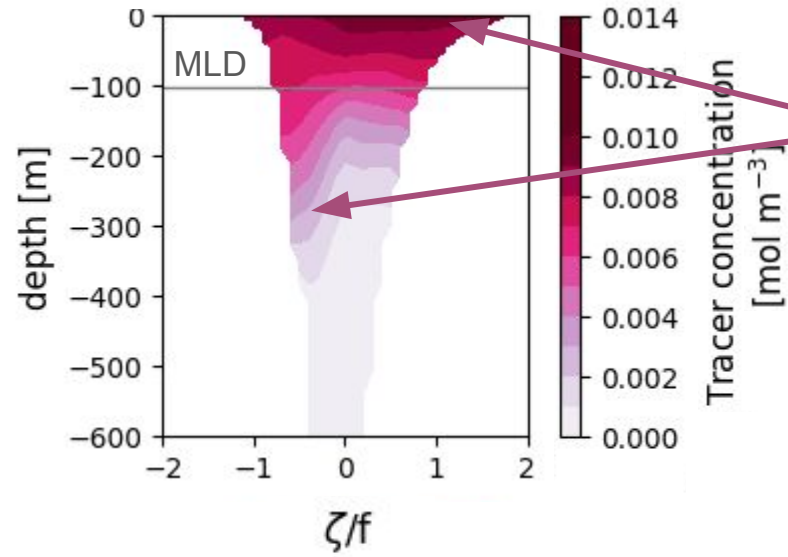


The **surface** (10m) is highly energetic and tracer is rapidly shaped by the small-scale flow



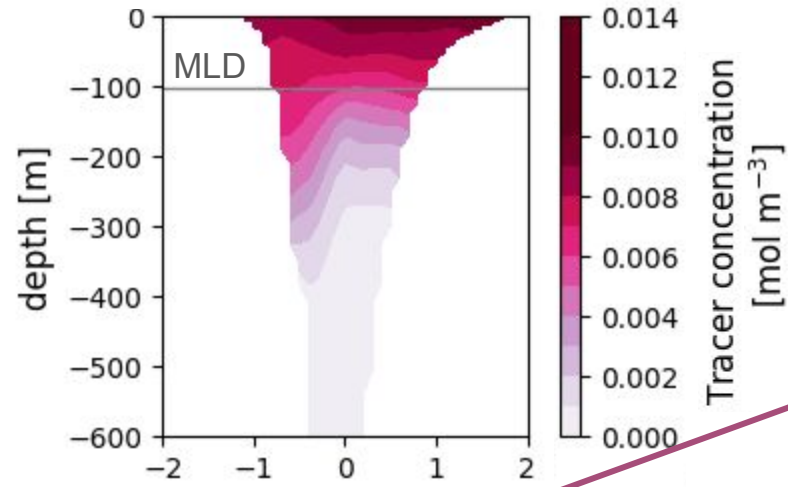
Tracers are punctuated **to depth** (350m) at the edges of eddies



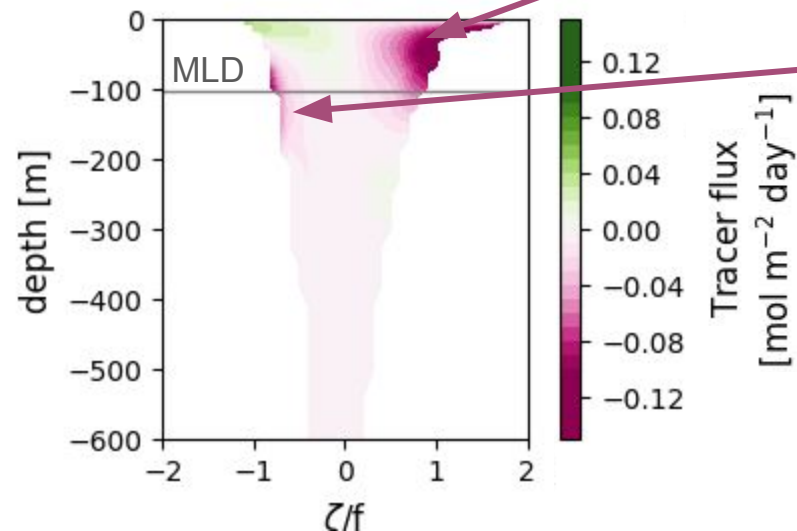


Tracer is trapped in cyclones at the surface but anticyclones dominate tracer concentration at depth

MLD: mixed layer depth

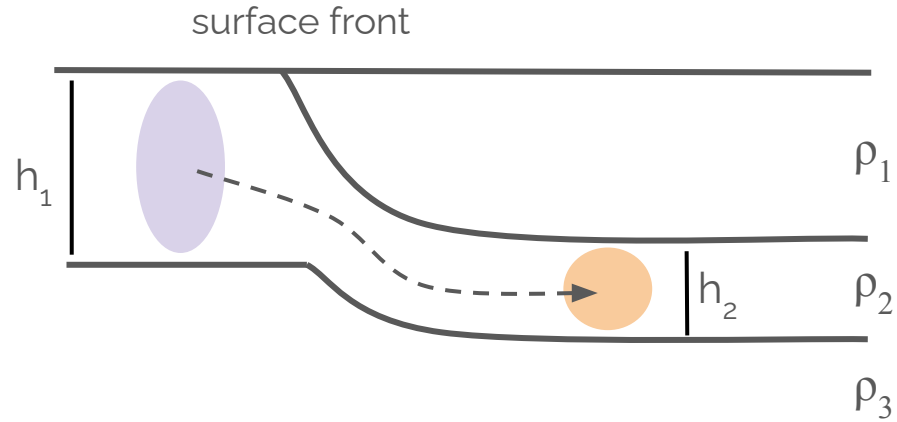


Within the mixed layer, cyclonic features dominate downward fluxes



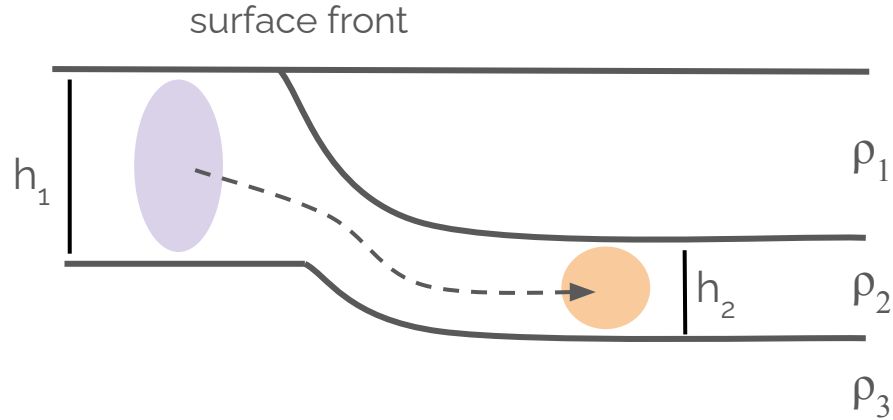
Outside of the mixed layer, tracer is found in anticyclonic features

When water subducts from the mixed layer, its “height” reduces



Adapted from Spall (1995)

When water subducts from the mixed layer, its “height” reduces



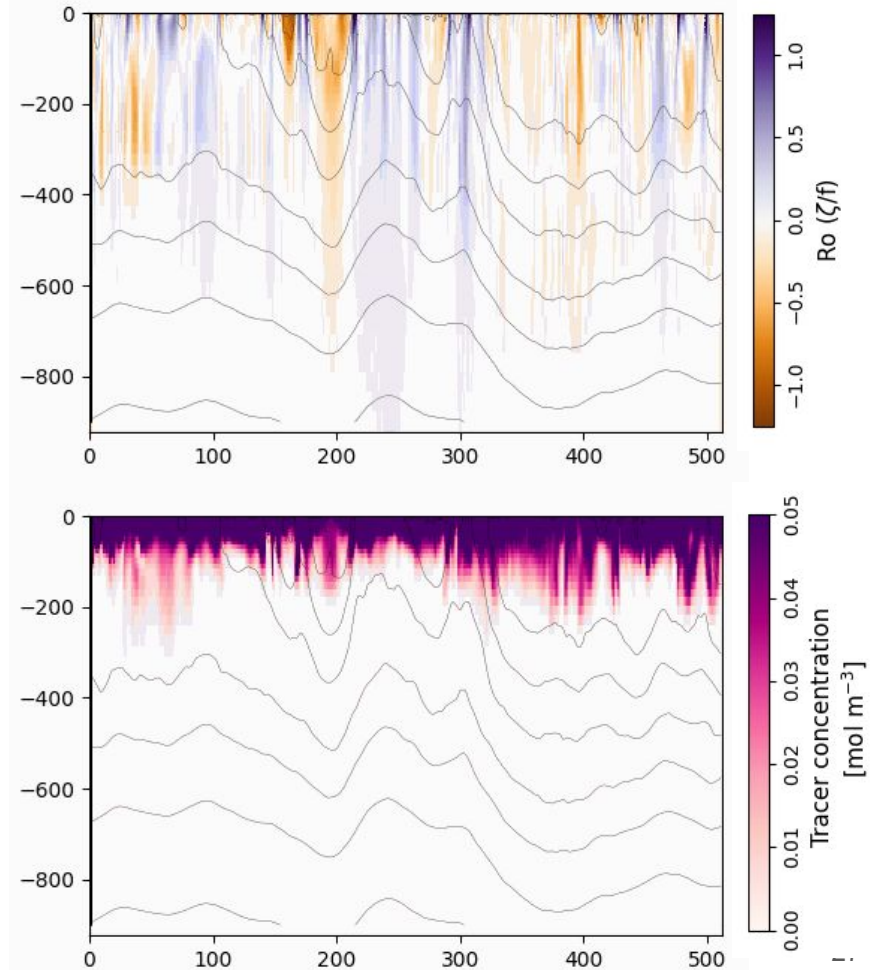
Adapted from Spall (1995)

$$\frac{f + \zeta_1}{h_1} = \frac{f + \zeta_2}{h_2}$$

If the height of the parcel changes, the relative vorticity must change to conserve PV.

Specifically, if h decreases, ζ decreases.

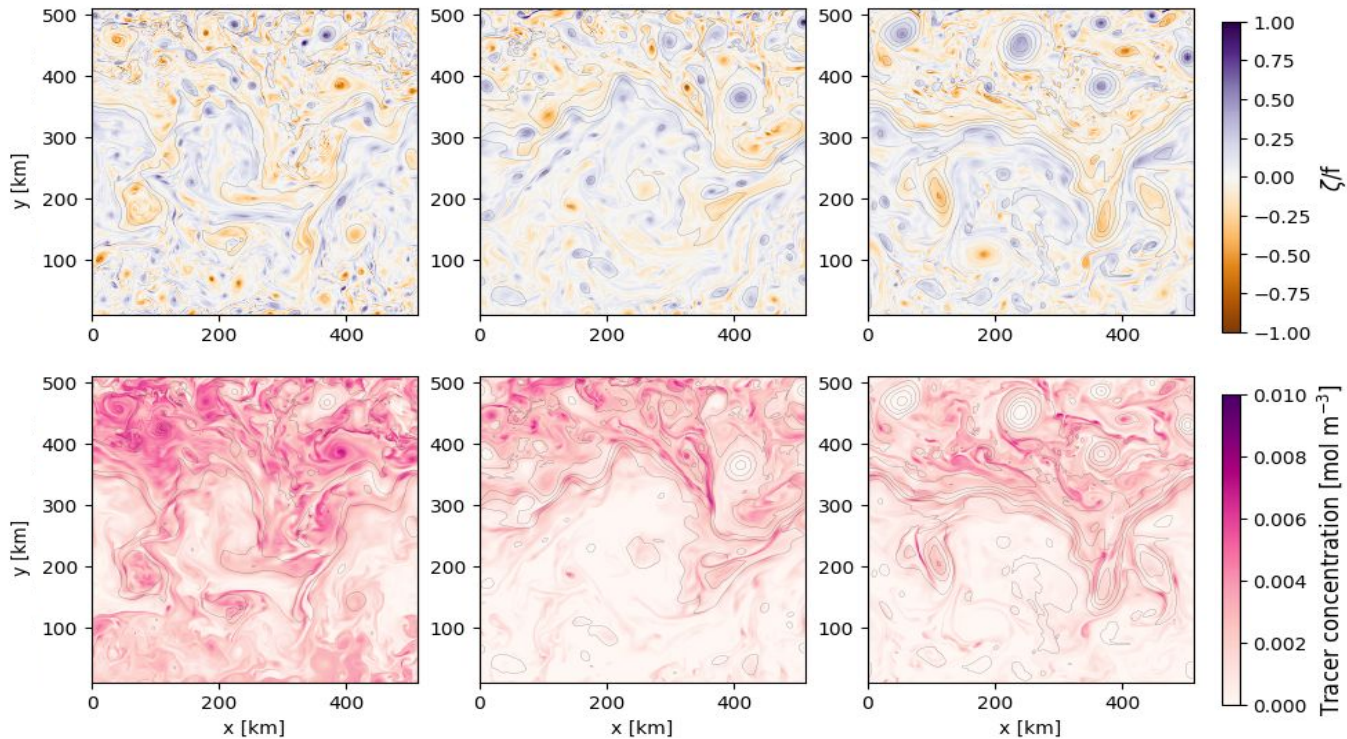
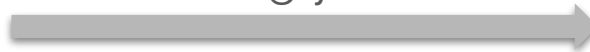
Subduction occurs at steeply sloping density surfaces and **anticyclones** are the physical subsurface signature of this subduction



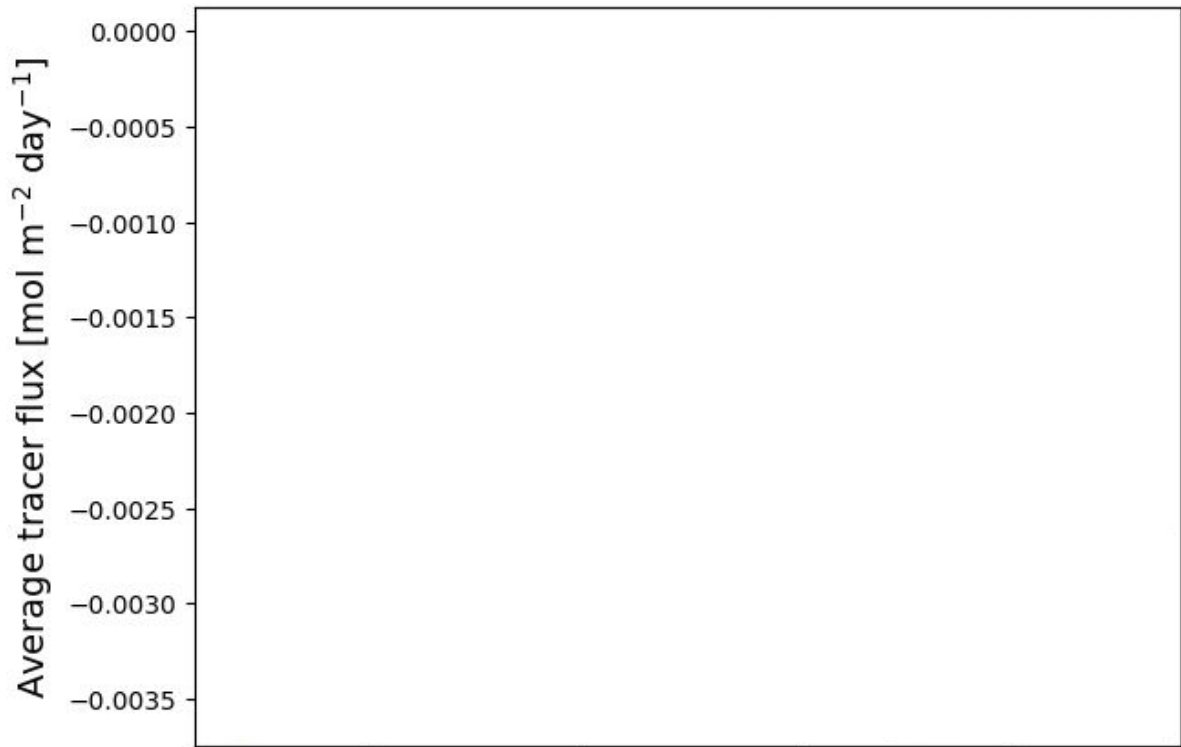
How will changing ocean stratification impact ventilation?

How will changing ocean stratification impact ventilation?

Increasingly stratified



Greater
downward
flux



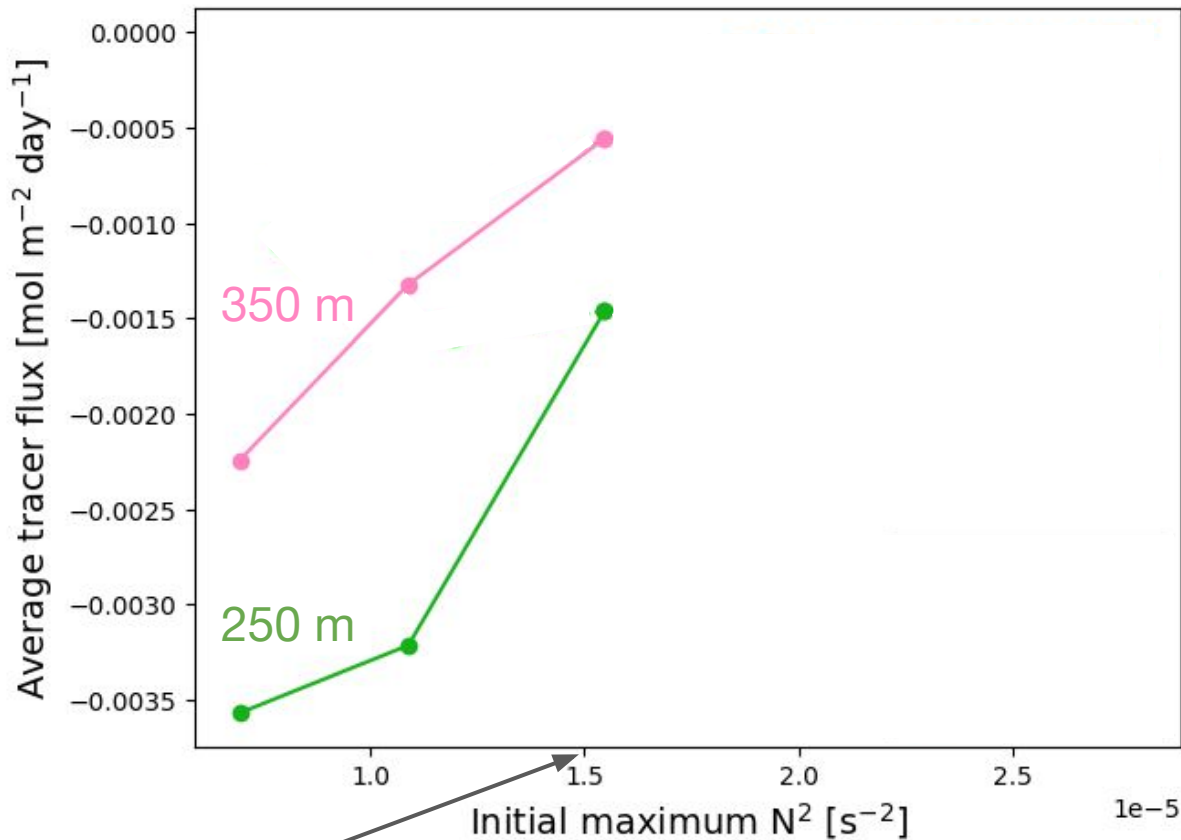
1.0 1.5 2.0 2.5 $1e-5$
Initial maximum N^2 [s^{-2}]

Present-day
Southern Ocean



Increasing stratification
(our future)

Greater downward flux

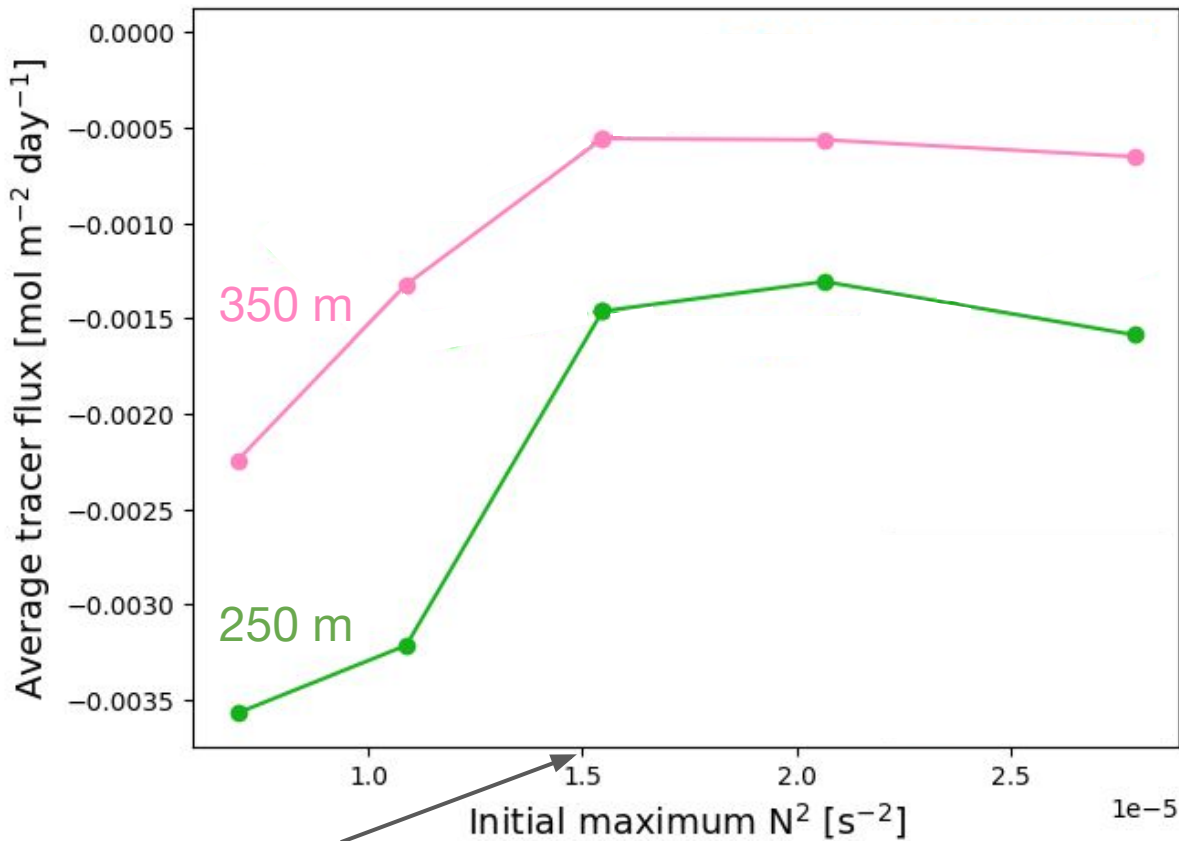


Decreased stratification leads to enhanced downward flux of surface tracer

Present-day Southern Ocean

Increasing stratification (our future)

Greater downward flux

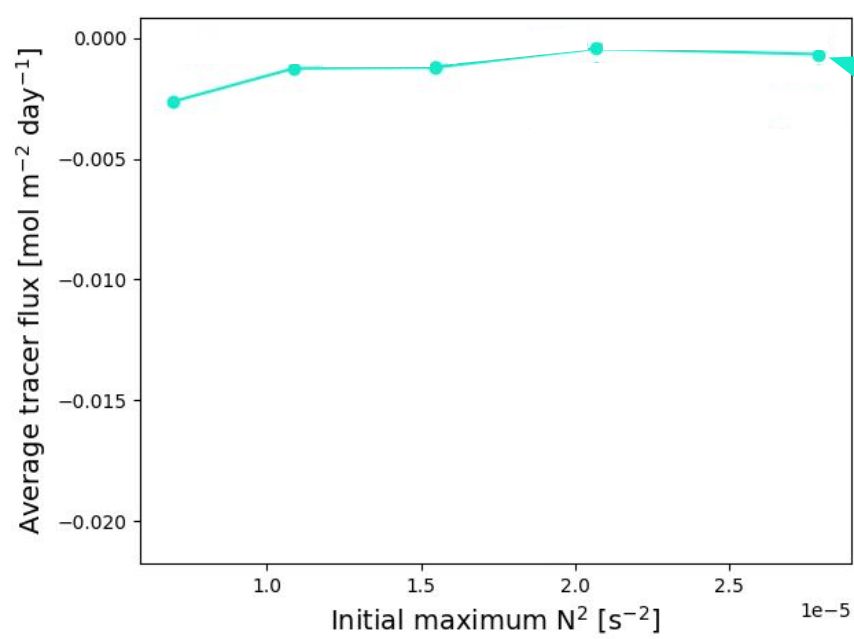


Decreased stratification leads to enhanced downward flux of surface tracer

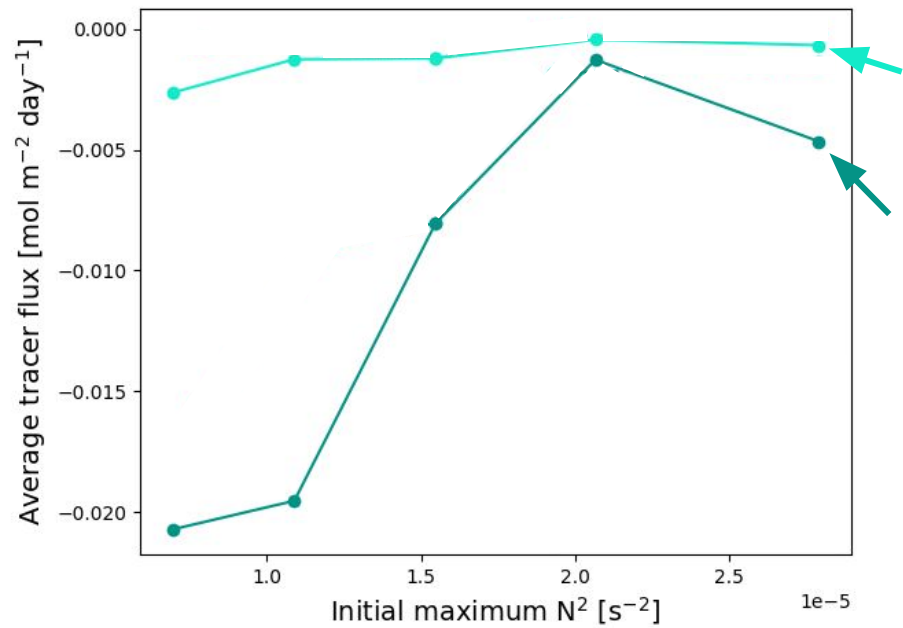
But tracer flux doesn't decrease with increasing stratification!

Present-day Southern Ocean

Increasing stratification (our future)



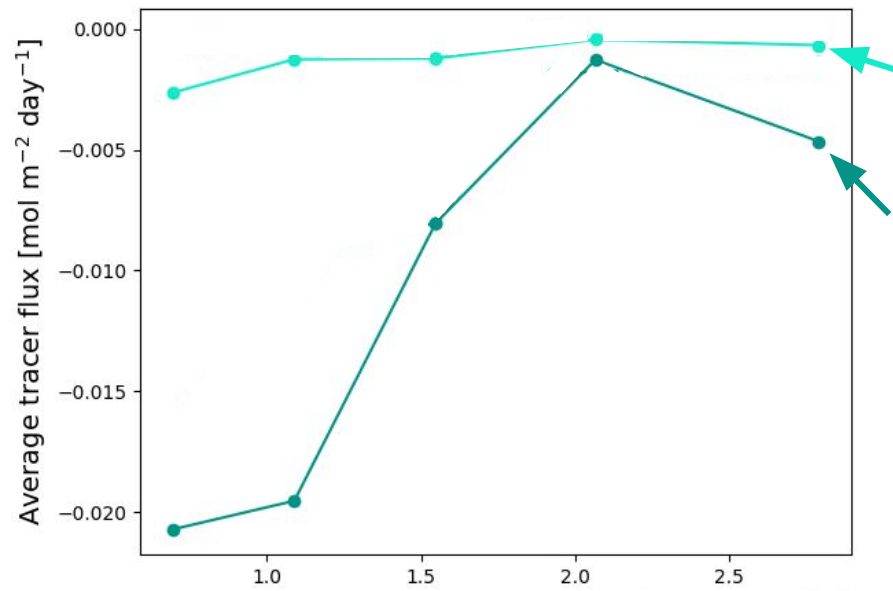
Flux at 350 m across the whole domain



Flux at 350 m across the whole domain

Only points that are **strongly anticyclonic** ($Ro < -0.5$)

Strongly anticyclonic features dominate downward fluxes

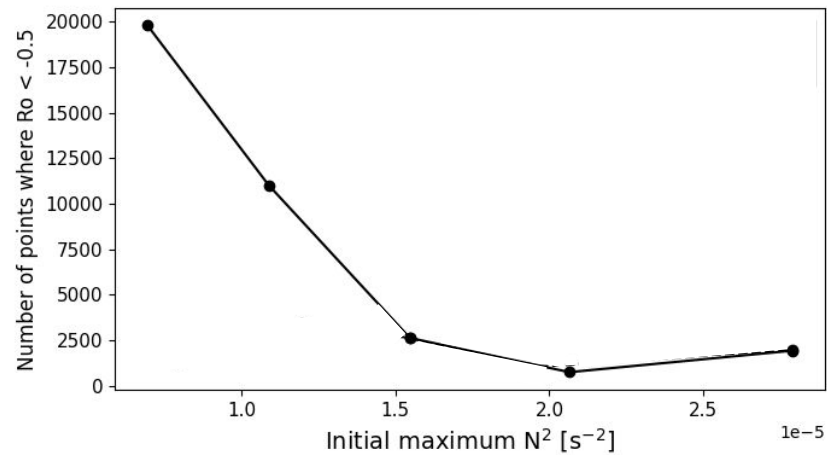


Flux at 350 m across the whole domain

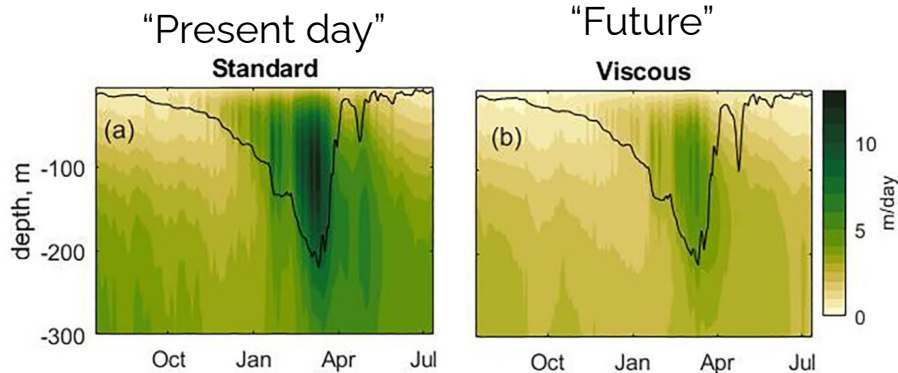
Only points that are **strongly anticyclonic** ($Ro < -0.5$)

Decreased stratification: **more ventilation** via fine scales

Increased stratification: **no change in ventilation** via fine scales



Previous understanding:

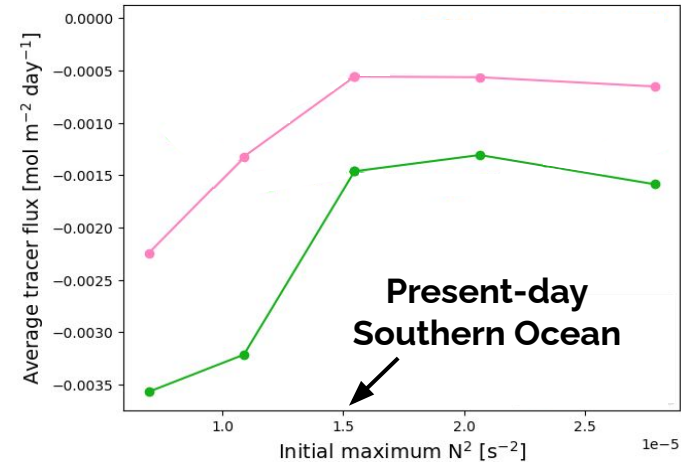


Brett et al. (2023)

Increasing stratification will result in reduced vertical velocities, reducing fine-scale ventilation

New understanding:

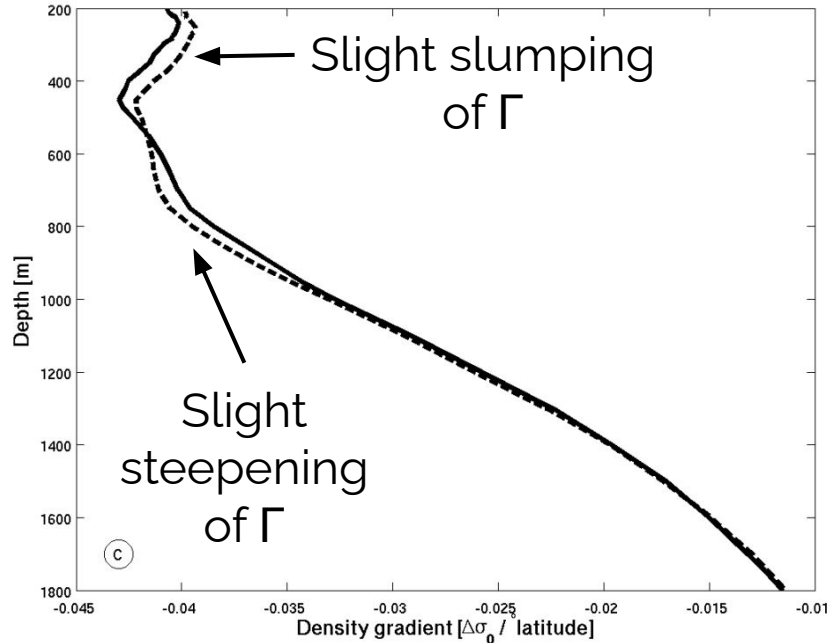
Changes in ventilation are **non-linear** with changes in stratification



Present-day ACC density structure may represent some kind of "inflection point"

Where do we go from here?

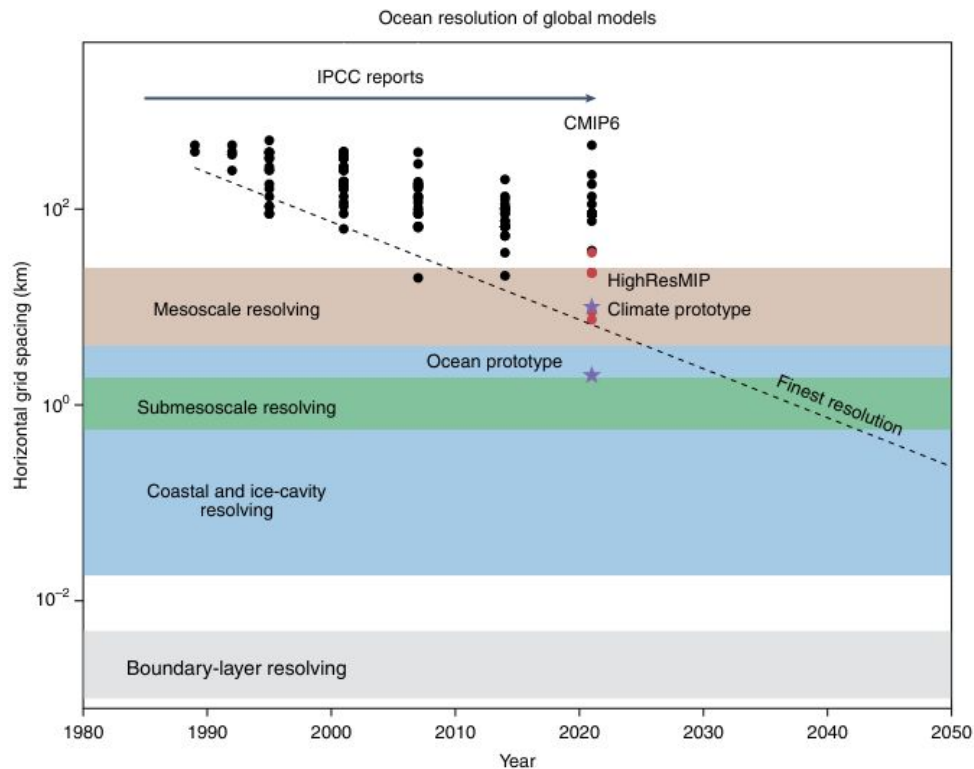
How is the ACC's slope really responding to warming and freshening?



To our best knowledge, the ACC's isopycnal tilt is staying constant (but opinions vary!)

Böning et al. (2008)

How do we parameterize fine-scale ventilation processes?

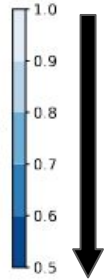
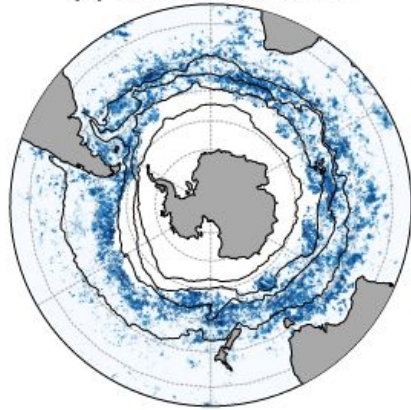
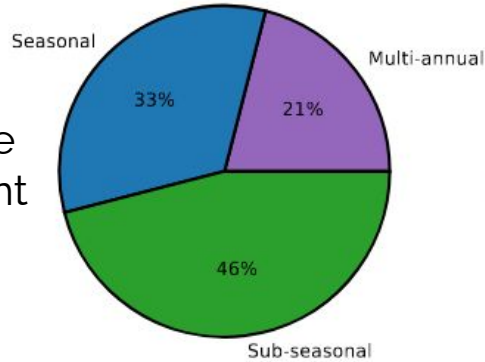


Hewitt et al. (2022)

Fine-scale ventilation may be of $O(1)$ importance for tracer budgets, but is not represented in most climate models.

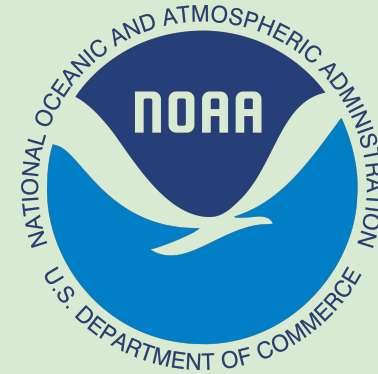
What about carbon and biogeochemistry?

Southern Ocean
Chlorophyll variance
explained on different
timescales



Increased
importance of
fine-scale
processes to
“explaining”
Chlorophyll

What plankton species are
being subducted and how
does changing stratification
impact carbon storage?



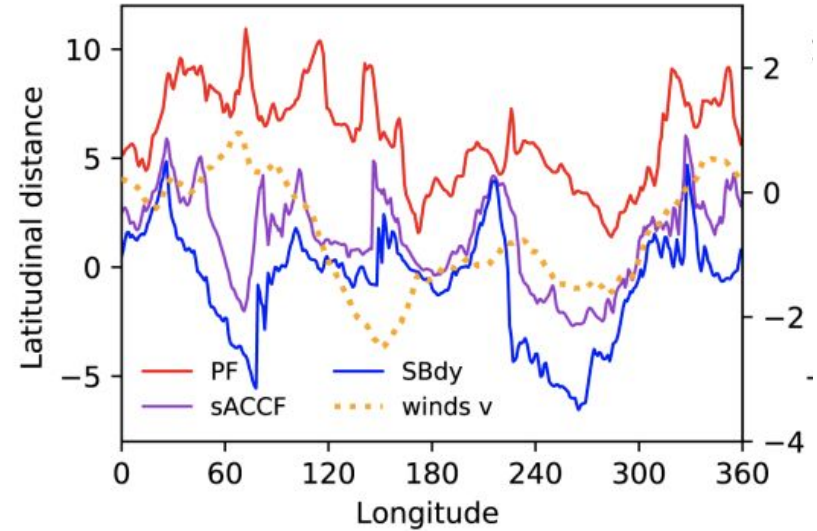
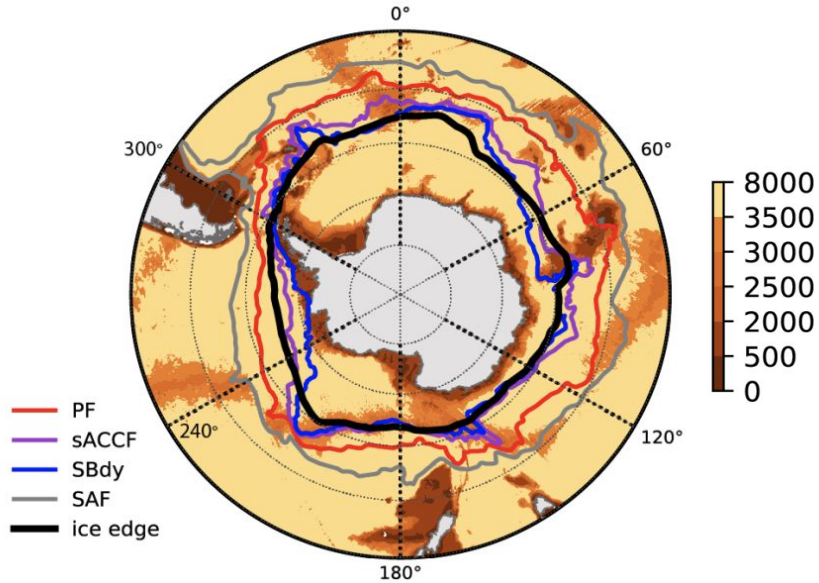
Collaborators:

Mara Freilich, Lia Siegelman, Baylor
Fox-Kemper, Paul Hall, & Ayushman Choudhury

A dramatic night sky featuring a vibrant green aurora borealis (Northern Lights) illuminating dark, swirling clouds. A bright, vertical streak of light, possibly a meteor or a satellite, cuts through the center of the frame. The overall atmosphere is mysterious and awe-inspiring.

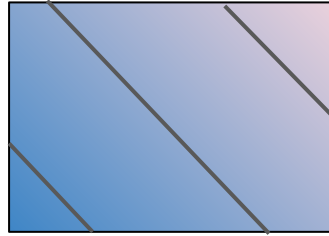
Questions?

The Antarctic Circumpolar Current is a dynamical barrier



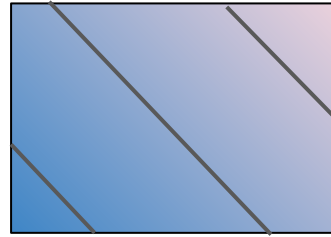
Goosse et al. (in review)

We test cases where the initial isopycnal slope is constant and where it varies



$$\Gamma = b_x / b_z$$

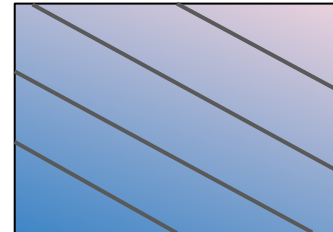
We test cases where the initial isopycnal slope is constant and where it varies



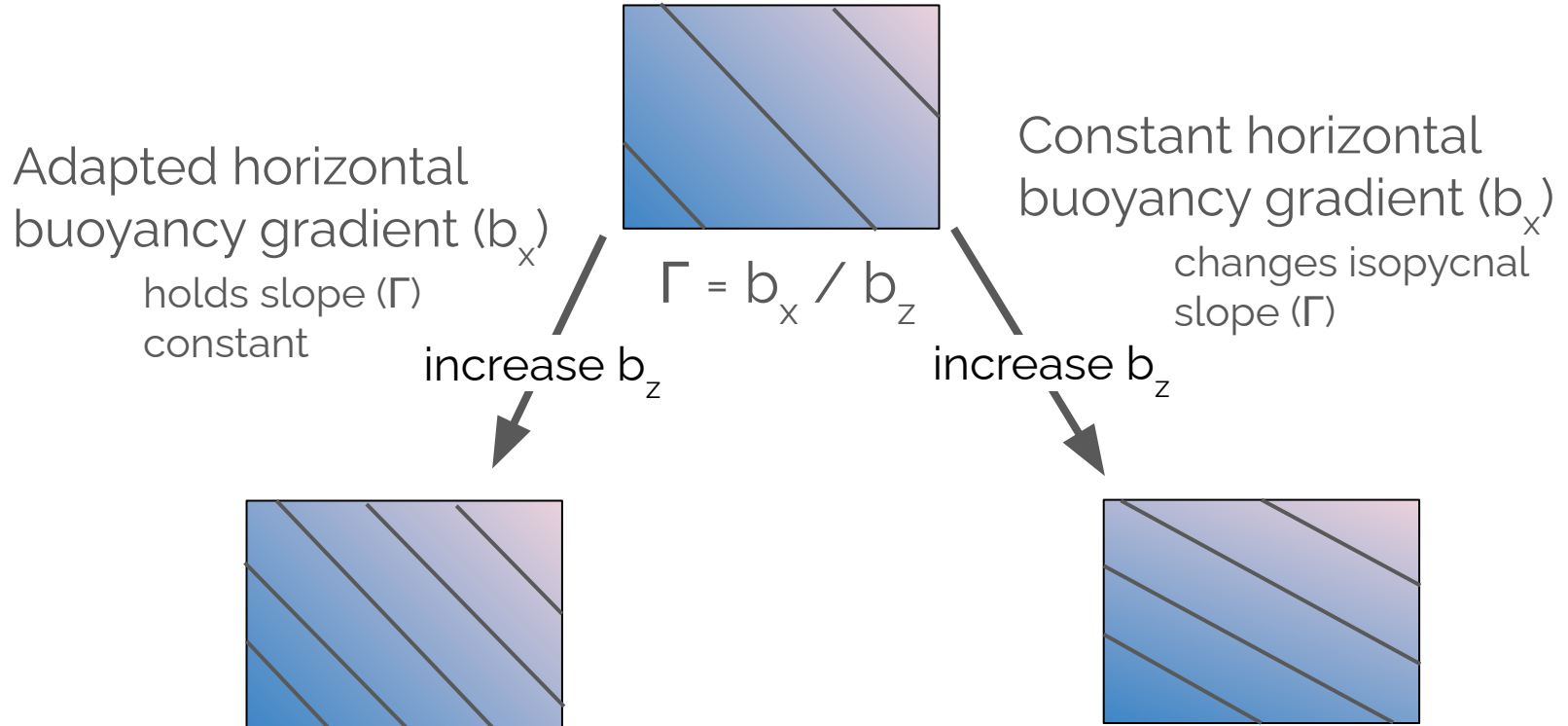
$$\Gamma = b_x / b_z$$

Constant horizontal buoyancy gradient (b_x)
changes isopycnal slope (Γ)

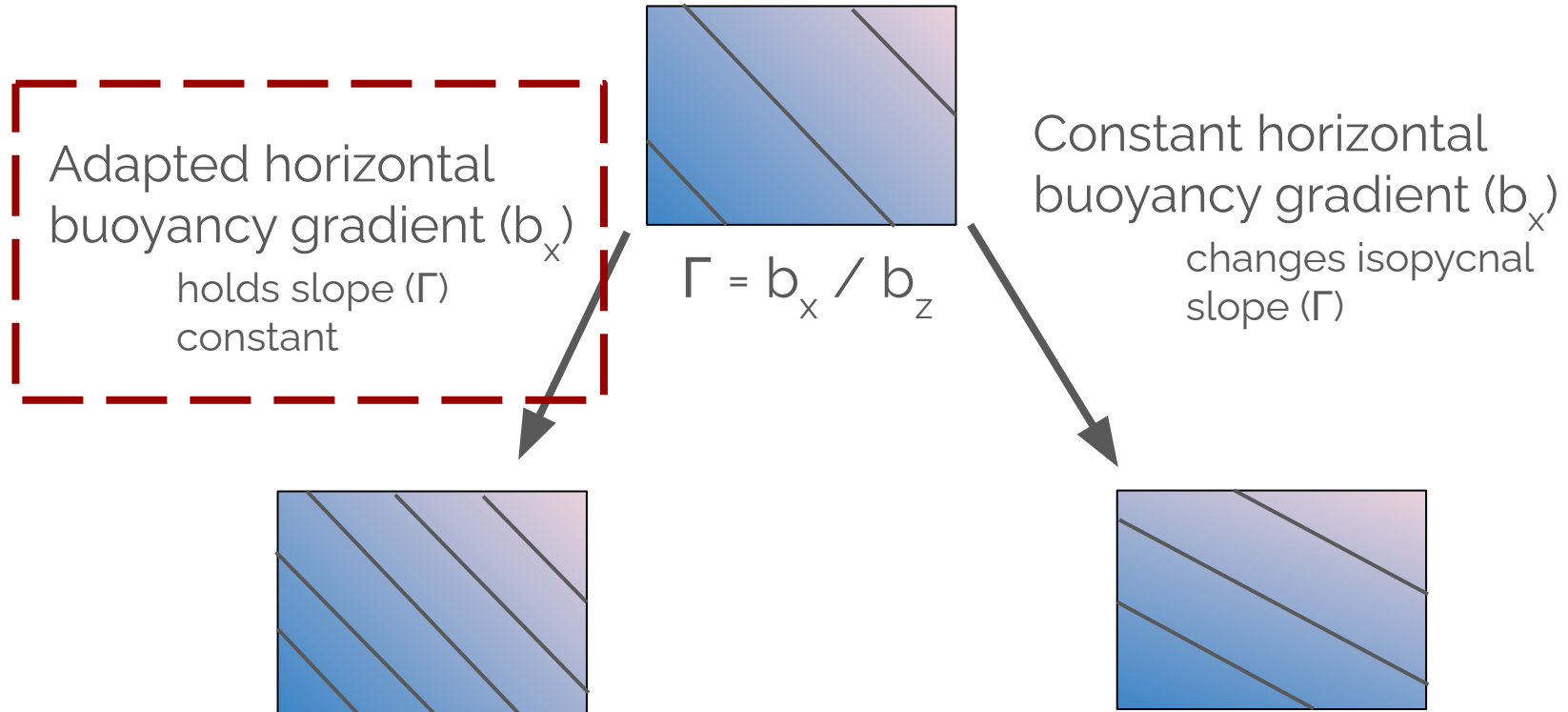
increase b_z



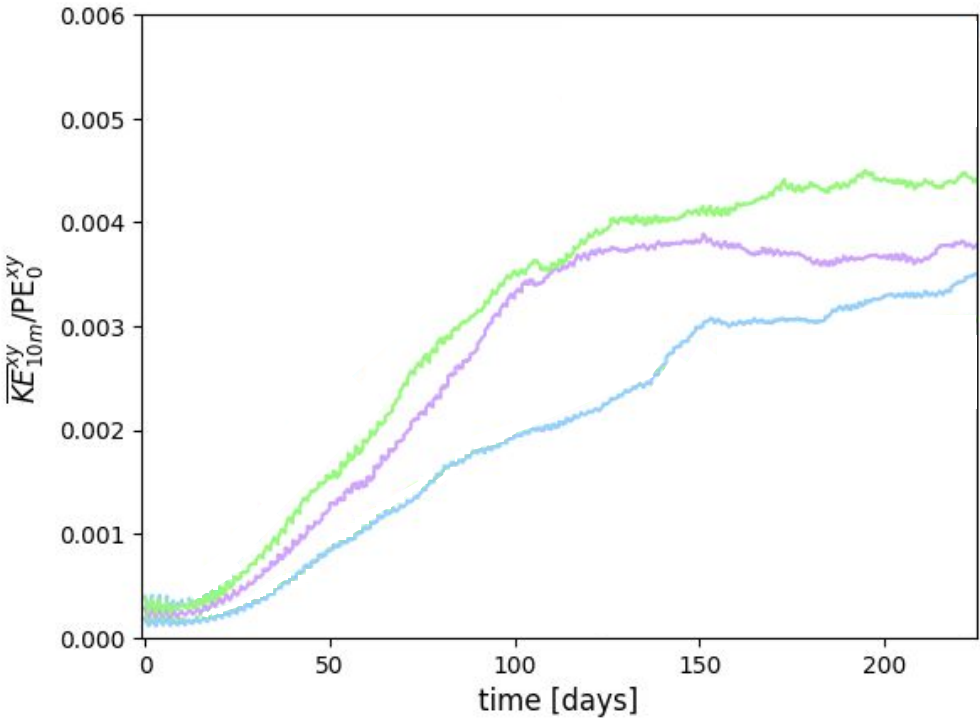
We test cases where the initial isopycnal slope is constant and where it varies



We test cases where the initial isopycnal slope is constant and where it varies

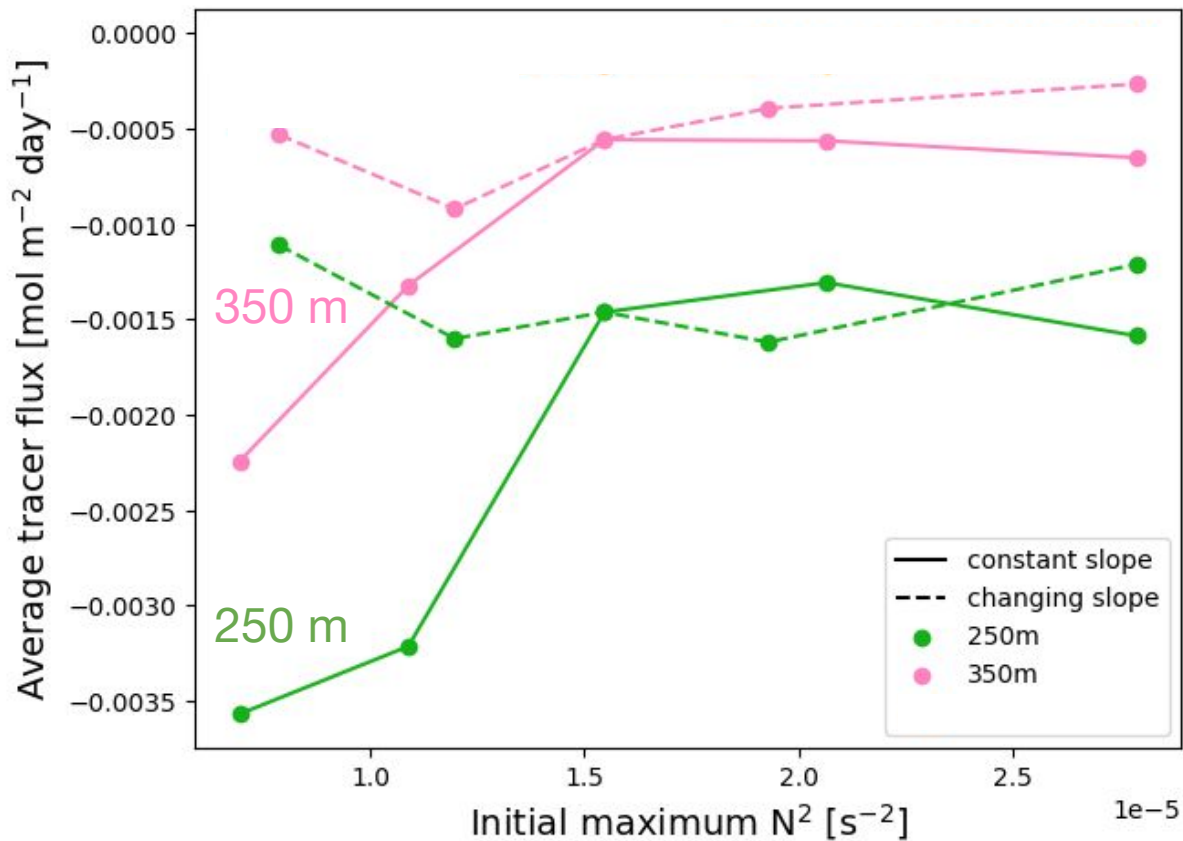


Conversion of potential energy to kinetic energy



Increased stratification
Baseline
Decreased stratification

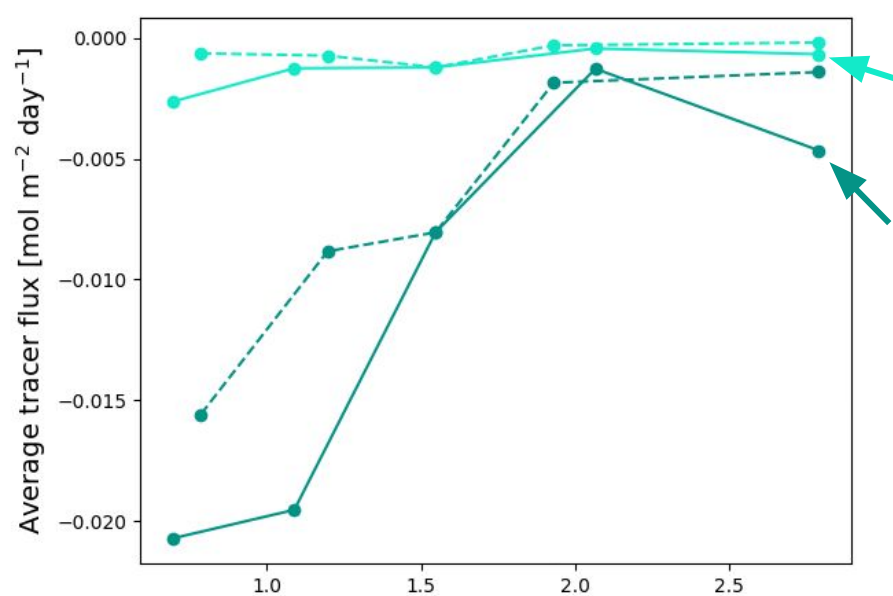
Greater downward flux



Present-day Southern Ocean



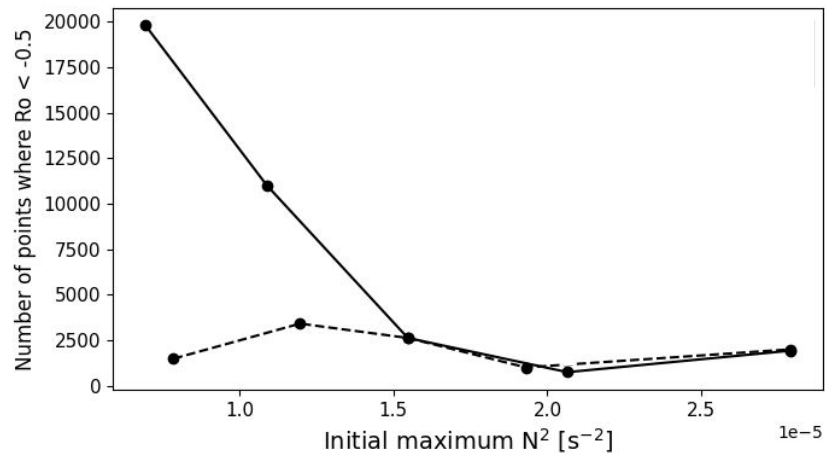
Increasing stratification (our future)



Flux at 350 m across the whole domain

Only points that are **strongly anticyclonic** ($Ro < -0.5$)

The number of strongly anticyclonic features **increases in decreased stratification conditions.**

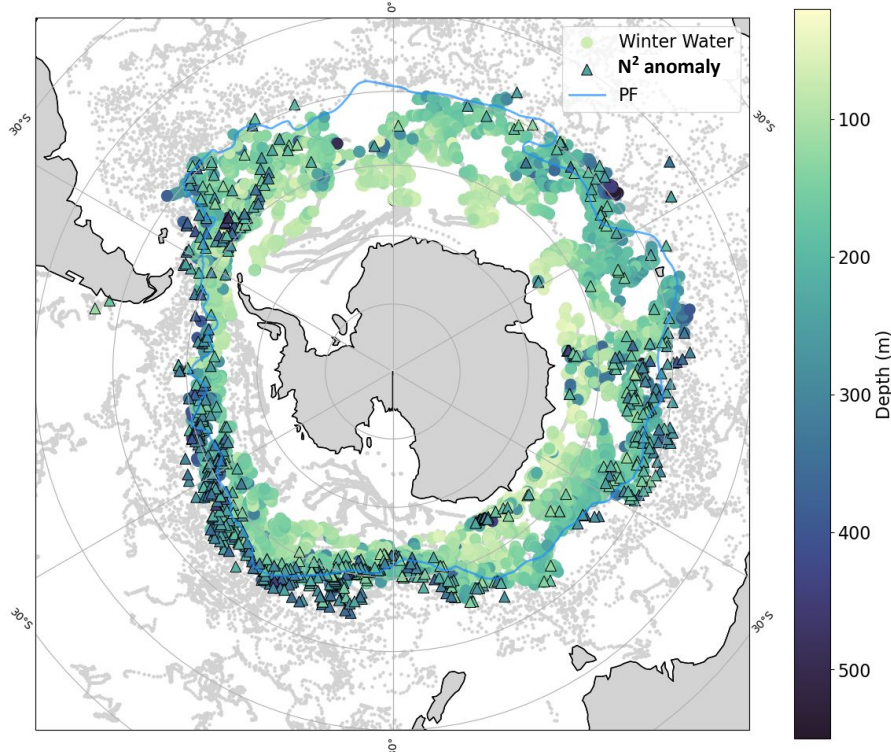


However, there is **not a change** in the number of subduction-relevant features **in increasing stratification conditions**

Anticyclonic features which typically have low internal stratification are a key physical signature of recent ventilation



Figure by **Maggie Gonzalez**
Brown Leadership Alliance REU student



40,000
float
profiles

Gonzalez, Dove, et al. (in revision at GRL)