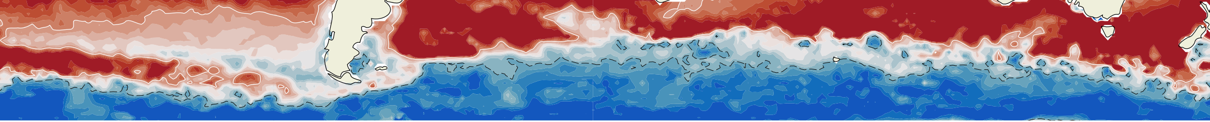


From alpha to beta ocean

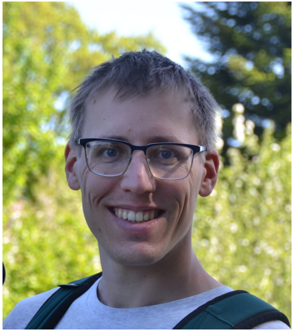
Exploring the role of surface buoyancy fluxes and seawater thermal expansion in setting the upper ocean stratification

Romain Caneill

VEPOSSSS seminar, September 25, 2024

Brief Curriculum

- 2014 – 2017 ENSL, physics and geophysics
- 2017 – 2018 CAP de menuiserie
- 2018 – 2024 PhD, Göteborg with Fabien Roquet
- 2024 – 2027 Postdoc, Grenoble, SASIP project



Grenoble, France
romain.caneill@univ-grenoble-alpes.fr
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fediscience.org/web/@rcaneill
PGP fingerprint:
70D5 7116 37B2 9335 9088
F124 D0FE 114E BFFD ED7F

Some of my interests:

- Python
- NEMO
- xnemogcm, xgcm, gsw-xarray
- Reproducible science
- Snakemake
- Free Software

For the science, follow this presentation :)

Where to find this presentation

https://romaincaneill.fr/2024/09/25/VEPOSSSS-seminar.html

The oceans store carbon and heat

The oceans have taken up about:

- 25 % of CO_2 produced by human activities;

The oceans store carbon and heat

The oceans have taken up about:

- 25 % of CO_2 produced by human activities;
- 90 % of excess heat.

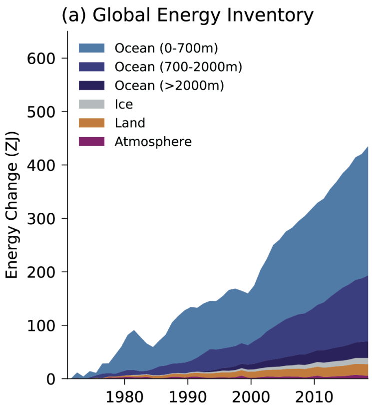


Figure adapted from the IPCC Sixth Report (Fox-Kemper et al., 2021)

The ocean absorbs anthropogenic CO_2

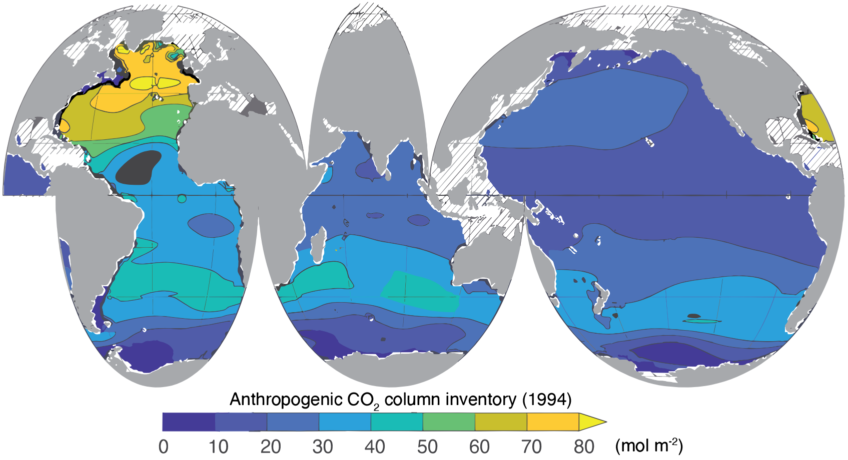


Figure adapted from Gruber et al. (2023)

Ocean and atmosphere exchanges properties through the mixed layer

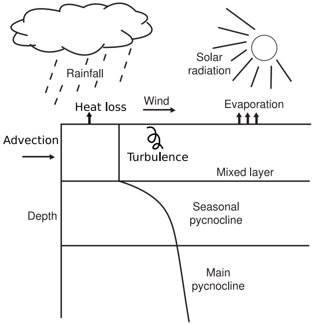


Figure adapted from Sprintall and Cronin (2009)

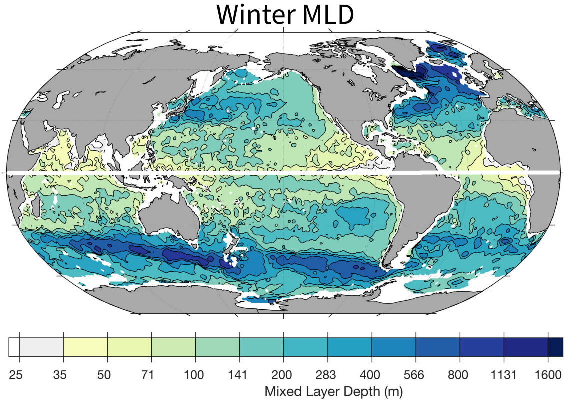


Figure adapted from Johnson and Lyman (2022)

The global circulation brings the water properties at depth

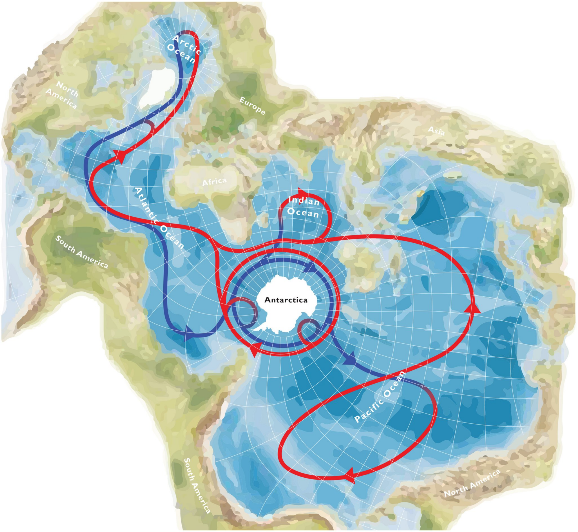
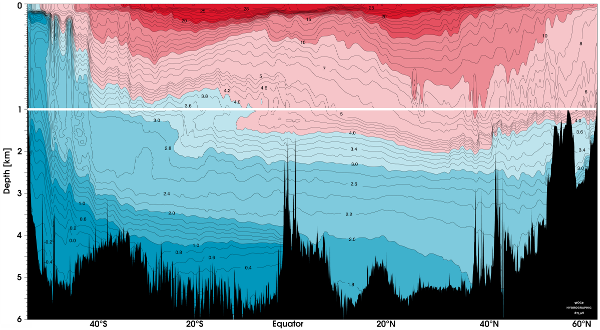
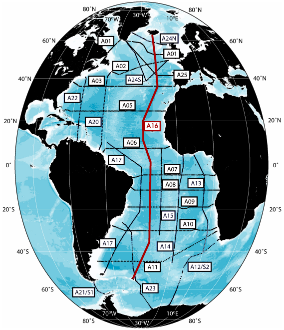


Figure adapted from Meredith (2019)

The large stratification inhibits vertical exchanges.



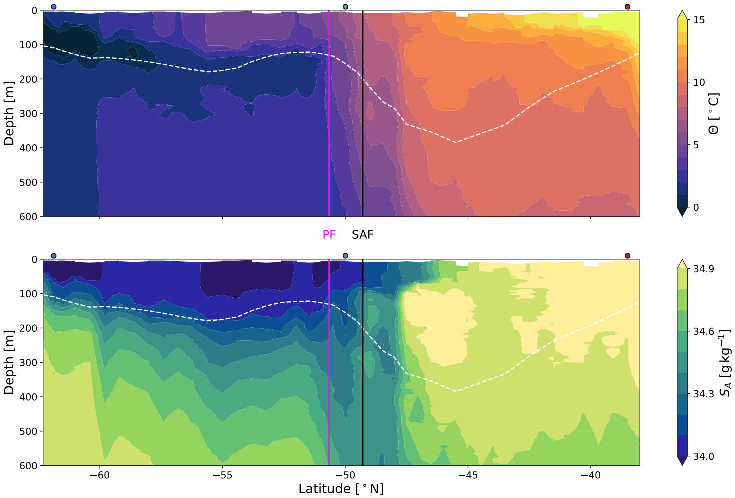


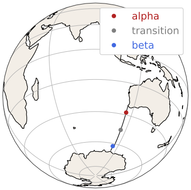
The ocean is mainly stratified because it is heated up at the surface.

Regimes of stratification

T-S section IO9S

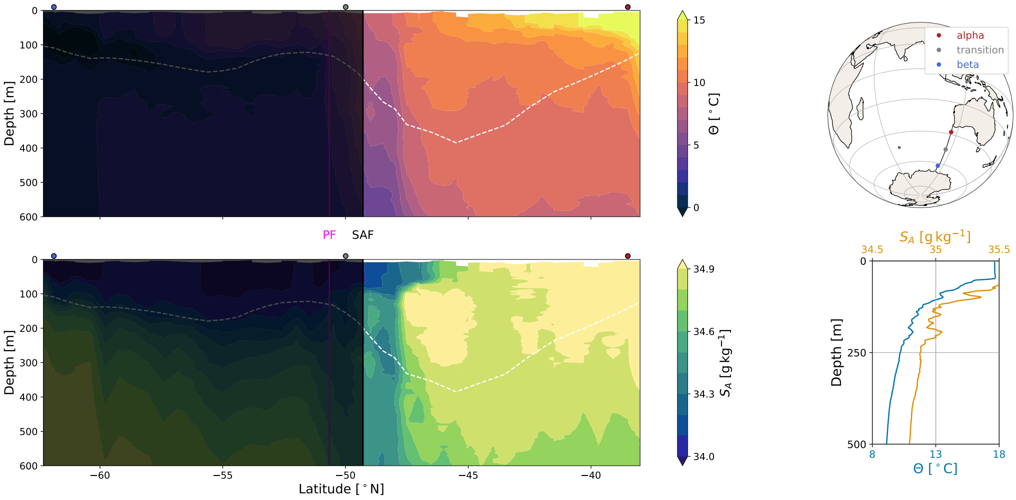
https://cchdo.ucsd.edu/cruise/09AR20120105





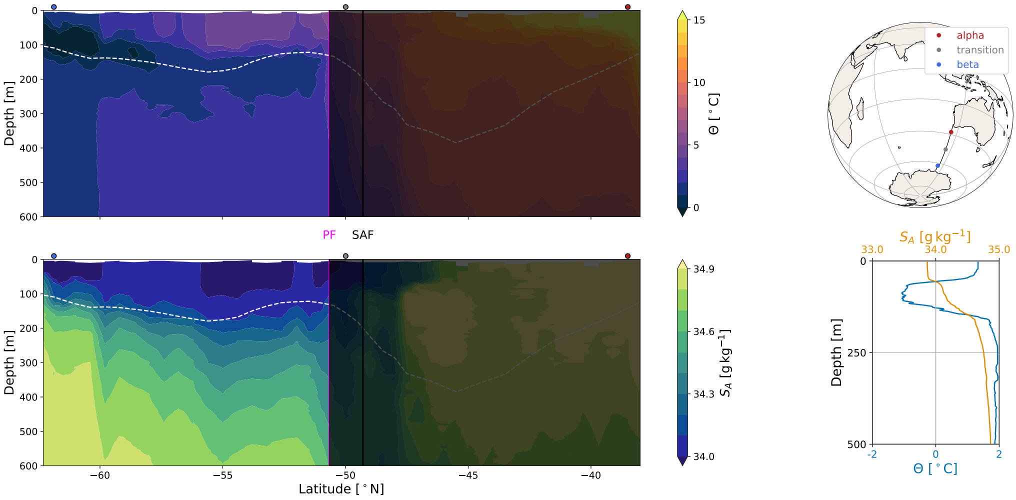
Regimes of stratification

Alpha ocean



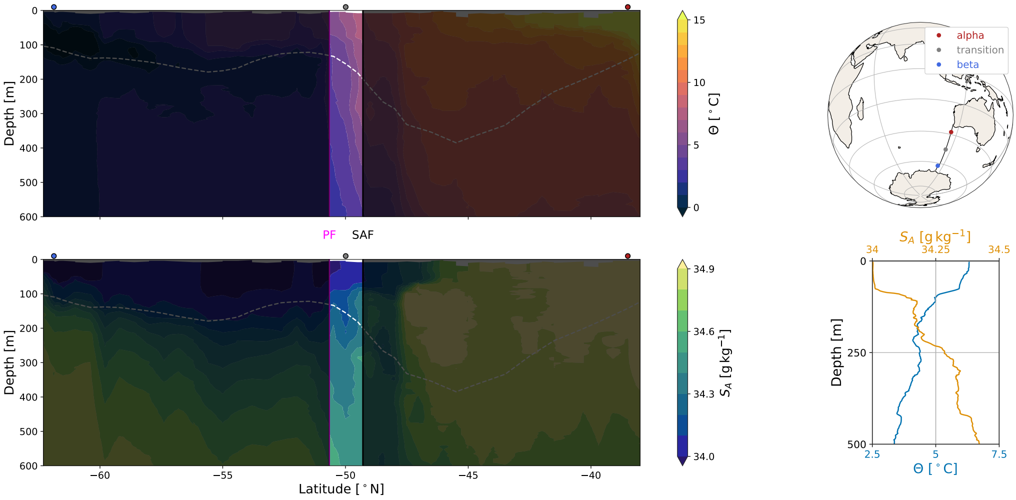
Regimes of stratification

Beta ocean



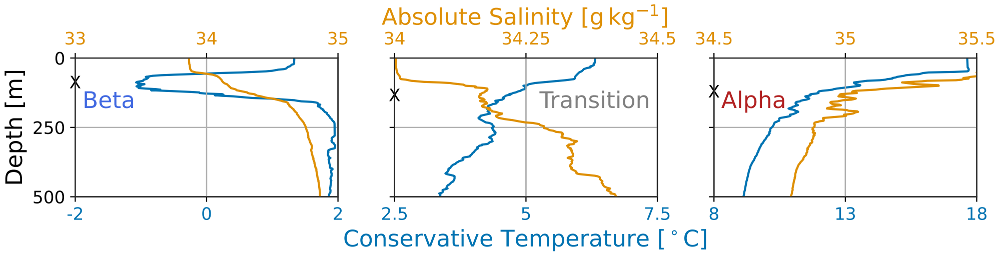
Regimes of stratification

Transition zone



Beta, transition, and alpha

T-S section IO9S, selected profiles

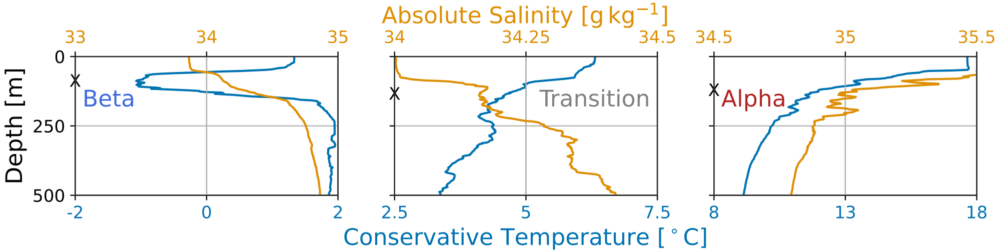


Temperature stratifies:
alpha ocean

(Carmack, 2007)

Beta, transition, and alpha

T-S section IO9S, selected profiles



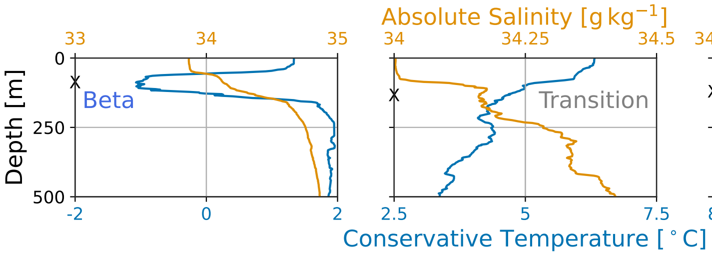
Salinity stratifies:
beta ocean

Temperature stratifies:
alpha ocean

(Carmack, 2007)

Beta, transition, and alpha

T-S section IO9S, selected profiles



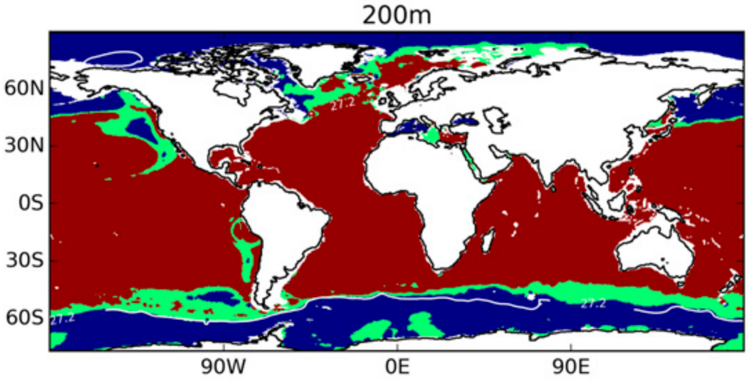
Salinity stratifies:
beta ocean

Both stratify:
transition zone

Temperature stratifies:
alpha ocean

(Carmack, 2007)

Alpha and beta oceans

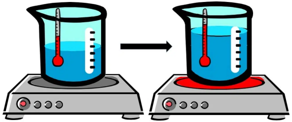


Called alpha – beta oceans in reference to α and β, thermodynamic properties of seawater.

Figure adapted from Stewart and Haine (2016)

The thermal expansion coefficient (TEC, α)

- Cold water is usually denser than warm water.



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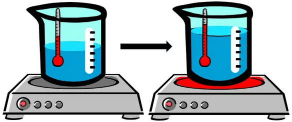
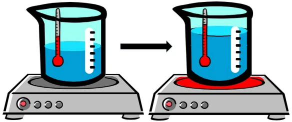


The thermal expansion coefficient (TEC, α)

- Cold water is usually denser than warm water.
- Ocean warms $\implies$ volume increases (1/2 of observed sea-level rise)
- The TEC quantifies the relative change of density with temperature:

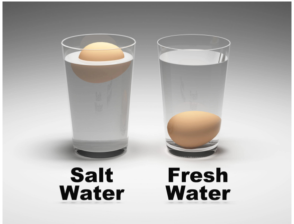
$$\alpha = -\frac{1}{\rho}\frac{\partial \rho}{\partial \Theta}$$



Public Domain

The haline contraction coefficient (HCC, β)

- Salty water is denser than freshwater



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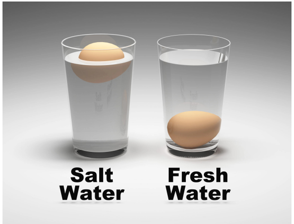
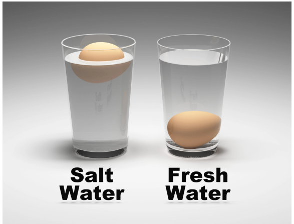


The haline contraction coefficient (HCC, β)

- Salty water is denser than freshwater
- The HCC quantifies the relative change of density with salinity:

$$\beta = \frac{1}{\rho}\frac{\partial \rho}{\partial S}$$



Properties of the TEC and HCC

- The TEC follows a (quasi) linear relation with temperature

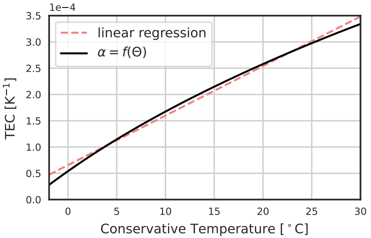
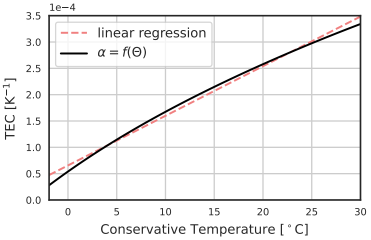


Figure adapted from Caneill et al. (2024)

Properties of the TEC and HCC

- The TEC follows a (quasi) linear relation with temperature
- The HCC variations in the ocean are negligible
$\beta \simeq 7.5 \times 10^{-4}\,\mathrm{kg\,g^{-1}}$



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Properties of the TEC and HCC

- The TEC follows a (quasi) linear relation with temperature
- The HCC variations in the ocean are negligible
  $\beta \simeq 7.5 \times 10^{-4}$ kg g^{-1}
- It was assumed that the role of salinity is enhanced in polar regions due to low values of the TEC

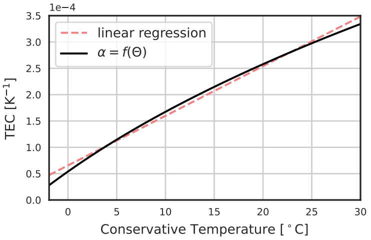

Figure adapted from Caneill et al. (2024)

What is the origin of alpha and beta oceans?

Objectives

From alpha to beta ocean: Exploring the role of surface buoyancy fluxes and seawater thermal expansion in setting the upper ocean stratification

Objective A

Describe alpha – beta oceans using observations

Objective B

How do buoyancy fluxes shape the upper stratification?

Objective C

Assess the role of the local value of the TEC.

TEC = Thermal expansion coefficient

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Objective A	Objective B	Objective C
Describe alpha – beta oceans using observations Paper III	How do buoyancy fluxes shape the upper stratification? Papers I, II	Assess the role of the local value of the TEC. Papers I, II, and IV

Paper III Caneill, R., & Roquet, F. (2024). Temperature versus salinity: Distribution of stratification control in the global ocean. *in preparation for Ocean Science*

Stratification Control Index (SCI)

$$SCI = \frac{\alpha \partial_z \Theta + \beta \partial_z S}{\alpha \partial_z \Theta - \beta \partial_z S} \quad (1)$$

The SCI quantifies the relative effect of temperature and salinity on stratification.

SCI > 1: alpha | -1 < SCI < 1: transition | SCI < -1: beta

Compute climatology of winter SCI

- Based on about 20 years of observation profiles (EN4 database, includes ARGO, ship-based CTD, MEOP, etc)
- Compute the SCI at the bottom of winter mixed layer
- Interpolation to produce climatology

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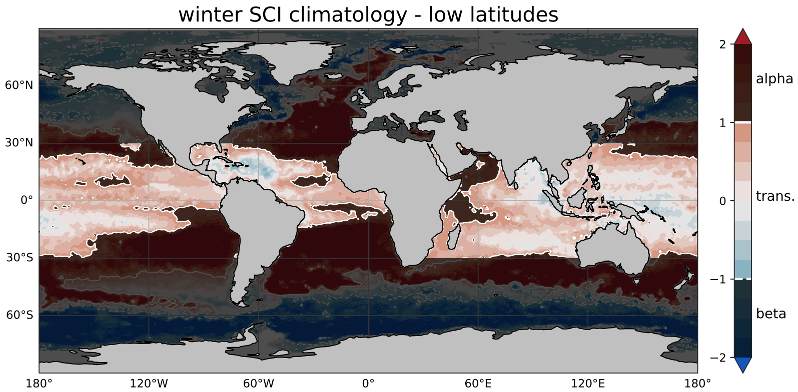
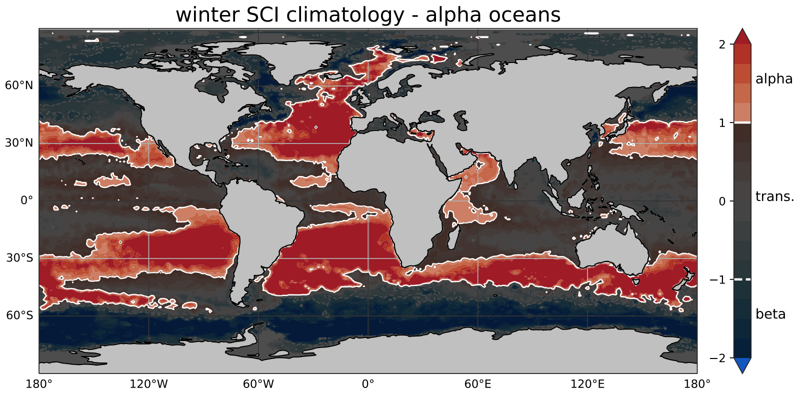
Global maps of the winter SCI (Paper III)



- Low-latitudes: transition zone
- Mid-latitudes: alpha ocean
- Between alpha and beta: PTZ
- High-latitudes: beta ocean

PTZ = polar transition zone

Global maps of the winter SCI (Paper III)



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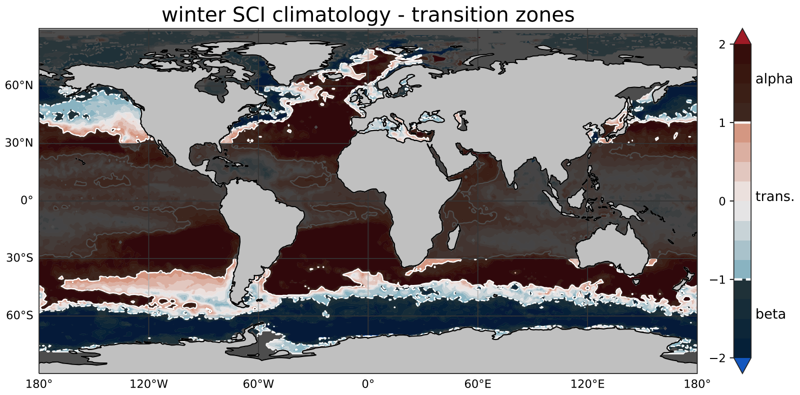

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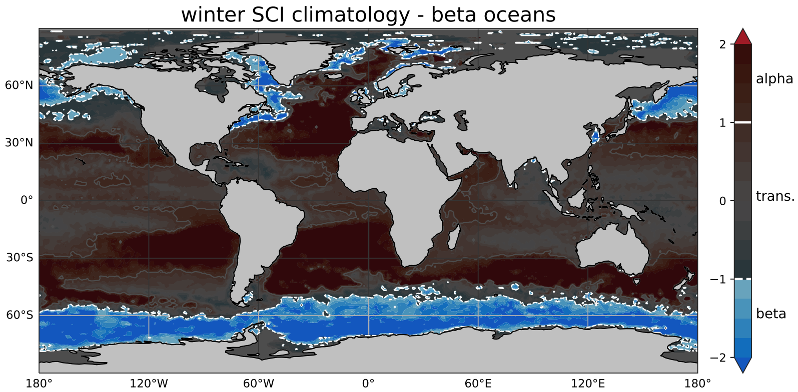

- Low-latitudes: transition zone
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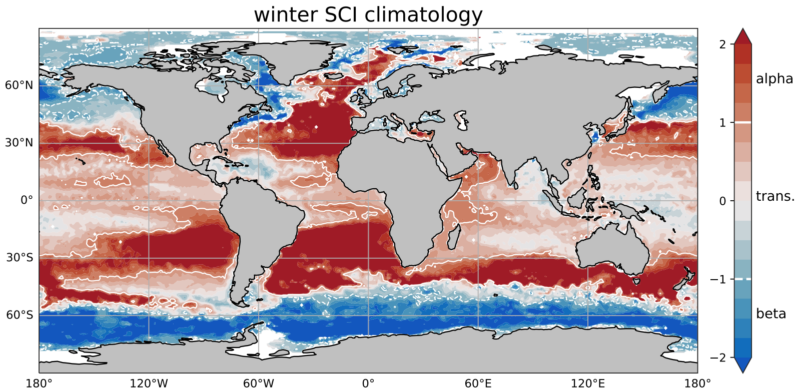
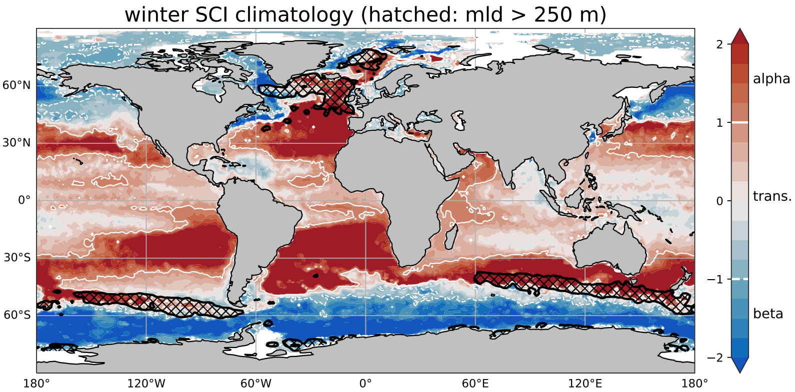
Global maps of the winter SCI (Paper III)



- Zonation with: transition zone → alpha → PTZ → beta
- Wide and zonal North Pacific PTZ
- Narrow and diagonal North Atlantic PTZ



Deep MLs located at the poleward flank of alpha oceans.

- Deep MLs mostly found in alpha oceans
- Bimodal distribution of the SCI, centred around ± 1.5

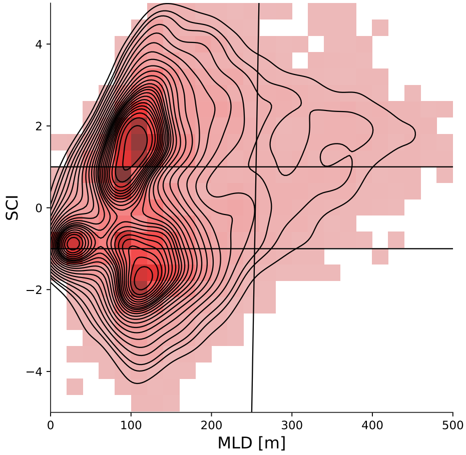


Figure for $|\varphi| \geq 30°$

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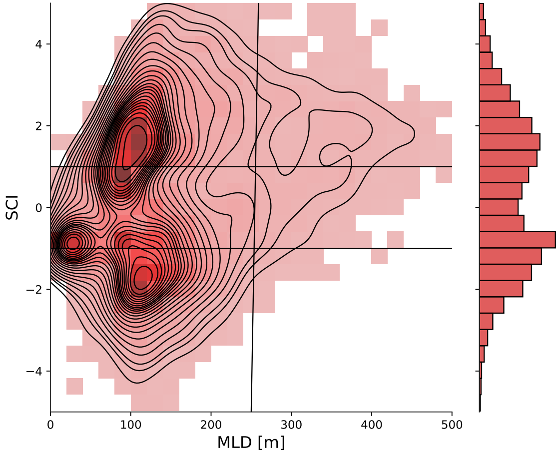

Figure for $|\varphi| \geq 30^\circ$

Objective B

Objective A

Describe alpha – beta oceans using observations

Paper III

Objective B

How do buoyancy fluxes shape the upper stratification?

Papers I, II

Objective C

Assess the role of the local value of the TEC.

Papers I, II, and IV

Paper I Caneill, R., Roquet, F., Madec, G., & Nycander, J. (2022). The Polar Transition from Alpha to Beta Regions Set by a Surface Buoyancy Flux Inversion. *Journal of Physical Oceanography*

Paper II Caneill, R., Roquet, F., & Nycander, J. (2024). Southern Ocean deep mixing band emerges from competition between winter buoyancy loss and stratification. *Ocean Science*

This presentation

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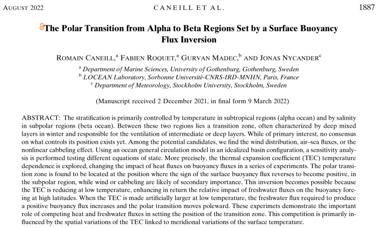


AUGUST 2022 CANEILL ET AL. 1887

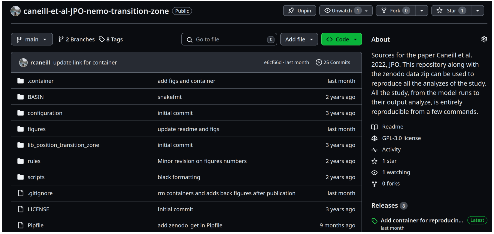
The Polar Transition from Alpha to Beta Regions Set by a Surface Buoyancy Flux Inversion

ROMAIN CANEILL,[a] FABIEN ROQUET,[a] GURVAN MADEC,[b] AND JONAS NYCANDER[c]

[a] *Department of Marine Sciences, University of Gothenburg, Gothenburg, Sweden*
[b] *LOCEAN Laboratory, Sorbonne Université-CNRS-IRD-MNHN, Paris, France*
[c] *Department of Meteorology, Stockholm University, Stockholm, Sweden*

(Manuscript received 2 December 2021, in final form 9 March 2022)

ABSTRACT: The stratification is primarily controlled by temperature in subtropical regions (alpha ocean) and by salinity in subpolar regions (beta ocean). Between these two regions lies a transition zone, often characterized by deep mixed layers in winter and responsible for the ventilation of intermediate or deep layers. While of primary interest, no consensus on what controls its position exists yet. Among the potential candidates, we find the wind distribution, air–sea fluxes, or the nonlinear cabbeling effect. Using an ocean general circulation model in an idealized basin configuration, a sensitivity analysis is performed testing different equations of state. More precisely, the thermal expansion coefficient (TEC) temperature dependence is explored, changing the impact of heat fluxes on buoyancy fluxes in a series of experiments. The polar transition zone is found to be located at the position where the sign of the surface buoyancy flux reverses to become positive, in the subpolar region, while wind or cabbeling are likely of secondary importance. This inversion becomes possible because the TEC is reducing at low temperature, enhancing in return the relative impact of freshwater fluxes on the buoyancy forcing at high latitudes. When the TEC is made artificially larger at low temperature, the freshwater flux required to produce a positive buoyancy flux increases and the polar transition moves poleward. These experimets demonstrate the important role of competing heat and freshwater fluxes in setting the position of the transition zone. This competition is primarily influenced by the spatial variations of the TEC linked to meridional variations of the surface temperature.



100 % reproducible with few commands

https://doi.org/10.1175/JPO-D-21-0295.1

https://github.com/rcaneill/caneill-et-al-JPO-nemo-transition-zone

This presentation

Paper II

Caneill, R., Roquet, F., & Nycander, J. (2024). Southern Ocean deep mixing band emerges from competition between winter buoyancy loss and stratification. *Ocean Science*

Ocean Sci., 20, 601–619, 2024
https://doi.org/10.5194/os-20-601-2024

Ocean Science Open Access EGU

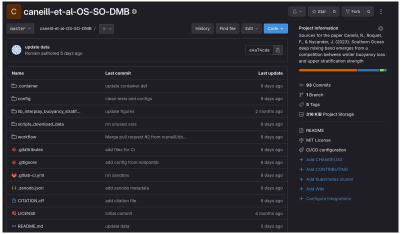
The Southern Ocean deep mixing band emerges from a competition between winter buoyancy loss and upper stratification strength

Romain Caneill[1], Fabien Roquet[1], and Jonas Nycander[2]

[1]Department of Marine Sciences, University of Gothenburg, Gothenburg, Sweden
[2]Department of Meteorology, Stockholm University, Stockholm, Sweden

Correspondence: Romain Caneill (romain.caneill@gu.se)

Received: 18 October 2023 – Discussion started: 19 October 2023
Revised: 16 February 2024 – Accepted: 21 February 2024 – Published: 19 April 2024



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https://doi.org/10.5194/os-20-601-2024

https://gitlab.com/rcaneill/caneill-et-al-OS-SO-DMB

Why does the TEC play a role?

The TEC scales the effect of

temperature on stratification

$$B_{250} = \underbrace{\frac{g}{\Delta t}\int_{-250}^{0} \boldsymbol{\alpha}(z)\frac{\partial \Theta}{\partial z} z \mathrm{d}z}_{B_{250}^{\Theta}} - \underbrace{\frac{g}{\Delta t}\int_{-250}^{0} \beta(z)\frac{\partial S}{\partial z} z \mathrm{d}z}_{B_{250}^{S}} \tag{2}$$

heat fluxes on buoyancy fluxes

$$\mathcal{B}^{surf} = \underbrace{\boldsymbol{\alpha}\frac{g}{\rho_0 C_p} Q_{tot}}_{\mathcal{B}_{\Theta}^{surf}} - \underbrace{\frac{g\beta S}{\rho_0}(E - P - R)}_{\mathcal{B}_{S}^{surf}} \tag{3}$$

$\boldsymbol{\alpha}$ is the TEC

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heat fluxes on buoyancy fluxes

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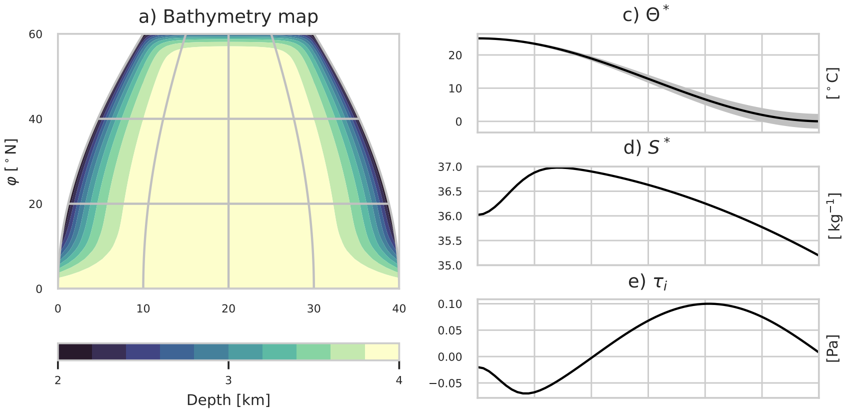
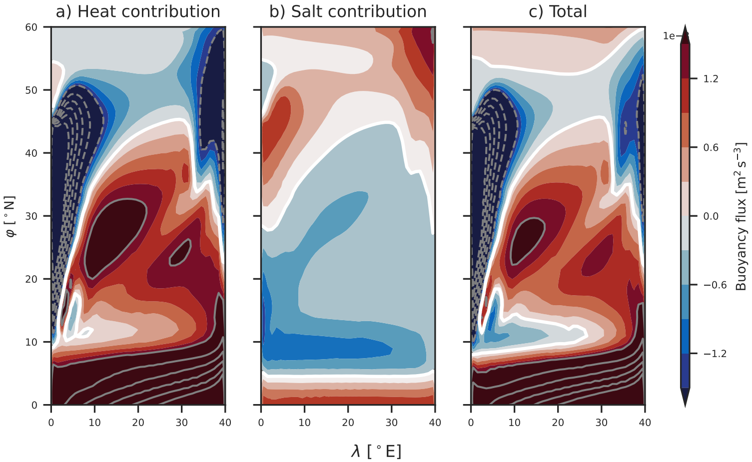
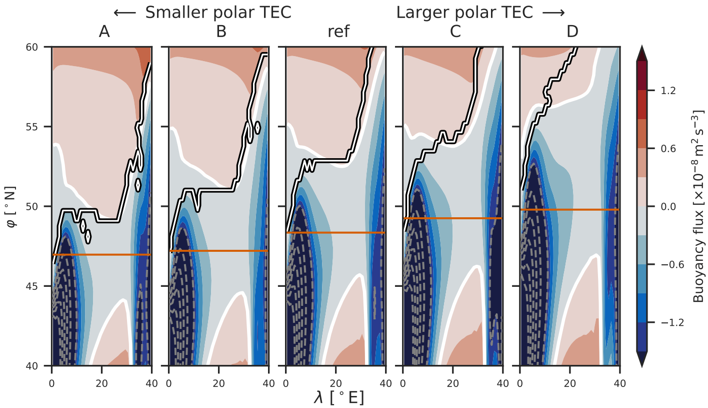


Idealised configuration that allows to study the role of annual buoyancy fluxes, by modification of the equation of state (thus changing the TEC).

Annual buoyancy fluxes: competition (Paper I)

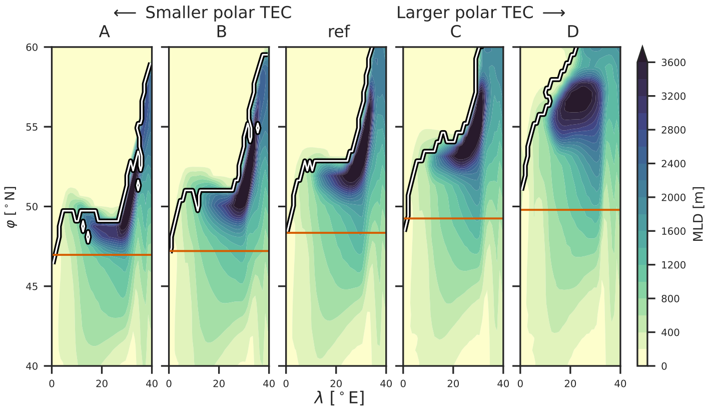


Reference run



Wind kept unchanged!

Poleward shift of the PTZ with increased TEC (Paper I)



Will fronts move poleward due to increased ocean temperature?

Poleward migration of transition zone due to global warming?

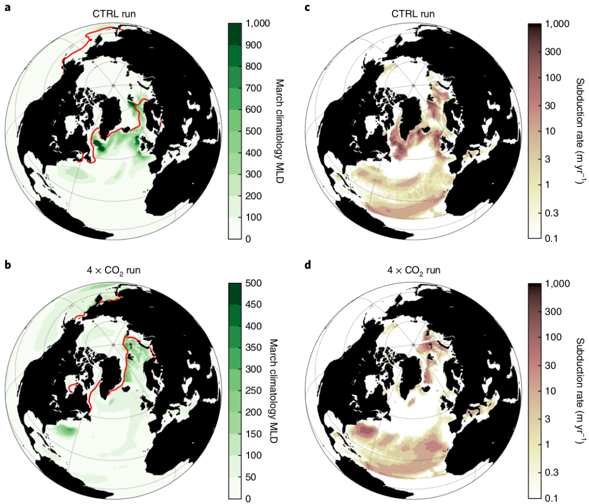
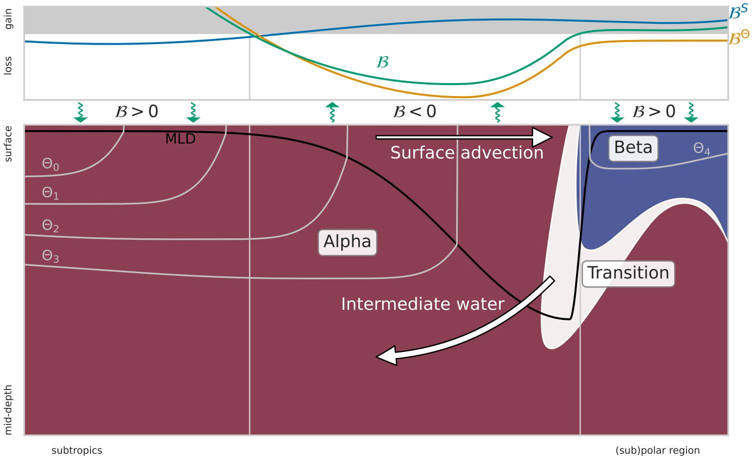
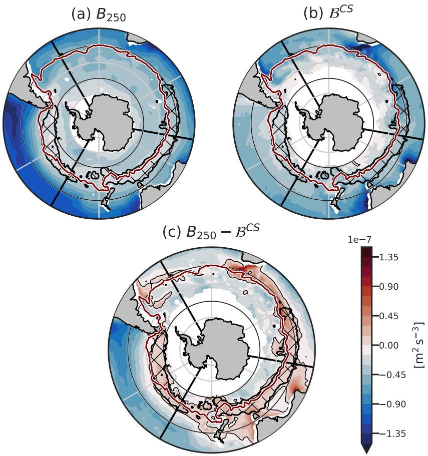


Figure from Lique and Thomas (2018)

Annual buoyancy fluxes set the transition (Paper I)



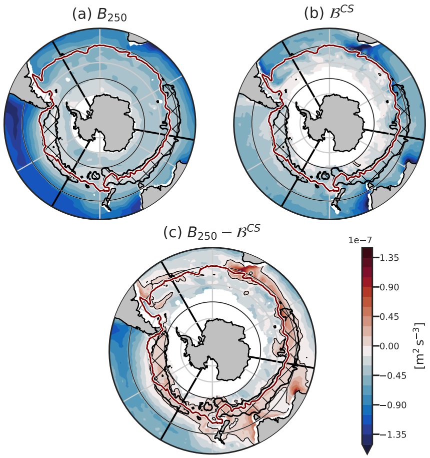


- B_{250}: measure of stratification
- $\mathcal{B}^{CS}$: buoyancy loss
- Hatched region: the DMB

- The position of the deep MLs is set by the balance between buoyancy loss and stratification
- Buoyancy fluxes control the stratification regimes

DMB = deep mixing band

Winter buoyancy loss erodes stratification (Paper II)



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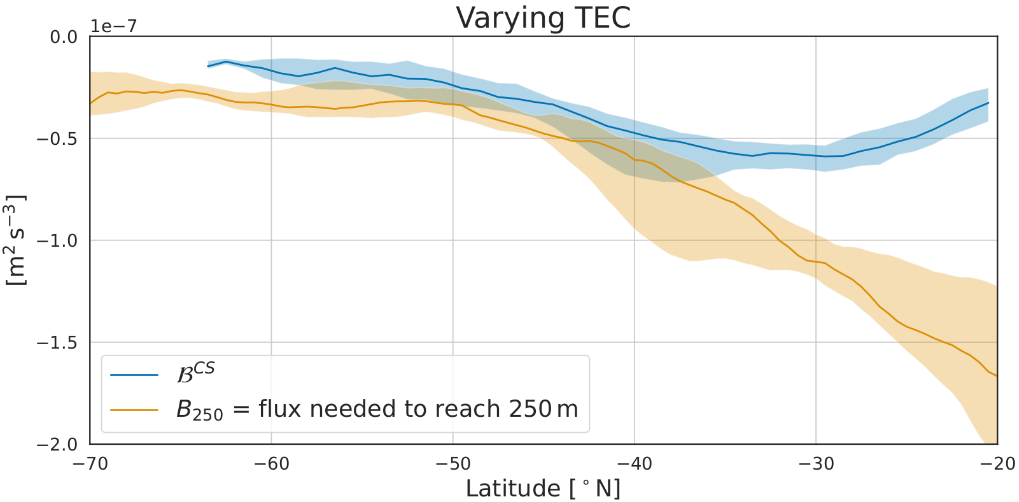

Varying TEC
1e−7
0.0
−0.5
−1.0
−1.5
−2.0
[m^2 s^{-3}]
−70
−60
−50
−40
−30
−20
Latitude [° N]
$\mathcal{B}^{CS}$
B_{250} = flux needed to reach 250 m

Objective C

Objective A	Objective B	Objective C
Describe alpha – beta oceans using observations	How do buoyancy fluxes shape the upper stratification?	Assess the role of the local value of the TEC.
Paper III	Papers I, II	Papers I, II, and IV

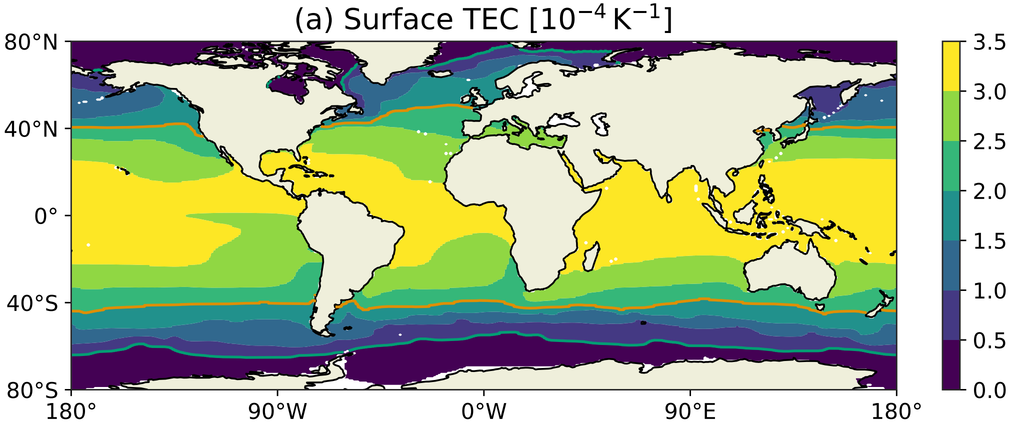
Paper I Caneill, R., Roquet, F., Madec, G., & Nycander, J. (2022). The Polar Transition from Alpha to Beta Regions Set by a Surface Buoyancy Flux Inversion. *Journal of Physical Oceanography*

Paper II Caneill, R., Roquet, F., & Nycander, J. (2024). Southern Ocean deep mixing band emerges from competition between winter buoyancy loss and stratification. *Ocean Science*

Paper IV Roquet, F., Ferreira, D., Caneill, R., Schlesinger, D., & Madec, G. (2022). Unique thermal expansion properties of water key to the formation of sea ice on Earth. *Science Advances*

The TEC varies with temperature (Paper IV)

- Follows a (quasi) linear relation with temperature
- Decreases the impact of temperature and heat in polar regions



Why does the TEC play a role?

The TEC scales the effect of

temperature on stratification

$$B_{250} = \underbrace{\frac{g}{\Delta t}\int_{-250}^{0} \boldsymbol{\alpha}(z)\frac{\partial \Theta}{\partial z} z \mathrm{d}z}_{B_{250}^{\Theta}} \underbrace{- \frac{g}{\Delta t}\int_{-250}^{0} \beta(z)\frac{\partial S}{\partial z} z \mathrm{d}z}_{B_{250}^{S}} \quad (4)$$

heat fluxes on buoyancy fluxes

$$\mathcal{B}^{surf} = \underbrace{\boldsymbol{\alpha}\frac{g}{\rho_0 C_p} Q_{tot}}_{\mathcal{B}_{\Theta}^{surf}} \underbrace{- \frac{g\beta S}{\rho_0}(E - P - R)}_{\mathcal{B}_{S}^{surf}} \quad (5)$$

$\boldsymbol{\alpha}$ is the TEC

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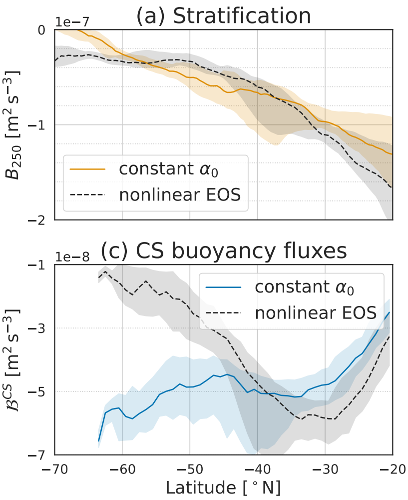
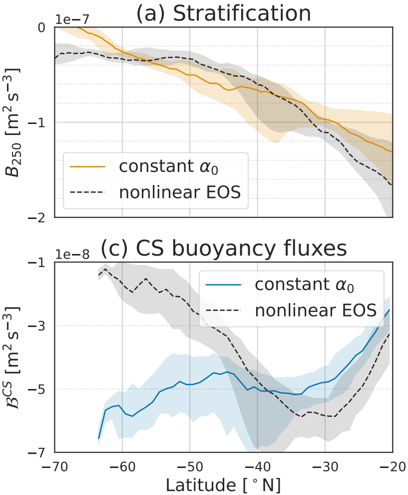
$\boldsymbol{\alpha}$ is the TEC

The impact of the variable TEC (Paper II)



The decrease in the TEC:

- allows for stable beta ocean
- damps buoyancy loss in polar region



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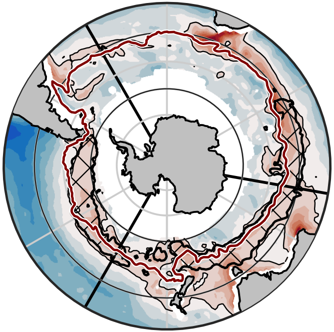
The impact of the variable TEC (Paper II)

Obj. C

$B_{250} - \mathcal{B}^{CS}$

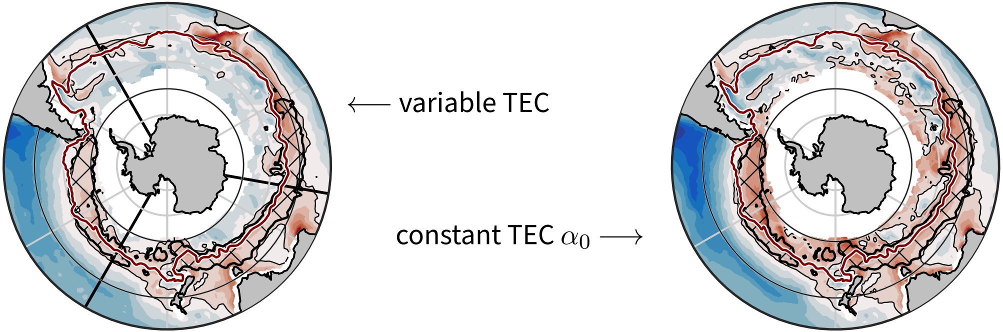


⟵ variable TEC

- The variable TEC controls the width of the DMB
- The decrease in the TEC limits the southward extent of the DMB
- Beta oceans exist because the TEC becomes small

The impact of the variable TEC (Paper II)

$B_{250} - \mathcal{B}^{CS}$



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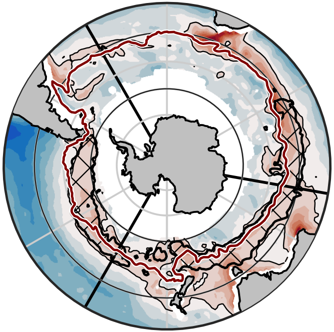
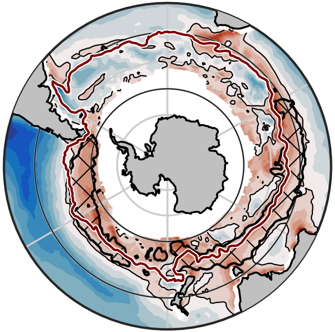


← variable TEC

constant TEC α_0 →



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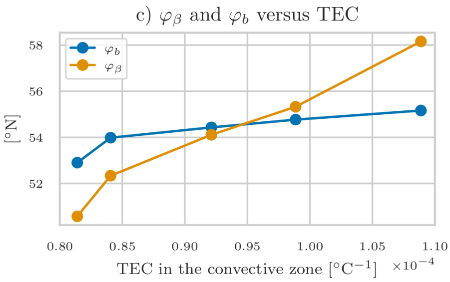
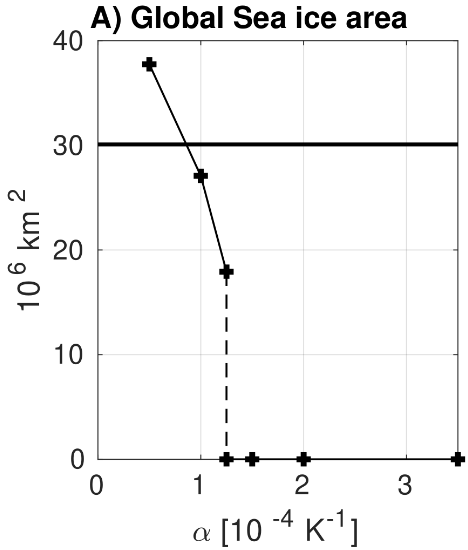
The polar value of the TEC as global controller (Papers II and IV)





Conclusions

Describe alpha – beta oceans using observations. Obj. A

- Global zonation: alpha $\longrightarrow$ transition zone $\longrightarrow$ beta
- ML deeper in alpha- than beta-oceans

How do buoyancy fluxes shape the upper stratification? Obj. B

- The transition zone is located at the sign inversion of annual buoyancy fluxes
- Buoyancy loss erodes stratification and produces the DMB

Assess the role of the local value of the TEC. Obj. C

- The decrease in the TEC in polar regions decreases buoyancy loss
- The small polar value of the TEC permits beta ocean formation
- My thesis confirms that the origin of alpha – beta oceans lies in thermodynamic of seawater

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Perspectives

- The sea surface temperature exerts a strong control on the stratification by its link with TEC.
- Buoyancy fluxes are not simply the sum of heat and freshwater fluxes.
- Warming $\Longrightarrow$ larger values of the TEC. But also increases freshwater fluxes in the polar regions. Who will win?

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