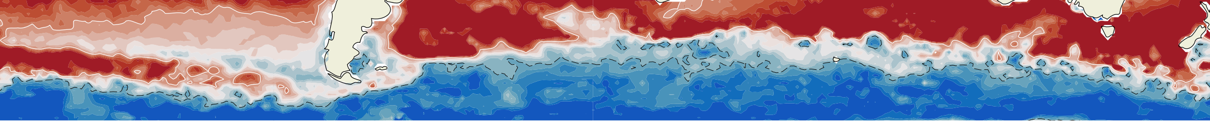


From alpha to beta ocean

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

Romain Caneill

PhD Defence, January 18, 2024

Supervisor: Fabien Roquet
Examiner and president of jury: Göran Broström
Opponent: Thomas Haine
Committee: Hans Burchard, Kristofer Döös, Alexa Griesel, and Göran Björk

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.

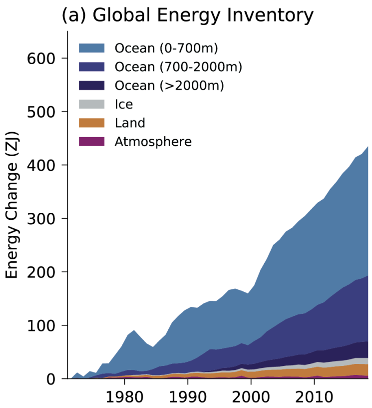
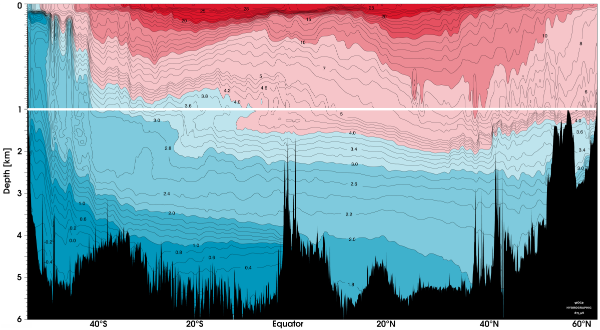


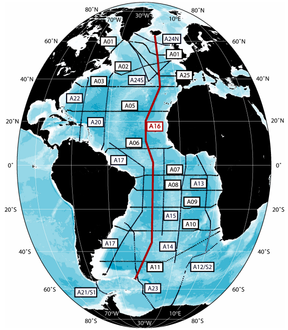
Figure adapted from the IPCC Sixth Report (Fox-Kemper et al., 2021)

Ocean stratification

WOCE A16 section of potential temperature

The large stratification inhibits vertical exchanges.





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

Ocean and atmosphere exchanges properties through the mixed layer

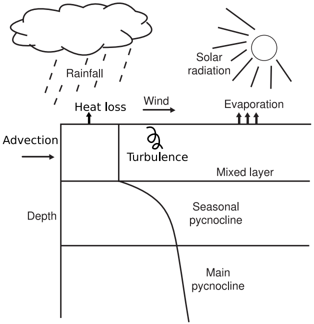


Figure adapted from Sprintall and Cronin (2009)

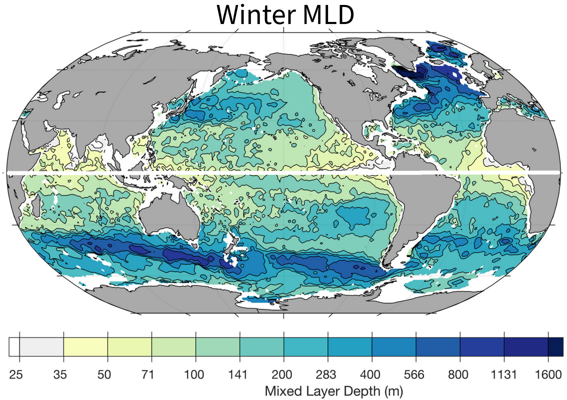
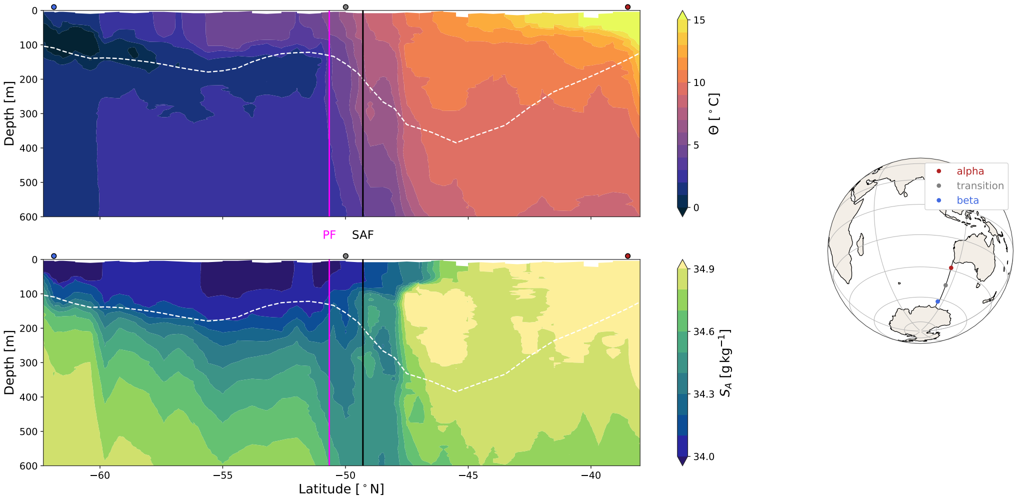


Figure adapted from Johnson and Lyman (2022)

Regimes of stratification

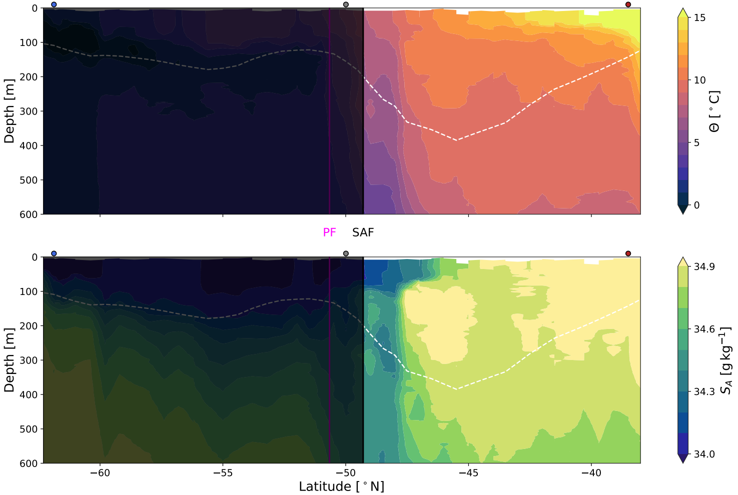
T-S section IO9S

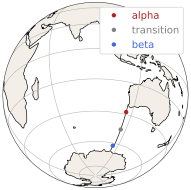
https://cchdo.ucsd.edu/cruise/09AR20120105

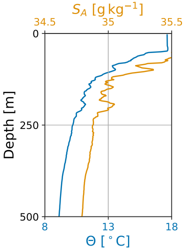


Regimes of stratification

Alpha ocean

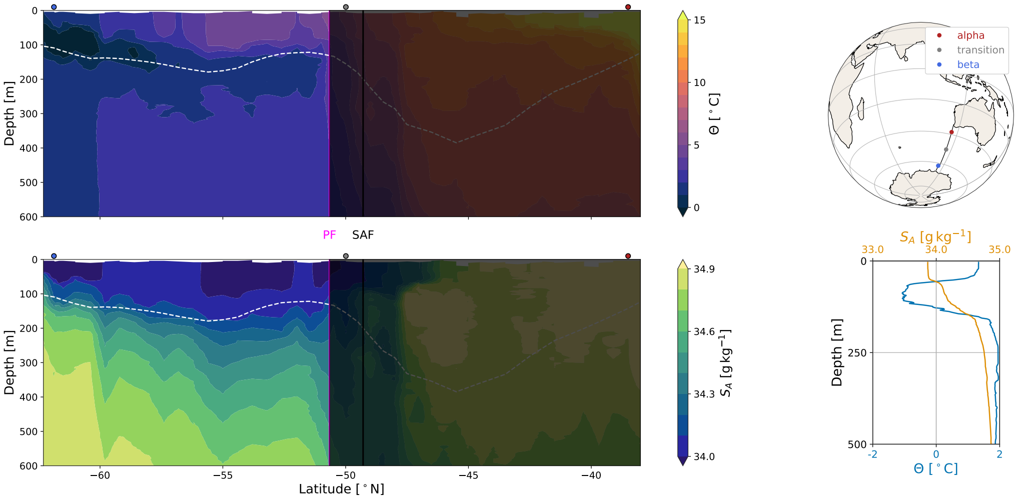






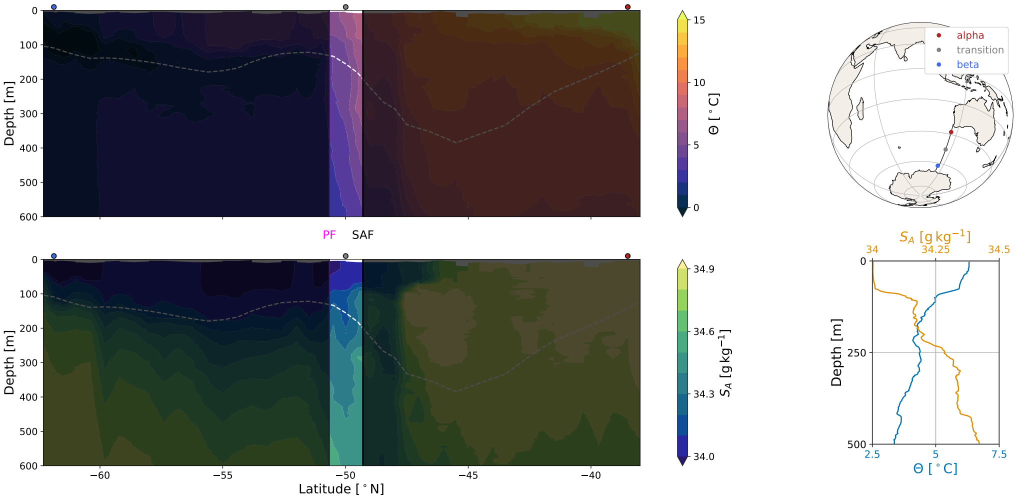
Regimes of stratification

Beta ocean



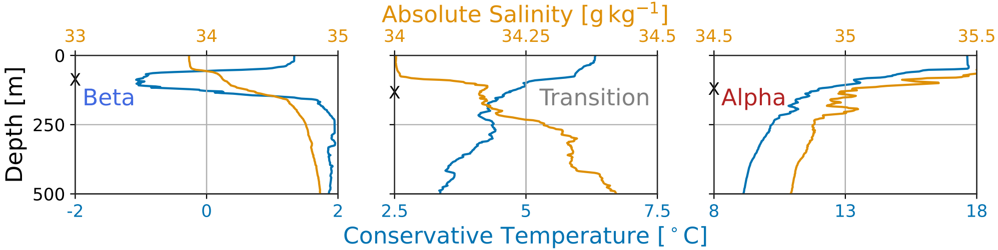
Regimes of stratification

Transition zone



Beta, transition, and alpha

T-S section IO9S, selected profiles

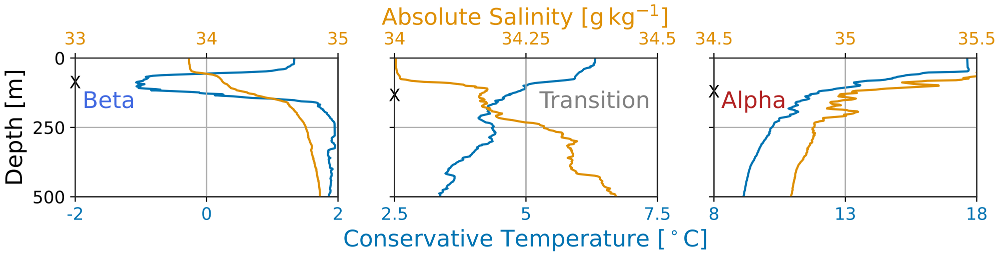


Temperature stratifies:
alpha ocean

(Carmack, 2007)

Beta, transition, and alpha

T-S section IO9S, selected profiles



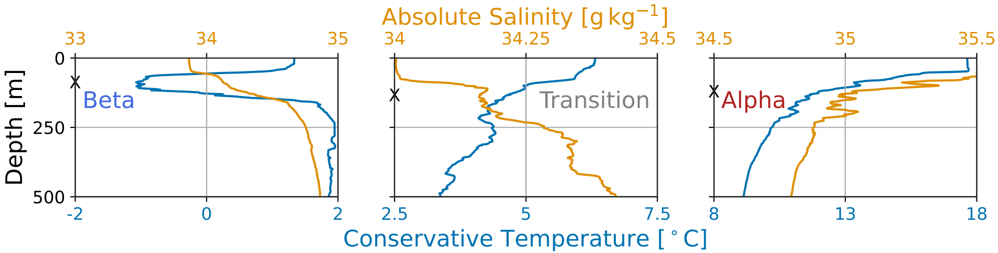
Salinity stratifies:
beta ocean

Temperature stratifies:
alpha ocean

(Carmack, 2007)

Beta, transition, and alpha

T-S section IO9S, selected profiles



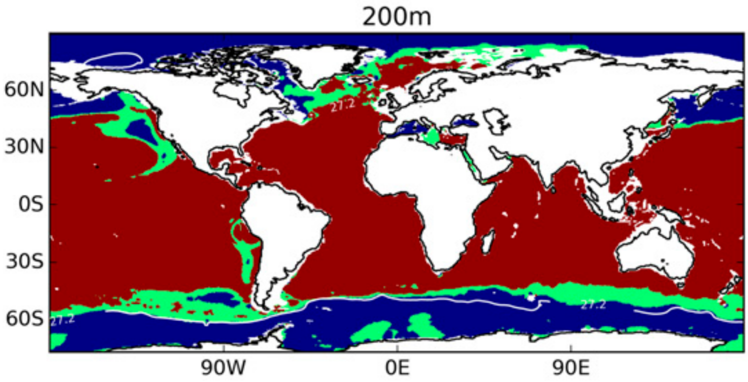
Salinity stratifies:
beta ocean

Both stratify:
transition zone

Temperature stratifies:
alpha ocean

(Carmack, 2007)

Alpha and beta oceans

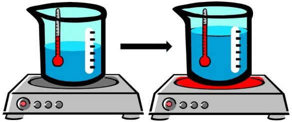


Called alpha – beta oceans in reference to α and β, thermodynamic properties of seawater.

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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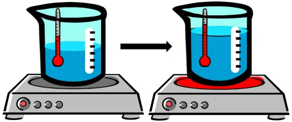
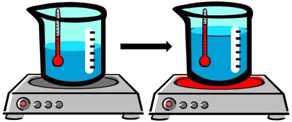
- Ocean warms $\Longrightarrow$ volume increases (1/2 of observed sea-level rise)



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:

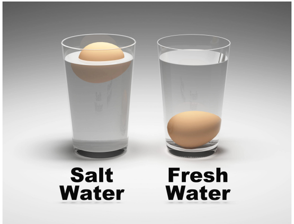
$$\alpha = -\frac{1}{\rho}\frac{\partial \rho}{\partial \Theta}$$



Public Domain

The haline contraction coefficient (HCC, β)

- Salty water is denser than freshwater



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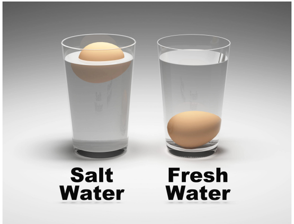
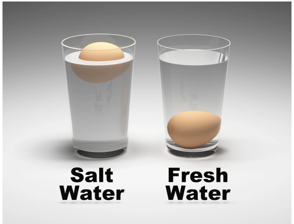


The haline contraction coefficient (HCC, β)

- 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

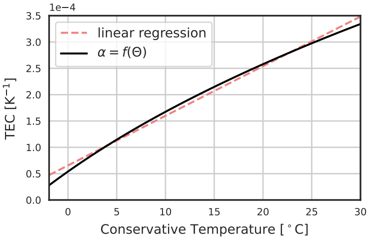
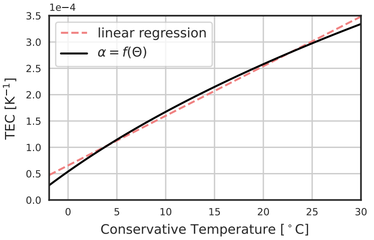


Figure adapted from Caneill et al. (2023)

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 $\beta \simeq 7.5 \times 10^{-4}\,\mathrm{kg\,g^{-1}}$
- It was assumed that the role of salinity is enhanced in polar regions due to low values of the TEC

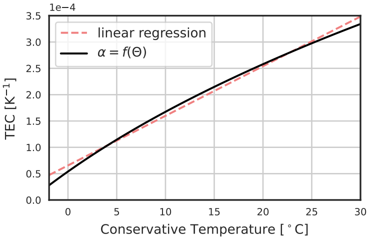

Figure adapted from Caneill et al. (2023)

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	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.

TEC = Thermal expansion coefficient

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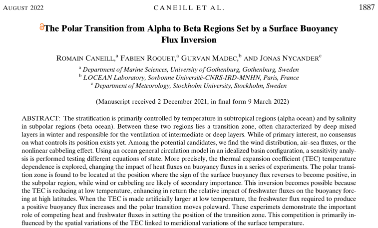


AUGUST 2022 CANEILL ET AL. 1887

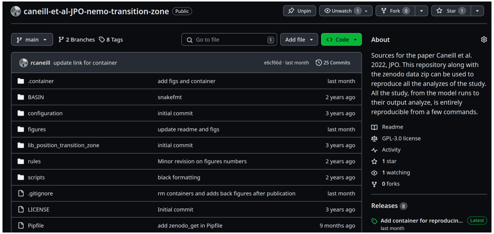
The Polar Transition from Alpha to Beta Regions Set by a Surface Buoyancy Flux Inversion

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 thesis

Paper II

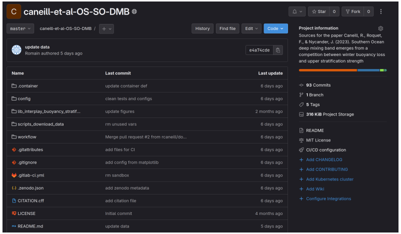
Caneill, R., Roquet, F., & Nycander, J. (2023). Southern Ocean deep mixing band emerges from competition between winter buoyancy loss and stratification. *revision submitted to Ocean Science*

https://doi.org/10.5194/egusphere-2023-2404
Preprint. Discussion started: 19 October 2023

EGUsphere
Preprint repository

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, Göteborg, Sweden
[2]Department of Meteorology, Stockholm University, Stockholm, Sweden
Correspondence: Romain Caneill (romain.caneill@gu.se)



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https://doi.org/10.5194/egusphere-2023-2404

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

Caneill, R., & Roquet, F. (2023). Temperature versus salinity: Distribution of stratification control in the global ocean. *in preparation for Ocean Science*

This thesis

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*

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HOME > SCIENCE ADVANCES > VOL. 8, NO. 46 > UNIQUE THERMAL EXPANSION PROPERTIES OF WATER KEY TO THE FORMATION OF SEA ICE ON EARTH

RESEARCH ARTICLE | CLIMATOLOGY

Unique thermal expansion properties of water key to the formation of sea ice on Earth

FABIEN ROQUET, DAVID FERREIRA, ROMAIN CANEILL, DANIEL SCHLESINGER, AND GURVAN MADEC Authors Info & Affiliations

SCIENCE ADVANCES • 16 Nov 2022 • Vol 8, Issue 46 • DOI: 10.1126/sciadv.abq0793

Objective A

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 III Caneill, R., & Roquet, F. (2023). 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)
- Compute the SCI at the bottom of winter mixed layer
- Interpolation to produce climatology

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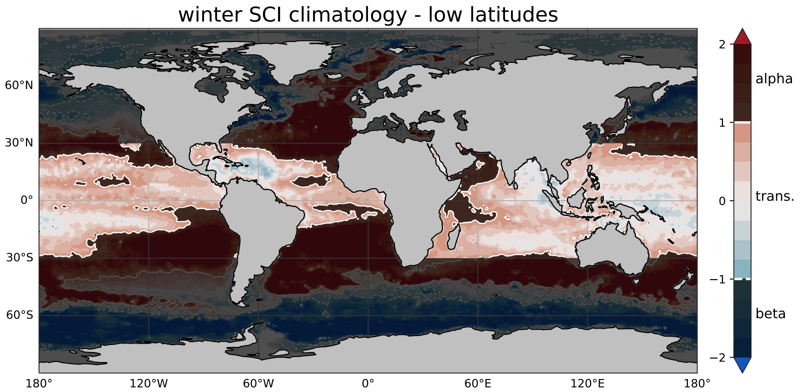
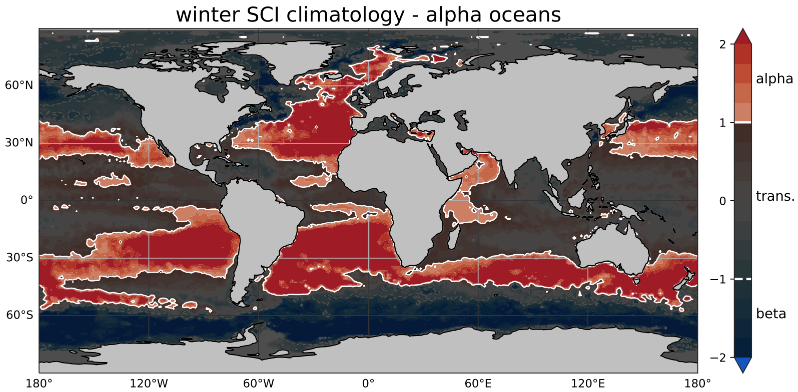
Global maps of the winter SCI (Paper III)



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

PTZ = polar transition zone



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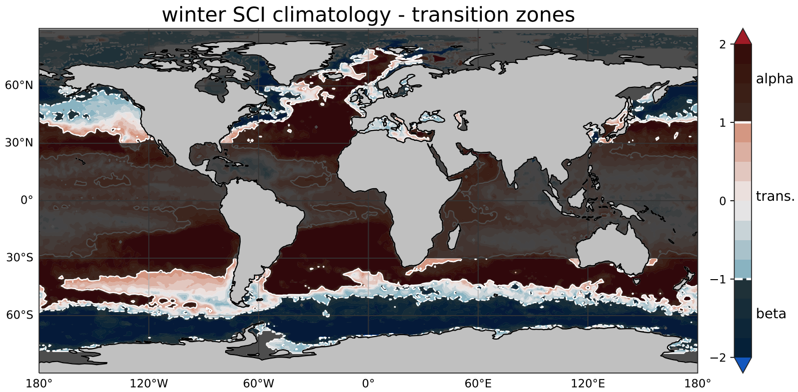

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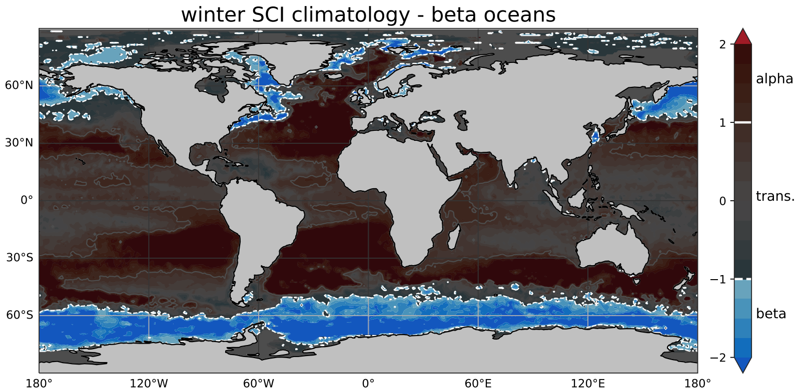

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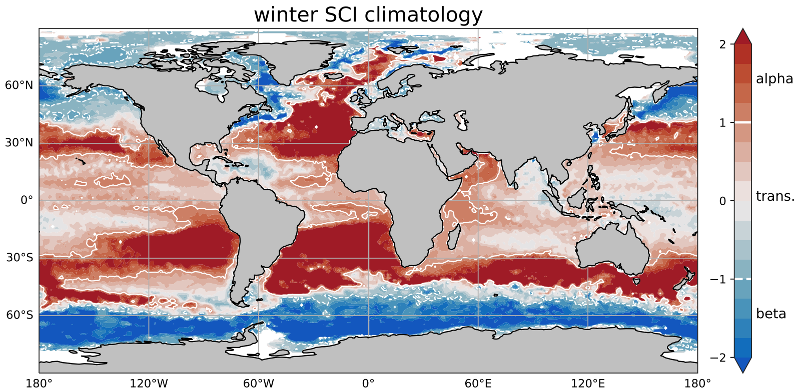
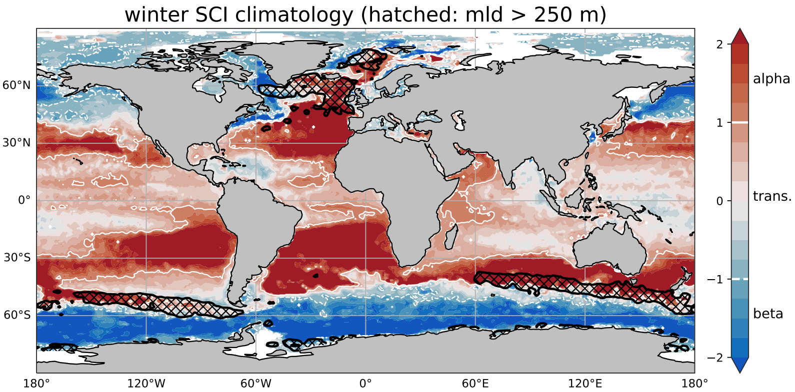


- Zonation with: transition zone $\rightarrow$ alpha $\rightarrow$ PTZ $\rightarrow$ beta
- Wide and zonal North Pacific PTZ
- Narrow and diagonal North Atlantic PTZ



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

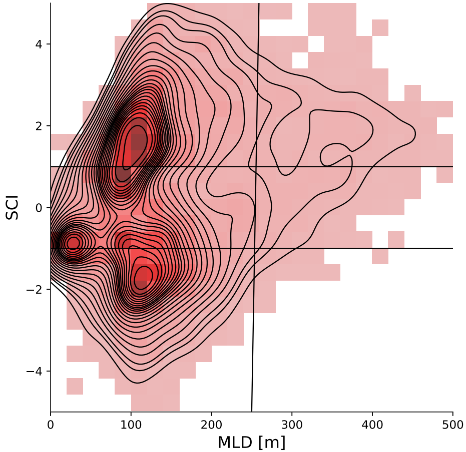


Figure for $|\varphi| \geq 30^{\circ}$

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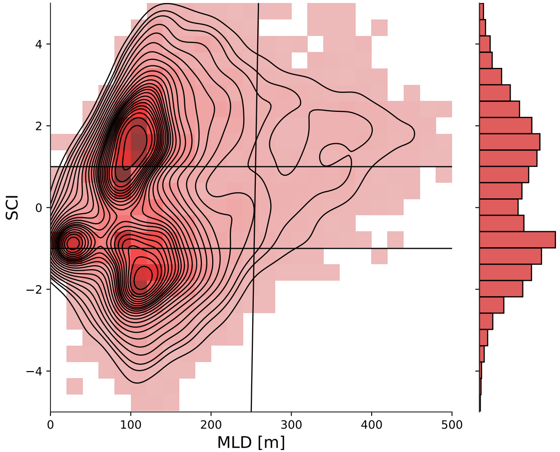

Figure for $|\varphi| \geq 30^\circ$

Objective B

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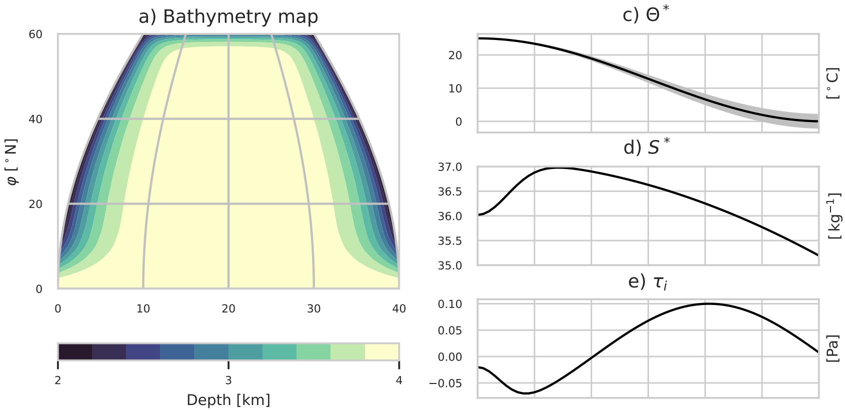
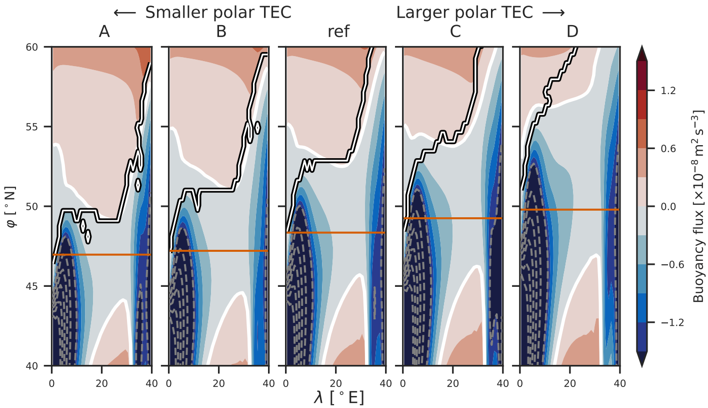
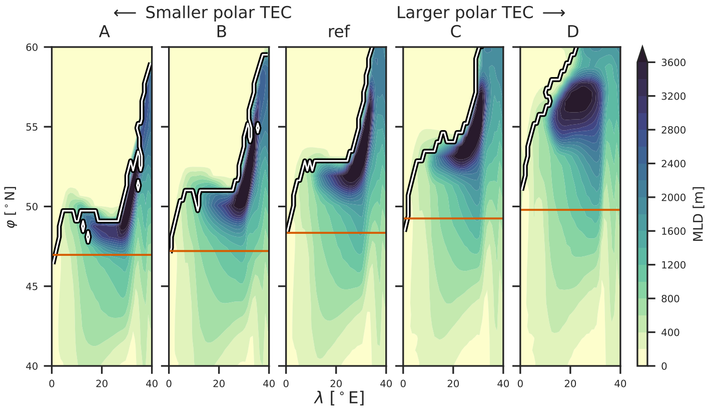


Idealised configuration that allows to study the role of annual buoyancy fluxes, by modification of the equation of state (thus changing the TEC).

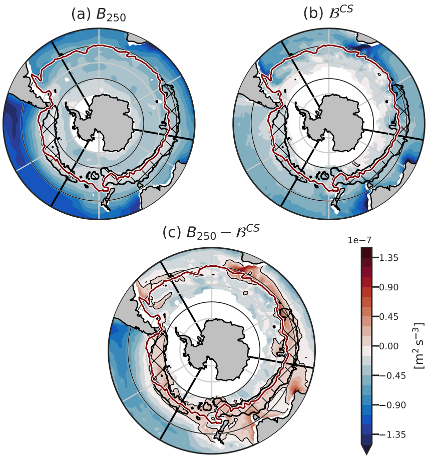


Wind kept unchanged!



Will fronts move poleward due to increased ocean temperature?

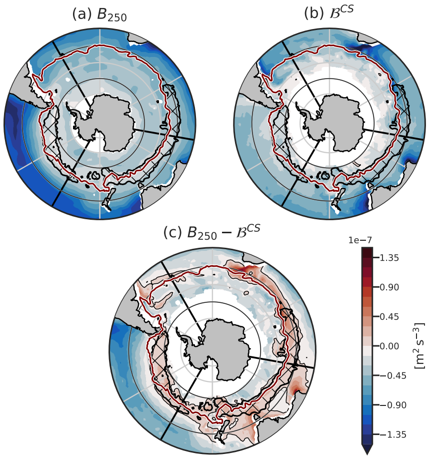
Winter buoyancy loss erodes stratification (Paper II)



- 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



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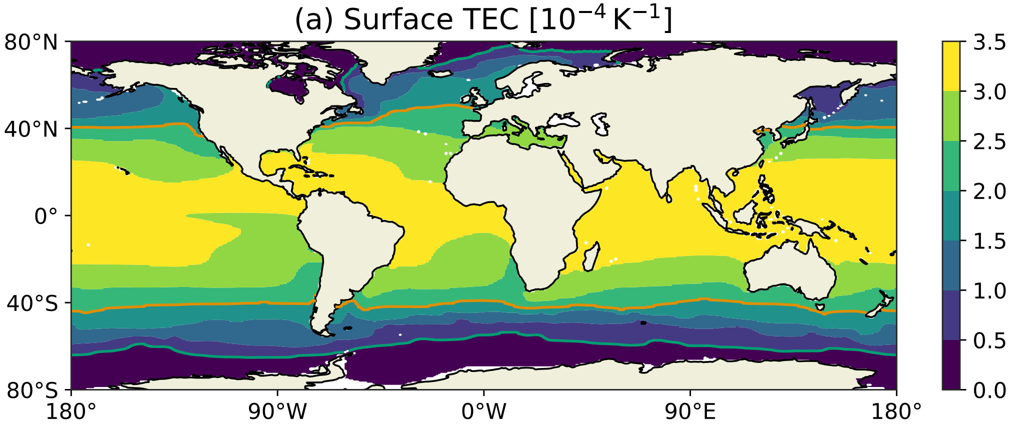
Paper IV Roquet, F., Ferreira, D., Caneill, R., Schlesinger, D., & Madec, G. (2022). Unique thermal expansion properties of water key to the formation of sea ice on Earth. *Science Advances*

- 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

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

heat fluxes on buoyancy fluxes

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

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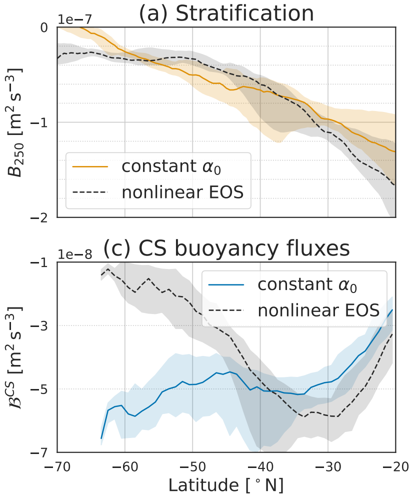
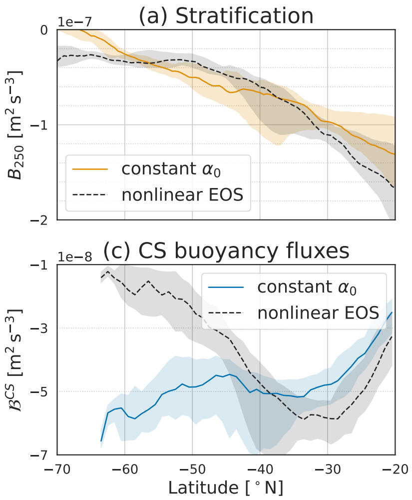
$\boldsymbol{\alpha}$ is the TEC

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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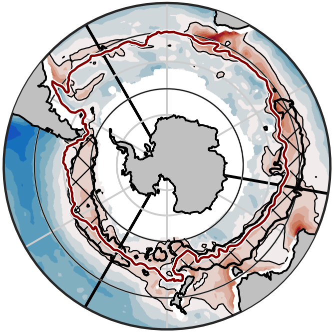
The impact of the variable TEC (Paper II)

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

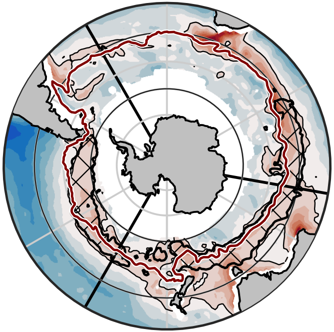


← variable TEC

- 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

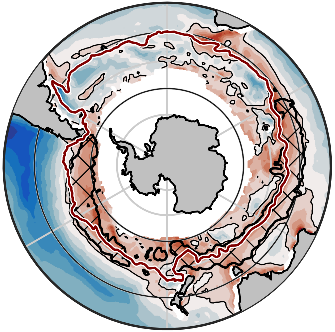
The impact of the variable TEC (Paper II)

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



$\longleftarrow$ variable TEC

constant TEC α_0 $\longrightarrow$



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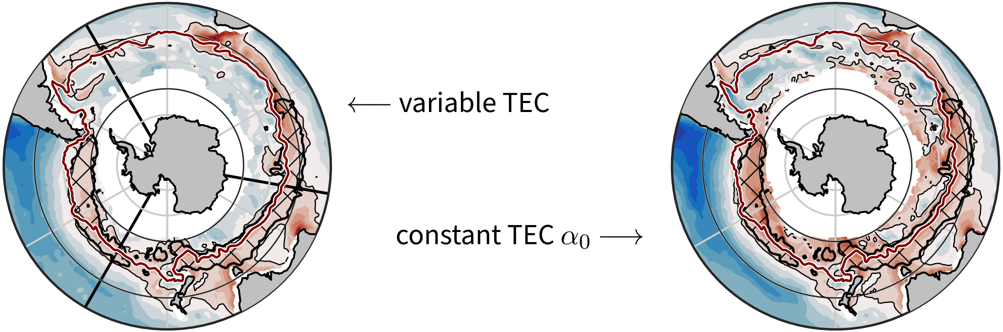

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- Beta oceans exist because the TEC becomes small

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

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- My thesis confirms that the origin of alpha – beta oceans lies in thermodynamic of seawater

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 $\implies$ larger values of the TEC. But also increases freshwater fluxes in the polar regions. Who will win?
- Sea ice only forms in beta ocean. A poleward shift of the PTZ could amplify climate change.

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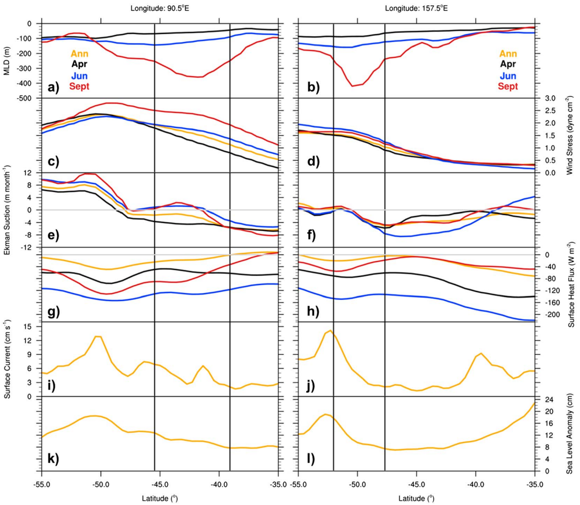
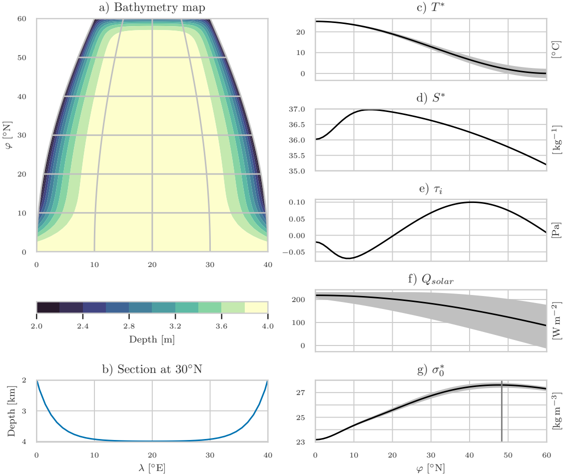


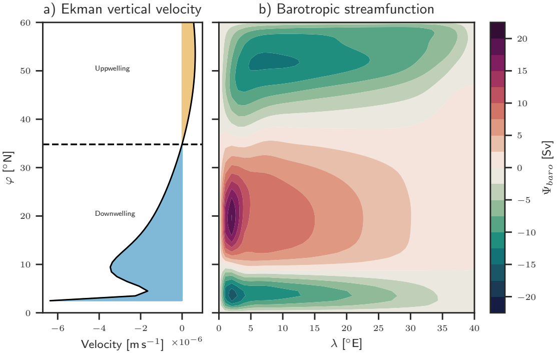
Figure from (DuVivier et al., 2018).

Fig. 1

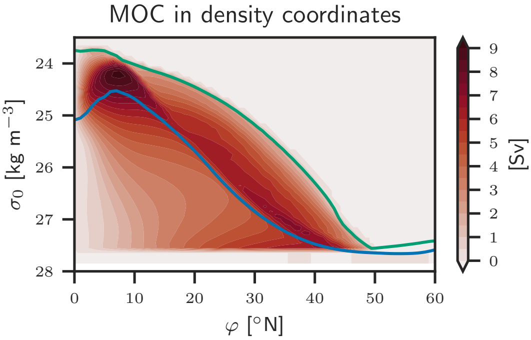


Bathymetry of the basin in (a) and (b). Forcing fields used by the model, with (c) the restoring temperature, (d) the restoring salinity, (e) the zonal wind stress, (f) the solar heat flux, and (g) the restoring density anomaly. The average values are plotted in black. For panels (c), (f), and (g), the gray zone represent the seasonal variation range. The vertical line in (e) represents φ_M, the latitude of the winter maximum restoring density.

Fig. 2

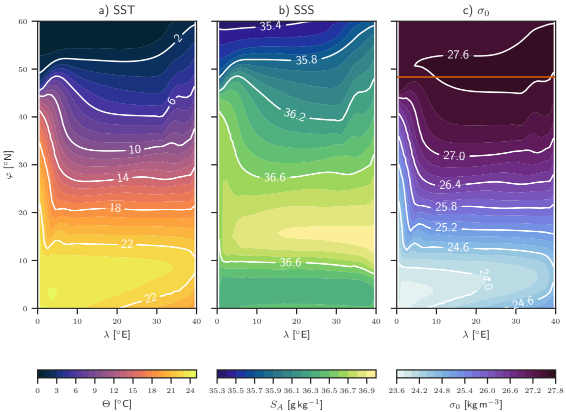


Wind induced circulation: (a) theoretical Ekman vertical velocity, and (b) barotropic response for the reference run. The Ekman velocity is not shown south of 2°N, as it diverges to minus infinity.



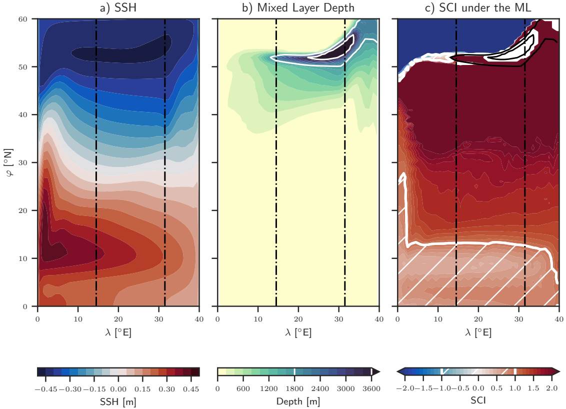
Meridional overturning streamfunction computed in density coordinates. The green and blue lines represent the zonal minimum and maximum surface densities, respectively. Following standard conventions, the circulation is clockwise around maximum streamfunction values.

Fig. 4



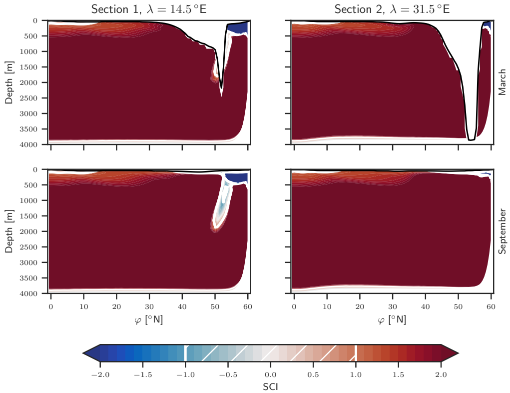
a) SST, b) SSS, and c) surface density anomaly for reference run. The horizontal orange line on panel c) indicates φ_M.

Fig. 5



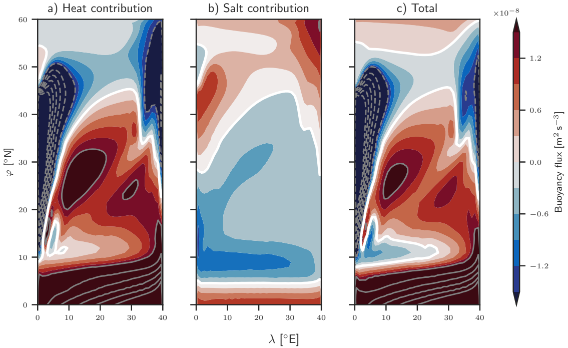
(a) Sea surface height, (b) annual deepest mixed layer depth, and (c) stratification control index under the mixed layer for the reference run, taken in each point at the time of the year when the mixed layer is the deepest. The white contour in the panel (c) indicates the transition zone, i.e. $-1 < SCI < 1$, while the 2 black contours emphasize the 1800 m and 3600 m MLD (these contours correspond to the 2 white contours of panel (b). When the mixed layer reaches the bottom cell, no value is used for the SCI (white areas). The black dashed lines represent the location of the sections presented in Figure 6.

Fig. 6



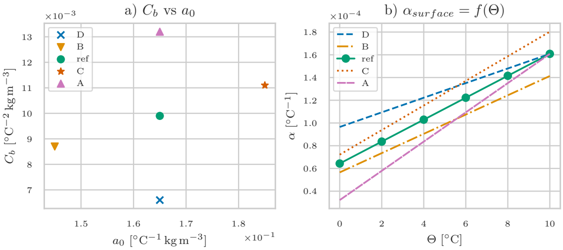
Sections of the SCI in March and September for the longitudes $14.5°$E and $31.5°$E. The mixed layer reaches the bottom in March at $31.5°$E, and below 2000 m all the ocean has a SCI greater than 2.

Fig. 7

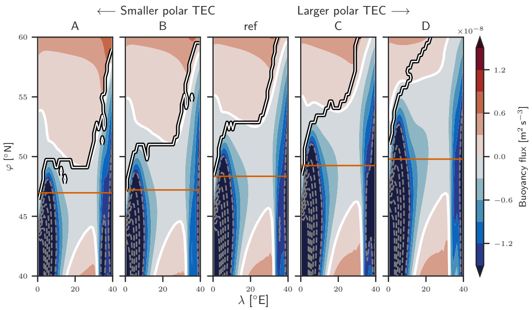


Buoyancy fluxes: (a) the heat contribution, (b) the salt contribution, and (c) the total flux. The colors are saturated at $\pm 1.5 \times 10^{-8}$ m^2 s^{-3} so that the variations of the salt contribution are visible. The gray lines are separated by 1.5×10^{-8} m^2 s^{-3} and the white line here underlines the 0 m^2 s^{-3} contour.

Fig. 8



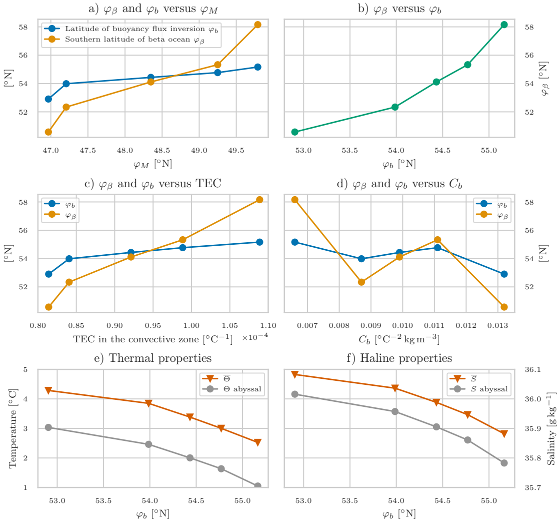
(a) C_b vs a_0 scatter plot, and (b) variation of the TEC with respect of the temperature for the five experiments.



Net buoyancy flux for every run. No major difference is visible south of 40 °N so the figures have been cropped. The white line with black contour represents the -1 value of the SCI under the ML. As the polar transition zone is very narrow between the alpha and beta oceans, this line corresponds very well to the transition between the alpha and beta oceans. The orange line represents the latitude of φ_M, the latitude of maximum value of σ_0^*.

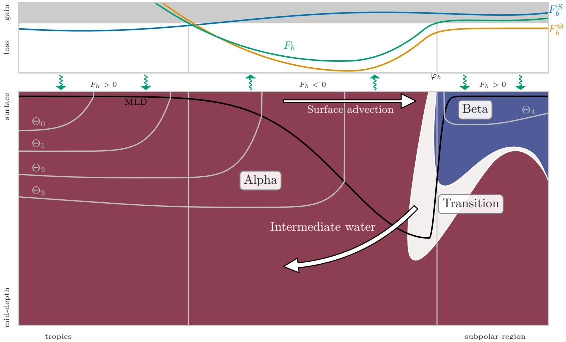
Paper I

Fig. 10



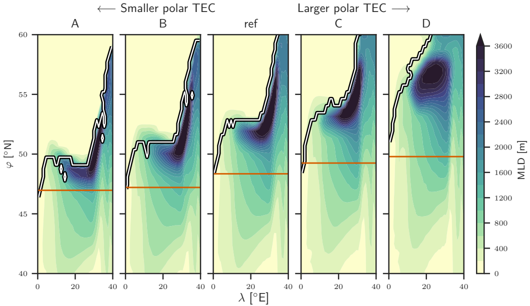
(a) Latitude of the southern boundary of the beta ocean φ_β and latitude of the buoyancy front φ_b versus φ_M the latitude of maximum σ_0^*, (b) φ_β versus φ_b, (c) φ_b function of the value of the TEC in the convective area, (d) φ_β and φ_b versus cabbeling parameter C_b. Evolution of the basin average and abyssal (e) temperature and (f) salinity as a function of the front latitude. The abyssal properties are computed as latitude – longitude averages over the bottom cell of the ocean.

Fig. 11



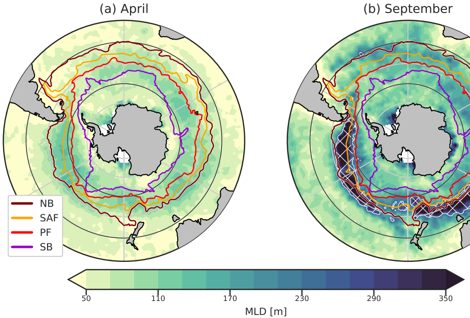
Zonal conceptual view of the ocean. The upper panel presents the surface buoyancy fluxes, the gray background is for positive fluxes, the white one for negative fluxes. The green wavy arrows represent the surface buoyancy flux: they are oriented downward for buoyancy gain, and upward for buoyancy loss. The two latitudes of buoyancy flux inversion are indicated by the vertical gray lines. The zonal view of the ocean is shown on the lower panel. Red color are used for alpha ocean, blue color for beta ocean and white for the transition zone. The mixed layer depth is represented by the black line, and the 5 gray lines represent 5 isotherms named by Θ_n with n between 0 and 5.

Fig. A1



Annual maximum of MLD for every runs. The white line with black contour represents the -1 value of the SCI under the ML. As the transition zone is very narrow between the alpha and beta oceans, this line corresponds very well to the transition between the alpha and beta oceans. The orange line represents the latitude of φ_M, the latitude of maximum value of σ_0^*.

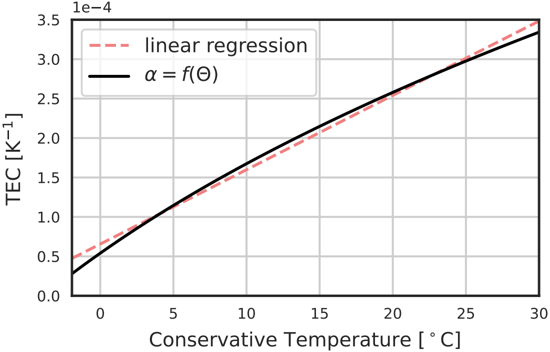
Fig. 1



Mixed layer depth climatology in the SO with the major ACC fronts in (a) April and (b) September. From north to south, the NB (maroon colour), SAF (yellow), PF (red), and SB (purple) fronts from Park et al. (2019) are plotted. Hatches and white contour represent the DMB. For these maps, and for the following maps of this paper, the northern boundary is at 30 °S. In latitude, grid lines are spaced every 10 degrees, with black lines at 40 °S and 60 °S.

Paper II

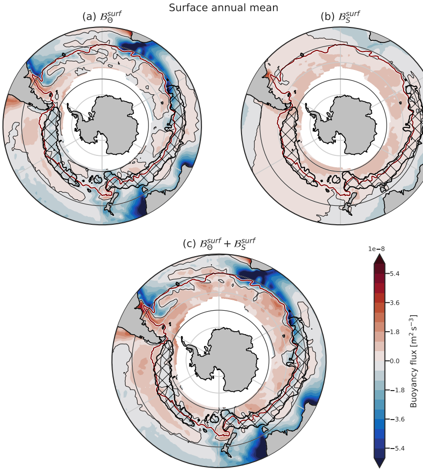
Fig. 2



Thermal Expansion Coefficient function of Conservative Temperature. The pressure is 0 dbar and the Absolute Salinity 35 5 g kg^{-1}. The graph stops at -1 9 $^\circ$C, the freezing point.

Paper II

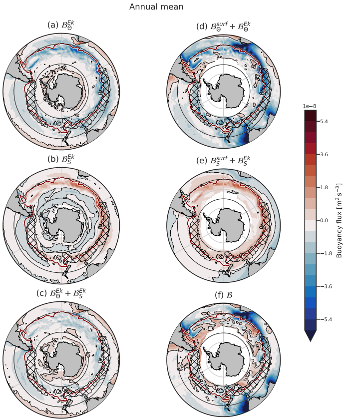
Fig. 3



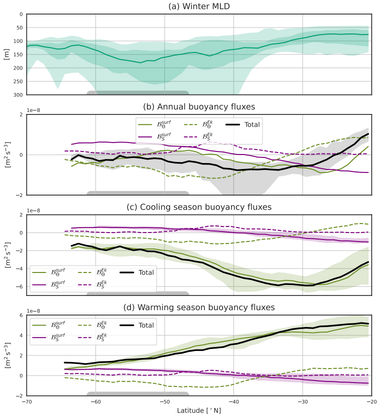
Climatology of the annual components of the surface buoyancy fluxes. The heat component (a), haline component (b), and their sum (c) are plotted. On every plot, the thin black lines represent the 0 of the fluxes, and the maroon line is the northern boundary of the ACC, defined as the northernmost closed contour of Mean Dynamic Topography, as defined by Park et al. (2019). Hatches represent the DMB. The northern boundary is at 30 °S. In latitude, grid lines are spaced every 10 degrees, with black lines at 40 °S and 60 °S.

Paper II

Fig. 4

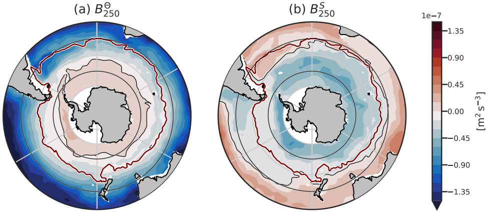


Climatology of the annual components of the Ekman induced buoyancy fluxes, and the sum with the surface fluxes. The subplots are organized as follows: the columns show the Ekman fluxes and the sum of Ekman and surface. The rows show the thermal component, haline component, and their sum.



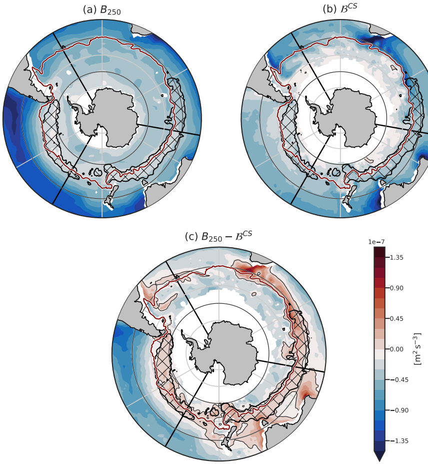
(a) Winter MLD. The shading represents respectively the 5th – 95th, and 25th – 75th percentiles, and the solid line is the zonal median. Mixed layers deeper than 250 m are found between 40 °S and 60 °S depending on the SO sector. (b) annual mean of the buoyancy flux components, (c) cooling season means, and (d) warming season means. The solid lines are the zonal medians, and the shading represents the region between the 25th and 75th percentiles. The black line is $\mathcal{B}$ the sum of surface and Ekman fluxes. The vertical grid spacing is constant between panels. The black, green, and purple colours are for the total, heat surface, and salt surface components. The majority of the zonal differences arise from the surface heat component. The gray box in the bottom represents a median position of the ACC.

Fig. 6



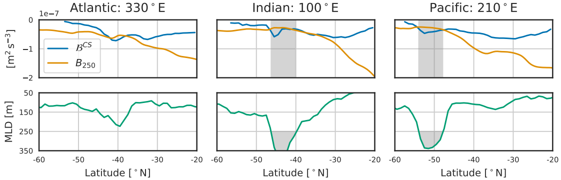
Climatology of (a) the thermal and (b) haline components of B_{250}, computed in April.

Fig. 7



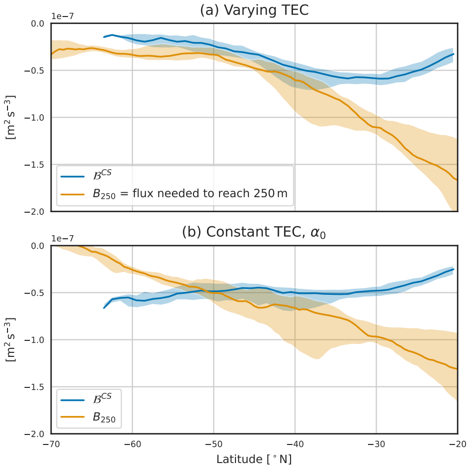
Climatology of (a) the intensity of late summer stratification characterised by B_{250}, (b) the buoyancy fluxes during the cooling season, and (c) the difference $B_{250} - \mathcal{B}^{CS}$. The hatches surrounded by the black contour represent the DMB.

Fig. 8



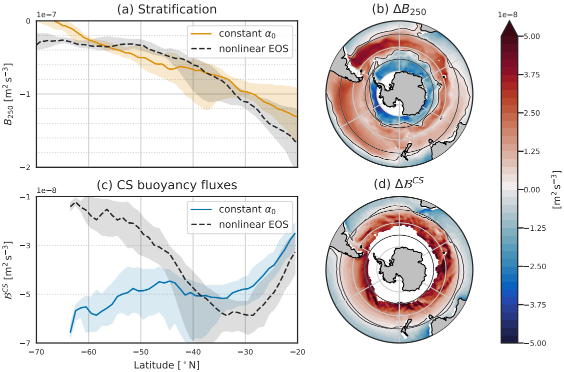
B_{250} (orange curves) and $\mathcal{B}^{CS}$ (blue curves) (upper row), and observed winter MLD (green curve in lower row), for 3 different transects in the Atlantic, Indian, and Pacific sectors of the SO. The gray box represent the DMB.

Fig. 9



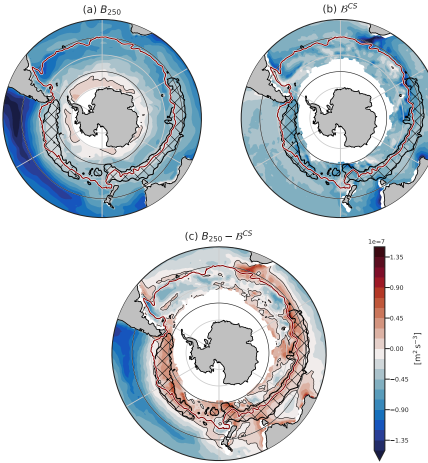
Buoyancy fluxes during the cooling season (blue) and B_{250}, the buoyancy fluxes needed to produce a 250 m deep mixed layer (orange). (a) is computed using the realistic varying TEC and (b) is computed with α_0. Shaded areas correspond to the 1st and 3rd quartiles, and the solid lines are the zonal medians. This plot extends to 20 $^\circ$S to highlight the increase of stratification towards the tropics, and the maximum buoyancy loss located around 30 $^\circ$S.

Fig. 10



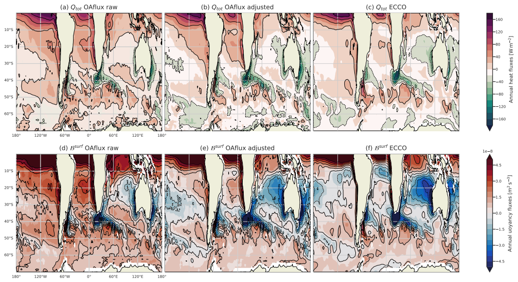
Stratification and buoyancy fluxes and computed using the nonlinear EOS or a constant α_0. In panels (a) and (c), black dashed lines are for the nonlinear EOS, and blue or orange continuous lines are with constant α_0. The spacing between the horizontal dotted gray line is the same in these two panels and equal to 2×10^{-8} m^2 s^{-3} The light shadings correspond to the 25th and 75th percentiles. Panels (b) and (d) are the difference between using the varying TEC and the constant α_0, for B_{250} and $\mathcal{B}^{CS}$ respectively.

Fig. 11



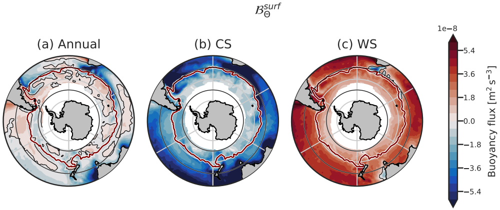
Same as Fig. 7 but using α_0 in computations. Hence, (c) represents where the ocean could form the DMB if the TEC was constant. The hatches represent the observed DMB. The region with sea-ice around Antarctica is masked in white.

Fig. A1

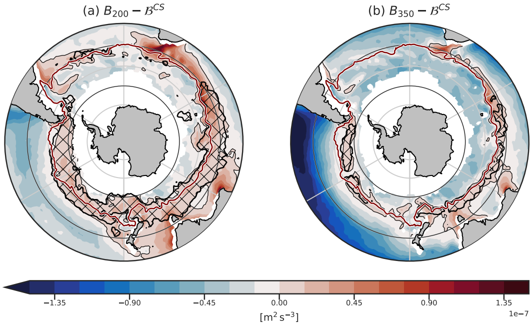


Heat fluxes (first row) and surface buoyancy fluxes (second row) are presented. The first column is the climatology annual mean without any correction, the second column is with our adjustment, and the 3rd column has been computed with the fluxes from ECCO.

Fig. B1

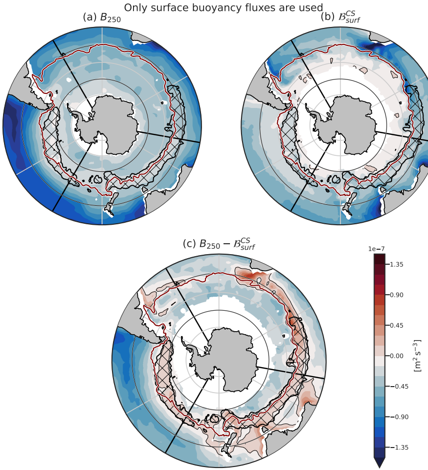


Climatology of the annual, Cooling Season, and Warming Season surface heat component of the buoyancy flux.



Balance between the columnar buoyancy and buoyancy loss using a depth of (a) 200 and (b) 350 m as threshold for the DMB (hatched area) and columnar buoyancy (B_{200} and B_{350}, respectively).

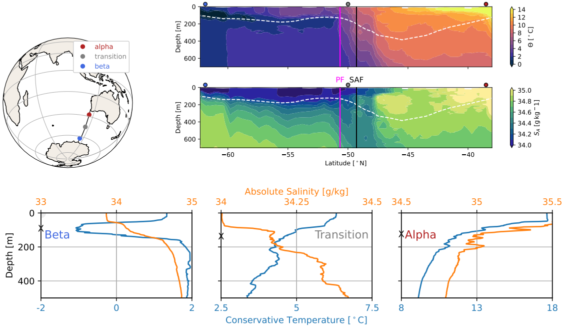
Using only surface buoyancy in balance



Climatology of (a) the intensity of late summer stratification characterised by B_{250}, (b) the *surface* buoyancy fluxes during the cooling season, and (c) the difference $B_{250} - \mathcal{B}^{CS}_{surf}$. The hatches surrounded by the black contour represent the DMB.

Paper III

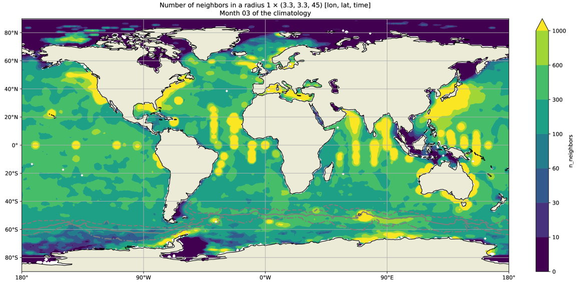
Fig. 1



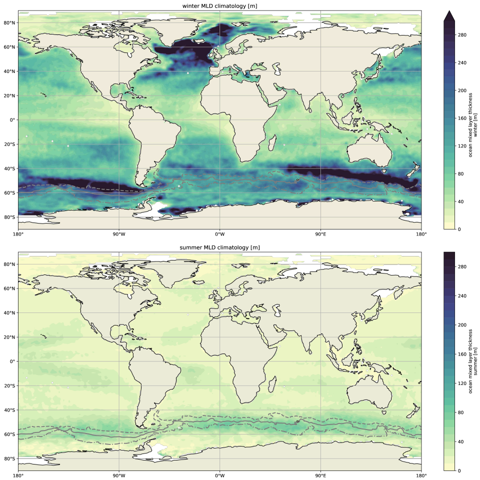
Data are from the hydrographic cruise 09AR20120105 (CCHDO Hydrographic Data Office, 2023). The vertical lines mark the boundaries of, from north to south, alpha ocean, transition zone, and beta ocean. These boundaries are determined by the Subantarctic Front (SAF, black line) and the Polar Front (PF, purple line). The white and dashed line represents the climatological winter mixed layer depth (from (de Boyer Montégut, 2023)). The three bottom panels correspond to the three dots of the upper panels. The black crosses on the left vertical axes represent the climatological winter mixed layer depth.

Paper III

Fig. 2



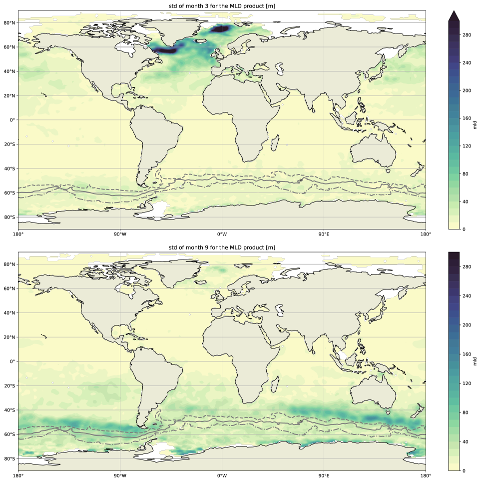
Number of profiles in a circle of distance 1 of each grid point for the month March. All years are taken into account. The distance is unitless.



Climatologies of winter (deepest) and summer (shallowest) MLD. In the SO, the 3 gray lines represent from north to south the SAF, the PF, and the SACCF.

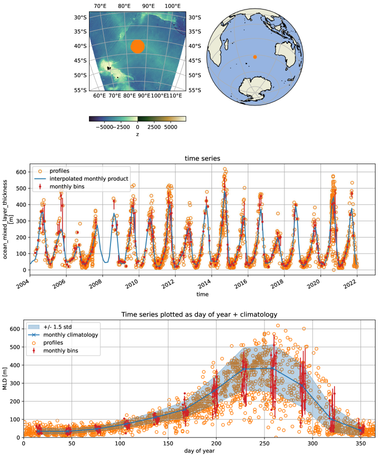
Paper III

Fig. 4



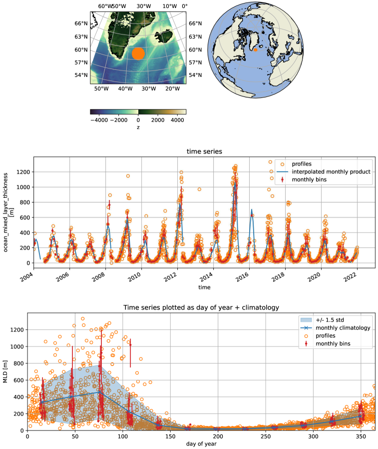
Standard deviation of monthly MLD for 2004–2021 period in March and September.

Fig. 5



Time series of the MLD north of the Kerguelen Plateau, in the deep mixing band of the SO. The bathymetry and location of the profiles are shown in the upper row, the middle row presents the time series of the profiles MLD, the median and quartiles of monthly binned profiles, and our monthly interpolated product. The ticks and vertical lines are plotted the 1st of January of the years. The bottom row present our monthly climatology. All profiles in a distance 1 of the point (85.5E, 42.5S) are used.

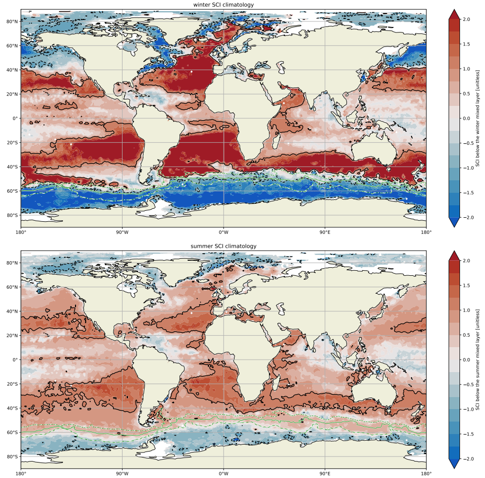
Fig. 6



Time series of the MLD in the Irminger Sea. The bathymetry and location of the profiles are shown in the upper row, the middle row presents the time series of the profiles MLD, the median and quartiles of monthly binned profiles, and our monthly interpolated product. The ticks and vertical lines are plotted the 1st of January of the years. The bottom row present our monthly climatology. All profiles in a distance 1 of the point (325.5E, 61.5) are used.

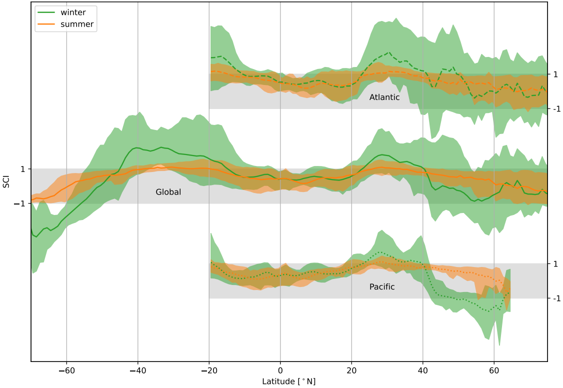
Paper III

Fig. 7



Climatologies of winter (deepest) and summer (shallowest) MLD. In the SO, the 3 gray lines represent from north to south the SAF, the PF, and the SACCF.

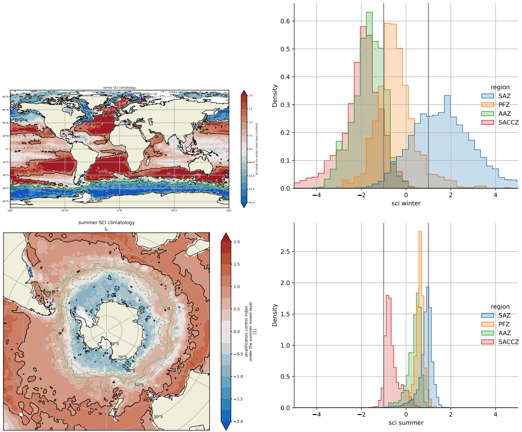
Fig. 8



Zonal climatology of winter (green) and summer (orange) SCI below the mixed layer. The lines are the zonal means, and the shadings are the 10th and 90th percentiles. The middle lines are the global zonal means. The upper and lower lines, starting at 20°S, separate the Pacific basin, where the SCI is approximately zonally constant, from the Atlantic basin, where the SCI encounters large longitudinal variations. The Atlantic and Pacific zonal means have been shifted vertically for clarity, and they refer to their own axis on the right. The gray bands represent $-1 < SCI < 1$.

Paper III

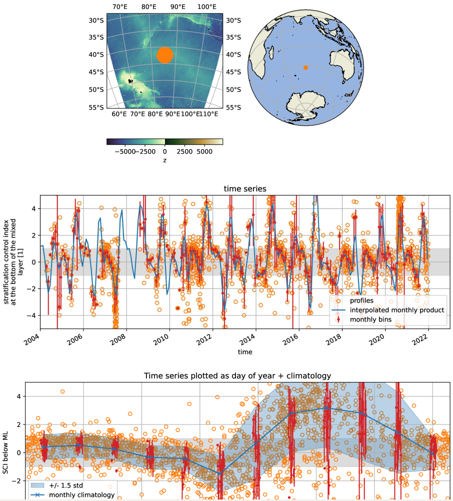
Fig. 9



Climatology of the winter / summer SCI (left column), and histograms of the SCI per zone of the SO (right column).

Paper III

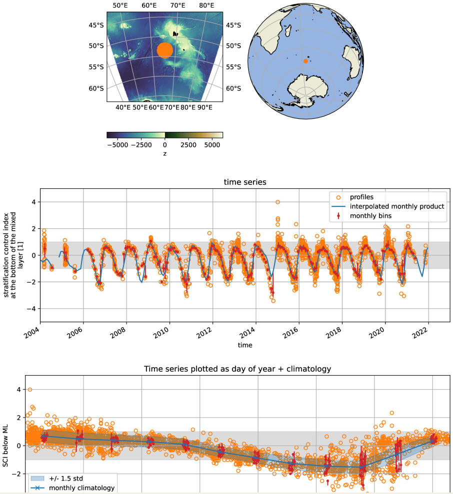
Fig. 10



Time series of the SCI in the DMB, north of the Kerguelen Plateau. The location in alpha ocean in winter.

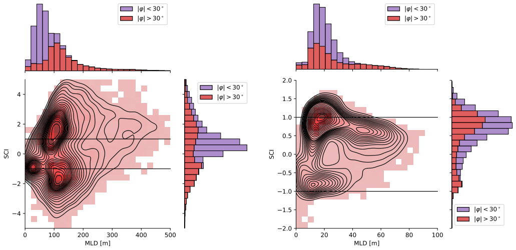
Paper III

Fig. 11



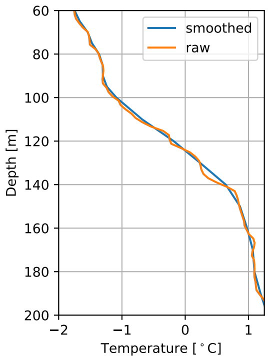
Time series of the SCI south-west of the Kerguelen Plateau. The location is in beta ocean in winter.

Fig. 12



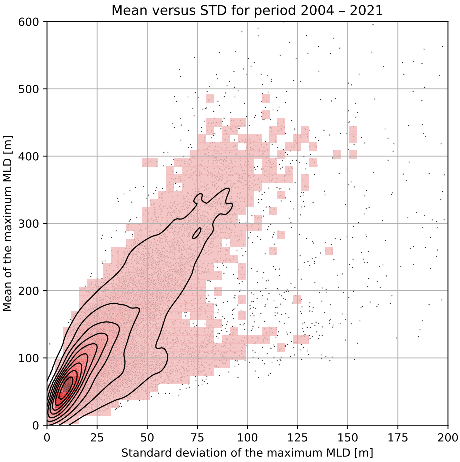
SCI versus MLD in winter (left) and summer (right). The centre figures represent a 2 dimensions histogram (colours), with a kernel density estimation (contour lines) superimposed. For the centre figures, only data with a latitude $|\varphi| > 30^\circ$ are shown. The histograms on the sides are split into the tropical regions ($|\varphi| < 30^\circ$) in purple, and the rest of the ocean ($|\varphi| > 30^\circ$) in red. The upper histograms are for the MLD, and the histograms on the right are for the SCI. Data are taken from the 1° climatologies. Each data point is weighted by the area of its corresponding cell of the 1° grid.

Fig. A1



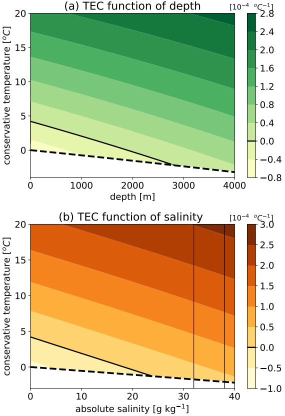
Comparison of raw and smoothed temperature profile.

Fig. B1



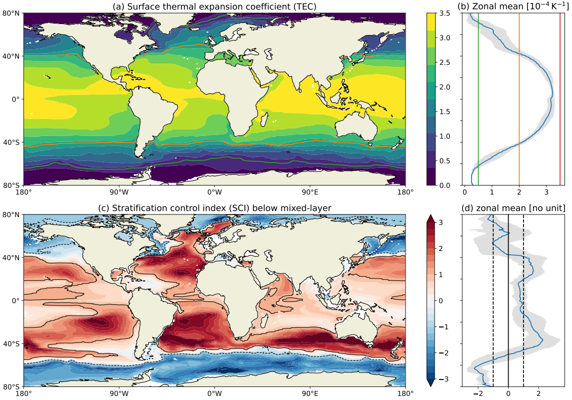
Mean of the MLD versus the standard deviation (for winter). The means are taken along years of the monthly product.

Fig. 1



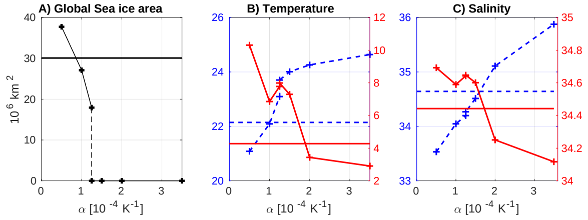
Variation of the Thermal Expansion coefficient (TEC) with respect to temperature, salinity and depth. (a) TEC function of temperature and depth for freshwater, i. e. at salinity S=0 g kg^{-1}. Here, depth is taken proportional to pressure (1 m $\simeq$ 1 dbar). (b) Variation of the TEC with respect to temperature and salinity at atmospheric pressure p=0 dbar. The typical salinity range of seawater is indicated with light solid contours. The TEC decreases quasi linearly with respect to temperature, pressure and salinity. In both panels, the dashed line indicates the freezing point, while the solid line indicates where the TEC changes sign.

Fig. 2



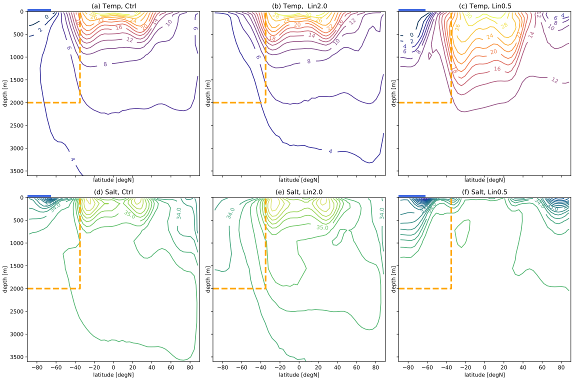
Stratification control and surface TEC in the ocean. (a) Surface distribution of the TEC, showing a striking correlation with sea surface temperature. (b) Zonal-mean TEC showing an order of magnitude of var. (c) Stratification control index (SCI, see core text for the definition). Blue: stratification dominated by salinity (beta regions), red: dominated by temperature (alpha regions). (d) Zonal-mean SCI. All figures are based on the ECCO state estimate, version 4, Release 4 (Forget et al., 2015). For each year, the SCI was computed on the layer found between 10 m and 30 m below the mixed layer for the month of deepest mixed layer. The SCI distribution is obtained by averaging over the 21 years available in ECCO.

Fig. 3



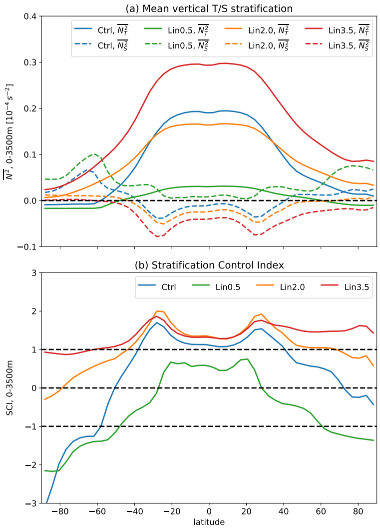
Climate model sensitivity to different prescribed TECs. (a) sea ice area, (b) sea surface temperature (0-40 m, blue) and bottom temperature (3000-4000 m, red) and c) sea surface salinity (blue) and bottom salinity (red). Bottom values are averaged over the lowest kilometer (3000-4000 m) while surface values are averaged over the top 40 m. The horizontal lines denote the corresponding values in **Ctrl**.

Fig. 4



Global modifications of the mean thermohaline stratification for different prescribed TECs. Zonally-averaged sections of temperature (top) and salinity (bottom): (a-d) **Ctrl**, (b-e) **Lin2.0**, and (c-f) **Lin0.5**. Dashed orange lines in upper left corner denote the zonally reentrant section above the seal and south of the continents. Blue squares indicate the sea ice extent.

Fig. 5



Relative contributions of temperature and salinity on the stratification controlled by the TEC. (a) Zonally-averaged haline (N_S^2) and thermal (N_Θ^2) buoyancy frequencies averaged from surface to bottom, shown for the control run and the three sensitivity experiments. (b) SCI computed using vertically and zonally averaged buoyancy frequencies. The mean SCI of **Ctrl** compares well with that of **Lin0.5** in polar regions, especially in the Southern ice-covered domain, but is closer to **Lin2.0** and **Lin3.5** in sub-tropical regions. These variations in SCI are consistent with changes in surface TEC in **Ctrl** related to sea surface temperature changes.