# **Formation** of deep **mixed layers** in the Southern Ocean is shaped by the **competition** between **buoyancy flux components** and **stratification resistance**.

Investigating surface buoyancy flux and Ekman transport influence on the Southern Ocean's upper ocean pycnocline


**Romain Caneill**[1], Fabien Roquet[1], Gurvan Madec[2], and Jonas Nycander[3]

[1] University of Gothenburg, Sweden
[2] LOCEAN-IPSL Sorbonne University, France
[3] Stockholm University, Sweden


## Context

The upper ocean stratification is impacted by the density change at the surface due to buoyancy fluxes. These fluxes are formed through the combined effect of heat and freshwater fluxes, scaled by the thermal expansion and haline coefficients. It is common that these 2 fluxes have an opposite sign, and thus enter in competition (*Schmitt et al.*, 1989). Another competitor in the upper ocean buoyancy budget is the Ekman horizontal water transport induced by wind stress.

In winter, large buoyancy loss (along with turbulent vertical mixing induced by wind stress) helps to create a deep mixing band in the Southern Ocean (SO). This band is located just north of the Antarctic Circumpolar Current and is present in the Indian and Pacific sectors of the SO.

The competition between heat and freshwater fluxes is unequal in the polar part of the SO. This is a result of the nonlinearities of the equation of state (EOS). The nonlinear effect of interest for the buoyancy fluxes is that the thermal expansion coefficient decreases in cold water (Figure 1). In the polar region, this makes heat fluxes and temperature negligible in setting respectively the buoyancy fluxes and stratification, which have important effects on the global ocean state (*Caneill et al.*, 2022; *Roquet et al.*, 2022).

## Objectives

1. Compare the role of the different components of the buoyancy fluxes
2. Enlighten the equally important role of the existing ocean stratification
3. Show that the position of deep mixed layers is directly linked to the nonlinear EOS

## Methods

### Climatology of buoyancy fluxes

We compute annual ($\overline{\mathcal{B}}$) and seasonal (Autumn-Winter $\overline{\mathcal{B}}^{AW}$, Spring-Summer $\overline{\mathcal{B}}^{SS}$) climatologies of the buoyancy fluxes, based on OAFLux, ISCCP, GPCP, CMEMS, and ARMOR3D.

$$\mathcal{B}^{atm} = \overbrace{\frac{g\alpha}{\rho_0 C_p}Q_{tot}}^{\mathcal{B}^{atm}_\Theta} \overbrace{-\frac{g\beta S}{\rho_0}(E-P)}^{\mathcal{B}^{atm}_S} \quad (1)$$

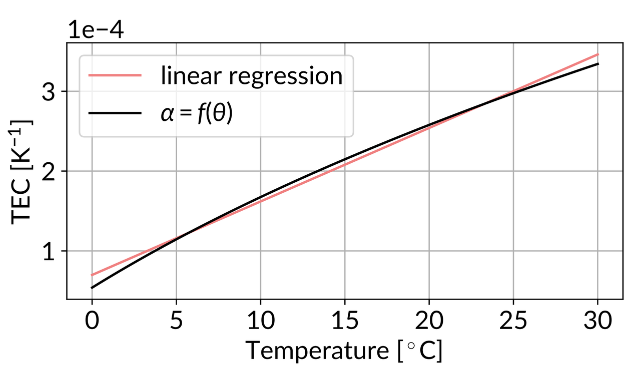
$$\mathcal{B}^{Ek} = \underbrace{-\frac{g\alpha}{\rho_0 f}\left(\tau^y\frac{\partial\Theta}{\partial x}-\tau^x\frac{\partial\Theta}{\partial y}\right)}_{\mathcal{B}^{Ek}_\Theta} \underbrace{+\frac{g\beta}{\rho_0 f}\left(\tau^y\frac{\partial S}{\partial x}-\tau^x\frac{\partial S}{\partial y}\right)}_{\mathcal{B}^{Ek}_S} \quad (2)$$

### Ocean stratification

Using MIMOC, we compute the buoyancy flux (loss) necessary to create a 250 m deep mixed layer:

$$B_{250} = \frac{1}{6\,\text{months}}\frac{-g}{\rho_0}\int_{-250}^{0}[\rho(-250)-\rho(z)]\mathrm{d}z \quad (3)$$

### Thermal expansion coefficient




$$\alpha = -\frac{1}{\rho_0}\frac{\partial\rho}{\partial\Theta}\bigg|_{S_{A,p}} \quad (4)$$

Figure 1. Evolution of $\alpha$ with temperature.

## Results

### 1. Compare the role of the different components of the buoyancy fluxes

Except close to the western boundary currents, no component is significantly prevailing (Figure 2). $\overline{\mathcal{B}^{atm}}$ is negative north of ACC, and in a narrow band close to the northern boundary of ACC. On opposite, $\overline{\mathcal{B}^{Ek}}$ is slightly destabilizing everywhere in the SO. The seasonal cycle is however almost only driven by $\mathcal{B}^{atm}_\Theta$ (Figures 3 and 4).

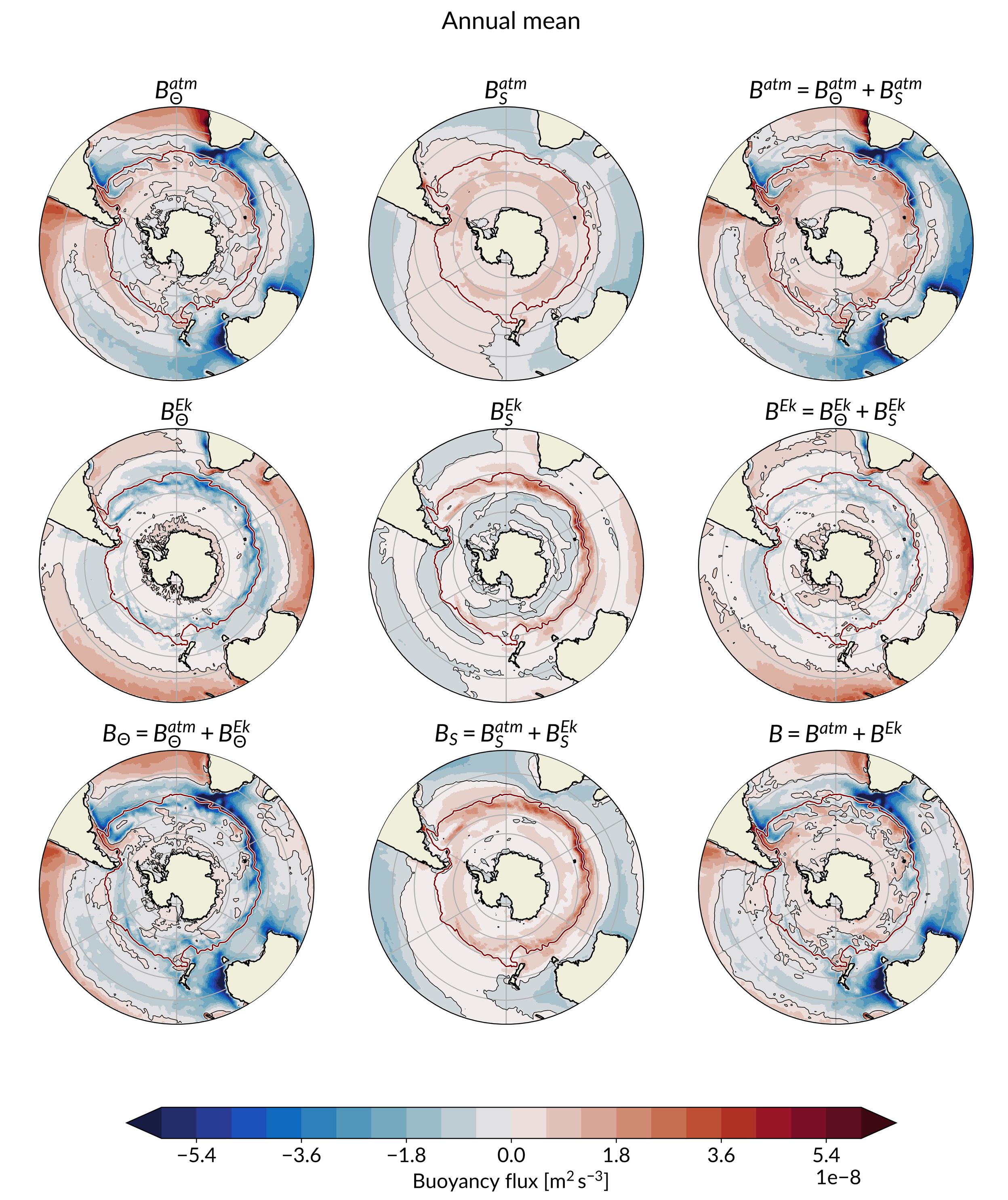



Figure 2. Annual mean of the buoyancy flux components. Maroon contour is northern boundary of ACC.

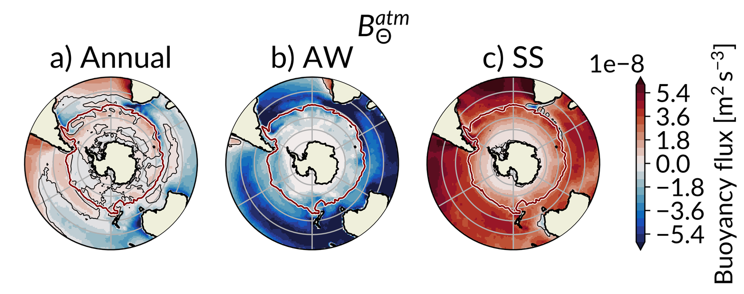



Figure 3. Seasonal variation of the atmosphere heat component.

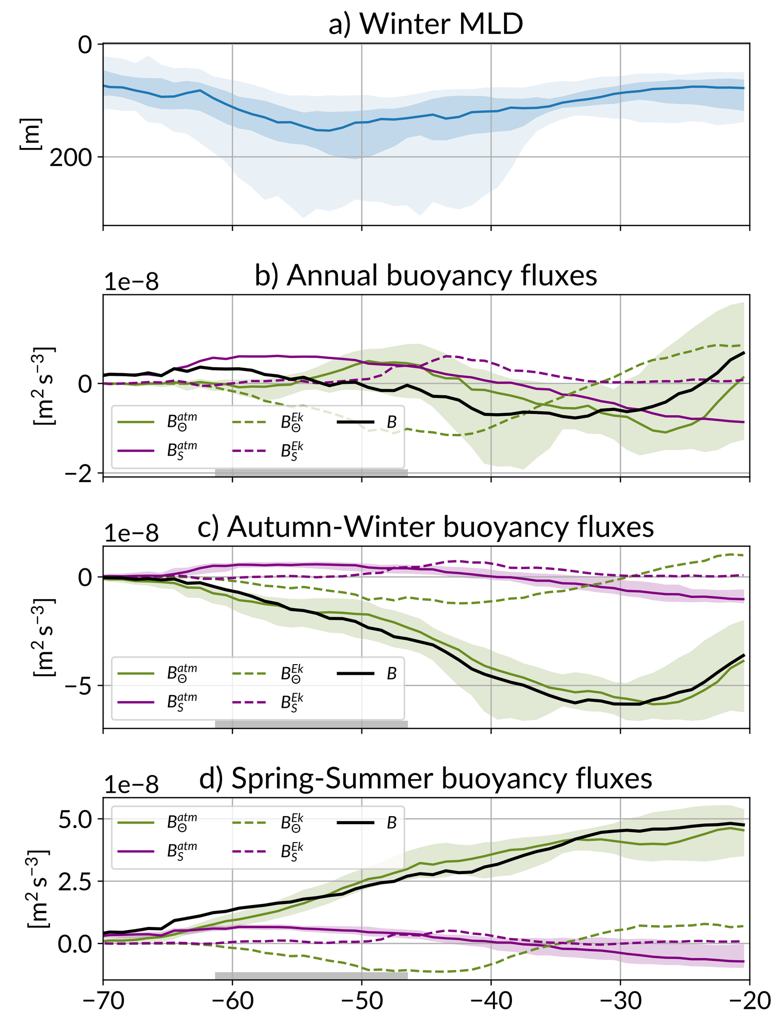



Figure 4. Zonal view of the MLD and the buoyancy fluxes components. Gray box represents the ACC.

### 2. Enlighten the equally important role of the existing ocean stratification

The region of largest winter buoyancy loss is found around $-30\,°$N, but is however located in a highly stratified region (Figure 5). It is only between $-45\,°$N and $-55\,°$N that the stratification becomes small enough that it can be eroded in winter (overlap between blue and orange shading).

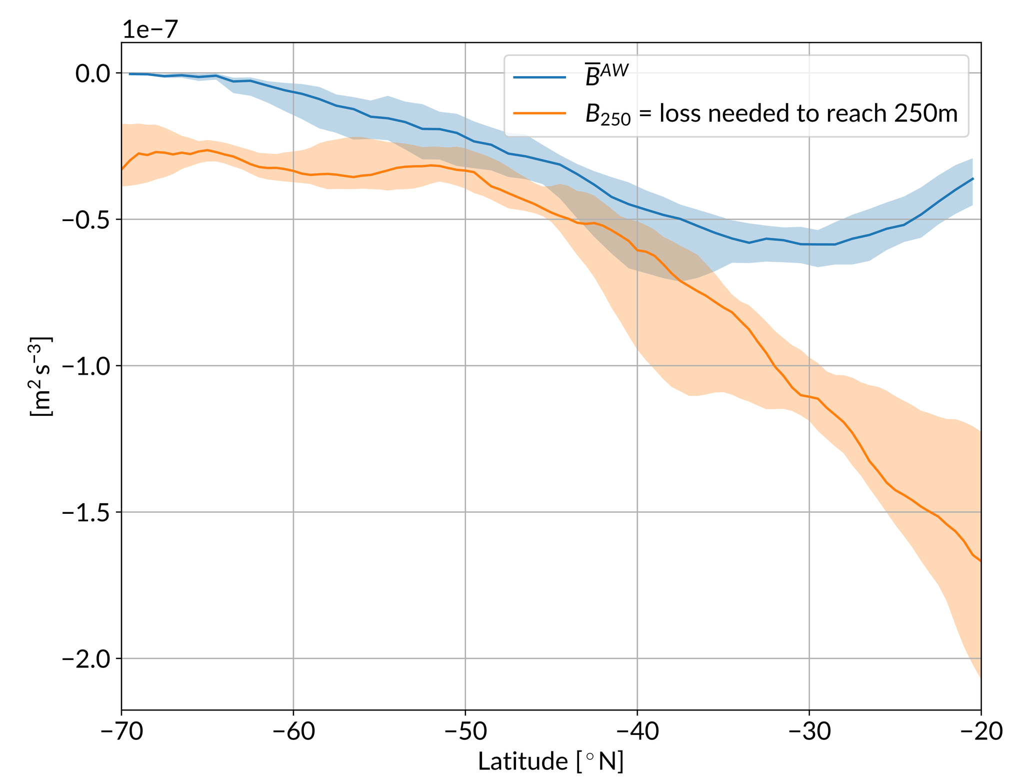



Figure 5. Autumn-Winter buoyancy loss (blue line) compared to stratification (orange line).

### 3. Show that the position of deep mixed layers is directly linked to the nonlinear EOS

Autumn-Winter buoyancy fluxes become very small south of the ACC, because of the decrease of $\alpha$ in cold water, and not because of a decrease of heat fluxes (Figures 1 and 6). If $\alpha$ were constant (green line), $\overline{\mathcal{B}}^{AW}$ would be 5 times larger, and could be sufficient to erode the stratification south of the ACC.

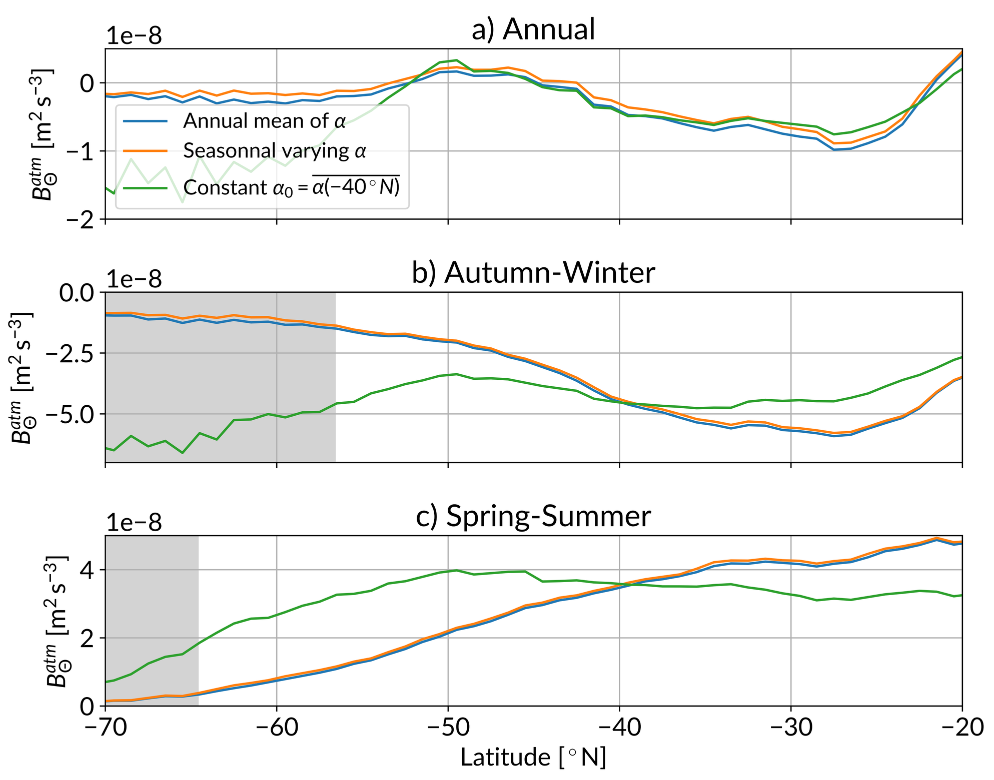



Figure 6. $\overline{\mathcal{B}^{atm}_\Theta}^{AW}$ with and without EOS nonlinearities.

## Conclusions

Formation of deep MLs in the Southern Ocean is shaped by two competitions. The first one between each component of the buoyancy fluxes. The second one, between the winter buoyancy loss and the existing stratification. The nonlinearities of the EOS make the heat fluxes become negligible south of the ACC, and thus prevails the deepening of the ML.

### References


Caneill, R., F. Roquet, G. Madec, and J. Nycander (2022), The Polar Transition from Alpha to Beta Regions Set by a Surface Buoyancy Flux Inversion, *Journal of Physical Oceanography*, *52*(8), 1887–1902, doi:10.1175/JPO-D-21-0295.1.

Roquet, F., D. Ferreira, R. Caneill, D. Schlesinger, and G. Madec (2022), Unique thermal expansion properties of water key to the formation of sea ice on Earth, *Science Advances*, *8*(46), doi:10.1126/sciadv.abq0793.

Schmitt, R. W., P. S. Bogden, and C. E. Dorman (1989), Evaporation Minus Precipitation and Density Fluxes for the North Atlantic, *Journal of Physical Oceanography*, *19*(9), 1208–1221, doi:10.1175/1520-0485(1989)019<1208:EMPADF>2.0.CO;2.