Long-term temperature trends in Antarctic water masses across the New Zealand–Antarctica chokepoint

A.I. Ferola[1], Y. Cotroneo[1], G. Budillon[1], P. Castagno[2], P. Falco[3], G. Fusco[1], E. Zambianchi[1] and G. Aulicino[1]

[1]*University of Napoli Parthenope, Naples, Italy;* [2]*University of Messina, Messina, Italy;* [3]*Marche Polytechnic University, Ancona, Italy*

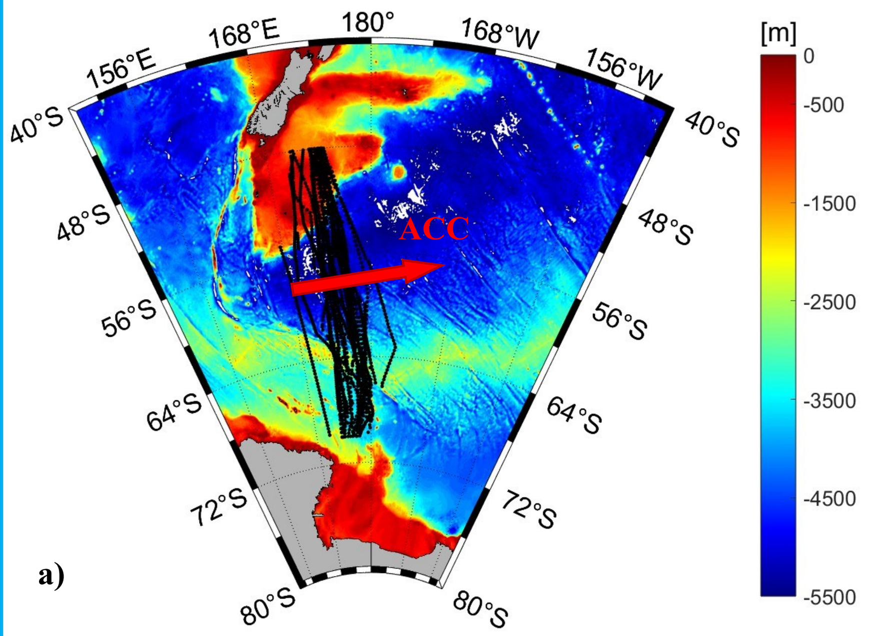
This presentation participates in OSPP

EGU

Outstanding Student & PhD candidate Presentation contest

Here we use a 29-year time series of summer Expendable Bathythermographs data collected along the New Zealand-Antarctica 'chokepoint' of the Antarctic Circumpolar Current to analyse the temperature variability of the surface and intermediate layers of the Southern Ocean from 1994 to 2023. Results unveil significant warming in the northern Antarctic Circumpolar Current flank of the Southern Ocean, while areas south of the Polar Front experience no significant temperature trends. Moreover, we investigate the temperature trends within the primary water masses that characterize the Antarctic Circumpolar Current, providing more details of the warming portrait of the Southern Ocean section under study. Results point out strong warming trends of approximately 0.18°C/decade and 0.15°C/decade over the study period, respectively for Sub Antarctic Mode Water and Antarctic Intermediate Water. These trends are significantly determined by the rise in temperatures observed in the last decade. Conversely, Antarctic Surface Water and Circumpolar Deep Water show negligible and/or not significant trends.

Data Spatial Distribution and Preliminary Analysis



Based on the XBT data collected during the analysed 30 repeated surveys across the New Zealand – Antarctica PX36 transect (Fig. 1.a), we provide in Figure 1.b a summer temperature climatological mean vertical section over the last three decades and identify the location of the main ACC fronts (i.e., from north to south: Northern Subantarctic Front - NSAF, Southern Subantarctic Front - SSAF, Polar Front - PF, Southern Antarctic Circumpolar Front - sACCf). Additionally, we delineate the climatological areas of residence along this section of the Southern Ocean (SO) for the main water masses constituting the ACC ,i.e. Sub Antarctic Mode Water (SAMW), Antarctic Intermediate Water (AAIW), Antarctic Surface Water (AASW), and Circumpolar Deep Water (CDW). Furthermore, to evaluate the reliability of our dataset, we also analysed the temperature standard deviation along SO's study section (Fig 1.c). The standard deviation is higher near ACC fronts, due to their position variability over time, and reaches its maximum values in the proximity of the NSAF. This result may be associated with several factors. Firstly, the NSAF is the northernmost front of the ACC and the most unstable one. Eddies may also influence the NSAF position. In addition, the detected northern limit of the NSAF may depend on the ship track.

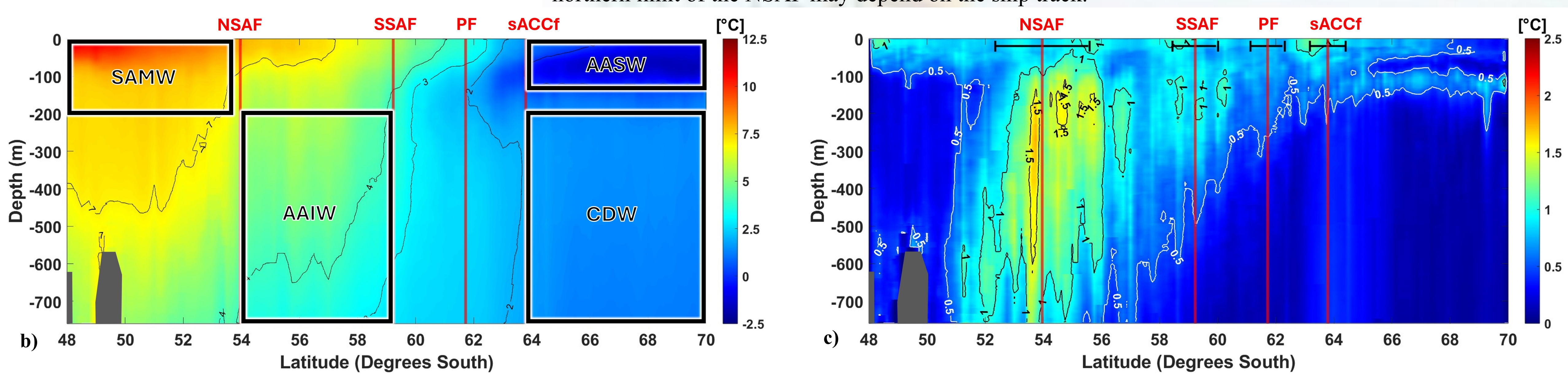
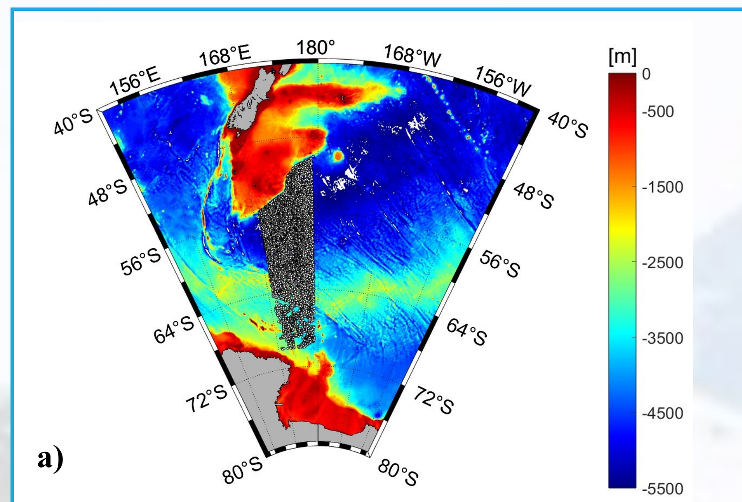
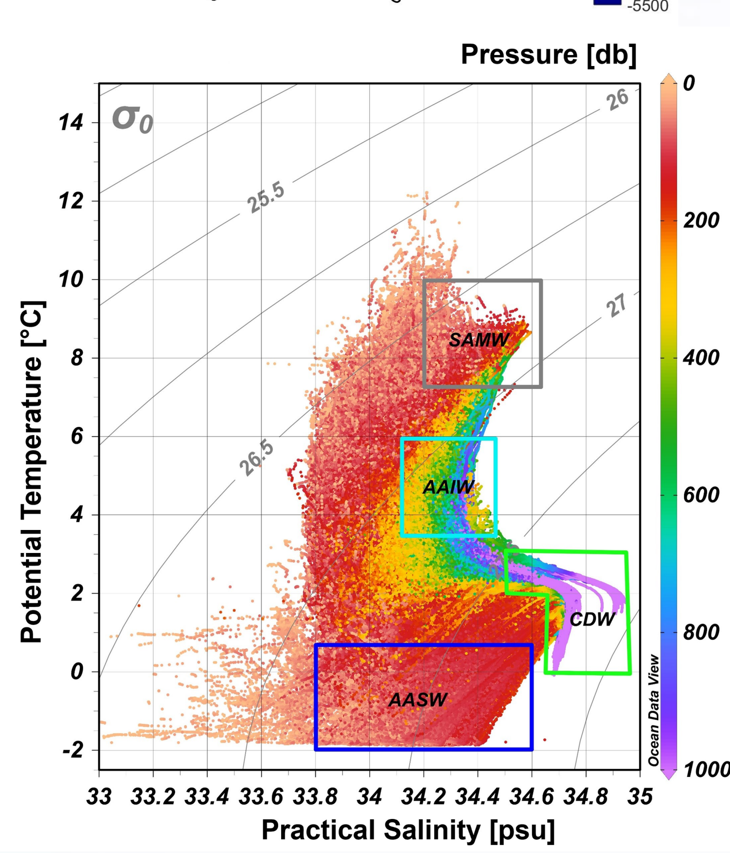


Figure 1. a) Map of the Southern Ocean area between New Zealand and Antarctica. The black dots represent the position of XBT casts used in this paper carried out between December 1994 and January 2023. b) Temperature vertical section along the New Zealand–Antarctica PX36 monitoring line. The represented black boxes identify water masses' climatological areas of residence. Missing data (e.g., due to bathymetry) are concealed using a dark grey mask.(this applies to all subsequent images as well). c) Temperature standard deviation vertical section along the New Zealand–Antarctica PX36 monitoring line. Vertical red lines identify the average ACC front positions, while the horizontal bars represent their standard deviation.

Water Masses Identification





To identify the regions characterized by the presence of the primary water masses of the analysed study area, we used the observations collected from the ARGO floats that circulated within the specific area defined by the latitude and longitude limits of the XBT oceanographic cruises (Fig. 2.a) and the World Ocean Atlas (WOA) information provided by the National Centers for Environmental Information (NCEI). Firstly, we used ARGO data to retrieve the characteristic values of temperature, salinity and density associated with these water masses in the specific study area (Fig. 2.b). To this goal, we referred to the general core values reported in literature for the SO. Then, we applied the new temperature and salinity core values obtained with the aid of ARGO data to the WOA average temperature, salinity and density sections for the period 2005-2017 (Fig. 2.c, d, e).

This allowed us to identify the latitude and depth ranges of the WOA sections within which the presence of SAMW, AAIW, AASW and CDW is found. These intervals of latitude and depth represent the **Climatological Areas of Residence** of the water masses along the PX36 transect.

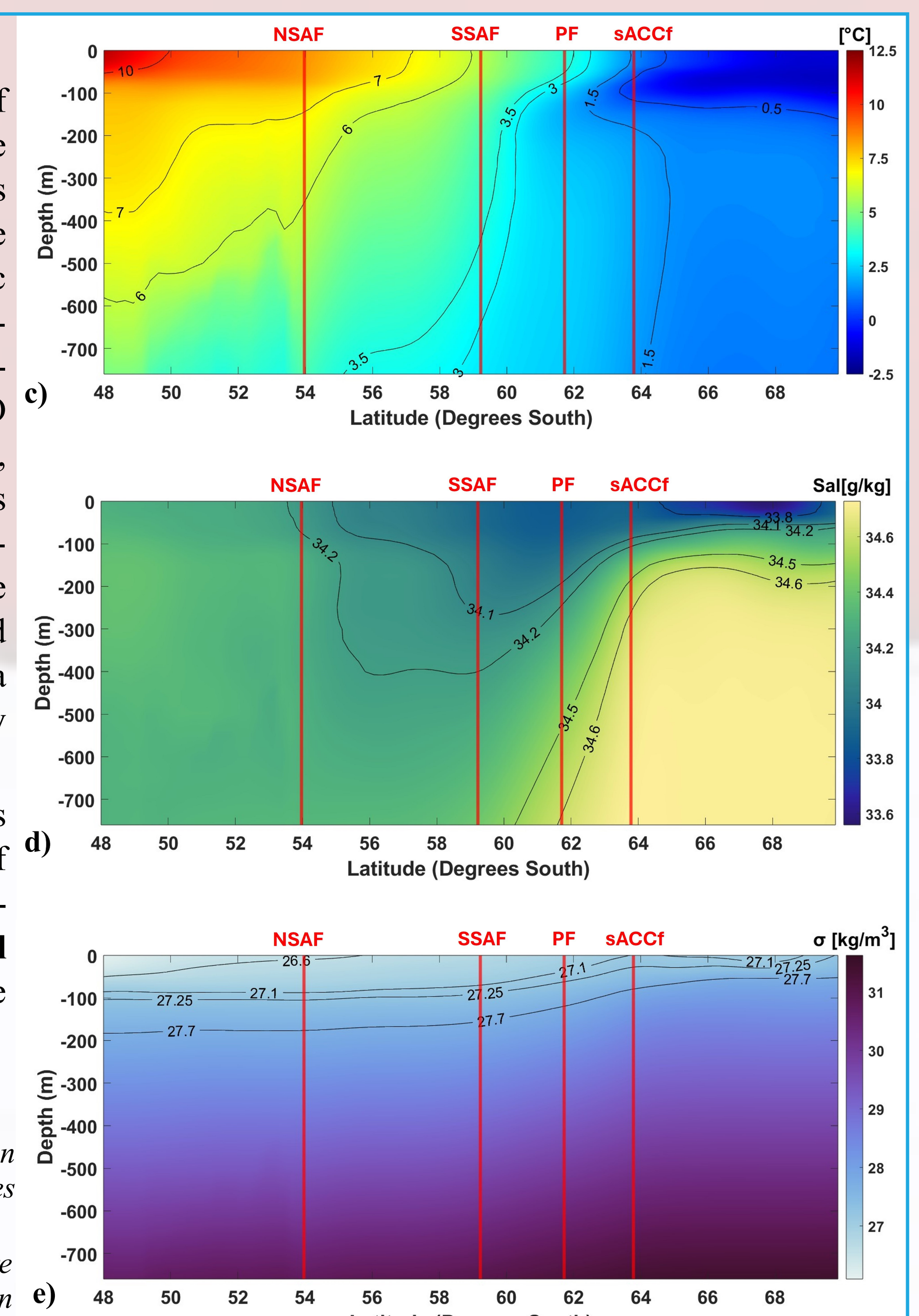


***Figure 2.** a) Bathymetry map of the Southern Ocean between New Zealand and Antarctica. The white dots with black edges represent all Argo data collection's position between 2004 and 2023. **b)** Potential temperature - salinity graph of the Argo data. The boxes of different colours identify the temperature and salinity core values of the SAMW, AAIW, AASW and CDW. **c)** Temperature, **d)** salinity and **e)** density vertical section along the New Zealand-Antarctica PX 36 monitoring line, based on the WOA dataset 2005-2017. The red vertical lines represent the average main ACC's front position between 1994 and 2023.*

Temperature Variability along the PX36 Transect between 1994 and 2023

The temperature variability along the PX36 transect over the past three decades is described in Figure 3 where a section of the SO temperature trend is presented. These results provide new insights about the different warming of the primary ACC water masses and confirm warming rates reported in previous studies.

The larger temperature trends are associated with areas of positive (temperature increase) variations in the northernmost sector of the section, with a maximum value of 0.8°C per decade. Conversely, the southern part of the section exhibits greater interannual variability and is indeed characterized by much weaker temperature trends, ranging between 0.2 and -0.2°C per decade. We also identify the areas in which the trend is negligible compared to the interannual variability (crossed out with black dashed lines inclined up to the right in Figure 3). The signal of interannual variability often prevails in the southernmost areas and, close to the NSAF, where lower temperature trends are identified. This is explained by the large standard deviation across the NSAF, the outermost front of the ACC, as reported in Figure 1.c. Nevertheless, the positive trend values found between 48°S and the SSAF are statistically significant, supporting the observed oceanic temperature increase in the northernmost

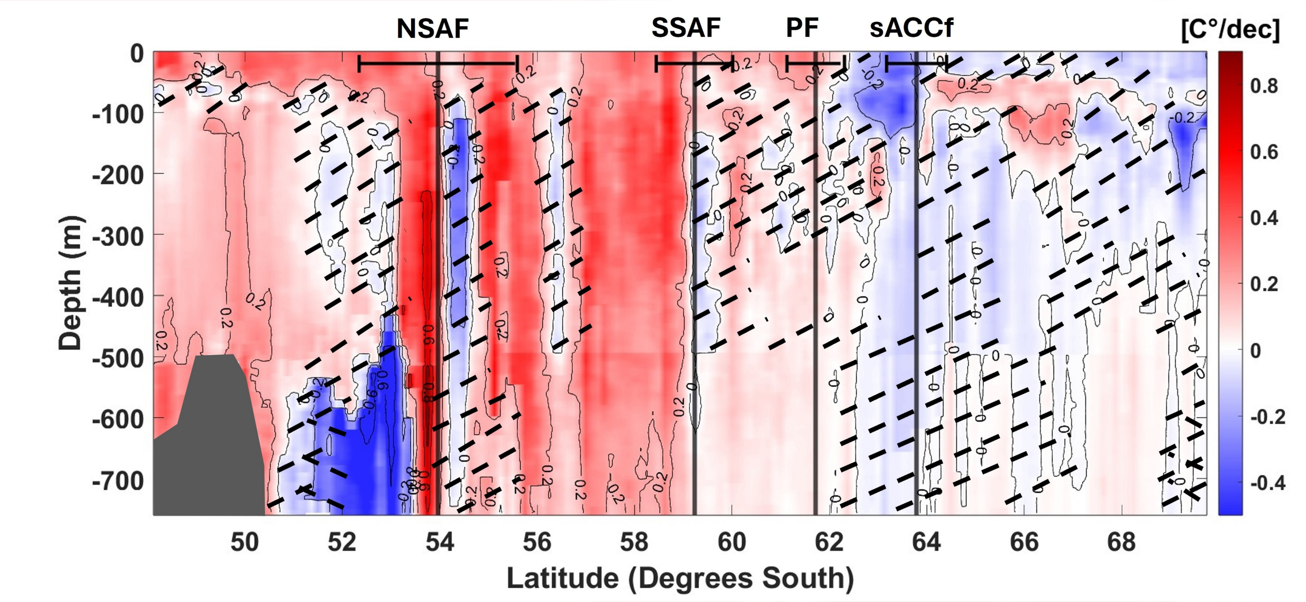
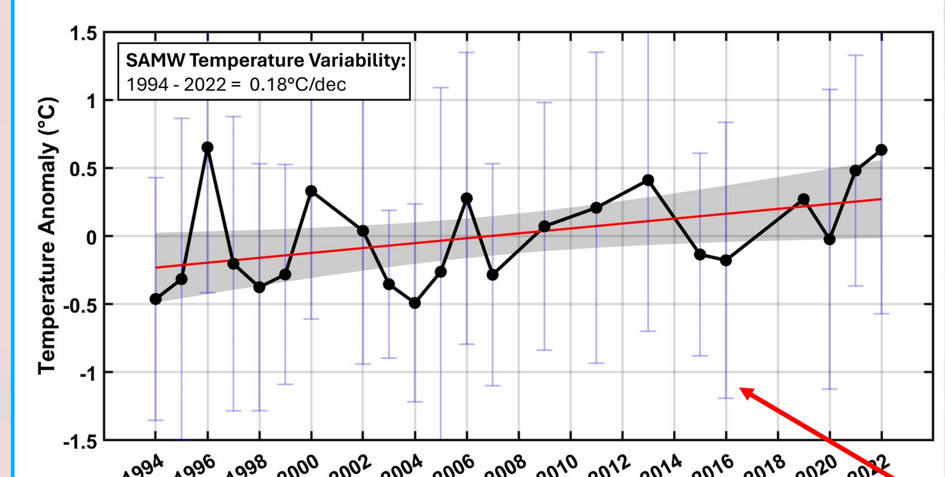


Figure 3. Vertical section of the temperature variability measured through XBT casts (expressed in Celsius degrees per decade) along the New Zealand-Antarctica transect. Vertical black lines identify the average ACC front positions, while the horizontal bars represent their standard deviation. The dashed black lines rising to the right indicate regions where the trends have lower significance compared to the water mass interannual variability. Conversely, the dashed black lines rising to the left indicate areas where the trends have low reliability due to a short temporal series of data (e.g., due to bathymetry features).

Water Masses Temperature Variability between 1994 and 2022 Austral Summers

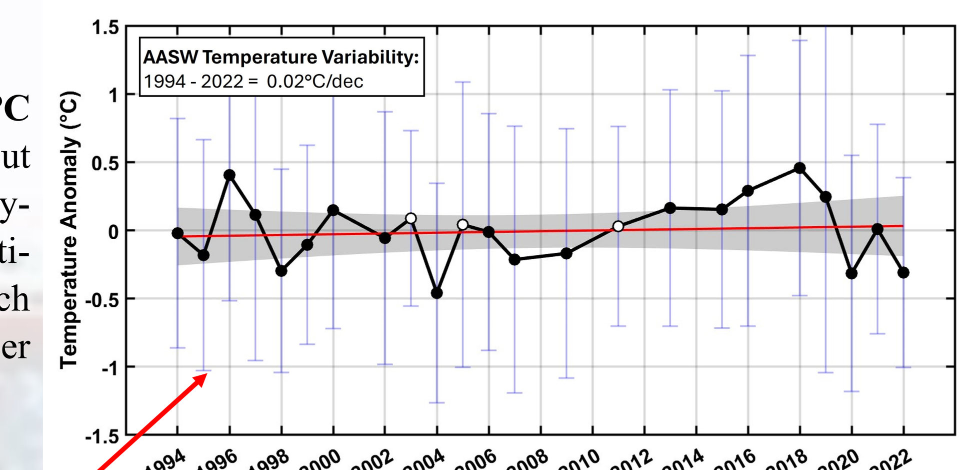
Finally, to gain more insights into the observed temperature changes, we also analysed individually the temperature variability associated with the main water masses identified in the study area and we examined how each one evolves. Thus, we estimated the temperature trend during the study period from November 1994 to January 2023 for each water mass (Fig. 4). The results clearly demonstrate that the northern water masses experienced significant warming over time, whilst the opposite is revealed for the southerly ones.

Although less statistically significant in some cases, we also explored the decadal temperature variability trend for the identified water masses, revealing a different behaviour during the three decades 1994-2003, 2004-2013 and 2014-2023.



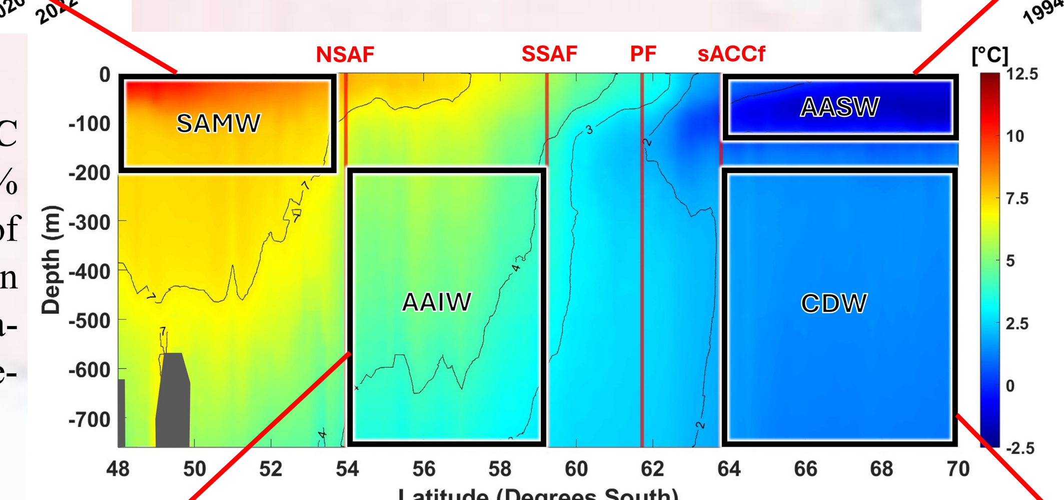
SAMW

The SAMW shows a warming trend of **0.18°C per decade** with a significance level of about 99% (p value = 0.01). Furthermore, when analyzing the data over three decades, it shows a positive trend during each of the three decades, which progressively increases from 0.08 to 0.88 °C per decade (p value = 0.05).



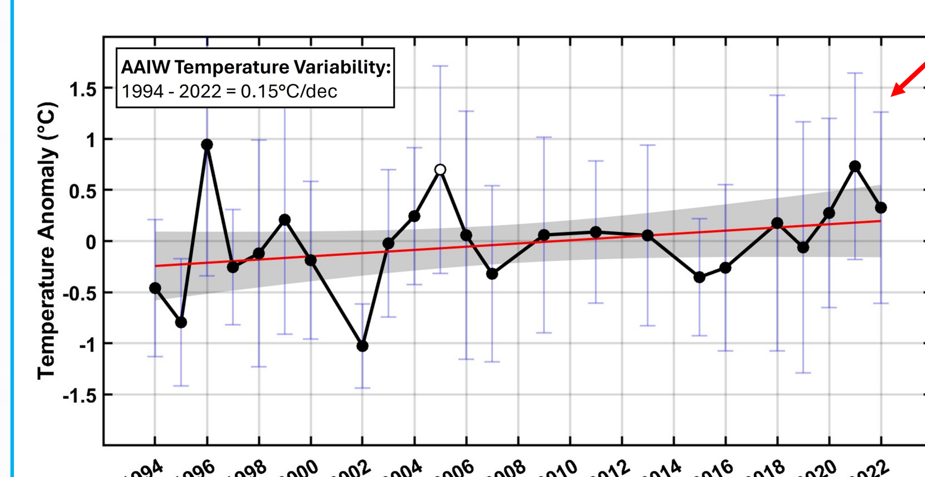
AAIW

The AAIW demonstrates a warming trend of **0.15°C per decade** with a significance level of about 95% (p value = 0.04).Surprisingly, after twenty years of relative temperature stability, AAIW presents an even more intense trend of 2.27 °C per decade (p value = 0.05) during the last decade, which considerably impact on the overall trend.



AASW

The AASW exhibit negligible trends in temperature. The absence of an evident 30-year trend for the AASW is indeed due to a stable behaviour between 1994 and 2003, followed by a positive trend during the 2004-2013 period and an opposite, similar in magnitude, negative trend during the most recent decade.



CDW

The CDW presents a general absence of any clear tendency even when considering the trend analysis conducted separately for each decade. As known the CDW is an "old" water mass that exhibits greater stability and persists for longer periods. This makes the CDW the most stable water mass in our study.

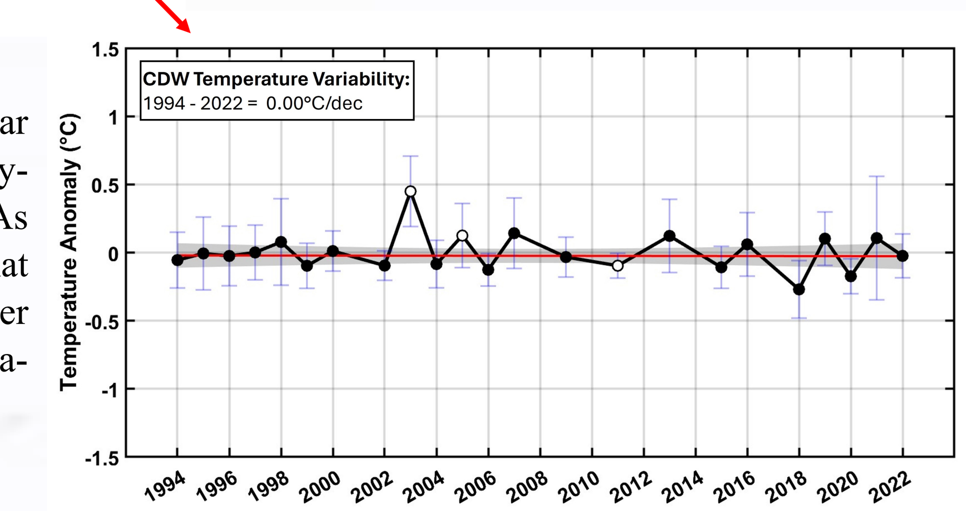


***Figure 4.** Mean temperature anomaly for the SAMW, AAIW, AASW and CDW between 1994/1995 and 2022/2023 austral summers. The solid red line corresponds to the linear temperature trend over the study period, expressed in degrees Celsius per decade. The grey shaded area shows the 95% confidence interval of the trend. The blue vertical lines are the standard deviations of the average temperature values obtained for each austral summer. The hollow black dots indicate water mass temperature values that are not significant and, consequently, not considered for the trend calculation.*