Southern Ocean in-situ temperature trends over 25 years emerge from interannual variability

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Article

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Abstract

Despite playing a major role for the global ocean heat storage, the Southern Ocean remains the most sparsely measured region of the global ocean. Here, a unique 25-year temperature time-series of the upper 800 m, repeated several times a year across the Southern Ocean, allows us to document the long-term change within water-masses and how it compares to the interannual variability. Three regions stand out as having strong change that is radically different from the interannual variability: warming of the subantarctic waters (0.29±0.09°C per decade); cooling of the near-surface subpolar waters (-0.07±0.04°C per decade); and warming of the subsurface subpolar deep waters (0.04±0.01°C per decade). Our results highlight that this subsurface warming of subpolar deep waters is, counter-intuitively, the largest change of the section regarding interannual variability. This robust warming is associated with a large shallowing (39±11 m per decade), which has been significantly underestimated by a factor of 3 to 10 in past studies. We find temperature changes of comparable magnitude to those reported in West Antarctica, which calls for a reconsideration of current ocean changes with important consequences for our understanding of future Antarctic ice-sheet mass loss.

Introduction

The Southern Ocean has been rapidly changing over the past decades with widespread consequences for the global climate. It has stored an outsized amount of heat associated with climate change that has been extracted from the atmosphere and stored in its subsurface water-masses1,2. The Southern Ocean alone has stored 35-43% of the global upper 2000 m ocean heat gain from 1970 to 2017, and an even greater proportion in recent years, with an estimate of 45-62% from 2005 to 20172. This heat storage, as well as concomitant change in its vertical stability due to change in surface salinity3-5, translated into significant warming of subsurface water-masses6. The overall water-mass warming since 1970 is composed of significant warming north of and within the eastward flowing Antarctic Circumpolar Current7-9 (ACC), contrasting with slight cooling of the surface subpolar waters10, and hints of slight warming and uplifting of the subpolar Upper Circumpolar Deep Waters that lie directly offshore the Antarctic continental shelf, threatening to invade onto the continental shelves with drastic potential consequences for the melt of Antarctic Ice Shelves and subsequent global sea level rise11.

Despite those emerging results, there are inherent limitations in our past and current observation system that pose a strong limitation in our confidence of any of these climate-scale changes that occurred in the Southern Ocean12,13. For most changes in the Southern Hemisphere, with the exception of changes in the atmospheric large-scale circulation, it remains unclear whether the natural and interannual variability can cause the observed change or overwhelms the forced response13. A recent study based on numerical simulations suggests that warming north of the Antarctic Circumpolar Current is largely human induced and overwhelms the natural variability14. But this remains one study using one single climate model, and our limited confidence in the representation of subpolar Southern Ocean processes in climate models drastically hampers our confidence at higher latitude2. Observations are needed, more than in any other
region, to shed more light on long-term ocean trends and understand how they compare to natural and interannual variability.

In this paper, we unlock these limitations by presenting an unprecedented observation dataset of the most frequently repeated and longest time-series of a temperature section across the Southern Ocean in the upper 800 m, from its northern boundary to Antarctica. The temperature section, referred to as Section IX28, is the longest of the three long-term high-resolution repeat upper ocean XBT temperature monitoring lines that have made observations of the seasonal heating cycle across the Southern Ocean. IX28 has been repeated several times a year since 1993 at 140°E, from Hobart, Tasmania to Antarctica (Fig. 1a), providing us with a unique 25-year temperature time-series to robustly estimate summer temperature changes consistently across an entire meridional section, and document for the first time from observations how temperature changes compare to typical interannual variability.

Results

25-year Climatological state and long-term change

Based on the 148 repeats of the same section, we construct a summer temperature climatological mean over the 25 years, which shows the main Southern Ocean water-masses and the fingerprints of the main fronts associated with the Antarctic Circumpolar Current (Fig. 1b; see Methods). The warmest water-masses on the section, the Subtropical Water (STW) and Subantarctic Mode Water (SAMW) are located in the northern part of the transects. Their southern extent is limited by the Subtropical Front (11°C at 150m) and the Subantarctic Front (strongest temperature gradient between 3-8°C at 300 m depth, respectively. SAMW is found down to 600 m depth, beneath the summer mixed layer, consistent with previous studies. Antarctic Surface Waters (AASW) are located in the upper 250 meters of the Southern Ocean and south of the Polar Front (most northern extent of the subsurface 2°C water). AASWs are composed of a remnant subsurface tongue of cold water produced in winter (Winter Water), and warmer surface waters produced in summer. Below the Winter Water tongue lies the Upper Circumpolar Deep Water (UCDW), slightly warmer and saltier water than Winter Water, that are advected at depth around the Southern Ocean, partly originating from the North Atlantic Deep Water.

We are interested in how this temperature structure is changing over time on a multi-decadal timescale. Over the past decades, the temperature has been warming overall across the section, but with a structure showing marked patterns, which are related to the different water-masses of the region. The largest warming reaching 0.4 to 0.8 °C per decade is observed on the northern end of the section, north and within the ACC (region A in Fig. 2b) in the subtropical waters and subantarctic Mode Waters. In contrast, on the southern end of the section, a significant cooling of 0.1 to 0.3°C per decade, extending from the surface to about 200 m is observed in the coolest water-mass of the region (region B in Fig. 2b). Hints of cooling trends are apparent in the surface layer further north, but the trends are not significant (lower than their standard error) north of ~61°S in the surface layer. At deeper depth, in the Upper Circumpolar Deep
Water layer (region C in Fig. 2b), subtle but significant (greater than their standard error) warming trends of around 0.05°C per decade are observed from -62.5°S to -52°S.

The temperature change structure shown across the section concurs well with past studies that have investigated long-term temperature trends in the Southern Ocean (ref 6, and references therein). Here, we however bring an important step forward in our understanding of past changes by showing for the first time that Southern Ocean water-mass temperature trends is robust over a 25-year period, relevant in a climate change context (i.e. beyond decadal timescales). But more importantly, we are able to estimate the typical interannual variability (referred to as noise) to better interpret the observed trends over a 25-year period (referred to as signal; see Methods). In other words, for the first time from observations in the Southern Ocean, we are able to estimate whether the signal of temperature change has emerged above the interannual variability noise. A latitude-vertical section of this trend signal-to-noise ratio is shown in Fig 2c. The three regions highlighted above with significant trends clearly stand out, experiencing temperature changes that emerge above the background interannual variability over the past 25 years. Counter-intuitively, it is in the Upper Circumpolar Deep Water layer, where the long-term change amplitude is the lowest of the section, that the signal-to-noise ratio is the largest because interannual variability is actually very weak. This clearly pinpoints that, while subtle, the observed temperature increase in the Upper Circumpolar Deep Water represents a radical deviation from its mean state. In other water-masses with a more recent surface connection, the 25-year trends are weaker compared to the typical interannual variability. A signal-to-noise ratio lower than one does not mean trends are insignificant, rather it remains unclear whether the measured long-term change reflects a robust change departing from its typical interannual variability. A robust long-term trend might be hidden behind a low signal-to-noise ratio, but one would have to accumulate more years of repeat observations to observe its emergence above the interannual noise.

**Water-mass temperature time-series and forcing**

We next compute time-series and associated trends, averaged over the three regions identified above where trends overcome both their standard error, and the typical interannual variability: in the subantarctic and subtropical region north of 52.5°S (region A); in the near-surface subpolar region, in the upper 200 m, south of 61°S (region B); and in the subsurface Upper Circumpolar Deep Water, deeper than 250 m, and between 62.5°S-55°S (region C).

When averaged over the entire Subantarctic and Subtropical Mode Water region (region A), the temperature has increased overall by 0.29±0.09 °C per decade, with a 25-year signal to noise ratio of 2.45, indicating a signal much greater than the estimated interannual noise (Fig 3a). Locally the trend can be as high as 0.8°C per decade (Fig. 2b), with the strongest warming organized in deep-reaching localized cells. Based on a shorter 13-yr time-series, ref 26 proposed that this warming was due to the southward movement of both the STF and the SAF, reflecting the consensus when the study was published that ACC fronts were shifting southward. After a decade of scientific debate, a new consensus emerges that on a circumpolar average, the SAF has been shown to be stable and not moving meridionally in the last
decades and that the warming might instead be due to increased heat uptake from the ocean surface. While the warming trend is relatively constant over the 25-year period, there are periods of distinct cooling, for example in 1996 and 2005, and stronger warming in 2001-2002 and in 2014-2016. Similar interannual variability is also evident in the sea-surface temperature fields, with a correlation of 0.64, and a slightly lower 25-yr trend of 0.15-0.09°C per decade, consistent with the trend distribution within the zone (Figure 2b). Part of the observed interannual variability might be due to intermittent incursions of subtropical waters carried by the Tasman Sea extension south of Tasmania, impacting the volume of STW, as well as local eddy activity around the SAF (See Supplementary Information S6).

The overall cooling in the surface subpolar waters close to Antarctica, from the surface to 200 m and from 66°S to 61°S (region B), is -0.07±0.04°C per decade, with a signal-to-noise ratio of 0.97 (Fig. 3b). The cooling appears mostly associated with the coolest waters in the regions (Fig 2b); when isolating only data points cooler than 0°C, the cooling is slightly more marked (-0.08±0.05°C per decade, signal-to-noise ratio of 1.08; Fig. 4a). This cooling of subpolar waters is also accompanied by a freshening of the surface waters over the same period, as well as an increase in sea-ice cover. Region B has a lower signal-to-noise, and the interannual variability in temperature, SSS and sea-ice is impacted by local coastal circulation changes and increased ice flow from 2011 onwards, following the Mertz Glacier calving just upstream. Such high-latitude cooling is also consistent with local sea surface cooling observed from satellite observations (Figure 2c, correlation r=0.80), and more generally with the surface cooling of a large part of the Southern Ocean that have been observed from observations in the subpolar waters over the past three decades. This cooling might be explained by the increased stratification associated with freshening of the surface layer which would tend to reduce mixing with the slightly warmer underlying Lower and Upper Circumpolar Deep Water. Locally, ref 5 found a link between the freshening of the subpolar waters near 140°E, the sea-ice cover and a large-scale northward shift of the zero- zonal wind position from 1999 onwards.

Interestingly the winter water tongue extending further north does not show a similar cooling. Small pockets of cooling exist but the WW trend signals are dominated by interannual variability (0.28 signal to noise ratio). When focusing only on the temperature of the core of the Winter Water layer, defined as the layer with temperature colder than 2°C between 55°S and 61.5°S, the large interannual variations overwhelm any long-term change, with peak-to peak temperature ranging from 0.40 to 0.65°C (Fig. 4b). These temperature variations within the Winter Water core are positively correlated (r=0.68) with the sea surface temperature of the previous winter further upstream in the subpolar Australian-Antarctic basin (120-145°E; 57-61°S) (Fig. 4b), where the Winter Waters were modified at the surface (See Supplementary Information S8).

The Upper Circumpolar Deep Water from 62.5°S to 55°S, and over 300-800m depth (region C exhibits a small overall warming trend of 0.04 ± 0.01 °C per decade, associated with a high signal to noise ratio of 3.27. Consistently, the time-series show relatively weak interannual variability, but a steady warming of the layer. The maximum temperature increase sits directly below the seasonally variable surface layer, in the upper and warmer part of the water-mass around 300-500 m (Fig 2b). When the temperature time-
series is computed in this core of temperature maximum, the warming trend is even greater, reaching 0.05±0.01°C per decade, with a signal to noise ratio of 4.09 (when excluding 2012 which appears as a clear warm outlier, the trend is slightly lower: 0.048°C per decade instead of 0.054°C per decade; we give the rounded value of 0.05±0.01°C per decade). Previous authors have suggested the warming of the Upper Circumpolar Deep Water might be driven by increased stratification at the base of the Winter Water layer due to freshening, which would reduce mixing between the two layers and heat removal from the Upper Circumpolar Deep Water to the atmosphere10,39,40. Since we have only temperature profiles, the role of the salinity stratification cannot be verified directly. However, in accordance with this hypothesis, we observe larger warming in the upper part of the layer, directly underlying a near-surface water mostly affected by interannual variability (Fig 4b) but with a few hints of local cooling (Fig 2b). In addition to the warming of Upper Circumpolar Deep Water, the depth of the core of maximum temperature is observed to shallow at a rate of 39±11 m per decade (Fig 4d, three to ten times higher than previously reported (5-10 m per decade11), and within the error envelope of the rate observed in West Antarctica (50±18 m per decade11). The shallowing of the layer, which has a strong trend signal emerging from the interannual variability noise (signal to noise ratio of 2.24), might be driven by large-scale atmospheric pattern changes, driving stronger upwelling favorable winds. Indeed, there is a small trend in negative wind stress curl (upwelling favorable) although the standard error around the trend is large (Figure S7). The cause of the CDW shallowing remains an open question, as a dedicated study investigating the mechanistic understanding of subsurface temperature depth change is still missing11.

Discussion

Our findings carry important implications for our understanding of Southern Ocean temperature change, a region of the world that remains poorly observed and understood, though with a pivotal role in global climate. Using a unique observation time-series repeated several-times per year over the past 25 years across the Southern Ocean, we document with unprecedented accuracy the temperature trend over the upper 800 m, and shed light on three main regions where the temperature change dominates over typical interannual variability. Interestingly, only one of these three regions have been shown to be associated with a human-induced forced signal that has already emerged over natural variability14, though recent work suggests that forced warming in the sub-surface subpolar ocean does emerge over natural variability by the end of the 20th century or early decade of the 21st 41. We note that these studies are based on climate models with significant limitations in their representation of the Southern Ocean2, hence it is important to provide robust observational targets for future improvement.

The repeat meridional temperature sections used in this study cross a Southern Ocean region of inter-ocean exchange, where waters from the Pacific can flow south of Tasmania into the Indian Ocean30,42. The northern part of the IX28 section exhibits strong interannual variations in the temperature data, impacted by ENSO/SAM climate modes and eddy movements across 140°E43. Despite this, our 25-year trend calculations have a strong signal-to-noise, with the upper ocean warming trend exceeding the interannual variations. The warming of 0.29±0.09
°C per decade north of the ACC is in accordance with previous studies7-9. Close to the Antarctic continent, during the austral summer heating cycle, our temperature profiles confirm that the widespread surface cooling around Antarctica observed with satellite SST data extends to around 200 m depth at 140°E.

One of the most important results of our study is the large warming and shallowing of the subsurface temperature maximum in the subpolar Southern Ocean, in the Upper Circumpolar Deep Water. This water-mass sits directly below the surface layer and mostly flows eastward, feeding the Pacific basin, where major increase of basal melt have long been identified further downstream in the Amundsen-Bellingshaussen sector44. In addition we note that some of the water-masses at the southern end of the section, though probably south of the maximum Upper Circumpolar Deep Water warming we observe, might be part of a cyclonic Australian- Antarctic gyre45, with direct influence on the Wilkes basins that has recently been shown to be associated with important mass loss of many glaciers of this region44,46-48. Our 25-year study confirms two major threats (significant warming and shallowing of Upper Circumpolar Deep Water) that may enhance the ice-shelf melting downstream, with potential dramatic impacts for future global sea-level. Both of these changes that we observed at 140°E have been substantially underestimated in this part of the Southern Ocean until now and must imperatively be taken into account in future ice-sheet modeling predictions49, and more generally when developing future climate change narratives. Our observational study provides a basis for validating such models, and contributing toward these developments.

**Methods**

**SURVOSTRAL Program**

The dataset of temperature used in this study consists of 25 years (November 1992 to February 2017) of XBT profiles on a section from Hobart (Tasmania, 42.9°S, 147.3°E) to Dumont d'Urville (Adelie Land, 66.6°S, 140.0°E), as part of the SURVOSTRAL project (Figure 1a, [https://doi.org/10.18142/172](https://doi.org/10.18142/172)). Measurements are taken from the French Antarctic resupply vessel *L’Astrolabe*, with about six transects per year between late October and early March. Depending on ice and weather conditions, XBT measurements are sampled every 35km, with 18km sampling across the energetic polar frontal region. Temperature profiles extend down to 900 meters depth with a vertical resolution of about 0.7 meters. The XBT temperature profile accuracy is +0.1°C. XBT profiles over the entire series have been corrected for temperature and depth biases depending on the probe type, following refs 50,51. Corrected XBT measurements are available here: [http://thredds.aodn.org.au/thredds/catalog/IMOS/SOOP/SOOP-XBT/DELAYED/Line_IX28_Dumont-d-Urville-Hobart/catalog.html](http://thredds.aodn.org.au/thredds/catalog/IMOS/SOOP/SOOP-XBT/DELAYED/Line_IX28_Dumont-d-Urville-Hobart/catalog.html).

**Gridding process**

In order to compute anomalies and trends, 10238 XBT profiles are interpolated onto a regular line from North to South, following the mean path of the Astrolabe's transect, with 0.5° resolution in latitude (increasing to 0.25° in the polar frontal zone from 49-54°S), with 2 m depth resolution down to 800 m
depth. XBT profiles sampled further than 3° in longitude from the mean path of the Astrolabe are removed from the analysis. In the following sections, we will discuss three types of products on this regular grid.

Climatological monthly mean temperature sections are calculated for each month during the austral summer ONDJFM period and averaged over 25 Since the sections are not evenly distributed within a given month, each monthly temperature section is assigned to the median sampling day of all profiles in the month. These values are then linearly interpolated onto daily values before calculating temperature anomalies.

Temperature anomaly profiles are constructed by subtracting the corresponding climatological daily value at each latitude and depth from each measurement. These anomalies allow us to construct a gridded section of interannual temperature anomalies and the temperature anomaly trends for the 25-year observation

Annual austral summer (NDJF) mean temperature sections are constructed for each year from 1993 to 2017 (Figure S4). This product is only used in this study to locate the CDW temperature maximum. The data distribution and the main data processing techniques for these three products are provided in the supplementary materials. The monthly mean temperature sections from October to March (Figure S2 in supplementary materials) calculated from the 25-year time series are quite similar to those calculated by ref 23 based on only 8-years of SURVOSTRAL data. This highlights that the seasonal warming cycle is quite stable in this region on a long-term average. The water-masses with the strongest seasonal changes are at the surface: the Antarctic Surface Waters (AASW) south of the Polar Front show the largest monthly mean variations over the summer warming cycle with coolest waters observed in sampled months closest to winter, late Oct-Nov. In the north of the section, there is a seasonal southward and deepening expansion of Subtropical waters throughout the summer season.

**Trend section and zone trends**

The temperature trend latitude-depth section is constructed by computing a linear trend using the anomalies available at each grid point. Each profile is associated with a latitude in the grid and is interpolated onto the depth grid. No interpolation was made in latitude to avoid interpolation of anomalies over large data gaps (eg during storms). The yearly anomalies are weighted by 1/std of all of the anomalies obtained during the corresponding season. The number of measurements used to compute the 25-year trends for each grid point is represented on Figure S9. Surface trends are consistent with SST Reynolds52 product trends on summer NDJF periods (Figure 2a., r = 0.70). Trends averaged over zones [A], [B] and [C] are computed in the same way, but all anomalies available in each zone are averaged for each season.

CDW maximum temperature values and their depths are computed by selecting the warmest 10% temperature grid points on each austral summer temperature section within zone [C]. The mean depth of these selected grid points is then the depth of maximum CDW temperature, and the mean anomalies of
these selected grid points gives the evolution of the temperature maximum. CDW maximum temperature value and depth trend is computed only on the years when there is at least 2 out of 4 months with measurements on average for the summer NDJF mean for all the subset grid points. Missing data in 1993 occurs since data is available in less than 10% of the grid subset.

**Signal to noise ratio**

The amplitude of the trend compared to the strength of the interannual variability is evaluated for each zone and grid point, by computing the signal to noise ratio. Our signal is the temperature evolution following the linear trend over the 25 years, and our noise is the standard deviation of the error between the trend and the measured temperature:

If $T$ is the temperature evolution throughout the $ny = 25$ years, and $ax + b$ its linear regression, the signal to noise ratio $S$ is computed as:

$$ S = \frac{ny \cdot a}{STD(ax - T)} $$

$S$ represents the ratio between the trend and the interannual signal: if $S > 1$, the trend signal is dominant compared to the interannual variation.

**External data**

We use NOAA monthly optimum interpolation (OI) satellite and in-situ52 to verify the consistency of our XBT observations to surface changes in temperature. ECMWF ERA5 monthly surface turbulent wind stress product is used to investigate the effect of the wind on the temperature trends and variations (DOI: 10.24381/cds.f17050d7).

**Declarations**

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**Figures**
Figure 1
a) SURVOSTRAL observations over 25 years between Hobart and Dumont D'Urville (DDU). The mean trajectory is in dashed black. Data used in this study are in grey. A schematic circulation is represented. White, black and red arrows are respectively the Antarctic Circumpolar Current, the Antarctic Slope Current and Australian-Antarctic Basin gyre, and the East Australian Current. b) 25 year average of the summer (NDJF) mean temperature section. Average position of the fronts and water-masses positions are indicated, and black contours show the (0°, 2°, 5°, 8°, 11°C) mean isotherms.
Figure 2

a) Summer Reynolds SST Trends from 1993 to 2017 (NDJF). Black box indicated the region of SURVOSTRAL transects. b) Temperature trends from SURVOSTRAL XBT data. Hatched data represent...
zones where \( \text{abs(Trends} \times 25)/\text{STD}<1 \); i.e. where the trends are smaller than the interannual variability. c) is the ratio between the trend signal and interannual variability.

![Graphs showing temperature anomalies and trends in zones A, B, and C](image)

**Figure 3**

Panels a), b) and c) show the evolution (black line) and trend (red line) of the temperature anomalies within zones [A], [B] and [C], respectively. Green line is the NDJF SST Reynolds anomalies interpolated onto the SURVOSTRAL line for each zone. Errors bars are the standard deviation of the mean anomalies for each grid point within the zone.
Figure 4

a) Zone [B] anomalies, restricted to the gridpoints where the 25 years-mean temperature transect < 0. b) Black line is the WW temperature anomalies from SURVOSTRAL XBTs between 54-61.5°S, restricted to the Tmin gridpoints where the 25 year-mean temperature transect is less than 2°C. Yellow line is the MJJA SST anomalies upstream of SURVOSTRAL WW, between (120-145°E; 57-61°S). c) CDW maximum temperature evolution (see Methods). Red dots are the years the linear trend is computed on; i.e. years when there is at least 2 months with data on average for each grid point for NDJF months. d) CDW maximum temperature depth (see Methods). Errors bars are the standard deviation of the mean temperature anomalies (depth for panel d) for each grid point within the zone.

Supplementary Files
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