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Sudden, local temperature increase above the continental slope in the Southern Weddell Sea, Antarctica

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Abstract. Around most of Antarctica, the Circumpolar Deep Water (CDW) shows a warming trend. At the same time, the thermocline is shoaling, thereby increasing the potential for CDW to enter the shallow continental shelves and ultimately increase basal melt in the ice shelf cavities that line the coast. Similar trends, on the order of 0.05 °C and 30 m per decade, have been observed in the Warm Deep Water (WDW), the slightly cooled CDW derivative found at depth in the Weddell Sea. Here we report on a sudden, local increase in the temperature maximum of the WDW above the continental slope north of the Filchner Trough (25-40°W), a region identified as a hotspot for potential changes in the flow of WDW towards the large Filchner-Ronne Ice Shelf. A combination of new and historical Conductivity-Temperature-Depth profiles and mooring records show that, starting in late 2019, the temperature of the warm water core increased by about 0.1°C over the upper part of the slope (700 - 2750 m depth). The increased temperature of the WDW is accompanied by an unprecedented (in observations) freshening of about 0.1 g kg^{-1} in the overlying Winter Water. Mooring records from the continental shelf further south, in the inflow pathway, do not show increased temperatures during the same period, suggesting that factors other than the WDW core temperature over the slope determine the variability in the heat content on the shelf.

1 Introduction

The Antarctic ice sheet stores a large amount of freshwater with the potential to significantly increase the global sea level. The Antarctic continent is fringed by floating ice shelves, buttressing and slowing down the ice streams into the surrounding ocean. However, in recent decades the ice shelves have been losing mass at an accelerated rate (Paolo et al., 2015). The largest ice shelf melt rates are found in the Amundsen Sea, where the narrow continental shelves allow nearly uninhibited access of warm Circumpolar Deep Water (CDW) to the ice shelf cavities. The southward oceanic heat fluxes are further amplified by the continuing warming of the Southern Ocean (Schmidtko et al., 2014) and are likely to result in meltwater that can change the oceanic density structure. For example, the freshening observed throughout the last decades in the Ross Sea that may ultimately

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affect the dense water formation and thus impact the global ocean circulation, is likely a consequence of increasing Amundsen Sea meltwater input upstream (Jacobs et al., 2022). The Filchner-Ronne Ice Shelf (FRIS) is the earth's largest ice shelf by volume and presently features comparatively moderate basal melt rates. While the Weddell Sea, in concert with the global ocean, also shows multi-decadal warming and freshening (Strass et al., 2020), FRIS is protected from the oceanic heat by the vast cold southern Weddell Sea continental shelf. This shelf is an important sea ice formation region, which results in the production of High Salinity Shelf Water (HSSW), a near-freezing dense water mass, that enters the cavity of the Ronne ice shelf. The HSSW then interacts with the base of the ice shelf at several hundred meters depth, where the local freezing point is a few 10s of a degree lower than at the surface. This leads to ice shelf melt and transformation of the HSSW into slightly fresher and colder Ice Shelf Water (ISW). ISW then exits across the front of the Filchner Ice Shelf into the Filchner Trough (FT), and thus completes a anti-cyclonic circulation. Both HSSW and ISW are exported down the continental slope and form the precursors of Antarctic Bottom Water (AABW, Foldvik et al., 2004), which is an important part of the global ocean circulation. Furthermore, these cold and dense waters dominate the water masses on the continental shelf and block any large-scale presence of Warm Deep Water (WDW) on the continental shelf. WDW is the slightly colder Weddell Sea equivalent of Circumpolar Deep Water and occupies the subsurface Weddell Sea basin north of the continental slope. The WDW lies below a layer of Winter Water (WW), with temperatures at or close to the surface freezing point. The WDW-WW interface, which equals the thermo- and pycnocline, deepens towards the continental shelf break, where it forms the Antarctic Slope Front and the associated Antarctic Slope Current, which flows westward along the shelf break. Seasonal changes in wind forcing and stratification (Hattermann, 2018) cause the thermocline to deepen during winter and relax during summer, leading to a seasonal inflow of WDW, or its modified form (mWDW), on the continental shelf east of the FT (Årthun et al., 2012; Ryan et al., 2017) that may reach the Filchner ice front (Darelius et al., 2016). Modified WDW also enters the continental shelf in a trough further west (Nicholls et al., 2008), where it, strongly modified, reaches (Janout et al., 2021) and enters (Davis et al., 2022) the Ronne Ice Shelf cavity. On the large scale, however, dense and cold waters dominate the southern Weddell Sea shelf, although numerical modeling experiments project changing conditions toward the end of this century (Hellmer et al., 2012). In these projections, strongly enhanced mWDW inflow over the eastern continental shelf drastically increases basal melt rates underneath FRIS. Regional modeling efforts, however, suggest that the system is relatively resistant to changes in wind forcing and thermocline depth (Daae et al., 2019), while FRIS melt rates respond linearly to changes in the salinity changes of the Antarctic Slope Current (Bull et al., 2021).

Here we present new observational data, Conductivity-Temperature-Depth (CTD) profiles collected during the COSMUS expedition to the region in February-March 2021, and oceanographic records from moorings recovered during the same cruise. The data show a sudden, local warming of the WDW above the upper part of the continental slope in the FT region.

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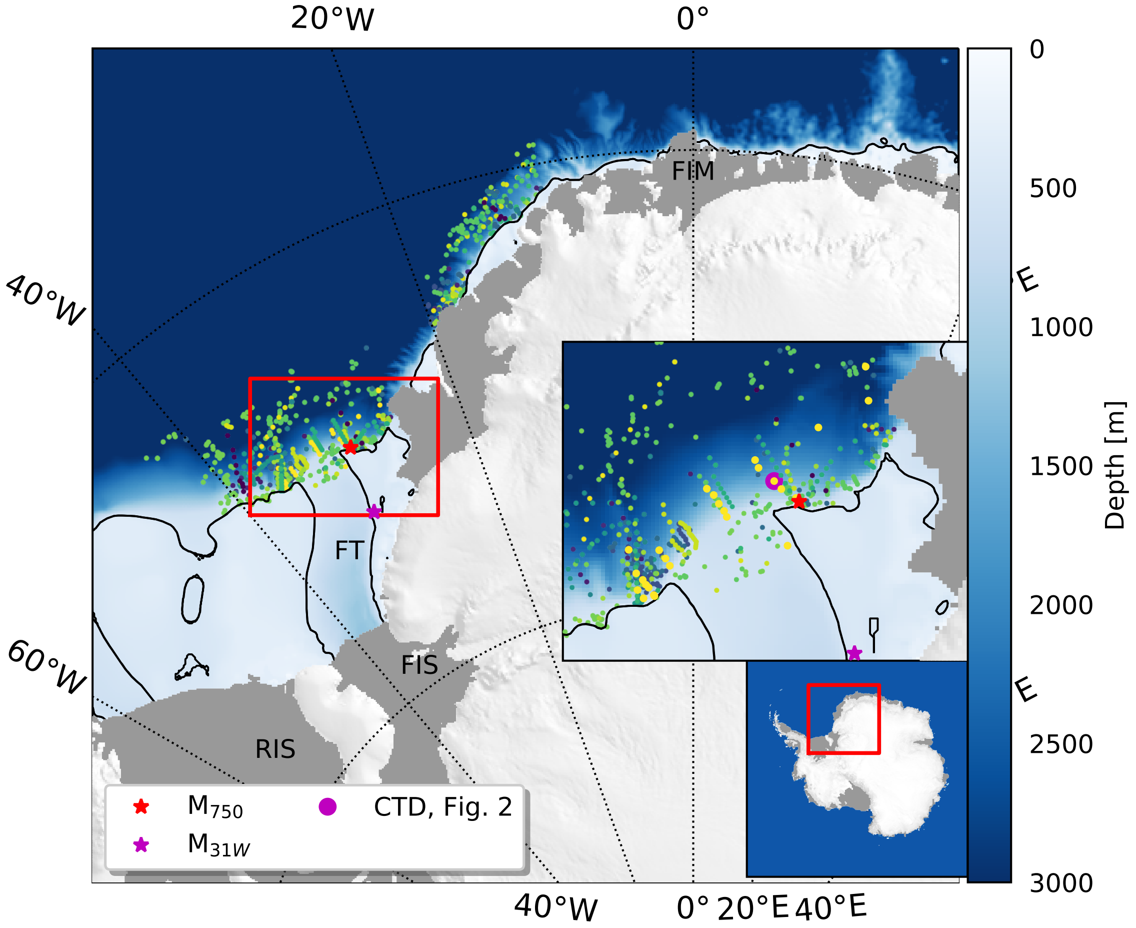

Figure 1. Map showing the bathymetry (Bedmap2, blue shading) of the south-western Weddell Sea (red box in lower inset) and the location of CTD – profiles included in the study (color-coded in time using the same color bar as in Fig. 3). Floating ice shelves are marked in grey and the 500 – m isobath is shown in black. Mooring positions are indicated with colored stars according to the legend. FT: Filchner Trough, FIS: Filchner Ice Shelf, RIS: Ronne Ice shelf, FIM: Fimbul Ice Shelf. The upper inset shows a zoom-in on the study area (red box), with CTD – profiles from PS124 in 2021 highlighted (larger, yellow dots). The position of the profile shown in Fig. 2 is marked with a magenta circle.

2 Data and methods

2.1 Conductivity-Temperature-Depth (CTD) profiles

More than 1000 historical CTD profiles (of which over 600 were collected by ship and over 200 by instrumented Weddell Seals) from the continental slope in the southern Weddell Sea (between 45-10°W, 500-3500 m depth) are included in the study. The majority of the seal profiles available from the slope area were excluded since the animals rarely dive deep enough over the slope to capture the temperature maximum. The historical data set spans the time period between 1973 and 2020, where the majority of the profiles are obtained during the Austral summer (January-February), see Fig. A1. The bottom depth at the profile location was interpolated from BEDMAP2 (Fretwell et al., 2013).

The historical data set is complemented by 25 profiles collected between 11 February - 15 March 2021 during PS124 onboard RV Polarstern as part of the COSMUS (Continental Shelf Multidisciplinary Flux Study)- Expedition (Hellmer and Holtappels, 2021). The profiles were collected using a standard CTD/Rosette SeaBird SBE911plus system, equipped with double sensors for temperature, salinity, and oxygen and one sensor each for pressure, substance fluorescence chlorophyll *a*, and beam transmission. In addition, 24 12-liter OTE bottles for water sampling were attached to the CTD frame. Sensors were calibrated by the manufacturer before and after the cruise. Additionally, water samples were taken and measured with the Optimare Precision Salinometer (OPS) for in-situ calibration of the conductivity sensor.

The location of the available CTD profiles is shown in Fig. 1, and the analysis is carried out over four different portions of the slope; the area just upstream of the FT (25-31°W), the area north of the FT (31-35°W), the area downstream of the Trough (35-45°W) and the slope further upstream (10-20°W).

Temperature and salinity are reported in Conservative Temperature, Θ, and absolute salinity S_A (McDougall, 2011; IOC et al., 2010).

2.1.1 Mooring records

The CTD data are complemented by records from a mooring location on the continental slope east of the FT; M3 at 750 m depth. The mooring will in the following be referred to as M_{750} , where the subscript indicates the mooring depth. The moorings were deployed during cruise JR16004 in 2017 and recovered during PS124 in 2021, providing up to four-year-long records of temperature, salinity, and current speeds. In addition, one-year-long historical records from the M_{750} position in 2009-2010 are included (Jensen et al., 2013; Semper and Darelius, 2017; Fer, 2016). To investigate the potential on-shelf propagation of the signal observed above the slope, we include temperature records from mooring M_{31W} (the subscript here denotes the longitude), deployed at 450 m depth on the continental shelf further south (Ryan et al., 2017, 2020). The historical records (2014-2018, Schröder et al., 2017, 2019) are extended to 2021 (Janout et al., 2022). Mooring positions are indicated in Fig. 1, and details about the mooring are given in Table 1.

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Table 1. Information about the moorings included in the study. Mooring locations are shown in Fig. 1.

	Lon	Lat	Bottom depth [m]	Deployment periods
M_{750}	29.91°W	74.55°S	750	2009, 2017-2021
M_{31W}	30.99°W	76.05°S	450	2014-2016, 2016-2018, 2018-2021

3 Results

The CTD profile obtained above the continental slope at 1500 m depth east of the FT (25-31 °W) in February 2021 (Fig. 2) shows the water mass layering typical for the region and the season: a shallow (35 m), relatively fresh (S_A<34 g kg^{-3}, not shown), and solar heated surface layer overlaying a quasi-homogeneous layer of WW with Θ just above the freezing point (Θ_{FP}) and S_A $\simeq$34.5 g kg^{-3}. Below the WW-layer, which at this station extends down to about 400 m depth, the temperature increases rapidly towards a maximum of Θ=0.76°C at about 850 m depth. This is the core of the Warm Deep Water (WDW), the slightly cooled Weddell Sea version of the Circumpolar Deep Water. Below the WDW core, the temperature decreases towards that of Weddell Sea Deep and Bottom Water, which is found at greater depths in the Weddell basin.

We note in Fig. 2a), that the maximum temperature of the WDW core in 2021 was more than 0.1°C warmer than the core temperature of any previous Θ-profile from this part of the slope. Similarly, anomalously high temperatures are observed all over the upper part of the slope, both east, north, and west of the FT (Fig. 3a-c). While temperatures around 0.8°C are regularly observed above the deeper part of the slope, only the profiles from 2021 display temperatures in this range for bottom depths smaller than about 2000 m. The signal is clearest east of the FT (Fig. 5a), where one has to move even further down the slope to find historical observations of water that is around 0.8°C. Moving further east, e.g. to the steep continental slope between 10-20°W, the core temperature above the slope is generally higher, also above the upper part of the slope (Fig. 3d). Unfortunately, there are no data from this region in 2021. While the profiles from 2021 were collected relatively late in the summer season, there is no indication in the data that the time of sampling can explain the high temperatures observed (Fig. A2).

The high temperatures of the WDW core are accompanied by relatively high salinities in the WDW depth range. Still, the most noteworthy feature of the salinity profile from 2021 in Fig. 2b is the low salinity of the WW layer. The WW is about 0.025 and 0.01 g kg^{-1} fresher than the mean value and the previously observed minimum, respectively. Similarly, low values of WW-layer salinities were observed at all stations east of the FT in 2021 (Fig. 4). While it is beyond the scope of this paper, the freshening appears to align with a general freshening trend of the WW layer in the FT region. The WW-layer typically erodes towards the west due to thermocline shoaling (see Fig. 5 and Darelius et al, in review) and mixing, and while the salinities at 250 m west of the FT were in the lower end of the observed range (Fig. 4a), the signal is strongest north and east of the FT. Mooring data suggest a pronounced seasonality in the 300 m salinity, with a drop in salinities occurring in April (Darelius et al., 2023), potentially as a result of an advected freshwater anomaly from the east (Graham et al., 2013), but the CTD profiles from

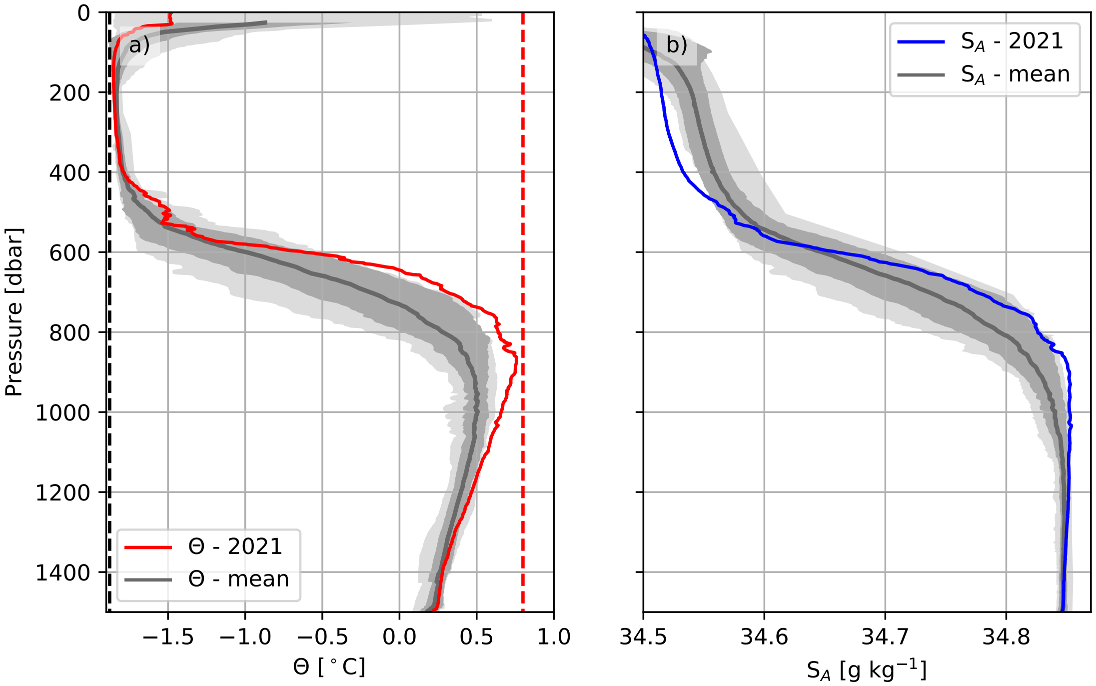

Figure 2. Profiles of a) Conservative Temperature (Θ, red line) and b) Absolute Salinity (S_A, blue line) obtained 1515 m depth on February 13th, 2021, on the continental slope east of the FT (see Fig. 1 for location). Mean profiles of Θ and S_A (gray lines) from 13 stations occupied in the 1300-1700 m depth range east of the FT (25-31°W) in the period 1973-2017 are included for comparison. The dark shaded area denotes ± one standard deviation, and the light, shaded area is the range of values observed at a given depth. The freezing temperature (Θ_{FP}, dashed black line) and Θ=0.8°C (dashed red line) are highlighted in (a).

2021 were obtained in mid-February to mid-March and there is no indication in the mooring records of an early freshening in 2021.

Fig. 2 suggests that the 2021 profiles, in addition to a higher core temperature, also display a shallower thermocline. This is, in general, not true, especially not north of and west of the FT (Fig. 5). It is, however, not straightforward to interpret potential interannual variability in thermocline depth from the scattered CTD profiles, since the thermocline depth varies spatially and temporally, both on seasonal (Årthun et al., 2012; Semper and Darelius, 2017) and shorter time scales (Darelius et al., 2009; Middleton et al., 1982; Jensen et al., 2013). The shoaling of the thermocline west of the FT discussed by Darelius et al (in review) is evident in Fig. 5.

The results from the CTD profiles are corroborated by mooring records obtained from the slope. Since the temperature variability is high on daily time scales (due to shelf waves advecting the thermocline across the slope; Jensen et al., 2013;

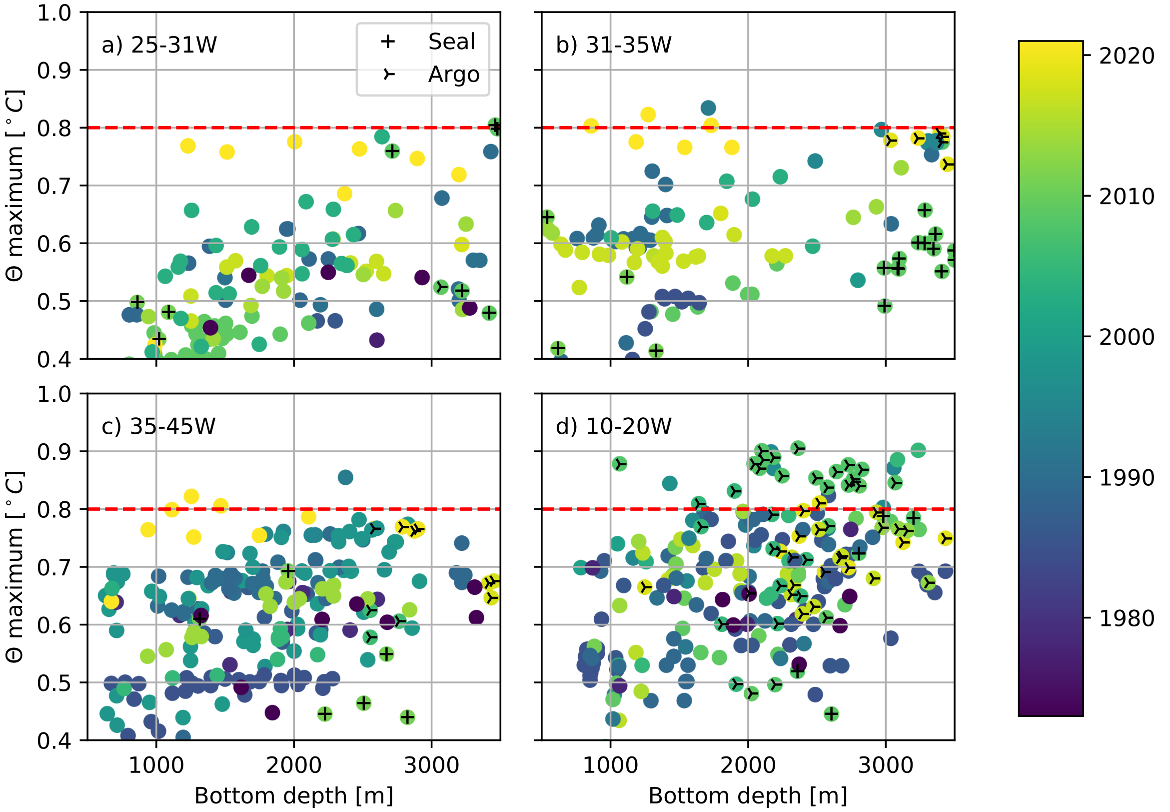

Figure 3. Temperature maximum above the continental slope as a function of bottom depth a) east of the FT (25-31W) b) north of the FT (31-35W) c) west of FT (35-45W) and d) upstream of the FT region (10-20W). The data points are color-coded with respect to time, and profiles obtained by seals or profiling floats are marked according to the legend. Note that seal profiles rarely cover the temperature maximum; the temperature shown is the highest temperature observed during a dive. The red, dashed line marks 0.8°C and is included in all panels (and in subsequent figures when relevant) to facilitate comparison.

Semper and Darelius, 2017), we consider the mean and maximum temperature in two-week-long windows (Fig. 6a-d) and refer to them as mean$_{2w}$ and maximum$_{2w}$ temperature, respectively. The mean$_{2w}$ temperature records from M$_{750}$ show the seasonality typical for the region during the first part of the record, with a late summer maximum, when the mooring is surrounded by (m)WDW, and a minimum in winter when WW is observed to reach down to the bottom (Semper and Darelius, 2017). However, towards the end of 2019, something appears to change. The maximum$_{2w}$ temperature increases by about 0.1°C, and for the rest of the record, it never drops below the average maximum$_{2w}$ temperature, not even in winter. The seasonal signal in 2020 is similarly disrupted; throughout much of the winter, the mean$_{2w}$ temperature is above the seasonal

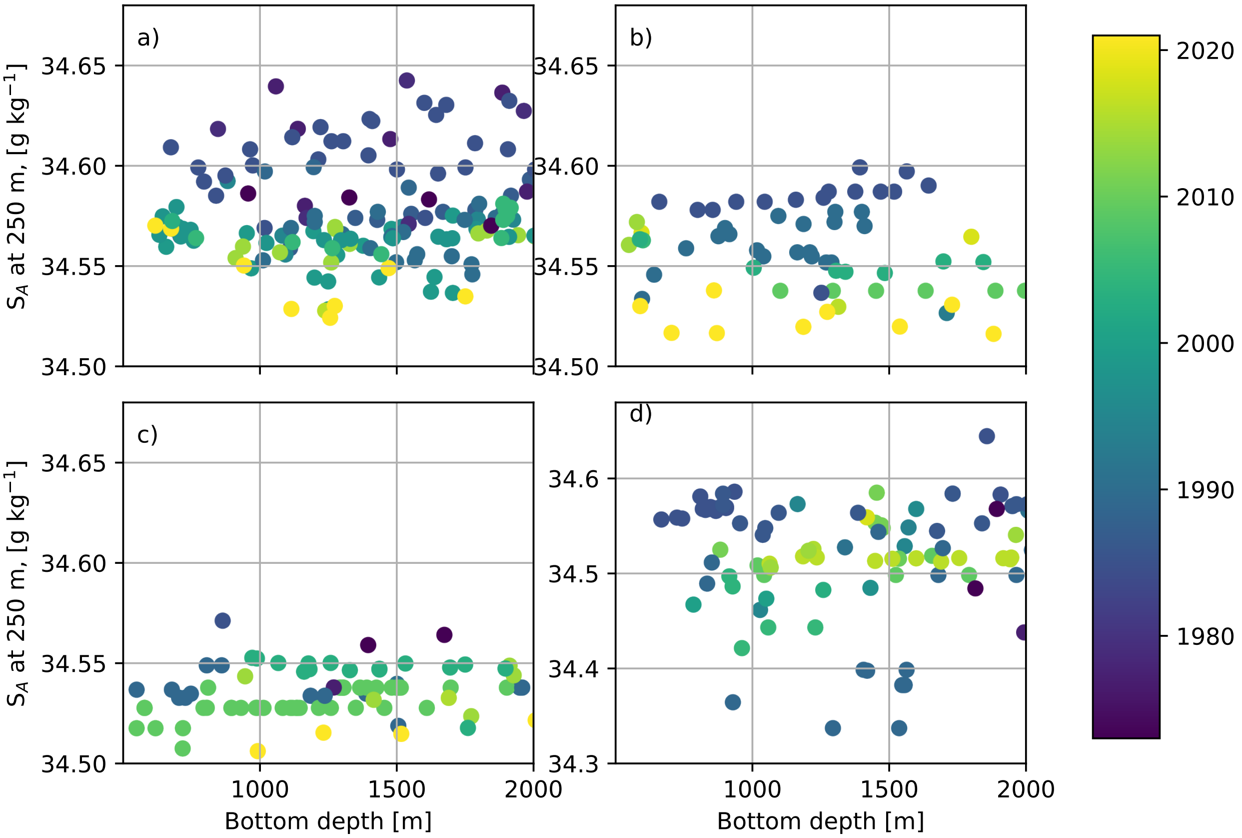

Figure 4. Absolute salinity at 250 m depth as a function of bottom depth a) west of the FT (25-31W) b) north of the FT (31-35W) c) east of FT (35-45W) and d) upstream of the FT region (10-20W). Profiles obtained by seals or profiling floats are excluded from the analysis. Note that the scale in panel (d) differs from that of the other panels.

average (which is inferred from the 5-year long time series). The absolute maximum$_{2w}$ temperature (0.76°C) occurs in January 2021 and is roughly 0.30°C higher than the average maximum$_{2w}$ temperature and 0.17°C warmer than the highest temperature observed prior to November 2019.

130 Energetic shelf waves traveling along the upper part of the slope can potentially affect the temperature observed at M_{750} (see discussion). The eddy kinetic energy (EKE) associated with the diurnal shelf waves varies seasonally, with a maximum in summer, as changing hydrography and currents modify their dispersion relation and the possibility for resonance (Semper and Darelius, 2017). A similar seasonality (suggested by Jensen et al., 2013, based on one year long records) is apparent for shelf waves with a period of 35h in the M_{750} records (Fig. 6f). The mid-depth (250-500 m) EKE records (Fig. 6f) show that i) the

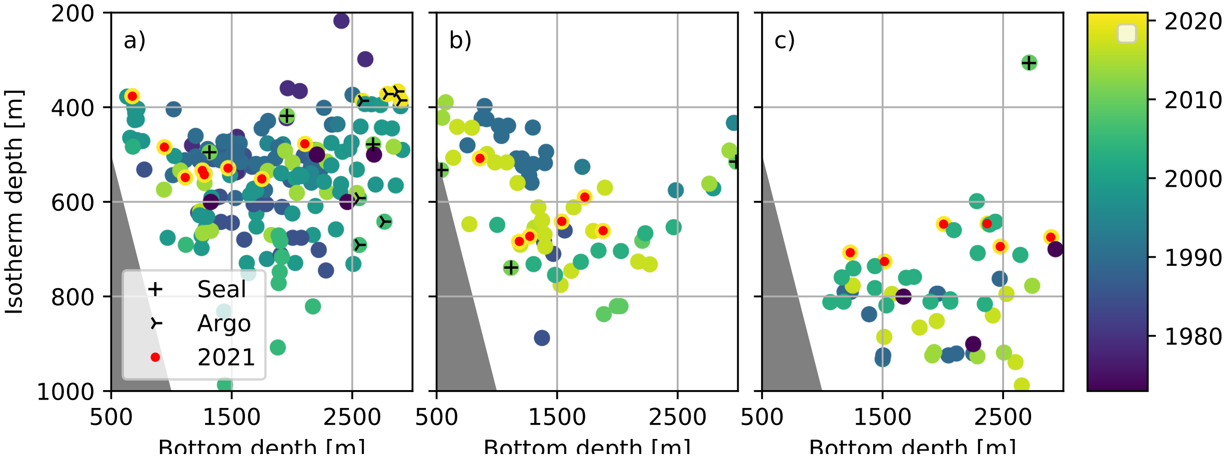

Figure 5. Scatter plot of the depth of the 0.5° isotherm versus bottom depth, where the color code indicates the bottom depth a) west of the FT (25-31W) b) north of the FT (31-35W) and c) east of FT (35-45W). Profiles obtained by instrumented seals, Argo floats, or in 2021 marked according to the legend.

135 summertime peak in EKE is reduced in 2020 - 2021 (or already in 2019 for the 35h-band) and ii) the (smaller) wintertime peak in tidal EKE is enhanced in 2020 (Fig. 6f, green line) when the mean$_{2w}$ temperature is above the seasonal average. From the tidal forcing alone, we would expect quasi-symmetric bi-annual peaks for the EKE related to diurnal tides (see e.g. Semper and Darelius, 2017, Fig. 6).

3.1 Discussion

140 Observations from the southern Weddell Sea show a sudden, local warming of the WDW-core above the upper part of the continental slope in the region north of the FT (Fig. 1). CTD profiles from 2021 reveal that the temperature maximum now is about 0.1°C warmer than previously observed. The changes are most pronounced east of the FT above the upper part of the slope (shallower than 2750 m). Mooring records suggest a change to have occurred during 2019, as the maximum$_{2w}$ temperatures observed on the mooring from November 2019 and onward are markedly higher than before. During 2020, the 145 seasonal signal in temperature (Semper and Darelius, 2017; Årthun et al., 2012), which is evident in the early part of the record, is not as dominant, and mean$_{2w}$ temperatures are markedly higher during winter.

The temperature of the WDW above the slope is relevant in at least three ways; the WDW enters the continental shelf where it acts as a precursor to HSSW formation (Nicholls et al., 2009), and where it, if it enters the FRIS cavity, can increase basal melt (Hellmer et al., 2012, 2017). In addition, the WDW is one of the main components of the bottom water produced in the 150 Weddell Sea, as it is entrained into the plumes of dense shelf waters that descend the continental slope (Foldvik et al., 2004). The effects of the observed temperature increase for these processes will be briefly discussed below. Modified (m)WDW is known to enter the continental shelf east of the FT seasonally (Årthun et al., 2012), and to flow southwards towards the Filchner

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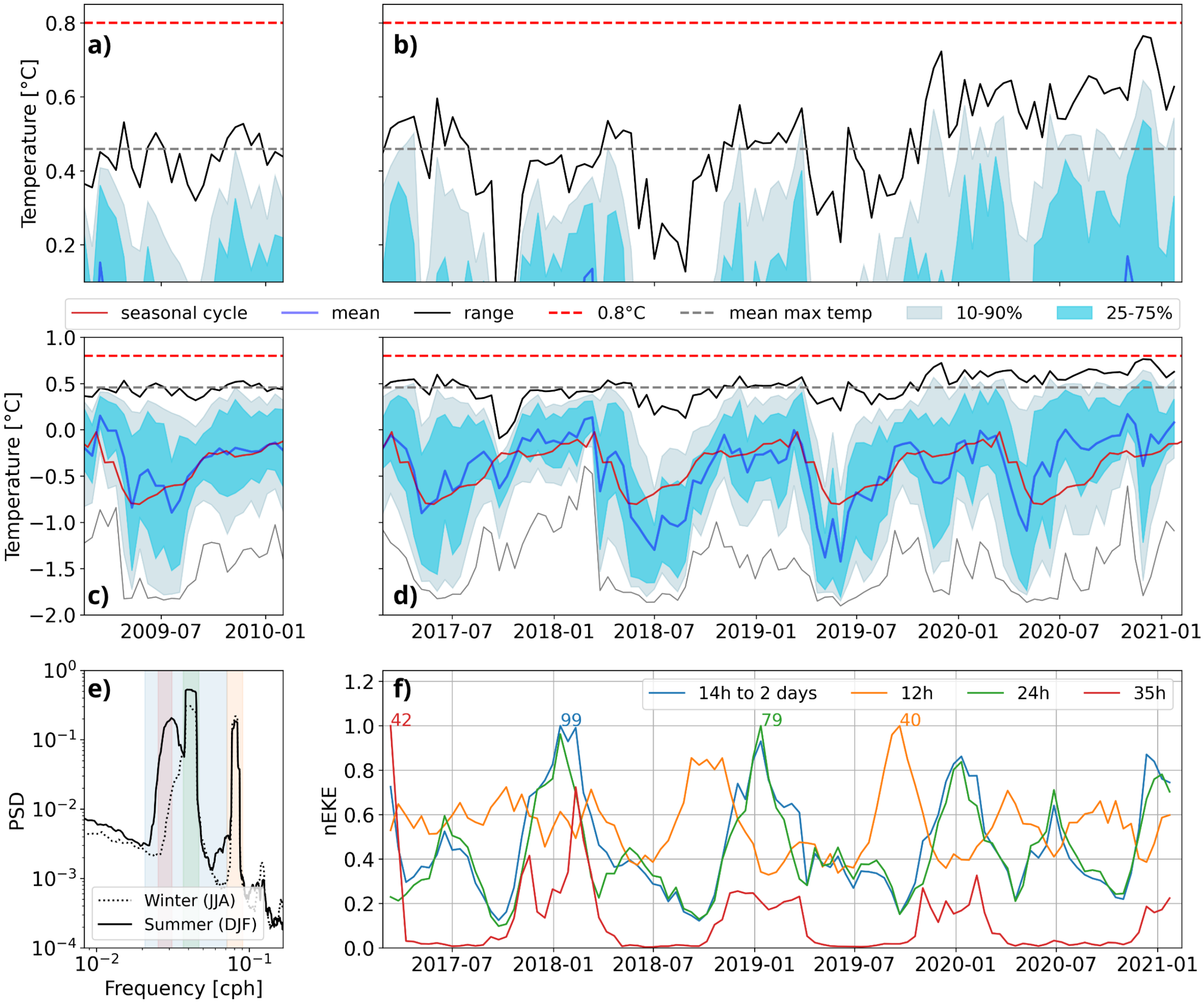

Figure 6. a-d) Time series of bottom temperature from M_{750}. a-b) is a zoom-in of the highest temperature range at M_{750} (black). Maximum (black), minimum (grey), mean (blue), the $10-90$ (filled, grey), and $25-75$ (filled, light blue) percentiles of temperature are calculated in two-week long windows. The average upper range (grey dashed line), and 0.8°C (red dashed line) are indicated. e) Frequency spectra of across-slope velocity (250-500 m depth) at M3 for winter (dotted line) and summer (black). The shading marks the B35, B24, B12, and 2 days to 14 hours frequency bands, color-coded by the legend in panel f). f) Time series of normalized vertical mid-range EKE (250-500 m depth) at mooring M_{750} in four frequency bands: 12 hours to 2 days (blue), B12 (orange), B24 (green), and B35 (red). The corresponding colored numbers show the maximum EKE value.

ice shelf cavity (Ryan et al., 2017; Darelius et al., 2016). While the warm inflow was "exceptionally warm and prolonged" in 2017 (Ryan et al., 2020), the inflow in 2020 - when temperatures above the slope were increased and the seasonality reduced,

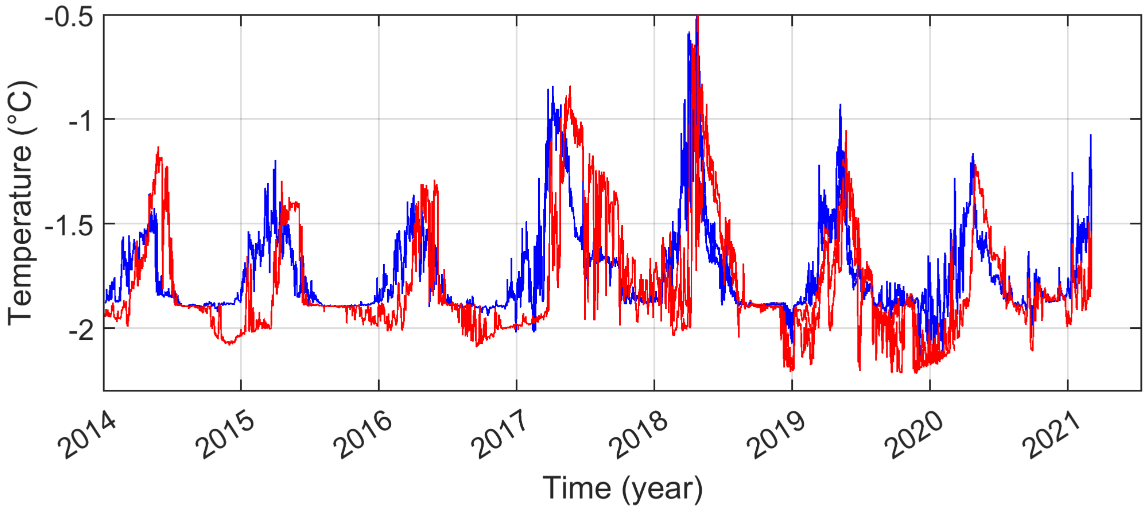

Figure 7. Time series of temperature at 340 m (blue) and 430 m (red) depth from mooring M_{31W} (A253) on the continental shelf at 76°S, east of the FT (Ryan et al., 2017, 2020).

Fig. 6 - was neither exceptionally warm nor long (Fig. 7). This suggests that processes and factors other than the WDW core temperature on the upper part of the slope determine the temperature, strength, and duration of the warm inflow.

The mWDW on the upper part of the continental slope enters the continental shelf also in a depression east of the FT (Nicholls et al., 2008) where it is suggested to be the main source water for the production of HSSW in front of the Ronne Ice Shelf (Nicholls et al., 2009). A temperature increase in the source water could hence potentially influence the density and/or quantity of the HSSW produced. Back on the envelope estimates following Nicholls et al. (2009) suggests that a 0.1°C increase would increase the heat flux needed by 10% - or, for constant heat flux and HSSW production rate, reduce the density of the

HSSW by 0.01 kg m^{-3} - but since their estimates are based on relatively cold and highly modified mWDW these numbers must be considered an upper limit.

The outflow of ISW from the FT forms a gravity-driven plume on the continental slope west of the FT sill (Foldvik et al., 2004; Darelius et al., 2009). During its descent towards the deep ocean, the plume water entrains and mixes with the overlying mWDW, to eventually form Weddell Sea Dense and Bottom Water. As the ratio of ISW to entrained mWDW is on the order of $R_{ISW:mWDW} \simeq$1:1.5 (Foldvik et al., 2004), variability in the properties of the entrained mWDW will translate directly to the properties of the produced bottom water. The seasonality observed in the hydrography of the ambient water at the shelf break is, for example, evident in the plume properties at 1600 m depth (Darelius et al., 2014b). If other factors remain unchanged, we can estimate the imprint of the observed WDW temperature increase on the bottom water temperature following Foldvik et al. 2004: using an outflow temperature of -1.9°C, a mean temperature of the entrained mWDW of 0°C (prior to 2021) and $R_{ISW:mWDW}$ from above suggest that the bottom water produced in 2021 would be about 0.06° warmer than before. At 4000 m depth, the slight increase in temperature would cause the produced bottom water to be (assuming unchanged salinity) 0.01 kg m^{-3} lighter. (Due to the effect of temperature on the compressibility of seawater - cold water is more compressible than warm water - the effect of the temperature increase on density increases with depth). In comparison, the seasonality of the bottom water outflow from the Weddell Sea east of the South Orkney Islands at 4500 m depth has an amplitude of about 0.05°C (Gordon et al., 2010), while the warming trend observed in the bottom waters of the Southern Ocean between the 1990s and 2000s was on the order of 0.03 °C per decade (Purkey and Johnson, 2010) and the range of variability in the mean temperature of the Weddell Sea Deep and Bottom Water at the Greenwich meridian between 1984 and 2008 was on the order of 0.02°C (Fahrbach et al., 2011).

What is the origin of the observed local warming? The high WDW temperatures are anomalous for the upper part of the slope, but water this warm is readily observed both upstream (3d) and further offshore (3a-c). One can hence easily imagine an "advective" origin of the signal, where the main WDW core is brought closer to the shelf break, or potentially a "mixing" origin, where the mixing and entrainment of colder water into the WDW-core is reduced.

The continental slope region north of the FT is known to be greatly influenced by continental shelf waves (Jensen et al., 2013; Semper and Darelius, 2017) and local mixing is additionally enhanced by the co-location of near-critical slopes and the critical latitude for the semi-diurnal tide (Fer et al., 2016). Shelf waves can be expected to influence the observed maximum_{2w} temperature at M_{750} in (at least) two ways; firstly, the waves effectively advect the thermocline up and down the slope (Jensen et al., 2013) and more energetic shelf waves could potentially bring warm water farther up the slope and hence increase the maximum_{2w} temperature. Secondly, however, a larger amplitude in the (largely barotropic, Jensen et al., 2013) velocity signal associated with the waves implies larger bottom shear and more mixing in the bottom boundary layer. This would tend to decrease the maximum_{2w} temperature at M_{750}, since the temperature increases towards the bottom. The time series of M_{750} temperature and EKE (Fig. 6) suggest that the waves associated with the enhanced peak in EKE during the winter of 2020 could have brought warm water higher up on the slope and caused the observed increase in maximum$_{2w}$ temperature at M$_{750}$, but it could also be the other way around, i.e. that the EKE is enhanced because the hydrographic conditions are more summer-like and more prone to resonance (Semper and Darelius, 2017). The high maximum$_{2w}$ temperatures during the summers of 2019/20 and 2020/21 could potentially be linked to decreased mixing, as the summer peaks in EKE then are lower than during 2017-2019. We can not rule out that changes in shelf wave activity (through their effect on mixing and/or advection across the slope) are contributing to the changes in observed maximum$_{2w}$ temperature at M$_7$50, but it seems unlikely that *all* of the stations from the shallow part of the slope in 2021 should coincide with extreme upslope advection of WDW or that barotropic (depth-independent) waves would contribute to mixing at mid-depth where the temperature maximum is located.

We note two major events that can potentially be linked to the observed temperature increase and the fresh WW layer: the Weddell Sea ice minimum that occurred in 2016 (Turner et al., 2020) and a hydrography transition that occurred in the FT between 2017 and 2018 (Janout et al., 2021).

The sea ice minimum was hypothesized by Ryan et al 2020 to have caused a longer and warmer than usual inflow of mWDW onto the continental shelf east of the FT (observed at e.g. at M$_{31W}$, Fig. 7). The decrease in sea ice concentration also coincides with the onset of a long period with increased inflow of mWDW into the Fimbul Ice Shelf cavity (see Fig. 1 for position) that led to enhanced basal melt rates and stronger cavity circulation (Lauber et al., 2022). The regime shift at Fimbul Ice Shelf is linked to anomalous wind stress forcing, a reduced gradient in Sea Surface Height between the coast and off-shore and a weaker Antarctic Slope Current (ASC). While barotropic changes in the ASC strength would propagate quickly along the slope (Le Paih et al., 2020; Spence et al., 2017), a freshening signal caused by e.g. increased melt beneath the Fimbul Ice Shelf (and potentially other ice shelves along the coast) would need time to develop and to propagate from the source region upstream towards the FT. Graham et al. 2013 estimated (based on results from numerical simulations) that the advective timescale for the fresh anomaly that develops in the eastern Weddell Sea during summer to reach the FT region is on the order of three months. The low sea ice concentration and increased ice shelf melt along the coast upstream could both contribute to the observed fresh WW layer. The results by Bull et al. (2021) suggest that there is a potential link between the low salinity of the WW layer and the observed high WDW temperatures. In their numerical simulations, a freshening of the ASC (i.e. a salinity perturbation and positive values of their Slope Current Index, SCI) is associated with increased bottom temperatures above the upper part of the continental slope (their Fig. 8c), consistent with the observations reported on here. Bull et al. (2021) do not, however, further investigate the dynamical link between the ASC freshening and the warming. While we are not able to quantify the effect, we note that the low salinity of the WW layer increases the stability of the water column. Hence, the energy needed to mix the cold WW with the warmer WDW below increases accordingly.

Janout et al. (2021) identified a transition from Ronne-sourced to Berkner-sourced ISW within the FT between 2017 and 2018, as the circulation beneath FRIS intensified due to anomalous wind and sea ice forcing (Hattermann et al., 2021). The system has, however, transitioned between Berkner and Ronne sourced ISW several times within the time span of available observations (Darelius et al., 2014a; Janout et al., 2021), and the change in the density of the FT ISW is relatively small (Janout et al., 2021). While we cannot rule it out, it seems unlikely that the 2017 transition is directly linked to the observed temperature increase on the slope occurring two years later.

4 Conclusions

Observations show that the temperature of the WDW core above the upper part of the continental slope in the western Weddell Sea was about 0.1°C warmer in 2021 than previously observed, while the WW-layer above showed a substantial (0.01 g kg^{-1}) freshening compared to previous observations. Mooring records suggest that a change towards higher temperature maximums occurred late in 2019. While we can not conclude on the origin of the signals, we hypothesize, based on the results by (Bull et al., 2021), that the warming and the freshening are linked and that the freshening is associated with the negative sea ice anomaly and increased basal melt rates upstream (Lauber et al., 2022).

Data availability. text

The historical CTD data analyzed in this study are available for download from pangaea.de, bodc.ac.uk, seanoe.org, coriolis.eu.org, ewoce.org, ncei.noaa.gov/products/world-ocean-database, and meop.net. CTD data from cruise ES006 (2003) are not searchable but are available from BODC on request (under accession number BAS220012). The doi of individual observational data sets included in the study are listed below.

The CTD data from 2021 will be made available on pangaea.de prior to publication.

Doi of CTD: https://doi.org/10.17882/54012
https://doi.org/10.1594/PANGAEA.61240
https://doi.org/10.1594/PANGAEA.293960
https://doi.org/10.1594/PANGAEA.527233
https://doi.org/10.1594/PANGAEA.527319
https://doi.org/10.1594/PANGAEA.527410
https://doi.org/10.1594/PANGAEA.527497
https://doi.org/10.1594/PANGAEA.527593
https://doi.org/10.1594/PANGAEA.527643
https://doi.org/10.1594/PANGAEA.527812
https://doi.org/10.1594/PANGAEA.733664
https://doi.org/10.1594/PANGAEA.734977
https://doi.org/10.1594/PANGAEA.734988
https://doi.org/10.1594/PANGAEA.735189

https://doi.org/10.1594/PANGAEA.735530
https://doi.org/10.1594/PANGAEA.738489
https://doi.org/10.1594/PANGAEA.742577
https://doi.org/10.1594/PANGAEA.742579
https://doi.org/10.1594/PANGAEA.742581
https://doi.org/10.1594/PANGAEA.756515
https://doi.org/10.1594/PANGAEA.756517
https://doi.org/10.1594/PANGAEA.770000
https://doi.org/10.1594/PANGAEA.772244
https://doi.org/10.1594/PANGAEA.833299
https://doi.org/10.1594/PANGAEA.854148
https://doi.org/10.1594/PANGAEA.859040
https://doi.org/10.1594/PANGAEA.897280
https://doi.org/10.1594/PANGAEA.527646 - 527691

Mooring data are available from www.pangaea.de using the following doi:
https://doi.org/10.1594/PANGAEA.869799
https://doi.org/10.1594/PANGAEA.944430
https://doi.org/10.1594/PANGAEA.875932
https://doi.org/10.1594/PANGAEA.903315

The recent data from M_{750} will be made available on www.pangaea.de prior to publication of the current draft.

Author contributions. ED compiled and analyzed the historical CTD-data, prepared most of the figures, and drafted the ms, VD analyzed the M_{750} mooring data and made Fig. 6. MJ prepared the temperature records from M_{31} and made Fig. 7. ST processed the COSMUS CTD data. All co-authors contributed to the text.

Competing interests. The authors have no competing interests.

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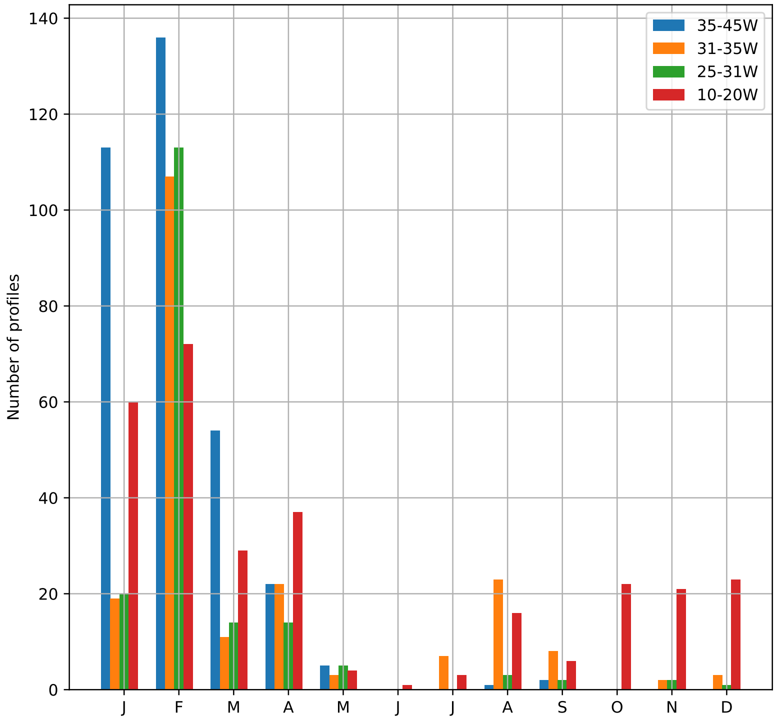

Figure A1. Number of profiles per month, per region, included in the study.

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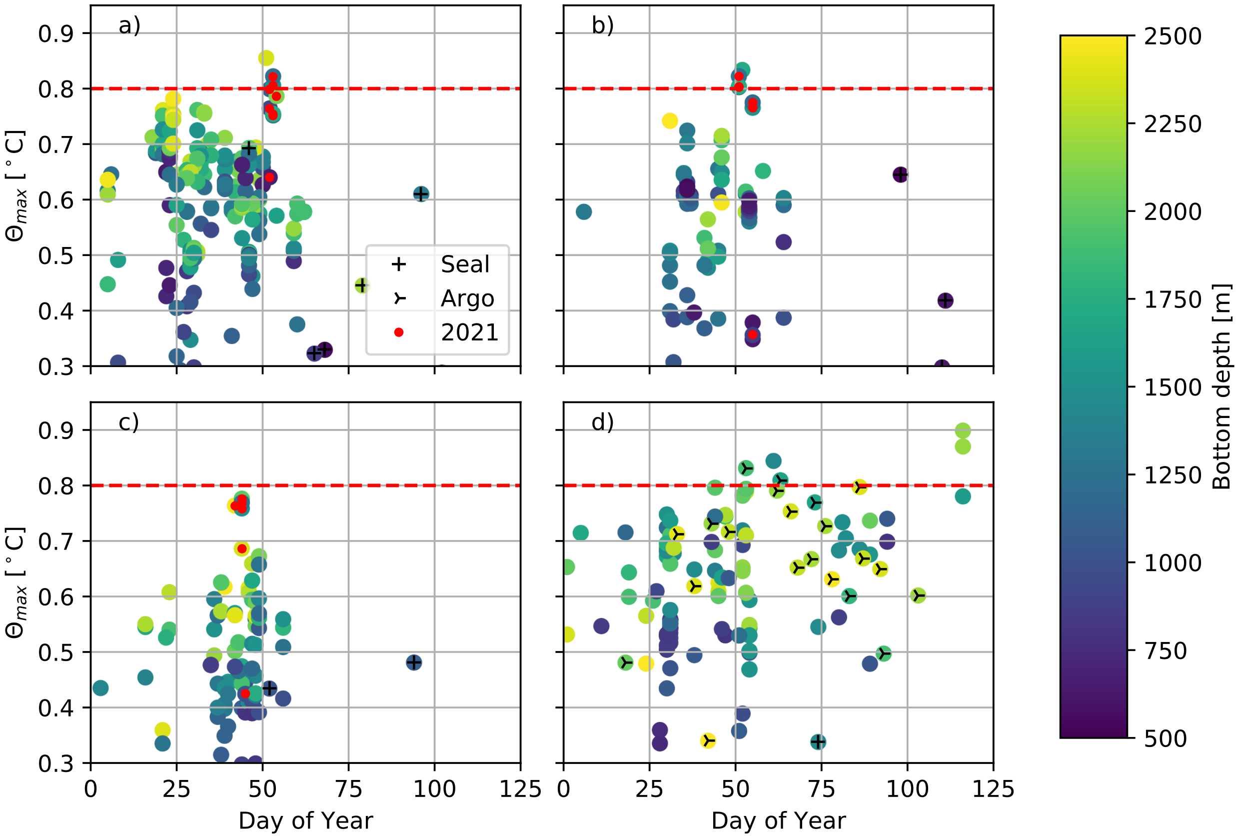

Figure A2. Scatter plot of Θ_{max} versus the day of the year that the profile was obtained, where the color code indicates the bottom depth a) west of the FT (25-31W) b) north of the FT (31-35W) c) east of FT (35-45W) and d) upstream of the FT region (10-20W). Profiles obtained by instrumented seals, Argo floats, or in 2021 marked according to the legend. The red, dashed line highlights 0.8°C.

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