Warming of the deep water in the Weddell Sea along the Greenwich meridian: 1977 - 2001

Lars H. Smedsrud *

Geophysical Institute, Allegaten 70, Bergen, Norway

Abstract

The Weddell Deep Water (WDW) warmed substantially along the Greenwich meridian following the Weddell Polynya of the 1970's. Areas affected by the polynya contained $\sim$ 14 GJ/m^2 more heat in 2001 than in 1977. This warming would require a flux of $\sim$ 390 W/m^2 if it were to take place over a year. Large variations in heat content of the WDW are found between the Antarctic coast and Maud Rise (64°S). The small variation found north of Maud Rise is opposite in phase to that to the south, and the warming was close to monotonic south of 68°S. The mean warming of WDW along the section is $\sim$ 0.032 °C per decade, comparable to the warming of the Antarctic Circumpolar Current. The mean warming compares with a surface heat flux of 4 W/m^2 over the 25 year period, an order of magnitude higher than the warming of the global ocean. As variation in mean salinity of the WDW follows the warming/cooling events, variation in inflow probably explains a cooling event between 1984 and 1989, and a warming event between 1989 and 1992. Cooling during the late 1990's is probably related to the reappearance of a polynya like feature in some winter months as an area 100 km in diameter close to Maud Rise with 10-20 % lower sea ice concentrations than the surrounding ocean.

Key words: Deep water, warming, air-sea-ice interaction, Antarctica, Weddell Sea, Maud Rise

1 Introduction

Over the last 50 years the mean volume temperature increase of the world ocean was about 0.06 °C (Levitus et al. 2000), while the global mean warming

* Bjerknes Centre for Climate Research (BCCR), University of Bergen, Norway
Email address: larsh@gfi.uib.no (Lars H. Smedsrud).
URL: www.gfi.uib.no/~larsh (Lars H. Smedsrud).

of the world atmosphere was 0.6 °C during the 20th century. But due to the ocean's larger density and mass, and therefore larger heat capacity, the related heat content of the warming is an order of magnitude larger for the world oceans. The average heating at the surface over the 50 years is 0.01 W/m^2 for the atmosphere, and 0.32 W/m^2 for the ocean, estimated from values given by Levitus et al. (2001). Thus much of the global warming to date finds its way down into the ocean interior (Levitus et al. 2000).

A data set of floats from the 1990's covering the Antarctic Circumpolar Current (ACC) between 35 and 65 ° S (700 - 1100 m depth) show an increase of 0.17 °C over the last 50 years compared to older hydro graphic data(Gille 2002), well above any other global ocean, but contains no data towards the Antarctic continental shelves. A recent global model integration of WOCE data (Stammer et al. 2003) shows a warming during 1993-2000 in the ACC of more than 0.5 °C at 600 m depth. If the recent past is a guide to the future it is becoming clear that regional climate change will have profound effects, and if such regional changes are not described our chances to predict future global changes may also be very limited.

In this work a section running northwards from the Antarctic continent along the Greenwich meridian will be discussed. Along this coast of Dronning Maud Land, warm water comes into contact with the floating Antarctic ice shelves. Mosby (1934) was the first to describe the vertical structure in this region, noting the temperature minimum of the winter water, the maximum temperature well above 0 °C at about 300 m depth, and the cyclonic circulation of the Weddell Gyre. Maud Rise, a sea mount at $\sim$ 1000 m depth, is located centrally in the otherwise $\sim$ 3500 m deep Weddell Sea. At or around Maud Rise open ocean convection takes place during winter, and a large anomaly in the surface heat fluxes took place here from 1973-1978: the Weddell Polynya (Martinson et al. 1981). The cooling effect of the Weddell Polynya was discussed by Gordon (1982), and subsequent warming of the waters along the continental slope of the Weddell Sea was described by Robertson et al. (2002). Recently Fahrbach et al. (2004) analyzed both a section in the central Weddell Sea as well as the Greenwich meridian for the period 1986 - 2002. A detailed presentation of the temperature and salinity fields, as well as averaged water mass properties for the 1990's may be found here.

Weddell Deep Water (WDW) is a mass of water found below the winter mixed layer in the Weddell Sea. Variation in the surface mixed layer is not discussed here, but were examined over the Weddell Gyre by Martinson and Ianuzzi (1998). The WDW used to be characterized by potential temperatures between 0 and 0.8 °C, and salinities between 34.64 and 34.72 (Foster and Carmack 1976). The deep water has now warmed significantly, and the maximum temperature presented here is 1.284 °C from 1992. This implies that the WDW temperature range should be re-defined to 0 - 1.3°C, and this is what has been

followed here. Fahrbach et al. (2004) found a mean warming of the WDW in the Weddell Sea from 0.40 °C in 1992 to 0.43 °C in 1998, with a subsequent cooling after wards. I here make an attempt to describe where these warming and cooling events have taken place. Section 2 describes the available data and methods, and section 3 contains the various parameters describing the thickness, salinity, maximum temperature and heat content of the WDW in the period 1977-2001. Section 4 discusses the nature of the warming, and also the processes that might have caused the observed cooling in the 1990's.

2 Methods

CTD data from the years 1977, 1984, 1989, 1992, 1996 and 2001 were used in this study. Various sources are utilized, including Norwegian Antarctic Research Expeditions (NARE) 1977 and 2001, the World Ocean Database (1998) and the AWI Oceanographic Observations Database (2002). A total of 130 stations are used in this study. The available sections cut through the southern part of the Weddell Gyre that transports warm water from the Antarctic Circumpolar Current (ACC) towards the central Weddell Sea (Schröder and Fahrbach 1999). A more detailed presentation of the data from 1977 may be found in Foldvik et al. (1985), for 1984 in Whitworth and Nowlin (1987), for 1992 and 1996 in Fahrbach et al. (2004), and in O'Dwyer (2002) for 2001. The uncertainty for the data generally decreased for the more recent cruises, but are better than ±0.006°C and ±0.005. Pressure was converted to depth using Ocean Data View (Schlitzer 2001). The uncertainty in the pressure or depth data is ignorable in comparison to the temperature when it comes to calculating the WDW depth and computing vertical integrals. The ±0.006°C translates into ± 20m for the lower boundary, while the upper boundary has a much stronger temperature gradient and has an uncertainty of ± 1m. Figure 1 shows the sections from the different years discussed.

Heat content of the WDW at each station is calculated by

$$Q = \int_{z_u}^{z_l} \rho_\theta C_p(\theta - T_f)dz \qquad [\mathrm{J/m^2} \ \text{ or } \ \mathrm{Ws/m^2}] \tag{1}$$

where ρ_θ is the potential density at surface pressure, C_p the specific heat, and θ the potential temperature (at surface pressure). Potential temperature, θ, is used consistently throughout this paper as a measure of temperature. Values for ρ_θ, C_p and θ were calculated based on in-situ measurements of temperature, salinity and pressure using derived variables in the "sea water" package using MATLAB (Morgan 1994). T_f is the surface freezing temperature for a given salinity (Millero 1978), but as the range in salinity is so small a constant

T_f = -1.9 °C is used. Appropriate mean values are $\bar{\rho_\theta}$=1032 [kg/m^3] and C_p=3981 [J/kg°C]. z_u is the upper and z_l is the lower depth of the integration, here taken as the 0 °C isotherm. The thickness of the WDW layer is thus $z_l - z_u$, and is presented in section 3.1. The z-axis is taken to be positive downwards.

Results for the heat content Q are mostly presented as a mean surface heat flux over a year. This is the constant heat flux needed to cool the underlying volume of WDW to the surface freezing point within a year. In order to do this as concisely as possible I have chosen to introduce a new unit for heat content 1 Mo = 31.536 $\times 10^6$ J/m^2. This is to honor the pioneering work of Håkon Mosby (Mosby 1934) in describing the layer of warm deep water and the other water masses of the "Atlantic Antarctic Ocean". 1 Mo is the heat gained or lost by applying 1 W/m^2 at the surface over a year.

A typical value of Q in this study is 12 $\times 10^9$ J/m^2. In the alternative unit this is 390 Mo, meaning that an imaginary heat flux of 390 W/m^2 over a year would remove the available heat from the WDW at this station. Natural heat fluxes are smaller, usually below 50 W/m^2, meaning that the WDW contains large amounts of heat that will require several years of normal surface heat flux, or especially high fluxes over a shorter period, to be significantly cooled. Instrumental uncertainties for Q are $\pm$0.016 Mo as a product of the uncertainties for WDW thickness and θ and the mean values of the constants.

Mean salinity at a station is calculated by

$$S_{WDW} = \frac{1}{\bar{\rho_\theta}(z_l - z_u)} \int_{z_u}^{z_l} \rho_\theta S_w dz. \qquad (2)$$

where S_w is the in situ measured salinity.

The seasonal signal close to the surface is removed when performing the integrals (1 and 2): The first appearance of the 0 °C isotherm below 70 m depth was set as z_u, after checking that the WDW was not found closer to the surface at any station. As z_l the 0 °C isotherm below the WDW was used rather than a fixed mean depth. This ensures that changes in the volumes of WDW at each station are incorporated into the heat content values. The salinity of z_l was fairly stable. Apart from in 1977, the maximum difference in one year at the lower boundary in S_w was 0.09 and the overall variation 34.663 - 34.764. In 1977 the range was 34.659 - 34.682. Instrumental uncertainties for S_{WDW} are equal to the original measurements $\pm$ 0.005.

Mean values are calculated for 2° latitude bins (60-62, 62-64, 64-66, 66-68 and 68-70) to make it easier to interpret results, and remove the effect of denser station spacing in some years. Bin values were calculated from 2 or more stations except in 2001 for the 60-62 and 62-64 bins, which had only 1 station

each. Maud Rise at 65°S divides the section conveniently in two, and is often used as a landmark even though the longitude is 2.7 °E.

Results show that properties of the WDW along the Greenwich meridian vary both in time and space. However, the northern end, the 60-62 °S bin, experiences only small long term changes, and may therefore represent an estimate of the spatial and temporal variation. The average heat content for the 1977-2001 period is 294 Mo, and the standard deviation for 16 available stations in this bin is 16 Mo.

Eddies and small scale spatial variation also represent an uncertainty when looking at long term changes, and most of the station spacing is ∼50 km. A cold eddy observed in 1977 (Gordon 1978) had a radius of 14 km, and a typical size of the eddies is normally taken as the baroclinic Rossby radius, about 8 km in the area. Much of the local variation may thus be unresolved. However, in 2001 17 stations were occupied along 69 °S with a station spacing of ∼ 16 km (Figure 1). The average heat content value for these stations is 474 Mo, with a standard deviation of 36 Mo. For salinity the average is 34.686, with a standard deviation equal to the instrumental uncertainty of ± 0.005.

The heat content decrease towards the west along 69 °S in 2001. This is in the direction of the mean flow of the Weddell Gyre. The maximum is 515 Mo at 2.1 °E and the minimum is 416 Mo at 1 °W. A maximum estimate of the east west gradient would be ∼-10 Mo/°W. Assuming this is representative for all years along the section, a linear correction was performed to interpolate the available stations to the Greenwich meridian exactly. Such a correction leads to a warming of the values south of 66 °S in 1989 with 50-80 Mo. The section mean in 1989 increase from 379 to 414 Mo. Apart from the values in 1989 changes are minor, and the warming and cooling events look very similar. I have therefore chosen not to present the east-west corrected values. Altogether an estimate of the uncertainty due to limited sampling in time and space when looking at long term changes would be ± 16-36 Mo for Q, and ± 0.005 for S_{WDW}.

3 Results

A significant warming of the deep water in the Weddell Sea is observed after 1977. As a simple first illustration three profiles from 1977, 1992 and 2001 are shown in figure 2. The winter surface mixed layer is illustrated by the station from 1992 occupied in June, extending from the surface to about 70 m depth. Below this mixed layer in winter, or below a temperature minimum as a remnant of the winter mixed layer in summer, the temperature increases to a temperature maximum, θ_{max}.

As already discussed by Robertson et al. (2002) θ_{max} has increased off Dronning Maud Land and further along the shelf break in the Weddell Gyre from ∼0.6 °C in 1975 to ∼0.9 °C in 2000. The profiles in figure 2 show that the Weddell Polynya in 1973-1976 produced θ_{max} as low as 0.16 °C, and that $\theta_{max} \sim 1.2$ °C in 1992, with a subsequent cooling towards 2001.

While θ_{max} provides a simple illustration of the warming that has taken place after 1977, it does not represent the total heat content of the water column, nor does it show how much heat that has been transported into the area. Likewise, θ_{max} can not be compared to changes in the surface heat fluxes, so values of Q from (1) should add further understanding to the post 1977 warming. There is only one of the 130 stations where such an integral could not be performed: a cold eddy observed in 1977 (Gordon 1978). At this station the summer mixed layer temperature of 1.36 °C at 50 m depth decreased steadily downwards to –0.31 °C at 205 m, and there was no WDW present below, so $Q = 0$.

The total mean for 130 stations in the section 1977-2001 (figure 1) is Q=12.3 GJ/m^2. Removing this heat over one year, i.e. cooling the WDW to T_f, would require a steady heat flux of 390 W/m^2, and the mean heat content of the section is thus 390 Mo. Averaging over 2 ° before computing a section mean lowers the average to 382 Mo, meaning that more stations are available in the warmer parts of the section. The total mean salinity for the section is S_{WDW}=34.66.

For the three stations at 67.5 °S, shown in figure 2, WDW was present between 144 and 389 m depth in 1977, between 83 and 1790 m in 1992, and between 140 and 1700 m depth in 2001. Q increased from 63 Mo in 1977 to 535 Mo in 1992, and decreased to 473 Mo in 2001 (the alternative values are 2.0 GJ/m^2, 16.9 GJ/m^2 and 14.9 GJ/m^2).

3.1 Thickness of the WDW

Figure 3 shows the WDW layer thickness as a function of latitude for the different years. Two general properties of the data are clear: There is little variation between the years north of 63°S, and even though the data stretches between 8°W and 3°E (figure 1) there is little significant East-West variation (note the eastward running section from 2001 at 68.8°S). The three profiles shown in figure 2 are the values from 1977, 1992 and 2001 at 67.5°S.

To illustrate the mean differences along the Greenwich meridian, the average bin values are plotted with a larger size at the mid latitudes (61,63,65,67,and 69°S) in figure 3. The total averages for each individual year are plotted to the far right (at 59 °S). The mean WDW thickness for the section is 1040 m in 1977, and varies between 1350 m and 1380 m from 1984 to 2001.

After 1977 the thickness of the WDW layer is re-established to around 1600 m between 64 and 69 °S in 1984. It then thins in 1989 to around 1300 m in the latitudes around Maud Rise (64 to 67 °S), before thickening during the 90's and thinning again in 2001 close to the 1989 level.

The changes in the WDW layer thickness are mostly caused by variation of the lower boundary. A representative mean value for z_u is 130 m depth. z_l is found at $\sim$ 1700 m northwards to Maud Rise, rising to 1200 m north of 63°S.

The total range in z_u is 70 - 220 m north of 68.8°S. Along the southern margin the lowest upper boundary of WDW is found due to fresher and colder surface waters in the coastal current: from 196 m in 1989 down to 490 m depth in 1977.

3.2 Salinity of the WDW

Mean salinity S_{WDW} from (2) is shown in figure 4. An overall increase in salinity after 1977 is clear, with the largest increase up to 1984. Although the section mean salinity variation after 1984 is of the same magnitude as the uncertainty, the individual bins have significant variation in this period. A period of freshening south of Maud Rise is found between 1984 and 1989, and for some of the southern bins after 1992.

The increase in mean salinity takes place over the same periods as the increase in WDW thickness up to 1992. Likewise there is a decrease in mean salinity parallel to a decrease in WDW thickness. Between 1992 and 1996 there is an increase in WDW thickness with a decrease in salinity, and for 1996-2001 the WDW thickness decreases while the salinity increases.

For all years figure 4 shows that the section mean salinity and that of the southern part (64-70°S) are opposite in phase to that of the northern part (60-64°S). This is also true for the WDW thickness in figure 3 although it is hard to work out in the presented figure.

3.3 Maximum temperature of the WDW

The striking aspect of θ_{max}, shown in figure 5, are the extremely cold values near 67°S in 1977. Apart from the cool 1977 there is little systematic change over the years. In fact, every year has a maximum θ_{max} somewhere along the meridian, even 1977. 1977 has the maximum θ_{max} at 63.5°S, 1984 has the maximum θ_{max} at 66°S, and so on.

While there has been a monotonic increase in θ_{max} close to the Antarctic continent (Robertson et al. 2002), this is not the case further north. On the contrary, values of θ_{max} close to Maud Rise are lower in 2001 than in 1977, for example.

The total averages for the individual years (at 59°S, figure 5) indicate a warming of the WDW from 1977 to 1992-1996, and a subsequent cooling towards 2001. An average of the bins south of 64 °S indicate a warming to θ_{max}=1.0 °C in 1992 and 1996, cooling to 0.8 °C in 2001.

The depth of θ_{max} is very stable in time for the total averages (not shown). From 260 m depth in 1977 it shoals to 250 m in 1984, down to 260 m again in 1989, and reaches the most shallow average in 1992 at 230 m. In 1996 and 2001 it is back down at 260 m. There is no particular shoaling or deepening of θ_{max} in 1977, and it is 2001 that is peculiar, with a shallower θ_{max} in the south and deeper between 64 and 68 °S.

3.4 Heat content of the WDW

The largest "inter annual" changes in the heat content of the WDW are found between 64 °S and the Antarctic coast as shown in Figure 6. This was also the case with the WDW thickness (figure 3). This indicates that the distribution of warm water is a better indicator of the heat content, than θ_{max}.

The values from 1977 around 67°S are the largest anomalies as expected, as the heat content, Q, is a product of the thickness of the WDW (figure 3) and θ as given by (1). With a WDW thickness of about 200 m and $\theta_{max} \sim 0.2$°C about 50 W/m^2 would remove all heat in the WDW over a year (figure 6).

Values above the mean, 382 Mo, are consistently found south of Maud Rise after 1977, while values below the mean are consistently found north of 63°S. The largest increase in heat content is clearly up to 1984, from then there is more of an oscillation. This is shown by the '60-70 °S' bin in figure 7. This variation in time is governed by heat changes in the '64-70 °S' bins, as they show increase and decrease with the same sign, but with a larger amplitude. Despite the large variations in time, the mean warming between 1977 and 2001 is ∼100 Mo for the section, or ∼4 W/m^2.

The southern bin has seen a close to monotonic rise in heat content since 1977, with only a slight cooling between 1992 and 1996 (figure 7). The warming between 1996 and 2001 is not altered significantly by the extra stations along 68.8°S, as they increase the mean in 2001 from 465.5 to 470 Mo only.

The next bin north, '66-68°S' warmed the most between 1977 and 1984, and

experienced only cooling after 1992. The '64-66 °S' bin around Maud Rise cooled the most in the 1980's and the 1990's. In 1989 data south of Maud Rise were collected as far west as 8°W. A linear correction based on the 2001 cross section lowered the heat content south of 66 °S in 1989 with 50-80 Mo. As noted earlier did this not affected any other years, and it is doubtful that the 2001 data represent a proper mean east west gradient, so the "corrected" data is not presented.

The variation over time in the northernmost bin, '60-62 °S' are remarkably small (figure 7). The changes in the '62-64 °S' bin seems to be opposite in phase to that of the southern part, as was also the case with thickness and salinity. So when the southern part is warming, the '62-64 °S' is cooling, and vice versa. This makes the cooling and warming periods less pronounced for the total means for the section.

4 Discussion

The source waters for WDW is Circumpolar Deep Water from the ACC entering the Weddell Gyre at approximately 30°E (Orsi et al. 1999). The mean flow of the Weddell Gyre is shown in figure 1. Schröder and Fahrbach (1999) estimated the westward transport at the Greenwich meridian south of 60°S to be 66 Sv in total for 1996. North of 60°S water flows east, so 60°S is the axis of the Weddell Gyre at the Greenwich meridian. The westward transport south of 60°S includes 39 Sv of 'warm regime' water close to Maud Rise, 5 Sv of 'cold regime' water north of Maud Rise, and 22 Sv in the coastal current.

Dividing the flux of 'warm'- and 'cold'-regime water by the mean WDW depth of 1350 m and the length of the section yields an average current for westward flow of WDW of 3.0 cm/s. Another WDW flow estimate is the average advection of the Weddell Polynya in the years 1973-1976 (Martinson et al. 1981) of $\sim$ 1 cm/s. With an average speed of 1-3 cm/s WDW takes 1.5-4 years from 30 °E in the ACC to Maud Rise. Current speeds are generally expected to increase towards the continent, reaching a maximum of 15 cm/s in the coastal current at 12 °W (Fahrbach et al. 1992). An obvious cause of the WDW heat content variations may therefore be variations in inflow as discussed by Fahrbach et al. (2004), and in the next section.

As the WDW continues around the Weddell Gyre, large volumes are transformed into the colder Weddell Sea Deep Water (WSDW) and Weddell Sea Bottom Water (WSBW) through mixing with colder shelf waters like the Ice Shelf Water (ISW, $\theta < T_f$ at the surface) overflowing in the Filchner Depression (**?**) and dense shelf water at T_f with relatively high salinities. A recent estimate of the transformation rates were: 8 Sv WDW + 1.7 Sv surface water

$\rightarrow$ 3.9 Sv WSBW + 5.8 Sv WSDW (Naveira Garabato et al. 2002). This water mass transformation will probably absorb much of a warming or cooling of the WDW, so that little variation in θ returns to the Greenwich meridian.

The heat content of the WDW may also vary due to varying heat loss upward toward the surface and downward toward the WSDW in the area. Of these the upward heat loss is the major part, and Fahrbach et al. (2004) show that there is little variation in WSDW temperature after 1992. Upward heat loss to the mixed layer takes place through many processes like double diffusion, deep convection events, shear instabilities, entrainment and intrusions, and has a climatic mean of 25-35 W/m^2 (Martinson and Ianuzzi 1998). At drift stations close to Maud Rise in 1994, the observed ocean heat flux from the WDW to the mixed layer was in the range 23 - 52 W/m^2 (McPhee et al. 1999). The observed mean heat content of 382 Mo is thus an order of magnitude higher than the average upward flux working over a year.

Between 60-64 °S the inter annual variability of thickness, salinity, and heat content for the WDW is small. The only parameter that exhibits any significant variation here is θ_{max}. The heat content in this area is about 100 Mo below the average for the section (figure 6), indicating a substantially cooler mass of water. This was also noted by Fahrbach et al. (2004) so the 'cold regime' found north of 64°S seems to be a permanent feature for the 1977-2004 period, and is a part of the inner circulation of the Weddell Gyre.

This inner circulation of the Weddell Gyre consists of water that has crossed the Greenwich meridian flowing east north of 60°S, before returning south-west wards again. Given the transformation rates of WDW described above, there is small chances for anomalies to 'survive' a whole circle in the gyre. If an average upward heat flux from the WDW of 20 W/m^2 is assumed, the 'cold regime' would have cooled 5 years longer than the 'warm regime' further south.

4.1 Variability of the inflow

The source waters for WDW from the ACC have experienced a close to linear warming of 0.17 °C during the last 50 years, or 0.034 °C per decade (Gille 2002). In this time frame the advection time of 1.5-4 years from the ACC to the Greenwich meridian is not significant. A close to linear increase in θ_{max} and Q is found close to the continent in the southern bin 68-70 °S, where θ_{max} has increased from 0.65 in 1977 to 0.95 °C in 2001. Thus a long-term linear warming trend of 0.12 °C per decade may be suggested along the Antarctic continent (Robertson et al. 2002). However, there is no monotonic increase in θ_{max} further north (figure 5), and in the bin around Maud Rise (64-66°S) the

coldest θ_{max} values are from 2001.

The recent cooling was also noted by Fahrbach et al. (2004) when looking at the WDW mean temperature for the longer 55-70°S section. They attribute the warming prior to 1998 to increased inflow caused by changes in the Weddell Front (southern boundary of the ACC), normally found at 55 °S. During the early 1990's the Weddell Front was found further south, and had weaker gradients, and Fahrbach et al. (2004) find this to have a connection with changes in the large scale atmospheric forcing. They show the temperature at 300 dbar along Greenwich instead of performing breakdown into latitudinal bins, or discuss θ_{max} values.

But describing the warming and cooling events based on temperature in one level has limited value, and figure 7 clearly show that the cold regime between 60-62°S has a remarkably constant heat content, Q, for the 1977-2001 period. This indicates that changes along the Weddell Front has minor importance, even though there has been a small gradual warming there since 1984 as described by Fahrbach et al. (2004).

It is the warm regime, 64-70°S, that has the large variations in Q. The warming is likely caused by inflowing water from the ACC as also noted by Fahrbach et al. (2004). But the pressure difference here (figure 10 (center) (Fahrbach et al. 2004)) has almost no trend after a small peak in 1991. So the atmospheric forcing might explain the increase in inflow between 1989 and 1992, but can not explain the cooling in the late 1990's. On the contrary - the pressure difference has been slowly increasing since 1998.

The decrease in Q and S_{WDW} between 1984 and 1989 (figure 7 and 4) indicates a reduction in inflow during these years. This is not found in the data of Fahrbach et al. (2004), and it does not compare well with an increasing pressure difference. The 1984-1989 cooling remains more than 50 Mo for the 64-66 °S bin even with the east-west correction, so it is not an artifact caused by western position of the stations this year. For the section mean value and the 66-68 °S bin the cooling vanishes with the east-west correction. But as this correction is based on the stations from 2001, the original uncorrected values were presented, and are probably the most correct. The cooling episode is not clear when looking at θ_{max} (figure 5), but is clearly seen as a thinning of the WDW (figure 3).

This all indicates that variations in inflow do occur, and are important. But variations in Q and S_{WDW} only follow changes in the sea level pressure during some periods, and it is therefore likely that the source water from the ACC is more important when it comes to explaining the warming events. In fact, as shown by figure 8 is the observed mean warming of the WDW along Greenwich surprisingly close to the linear trend from the ACC (0.034 °C per decade

covering the 700-1100m) (Gille 2002). The values cover the mean of the WDW thickness shown in figure 3, i.e. the deep waters between 100 and 1600 m depth.

Figure 8 shows that both the cold regime, and the water masses close to Antarctica warms in close agreement with the mean trend of the ACC. In contrast to the mean linear warming, latitudes 64-68 °S have experienced first a stronger warming up to 1984, and then a cooling of more than 0.1 °C between mid 1990's and 2001. I suggest that additional local processes must be important here, as outlined below.

4.2 Local variability

Heat loss from the Weddell Polynya was estimated from cooling of θ_{max} at about 20°W by ∼0.7 °C between 1973 and 1977 (Gordon 1982). This is comparable to the increase in θ_{max} around 67°S between 1977 and 1984. The Weddell Polynya initiated close to Maud Rise in 1973/74 and advected west wards, so it might seem strange that the Polynya could cool water at the Greenwich meridian to a large extent. However, the Weddell Polynya extended as far east as 10°E in 1974, and 5°E in 1975, and Bersch et al. (1992) finds a southwest-ward transport above the western slope of Maud Rise, overlaid by cyclonic and anti cyclonic disturbances. This could lead to a significant recirculation within the 'warm regime' around Maud Rise, as northeast-ward flow was recorded over several months on the southwestern slope.

The warming between 1977-1984 is probably a return to 'normal' after the Weddell Polynya, and is also associated with a large increase in salinity. Thus the Weddell Polynya freshened the WDW by bringing down less saline water from the mixed layer. The cooling during the late 1990's has a different character as S_{WDW} increases between 1996 and 2001 for 64-70°S. This is mainly caused by the increase for 68-70°S, but indicates an increasing inflow of warm and saline water with the 'warm regime' as well as additional cooling process.

For the Weddell Sea sector as a whole (20°E - 60°W) the sea ice area has increased with 2.0 % in the period 1979-1998 (Zwally et al. 2002), so the warming inflow has not directly affected the ice cover on a large scale. The increase in sea ice cover was mostly during summer along the Antarctic Peninsula, but changes along the Greenwich meridian are positive (3 %) north to 65°S, and negative (3 %) between 65 and 60°S.

If WDW is mixed upwards to the surface layer during winter, and no sea ice is present, the heat is able to keep the area free of ice for several weeks. This conclusion is drawn by a convection scenario governed by thermobaric instability (McPhee 2000) where an area of open water is the result of convection to more than 200 m depth, and subsequent up-welling of WDW. This is also

illustrated by Holland (2001) that argues that a cyclonic eddie shed off Maud Rise was the initiating factor of the Weddell Polynya. In this process the resulting divergent Ekman drift lead to a thinner layer of sea ice with lower concentration, and when WDW is mixed upwards, and convection starts, it takes several weeks before the surface waters reach T_f, and new ice formation may start. The two layer model of Martinson et al. (1981) also depended on overturn, i.e. removing of the fresher and colder surface layer, before a polynya could form.

The southwest-ward flow of the Weddell Gyre along Greenwich (figure 1), and the northern limit of the inter annual variability in heat content at 64°S indicates that the heat is lost from the WDW somewhere between the Antarctic coast and Maud Rise. A connection between Maud Rise and the polynya activity is therefore likely, and Maud Rise is found to be the site of an increased heat transfer from the ocean to the atmosphere (Bersch et al. 1992). The flow variability over Maud Rise may also be the initiating factor as suggested by Holland (2001).

As an example of the process suggested figure 9 shows that there was a large persistent area with reduced sea ice concentration close to Maud Rise during September 1994 (Cavalieri et al. 2002). This was the 'polynya' discussed by McPhee (2000) that developed after the field survey ending in early August. The term 'polynya' is used here although a portion of sea ice cover was always present. The centre of the polynya was at 64°S with a 50% cover of sea ice, and 70 % coverage extended between 63 and 65°S. In the following I will use the term 'Maud Polynya' for visible minima in the sea ice concentration fields close to Maud Rise. During some winter months of the late 1990's the Maud Polynya had a monthly mean sea ice concentration as high as 75-87.5 %. It might seem strange to call this a polynya at all, but minima do stand out in the otherwise 87.5-100 % covered sea, and no other term seems appropriate. The Maud Polynya in 1994 is visible from 7.th of August and throughout the winter in the daily sea ice concentration maps (Cavalieri et al. 2002).

A polynya will lead to increased heat loss to the atmosphere. A simple heat flux estimate for September for open water is 118 W/m^2, and for a fully sea ice covered ocean 8 W/m^2 (Martinson et al. 1981). Thus the Maud Polynya in 1994 would cool the $\sim$ 31500 km^2 area with 44 W/m^2 during September, using 60 % sea ice concentration. To illustrate the total effect of this Maud Polynya in 1994, a 65 % sea ice cover over the 4 months August - November is representative. This leads to a heat loss equal to 12.8 Mo, accounting directly for 25 % of the observed $\sim$ 50 Mo cooling between 1992 and 1996 shown in figure 7. As the strongest cooling was observed around 67°S between 1992 and 1996 (figure 6) this would imply that the cold anomaly was advected southwest-ward with the Weddell Gyre circulation from 1994 to 1996.

A polynya will also lead to freshening of the WDW as water from the mixed layer convects down. This is consistent with S_{WDW} decreasing from 1992-2001 for 66-68°S, and from 1996-2001 for 64-66°S (figure 4). For 68-70°S the sudden decrease in S_{WDW} between 1992 and 1996 stands out clearly in the time series, and the S_{WDW} at 69.5°S in 1996 is lower than any other year at this latitude (not shown). The small cooling during the same period is probably an artifact caused by two additional stations in the warmer water north of the coast in 1992 (figure 6). The freshening may thus be a sign of increased melting of the ice shelves along the Antarctic coast, and not of a reduction of the inflow from the ACC.

The observed heat content in 1977 was 180 Mo between 66-68°S. This is about 200 Mo lower than the section mean, and 300 Mo below the average for this latitude for 1984-2001 (figure 6). As Gordon (1982) suggest, this must be caused by the Weddell Polynya in 1974-1976. Over the 15 months (July-November) of the Weddell Polynya, an extra heat flux of about 120 W/m^2 could be assumed (Martinson et al. 1981), removing 50 Mo each year. To compare with figure 6 this works over the 3 years 1974-1976 removing a total of 150 Mo. As there is no available data from the Greenwich meridian prior to the Weddell Polynya in 1974, a plausible assumption could be a linearized warming of 4 W/m^2 up to the 1982 value of 350 Mo, making the $\sim$ 1972 level about 310 Mo. This assumption is supported by the similarity of the mean warming of the WDW and the long term trend (1950-2000) from the ACC (Gille 2002). Thus the effect of the Weddell Polynya was to cool the water column by 150 Mo from the estimated 310 Mo in 1972. Adding 5 years of the linear warming of 4 W/m^2 brings us to the observed level for Q of 180 Mo in 1977.

The Maud Polynya in 1994 is the first one that persisted over several winter months after 1977. The temporal evolution for 1992-2000 is shown in figure 10, where sea ice concentration minima are visible during June-October. During all years 1978-2000 the sea ice melts earlier close to 65 °S in November (Cavalieri et al. 2002), indicating that WDW has been entrained into the mixed layer in this region. The WDW is thus cooled by mixing in early spring (i.e. November) before the onset of an atmospheric heat flux can account for the ice melt (Gordon and Huber 1995).

During the 1990's signs of the Maud Polynya have been more and more frequent. This is also partly supported by the average open water area of the Weddell Sea that has increased with 7.0 % during winter in the period 1979-1998 (Zwally et al. 2002). A long term trend (or a decadal scale variation) in the sea ice concentration around Maud Rise is also noted by Venegas and Drinkwater (2001), showing a decrease from 1987 to 1994 caused by enhanced wind divergence of the sea ice. The Maud Polynya appeared clearly (sea ice concentration below 75 %) in October during 1992, 1994, 1995, 1996, 1999 and 2000: in 1997 and 1998 it appeared with a sea ice cover of 75-87.5 %.

Out of 20 months (July-October) in the 1996-2000 period, the Maud Polynya appeared in 12, and for 1992-1995 in 7 out of 16. The increasing occurrence of the Maud Polynya during the winters of the 1990's is probably connected with the efficient cooling in the 64-66°S bin presented in figure 7. In comparison there were few occurrences between 1979 and 1991 (July 1980, September 1982, October 1980, 1983, 1985, 1989 and 1991, not shown, see Gloersen et al. 1992), i.e. in 7 out of 52 months.

The Maud Polynya with the lowest monthly mean sea ice concentration (24 %) occurred during June 1998 at 8°W and 68 °S. This event was a sea ice cover forming around open water, rather than an opening created in an ice cover. Such a 'bay' in the sea ice cover towards Maud Rise is also visible during the years 1992, 1994, and 1997 (figure 10). Later in the winter of 1998, this polynya was visible only in July, and the following months had high sea ice concentrations. This points to some kind of limiting process: i.e. there is normally only a limited heat supply available for melting sea ice, or preventing ice growth.

It is worth noticing that only two winter months during 1992-2000 have reduced sea ice concentration close to the Antarctic coast. This is the "ice free bay" in 1998, and the strip of 50 % coverage at 3-13°E in 1995. The very persistent ice cover indicates that a warming inflow signal is left undisturbed to a large degree by cooling towards the surface. If cooling processes along the coast responded with a significant negative feedback, i.e. more efficient melting of ice shelves with increasing temperatures for instance, the warming trend in the WDW would not be the same as in the ACC. When the warming trends are similar, it is an indicator that no such feedback processes have operated.

5 Conclusion

The data set presented here covers the Greenwich meridian from the axis of the Weddell Gyre (60 °S) to the Antarctic coast (70 °S) for the years 1977 to 2001. The Weddell Deep Water (WDW) is defined by $\theta > 0$°C, and is usually found between 130 and 1600 m depth. The upper range of θ for WDW should be increased to 1.3 °C as the water mass has experienced significant warming since the classification in Foster and Carmack (1976).

WDW core temperatures were highest in the 1990's ($\theta_{max} > 1.2$°C), and there are large inter-annual variation for WDW thickness, salinity, and heat content south of 64°S. The mean thickness increased from 1040 m in 1977 to around 1500 m in later years. The volume of WDW probably increased between 1977 and 1984 due to warm water advected with the mean circulation of the Weddell Gyre from the Antarctic Circumpolar Current (ACC). This is a return to

"normal" after the Weddell Polynya 1973-1976.

The WDW mean temperature increase is similar to that of the ACC (Gille 2002): 0.034 °C per decade, and the WDW mean salinity has increased close to linearly with about 0.02 between 1977 and 2001. The vertically integrated heat content of the WDW, shows that the water mass is warming at a mean rate of $\sim$ 4 W/m^2. This warming is an order of magnitude more than the global average for the ocean: 0.32 W/m^2 (calculated from Levitus et al. 2001). The observed warming is comparable to the global average calculated by a constrained Global Circulation Model for 1993-2000 (Stammer et al. 2003), but their temperature increase of more than 0.5 °C for 600 m depth in the area during 1993-2000 is much higher than the observed values presented here.

The mean WDW temperature was at the maximum at the end of the 1990's (Fahrbach et al. 2004), and decreased after wards. This recent cooling is found around Maud Rise, while there has been a monotonic warming and increase in θ_{max} close to the Antarctic continent (Robertson et al. 2002). North of 64 °S WDW is in opposite phase (for heat, salt and thickness) to that of the mean for the section, and exhibit much smaller variation than in the south.

A new unit for heat content of a water column is suggested: 1 Mo = 31.536$\times$10^6 J/m^2. This is the heat comparable to a surface heat flux of 1 W/m^2 over a year. The mean warming of the WDW is thus close to 100 Mo in the period. A warming trend for the WDW based on the vertically integrated heat content Q over the section is more descriptive and easier to interpret than a warming trend based on θ_{max} or temperature at any constant depth.

Variation in inflow from the ACC explains some of the described variation in the WDW, and may be forced by atmospheric forcing (Fahrbach et al. 2004). This is true for a warming event (1989-1992), but less so for a cooling event (1984-1989). However, the WDW salinity increased with the warming, and decreased with the cooling, so both have an advective nature. The cooling event is not visible when looking at θ_{max}, and indicates that the vertical extent of the WDW is a better indicator of cooling/warming events for the water mass.

Water masses close to Maud Rise (64-68°S) exhibit a warming larger than the mean 1977-1984, and a significant cooling during the 1990's. The cooling is related to a reduction in the sea ice cover that was increasingly frequent during the Antarctic winters in this period. The reduced sea ice cover is always observed in the vicinity of Maud Rise, and was termed the Maud Polynya.

6 Acknowledgments

I am grateful to Tor Gammelsrød, Richard Bellerby, and Arne Foldvik for local support and encouragement, and Ole A. Nøst and Jane O'Dwyer (Norwegian Polar Institute, Tromsø) for helpful comments and sharing the data from 2001. Three anonymous reviewers helped improve the manuscript significantly. Data from 1996 was kindly supplied by G. Rohardt at the Alfred Wegener Institute, Bremerhaven, Germany. This research has been supported by the Norwegian Research Council under contract 143106/432. This is publication Nr. A80 from the Bjerknes Centre for Climate Research

References

AWI Oceanographic Observations Database (2002). Alfred Wegener Institute, Bremerhaven, Germany. http://www.awi-bremerhaven.de-/OZE/index.html.

Bersch, M., G. A. Becker, H. Frey, and K. P. Koltermann (1992). Topographic effects of the Maud Rise on the stratification and circulation of the Weddell Gyre. *Deep Sea Research 39*(2), 303–331.

Cavalieri, D., C. Parkinson, P. Gloerson, and H. J. Zwally (1999, updated 2002). Sea ice concentrations from nimbus-7 smmr and dmsp ssm/i passive microwave data. CD-ROM. National Snow and Ice Data Center, Boulder, CO, USA.

Fahrbach, E., M. Hoppema, G. Rohardt, M. Schröder, and A. Wisotzki (2004). Decadal-scale variations of water mass properties in the deep Weddell Sea. *Ocean Dynamics 54*, 77–91.

Fahrbach, E., G. Rohardt, and G. Krause (1992). The Antarctic Coastal Current in the southeastern Weddell Sea. *Polar Biology 12*, 171–182.

Foldvik, A., T. Gammelsrød, and T. Tørresen (1985). Hydrographic observations from the Weddell Sea during the Norwegian Antarcic Research Expedition 1976/77. *Polar Research 3*, 177–193.

Foster, T. D. and E. D. Carmack (1976). Temperature and salinity structure in the Weddell Sea. *Journal of Physical Oceanography 6*, 36–44.

Gille, S. T. (2002). Warming of the Southern Ocean since the 1950s. *Science 295*, 1275–1277.

Gloersen, P., W. J. Campbell, D. J. Cavalieri, J. C. Comiso, C. L. Parkison, and H. J. Zwally (1992). *Arctic and Antarctic sea ice, 1978 - 1987*. National Aeronautics and Space Administration, Washington, D.C.

Gordon, A. (1982). Weddell Deep Water variability. *Journal of Marine Research 40*, 199–217.

Gordon, A. L. (1978). Deep Antarctic convection west of Maud Rise. *Journal of Physical Oceanography 8*, 600–612.

Gordon, A. L. and B. A. Huber (1995). Warm Weddell Deep Water west of Maud Rise. *Journal of Geophysical Research 100*(C7), 13747–13753.

Holland, D. M. (2001). Transient sea-ice polynya forced by oceanic flow variability. *Progress in Oceanography 48*, 403–460.

Levitus, S., J. I. Antonov, T. P. Boyer, and C. Stephens (2000). Warming of the World Ocean. *Science 287*, 2225 – 2229.

Levitus, S., J. I. Antonov, J. Wang, T. L. Delworth, K. W. Dixon, and A. J. Broccoli (2001). Anthropogenic Warming of Earth's Climate System. *Science 292*, 267 – 270.

Martinson, D. G. and R. A. Ianuzzi (1998). *Antarctic ocean-ice interaction: implications from ocean bulk property distributions in the Weddell Gyre*, Volume 74 of *Antarctic Research Series*, pp. 243–271. Washington, D.C.: American Geophysical Union.

Martinson, D. G., P. D. Killworth, and A. L. Gordon (1981). A convective model for the Weddell Sea Polynya. *Journal of Physical Oceanography 11*, 466–488.

McPhee, M. G. (2000). Marginal thermobaric stability in the ice-covered upper ocean over Maud Rise. *Journal of Physical Oceanography 30*(11), 2710–2722.

McPhee, M. G., C. Kottmeier, and J. H. Morison (1999). Ocean heat flux in the central Weddell Sea during winter. *Journal of Physical Oceanography 29*(6), 1166–1179.

Millero, F. J. (1978). Freezing point of sea water. In *Eighth Report of the Joint Panel on Oceanographic Tables and Standards*. UNESCO, Paris.

Morgan, P. P. (1994). *SEAWATER: A Library of MATLAB Computational Routines for the Properties of Sea Water* (Report 222 ed.). Hobart, Tasmania, Australia: CSIRO Marine Laboratories.

Mosby, H. (1934). The waters of the Atlantic Antarctic Ocean. In *Scientific Results of the Norwegian antarctic Expeditions 1927-1928 et SQQ*, Volume 1, pp. 1–131. Det Norske Videnskaps-Akademi i Oslo.

Naveira Garabato, A. C., K. J. Heywood, and D. P. Stevens (2002). Modification and pathways of Southern Ocean deep waters in the Scotia Sea. *Deep Sea Research PartI 49*, 681–705.

O'Dwyer, J. (2002). Report from NARE cruise 2001. Technical report, Norwegian Polar Institute.

Orsi, A. H., G. C. Johnson, and J. L. Bullister (1999). Circulation, mixing, and production of Antarctic Bottom Water. *Progress in Oceanography 43*, 55–109.

Robertson, R., M. Visbeck, A. Gordon, and E. Fahrbach (2002). Long-term temperature trends in the deep waters of the Weddell Sea. *Deep Sea Research Part II 49*, 4791–4806.

Schlitzer, R. (2001). Ocean Data View. http://www.awi-bremerhaven.de-/GEO/ODV.

Schröder, M. and E. Fahrbach (1999). On the structure and transport of the eastern Weddell Gyre. *Deep Sea Research Part II 46*, 501–527.

Stammer, D., C. Wunsch, R. Giering, C. Eckert, P. Heimbach, J. Marotzke, A. Adcroft, N. Hill, and J. Marshall (2003). Volume, heat and freshwater transports of the global ocean circulation 1993-2000, estimated from a general circulation model constrained by World Ocean Experiment (WOCE) data. *Journal of Geophysical Research 108*(C1), 3007, doi:10.1029/2001JC001115.

Venegas, S. A. and M. R. Drinkwater (2001). Sea ice, atmosphere and upper ocean variability in the Weddell Sea, Antarctica. *Journal of Geophysical Research 106*(C8), 16747–16765.

Whitworth, T. and W. D. Nowlin (1987). Water masses and currents of the Southern Ocean at the Greenwich Meridian. *Journal of Geophysical Research 92*(C6), 6462–6476.

World Ocean Database (1998). National Oceanographic Data Center, Silver Spring MD USA. http://www.nodc.noaa.gov.

Zwally, H. J., J. C. Comiso, C. L. Parkinson, D. J. Cavalieri, and P. Gloersen (2002). Variability of Antarctic sea ice 1979–1998. *Journal of Geophysical Research 107*(C5), 3041, doi:10.1029/2000JC000733.

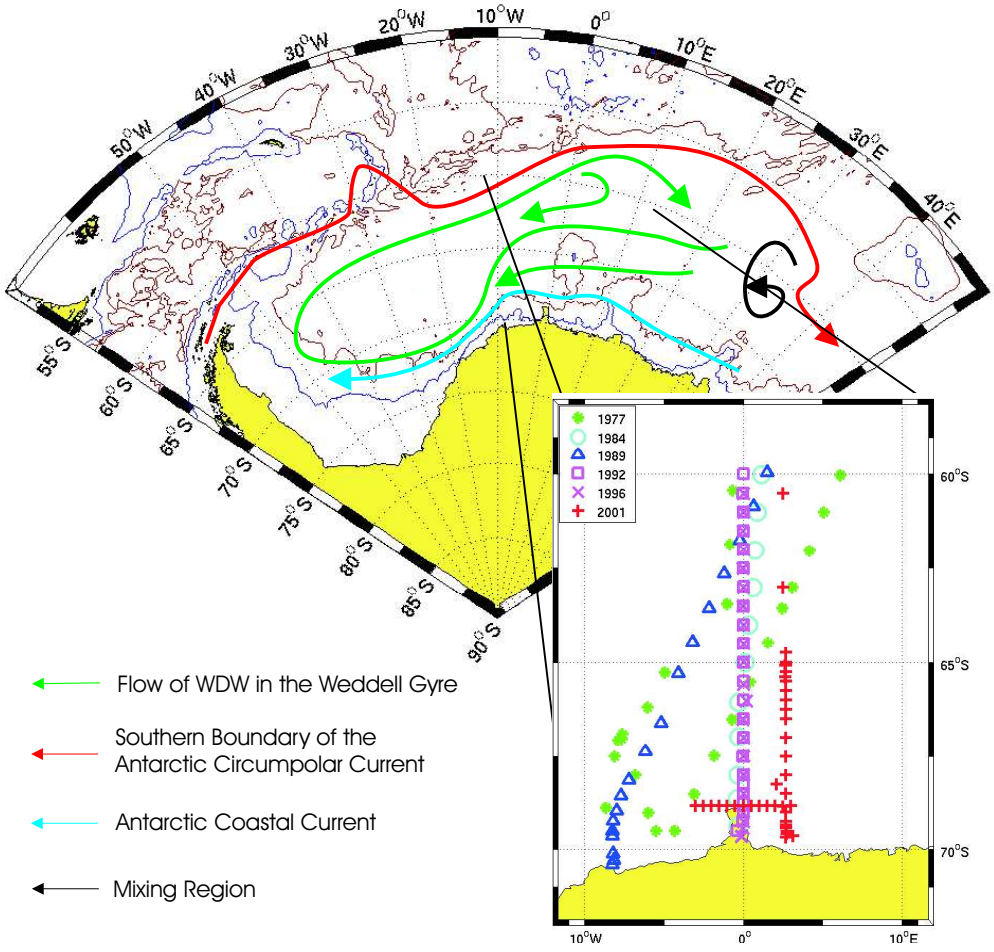


Fig. 1. The Weddell Gyre and a sketch of the mean flow north of Dronning Maud Land. Patterns of flow are based on Orsi et al (1999) and Schröder and Fahrbach (1999). Maud Rise is centrally located at 3°E and 65°S. Available CTD data from the years 1977(∗), 1984(∘), 1989(△), 1992(□), 1996(×) and 2001(+) are shown.

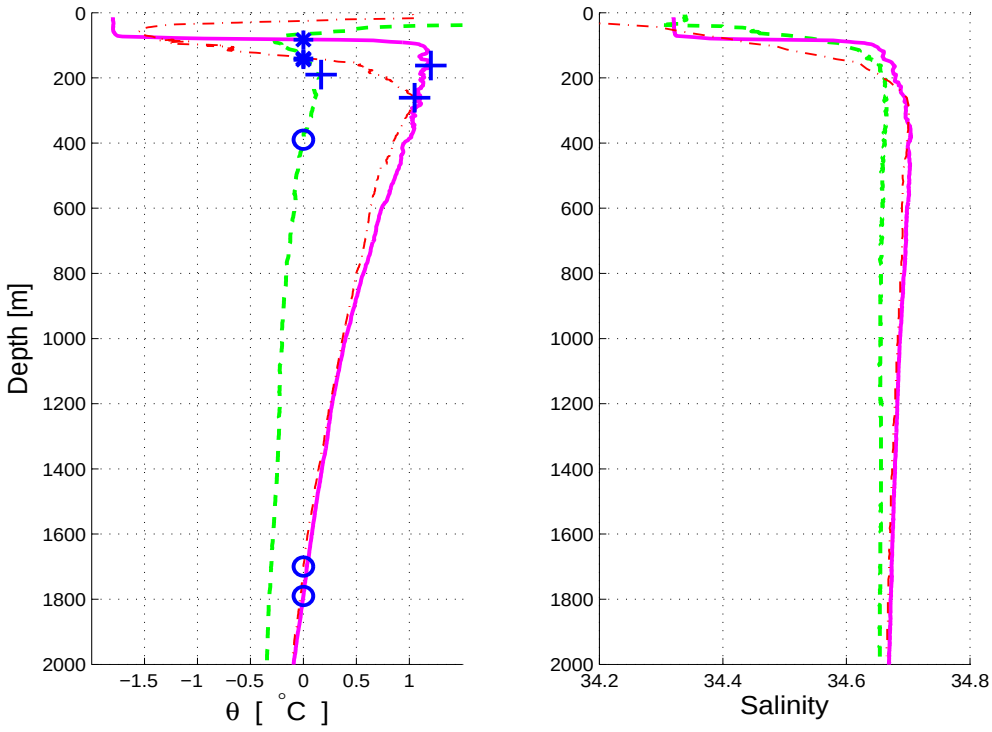


Fig. 2. Temperature and salinity of three selected stations in the Weddell Sea at 67.5 °S. The station from 1977 (– –) is station 82 from 1977 (8 °W), the one from 1992 is station 598 at the Greenwich meridian (—), and the one from 2001 (– · –) is station 35 from 2001 (2.7 °E). Upper boundary (∗), lower boundary (∘), and the core temperature θ_{max} (+) of the WDW are indicated. Uncertainty for temperature is ±0.006°C and ±0.005 for salinity.

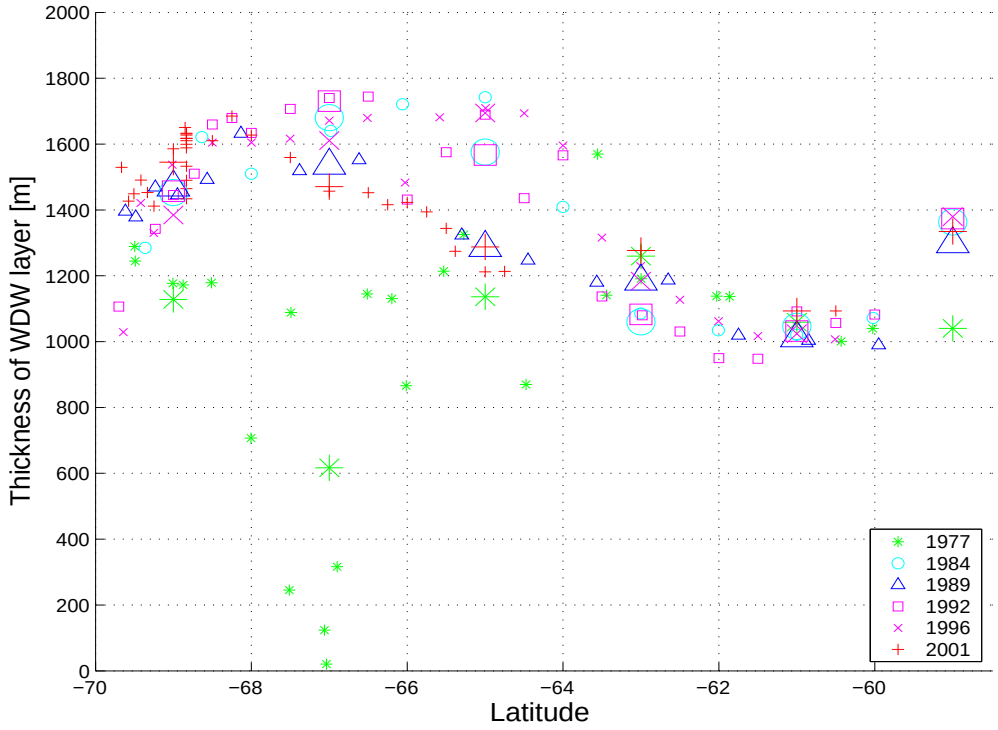


Fig. 3. Thickness of the Warm Deep Water layer along the Greenwich meridian between 1977 and 2001.Averages over the latitudes 60-62, 62-64, 64-66, 66-68, and 68-70 °S are plotted with larger size at the mid latitude. Total averages for the section 60-70 °S are plotted to the right (59 °S). Uncertainty of all data points are ±20 m.

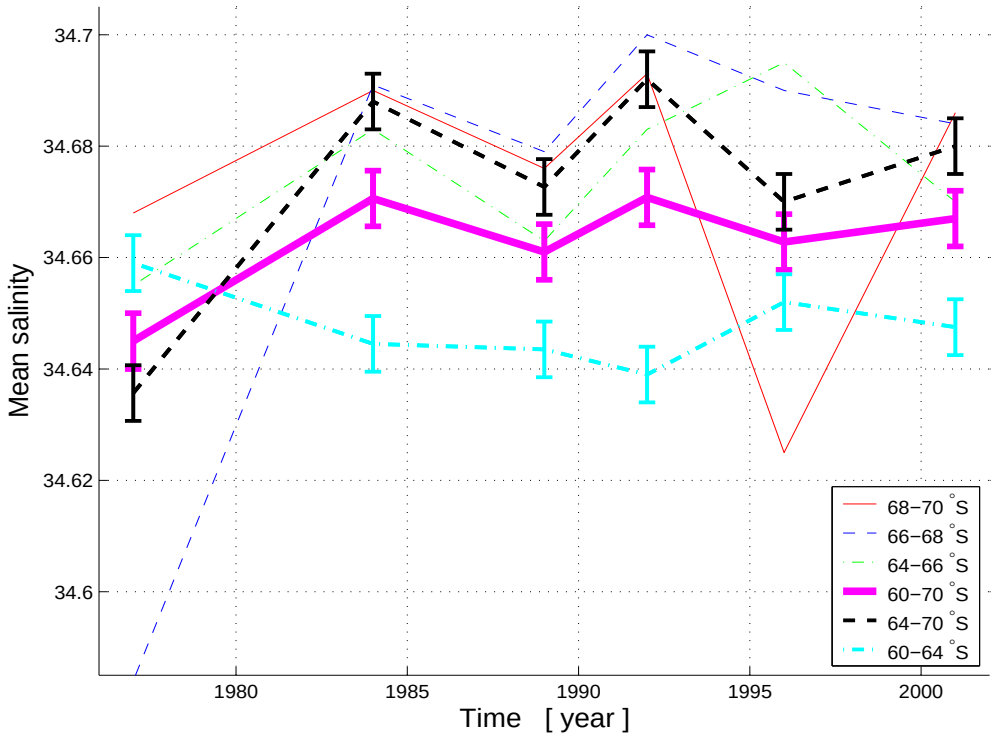


Fig. 4. Mean salinity of the WDW in latitudinal bins from the Greenwich meridian with time. Error bars of ± 0.005 apply to all curves and indicate instrumental uncertainty and the standard deviation along 69 °S in 2001.

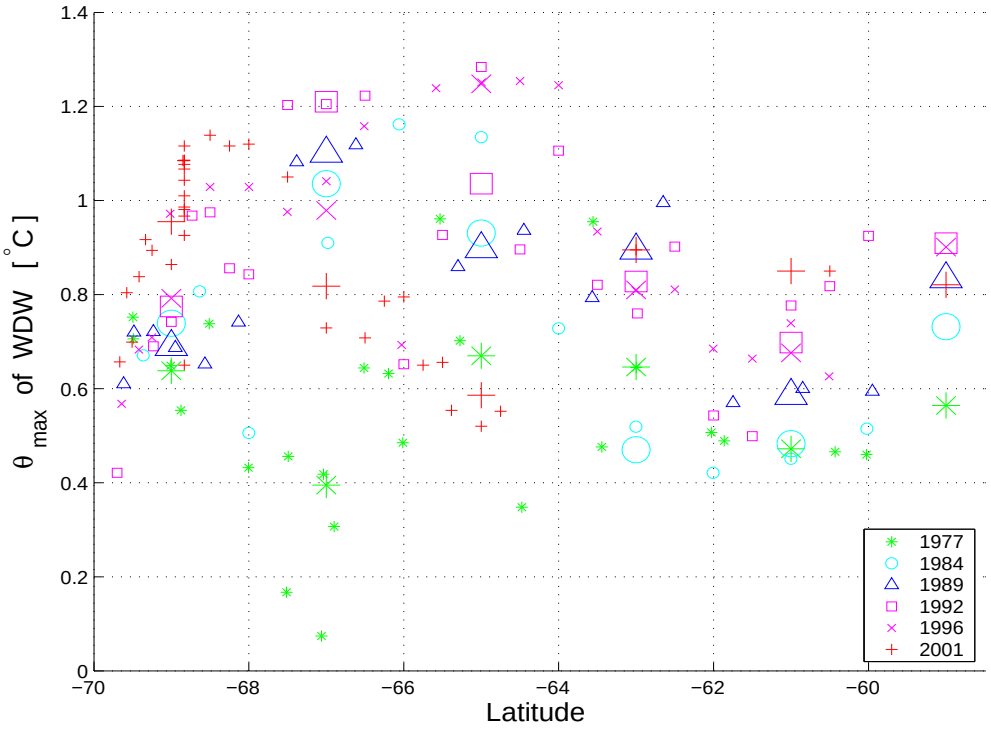


Fig. 5. Core temperature θ_{max} of WDW along the Greenwich meridian for 1977-2001. Averages over the latitudes 60-62, 62-64, 64-66, 66-68, and 68-70 °S are plotted with larger size at the mid latitude. Total averages over the latitudinal bins 60-70 °S are plotted to the right (59 °S). Instrumental uncertainty of all data points are ± 0.006°C.

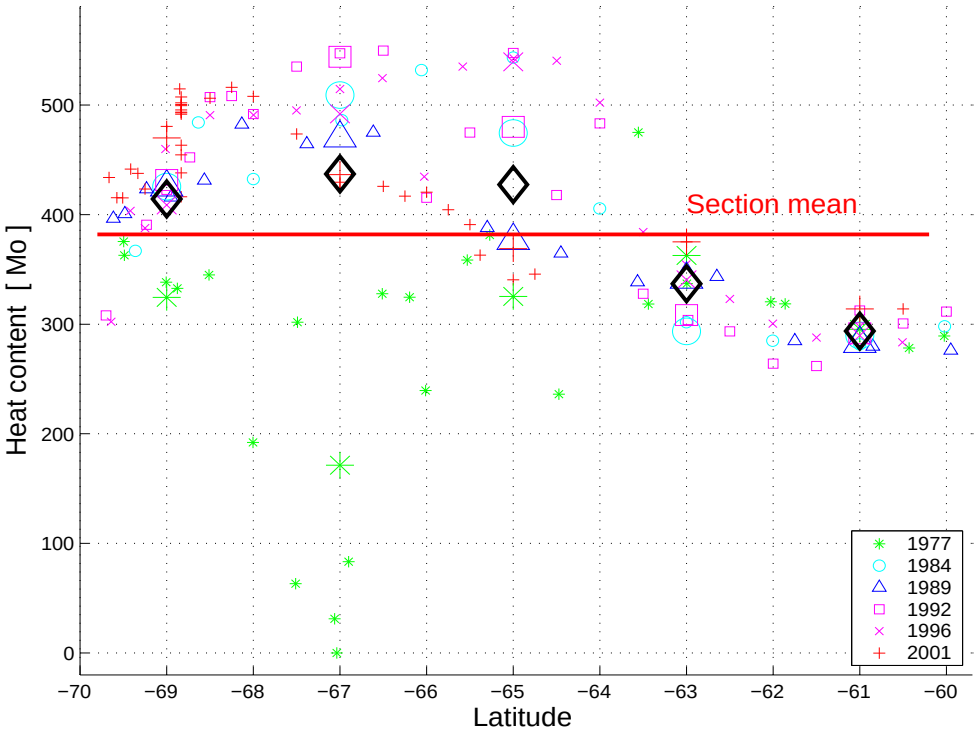


Fig. 6. Heat content of the WDW along the Greenwich meridian for 1977-2001 expressed in the unit 1 Mo = 31.536×10^6 J/m^2. This represents an imaginary constant heat flux needed for cooling WDW to the surface freezing point over a year. Average values for the 2 °S bins are plotted at the central latitude (69, 67, 65, 63 and 61 °S) with larger symbols. Average values for all years in one bin is plotted as large black diamonds. Instrumental uncertainties of all data points are ± 0.016 Mo.

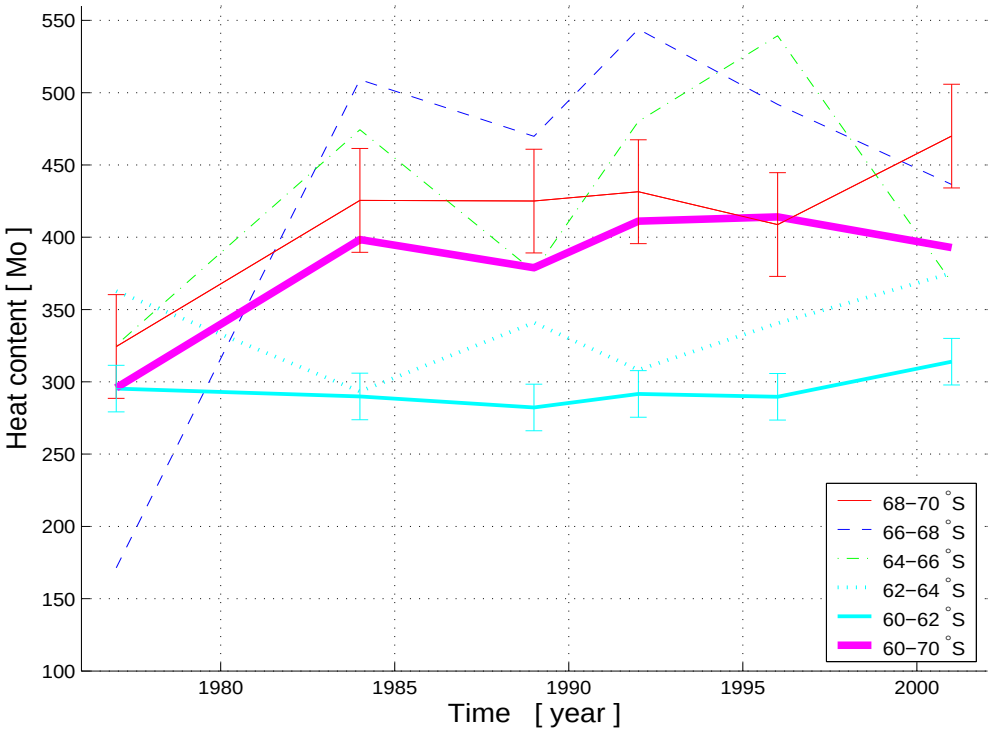


Fig. 7. Heat content in latitudinal bins from the Greenwich meridian with time. Instrumental uncertainties of ± 0.016 Mo are not shown, but two estimates of uncertainty due to natural variability within the bins are shown for the 60-62 and 68-70 °S (± 16 Mo and ± 36 Mo).

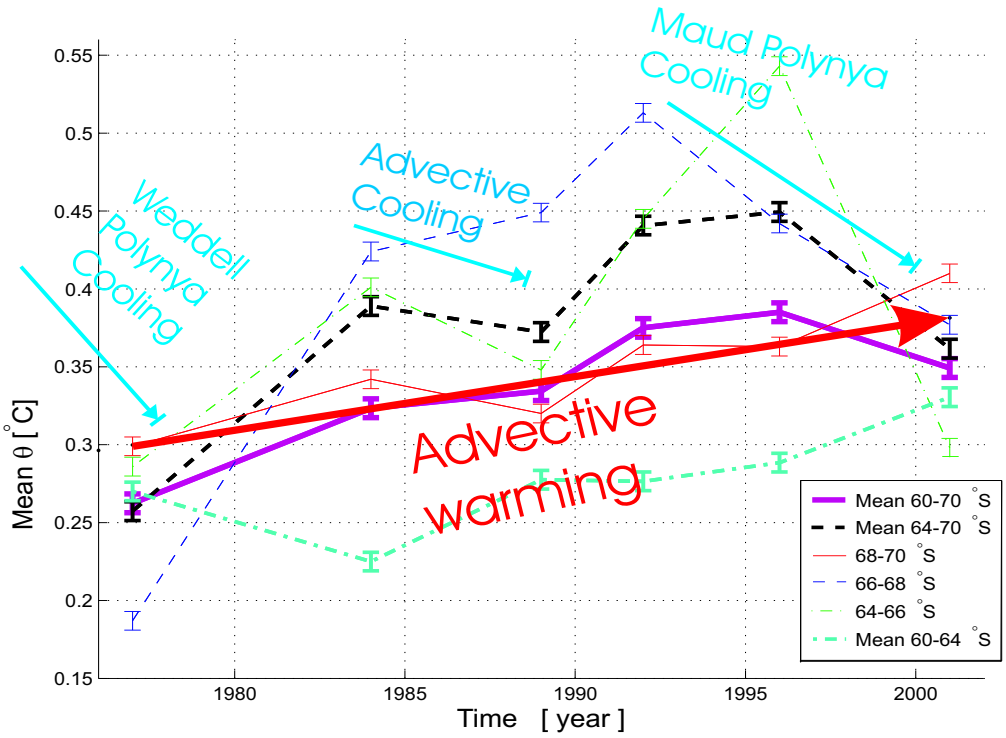


Fig. 8. Mean temperature of the WDW in latitudinal bins from the Greenwich meridian with time. The means are calculated over the varying thickness of the WDW. The linear 'Advective warming' trend is added from Gille (2002) (0.17 °C 1950-2000) and placed at 0.3 °C in 1977 for comparison.

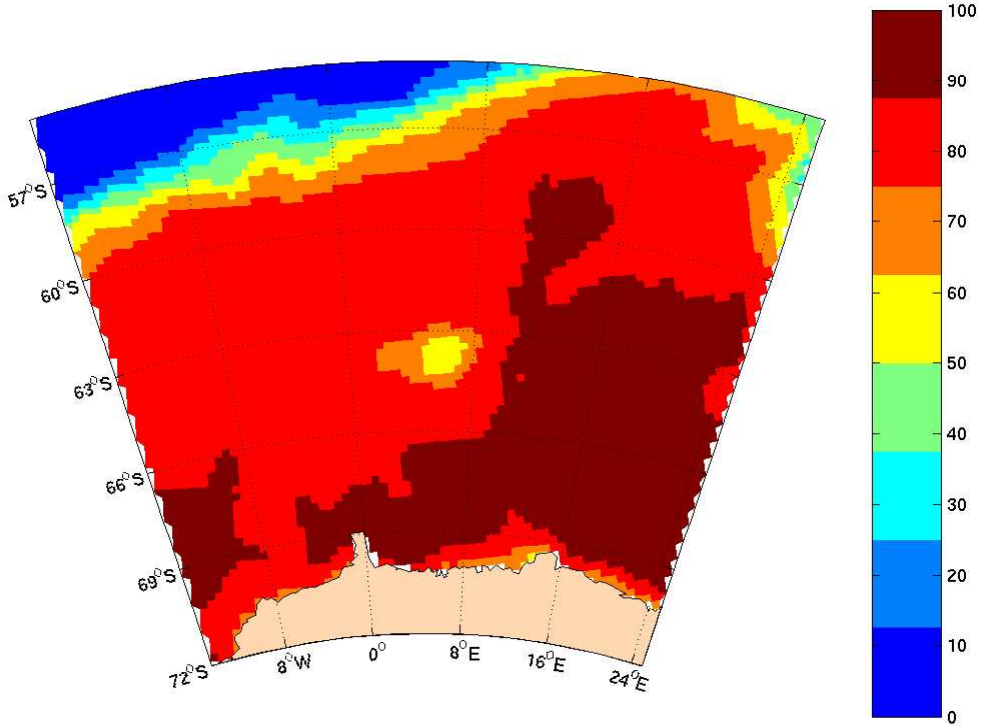


Fig. 9. Monthly mean sea ice concentration of the Weddell Sea during September 1994 from DMSP SSM/I Passive Microwave Data.

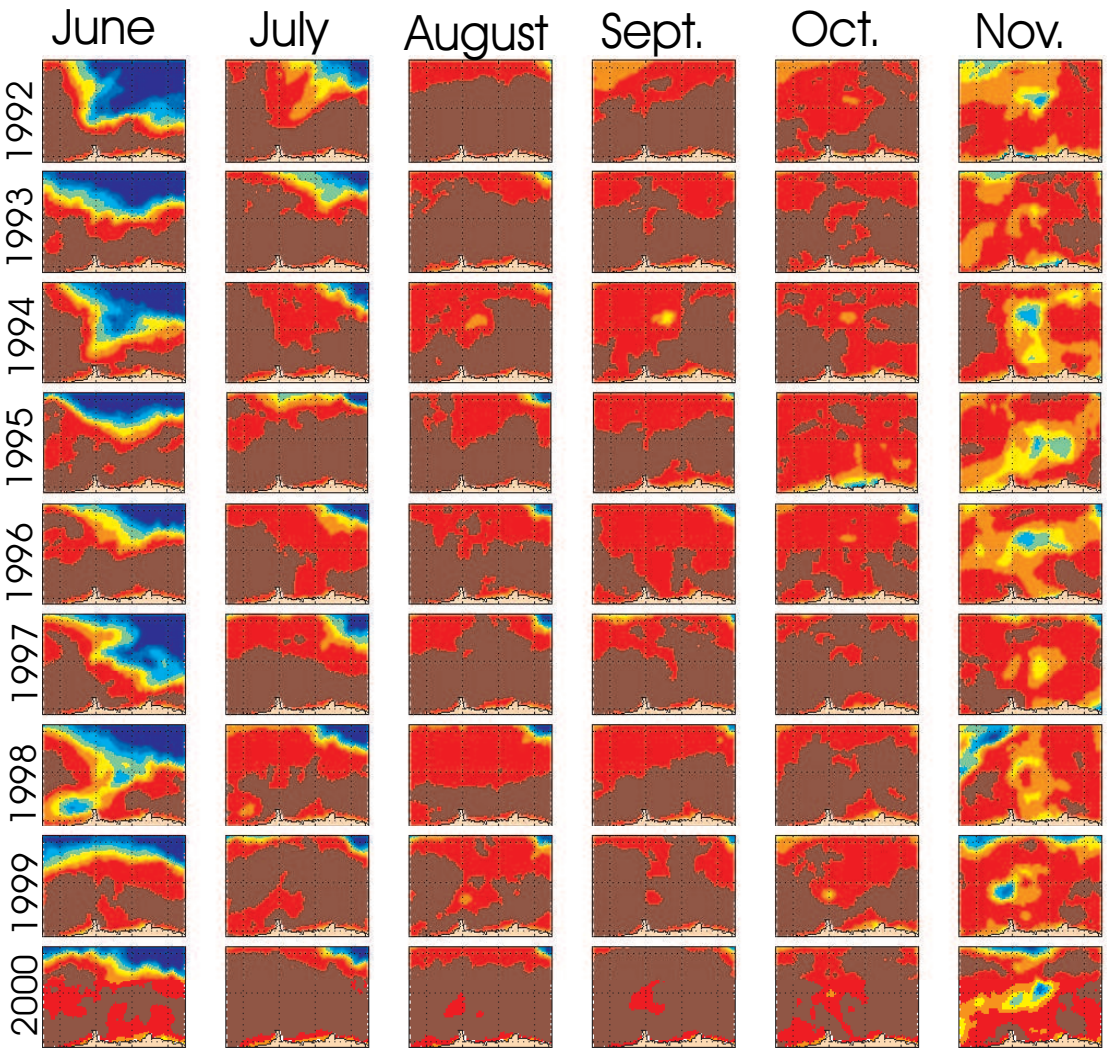


Fig. 10. Monthly mean sea ice concentration of the Weddell Sea during Antarctic winters between 1992 and 2000 from DMSP SSM/I Passive Microwave Data. Latitudes are plotted at 60, 65 and 70°S, longitudes at 10°W, the Greenwich meridian, as well as 10 and 20°E. The same color coding for the sea ice cover [%] as in figure 9 is used.