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Note

Causes of deep-water variations: Reply to comment by E. Fahrbach, M. Hoppema, G. Rohardt, M. Schröder and A. Wisotzki

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Abstract

Vertically integrated heat content from the Weddell Sea along 69 °S in vicinity of the Greenwich meridian from the 1977–2001 period is presented. This demonstrates that the east-west variability in the area is lower than the natural variability. The sensitivity on the choice of lower boundary for the heat content integral is discussed in relation to upwelling from the deeper water masses. The cooling around Maud Rise during the 1990's on the order of 20 W/m^2 remains significant, and may be explained by increased surface heat fluxes during winter months with lower than normal sea ice concentration.

1. Introduction

In order to describe and understand any process, it is good to critically challenge ideas put forward by others. I thus appreciate this opportunity to further build our understanding of the Weddell Sea on what has been, and probably will remain, a rather limited set of observations.

The Greenwich meridian is one of the better-sampled sections in the Southern Ocean, and what remains clear is that the Warm Deep Water (WDW) since 1977 has warmed comparable to a surface heat flux of 4 W/m^2. This is more than any other mass of water in the global ocean, and points to the importance of future surveys to this area. Fahrbach et al. (2004) describe data collected during 9 German cruises to the meridian between 1986 and 2002, and this is clearly the major observational contribution to our understanding of the processes in the area during the last decades.

In my recent article (Smedsrud, 2005), the aim was to extend our understanding by going back in time and incorporate older cruises, as well as to locate where the largest variations in heat content were observed along the meridian. Three questions raised in the comment from Fahrbach et al. in this issue are important in this regard, and I will attempt to answer them here: (1) Does the east–west spread in the observations used preclude any of the conclusions drawn? (2) How dependent are the heat content values on the choice of the lower boundary? and (3) What caused the estimated cooling of 20 W/m^2 between 1995 and 2000 around Maud Rise (64–68°S)?

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2. The Weddell front

The area of my investigation did not cover the Weddell Front as the Norwegian data from 1977 and 2001 is limited to south of 60°. When I discussed the plot of temperature at the 300 dbar level (Fig. 7 in Fahrbach et al., 2004) I was therefore not referring to the Weddell Front. The expression ‘warming and cooling events’ (page 251 in Smedsrud, 2005) was thus meant to refer to changes in heat content around Maud Rise. This should have been stated more clearly. The 300 dbar plot illustrates the changes in the Weddell Front in a good way, and also reflects the constant heat content between 60–62°S. The mean temperature trend of the WDW follows the warming trend in the Circumpolar Deep Water (CDW), and clearly warmer water is mixed into the Weddell Gyre along the front. It is, however, difficult to quantify variations in this mixing. The stronger Weddell Front after the mid 1990s might indicate a weaker inflow of CDW, but it remains to be quantified.

3. Natural variability

It is correct, as stated in the comment from Fahrbach et al., that there are large regional differences in heat content, and that the significant variability is on the order of 100 Mo (1 Mo ‘Mosby’ = 31.536×10^6 J/m^2, the heat content equal to 1 year with a surface flux of 1 W/m^2). To illustrate this variability I plotted each vertically integrated heat content value from the original profiles, as well as the bin and section averages. Knowing that the variability is large should not preclude attempts to discuss it; on the contrary, it is interesting to locate the spatially and temporally different regions. The ‘natural variability’ was estimated as the standard deviation of ±36 Mo for the 17 stations occupied in 2001 in the southern bin (68–70°S), thus 100 Mo compares to three standard deviations.

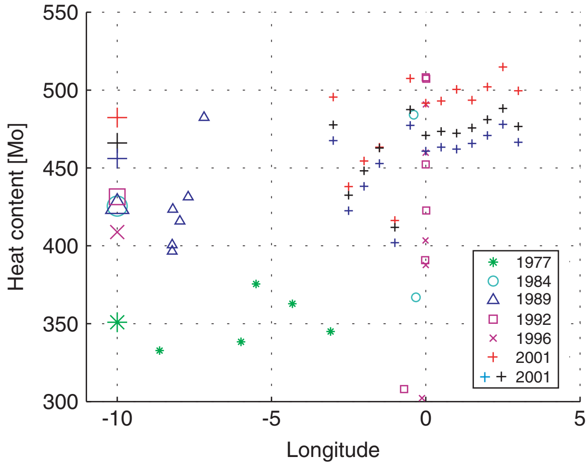

Fig. 1. Heat content of the Warm Deep Water in the Weddell Sea for different years. The values are vertical integrals of individual temperature profiles between 68 and 70°S as described in Smedsrud (2005). Large symbols at 10°W are the yearly bin-averages. The two lower 2001 values are included to illustrate the effect of using a fixed lower boundary of 1600 and 1640 m.

4. East–west spread of stations

The heat content of the southern bin plotted as a function of longitude is shown in the new Fig. 1. This is where the observations used in my analysis had the largest spread between the different years, and I hope it adds further information in the present discussion. My main conclusion is that the east–west spread does not add further variability. In fact it is the years with no east–west spread at all, 1992 and 1996 that have the largest variability within the bin. I therefore still hold the view that there is no need to ‘account’ for the observed east–west variability. My results indicate that the largest variability is found in the region around Maud Rise, both spatially and temporally, and not in the region with the largest horizontal spread.

5. Lower boundary sensitivity

To illustrate how sensitive the heat content of the WDW is to the choice of the lower boundary, I have also added two new sets of 2001 values to Fig. 1 using a fixed depth instead of the water mass definition ($\theta > 0$ °C). The values show that a depth of 40 m (50% change in the suggested Antarctic bottom water upwelling speed of 15 m/year from Orsi et al. (1999) applied over 5 years) compares to 10 Mo. Thus variations in the lower boundary do not seem critical, and are smaller than the ‘natural’ variability estimated for the fairly stable northern bin of ±16 Mo. The fixed depth heat contents were integrated to 1600 and 1640 m, giving averages of 456 and 466 Mo compared to the original 2001 value of 482 Mo.

6. Maud Rise cooling

The observed cooling between 1993/95 and 2000 close to Maud Rise is not affected by the east–west station spacing, and the magnitude of 20 W/m^2 (100 Mo over 5 years) is indeed significant. This cooling is comparable to the climatic mean upward heat flux from the WDW of 25–35 W/m^2 in the area (Martinson and Ianuzzi, 1998). There is additional cooling of the WDW towards the lower boundary, but it remains a future challenge to quantify this flux and locate the regions with the significant variation in heat content of the Weddell Sea Deep Water (WSDW) and the bottom water. The observations from 1977 and 2001 only covered the upper 2000 m, so it was not possible to include the deeper water masses in my analysis. Fahrbach et al. (2004) show that the average temperature of the WSDW for the section cooled between 1992 and 2001, indicating no increase in the downward flux until then, but also a subsequent increase the following 2 years.

If there was no extra surface cooling around Maud Rise between 1995 and 2000, this would imply almost no heat transport into this region over these years. The new observations from Klatt et al. (2005) show a steady southwestward current (2.9 cm/s) at 64°S and 2000 m depth between 1996 and 2001. The variation in time is not shown for the current meters at 206 and 784 m depth (4.4 and 4.5 cm/s), but if they also measured temperature it should be possible to estimate the heat transport during these years directly. But the flow around Maud Rise is complex, and much of the cooling can be explained by extra surface flux in the months with observed low sea ice concentrations as stated in Smedsrud (2005).

7. Concluding remarks

A lower than normal mixing of CDW into the Weddell Gyre during the late 1990s is of course also a possibility, and may well be a part of the explanation. But the mechanisms connecting Maud Rise heat content to the observed changes in the Weddell Front, more than 800 km away, remain unclear, including the advective pathways. In contrast are the heat fluxes in a polynya fairly well known; a $\approx$10% reduction in sea ice cover, as documented in the SSM/I data during 19 out of 36 (52%) of the winter months during the 1990s, compares with an increased surface heatflux of roughly 10 W/m^2. This still seems like a very possible explanation for a majority of the observed cooling. But I eagerly await the future results from the AWI long-time moorings near Maud Rise and dedicated numerical model experiments to see if they can change my view on what causes the variation in WDW heat content.

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