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Note

Causes of deep-water variation: Comment on the paper by L.H. Smedsrud "Warming of the deep water in the Weddell Sea along the Greenwich meridian: 1977–2001"

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1. Introduction

The recent paper by Smedsrud (2005) addresses long-term changes in the water masses of the Weddell Sea, and adds to other recent papers concerned with changes in this region (e.g., Venegas and Drinkwater, 2001; Robertson et al., 2002; Zwally et al., 2002; Fahrbach et al., 2004). As the region stands out as pivotal, changes therein have impact on the world oceans and climate, and thus it is highly desirable that more knowledge is gained. The paper by Smedsrud (hereafter called S2005) is a welcome addition to this. Some of the other papers that have appeared recently address very similar issues, based partly on the same data (Robertson et al., 2002; Fahrbach et al., 2004). Comparing the methods and results of these papers and the conclusions drawn, additional discussion appears necessary. Below we discuss some controversial points in S2005, where we emphasize issues related to our paper (Fahrbach et al., 2004; hereafter called F2004).

2. Heat content and data base

Thickness of the Warm Deep Water (WDW) layer is extensively discussed in S2005—the heat content is directly related to it. As a matter of fact, the concept of heat content is similar to that of the average temperature of the WDW layer as implemented in F2004. On page 246, S2005 states that changes in layer thickness are mostly caused by variation of the lower boundary. We note that the lower boundary is defined by the 0°C isoline, which in itself is not a firm bound. Vertical diapycnal mixing between the WDW and the underlying Weddell Sea Deep Water (which is colder) will change the depth of the boundary. Orsi et al. (1999) estimated the upwelling speed at the top of the Antarctic Bottom Water to be about 15 m yr^{-1}. As at the prime meridian, deep waters are advected along different pathways within the Weddell region, this is a significant source of variability, both for the WDW thickness and the heat content. Additionally, mixing with adjacent water masses will change the thickness and heat content. This holds particularly

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true for regions in which the gradients are large, such as along the rim of the Weddell Sea—the Antarctic coast or the adjacent open ocean, i.e. Antarctic Circumpolar Current (ACC)—and near topographic features like Maud Rise. Based on this, we expect that in S2005 the largest variability will occur in the southern bins (south of 64°) where Maud Rise and the rim are situated. The heat content distribution in S2005 shows exactly this behavior. Also, the northern edge is not covered by the limits as defined in S2005. Because of areas with relatively strong gradients, coarse resolution and spatial inhomogeneity of the data, a high "artificial" variability may be simulated.

In S2005 the author states that the heat fluxes associated with processes as discussed above are an order of magnitude lower than the mean heat content of the WDW, thus assuming them to be negligible. However, the mean heat content of the WDW is not the relevant quantity as a reference of variations. Of importance are the regional differences in the heat content between the inflow area in the south and the cold regime in the north, since they reflect the amount of heat that is actively involved in Weddell Sea processes and not heat only passively circulated around. These regional differences are on the order of 100 Mo, i.e., much lower than the mean heat content of 382 Mo—the unit Mo is defined by S2005 as being the heat comparable to a surface heat flux of 1 W m^{-2} during 1 year. Therefore, the variability of such a magnitude inherent to the data due to spatial variability poses a major problem and strongly diminishes the reliability of the analysis performed in S2005.

It must be added that the data base used in S2005 is particularly sensitive to the uncertainties outlined above because it contains large zonal differences of station locations. Smedsrud addressed this issue, and assessed the influence to be minor based on a zonal section at 69°S. We note that especially in the south, with the rough topography, the east–west variability in temperature is extremely large (see e.g., Orsi et al., 1993). Also in S2005 one can see that the range of the heat content over three degrees of longitude is about 100 Mo, which is definitely significant at a mean level of 382 Mo, and even more considering differences between the southern and northern limb on the order of 100 Mo (see previous paragraph). Note that in S2005 the largest zonal spread of stations occurs in the south, whereas towards the north this spread becomes smaller. This spatial pattern exactly coincides with the meridional variability of the heat content presented in S2005, where the variability in the northern part is indeed much smaller than in the south. The point that we want to make is that it is very difficult to discriminate between real and data-related causes for deduced variability in the heat content. Although our own data as presented in F2004 largely minimizes spatial variability (because all our sections are situated exactly along the prime meridian), the variability is still that large as to hamper an analysis based on regional bins. Therefore, we considered in F2004 only changes of horizontally integrated properties all across the gyre to avoid bias due to local data uncertainties. Finally, data from the entire cross section of the Weddell Gyre at the prime meridian, i.e. from 55°S (WF) to the Antarctic continent, were incorporated, which assures that all variability within the gyre and the transition zone is captured (see below). Although we do not doubt that the processes discussed by Smedsrud do occur in the Weddell Gyre (the occurrence of the Weddell Polynya in the 1970s is evidence enough) and may play some role in changes of heat content, the large source of variability, unaccounted for in Smedsrud's analysis, strongly reduces confidence in his conclusions.

3. Water exchange at the boundary: atmospheric forcing

A major point of disagreement between S2005 and F2004 is the role of the Weddell Front (WF)—between the ACC and the Weddell Gyre—, or the Southern boundary of the ACC, in causing variability of the inflow of Circumpolar Deep Water (CDW) into the Weddell Gyre. The main argument brought forward in S2005 against the importance of variations in water mass intrusions at the WF is that the heat content at 60–62°S is relatively constant. However, this ignores the fact that major changes in the heat content of the gyre occur north of that, due to frontal variability between 55°S and 58°S (F2004). Independent evidence that at the northern boundary of the Weddell Gyre, large water exchange takes place is found in Bagriantsev et al. (1989). In addition, a recent analysis involving the heat content of the gyre suggests that major exchange of the gyre with the ACC occurs west of the prime meridian (Klatt et al., 2005).

The traditional view is that the CDW enters the Weddell Gyre near its eastern edge (Deacon, 1979), from where it flows as intermediate water within the southern limb of the gyre. It should be realized, though, that the southern limb is not composed purely of inflowing CDW, but that mixing with already longer circulating CDW, modified within the gyre, takes place in the eastern region. Different kinds of eddies appear to play a role in this (Gouretski and Danilov, 1993; Schröder and Fahrbach, 1999). More recently, indications were found that also at other locations along the northern edge water exchange occurs (Bagriantsev et al., 1989; Klatt et al., 2005). Water entering the gyre at the northern edge will be redistributed within the gyre, first being transported eastward with the main flow, where near the eastern edge it will also join the southern limb flow. The exact flow paths are not well known. Circulation and recirculation of different varieties of intermediate water modify the lateral distribution of the CDW within the gyre. Thus the Weddell Gyre is influenced all along its northern edge and the influence is transferred into the gyre interior and southern limb. It is manifest that the structure of the Weddell Front should be a useful indicator for water exchange and also for variations in the southern limb.

As part of this discussion in S2005, the author states that a Hovmöller diagram of temperature at the 300 dbar level along the prime meridian section as depicted in F2004 "has limited value" for detecting temporal changes in the WF structure. The diagram at 300 dbar was introduced by us for illustrating the entire picture qualitatively. But it should be appreciated that the 300 dbar level is highly representative for the potential temperature maximum ($\theta_{\max}$) at the prime meridian as can be seen in contour plots (Fig. 2 in F2004, in which also the direct intrusion of water from the ACC into the gyre is clearly visible). Besides that, the fact that the variability of the heat content north of 64°S is the lowest in S2005 is fully consistent with the θ distribution in the 300 dbar level. Therefore, it can only be concluded that the long-term changes with regard to the WF are real, i.e., a weak front during the period from mid-1980s to mid-1990s allowing more intrusions of CDW into the gyre and a sharp front after the mid-1990s reducing CDW exchange across the WF. Although we are well aware of the fact that it is not easy to present conclusive evidence for the causes of the varying water exchange, we noticed that the air pressure difference 60–65°S, which is taken as a measure of the wind field over the southern ACC and the northern Weddell Gyre, shows a steady increase from the late 1980s to the late 1990s. This may point to a weak flow in the northern gyre during the late 1980s, and an increase after that. The weak flow in turn would facilitate intrusions of CDW from the north. We disagree with Smedsrud's contention that a relatively stable heat content at 60–64°S is evidence for minor importance of changes along the WF for the whole gyre. This is the more obvious as in the region east of the prime meridian, water masses from the northern limb of the gyre recirculate to the west (Orsi et al., 1993; Schröder and Fahrbach, 1999). Consequently, water exchange at the WF will have influence on the remaining gyre and contribute to the heat content of more southern parts (see previous paragraph).

Similarly as above, in F2004 we suggest that the warming of the WDW during the first part of the 1990s is due to an elevated inflow of deep water from the ACC during the late 1980s and early 1990s (there may be a time lapse of a few years for the water to move from the ACC to the southern limb of the gyre). This was deduced from an increase of the air pressure difference 70–65°S from the mid-1980s to about 1992–1993. Smedsrud appears to agree that variability in the inflow will cause variations of the heat content. He notes (rightly) that after that period the air pressure difference is lower and has no trend at all, which prompts him to the suggestion that this is contradictory with the observed cooling trend, as first reported by F2004. However, to our understanding, the apparent cooling of the WDW in the second half of the 1990s simply follows from the relaxation of the inflow as compared to the previously high inflow during the late 1980s and early 1990s; this does not require any particular cooling process whatsoever, as proposed in S2005. Data from S2005 appear to support our argument, as the heat loss in the bins 64–68°S in the late 1990s is on the order of 100 Mo (S2005, his Fig. 7), which equals about $20\,\mathrm{W\,m^{-2}}$. This is well within the range of "usual" heat losses for this area, and hence there is no need to invoke additional cooling processes involving polynyas or an enhancement of the "halo" of low ice concentration around Maud Rise (Lindsay et al., 2004). We fully agree that the trend in that air pressure difference is not the only and definite explanation, but this does not imply that it has no value. On the contrary, it is a crucial part of the explanation, but the inflow is additionally forced by activity at the WF and the flow in the northern limb of the gyre, and by possible recirculations west and east of the prime meridian. This was illustrated in F2004 by the air pressure differences in other relevant regions.

4. Concluding remarks

There is agreement between the different papers that the temperature and heat content of the WDW of the Weddell Gyre has increased from the 1970s until at least the mid-1990s. External factors, in particular the inflow from the ACC, appear to be the main forcing factor, which is in keeping with a decadal temperature increase in the ACC source water (Gille, 2002). Also a relaxation from the anomalous conditions during the great Weddell Polynya during the mid-1970s contributed significantly, but probably only in less than 10 years after that event (S2005). In the mid-1990s a steady cooling commenced. As Fahrbach et al. (2004) emphasize external factors and atmospheric forcing to be the main cause, which is consistent with a later paper by Klatt et al. (2005) based on additional data, Smedsrud (2005) pleads for internal processes around Maud Rise. We made the case for external factors to be the main cause as yet, although internal factors, such as polynya formation, have definitely the potential to significantly modify the heat content of the WDW. Unfortunately, it is largely unknown to what extent. For this purpose, the AWI has deployed long-time moorings near Maud Rise to monitor these processes (see also Klatt et al., 2005). With these and other data, future efforts are needed to disentangle internal from external forcing.

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