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INTERANNUAL CHANGES IN DEEP WATER MASSES ALONG THE WOCE SR4 SECTION (WEDDELL SEA, ANTARCTICA)

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1. INTRODUCTION

Recent studies have highlighted the importance of the oceans in climate variability and climate change (e.g. Simmonds and King 2004; Busalacchi 2004). In this sense, water masses act as important reservoirs of heat, salt and dissolved gases. They acquire their signatures from atmospheric processes near the formation zones and thus are excellent indicators of alterations in climatic conditions (e.g. Leffanue and Tomczak 2004). The Weddell Sea (WS) has an extreme importance because it is the main area of production and exportation of Antarctic Bottom Water (AABW) to the world ocean (Carmack 1977; Orsi et al. 1999). Those dense waters constitute important component of the global climate system and influence directly the entire Southern Hemisphere.

The water masses found at intermediate, deep and bottom layers in the Weddell Sea are respectively: Warm Deep Water (WDW), Weddell Sea Deep Water (WSDW) and Weddell Sea Bottom Water (WSBW). WDW is the main water mass forming the deep waters in the WS. WDW originates from Circumpolar Deep Water (CDW) transported by Antarctic Circumpolar Current (ACC), which enters inside the gyre between 20-30°E (Gouretski and Danilov 1993). The CDW displacement and mixing with surface waters alters its initials thermohaline characteristics resulting in WDW, which is cooler and fresher than CDW. WSDW is a mixing between WDW and the young WSBW formed mainly along the WS shelf breaks. WSDW is the main component of the AABW that escapes from the WS as WSBW is topographically constrained and remains in the area (Fahrbach et al. 1995; Orsi et al. 1999).

The present study aims to describe the variability and changes observed in the distribution and concentration of the main deep water masses along the WOCE SR4 repeat section (Figure 1). Some evidences that correlate the observed water masses anomalies and the Southern Annular Mode (SAM; Thompson and Wallace 2000) are presented. That correlation shows the influence exerted by the SAM forcing on the WSBW production.

2. METHODOLOGY AND DATA

Optimum Multiparameter (OMP) analysis (see Tomczak and Large 1989) was used to quantify the mixing between the major water masses present in the intermediate and deep layers of the WS. The data used were collected during the WOCE program and cover the WS central region approximately from 63°S and 71°S (Figure 1; see Fahrbach et al. (2004) to obtain more details of the dataset). Five years were considered in the analysis (i.e. oct/1989; dec/1990; dec/1993; apr/1996 and apr/1998) and the following water masses were separated by OMP: WDW, WSDW and WSBW. Table I shows the index parameters used to the model input.

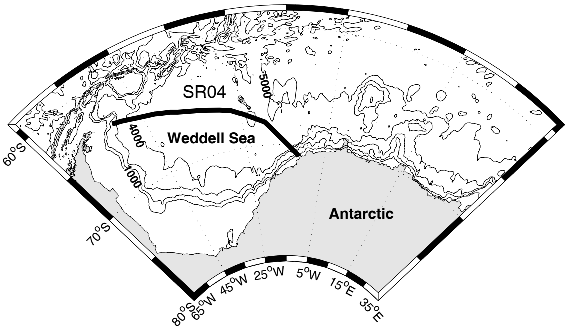

Figure 1 – Hydrographic sections position occupied during WOCE program.

Table I – SWT, parameters and weights for model input. Potential temperature (θ), Dissolved Oxygen (DO).

SWT Parameter	WDW	WSDW	WSBW	Weight
θ (°C)	0.5	-0.3	-0.9	11.5
Salinity	34.70	34.66	34.64	11.5
DO (μM)	212	234	263	11.9

OMP output data were objectively mapped onto a regular grid and differences between water mass relative contribution and mean (i.e. the anomalies) were computed at each mesh point. After, the anomalies were standardized. The anomalies were calculated only if the water mass contribution to the mixing was greater than 30%.

3. RESULTS AND DISCUSSION

The anomalies show an increase trend in the WDW contribution and a corresponding decrease in the WSBW contribution between 1989 and 1998. WSDW contribution show higher

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changes in its shallower levels, probably due to mixing with WDW in depths between 1000-2000m, where the anomalies show decreasing values. WSDW below 2000m shows stable conditions with small anomaly values (i.e. conditions around the mean).

We focus the discussion mainly on the WSBW contribution, showing here the results only for the years 1990 and 1996, which displayed extreme opposite phase (Figure 2). The 1990 cruise was exceptional since the highest positive anomalies corresponding to WSBW and highest negative anomalies corresponding to WSDW were observed. That suggested the WSBW is produced by pulses, which is in agreement with the theoretical work by Timmermann et al. (2001). The negative WSBW anomalies found in 1996 can be indicating a direct production of a water mass with another density, as WSDW (Meredith et al. 2000), possibly due to particular hydrographic characteristics of the source waters during that year. That is supported by the increased of the WSDW anomalies at depth around 3000-4000m (Figure 2).

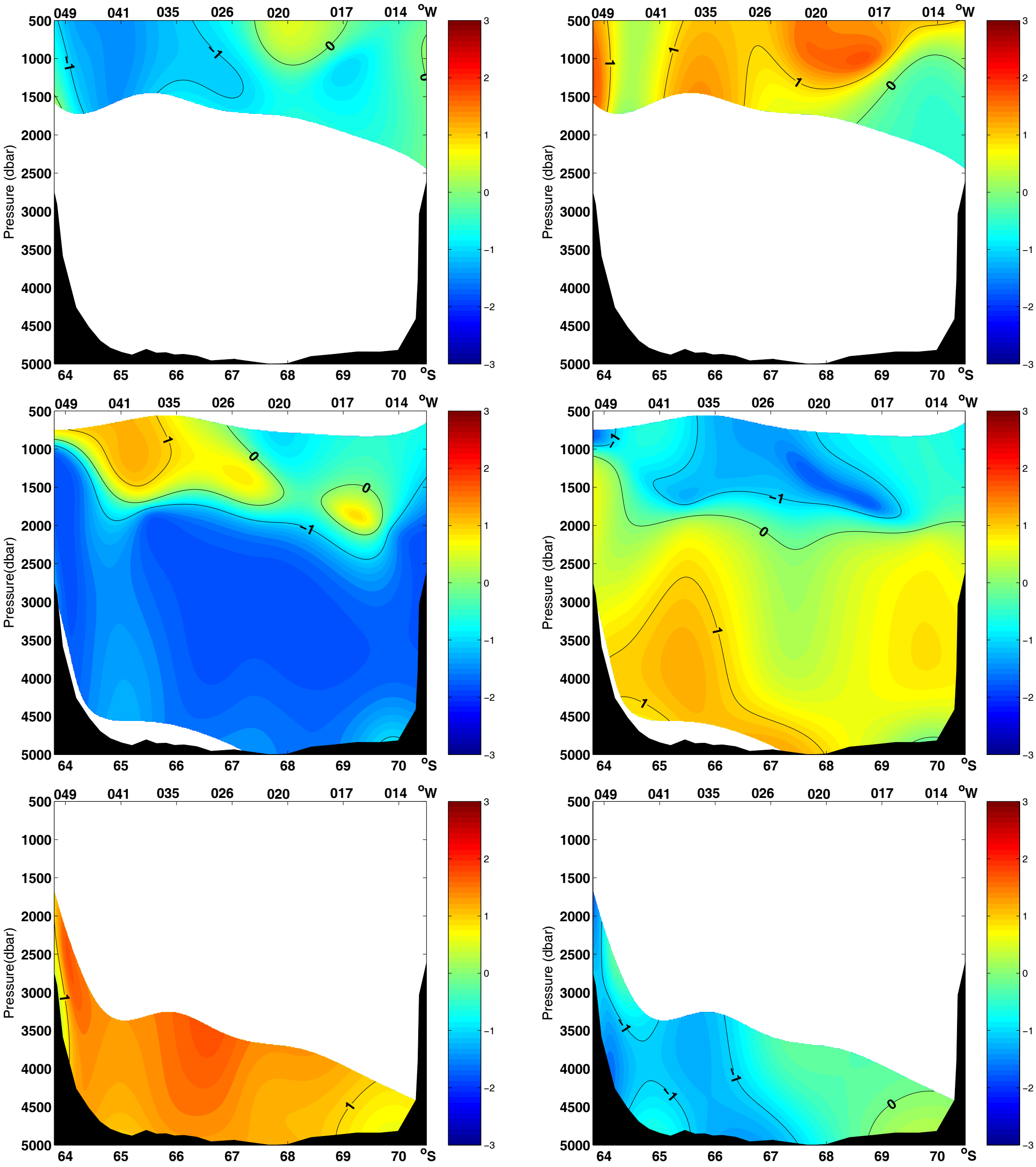

Figure 2 – Water mass anomalies distribution during cruises 1990 (left) and 1996 (right). Warm Deep Water (upper), Weddell Sea Deep Water (middle) and Weddell Sea Bottom Water (bottom).

The literature presents a good correlation between SAM and the ACC transport and flux variability (Hughes et al. 2003; Meredith et al. 2004) or still between SAM and the sea ice variability (Kwok and Comiso 2002; Liu et al. 2004). Some evidences point to a correlation between WSBW anomalies and a positive SAM index. Figure 3 shows the possible evidences that a positive SAM index may influence the WSBW production/contribution.

A positive SAM index intensifies the ACC and the meridional currents. That causes an increase of the sea ice advection that leaves the WS towards lower latitudes (Hall and Visbeck 2002). The sea ice outflow causes more open water conditions in the WS, which facilitates new sea ice formation and thus intensifies the dense shelf water production (Liu et al. 2004). The currents intensification also causes instabilities in the Weddell Front, which permit an injection of the WDW inside the gyre (Fahrbach et al. 2004). In parallel, model results indicates that during positive SAM index, it occurs an enhancement of the WDW upwelling which destabilize the water column due to the increase of the surface density (Lefebvre and Goosse 2005). Therefore, denser source waters become available and the process involved in WSBW formation is accentuated during positive SAM years. In this sense, a correlation between the SAM index and the observed WSBW anomalies is expected.

As the water masses acquire their signature from atmospheric processes and the present analysis does not occur only in source areas, it becomes necessary to look back at how was the SAM index during the WSBW formation period. Based in the literature (Schlosser et al. 1991; Mensh et al. 1998a; 1998b; Klatt et al. 2002) the WSBW age observed during the SR4 cruises varied between 10-15 years old. The time-window that comprehends the formation years relative to 1990 and 1996 are respectively 1975-1980 and 1981-1986 (Figure 4).

At those times the positive SAM index reveals reasonable correlations with an increment on WSBW contribution/production. However, better correlations are found between the SAM index gradient (i.e. negative to positive indices) and the WSBW positive anomalies. The SAM index shows a distinct pattern during the periods (Figure 4) analyzed indicating that the strong SAM index positive gradient during the time of the water mass formation is associated with a positive WSBW contribution anomaly.

The cross-correlation analysis between the SAM index and the sea ice anomalies (not shown) for the entire Southern Ocean allowed an evaluation of the time lag between those series. The result reveals that the SAM mode of variability influences the sea ice cover at different time scales. One can also observe features with interanual and decadal variability. That shows that the response of the water masses due to the variability of the atmosphere occurs during similar periods. Therefore, it is possible that the water masses anomalies are reflecting the atmosphere variability during their formation time.

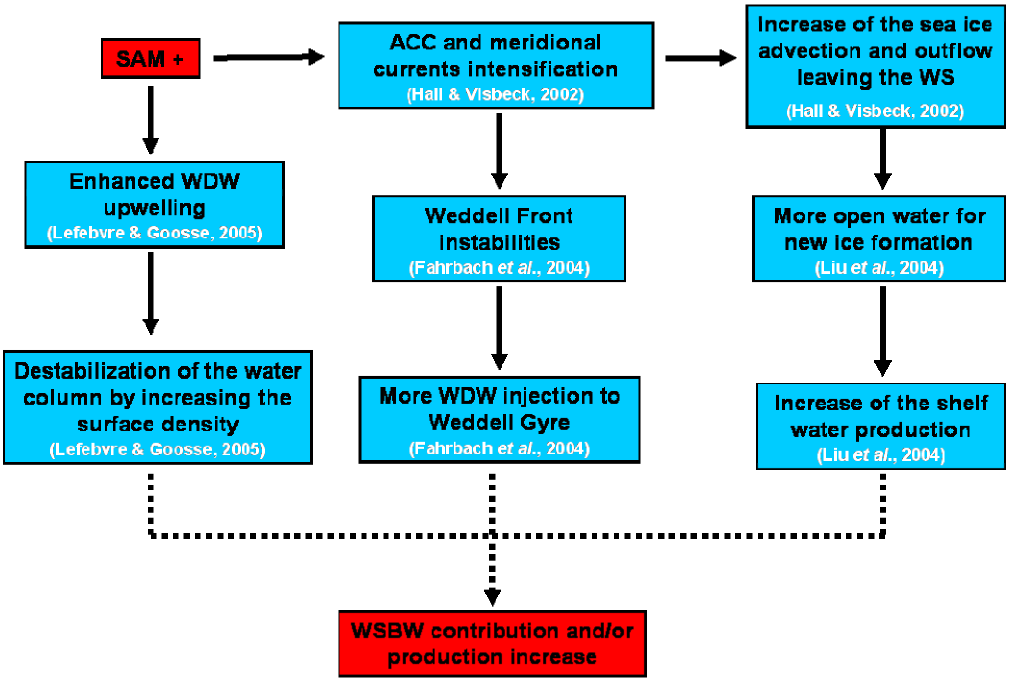

Figure 3 – Evidences of the correlation between SAM and WSBW contribution.

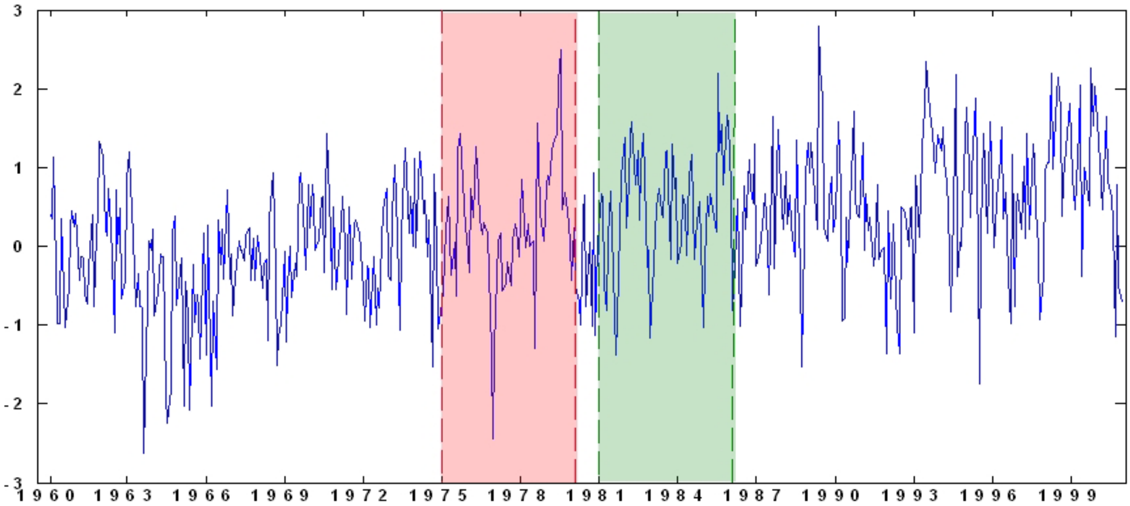

Figure 4 – Monthly SAM index between 1960 and 2000. Red (green) time-window related with the possible formation time for WSBW sampling at 1990 (1996).

4. CONCLUSION

The relationship between atmospheric and oceanic variability has been investigated in recent research. The present study considered some evidences that point to a possible correlation between SAM gradient and WSBW contribution/production in the WS, also indicating that the coupled processes responsible for deep water mass formation between atmosphere, ocean and sea ice are correlated in different time scales. However, further studies must be carried out to prove those evidences.

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