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Interannual variations of water mass volumes in the Southern Ocean

MATTHIAS TOMCZAK* and SHARON LIEFRINK

School of Chemistry, Physics and Earth Sciences, The Flinders University of
South Australia, GPO Box 2100, Adelaide SA 5001, Australia

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Water mass volumes in the Southern Ocean are evaluated in a section between Antarctica and Tasmania for the period 1991–1996. Antarctic Bottom Water consisted of Weddell Sea Bottom Water and water formed along the Adélie Coast. The volume of the Adélie Coast component was found to decrease slightly over the observation period, while the volume of the Weddell Sea component remained unchanged. The volume of Circumpolar Deep Water increased slightly, with a pronounced trend toward Lower at the expense of Upper Circumpolar Deep Water. The volumes of Antarctic Surface Water, Western South Pacific Central Water, Subantarctic Mode Water, Antarctic Intermediate Water and Antarctic Bottom Water were smaller by up to one order of magnitude but their variations relative to their volumes were significant.

Keywords: Water masses; Southern Ocean; Climate variability

1. Introduction

The Southern Ocean is the formation region of several water masses that ventilate the abyssal and intermediate depths of the world ocean. These water masses play an important role in the global climate system as reservoirs of heat, freshwater and dissolved gases and act as a damping mechanism on variations in the global climate.

Climate variability on time scales of years to decades impacts on water mass formation rates and results in a redistribution of volumes between water masses by influencing their formation processes (convection or subduction). Monitoring the rate of water mass formation can assist in determining climate trends.

Direct observation of water mass formation at high latitudes is a difficult task, and most information on polar and subpolar water masses is obtained from observations downstream from the formation regions. Even if this approach is adopted it is usually difficult to build a time series from field measurements, suitable for quantifying variations in water mass formation rates.

The World Ocean Circulation Experiment (WOCE) included several repeat hydrographic sections where observations were made over several years. The Southern Ocean Repeat Section, SR03 was one of these; it is located between

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*Corresponding author. Email: matthias.tomczak@flinders.edu.au

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Tasmania (Australia) and Antarctica and was conducted six times between 1991 and 1996. In this article, we use the data from SR03 to estimate the interannual variability of water mass volumes in the Southern Ocean during the first half of the 1990s.

2. Data and methods

WOCE Repeat Section SR03 extended across one of the constriction points of the Antarctic Circumpolar Current (ACC) between 130°E and 150°E (figure 1). Following the WOCE protocol, Conductivity-temperature-depth (CTD) and Niskin bottle stations were taken approximately every 30 nautical miles, and more frequently over rapidly varying topography or in the vicinity of the Subantarctic Front (SAF).

During 1991, the weather conditions led to the disruption of the section during the outbound voyage to Antarctica and to its completion during the return voyage. The two partial data sets were combined into a single section for this study, which therefore contains five complete transects for the years 1991–1996. Table 1 gives the dates of individual transects.

Water mass volumes were determined by integration over the relative contributions of each water mass to the observed distribution of variables. The relative contributions were determined using Optimum Multiparameter (OMP) analysis (see for example (Poole and Tomczak 1999) for a description of the method) based on potential temperature, salinity, oxygen, phosphate, nitrate and silicate.

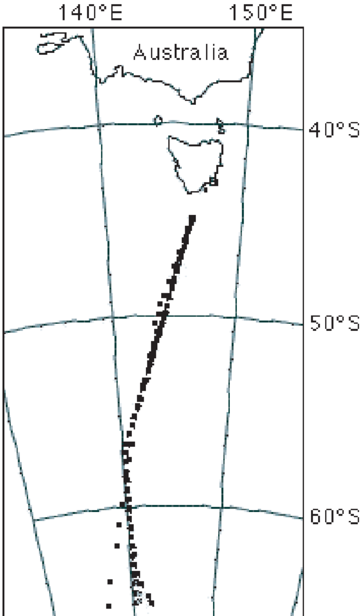

Figure 1. Location of WOCE Repeat Section SR03. Squares indicate station locations occupied during 1991–1996. The four stations west of 140°E were occupied in 1991.

Table 1. SR03 Repeat Sections.

Year	Date	Coverage
1991	25/9–27/10	44°S 146.3°E–64.9°S 136.4°E
1993	11/3–3/4	44°S 146.3°E–65.1°S 139.8°E
1994	1/1–16/1	44°S 146°E–66°S 140°E
1995	17/7–2/9	44°S 146.3°E–65.5°S 139.7°E
1996	2/8–22/9	44°S 152.3°E–65.7°S 139.8°E

Since the integration is performed over the entire water column, objective comparison between water mass volumes for different years requires identical topography, particularly for water masses present above the ocean floor. The ship's track for the repeat sections was therefore projected onto a standard track with identical bottom profile and the observations interpolated by projection of the actual station positions onto the standard track as follows.

Data was interpolated vertically onto a 50 m grid over the depth range 50–4250 m. Latitudes were restricted to the latitude range common to the data sets for all the years, which was 44°42.2′S–64°53.3′S; stations outside this range were excluded from the analysis.

Since the bathymetry along the ship's track was different for each year and the number of stations and their positions varied for each transect, a way had to be found to arrive at a common bathymetry. Initially stations from different years were grouped into relatively close latitude positions and the bottom depths adjusted to the minimum depth of the group. Gaps in some years due to varying station distance were filled by linear interpolation. The resulting bathymetry was compared again between the years and bottom depths adjusted to arrange the stations into uniform segments. This allowed each transect to have a different number of stations in each segment whilst maintaining the same bathymetry.

OMP analysis was performed on the data and the volume was determined by multiplying the total water mass content of the combined stations within a segment by the segment area. To avoid uncertainties introduced through biochemical modification of water mass properties, particularly for water masses not formed in the Southern Ocean, the OMP analysis did not use Redfield ratios, but was based on local water mass definitions (water types) derived by comparison of the observations with the climatological mean state given by the World Ocean Atlas 1998 (WOA98 1998). Parameter weights W were determined following the procedure of (Tomczak and Large 1989) as $W = \sigma^2/\delta_{\max}$, where σ^2 is the parameter variance of the source water type matrix and $\delta_{\max}$ is the largest variance in the formation regions. Only Central Water and Intermediate Water were considered in the determination of $\delta_{\max}$, as deeper water masses show much smaller variations in their properties. The standard deviations given in the WOA 1998 were squared to give the variances of these two water masses, based on the area 30°–33°S, 160°–174°E for Central Water and 49°–63°S, 93°–148°E for Intermediate Water.

3. Water masses

Eight water masses determine the hydrographic characteristics of the WOCE SR03 Repeat Section. Summer Surface Water (SSW) is a highly variable layer found above a seasonal halocline characterized by low salinity (Smith *et al.* 1984). Antarctic Winter Water (WW) is a temperature minimum layer found below the SSW. Its potential temperature is between −1.9°C and −1.5°C and its salinity (S) is between 34.2 and 34.5. It is a remnant of the surface water formed from winter convection (Wong *et al.* 1998) that deepens and thickens as it is transported northward by the westerlies, sinking at the southernmost limit of the Polar Front Zone around 61° (Smith *et al.* 1984). SSW and WW together are considered the two components of Antarctic Surface Water (ASW). In this study the water type definition of Antarctic Surface Water is based on the Antarctic WW properties.

Western South Pacific Central Water (WSPCW) forms through subduction at the Subtropical Convergence of the region (Karstensen and Quadfasel 2002). It has properties which are close to those of Indian Central Water and South Atlantic Central Water (Tomczak and Hao 1989) and is the most saline of the six thermocline water masses found in the Pacific Ocean (Tomczak and Godfrey 2003). Since it is characterized by a nearly linear temperature–salinity relationship, two water types can represent it.

Subantarctic Mode Water (SAMW) is formed by deep convection in late winter on the equatorward side of the ACC. Major formation regions for SAMW are in the Southern Ocean (Sloyan and Rintoul 2001b) and in the south eastern Indian Ocean (Ribbe 1999). SAMW from the Southern Ocean is cooled and freshened from consecutive deep winter mixing events during its flow path eastward with the ACC and northward into the adjacent subtropical gyres (McCartney 1977; Sloyan and Rintoul 2001b). The result is a cooler and fresher SAMW found in the southeast Pacific than that of the SAMW produced in the Indian Ocean (Sloyan and Rintoul 2001b). The boundary between the two SAMW varieties is located near the Campbell Plateau, south of New Zealand (Rintoul and Bullister 1999), which means that SAMW found in the SR03 section is of Indian Ocean origin. The water type definition for SAMW is therefore based on SAMW properties found in the Indian Ocean.

Antarctic Intermediate Water (AAIW) is identified by a prominent salinity minimum. Various processes contribute to its formation along the Antarctic Polar Front (Sorensen *et al.* 2001). A region of strong convective formation is located in the southeast Pacific Ocean (England *et al.* 1993). Recirculation of AAIW from that region in the subtropical gyre brings it close to New Zealand, where mixing with AAIW from the Atlantic and Indian Oceans is observed (Stanton 2002). The general circulation pattern suggests that AAIW found in the SR03 section originates from the south where it is noted to be cold and fresh as it enters the southern Tasman Sea. It circulates back to the west and south across the SR03 section without entering the Tasman Sea subtropical gyre flow north of 30°S. AAIW becomes warmer and more saline as it ages and mixes with older subtropical water (Rintoul and Bullister 1999). However, the water type definition is based on the colder, fresher AAIW originating from the south.

Circumpolar Deep Water (CDW) is a major water mass in the Southern Ocean, as it is involved in the formation of all others (Whitworth 3rd *et al.* 1998). It is the product of North Atlantic Deep Water (NADW) being modified through mixing with deep waters from the Indian and Pacific Oceans during its eastward passage with the ACC. The contributions from different sources can be traced to some extent and several investigators distinguish Upper Circumpolar Deep Water (UCDW), which is characterized by an oxygen minimum and nutrient maxima, and Lower

Circumpolar Deep Water (LCDW), characterized by its high NADW salinity (Whitworth 3rd *et al*. 1998).

Antarctic Bottom Water (AABW) is formed by deep convection at the Antarctic continent, particularly in the Weddell Sea, the Ross Sea and Adélie Land. The three regions produce AABW of slightly different characteristics (Orsi *et al*. 1999). Adélie Land Bottom Water (ADLBW) is thought to form on the continental shelf of the Wilkes–Adélie Land (Bindoff *et al*. 2000) and is possibly the second largest source of Bottom Water (Rintoul 1998). It has been demonstrated (Rintoul 1998) that a cold, fresh and dense variety of bottom water is formed between 140°E and 147°E and in sufficient volume to erase the high salinity signature of the Ross Sea Bottom Water before it has reached 140°E. With this in mind and the fact that Ross Sea Bottom Water flows eastward from its formation region with the ACC and would need to complete one circumnavigation of Antarctica prior to reaching the section south of Australia, it is thought that its influence in the region under investigation is minimal. Two types of AABW were therefore identified in the present study. The warmest ($\Theta = -0.6°\text{C}$) and most saline ($S = 34.69$) was considered Adélie Land Bottom Water (ADLBW: $-0.8 < \Theta < -0.4°\text{C}$, $34.62 < S < 34.68$). The coldest and freshest bottom water with a potential temperature of −1.4°C and salinity of 34.6 was placed under the description of the Weddell Sea Bottom Water.

Table 2 gives the water type definitions for all water masses considered. To increase the stability of the analysis not all water masses were considered present at all stations. The section was divided into six parts by separating by latitude south and north of 52.5°S and by depth ranges above 800 m, 800–1500 m and below 1500 m. Table 3 gives details of the water masses included in the analysis and the weights used in the different cases.

4. Results and discussion

Table 4 lists the calculated water mass areas (volumes for a section of unit width) for the five repeat sections. Figure 2 displays the same information as contributions to the total volume. CDW occupies more than half the volume. In most years the largest contribution comes from LCDW, except in the year 1991 where UCDW contributes more to the total CDW volume. Bottom Water is the second most prominent water mass; most of it derives from ALBW and only a minor amount from Antarctic (Weddell Sea) Bottom Water. The contributions from AAIW and Subpolar Mode Water are smaller by an order of magnitude, while the contribution from WSPCW and ASW are all but negligible.

The small contribution from WSPCW can be understood if it is recalled that Central Water exists only equatorward of the Subtropical Front, where it is found at the surface. As it moves toward the tropics it fills more of the upper kilometre of the ocean; but in the SR03 section very little of it is seen below 300 m. SAMW, on the other hand, is formed by convection to at least 500 m depth and is advected from the west. As a consequence, most of the depth range above AAIW is occupied by SAMW.

Figure 2 indicates that the period 1991–1996 was characterized by a transient decrease in the volume of Bottom Water, which was nearly compensated by a corresponding increase of the volume of CDW. There is also a clear trend toward more prominence of UCDW at the expense of LCDW in the Deep Water range.

Table 2. Source water type definitions.

Parameter	ASW	WSPCW (upper)	WSPCW (lower)	SAMW	AAIW	CDW (upper)	CDW (lower)	AABW	ADLBW
Pot. temperature (°C)	−1.87	14.985	9.2	8.75	4.4	2.15	2.06	−1.4	–0.6
Salinity	34.45	35.66	34.67	34.58	33.75	34.4	34.77	34.6	34.69
Oxygen (µmol/kg)	310	255	270	250	310	165	195	275	235
Phosphate (µmol/kg)	2	0.05	0.9	1.2	1.5	2.6	1.9	2.1	2.4
Nitrate (µmol/kg)	31	0.1	13	17	24	36	29	30.5	33
Silicate (µmol/kg)	60	0.5	2.3	6	1.5	55	95	88	145

Table 3. Water masses included in the analysis and parameter weights.

		Weights					
Region	Water mass	Potential temp. (°C)	Salinity	Oxygen (µmol/kg)	Phosphate (µmol/kg)	Nitrate (µmol/kg)	Silicate (µmol/kg)
Upper north 50 m–800 m 44.7°S–52.5°S	WSPCW (upper) WSPCW (lower) SAMW AAIW CDW (upper)	17.7	37.2	9.1	44.5	31.6	13.7
Upper south 50 m–800 m 52.5°S–64.9°S	ASW AAIW CDW (upper) CDW (lower) AABW (Adélie) AABW (Weddell)	6.7	10.6	11.8	7.7	2.9	56.9
Middle and lower north 800 m–4500 m 44.7°S–2.5°S	SAMW AAIW CDW (upper) CDW (lower) AABW (Adélie) AABW (Weddell)	15	10.9	9	14.6	8.3	76.5
Middle and lower south 800 m–4500 m 52.5°S–64.9°S	CDW (upper) CDW (lower) AABW (Adélie) AABW (Weddell)	3.4	2	7.4	5	1.7	34.2

Table 4. Water mass volumes for a 1 m wide strip along section SR03 ($10^9\,m^2$).

	1991	1993	1994	1995	1996	Mean (1991–96)	Std (1991–96)
ASW	0.13	0.07	0.10	0.11	0.09	0.10	0.02
WSPCW	0.11	0.13	0.19	0.12	0.20	0.15	0.04
SAMW	0.51	0.46	0.43	0.46	0.38	0.45	0.05
AAIW	0.26	0.31	0.38	0.36	0.45	0.35	0.07
UCDW	2.56	2.20	2.52	2.20	1.75	2.24	0.33
LCDW	1.88	2.99	2.62	2.97	3.39	2.77	0.57
ADLBW	2.07	1.45	1.14	1.37	1.19	1.44	0.37
AABW	0.29	0.19	0.42	0.23	0.35	0.29	0.09

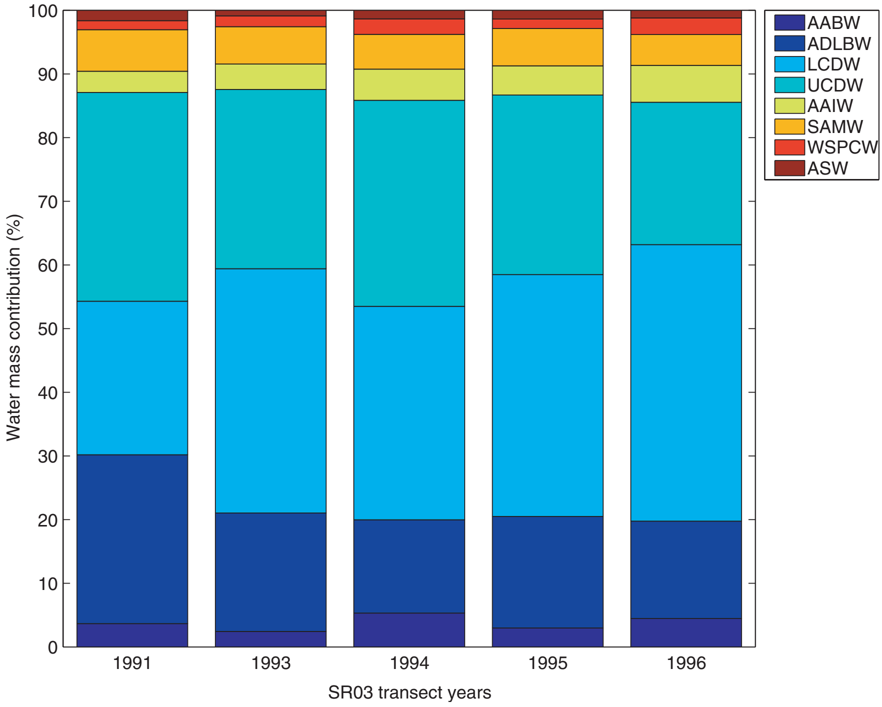

Figure 2. Water mass contributions for each repeat section in the years 1991–1996, expressed as contributions to the total volume.

Figure 3 shows the water mass contributions as a function of latitude and depth, based on the latitude and depth divisions used in the OMP analysis. This allows a clearer appreciation of the change over time in the water masses of the upper ocean, which in figure 2 are represented in only very small volumes. It is seen that the volume of Western South Pacific Water increased during the observation period, at the expense of SAMW. SAMW and WSPCW have comparable temperature–salinity characteristics (SAMW is at the low temperature end of WSPCW, and the two water masses are mainly differentiated through

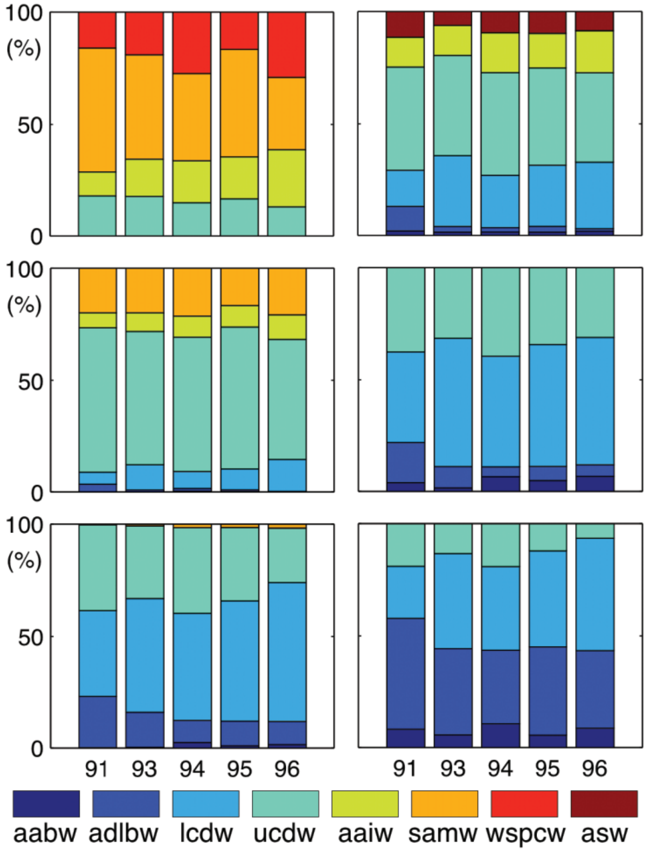

Figure 3. Water mass contributions as functions of latitude and depth, based on the latitude and depth divisions used in the OMP analysis, for each repeat section in the years 1991–1996.

their different nutrient levels) and therefore compete in the occupation of a limited density range. The volume of UCDW decreased particularly below the 1500 m depth.

As an example of the distribution of the water masses across SR03, figure 4 shows the water mass contribution for the year 1996, using the same latitude and depth divisions as figure 3. It demonstrates the latitudinal and depth separation of the various water masses that allows OMP analysis to proceed on different sets of water types in each latitude/depth subdivision. The largest inaccuracy occurs in the estimate for WSPCW, which is still present with about 10% at the southern end of the northern subdivision, but not included, and may thus be present with a small volume at the northern end of the southern subdivision.

Do the observed volume variations represent physical processes, or are they an artefact of the method? Bindoff and McDougall (1994) distinguished three possible processes during water mass formation that lead to changes in the water mass structure, warming, freshening and a change of volume due to variations of the wind stress curl, which they called "heaving". OMP analysis is based on the assumption that the source water types are known and do not change with time. It is thus ideally suited to detect heaving but will produce erroneous results if warming or

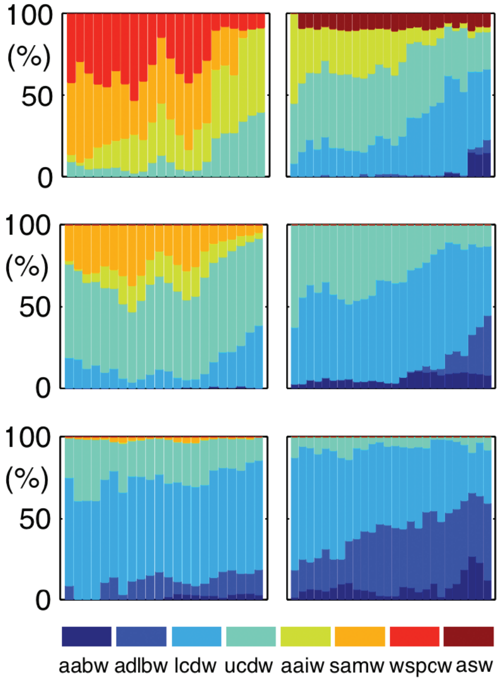

Figure 4. The water mass contributions for the year 1996, using the same latitude and depth divisions as figure 3.

freshening are significant. It is conceivable that an analysis based on constant source properties might reflect these as volume variations of the water masses.

To test this possibility, the source water types of AABW, CDW and AAIW were varied by one standard deviation (given by the slight variations in the yearly source water types seen in the data) and the results compared. The variations produced through this procedure were clearly smaller than the variations given in table 4. Time variations of source water properties are thus unlikely to be the sole cause of the observed volume variations.

The presence of water masses in the section not included in the OMP analysis could be another shortcoming of the study. Rintoul and Bullister (1999) reported two distinct varieties of AAIW south of Tasmania and noted the existence of strong temperature and salinity gradients on isopycnals at the SAF. They suggest that AAIW may have several formation regions with distinct source water properties. However, AAIW has such distinct properties when compared with the other water masses – it stands out particularly through its much lower salinity – that several sources with slightly different properties can be subsumed under a single water type without producing artefacts.

These arguments lend support to the interpretation of the observed volume variations as "heaving". Variations in the transport of the ACC cannot be responsible for them, since integration along a transect across the current is independent of the current's speed. Eddies and meanders of the fronts can take isolated water mass parcels into regions usually occupied by a different water mass and are therefore of more consequence. As the sections are snapshots they can easily be distorted by eddies.

The SR03 section crosses the SAF, the strongest front and main jet of the Circumpolar Current (Sokolov and Rintoul 2002). According to Sokolov and Rintoul (2002) the meander envelope of the SAF across the SR03 transect is relatively narrow, but widens toward the Macquarie Ridge at 60°S into an eddy rich region. This would suggest that eddy activity is not a major factor in water mass volume variation. In any case eddy activity is unlikely to cause the observed trend of WSPCW and SAMW and the observed volume shift from UCDW to LCDW.

Sloyan and Rintoul (2001a) combined nine hydrographic sections obtained over the 18 year time span 1976–1994 into an inverse model of the Southern Ocean circulation and determined water mass conversion rates produced by diapycnal downwelling and upwelling between AABW, LCDW and UCDW. Their model represents a mean state of the circulation, a state that may be biased toward contributions of particular water masses through the combination of sections from different years. Our study shows that if the assumption of a steady state in source water types is correct, significant changes occur in the water mass volumes, suggesting large variations in downwelling and upwelling. A steady state in the source water types requires a steady state in the atmospheric conditions during water mass formation, a situation that is unlikely to persist for a long time. The task remains to quantify the importance of atmospheric interannual variability in the water mass formation regions and its impact on the properties of freshly formed water masses.

Bindoff and McDougall (1994) analyzed sections in the southern Tasman Sea that were 6 months and 23 years apart. They found that differences over 6 months were dominated by heaving, while differences over 23 years were mainly the result of warming and freshening due to slow climate change. Our analysis covers the intermediate time scale of changes over several years. While it is conceivable that a time span of 6 years shows more similarity with changes over 6 months than 23 years, a complete analysis will have to allow for variations in the source water properties. This requires an extension of OMP analysis into a non-linear minimization scheme that allows variations of source water types with time. This work is currently in progress.

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