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Prominent renewal of Weddell Sea Deep Water from a remote source

by Mario Hoppema[1], Olaf Klatt[1], Wolfgang Roether[1], Eberhard Fahrbach[2], Klaus Bulsiewicz[1], Christian Rodehacke[1] and Gerd Rohardt[2]

ABSTRACT

Three transient tracer sections of CFC-11 across the Weddell Sea are presented, collected during "Polarstern" cruises ANT X/4 (July 1992), ANT XIII/4 (May 1996) and ANT XV/4 (April 1998). The corresponding sections of silicate, a quasi-steady-state tracer, are displayed for comparison and as a supplement. Two distinct CFC-11 maximum layers are found in the deep water, one centered near 2200 m and another near 3500 m. These layers, previously observed by other investigators, represent recently ventilated Weddell Sea Deep Water. The deeper, more pronounced core, occurs along the southern continental slope, whereas the shallower core occurs in the northern Weddell Sea. The deeper CFC-11 maximum layer coincides with a pronounced silicate minimum layer. Quantitatively, the deeper core constitutes a ventilation route for the Weddell Sea of utmost importance, the amount of ventilated surface water involved being 2.7 ± 0.9 Sv. Most of the deep interior Weddell Sea appears to be ventilated by this external source. The ventilation rate of the Weddell Sea due to the inflow from the east is at least as high as that from the local southern and western sources that produce bottom water. Associated with the deep CFC-11 maximum core are discontinuities in the potential temperature-property diagrams of silicate, oxygen, total carbon dioxide, nitrate and salinity. The recently ventilated deep water is characterized by low concentrations of silicate, total carbon dioxide and nitrate, and by high oxygen content and salinity as compared to the deep water at the same potential temperature formed by mixing of Warm Deep Water and Weddell Sea Bottom Water.

1. Introduction

Ventilation of the abyssal world oceans takes place in the polar and subpolar regions. This process maintains the abyssal world oceans in an oxic state, which is a crucial condition for many biological and chemical processes. Within the Southern Ocean, the Weddell Sea has long been considered the key region in this respect (Brennecke, 1921; Mosby, 1934). Ventilation in the Weddell Sea is thought to be brought about mainly by bottom water formation (e.g., Foster and Carmack, 1976; Gordon, 1998). Weddell Sea Bottom Water (WSBW), defined by potential temperatures (θ) below −0.7°C (Carmack

1. Institute of Environmental Physics, Department of Oceanography, University of Bremen, FB1, P.O. Box 330440, D-28334 Bremen, Germany. ***email: hoppema@physik.uni-bremen.de***

2. Alfred Wegener Institute for Polar and Marine Research, P. O. Box 120161, D-27515 Bremerhaven, Germany.

and Foster, 1975), is produced from shelf water and Warm Deep Water (WDW) by two different processes in the south and west Weddell Sea (Foster and Carmack, 1976; Foldvik *et al.*, 1985; Weppernig *et al.*, 1996). At least three types of WSBW from different formation areas and slightly different properties could be identified (Gordon, 1998). Part of the newly formed WSBW, hanging on the slope along the Antarctic Peninsula, may leave the Weddell Sea directly through gaps in the South Scotia Ridge (Carmack and Foster, 1975; Fahrbach *et al.*, 1995). Another part flows along the base of the northern Weddell Sea slope and replenishes the abyssal Weddell and adjacent Enderby Basins (Carmack and Foster, 1975; Orsi *et al.*, 1993). In a modified form, it abandons the Weddell Gyre in the east (Haine *et al.*, 1998).

Within the Weddell Sea interior, the WSBW occupies a layer of at most 1000 m thick. Underneath the pycnocline at 150-200 m, the Warm Deep Water is found, featuring temperature, salinity and nutrient maxima, and extending to 1000-1500 m depth ($\theta >$ 0.2°C; Whitworth and Nowlin, 1987; Hoppema *et al.*, 1997). Between the lower boundary of the WDW and the top of the bottom layer (at about 4000 m), the voluminous layer of Weddell Sea Deep Water (WSDW) is found. It is thought to be formed through mixing between WSBW and WDW (Foster and Carmack, 1976; Orsi *et al.*, 1993). Such a vertical balance would imply a linear potential temperature-salinity relationship. However, nonlinear structures were already noted by Carmack and Foster (1975). Further indications for the formation of Weddell Sea Deep Water by different processes have been reported by Orsi *et al.* (1993), Fahrbach *et al.* (1995), Weppernig *et al.* (1996) and Mensch *et al.* (1996), among others. Meredith *et al.* (2000) identified a major core of recently ventilated WSDW in the southeastern Weddell Sea. According to them and Orsi *et al.* (1999), this deep water is advected within the coastal current from east of the Weddell Sea, where indeed ventilated deep and bottom waters have been observed (Jean-Baptiste *et al.*, 1991; Mantisi *et al.*, 1991; Archambeau *et al.*, 1998; Rintoul, 1998).

The circulation of the Weddell Sea and the adjacent Enderby Basin is dominated by the cyclonic Weddell Gyre, which may indeed consist of two subgyres (Gordon *et al.*, 1981; Orsi *et al.*, 1993; Beckmann *et al.*, 1999). In the south and west, the gyre is bounded by the Antarctic margins, whereas in the east it extends well into the Enderby Basin up to about 26E (Schröder and Fahrbach, 1999). The northern boundary corresponds to the southern bound of the Antarctic Circumpolar Current. Circumpolar Deep Water (CDW) from the north is entrained into the Weddell Gyre at its east edge, then being known as Warm Deep Water (Deacon, 1979). Within the southern limb of the Weddell Gyre, water at all depths flows westward along the coastline, turning north upon meeting the Antarctic Peninsula and (north)eastward at the latter's tip, thus forming the northern limb of the gyre. High current velocities occur in the margins and low ones in the interior (Fahrbach *et al.*, 1994), suggesting that the residence time of water in the interior is relatively long compared to that in the margins. For the export of ventilated water from the Weddell Sea to the north, the WSDW is highly effective. WSDW is able to escape the Weddell Sea easily due to its density which is smaller than that of WSBW (Whitworth and Nowlin, 1987; Locarnini *et* *al.*, 1993). Thus, direct ventilation of WSDW, without prior formation of WSBW, would constitute a relatively rapid ventilation route for the abyssal world oceans.

Transient tracers, like chlorofluorocarbons (CFCs), are particularly suited for studying recent ventilation of the ocean interior. CFCs are present in the environment since the 1940s and enter the oceans via air-sea exchange. Any parcel of ocean water with nonvanishing CFC concentration must have been in contact with the atmosphere since the introduction of CFCs or must contain some fraction of ventilated surface water.

We show that direct renewal of WSDW, originating from outside the Weddell Gyre, affects a significant part of the deep water in the Weddell Sea. In our investigation we build on a recent study by Meredith *et al.* (2000), and on the pioneering work of Weiss *et al.* (1990), Schlosser *et al.* (1991) and Mensch *et al.* (1996). We portray WSDW properties using distributions of a transient tracer from different years, comparing this with the quasi-steady-state tracers such as silicate, salinity, nitrate, total CO_2 and oxygen.

2. Methods and data

Data presented here were collected during three WOCE surveys in the Weddell Gyre with the German ice-breaker "FS Polarstern," ANT X/4 in June-August 1992 (Lemke, 1994), ANT XIII/4 in April-May 1996 (Fahrbach and Gerdes, 1997) and ANT XV/4 in April-May 1998 (Fahrbach, 1999). At all hydrographic stations (Fig. 1) water samples were collected with a rosette water sampler equipped with 12-liter Niskin bottles and coupled to a Conductivity-Temperature-Depth (CTD) instrument. All analyses were performed on board. Subsamples for measurement of CFCs were drawn using glass syringes during ANT X/4 and flow-through glass ampoule containers (Bulsiewicz *et al.*, 1998) during the other cruises.

CFCs were measured by a gaschromatographic method using an analytical system developed at the University of Bremen (Bulsiewicz *et al.*, 1998). Only during the 1992 cruise, a system similar to that of Bullister and Weiss (1988) was employed (Roether *et al.*, 1993). The system has been subject to regular modifications, e.g., a capillary-type column has been applied to enable the concomitant determination of CFC-113 and CCl_4. Further details, also about sample handling and calibration, can be found in Roether *et al.* (1993) and Bulsiewicz *et al.* (1998). CFC-11 concentrations are reported on the Scripps Institution of Oceanography 1993 (SIO 1993) scale. The precision is 1.4% or 0.006 pmol kg^{-1} (whichever is greater) in the case of cruise ANT X/4, and 1.0% or 0.004 pmol kg^{-1} (whichever is greater) for the other cruises.

Silicate data of these three cruises were measured using standard colorimetric methods. During cruise ANT X/4 (1992) it was measured with a Technicon Autoanalyzer-II system with an estimated precision of 0.3 μmol dm^{-3}. During the 1996 and 1998 cruises, silicate was determined using a rapid flow (60 samples/hour) TRAACS autoanalyzer (Technicon). Daily diluted stock standards were used for calibration. A reference standard, consisting of a mixture (100-fold diluted) of phosphate, nitrate and silicate, was used for statistical purposes and data correction. The precision of silicate is 0.5 μmol dm^{-3} and 0.3 μmol dm^{-3}

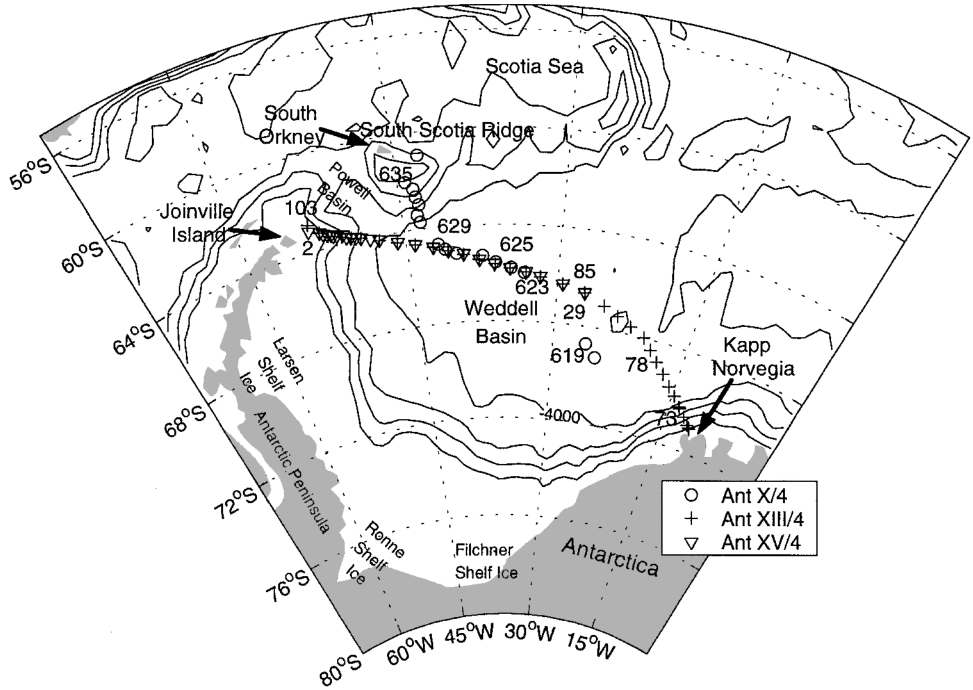


Figure 1. Map of the Weddell Sea with station locations of 1992 (ANT X/4), 1996 (ANT XIII/4) and 1998 (ANT XV/4) cruises. A part of the central Weddell Basin was visited in all three years. Station numbers below 30 (only western part) belong to cruise ANT XV/4; numbers between 73 and 103 (complete crossing of the basin) are from ANT XIII/4; numbers above 600 (central basin and toward South Orkney) from cruise ANT X/4. Stations have a numerical sequence.

(0.23%) for 1996 and 1998, respectively. Total CO_2, nitrate and oxygen data shown here were collected during cruise ANT XIII/4 (1996). The total carbon dioxide (TCO_2) concentration was determined by a coulometric technique (Johnson *et al.*, 1987). The precision, expressed by the mean standard deviation of all duplicates, amounts to 1.0 μmol kg^{-1}. Standardization was accomplished through certified reference seawater (DOE, 1994), made available by Prof. A. Dickson of SIO. The concentration of nitrate was determined simultaneously with that of silicate, the precision being 0.21 μmol dm^{-3}. Dissolved oxygen (O_2) was measured with a standard automated Winkler technique with photometric end-point detection, precision 0.2%. Temperature and salinity data were obtained from the CTD. The accuracy of temperature was set by shore-based calibration and is better than 0.003°C. Salinity data are given on the practical salinity scale, accuracy 0.003.

3. Results

Three vertical sections of CFC-11 across the Weddell Sea, collected in different years are shown in Figure 2. The 1996 section is a complete crossing of the basin from the

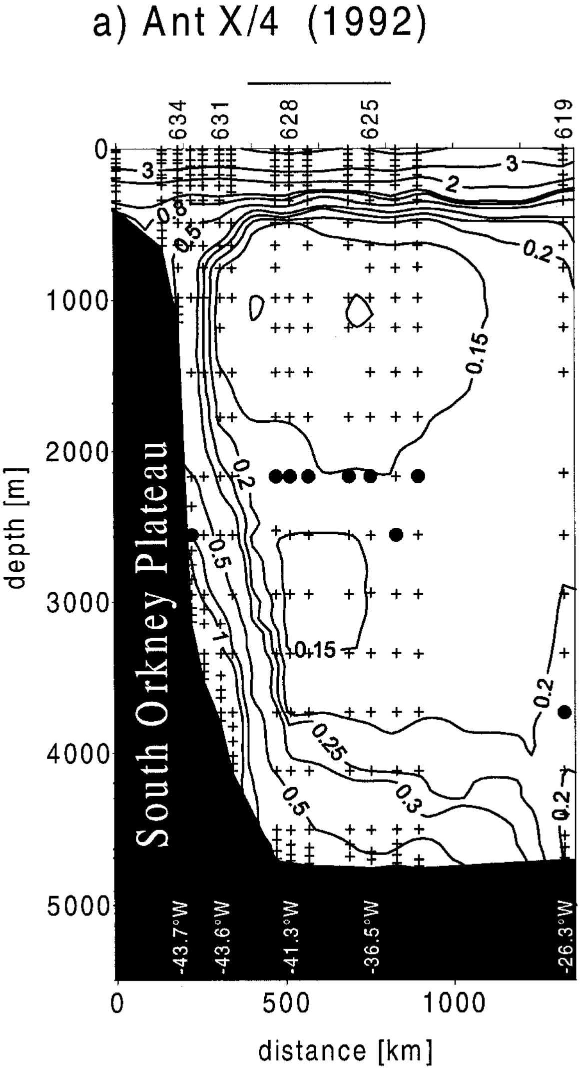


Figure 2. Vertical sections of CFC-11 in the Weddell Sea, (a) from Kapp Norvegia (right) to the South Orkney Plateau (left) during cruise ANT X/4, 1992, (b) from Kapp Norvegia (right) to the Joinville Island (left) during cruise ANT XIII/4, 1996 and (c) from Joinville Island (left) into the central Weddell Basin during cruise ANT XV/4, 1998. Crosses denote sampling depths and thick dots denote the positions of deep CFC-11 maxima. The horizontal line above the station numbers indicates the portion of the section that is geographically exactly equal during all three realizations. Contouring is biased toward the lowest CFC-11.

southeast to the northwest, whereas the 1992 section covers only part of the central basin, and the 1998 section most of the western and central part (all on the same transect; see Fig. 1). Note that the northern part of the 1992 section (Fig. 2a: stations 630-635) is off this

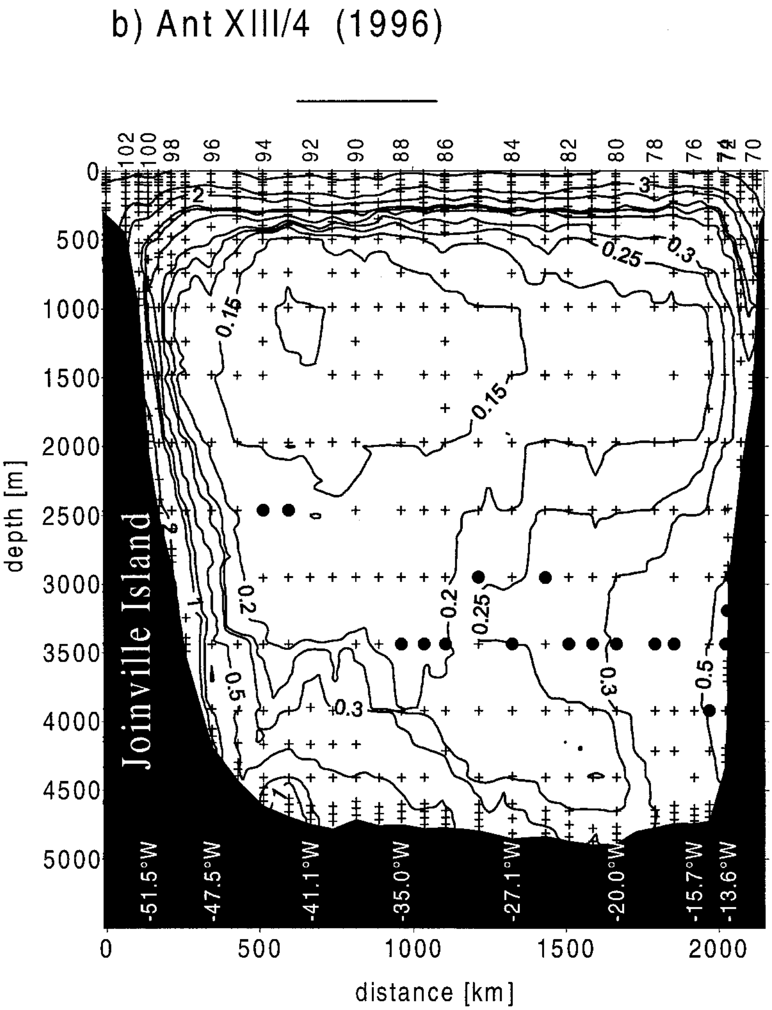
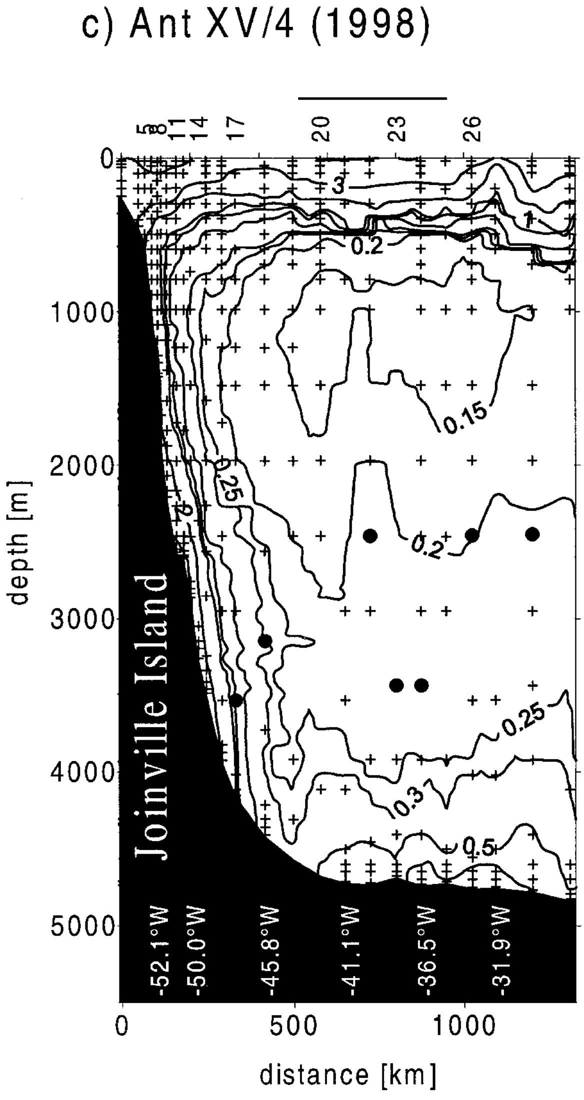


Figure 2. (Continued)

transect. The part of the section that is geographically equal for all three years is indicated by a horizontal line above the contour plots of Figure 2 (and Fig. 3, see further). We use the term "central Weddell Basin" for the offshore area, roughly off the continental slopes. Basically, in all three years similar structures in the CFC-11 distributions are observed. The CFC-11 concentration in the Weddell Gyre is high in the surface layer, as expected due to interaction with the atmosphere. Below that, a CFC-11 minimum layer is found, which characterizes the Warm Deep Water. Since this water mass derives from the Circumpolar Deep Water, it is only poorly ventilated (Roether *et al.*, 1993). The lowest concentrations in the CFC-11 minimum layer at 1000-1500 m depth (Fig. 2b) are found on the western



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side of the central basin (41-43W), which is indicative of the axis of the Weddell Gyre. At the bottom of the central Weddell Basin and over the western continental slope, a CFC-11 maximum is found, which identifies the Weddell Sea Bottom Water. The relatively high CFC-11 concentration is caused by its surface-water source component. From the CFC-11 minimum layer, the CFC-11 concentration increases toward the bottom. As a rule this is not a monotonic increase, especially not in the eastern part of the basin (Fig. 2b).

In general, the low CFC-11 levels in the intermediate and deep water (about 500 to

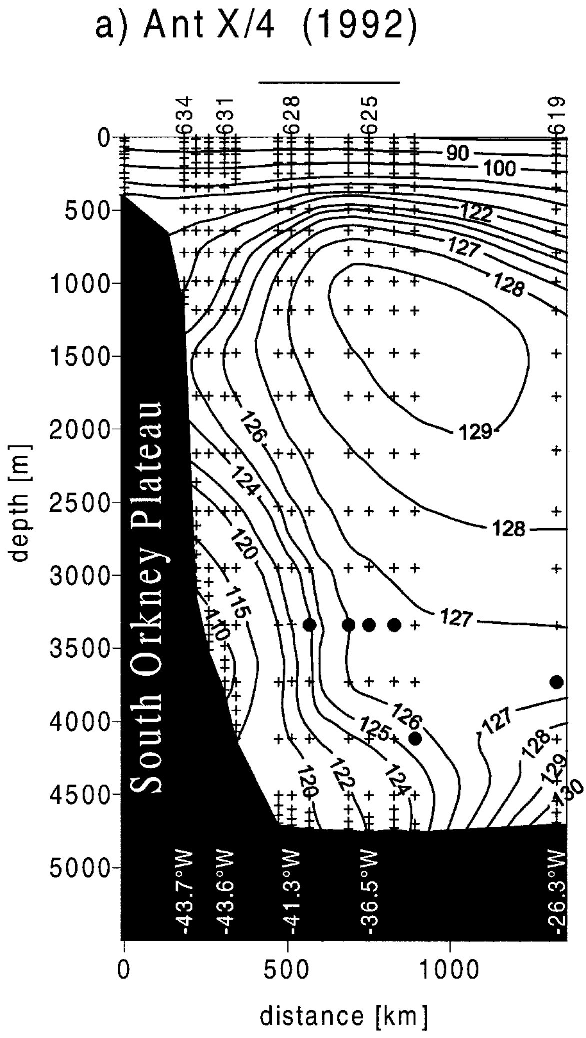
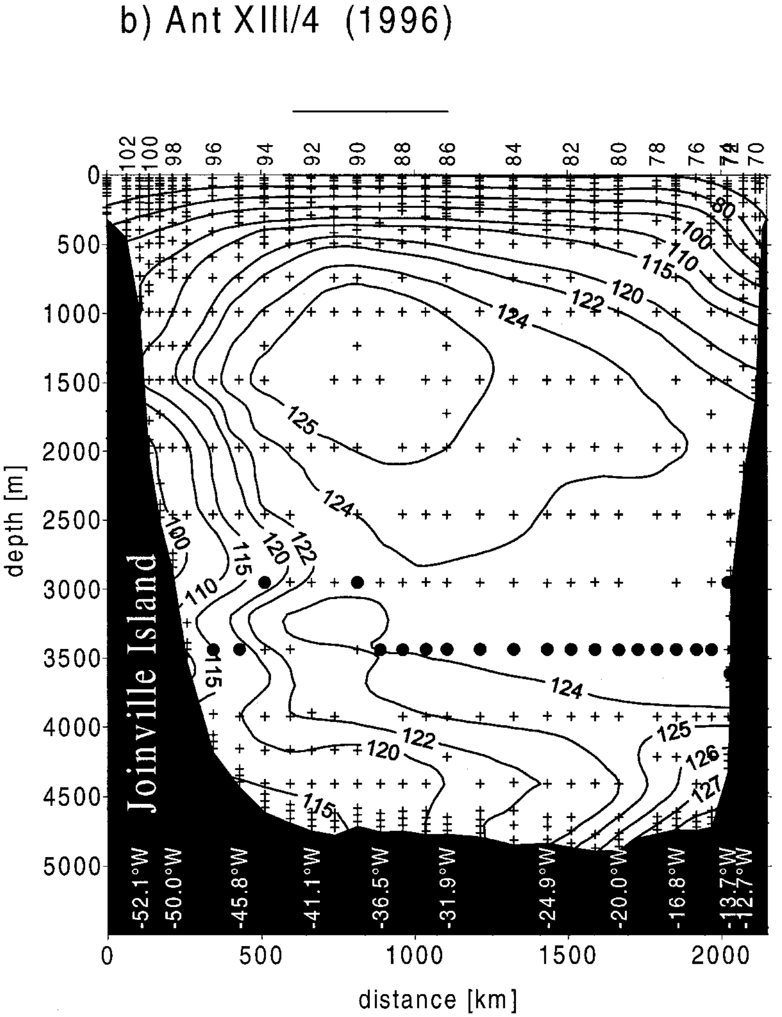


Figure 3. Vertical sections of silicate across the Weddell Sea, (a) from Kapp Norvegia (right) to the South Orkney Plateau (left) during cruise ANT X/4, 1992, (b) from Kapp Norvegia (right) to the Joinville Island (left) during cruise ANT XIII/4, 1996 and (c) from Joinville Island (left) into the central Weddell Basin during cruise ANT XV/4, 1998. Crosses denote sampling depths and thick dots denote the positions of deep silicate minima. The horizontal line above the station numbers indicates the portion of the section that is geographically exactly equal during all three realizations. Contouring is biased toward the highest silicate concentrations.

3500 m depth) have increased between 1992 and 1998 (compare the same geographical region in the central Weddell Sea; Fig. 2) as a consequence of the atmospheric increase of CFC-11. That the increase is but slight, reflects the relatively slow but continuous renewal of these deep waters. The CFC-11 distribution in the bottom water layer is highly variable



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for the time period 1992-1998. In 1996 a CFC-11 maximum core with concentration above 1 pmol kg^{-1} was observed at the base of the continental rise, which was absent in 1998. However, in 1998 a relatively wide core was present in the central part (29-41W). In 1992 a CFC-11 maximum core with high concentration (above 1 pmol kg^{-1}) was observed at the lower slope of the South Orkney Plateau (Fig. 2a). This is recently ventilated bottom water originating from the western Weddell Sea (Fahrbach *et al.*, 1995; Sültenfuss, 1998), and as such is a downstream remnant of the high-CFC-11 layer on the slope of the Antarctic Peninsula (Figs. 2b and c). It is part of the northern rim current of the Weddell Gyre and has not yet reached the very bottom of the basin.

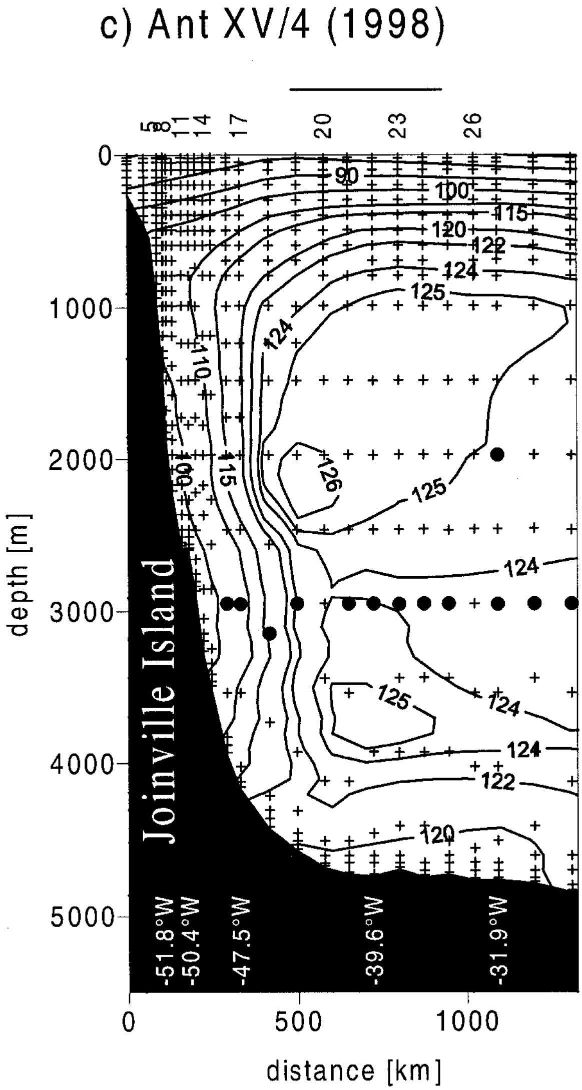

Figure 3. (Continued)

There are some remarkable differences within the repeated portions of the deep water stratum for the different years. In 1992, all stations in the central basin (623-629) display a faint CFC-11 maximum near 2200 m (Fig. 2a). The systematic occurrence of this maximum indicates that it is not an artifact, but an indicator of a distinct water layer with specific characteristics. At station 619 somewhat more to the east (26W), the CFC-11 maximum at 2200 m is not present, but instead there is a deeper, more pronounced maximum near 3800 m. In contrast in 1996, a CFC-11 maximum at 2200 m was absent in the central basin; but only in the western part (42.5-44W) a comparable maximum near 2500 m was observed (Fig. 2b). Additionally, in 1996 in the central basin a weak CFC-11 maximum was observed near 3500 m, which extends from the continental slope off Kapp Norvegia with its core between 3000-4200 m. Off Kapp Norvegia the CFC-11 concentration is highest, above 0.5 pmol kg^{-1}, and it decreases toward the west. In 1996 this maximum was observed almost all across the basin. In 1992 this deep CFC-11 maximum was only observed at station 619 at 26W, and not at the adjacent station 623 at 33W (Fig. 2a). In 1998, a CFC-11 maximum at 3500-3600 m was also present at some stations (Fig. 2c). However, it is difficult to fix its exact spatial extent because of less dense vertical sampling of CFC-11. At some central basin stations an additional CFC-11 maximum at 2500 m was found in 1998 (Fig. 2c), which is different from the situation in 1996.

In Figure 3, the sections corresponding to Figure 2 are portrayed for the quasi-steady-state tracer silicate. Note that overall, the silicate concentrations are higher by about 3-4 μmol kg^{-1} for the 1992 cruise (Fig. 3a) than for the other cruises (Figs. 3b and 3c). This is caused by the use of different standardization procedures. It does not have any influence on the precision within one single cruise, which is much better than this intercruise difference. The silicate distribution in the Weddell Sea is characterized by relatively low concentrations in the surface layer due to biological consumption, and a minimum in the bottom water due to its surface water component. An exception for the latter is the eastern end of the 1992 and 1996 sections (Figs. 3a and 3b), where a silicate maximum is observed at the bottom. This is caused by large *in situ* fluxes from the sediments (Hoppema *et al.*, 1998). The intermediate-depth silicate maximum is caused by dissolution of sinking siliceous material from the surface layer (Rutgers van der Loeff and Van Bennekom, 1989) and advection from the Antarctic Circumpolar Current (Orsi *et al.*, 1999). In the 1996 section, a silicate-minimum stratum centered around 3500 m depth is present from Kapp Norvegia extending far into the western part of the Weddell Basin (Fig. 3b). This silicate minimum clearly coincides with the CFC-11 maximum layer on this section (Fig. 2b). The spatial extent of the silicate minimum is slightly different from that of the CFC-11 maximum, but this could be explained by the different vertical resolutions of these extrema, which in the central basin are so weak that they are close to the precision of the CFC-11 and silicate measurements. Such a minimum cannot be formed between the intermediate-depth silicate maximum and the low-silicate bottom layer by vertical mixing alone. Thus, the silicate minimum layer bears witness to horizontal advection of a water mass with low-silicate characteristics.

Also in the 1992 section (Fig. 3a) a deep silicate minimum at 3400-3800 m is observed at most of the stations. This is not in conformity with the CFC-11 section, which almost everywhere on the section reveals maxima only at 2200 m. Only at the one eastern station 619 there is a corresponding deep CFC-11 maximum (Fig. 2a). For the CFC-11 maximum at 2200 m (Fig. 2a), no analogue in the silicate distribution can be found. In 1998 there seems to be a higher correspondence again for the occurrences of the deep silicate

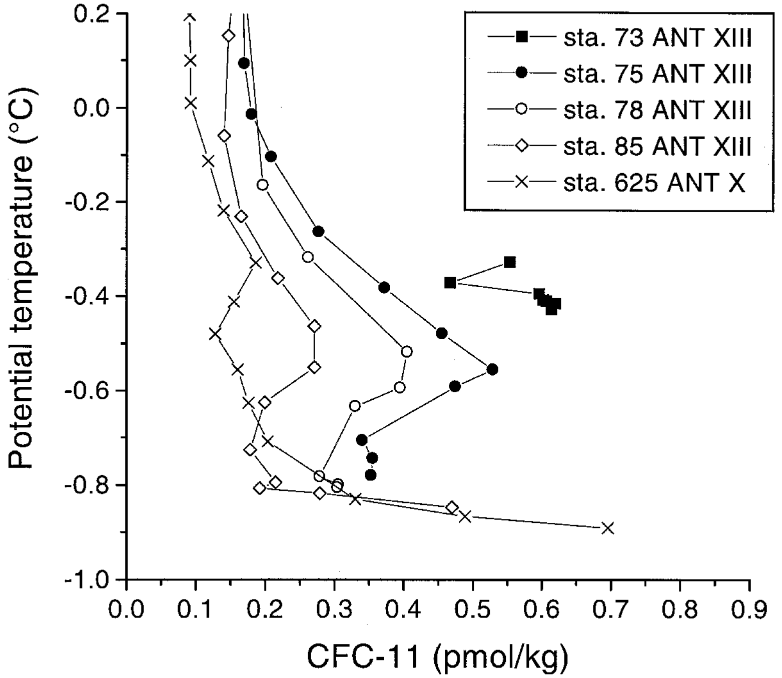

Figure 4. Typical plots of CFC-11 against potential temperature. Only data with potential temperature below 0.2°C are shown. Station 73 (bottom depth 3670 m) lies above the continental slope off Kapp Norvegia, station 75 and 78 in offshore direction of this (bottom depth over 4700 m). Stations 85 (1996) and 625 (1992) are situated in the central Weddell Sea. See Figure 1 for station positions.

minimum and CFC-11 maximum (Figs. 2c and 3c). However, note that the silicate minima generally occur somewhat shallower at about 3000 m.

CFC-11 concentration as a function of potential temperature for selected stations is portrayed in Figure 4 for illustrating the spatial variation of the deep CFC-11 maxima. Stations 73, 75 and 78 display the spatial extent of the deep southeastern core (Fig. 2B), whereas stations 85 and 625 describe the central Weddell Basin. The highest CFC-11 in the southeastern core occurs as a bottom maximum on the continental slope off Kapp Norvegia at potential temperature of about −0.4°C (station 73). Somewhat farther off the coast (at larger bottom depths) the maximum is of smaller magnitude and is located 1000-1200 m above the seafloor; the potential temperature in this maximum is between −0.5°C and −0.6°C (stations 75 and 78). The simultaneous decrease of the CFC-11 concentration and the potential temperature in the core suggests that a relatively warm, CFC-rich water mass from the east mixes with colder water with lower CFC-11 concentration from the Weddell Sea. Station 625 from the central Weddell Sea in 1992 shows only the aforementioned shallower CFC-11 maximum at a potential temperature of about −0.3°C. In 1996, the profiles in the central Weddell Sea look quite different (station 85). The deep CFC-11 maximum in 1998 being difficult to detect because of less dense CFC-11 sampling, instead it is noticed that the deep silicate minimum analogue occurs at about 3000 m, i.e., shallower than in the other years (Fig. 3). Thus, also the potential temperature at the silicate minimum is somewhat higher in 1998 (between −0.45 to −0.5°C) than in the other years. The corollary to this is that in 1998 less cold water of the Weddell Sea was involved in the mixing of the deep core with these local waters.

In Figure 5 silicate data for the central Weddell Sea of 1996 are shown as a function of potential temperature, together with corresponding plots for salinity, oxygen, nitrate and TCO_2. The vertical silicate minimum at 3500 m (see Fig. 3b) is clearly distinguishable at $-0.5 < \theta < -0.6$°C (Fig. 5a). The large silicate variation in the bottom water (potential temperature near −0.8°C) is due to spatially variable interactions with the sediments (Rutgers van der Loeff and Van Bennekom, 1989; Hoppema *et al.*, 1998). It is obvious that the relationships of salinity, oxygen, nitrate and TCO_2 with potential temperature are consistently nonlinear (Fig. 5). All exhibit a discontinuity in the range between −0.5 and −0.6°C. This is at variance with the formation of WSDW through vertical mixing of Weddell Sea Bottom Water (low TCO_2/nitrate and salinity, high oxygen) and Warm Deep Water (high TCO_2/nitrate and salinity, low oxygen) alone.

4. Discussion

Our data from the Weddell Sea reveal two distinct cores of recently ventilated deep water as evidenced by CFC-11 maximum layers; one centered near 2200-2500 m depth concentrated toward the northern limb of the Weddell Basin (Fig. 2a; stations 623-629; potential temperature about −0.3°C), and the other near 3500 m concentrated toward Kapp Norvegia (Fig. 2b; stations 73-88; $-0.5°C < \theta < -0.6°C$). We discuss these cores successively.

a. The shallower, northern core

A CFC-11 maximum core, corresponding to our shallower core, was noted in the Weddell Gyre by Mensch *et al.* (1996) and Orsi *et al.* (1999). Mensch *et al.* (1996) hypothesized that it may be formed through open ocean deep convection or processes at the Scotia Ridge. Orsi *et al.* (1999), however, showed that high intermediate CFC-11 concentrations derive from the Weddell-Scotia Confluence, and these cause a maximum in the Weddell Gyre through lateral ventilation. The apparent concentration of this core toward the northern limb of the gyre (Fig. 2) is well compatible with a Weddell-Scotia Confluence source. Our observations display its southern bound in the central Weddell Sea. Note that Orsi *et al.* (1993) suggested exchange of deep water between the Weddell Sea and the Scotia Sea in the region around 40W. Manifestations of the core can also be found in the data of Meredith *et al.* (2000), and Klatt *et al.* (2001) report a signature of it at the prime meridian. Near to the western margin of the Weddell Sea, Weppernig *et al.* (1996) observed a ^{4}He maximum off the Larsen Ice Shelf at the potential temperature of the core

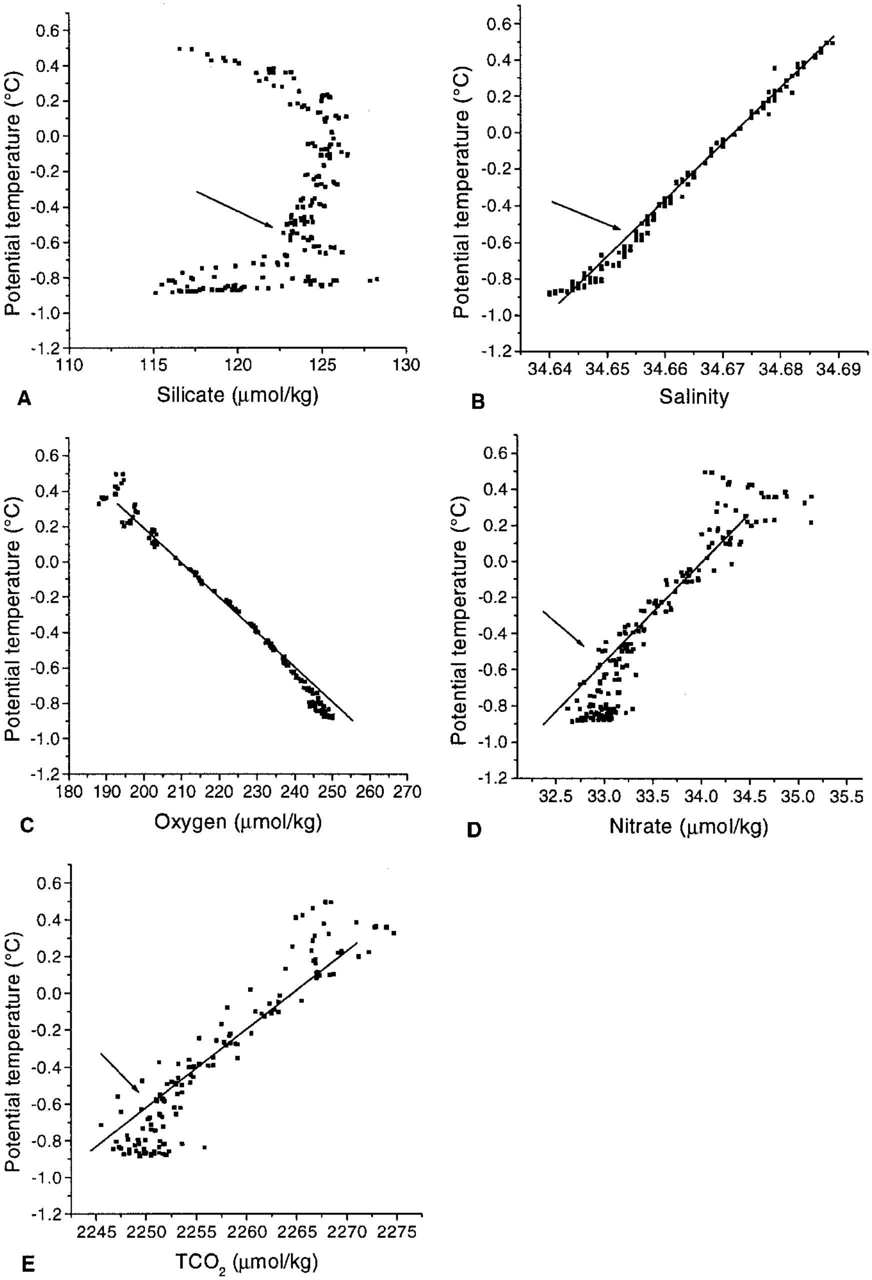

Figure 5. Scatter diagrams of silicate (A), salinity (B), oxygen (C), nitrate (D) and TCO_2 (E) against potential temperature for the central Weddell Sea (stations 82-92) during cruise ANT XIII/4, 1996. Arrows indicate discontinuities. Lines are drawn through the anticipated linear part of the diagram only to enhance the discontinuities.

(– 0.3°C). As it is unlikely that a core of ventilated deep water in the western margin that far south derives from the Weddell-Scotia Confluence alone, an additional origin for this ^{4}He core is suggested. The extra source may be WSDW formed by the shelf water plumes that also produce WSBW, when the waters formed are not dense enough to sink beyond the depths at which the core is found (Fahrbach *et al.*, 1995; Weppernig *et al.*, 1996). It should be realized that bottom water formation results in multiple bottom water varieties with different characteristics (Foster and Carmack, 1976; Gordon *et al.*, 1993; Mensch *et al.*, 1996; Gordon, 1998), but also less dense varieties may be produced.

The CFC-11 maximum near 2200 m as observed in 1992 had vanished toward 1996. We ascribe these changes to the transient nature of the CFC-11 concentrations, in that a CFC-11 increase in the layers beneath the core tended to mask the CFC-11 maximum in question. Although, the limited vertical resolution of the CFC-11 data set may to some extent disguise the true temporal development. In 1998 the shallower CFC-11 maximum was observed again in the central basin, despite the continuing increase of the CFC-11 concentration in the deeper layers. This hints that the strength from the Weddell-Scotia Confluence source of deep CFC-11 has increased compared to the deep CFC-11 concentration caused by other sources.

b. The deeper, southern core and its role in replenishing WSDW

The deeper, southern core, which is clearly more prominent in comparison (Fig. 2b), is also the more relevant one. The southern core was likewise noted previously by various authors (Weiss *et al.*, 1990; Schlosser *et al.*, 1991; Mensch *et al.*, 1996; Meredith *et al.*, 2000). Meredith *et al.* (2000) observed it off the Antarctic coast near 20W (i.e., just west of our 1996 section) and ascribed it to recently ventilated WSDW, originating east of the Weddell Gyre. These authors also considered the possibility of an origin in the Weddell Sea itself. In fact, the waters along the northern South Orkney slope (Fig. 2a, stations 632-634) have CFC-11 concentrations high enough to explain the elevated concentrations in the southern core. However, Meredith *et al.* (2000) in a comprehensive analysis made a strong case for the eastern origin of the southern core, and exactly the same conclusion was reached by Klatt *et al.* (2001) from the analysis of CFC-11 time series data at the prime meridian. If the southern core would in fact derive from the northern Weddell Gyre limb, the high CFC signal would have to be found also somewhere in the interior Weddell Gyre. No such signature, however, is evident in any of the available CFC data sets (Weiss *et al.*, 1990; Mensch *et al.*, 1996; Meredith *et al.*, 2000; Klatt *et al.*, 2001). Besides this, east of the Weddell Gyre a high CFC core at 3000-4500 m depth along the continental slope has been observed within the westward flowing coastal current (Mantisi *et al.*, 1991; Jean-Baptiste *et al.*, 1991; Archambeau *et al.*, 1998). The combined evidence makes a strong case for a predominant origin of the high CFC-11 concentrations along the southern continental slope outside the Weddell Gyre.

Within the Weddell Gyre, the southern core can be traced from the prime meridian (Orsi *et al.*, 1999; Klatt *et al.*, 2001) to Kapp Norvegia (Fig. 2b). Its continuation to the southwest up to 30W can be seen in the data of Mensch *et al.* (1996). Our data reveal the continuation up to off Joinville Island (Fig. 2b), probably as part of the main Weddell Gyre flow along the margins. Note though, that off Joinville Island the CFC-11 signature of the deep water is clearly dominated by the recently formed local deep and bottom waters. Based on silicate distributions, this flow path along the Weddell Sea margin was also deduced for the bottom water (Hoppema *et al.*, 1998). An attenuated signal of the deep CFC-11 maximum/silicate minimum is also found in the entire central basin (Figs. 2b and 3b). Recognizing that the deep CFC-11 maximum and silicate minimum originate from east of the Weddell Gyre, this implies that the major part of the deep water of the Weddell Sea proper is replenished and ventilated from the east, i.e., from outside the Weddell Gyre.

An important feature of the southern core off Kapp Norvegia is its broad width (Fig. 2b, 1996). The width is less clear in the other years when our sections unfortunately did not extend all the way to Kapp Norvegia, but it is certain that in 1992 the core did not reach so far into the central basin as in 1996 (see Results section). Between 1992 and 1998, we believe there is a steady increase in the CFC-11 concentrations in the waters between about 2500 to almost 4000 m depth in central basin (Fig. 2). For example, the 1992 data show a CFC-11 concentration minimum in the western part of the section off the boundary current displaying concentrations below 0.15 pmol kg^{-1}, while in 1996 the minimum appears to be partly filled in. In 1998 it is entirely filled in, such that the 0.2 pmol kg^{-1} isoline became rather horizontal (Fig. 2c). At 25W the 0.2 pmol kg^{-1} isoline is found at about 3000 m depth in 1992, while it is found at 2000 m in 1996. We interpret these findings as indicative of a northwesterly progression of more recently ventilated waters supplied by the core. It is important to note that the silicate minimum related to the core in question (Fig. 3) shows up consistently in all three years, which means that the temporal changes in the CFC-11 distribution cannot simply be the result of changes in water mass distributions. Thus, observations suggest that the waters supplied by the deep southern core form a steady feature in which the arrival of more recently ventilated waters is reflected by a rise of CFC-11 concentrations. Furthermore, the wide extension of the silicate minimum across the basin (Fig. 3) shows that the southern core enacts a pronounced influence over most of the interior WSDW.

The remote ventilation of the lower WSDW also seems to affect the ventilation of the upper WSDW and lower Warm Deep Water above it. Our deliberations are the following. This stratum at 1000-1500 m depth features a CFC-11 minimum (Fig. 2b). Higher CFC-11 concentrations in the CFC-11 minimum are found in the southeast (off Kapp Norvegia) and lower ones in the northwest (Fig. 2b). This spatial distribution is congruent with the spatial distribution of CFC-11 in the underlying deeper WSDW core (Fig. 2b). Hence, though very slowly, also the lower WDW and upper WSDW are indirectly ventilated through the lower WSDW underlying it, the source of which is outside the Weddell Gyre. This ventilation for the lower WDW and upper WSDW implicates that the lowest CFC-11 concentrations in the CFC-11 minimum should occur in the northern limb of the Weddell Gyre, because that part is farthest away from the lower-WSDW source, which enters the gyre in the southern limb. Indeed, the lowest CFC-11 concentrations in the lower WDW and upper WSDW are observed in the northern limb as can be seen in the Jane Basin near 35W (unpublished Bremen data, Meteor cruise M11/5), at 30W (Meredith *et al.*, 2000) and at the prime meridian (Klatt *et al.*, 2001).

c. Rate of ventilated deep water from the eastern source

Our notion that the CFC load of the southern core is essentially derived from a source east of the Weddell Gyre enables us to determine the influx rate of ventilated surface water associated with this source. The determination is performed in two steps, (1) obtaining a CFC-11 flux affected by the southern core across the Kapp Norvegia section, and (2) converting this into a flux of ventilated surface water. The CFC-11 flux is calculated as the areal integral over the width of the southern core of the product of the CFC-11 concentrations at the section and the across-section flow velocity. The CFC-11 concentrations used are those of 1996 (Fig. 2b). We delimit the core by the 0.25 pmol kg^{-1} isoline, extrapolating this isoline to the bottom at station 80 (20W), and at 2000 m depth to the continental slope at station 75 (14.7W). As current velocities we use values determined along the same section (Fahrbach *et al.*, 1994). The values are temporal averages based on data for the period 1989 to beginning 1993 from a large array of current meters (more closely spaced toward the margins), which were combined with hydrographic observations in the usual fashion. We assume that this flow field is also representative for 1996 when the CFC-11 observations were obtained. This is a reasonable assumption considering that the velocities represent a multi-year average. Note that the use of the 0.25 pmol kg^{-1} CFC-11 isoline as the core boundary is not very critical because the flow is concentrated toward the slope such that at this isoline the velocities have become quite small. The area of the core was subdivided into boxes of 50 km (horizontally) by 50 m (vertically), and the integral was obtained by summing up over these boxes. The resulting CFC-11 transport by the core is $8.0\ 10^{-3}$ mol s^{-1}, and the corresponding water volume transport is 15.4 Sv (1 Sv = 10^6 m^3 s^{-1}). This is a large fraction of the total transport of the Weddell Gyre across the section, which amounts to 30 Sv (Fahrbach *et al.*, 1994). The reported uncertainty of the total water transport of the Weddell Gyre is about 30% (Fahrbach *et al.*, 1994). The CFC-11 data error is small in comparison, so that the CFC-11 transport should also have an uncertainty of approximately 30%.

To convert this CFC-11 flux into the corresponding rate of addition of ventilated surface water, the CFC-11 concentration of the ventilated surface water has to be known. This concentration follows the atmospheric trend, but one has to account for the fact that the surface layer waters, due to the quasi-permanent ice cover, distinctly lag behind the solubility equilibrium with the concurrent atmospheric CFC-11 partial pressure. The critical issue is to determine the point in time when the ventilated waters at the 1996 section actually descended from the surface layer in their area of origin; i.e., one must know the age of the ventilated waters at the section. The ventilated portion becomes diluted by an admixture of subsurface waters *en route*, which we assume to be tracer-free (see below).

Meredith *et al.* (2000) applied the CFC-11/CFC-12 ratio age method to the southern core and obtained an apparent age of the ventilated component of 18 years, but they also noted that their method has severe limitations. Alternatively, an average age of 13 ± 2 years was obtained by Klatt *et al.* (2001) for the core at the prime meridian. The mean age obtained was based on CFC-11 observations in the core repeated over more than a decade, and the authors employed a concept in which the ventilation age was nonuniform; rather, the ventilation being spread out over several years. We tentatively add one year to account for transfer from the prime meridian to off Kapp Norvegia so that, on average, the ventilated observed in 1996 (Fig. 2b) were formed in 1982. In 1982, the winter surface water CFC-11 concentrations were approximately 2.9 pmol kg^{-1}, based on a model-fit of observed concentrations by Mensch *et al.* (1998). Their observations include the aforementioned undersaturation of CFC-11, which in their data amounts to approximately 38%, in keeping with other determinations (Keir *et al.*, 1992; Roether *et al.*, 2001; Huhn *et al.*, 2001). Using this concentration, it follows that the transport of 8.0 10^{-3} mol s^{-1} of CFC-11 by the core (see above) requires a volume flux of surface water of 2.7 Sv (CFC-11 transport divided by the surface concentration). Note that using the higher age of Meredith *et al.* (2000), i.e. 18 years, would only increase the required amount of ventilated surface water. We estimate the uncertainty due to our choice of the year of descent and the related concentration to be approximately 15%.

An assumption in our analysis is that the surface water that ventilates the southern core sinks in one place at one time. Multiple sources of surface water may exist, though. However, our analysis uses a mean age of the core, and the mean CFC-11 concentration belonging to this age is also expected to be fairly similar to the mean concentration of these possible multiple sources.

Two further sources of error are now considered. First, during the formation of the core, the ventilated surface water mixes with deeper waters, which, if not tracer-free, will contribute to the CFC-11 transport. One has to consider that the fraction of ventilated water in the core is only about 18% (i.e., 2.7 Sv/15.4 Sv). (Note that this is fully consistent with the independent estimate of Klatt *et al.* (2001) for this core, amounting to 20 ± 3% at the prime meridian.) With such a dominance of admixed deep waters, even quite moderate CFC-11 concentrations might contribute a sizable fraction of the CFC-11 transport in the core. However, according to data from the Indian sector of the Southern Ocean of Mantisi *et al.* (1991), the CFC-11 concentration in the deeper waters that would contribute, even in the late 1980s was less than 0.03 pmol kg^{-1}. Moreover, the Lower Circumpolar Deep Water, which feeds the deep subpolar waters, was found to be still tracer-free in Drake Passage in 1990 (Roether *et al.*, 1993). It follows that the conceivable CFC-11 concentrations in the deeper waters in question in the early 1980s when the ventilated waters in question were formed, would only contribute a small fraction of the CFC-11 transport. We estimate that the conceivable bias in our deduced rate of ventilated water supply arising from the assumption of negligible CFC-11 in the contributing deep waters could be at most about 10%.

The second source of error concerns mixing of core water with the surrounding water during the transit of the core from its region of origin to off Kapp Norvegia. The surrounding water has a low CFC-11 concentration. Any mixing of high CFC-11 core water with low-CFC-11 surrounding waters will result in a net loss of CFC-11 from the core, and hence lead to an underestimation of the CFC-11 flux from the source. The magnitude of this error is estimated by considering the volume and CFC-11 concentration of the waters adjoining the core, to the extent that addition from the core can be expected. We took the distance from the region of origin (Amery Basin; Meredith *et al.*, 2000) to the Weddell Sea to be 4000 km, the mixing path length perpendicular to the core to be 500 km (approximately the distance to the gyre axis) and the vertical extent of the water column affected to be 2 km, yielding a water volume to accumulate CFC-11 by mixing from the core of $4\ 10^{15}\ m^3$. Taking the average concentration in this volume as 0.05 pmol kg^{-1} (Mantisi *et al.*, 1991), its CFC-11 content becomes $2\ 10^5$ mol. This should be compared with the CFC-11 supply by the core, integrated in time over the period of CFC-11 supply to the ocean. The resulting CFC-11 supply is about $2.2\ 10^6$ mol; it was obtained by taking the supply to be $8\ 10^{-3}$ mol s^{-1} for 1996 as derived above, and reducing for the earlier years in proportion to the respective atmospheric CFC-11 partial pressures. It follows that the CFC-11 loss due to the mixing away from the core should be no larger than about 9%. The resulting bias in the deduced rate of ventilated water influx is thus again only minor, and moreover, it is in an opposite sense to the error due to the first assumption. The resulting error of both assumptions combined is at most 10%. Combined with the uncertainty in the choice of the year of descent of the ventilated waters (see above), the error is no larger than about 18%. This is clearly less than the error due to the uncertainty of the current velocities (about 30%). The overall uncertainty in the calculated rate of ventilated surface water in the southern core becomes about 35%.

The bottom line is that 2.7 ± 0.9 Sv of ventilated surface water are contributed to the WSDW by the southern core from a source east of the Weddell Gyre. These 2.7 Sv compare with estimated rates of ventilated surface water associated with bottom water formation in the Weddell Sea proper of only 0.5-1.3 Sv (Fahrbach *et al.*, 2001), or 1.5-1.7 Sv (Weppernig *et al.*, 1996; Mensch *et al.*, 1996; Haine *et al.*, 1998). On the other hand, the total of ventilated waters exiting the Weddell Sea has been estimated by Meredith *et al.* (2001) to be 3.7 ± 1.6 Sv, with an absolute upper limit of 6.6 Sv being suggested by these authors. The estimated exiting rate is thus substantially larger than the reported local formation rates, although these rates may to some extent be underestimated as there may be additional water too warm to be classified as Weddell Sea Bottom Water (i.e., warmer than -0.7°C). The rate of ventilated water contributed from outside the Weddell Sea by the southern core tallies well with the apparent difference in the above rates. In summary, it follows that the eastern source of ventilated waters advected by the southern core is at least as important for the ventilation of deep water of the Weddell Sea as the combined deep and bottom water sources within this sea.

d. Corresponding deep water characteristics of properties other than CFC-11

Water mass features associated with CFC maxima in the deep water have been reported earlier. Whitworth and Nowlin (1987) found a silicate minimum near 2500 m on the prime meridian, while Orsi *et al.* (1993) traced Weddell Sea Deep Water with relatively high dissolved oxygen and low temperature and salinity along the Antarctic coastline between 5E and 20E. These authors considered the structures to be local features. Carmack (1973) and Carmack and Foster (1975) found discontinuities in θ-S and θ-silicate relations at a potential temperature of −0.5°C in the western Weddell Sea, which they considered indications for horizontal advection of different water varieties in the WSDW range. Chen (1994) described discontinuities in TCO_2, pH and silicate at $\theta = -0.6°C$ for the eastern Weddell Gyre.

The deep CFC-11 maximum near 3500 m (Figs. 2 and 4), the silicate minimum (Figs. 3 and 5) and the discontinuities in the oxygen, nitrate and TCO_2 distributions (Fig. 5) all occur in the same potential temperature range between −0.5°C and −0.6°C. This is a strong indication that they have the same origin. Our data suggest that the effects of deep water ventilation are traceable in the distributions of many different properties over almost the entire central Weddell Sea.

The relationships between potential temperature and other properties are not linear (Fig. 5). It is beyond doubt that the bottom water of the Weddell Sea with $\theta < -0.7°C$ is produced by mixing between WDW and a surface water component (Carmack and Foster, 1975). Therefore, in a mixing diagram the bottom water should lie on a line connecting WDW (actually, its lower boundary near $\theta = 0.2°C$; Whitworth and Nowlin, 1987) and surface water. The ventilated deep water centered near a potential temperature of −0.5 to −0.6°C (Fig. 5) deviates from such a mixing line. Hence, the recently ventilated deep waters feature relatively low TCO_2, silicate, nitrate, and relatively high oxygen and salinity. This implies that either the surface water or the WDW endmember (or both) of this advected deep water must have lower TCO_2/nutrient and higher oxygen concentrations than the endmembers in the Weddell Sea. Summarizing, the distributions of all these different properties within the Weddell Sea support the above results for CFC-11.

5. Summary and conclusions

A major part of the Weddell Sea Deep Water is not ventilated through the mixing between Weddell Sea Bottom Water and Warm Deep Water, or injection of shelf water in the Weddell Sea water column. Rather, it appears that a highly important source of ventilation of the deep Weddell Sea is the advected ventilated deep water from east of the Weddell Gyre. Indirectly, the lower part of the Warm Deep Water within the Weddell Sea is (slowly) ventilated by this external source. Hence, contrary to previous insights this does not concern some small local sources. Quantitatively, the ventilation rate of the external source is at least as large as the reported rate of sources within the Weddell Gyre region itself. If no other significant sources of surface ventilated waters are found in the Weddell

Sea, this implies that the role of the Weddell Sea in the ventilation of deep waters of Antarctic origin has been overestimated in the past.

Another source of ventilated deep water exists, though, and derives from the Weddell-Scotia Confluence (Orsi *et al.*, 1999). We found faint signals of it in the central Weddell Sea as CFC-11 maxima at 2200-2500 m. A next goal should be to examine its source strength to be able to fully assess the role of the Weddell Sea in the ventilation of the abyssal oceans.

Contrary to most earlier investigations, we found discontinuities in the distributions of nutrients and oxygen in the larger part of the gyre. These are clearly associated with the recently ventilated deep water from the east. Budgetting of TCO_2, nutrients and oxygen should include additional terms representing the recently ventilated deep water. The recently ventilated deep water is characterized by relatively low concentrations of TCO_2, nitrate, silicate and a high concentration of oxygen as compared to the mixing sequence in the Weddell Sea involving WDW and shelf water. Exact source values should be determined. The recently ventilated deep water also has a different potential temperature-salinity field, which was already noticed by Carmack and Foster (1975), but often ignored in later work.

We have shown that deep water formation outside the Weddell Gyre is a substantial, possibly dominant source of ventilation for the Weddell Sea as compared to bottom water formation in the Weddell Sea itself. Unfortunately, because deep water formation has not been comprehensively studied, it appears conducive to the understanding of the ventilation of the global ocean to shift some research efforts toward deep water formation around Antarctica.

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