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# On the total carbon dioxide and oxygen signature of the Circumpolar Deep Water in the Weddell Gyre

Carbon dioxide
Oxygen
Circumpolar Deep Water
Weddell Sea
Circulation

$CO_2$
Oxygène
Eau profonde circumpolaire
Mer de Weddell
Circulation

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## ABSTRACT

Sections from two "*Polarstern*" cruises in austral winter 1992 and summer 1992/1993 were used to track the course of Circumpolar Deep Water (CDW) in the Weddell Sea. Total inorganic carbon ($TCO_2$) is a valuable tracer for that water mass because it permits identification of features that cannot be seen in the distributions of temperature and salinity. Upon entrance into the eastern Weddell Gyre, a shallow maximum in $TCO_2$ at about 200 m (together with a temperature maximum and oxygen minimum) indicates the depth level to which vertical mixing with Winter Water penetrates the CDW layer in the Weddell Gyre. The lower boundary of this CDW layer, which is not apparent in the temperature and salinity profiles, is a $TCO_2$ maximum at 1000-1500 m ($\sigma_\theta \approx 27.835$), originating *via* the superposition of the recently advected CDW from the Antarctic Circumpolar Current (ACC) and the Weddell Sea Deep Water (WSDW), with opposite vertical gradients. A coinciding, weak oxygen minimum is only present on the prime meridian, and is probably caused by the different biological histories of the CDW and underlying WSDW. Using this $TCO_2$ maximum, the newly injected CDW can be traced as a well-defined band around the Weddell Sea, extending to the south of the South Orkney plateau. Downstream in the northern limb of the Weddell Gyre at the prime meridian, its trace has disappeared.

The band of "new" CDW, as part of the boundary current, envelops a central area where currents are significantly smaller, and where a special modification of CDW, the Central Intermediate Water (CIW), can be distinguished. This water mass is characterized by a secondary $TCO_2$ maximum and oxygen minimum, with no comparable structures in the temperature and salinity fields. CIW is enriched in $CO_2$ compared to the CDW that enters the Weddell Gyre, and is most pronounced in the western part of the Weddell basin. Data in the west suggest that the CIW is related to the lower part of the "new"-CDW layer. Thus, the central Weddell basin is replenished from the western rather than the eastern side. Within the interior, the CDW is further modified by mixing with the underlying WSDW and by entrainment into the surface layer above. Part is also advected out of the Weddell Sea into the bottom layer of the ACC, conveying water that has been biologically enriched in $CO_2$ to the abyssal oceans.

## RÉSUMÉ

### Carbone inorganique total et oxygène, traceurs de l'eau profonde circumpolaire dans la mer de Weddell.

La trajectoire de l'eau profonde circumpolaire (CDW) a été suivie dans la mer de Weddell au cours de deux campagnes du N.O. *Polarstern* pendant l'hiver austral 1992 et l'été 1992-1993. Le carbone inorganique total ($TCO_2$) est un bon traceur de cette masse d'eau car il révèle des caractéristiques qui n'apparaissent pas dans les répartitions de température et de salinité.

A l'entrée de l'eau CDW (déviation locale du courant antarctique circumpolaire, ACC), dans l'est de la mer de Weddell, un maximum de $TCO_2$ (associé à un maximum de température et à un minimum d'oxygène) est observé à environ 200 m, profondeur où se fait le mélange entre l'eau superficielle d'hiver et l'eau CDW. Le niveau inférieur de la couche d'au CDW n'apparaît pas sur les profils de température et de salinité; il est marqué par un maximum de $TCO_2$ à 1000-1500 m, ($\sigma_\theta \approx 27.835$), qui résulte de la superposition de l'eau CDW et de l'eau profonde de la mer de Weddell (WSDW), avec des gradients verticaux opposés. L'oxygène présente un petit minimum, uniquement sur le méridien origine, lié probablement à l'histoire biologique différente des deux eaux.

Le maximum de $TCO_2$ permet de suivre la pénétration de l'eau CDW au long du circuit qu'elle décrit dans la mer de Weddell jusqu'à sa sortie au sud du plateau des Orcades. Au-delà, sa trace a disparu lorsque le courant atteint le méridien origine.

L'eau CDW "nouvelle", dont le circuit fait partie du courant limite, entoure une région centrale où les courants sont nettement plus faibles et où l'on distingue une dérivation de l'eau CDW, l'eau centrale intermédiaire (CIW). Cette masse d'eau est caractérisée par un maximum secondaire de $TCO_2$ et par un minimum d'oxygène, sans structures comparables dans les champs de température et de salinité; elle est plus riche en $CO_2$ que l'eau CDW qui entre dans la mer de Weddell. Ses caractéristiques sont plus marquées dans l'ouest du bassin où elle atteint le niveau inférieur de la couche d'eau CDW "nouvelle". Ainsi, l'alimentation du bassin central se fait par l'ouest plutôt que par l'est. A l'intérieur, l'eau CDW est modifiée par mélange avec l'eau profonde de la mer de Weddell sous-jacente et par l'entraînement de la couche d'eau supérieure. Une partie du courant CDW est rejeté en dehors de la mer de Weddell dans la couche de fond du courant antarctique circumpolaire, transférant vers les fonds de l'océan mondial une eau biologiquement enrichie en $CO_2$.

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## INTRODUCTION

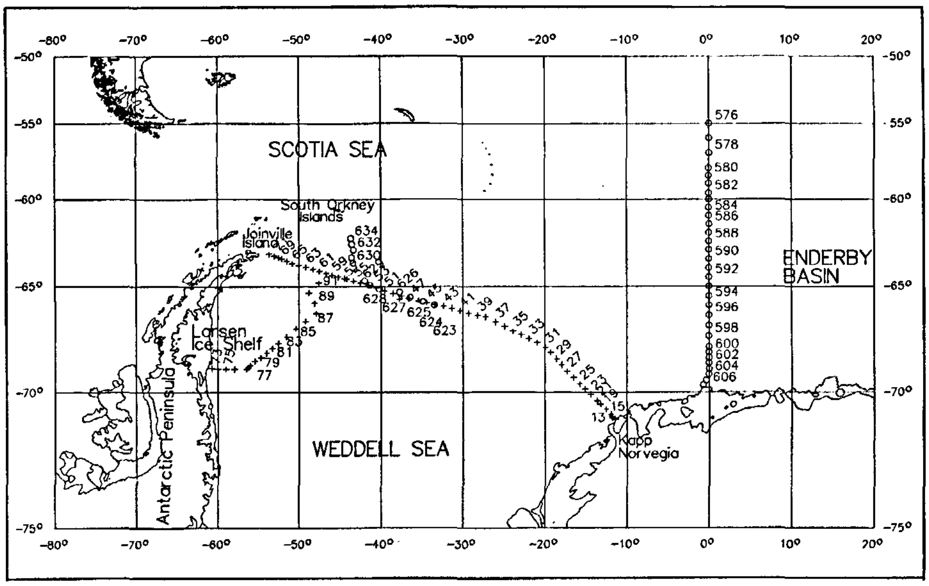
Among all the different oceanic regions of the Antarctic the Weddell Sea has since long perked special interest due to its reputation as the main bottom-water formation area (Brennecke, 1921; Mosby, 1934). The bottom- and deep water of the Weddell Sea are the main precursors of Antarctic Bottom Water (Deacon, 1937; Seabrooke *et al.*, 1971), which in turn significantly influences the abyssal characteristics of all world ocean basins (Wüst, 1939; Mantyla and Reid, 1983). Circulation in the Weddell Sea is dominated by a large, elongated cyclone, known as the Weddell Gyre (Fig. 1). It has also been suggested that the Weddell Gyre consists of two subgyres (Mosby, 1934; Klepikov, 1960; Treshnikov, 1964; Orsi *et al.*, 1993). In the south and west, the gyre is bounded by the Antarctic margin, whereas in the east it extends well into the Enderby basin, as far as 26-30° E (Gouretski and Danilov, 1993; Orsi *et al.*, 1993). The northern boundary is less clearly defined; while it is limited by a hydrographical front related to the Mid-Atlantic Ridge on the eastern side, it runs well into the Weddell-Scotia Confluence and Scotia Sea on the western side, *i.e.* beyond the "natural", topographical boundary formed by the South Scotia Ridge system (Orsi *et al.*, 1993).

The oceanic gyre circulation is driven by the large-scale atmospheric wind field, by differential heat and water exchange with the atmosphere and by sea ice formation. The flow is constrained by the bottom topography, which coerces the Circumpolar Deep Water (CDW) of the Antarctic Circumpolar Current (ACC) to the south (Koopmann, 1953; Deacon, 1979). With the CDW, relatively warm, saline, $CO_2$-rich and oxygen-poor water is entrained into the Weddell Gyre at its eastern edge. CDW obtains its characteristics from the deep and bottom waters of all ocean basins; in the Atlantic sector the influence of the North Atlantic Deep Water is dominant. Within the southern limb of the Weddell Gyre, CDW is transported westwards as part of the boundary current (Gill, 1973; Fahrbach *et al.*, 1992), participating in bottom-water formation processes at the southern and western continental shelves (Foster and Carmack, 1976; Gordon *et al.*, 1993; Fahrbach *et al.*, 1995). The volume transport as determined by an array of 18 current meters across the gyre amounts to 30 Sv, 90 % of which is transported by the boundary currents (Fahrbach *et al.*, 1994).

As CDW is essentially the only source water of the Weddell Sea advected from outside, all other water masses directly or indirectly derive from it. Through bottom- and deep water (Gordon, 1978; Orsi *et al.*, 1993) formation, the lower water column beneath the CDW is replenished. Surface water is formed through upwelling and entrainment of CDW into the surface mixed layer (Weiss *et al.*, 1979; Gordon

Figure 1

*Map of the Atlantic sector of the Antarctic Ocean depicting the Weddell Gyre with geographical names used in the text. Station numbers > 500 are from the winter cruise ANT X/4 and numbers < 100 from summer cruise ANT X/7.*



and Huber, 1984). This replenishment of the surface layer by the CDW has far-reaching implications for the role of the Weddell Sea in the carbon cycle. While, due to cooling, a potential sink for atmospheric $CO_2$, this is significantly counteracted by the upwelling of $CO_2$-rich deep water (Weiss *et al.*, 1979; Poisson and Chen, 1987). Recent studies in turn pointed out the potential of the biological pump mechanism to counteract this upward transport of $CO_2$ (Hoppema *et al.*, 1995; Wedborg *et al.*, 1996).

The CDW of the Weddell Gyre has also been designated Warm Deep Water or Weddell Deep Water (WDW). In the present communication, we shall use the term CDW since we are to discuss the direct propagation of CDW into and within the Weddell Gyre.

Within the framework of carbon cycling, the distribution of $TCO_2$ in the Weddell Sea has its own inherent value: the $TCO_2$ concentration of the CDW shows the amount of inorganic carbon being advected into the Weddell Sea. Also, in the present study, the Central Intermediate Water (Whitworth and Nowlin, 1987) is investigated, which, being a modified CDW layer, is expected to reveal enrichment in $CO_2$. Lastly, this study explores the details of the $CO_2$ distribution which, in combination with oxygen, is used to trace the newly-injected CDW through the Weddell Gyre, and to substantiate the circulation pattern described in Fahrbach *et al.* (1994).

## DATA, SAMPLING AND METHODS

Data were collected during two cruise legs aboard RV *Polarstern* (Fig. 1 for station positions). Leg ANT X/4 in June/July 1992 (Lemke, 1994) covered the prime meridian between Cape Town and the Antarctic continent, of which in the present study the Weddell part, south of 55° S, is presented. From this cruise, the transect between the central Weddell Sea and the South Orkney plateau (stations 623-636) is also treated. Since the cruise took place in mid-winter, the Weddell Sea was fully ice covered. On cruise leg ANT X/7 in December 1992/January 1993 (Fahrbach, 1994), a cross-section of the Weddell basin was occupied (stations 11-72), as was, because of unusually favourable ice conditions, another transect off the Larsen Ice Shelf towards the central Weddell Sea (stations 73-91).

On all hydrographic stations, continuous temperature and salinity profiles were measured with a Conductivity-Temperature-Depth instrument (NBIS Mark IIIb); discrete water samples, distributed over the entire water column, were collected with a 24-place General Oceanics rosette sampler. Accuracy of temperature was set by shore-based calibration and amounted to 3 mK. Salinity, given on the Practical Salinity Scale, was standardized using an Autosal 8400A salinometer and is accurate to 0.003. Dissolved oxygen was measured on discrete samples using a standard automated Winkler technique with photometric end-point detection, precision 0.2 % CV. More details on the measurements can be found in Fahrbach (1994).

The $CO_2$ data in this study are represented by the Total Carbon dioxide ($TCO_2$). This is the sum of all the species of the $CO_2$ system in sea water, *i.e.* dissolved $CO_2$ gas and carbonic acid, as well as the bicarbonate and carbonate ions. $TCO_2$ was analysed on board within 24 h of sampling, using a coulometric method (Johnson *et al.*, 1985). Software for automated data acquisition and operation of sample dispensing and $CO_2$ extraction was written by M. Stoll of the Netherlands Institute for Sea Research (see also Stoll, 1994). The precision obtained from all duplicates amounts to 0.85 µmol/kg. $TCO_2$ data of the second cruise leg were standardized using certified reference sea water of Dr. A. Dickson of the Scripps Institution of Oceanography (USA). Data of the first cruise, when reference sea water was not yet available, were adjusted to those of the second cruise by means of the $TCO_2$-potential temperature relationship in the Weddell Sea Deep Water. For more details, see Hoppema *et al.* (1995).

Variations in the freshwater content (represented by the salinity) also cause variations in the $TCO_2$. Therefore, in considering $TCO_2$ variability, the $TCO_2$ values have to be normalized to a constant salinity. In the present study, we focus on the CDW in the Weddell Sea, and here the salinity variation is minimal. Salinity variation within the CDW causes shifts between $TCO_2$ and normalized $TCO_2$ distributions of about 0.1 %, which is much less than the observed variations. Consequently, all observed structures are independent of salinity changes. The same holds true for dissolved oxygen.

## INFLOW OF CDW IN THE EASTERN WEDDELL GYRE

In the present data set, the most pristine CDW can be found on the prime meridian section as the CDW is injected into the Weddell Gyre near its eastern boundary. Vertical sections over the upper 2000 m are presented in Figure 2 for $TCO_2$, dissolved oxygen, potential temperature, salinity and the potential density anomaly. Recently injected CDW from the ACC is recognized by its high temperature maximum of up to >1 °C and high salinity of about 34.69-34.70. The pristine CDW on the prime meridian constitutes the warm regime (Gordon and Huber, 1984) and comprises stations 591 and 593-598. North of the warm regime (stations 579-592, excluding 591), the temperature maximum is much cooler, leading us to refer here to a cold-regime CDW. Being shed from the warm regime, station 591 represents a warm cell within the cold regime (Gordon and Huber, 1984; Bersch *et al.*, 1992). Following Gouretski and Danilov (1993), the division between the cold and warm regimes is at 0.8 °C, which is 0.3 °C higher than in Gordon and Huber (1984) and Whitworth and Nowlin (1987). Generally, the pristine, warm regime CDW flows westwards, whereas the cold-regime CDW flows to the east. In this paper, the newly injected pristine CDW will be referred to as "new" CDW.

On its path to and inside the Weddell Gyre, the CDW layer is elevated and its upper part is eroded by entrainment into the cold and low saline surface layer. Due to the monotonic temperature decrease with depth in the LowerCDW of the ACC (*i.e.* below the maximum of the UpperCDW), a maximum is formed at the lower boundary of the thermocline. At approximately the same depth as the temperature maximum, an oxygen minimum and $TCO_2$ maximum were observed (Figs. 2*a*, *b*, *c*). These extremes are induced in the same way as the temperature maximum through the oxygen-rich and $TCO_2$-poor surface layer. The shallow extremes form the top of the CDW in the Weddell Sea and were found in the density range of $\sigma_\theta$ 27.77-27.79. The salinity maximum occurred deeper than these other extremes. This maximum, however, is an advected property from the ACC, where the LowerCDW core is characterized by a salinity maximum.

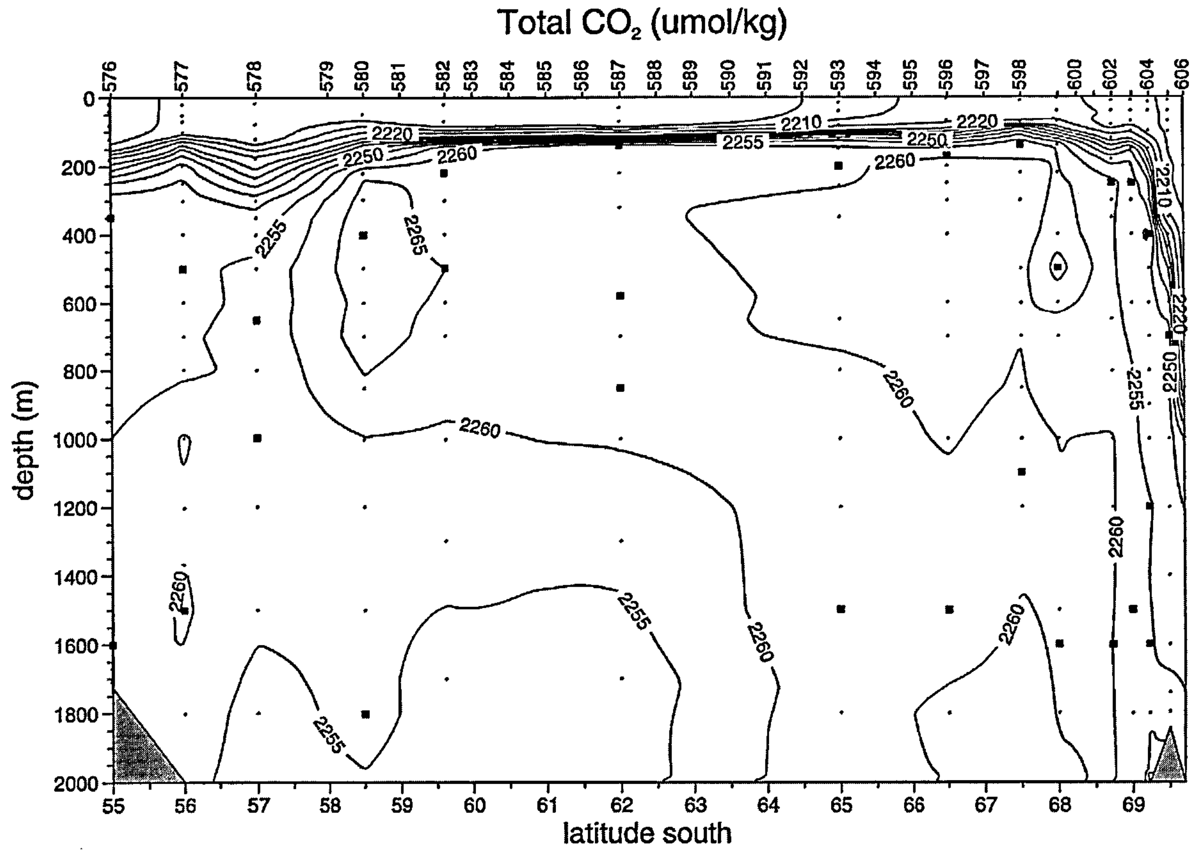
Upon entering the Weddell Gyre, "new" CDW slides over Weddell Sea Deep Water (WSDW) that has been resident in the Weddell Sea for a considerable time. What occurs at the interface where these water masses meet is sketched in Figure 3. Within the "new" CDW, temperature decreases and oxygen increases with depth, reflecting the monotonic gradients of the LowerCDW of the ACC. Where the "new" CDW and the WSDW in the Weddell Sea are superimposed, a barely detectable change of gradient (not of sign) of the above properties occurs at the boundary between the two layers. This is different in the case of $TCO_2$: in the "new"-CDW stratum, a $TCO_2$ minimum observed near 400 m, close to the salinity maximum (Fig. 2*d*), constitutes a continuation of the $TCO_2$ minimum from the LowerCDW of the ACC. Hence, below 400 m, $TCO_2$ *increases* with depth in the "new" CDW. In the underlying WSDW, $TCO_2$ *decreases* with depth due to the admixture of Weddell Sea Bottom Water (WSBW) with low $TCO_2$ concentrations (Fig. 2*a*). This implies that at the interface of "new" CDW and WSDW a $TCO_2$ maximum will be shaped. This absolute maximum is observed at 1200-1500 m ($\sigma_\theta$ about 27.835) in the warm regime defining the lower boundary of the "new"-CDW inflow. Temperature and salinity hardly reveal any structure at that boundary. At many stations, the $TCO_2$ maximum at 1200-1500 m was accompanied by a (relative) oxygen minimum, the explanation being that biological degradation has reduced the oxygen concentration in the resident WSDW as compared with the "new"-CDW inflow of about the same density. This process would also reinforce the $TCO_2$ maximum, but would leave temperature and salinity unaffected. We shall use this deep $TCO_2$ maximum/oxygen minimum at $\sigma_\theta$ 27.835 to trace the course of the "new" CDW through the Weddell Sea (Section 4).

We should point out that we use the terms "new" and "old" in reference to the residence time of water masses in the Weddell Sea and not to their ventilation. As the WSDW contains recently ventilated shelf and bottom waters, it is in all probability younger than the CDW but on the basis of its residence time in the Weddell Sea, we would describe it as "old".

An additional oxygen minimum was observed in the cold regime CDW (stations 579-589) in the range ($\sigma_\theta$ = 27.82-27.83. This is an expression of the Central Intermediate Water (CIW) as designated by Whitworth and Nowlin (1987). These authors demonstrated that the characteristics of that layer are formed by mineralization at depth. As a result of upwelling, the layer attains a shallower depth in the central Weddell Sea. $TCO_2$ also has a maximum in the CIW (Fig. 2*a*), while salinity and temperature extremes are usually not to be found. The density of the CIW extreme on our sections tends to be lower than in Whitworth and Nowlin (1987). Related to this might be the fact that the oxygen minimum of the CIW is observed at a somewhat greater depth by Whitworth and Nowlin (1987) than in the present study.

## COURSE OF NEW CDW THROUGH THE WEDDELL SEA

Vertical sections for $TCO_2$, dissolved oxygen and potential temperature are shown from Kapp Norvegia to Joinville Island (Fig. 4), off the Larsen Ice Shelf to the previous section (Fig. 5), and from the central Weddell Sea to the South Orkney plateau (Fig. 6). With these the course of the "new" CDW within the clockwise circulation of the Weddell Gyre is tracked. The distribution of salinity (not shown) is in conformity with that of the other properties treated here.



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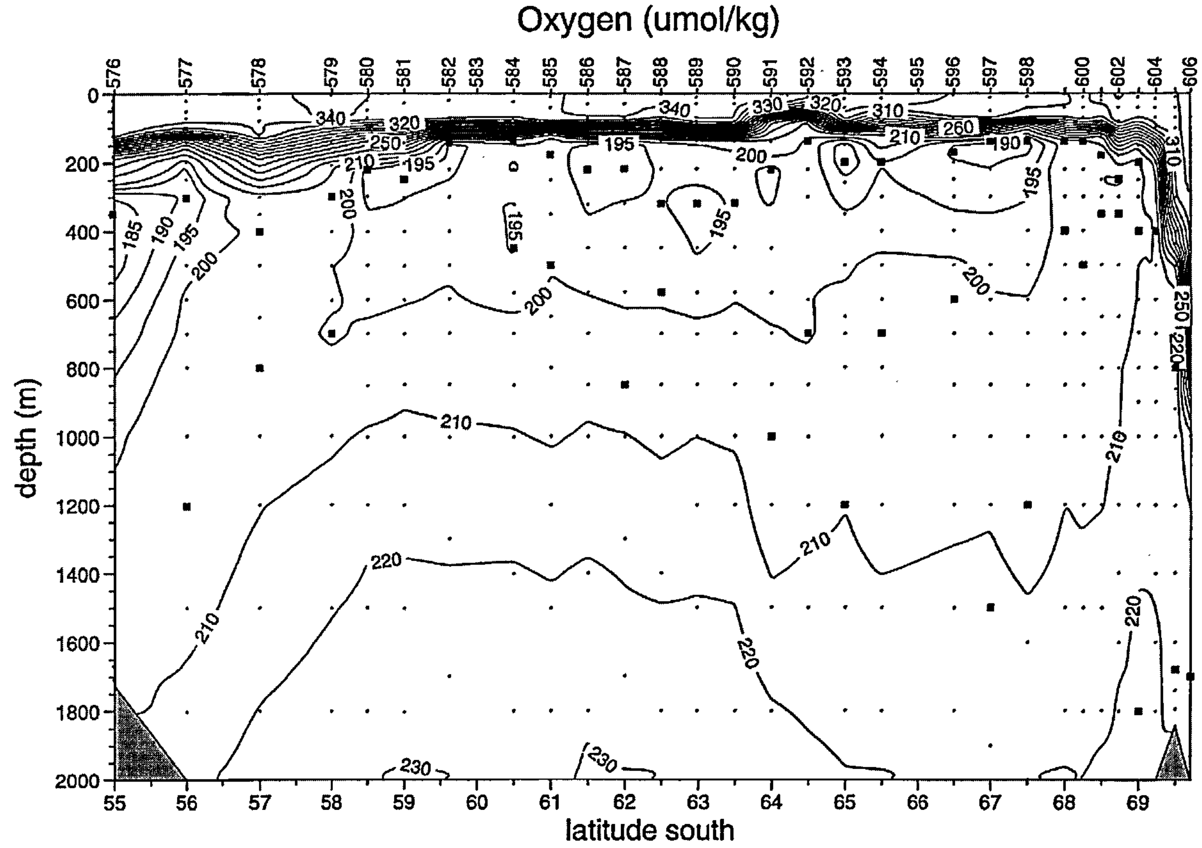

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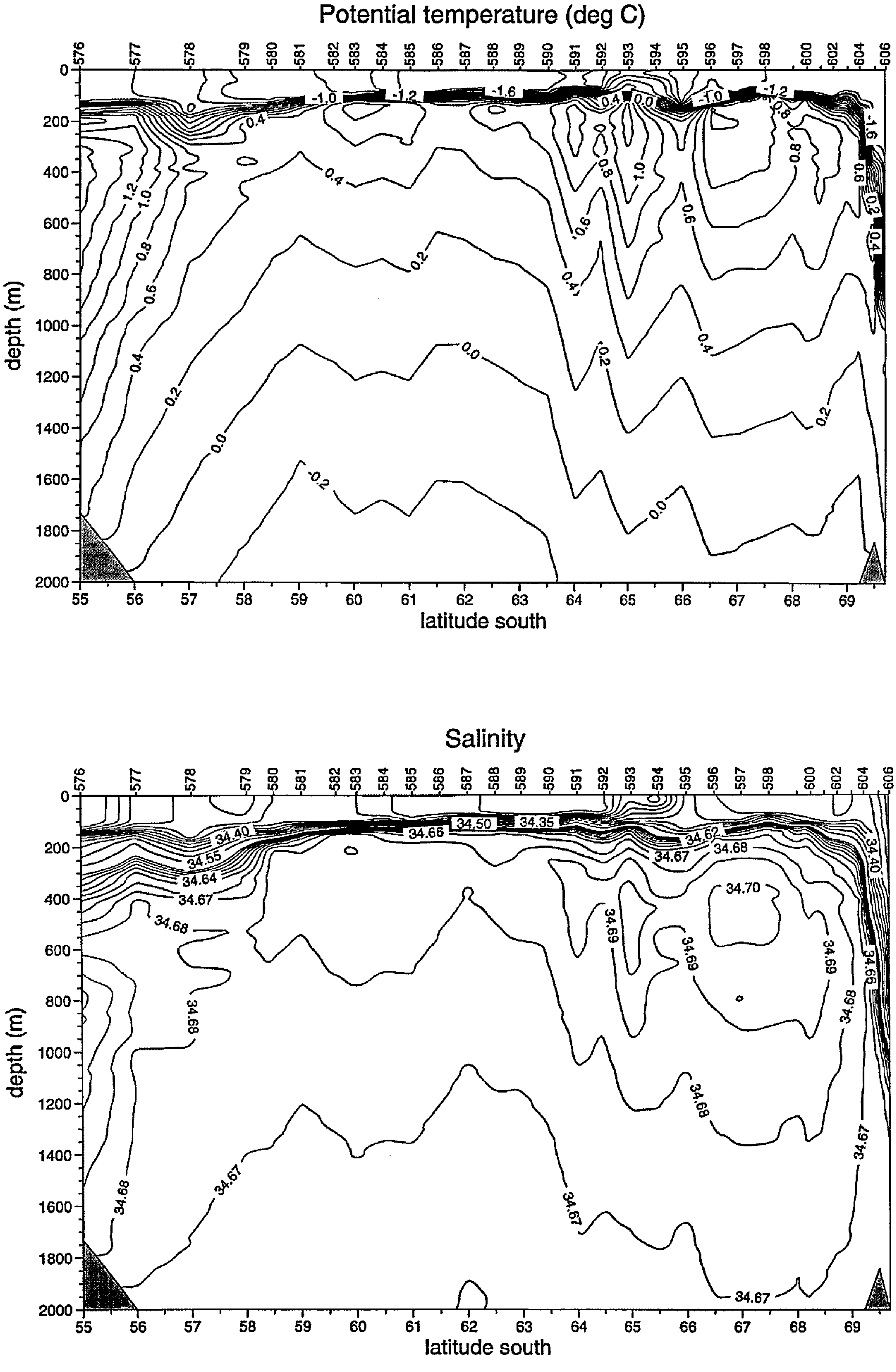
Figure 2*a*, *b*



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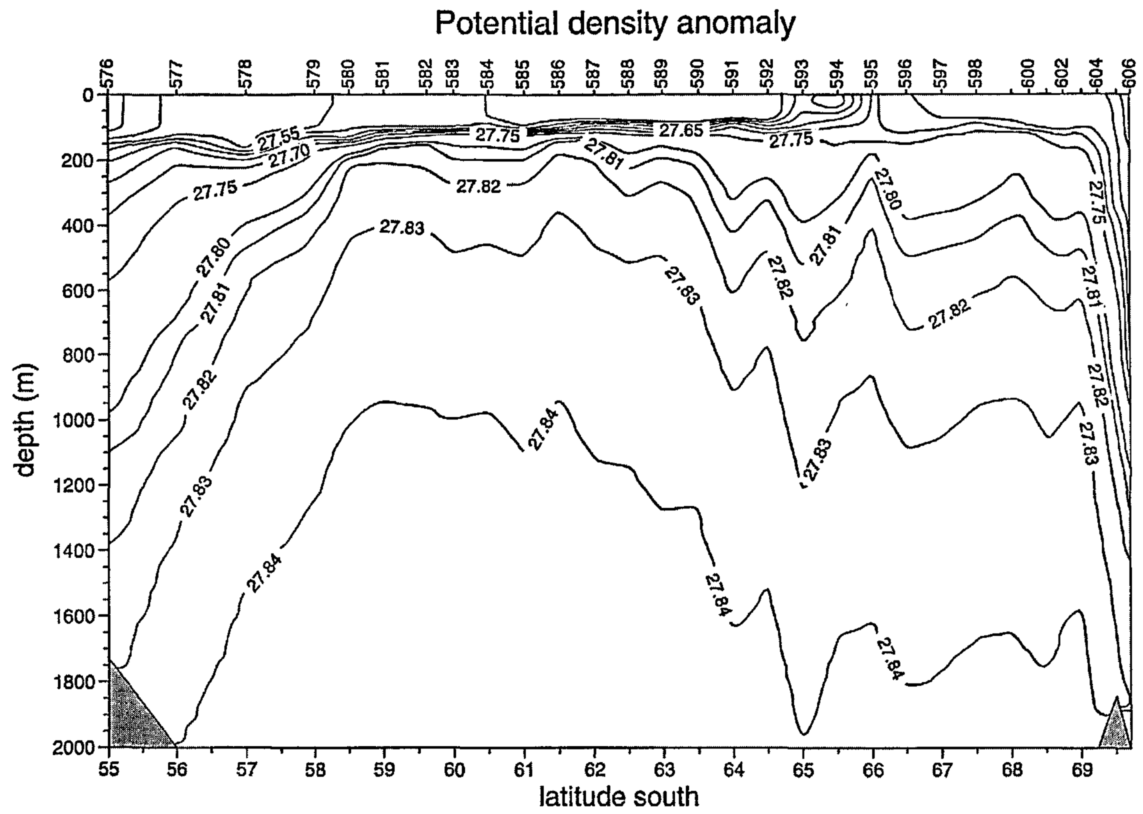

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Figure 2

*Vertical sections for the upper 2000 m of the water column of: (a) $TCO_2$; (b) oxygen; (c) potential temperature; (d) salinity; and (e) the potential density anomaly on the prime meridian between 55 °S and the Antarctic coastline. This is a north-south cross-section of the Weddell Gyre. Stars denote the positions of $TCO_2$ maxima and oxygen minima.*

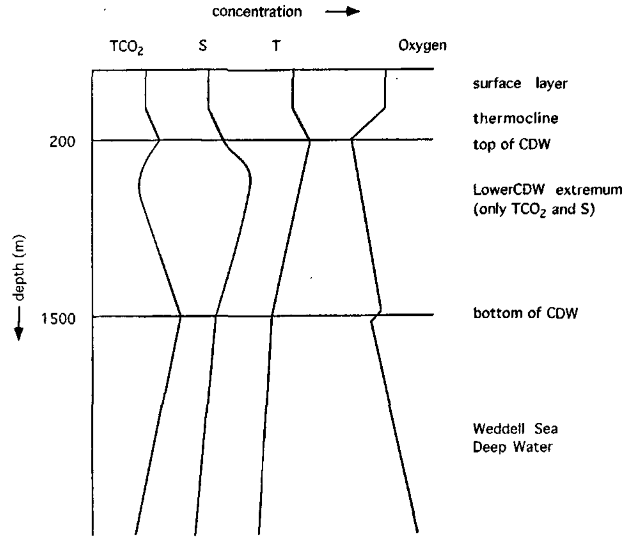
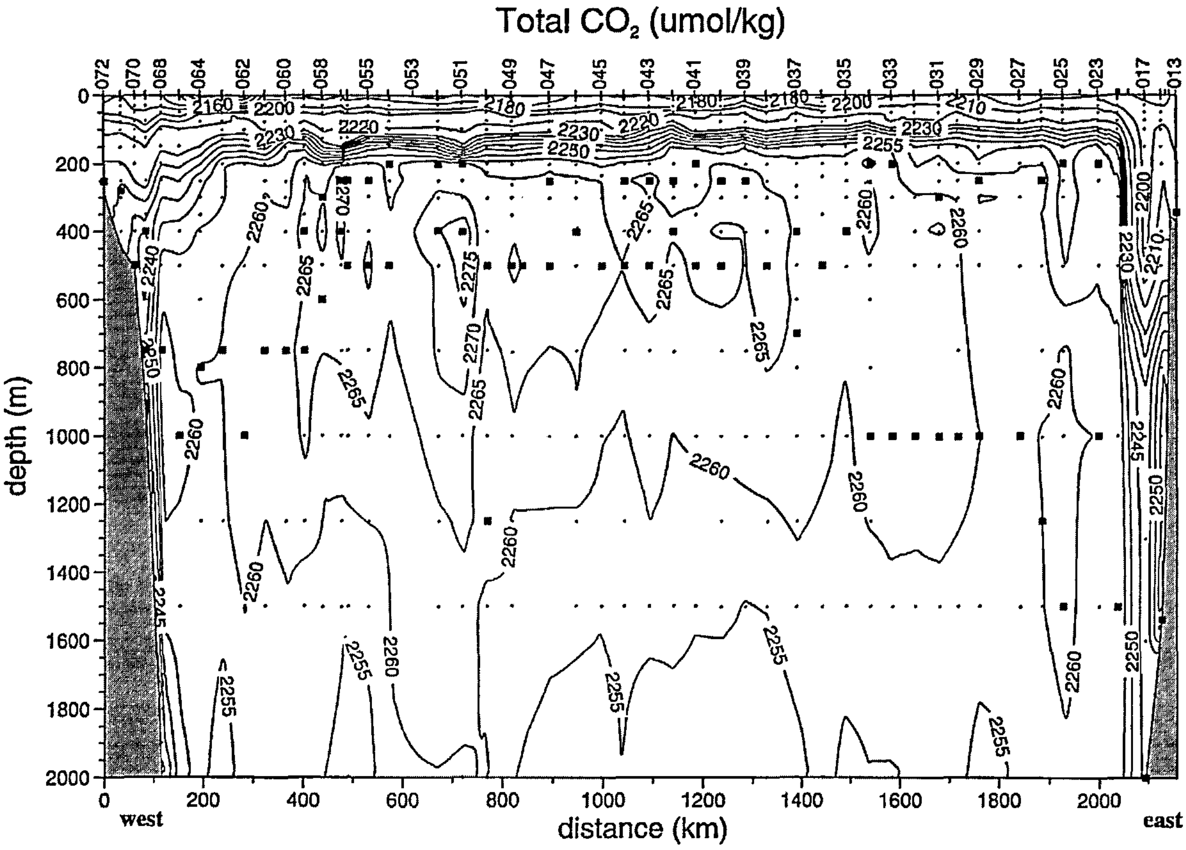


Figure 3

*Schematic representation of the vertical profiles of $TCO_2$, salinity, temperature and dissolved oxygen to elucidate the generation of extremes upon entry of the LowerCDW into the Weddell Gyre.*

At approximately the same density as the corresponding feature on the prime meridian, a deep $TCO_2$ maximum, typical of the bottom of the "new"-CDW layer, was observed at all sections in the margins of the Weddell Gyre, generally at a depth of about 1000 m. An accompanying oxygen minimum, like that observed on the prime meridian, was mostly absent (Figs. 4*b*, 5*b*, 6*b*). A closer look at the vertical profiles revealed that only remnants of an oxygen minimum were visible as inflections. Off Kapp Norvegia, where the boundary current arriving from the prime meridian takes a southwestward bend, the deep $TCO_2$ maximum was found between stations 23 and 35 (up to 600 km off the coastline). The magnitude (about 2262 μmol/kg) was the same as on the prime meridian. Thus, while the high temperature maximum off Kapp Norvegia gradually decreases in an offshore direction (Fig. 4*c*), the deep $TCO_2$ maximum is constant and spatially limited. The offshore limit of the deep $TCO_2$ maximum seems to mark the boundary of flow of "new" CDW. This renders the deep $TCO_2$ maximum a tracer for the propagation of the plume of "new" CDW. Some surface properties also delimit a special zone inshore of station 35, characterized by low temperature, high salinity, low oxygen and high $TCO_2$ (Fahrbach, 1994; Hoppema *et al.*, 1995). Also, ice concentration was enhanced in this zone. Intense advection of the boundary current is the most likely explanation for the coincidence of high temperatures in the CDW and the heavy ice cover.

In the western Weddell Sea, the plume of "new" CDW was observed both on the Larsen section offshore of station 82



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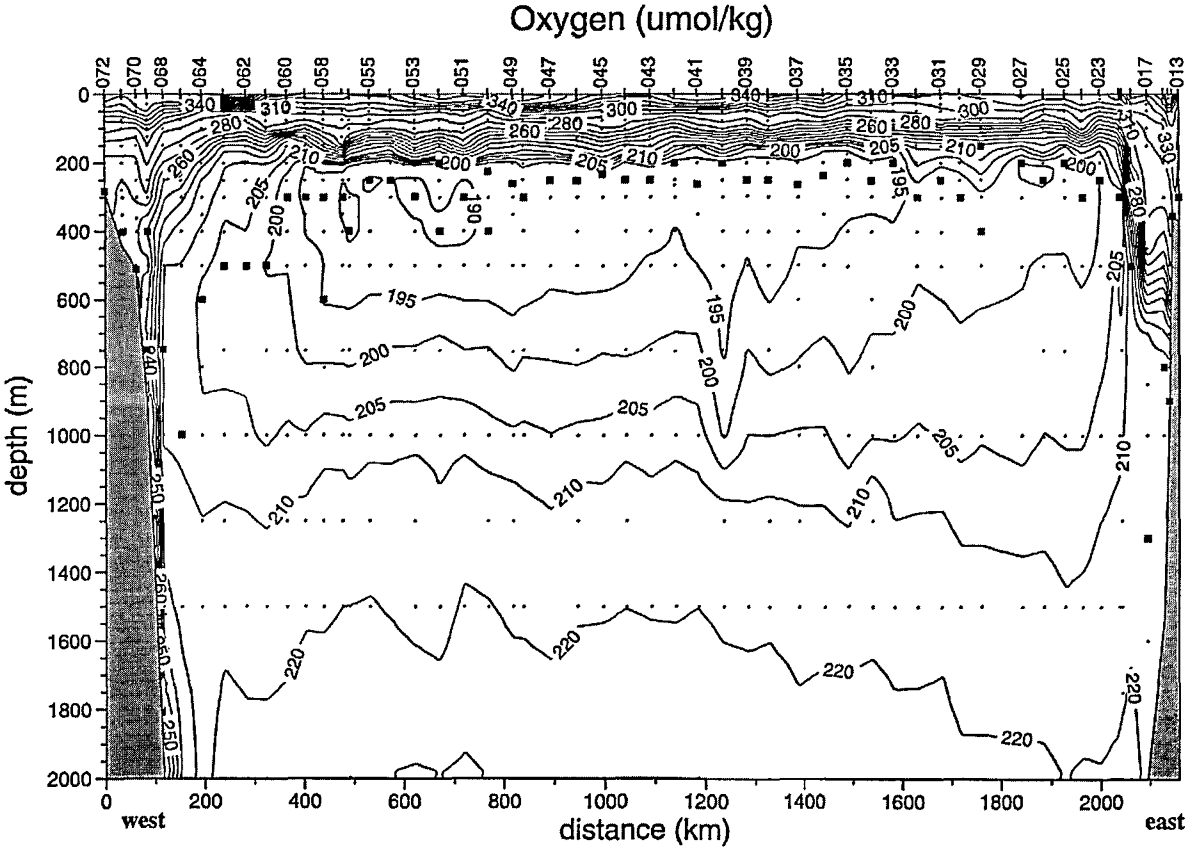

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Figure 4*a*, *b*

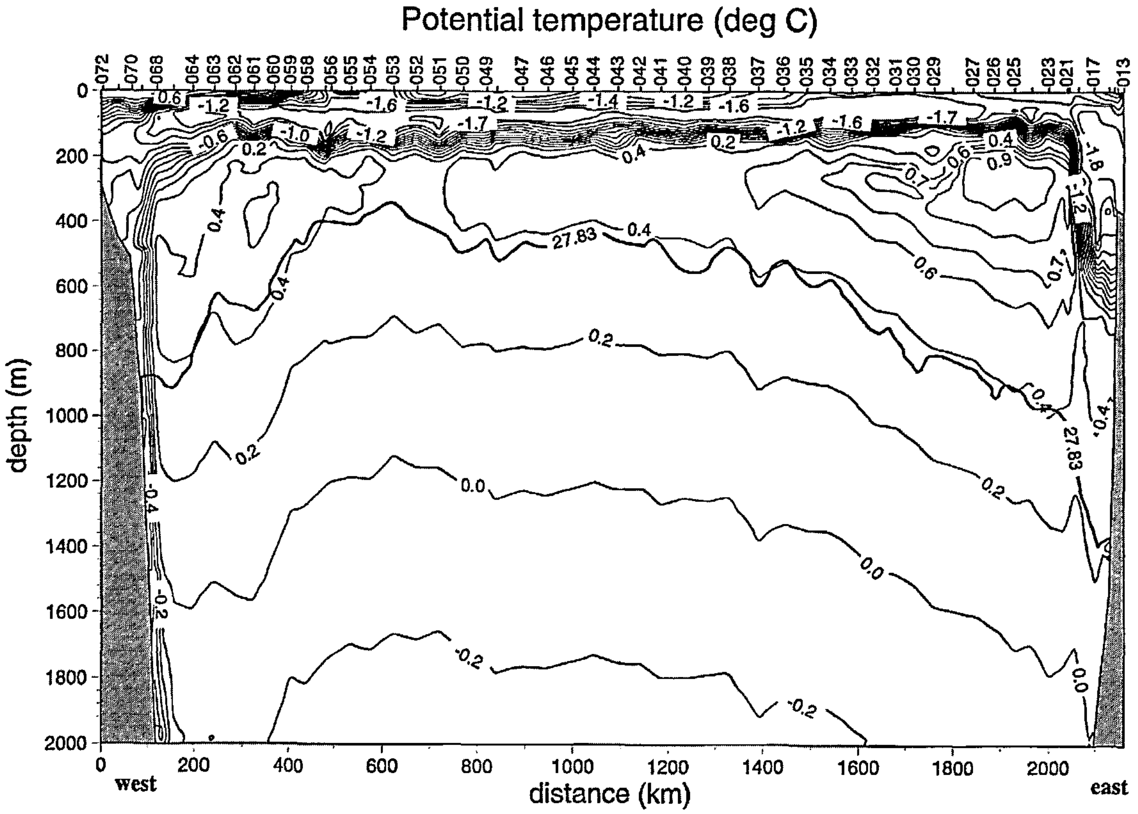

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Figure 4

*Vertical sections for the upper 2000 m of the water column of: (a) TCO$_2$; (b) oxygen; and (c) potential temperature in the Weddell Sea between Kapp Norvegia (right) and Joinville Island at the tip of the Antarctic Peninsula (left). Stars denote the positions of TCO$_2$ maxima and oxygen minima. In the potential temperature section a thick line indicates the isopycnal of 27.83 ($\sigma_0$).*

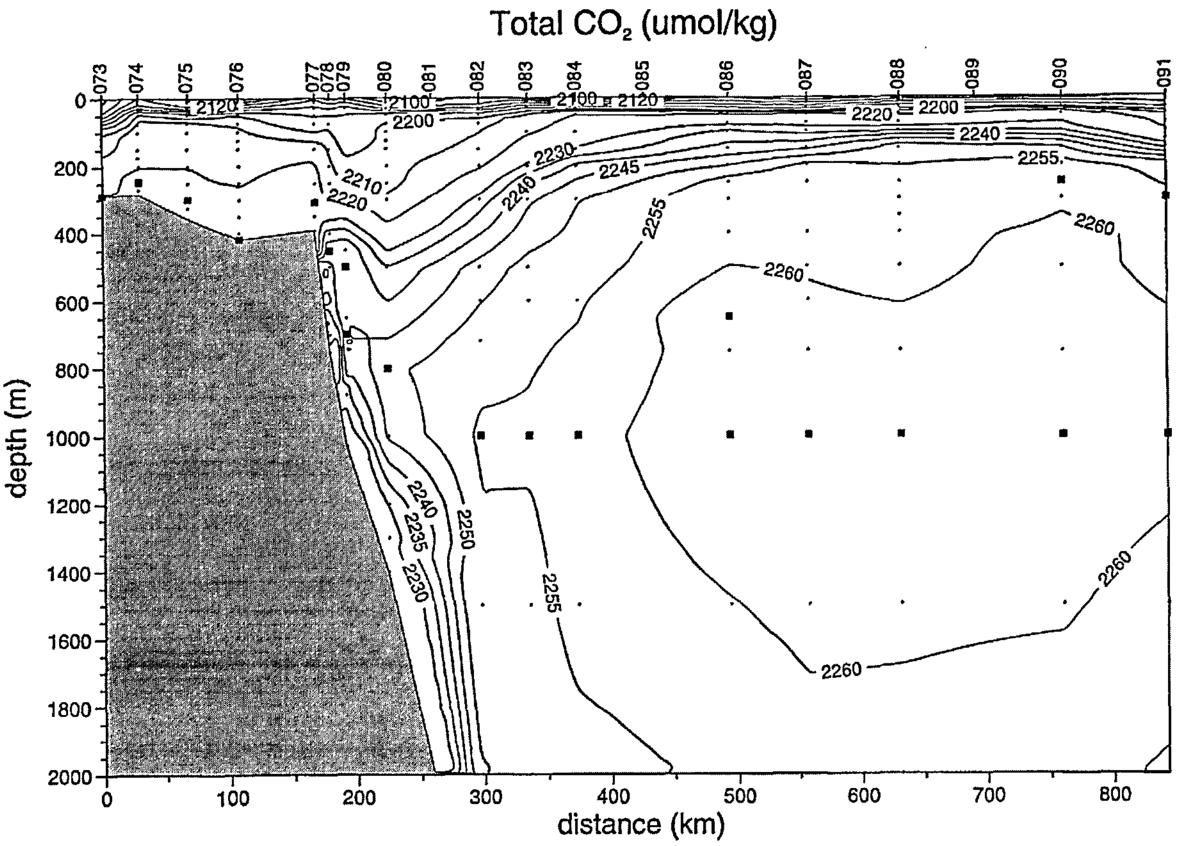
(Fig. 5*a*), as well as downstream of that on the main section off the tip of the Antarctic Peninsula at stations 68-58 (Fig. 4*a*). The presence of the deep TCO$_2$ maximum here suggests that "new" CDW has been advected from the eastern Weddell Sea within the boundary current. However, the width of the plume has decreased compared to the eastern Weddell Sea. It should be noted that at the onshore stations the temperature maximum/oxygen minimum, which constitute the top of the "new"-CDW layer, lie much deeper (about 700 m) than elsewhere in the basin. Obviously, the top of the "new"-CDW layer has been vigorously disrupted due to lateral injections of shelf waters and subsequent vertical mixing within the water column, accompanying bottom-water production in this region (Fahrbach *et al.*, 1995). The vertical profiles of all other properties are in conformity with this explanation as their upper parts seem to have been skimmed off, with heat, salt and CO$_2$ lost and oxygen gained. The reduction of the deep TCO$_2$ maximum towards the continental slope to values below 2260 μmol/kg suggests that the entire "new"-CDW stratum was affected by this process. Off the tip of the Antarctic Peninsula near the offshore extremity of the "new"-CDW plume, the deep TCO$_2$ maximum reaches values of up to 2267 μmol/kg, higher than all values downstream. This suggests lateral mixing with the central gyre, where water with the same density as in the TCO$_2$ maximum has a higher TCO$_2$ (Fig. 4*a*).

Beyond the Antarctic Peninsula, confinement by the Weddell basin is less clear-cut. The upper deep waters, including the stratum of "new" CDW, are light enough to spill over the South Scotia Ridge into the Scotia Sea along its entire length (Locarnini *et al.*, 1993). South of the South Orkney plateau, which lies 500 km east of the Antarctic Peninsula, the "new" CDW can still be detected as a distinct plume by the deep TCO$_2$ maximum at stations 630-633 (Fig. 6*a*). At station 630 the TCO$_2$ maximum is significantly higher, suggesting lateral mixing with the central gyre, as occurs off the Antarctic Peninsula.

In the northern limb of the gyre on the prime meridian, "new" CDW is detected at 1000-1500 m depth on stations 577 and 578 by virtue of the deep TCO$_2$ maximum (Fig. 2*a*). However, especially on station 577, the shallow temperature maximum (Fig. 2*c*) of about 1.4 °C (which is the top of the CDW stratum) suggests that this water mass is directly injected from the neighbouring ACC and not the progression of the "new"-CDW layer found south of the South Orkney plateau.

## CENTRAL INTERMEDIATE WATER

On stations 53 and 629 in the central Weddell Sea, the oxygen minimum has the lowest value of the entire Weddell Gyre (Figs. 4*b*, 6*b*), while its density is relatively high



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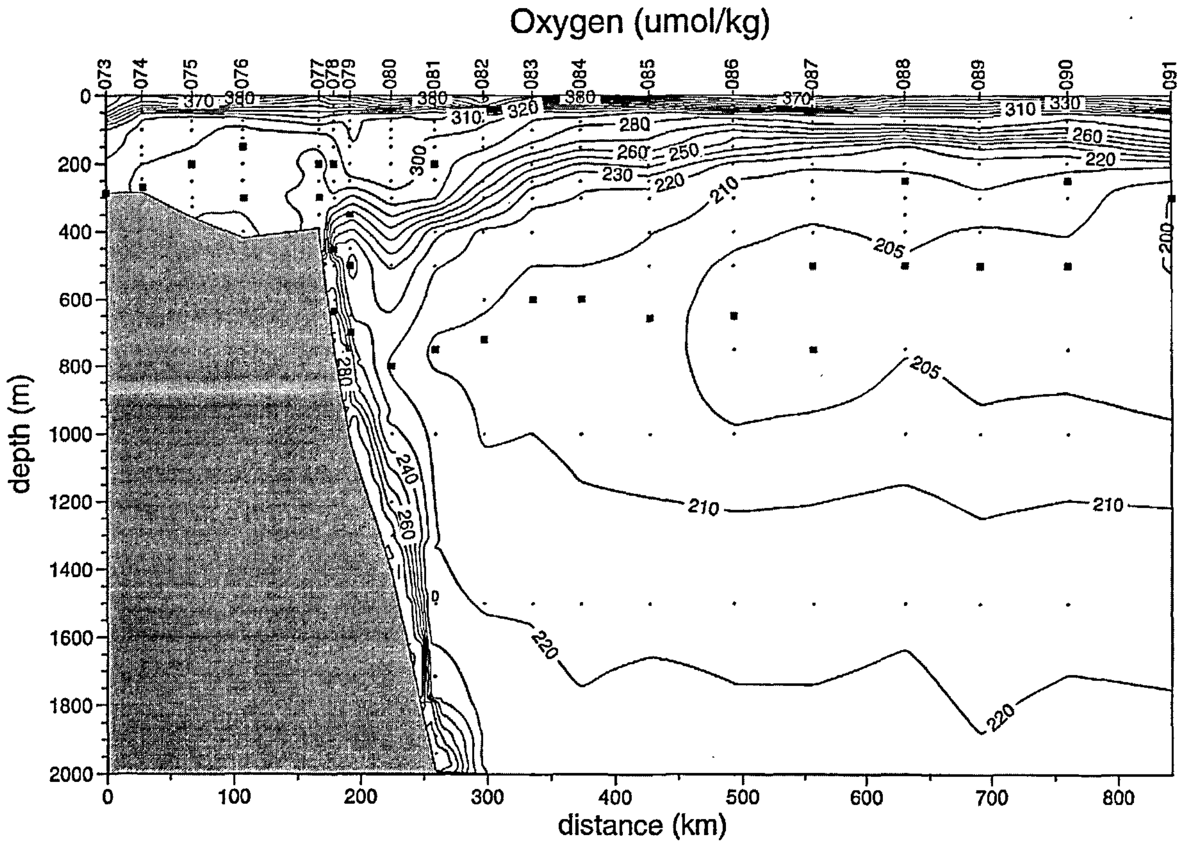

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Figure 5*a*, *b*

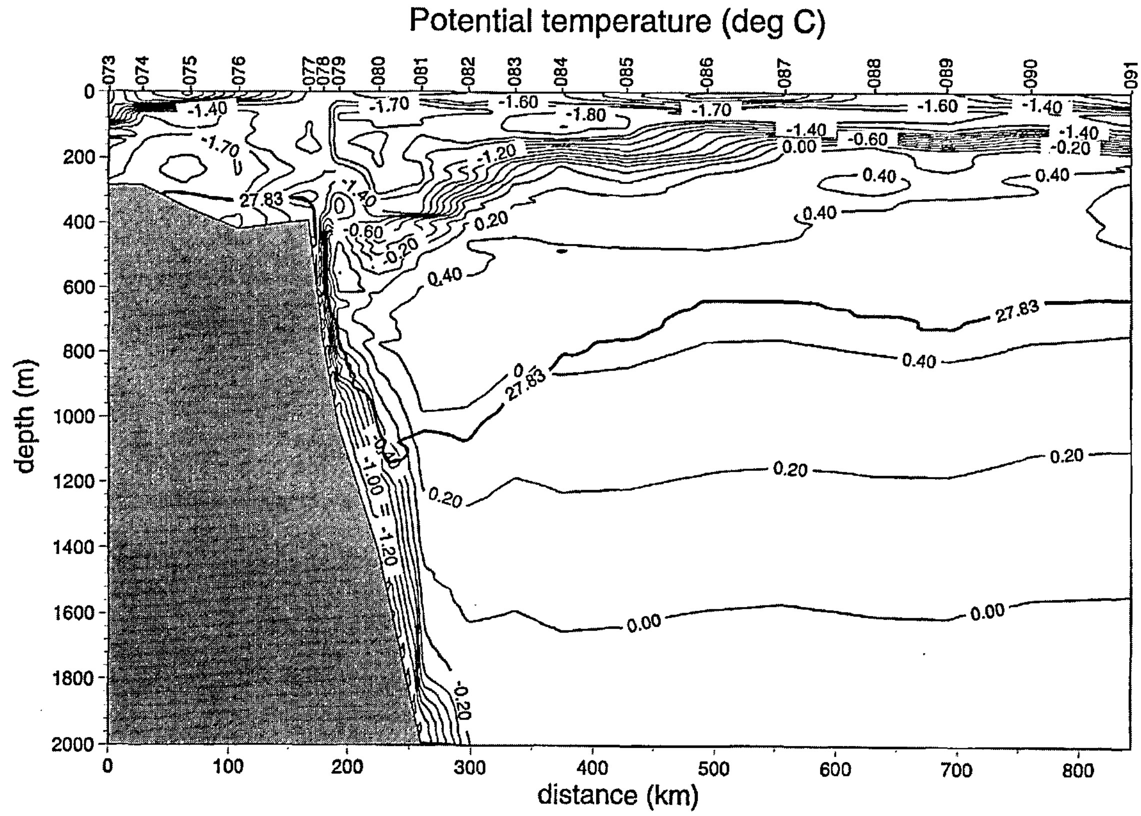

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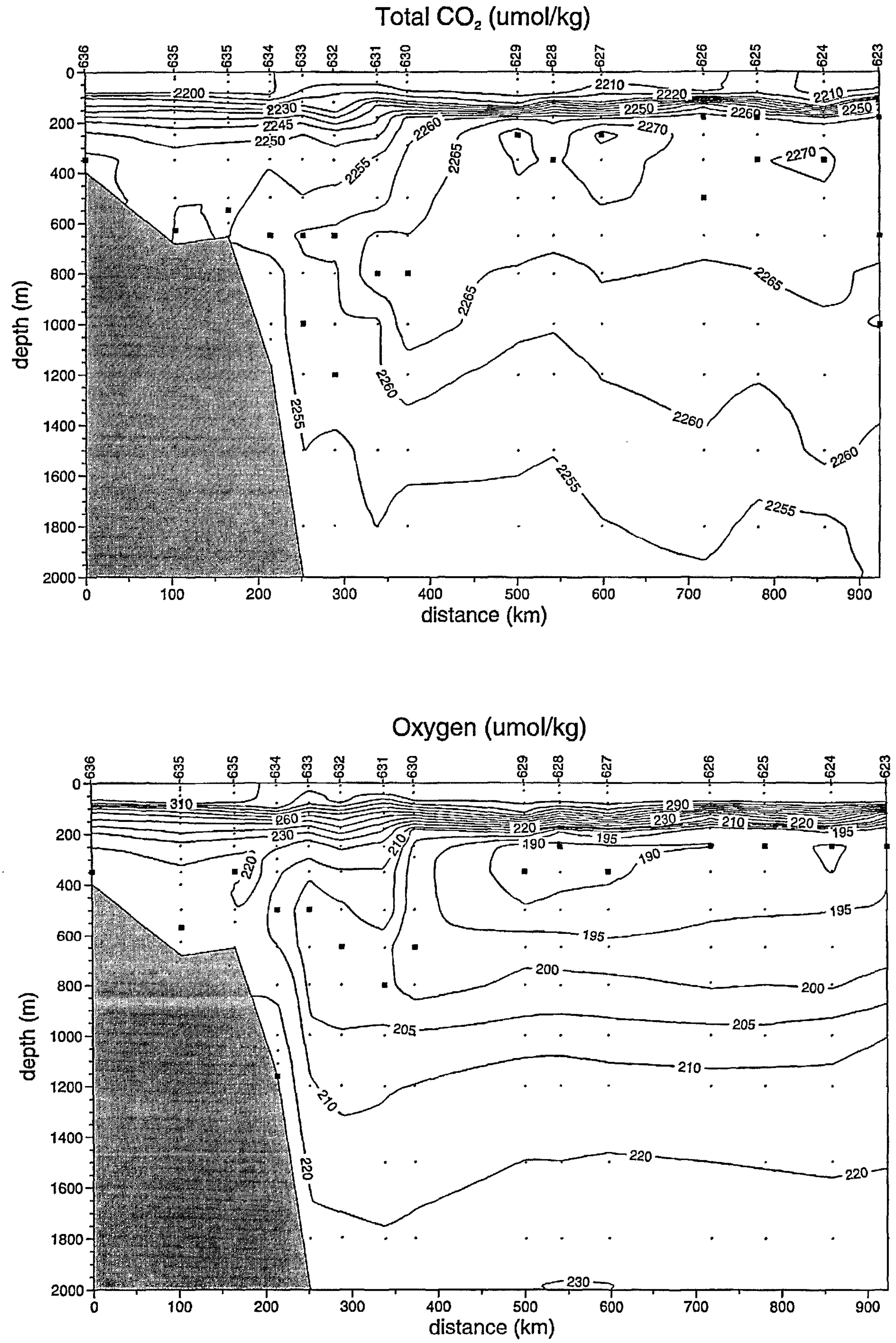
Figure 5

*Vertical sections for the upper 2000 m of the water column of: (a) $TCO_2$; (b) oxygen; and (c) potential temperature between the Larsen Ice Shelf and the central Weddell Sea (for locations, see Fig. 1). Stars denote the positions of $TCO_2$ maxima and oxygen minima. In the potential temperature section a thick line indicates the isopycnal of 27.83 ($\sigma_0$).*

(about 27.83). On neighbouring stations (50-52), an oxygen minimum was also detected at 27.83, but there it was lying at a greater depth (400-500 m) and beneath another shallow oxygen minimum. In contrast to the shallow oxygen minimum, there is no coinciding temperature maximum for this deeper, higher-density oxygen minimum, but it is accompanied by a $TCO_2$ maximum. This deeper oxygen minimum/$TCO_2$ maximum forms the core of CIW of the western Weddell Gyre. East of station 50, a CIW oxygen minimum as such is absent but there is always a $TCO_2$ maximum near 500 m at CIW density, the magnitude being lower there than west of station 50. Vertical profiles, however, show that there is a reduced-oxygen part near CIW density. The shallow LowerCDW-derived oxygen minimum and the CIW oxygen minimum are thus merged to form a wider oxygen minimum zone.

Figure 7 shows the $TCO_2$ and oxygen concentrations in the CIW density range on the three sections covering the western and eastern Weddell Gyre. Oxygen in Figure 7 is represented by the Apparent Oxygen Utilization (AOU), which is the difference between the observed value and the value at full saturation; this parameter accounts for possible changes in oxygen due to modifications of temperature and salinity, which are, however, very small in the Weddell Sea. On all sections the distributions of $TCO_2$ and AOU have roughly the same shape. The warm-regime CDW on the prime meridian (stations 593-598) contains water in the CIW density range that has not been circulating long enough in the Weddell Gyre to be significantly affected by biochemical processes. Hence, preformed concentrations for AOU and $TCO_2$ are about 140 and 2262 µmol/kg, respectively. Only onshore (all sections) $TCO_2$ and AOU are lower than the preformed values which must be caused by mixing with surface and shelf waters. Values not significantly different from those of the preformed CIW (Fig. 7*a*, 7*b*) are found at all locations where the plume of "new" CDW can be traced (see Section 4). This indicates that water at CIW density is not significantly affected by biochemical processes on the time scale of circulation of the boundary current at CDW level, *i.e.* a few years.

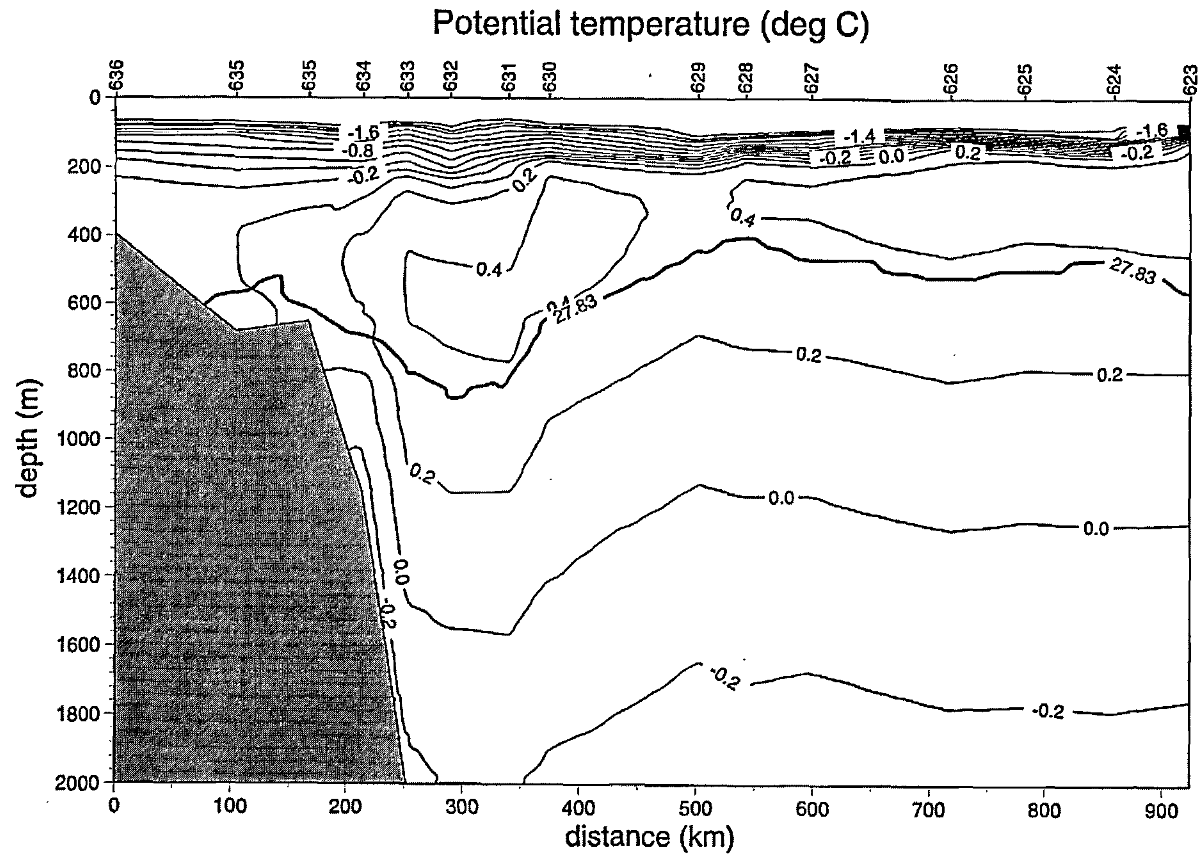
In the central Weddell Sea, all $TCO_2$ and AOU are enhanced as compared to the boundary regions (Fig. 7). This suggests that the residence time of CIW in the central Weddell Sea is significantly larger than that of the "new" CDW in the boundary current. This is not surprising since the current speeds are much lower in the gyre interior than in the boundary current (Fahrbach *et al.*, 1994). CIW characteristics are most pronounced in the western Weddell Sea. The $CO_2$-enriched CIW gives expression to the biologically mediated sink for $CO_2$ and counteracts the upwelling of $CO_2$-rich CDW into the surface layer and subsequent tendency for outgassing.



(*a*)

(*b*)

Figure 6*a*, *b*



(*c*)

Figure 6

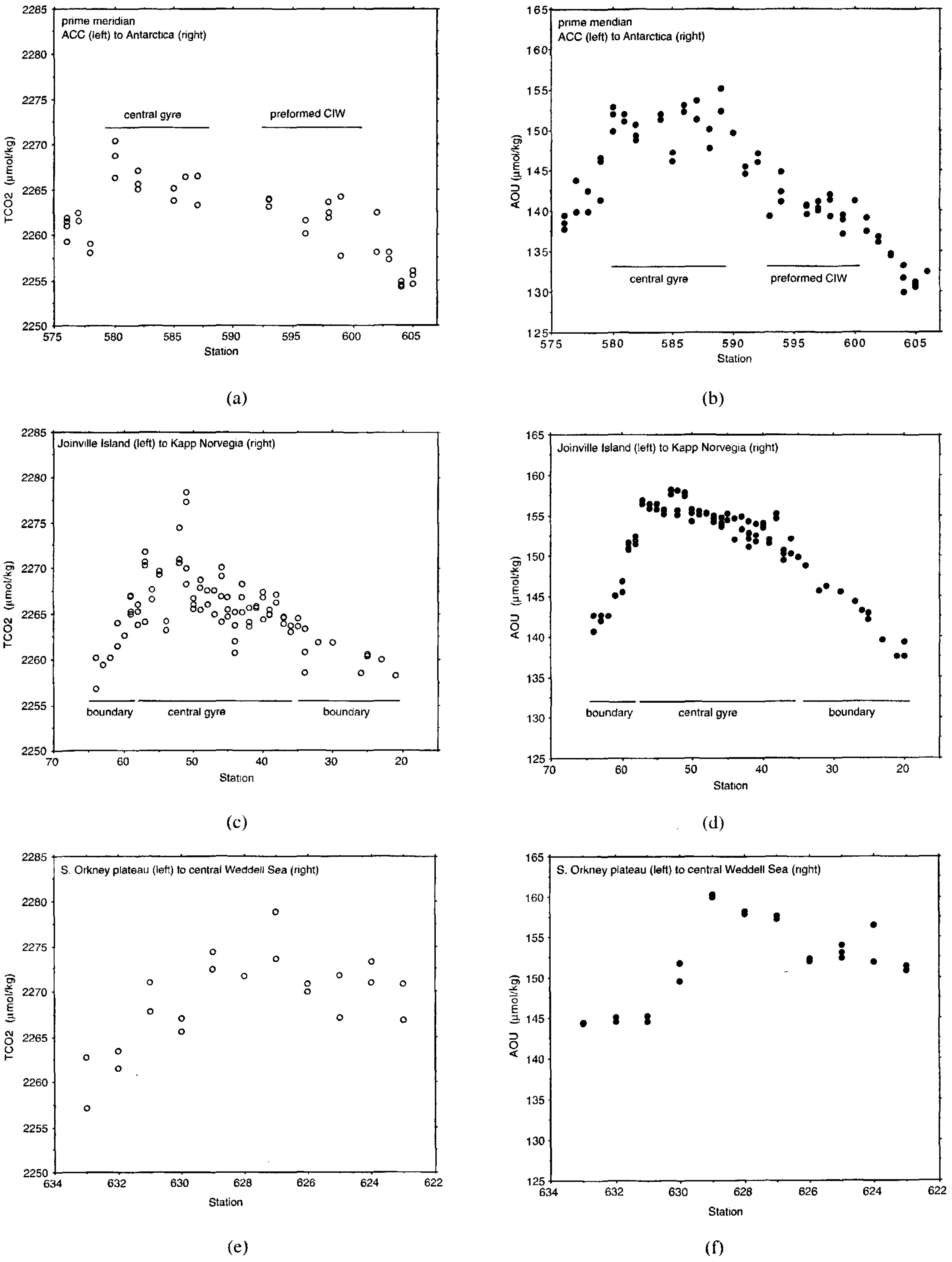
*Vertical sections for the upper 2000 m of the water column of: (a) $TCO_2$; (b) oxygen; and (c) the potential temperature between the central Weddell Sea and the South Orkney plateau (for locations, see Fig. 1). Stars denote the positions of $TCO_2$ maxima and oxygen maxima. In the potential temperature section a thick line indicates the isopycnal of 27.83 ($\sigma_0$).*

## DISCUSSION AND CONCLUSIONS

For budgeting purposes it is vital to know the lower boundary of the CDW, since it co-determines the amount of material entering the Weddell Sea. Usually, the lower boundary of the CDW within the Weddell Sea has somewhat arbitrarily been the 0 °C isotherm (*e.g.* Seabrooke *et al.*, 1971). Chen (1994) detected a weak break in the pH-potential temperature plot of Weddell Sea data at 0.08 °C. These data were from an area near the prime meridian, but only from the northern limb of the Weddell Gyre. Therefore, this break could not represent the lower boundary of newly-injected CDW, since the northern limb contains only "older" CDW. Whitworth and Nowlin (1987) reported a lower limit of the newly-injected CDW of about 0.2 °C. In the present study, we have argued that the lower boundary of the CDW that enters the Weddell Gyre is identifiable by a $TCO_2$ maximum. The potential temperature at this maximum is 0.1-0.2 °C.

The deep $TCO_2$ maximum which is central to the present study is accompanied by maxima of phosphate and nitrate. This is not surprising, since nutrients and $CO_2$ are subject to the same sort of processes. However, there are also processes unique to one of these parameters (for $CO_2$, for example, calcite formation and dissolution), while process rates, as well as physical and chemical properties of these parameters are not the same. This results in differences in parameter distribution. For example, the maxima do not always coincide. With respect to the CIW, the distributions of the nutrients and $TCO_2$ display pronounced differences, which might be related to different release rates during mineralization. Phosphate gradients in the deep Weddell Sea are extremely small (compare Whitworth and Nowlin, 1987), thereby rendering this parameter less suitable for use as a tracer of a relatively weak maximum. Nitrate has similar gradients to $TCO_2$, but its signal to noise ratio is higher. Another important point in favour of measuring and using $TCO_2$ is that certified reference material is now available, which permits comparison of data from different laboratories. Where nutrients are concerned, the lack of such a standard is still a serious disadvantage for obtaining an internally consistent data set.

Previous investigators (Klepikov, 1960; Treshnikov, 1964; Orsi *et al.*, 1993; Fahrbach *et al.*, 1994) have already noted that the Weddell circulation is not represented by just one single cyclonic gyre with small, varying currents in its interior. Moored current-meter measurements on a section between Kapp Norvegia and Joinville Island (which coincides with the section shown in Figure 4) showed an anticyclonic circulation pattern in the gyre



(a) (b)

(c) (d)

(e) (f)

Figure 7

*Distributions of* $TCO_2$ *and Apparent Oxygen Utilization (AOU) within the density range 27.82-27.83* ($\sigma_\theta$) *of the CIW: (a) and (b), on the prime meridian across the Weddell Gyre; (c) and (d), across the Weddell basin; (e) and (f), between the South Orkney plateau and the central Weddell Sea.*

interior. If this is not an artifact due to unstable mean values, the feature could be explained either by an interior countergyre, or by separation of the Weddell Gyre into two subgyres (Fahrbach *et al.*, 1994). The present study reveals clear-cut differences between the central gyre area in the west (Fig. 4) and in the east (*i.e.* on the prime meridian; Fig. 2). The temperature (<0.4 °C) and salinity maxima were clearly the lowest in the west, where the CIW characteristics (high TCO$_2$ maximum and low oxygen minimum) were also most pronounced. Such subsidiary centres within the central gyre might well indicate the existence of two subgyres (Klepikov, 1960; Orsi *et al.*, 1993).

According to Whitworth and Nowlin (1987), CIW stems from that portion of the ("new") CDW that lies too deep to participate in bottom-water production near the shelves. However, it was demonstrated above that the whole onshore "new"-CDW water column of about 1000 m was affected by shelf processes, although the actual shelf depth is only about 400 m. These observations suggest that it is neither the depth of the shelves nor the setting of the shelf-break front which determine the maximum associated with the CIW. Alternatively, we note the following: Off Joinville Island, near the offshore extremity of the "new"-CDW plume (stations 58/59; Fig. 4*a*), the magnitude of the deep TCO$_2$ maximum is higher (up to 2267 μmol/kg) than the "preformed" value of 2262 μmol/kg in the unperturbed boundary current regime. Similar observations were made south of South Orkney (Fig. 6*a*). In the contiguous central Weddell Sea, increased TCO$_2$ values are associated with biological degradation at depth, of which the CIW characteristics are an extreme expression. Hence, these observations suggest a link between the lower part of the "new"-CDW layer and the TCO$_2$-enriched water of the central Weddell Sea, and consequently a route of replenishment of the CDW of the Weddell Sea interior. This suggests that the TCO$_2$ maximum of the CIW in the Weddell Sea interior is merely a continuation of the TCO$_2$ maximum constituting the bottom of the "new"-CDW layer. In the eastern Weddell Sea off Kapp Norvegia, the transition from "new" CDW to the central Weddell Sea is different, *i.e.* the deep TCO$_2$ maximum ceases abruptly at station 35 (Fig. 4*a*). Also, the oxygen concentration at CIW density showed a sharp gradient between stations 34 and 35 (Fig. 7*d*). This is an indication that replenishment of the central Weddell Sea with CDW occurs mainly in the west.

In the area of stations 50-57, CIW characteristics (for oxygen and for TCO$_2$) were found to be most pronounced, especially at stations 51-53 (see Section 5). In Figure 4*a* it is seen that on latter stations in the entire water column the TCO$_2$ concentration is anomalously high compared to waters of the same density and depth on the rest of the section, *i.e.* also in the underlying WSDW. There are three possible causes for this. First, the residence time of the CDW is significantly longer in this region than in the remainder of the central Weddell Sea. The lateral mininum of the temperature (<0.4 °C) within the temperature maximum layer supports this, because it points to a high degree of vertical transport. Second, biological activity in this region and, consequently, the amount of degradation at depth are higher than elsewhere in the basin. The first and second explanations are related in that a longer residence time would also enhance the amount of degradation at depth. Third, intrusion of high-TCO$_2$ water from the Scotia Sea takes place here. This issue was raised by Orsi *et al.* (1993), based on anomalous distributions of oxygen and salinity. They discuss the feature, however, only for the WSDW level of the water column. The current-speed measurements in this region, however, also exhibit the required southward flow in the CDW level (Fahrbach *et al.*, 1994), which would make this Scotia flow a possible contributor to high TCO$_2$ and low oxygen values.

In the central gyre, the CDW is entrained into the surface layer, as well as into the underlying water. However, the ACC might also be a sink of CDW of the central gyre. In the ACC adjacent to the Weddell Gyre, a TCO$_2$ maximum is found some 200-300 m above the bottom (Hoppema, unpubl. data). This TCO$_2$ maximum represents the interface between the southward-spreading LowerCDW and the northward-spreading Antarctic Bottom Water, which is mainly of Weddell origin. This maximum is generated by the increase of the TCO$_2$ concentration with depth within the LowerCDW due to the influence of the TCO$_2$-poor North Atlantic Deep Water, and a decrease of TCO$_2$ in the water stemming from the Weddell Sea. As for all other properties the gradients in the deep ACC and in the Weddell Sea have the same sign, no extremes are produced. The magnitude of the near-bottom TCO$_2$ maximum and of other properties support the conclusion that this water originates in the Weddell Sea at 800-1200 m depth. This source layer in the Weddell Sea thus includes the lower portion of CDW.

Here we recognize another role for the CDW of the Weddell Sea with respect to TCO$_2$ transport. In the centre of the Weddell Gyre, the residence time of CDW is long enough to enable its TCO$_2$ concentration to increase significantly due to biochemical processes. As it is conveyed to the bottom of the ACC, the CDW forces down the water column the CO$_2$ which is involved in biological processes in the upper water column. Thus, more generally, it could be stated that the biological pump is an effective mechanism for the Weddell Sea.

Studying the CO$_2$ system in the Weddell Sea has its own inherent value. Additionally, it may be concluded that there is useful information to be gleaned from the TCO$_2$ signature in the light of water mass transport and transformation. Since recent development of the accurate and relatively rapid method of coulometry has brought more extensive TCO$_2$ data sets within reach, the TCO$_2$ signature could be more widely used as an additional constraint in water mass analyses.

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