# Distributions of oxygen and carbon stable isotopes and CFC-12 in the water masses of the Southern Ocean at 30°E from South Africa to Antarctica: results of the CIVA1 cruise

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**Distributions of oxygen and carbon stable isotopes and CFC-12 in the water masses of the Southern Ocean at 30°E from South Africa to Antarctica: results of the CIVA1 cruise**

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## Abstract

This study presents oceanic distributions of stable isotopes ($\delta^{18}O$ of water and $\delta^{13}C$ of $\Sigma CO_2$) and CFC-12 from samples collected during the CIVA1 cruise (February/March 1993), across the Southern Ocean, along a meridian section at 30°E, from South Africa (44°S) to Antarctica (70°S). The isotopic measurements show important variations between the subantarctic surface waters with low $\delta^{18}O$–high $\delta^{13}C$ values and the antarctic surface waters with very low $\delta^{18}O$–low $\delta^{13}C$ values. The surface distributions of $\delta^{13}C$ values follow the major frontal oceanic structures; the vertical distribution shows the progressive upwelling from the subantarctic zone to the antarctic divergence of $^{13}C$-depleted $CO_2$ derived from remineralization of organic matter. Along the Antarctic continental shelf, between 2500 and 4000 m, a core of water with $\delta^{18}O$ values close to −0.1‰ is associated with a relative maximum in CFC-12 concentration, although this core is not detected by its temperature and salinity parameters. This water mass, which corresponds to recently formed deep water, may originate from the eastward extension of the Weddell gyre or from bottom waters coming from the East and formed near Prydz Bay.

## Résumé

Cette étude présente les distributions dans l'océan Austral des isotopes stables ($\delta^{18}O$ de l'eau et $\delta^{13}C$ de $\Sigma CO_2$) et des CFC-12 provenant d'échantillons prélevés durant la mission CIVA1 (Février/Mars 1993), le long d'une section méridienne à 30°E, entre l'Afrique du Sud (44°S) et l'Antarctique (70°S). Les compositions isotopiques montrent des variations importantes entre les eaux de surface subantarctiques caractérisées par des valeurs basses de $\delta^{18}O$ et élevées en $\delta^{13}C$ et les eaux de surface antarctiques très appauvries en $^{18}O$ et pauvres en $^{13}C$. En surface, les valeurs de $\delta^{13}C$ varient en suivant les structures frontales océaniques; la distribution verticale de ce paramètre montre l'upwelling progressif de la zone subantarctique vers la divergence antarctique, de $CO_2$ appauvri en $^{13}C$ provenant de la reminéralisation de la matière organique. Le long de la marge continentale Antarctique, entre 2500 et 4000 m, des maxima relatifs des valeurs de $\delta^{18}O$ et de CFC-12 sont observés. Ils indiquent la présence d'une masse d'eau bien ventilée et récemment formée, bien qu'aucun indice ne soit révélé sur les profils de température et de salinité. Cette masse d'eau pourrait provenir soit de l'extension Est de

la gyre de Weddell soit des eaux profondes venant de l'est et formées dans la région de Prydz Bay.

Keywords: Stable isotopes; $^{18}O$; $^{13}C$; CFC-12

## Introduction

The Southern Ocean is a special area from where the main bottom and intermediate water masses of the world ocean originate. Many studies using dynamic and geochemical observations in the Weddell Sea and near Prydz Bay provide information on the formation of deep and bottom waters and on their circulation in this area; however numerous questions remain regarding the eastern extension of the Weddell gyre and the recirculation of the bottom water masses (Gordon, 1971; Foster and Carmack, 1976; Jacobs and Georgi, 1977; Carmack, 1977; Deacon, 1979; Weiss et al., 1979; Smith et al., 1984; Jean-Baptiste et al., 1991; Mantisi et al., 1991; Schlosser et al., 1991; Gouretski and Danilov, 1993, Orsi et al., 1993). Measuring distributions of $\delta^{18}O$ and $\delta^{13}C$ values, which are natural tracers of oceanic water masses, is of great interest because they add specific information to help understand the mechanisms responsible for internal variability of water masses in their source region and at depth, and allow one to follow their circulation far away from their source.

The data presented here were collected during the WOCE/CIVA1 cruise on the Marion Dufresne during February/March 1993 in the southwest Indian sector of the Southern Ocean, along a section at 30°E, from South Africa (44°S) to Antarctica (70°S) (Fig. 1). This study presents a novel set of isotopic data ($\delta^{18}O$ of water and $\delta^{13}C$ of $\Sigma CO_2$) at 10 vertical stations throughout the water column. In addition to the stable isotope measurements, CFC-12 measurements from the CIVA1 cruise are also presented as transient tracers of the origin and age of the water masses (Bullister, 1984; Mantisi et al., 1991).

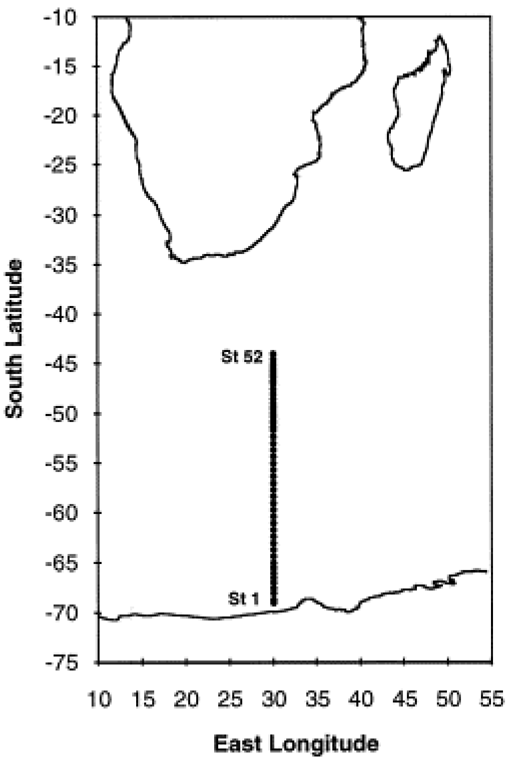


Fig. 1. Location of the hydrological stations sampled during the CIVA1 cruise.

## Methods

Seawater samples were collected by a rosette system fitted with twelve 12-l Niskin bottles and a Neil–Brown CTD. Onboard, seawater samples for $^{13}C$ measurements were siphoned from Niskin bottles into 125 ml glass bottles, then poisoned with 1 ml of a saturated solution of $HgCl_2$. The $\Sigma CO_2$ was extracted from seawater by acidification with phosphoric acid as described by Kroopnick (1974). The method used for $\delta^{18}O$ measurement was the classical water–$CO_2$ equilibration at 25°C as described by Epstein and Mayeda (1953). The isotopic compositions are expressed in the δ conventional units defined by:

$$\delta = [(R/R^*) - 1] \times 1000$$

where $R={}^{18}O/{}^{16}O$ or $^{13}C/^{12}C$ and R* refers to the reference: SMOW for $^{18}O/^{16}O$ ratio (Craig, 1961) and PDB for $^{13}C/^{12}C$ ratio (Craig, 1957). Reproducibility of these measurements is about ±0.05‰ and the standard deviation is about ±0.01‰.

The method for CFC measurement follows the technique of Bullister and Weiss (1988) and was described in detail by Mantisi et al. (1991). For CFC-12, the detection limits of the system were 0.01 pmol/kg and the standard deviation in the measurements is about 2%.

## Hydrography

The CIVA1 cruise was conducted during the austral summer 1993 along a meridian section at 30°E which crosses the main hydrological fronts of the Southern Ocean (Lutjeharms and Valentine, 1984; Park et al., 1993). These fronts are identified by abrupt changes affecting the isohalines (Fig. 2a) and isotherms (Fig. 2b). Along this section, the different fronts are located as follows: the SubAntarctic Front (SAF) at 48°S, the Polar front (PF) at 52°S and the Antarctic Divergence (AD) at 66°S. The different water masses, identified by their θ–S parameters, are those described previously for the Antarctic Ocean by Jacobs and Georgi (1977) and Whitworth and Nowlin (1987).

In the Antarctic zone, the Antarctic Surface Water (AASW) shows strong variability in temperature and salinity ($-1°C<\theta<4°C$; $33.7<S<34$) and is easily identified by a subsurface temperature minimum ($\theta\approx-1.7°C$) which characterizes the remnant signal of the Winter Water (WW). Beneath this layer of cold water lies the Circumpolar Deep water (CDW) which is characterized by temperature and salinity maxima ($\theta\approx1.4°C$; $34.67<S<34.72$) between 1000 and 3000 m. For depths greater than 3500 m, the Antarctic Bottom Water (AABW) is observed with $S\approx34.66$ and $\theta\approx-0.7°C$.

In the subantarctic zone, four main water masses are superimposed. The Subantarctic Surface Waters (SASW) are relatively warm with a large range of temperatures ($8°C<\theta<14°C$); the Antarctic Intermediate Water (AAIW) which is characterized by a salinity minimum ($S=34.25$), sinks at the SAF and lies at immersion depths from 200 m to 800 m; the CDW, which contains a major contribution of North Atlantic Deep Water (NADW) in this area, shows a temperature maximum ($\theta=2.6°C$) near 1600 m and a salinity maximum ($S=34.76$) near 2500 m; the AABW is still observed.

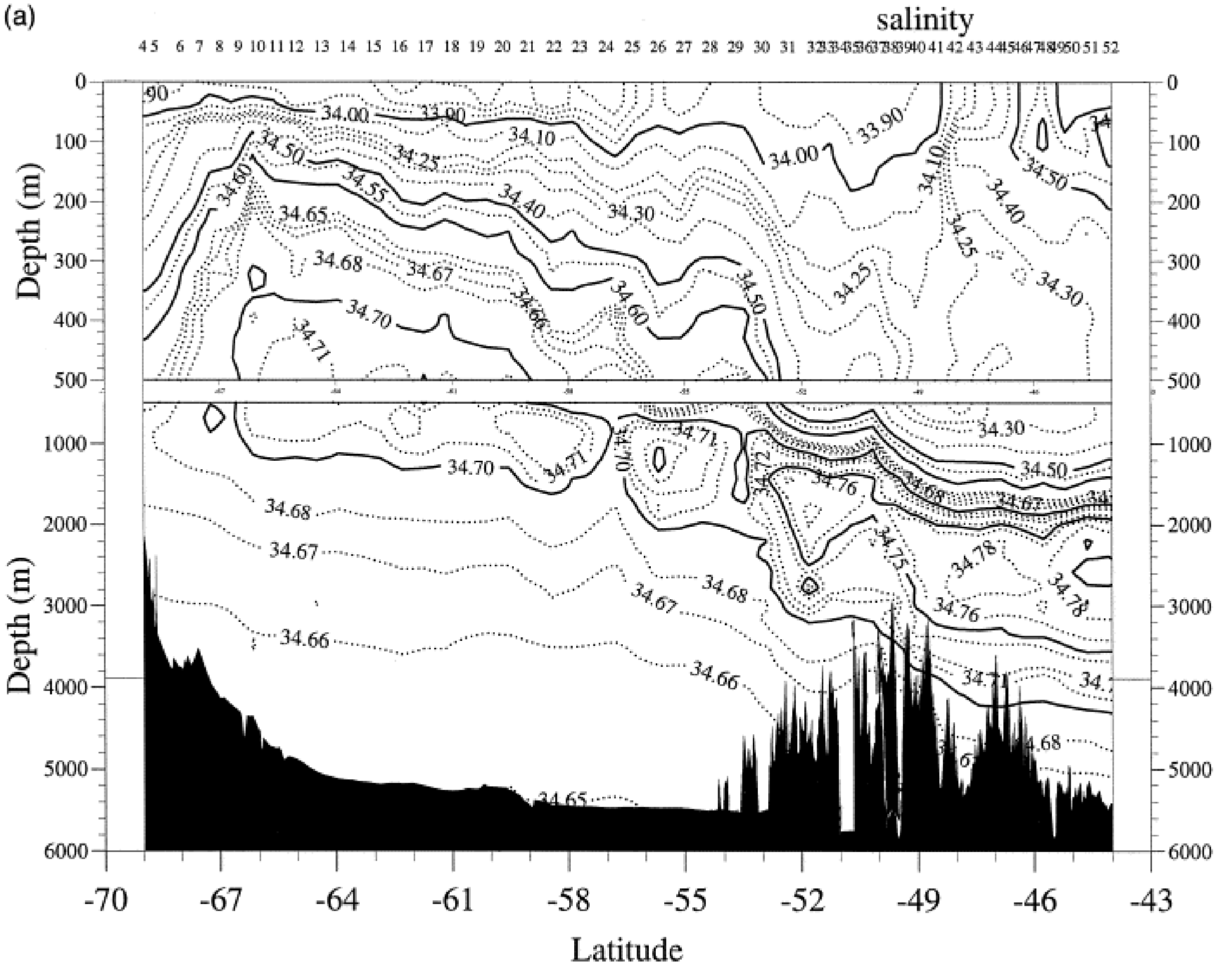


Fig. 2. (a) Latitudinal distribution of salinity

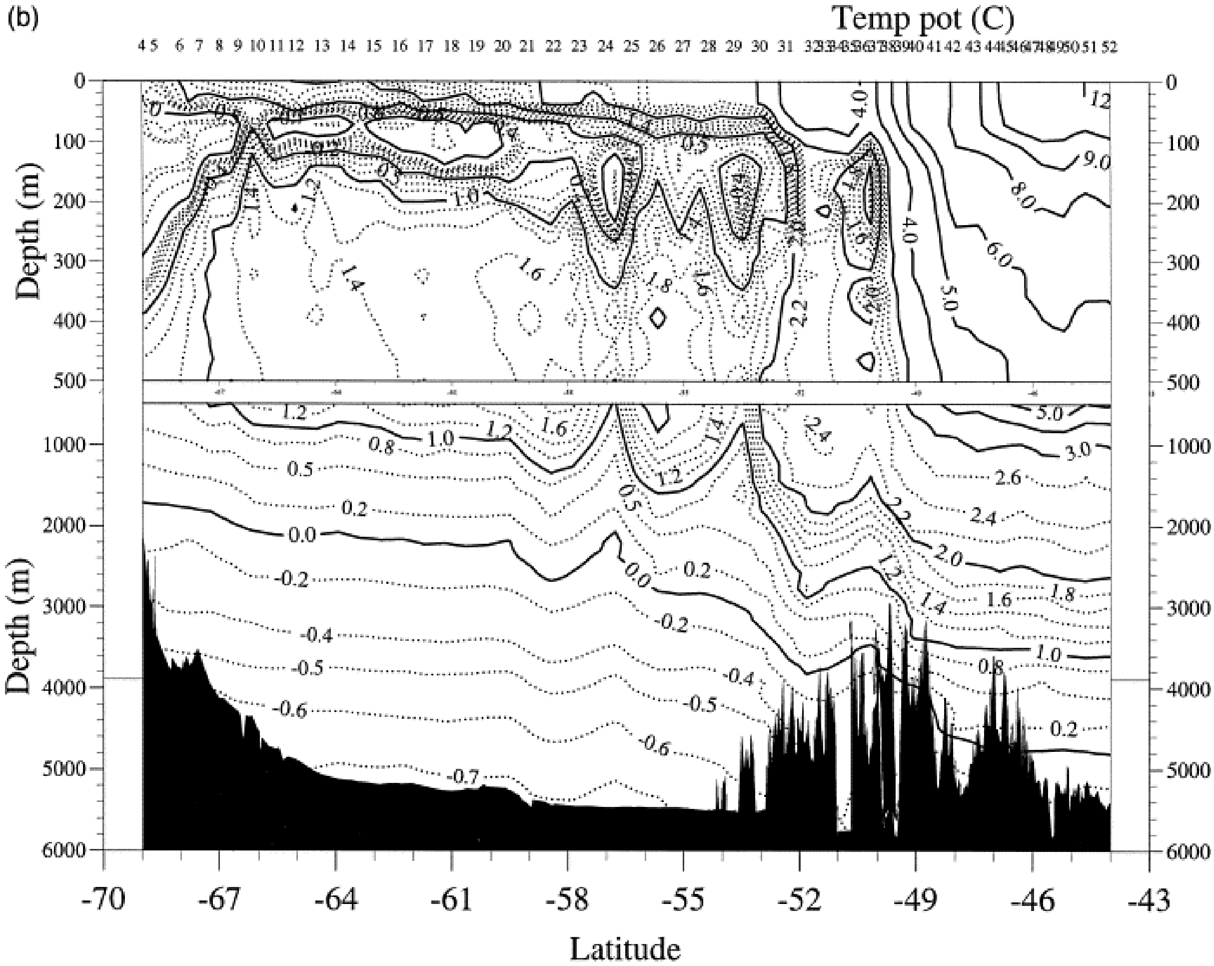


Fig. 2. (b) Latitudinal distribution of potential temperature (°C).

**The chlorofluorocarbons (CFC) distribution in the water masses**

The vertical distribution of CFC-12 along the section at 30°E (Fig. 3) gives information on the penetration of the transient tracers in this area of the Southern Ocean as well as on the global circulation at depth. The penetration of water with high CFC values in the subantarctic zone is observed down to 1000 m; this characterizes the sinking of newly formed AAIW (CFC-12=1.0 pmol/kg) at the SAF from 200 m to intermediate depths (800 m). The CDW, which largely extends in this area, is characterized by low CFC concentrations (0.05 pmol/kg<CFC-12<0.10 pmol/kg); its upwelling at the AD stops the penetration of atmospheric anthropogenic CFCs in the antarctic zone.

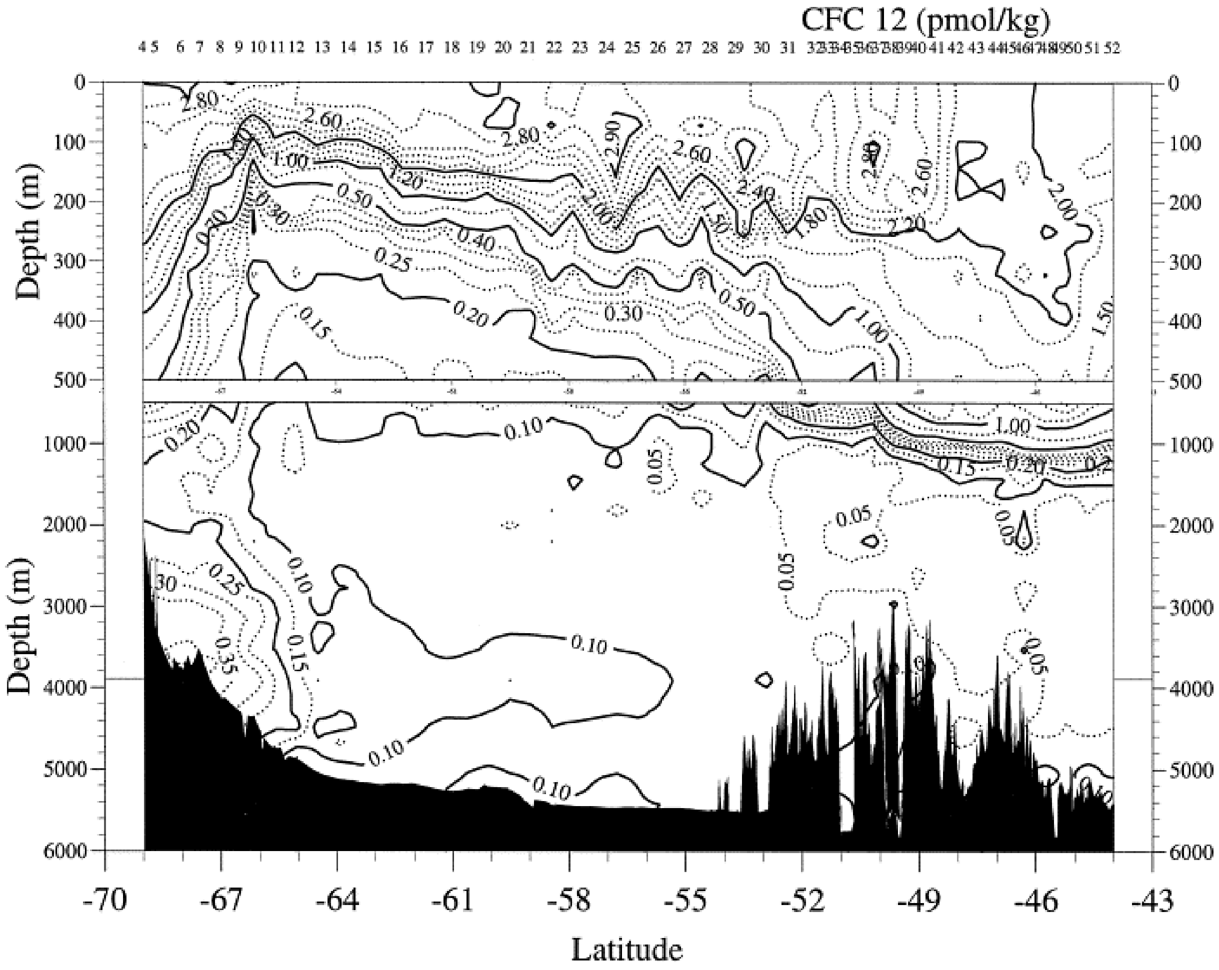


Fig. 3. Latitudinal distribution of CFC-12 (pmol/kg).

Along the Antarctic continental shelf, a relative maximum of CFC concentration is observed between 2000 and 4500 m (0.2 pmol/kg<CFC-12<0.4 pmol/kg), indicating that these waters were recently ventilated. Between the AD and 55°S, at an immersion depth of about 4000 m, a tongue of CFC rich water (0.1 pmol/kg<CFC-12<0.15 pmol/kg) indicates the existence of a "young" deep water mass. Another relative maximum occurs near the bottom, at 5000 m (0.1 pmol/kg<CFC-12<0.15 pmol/kg) which is correlated with a temperature minimum ($\theta = -0.7$°C) and an oxygen maximum (240<O2 µm/kg<245).

## The stable isotope composition of the water masses

The oxygen and carbon stable isotope compositions of ocean waters provide specific information on both the water and carbon cycles, providing insight to better understand the mechanisms and magnitude of the fluxes between the oceanic and atmospheric reservoirs.

The $\delta^{18}O$ values of ocean waters are sensitive to variations in the evaporation–dilution ratio; the concentrations of heavier isotopes in the ocean surface waters are enriched by evaporation and depleted by dilution due to precipitation. These processes cause linear relationships between oxygen-18 and salinity whose slopes depend on climatic constraints (Craig and Gordon, 1965). At high latitudes, the effect of freezing at the ocean surface increases the salinity, however it causes only a weak depletion of the

$\delta^{18}O$ values of the remaining liquid seawater. Leaving the surface, for intermediate or deeper depths, the water is no longer affected by air–sea exchange; the $\delta^{18}O$ parameter is thus conservative and its distribution follows the circulation pattern of the water masses (Craig and Gordon, 1965). The melting of sea-ice causes large changes in salinity and leaves the $\delta^{18}O$ almost unchanged (the resulting mixture may be slightly enriched in $^{18}O$), while continental-ice melt causes large drops both in salinity and $\delta^{18}O$. Therefore, at high latitudes, the $\delta^{18}O$ values of waters may also help to differentiate dilution effects induced by the melting of continental ice as opposed to sea ice (Schlosser et al., 1990).

The variations of $\delta^{13}C$ of $\Sigma CO_2$ occur mostly in the upper ocean waters and depend on the ocean–atmosphere $CO_2$ exchange and on the photosynthesis–respiration processes. Carbon isotopes are fractionated during the production of organic matter which incorporates preferentially the carbon-12. The $\delta^{13}C$ values in ocean waters are maximum at the surface where photosynthesis occurs; they decrease at depth where remineralization of organic matter releases $^{13}C$-depleted $CO_2$ (Kroopnick, 1985; see Table 1 Table 2).

**Table 1**: Stable isotope composition ($\delta^{18}O$ of water and $\delta^{13}C$ of $\Sigma CO_2$) and salinity data for the CIVA1 surface samples

| Station | Latitude (°S) | Longitude (°E) | Salinity | $\Theta$ (°C) | $\delta^{18}O$ (‰) | $\delta^{13}C$ (‰) |
|---|---|---|---|---|---|---|
| 1 | 68.98 | 30.13 | 33.4524 | −1.6376 | −0.42 | 0.91 |
| 2 | 68.98 | 30.08 | 33.4097 | −1.5796 | −0.59 | 1 |
| 3 | 68.99 | 29.98 | 33.3987 | −1.3862 | −0.38 | – |
| 4 | 68.98 | 29.85 | 33.715 | −0.7996 | −0.56 | – |
| 5 | 68.67 | 29.96 | 33.7513 | −1.0749 | −0.46 | 1.05 |
| 6 | 68.01 | 30 | 33.9122 | 0.2009 | −0.53 | 0.97 |
| 8 | 66.99 | 29.98 | 33.8657 | 0.646 | −0.47 | 0.54 |
| 10 | 66.01 | 29.99 | 33.8424 | 0.8639 | −0.61 | 0.81 |
| 11 | 65.51 | 29.98 | 33.8382 | 0.978 | – | 0.68 |
| 12 | 65.01 | 30 | 33.8243 | 1.004 | −0.47 | 0.76 |
| 13 | 64.35 | 30 | 33.8003 | 1.106 | – | 0.81 |
| 14 | 63.68 | 30 | 33.8285 | 1.026 | −0.46 | 0.96 |
| 15 | 63.01 | 29.99 | 33.7685 | 1.266 | – | 0.87 |
| 16 | 62.34 | 30 | 33.5923 | 1.6909 | – | 1 |
| 17 | 61.67 | 30 | 33.7085 | 1.551 | – | 0.92 |
| 18 | 61 | 30 | 33.6881 | 1.7759 | −0.49 | 0.88 |
| 19 | 60.34 | 29.99 | 33.6306 | 1.779 | – | 0.89 |

| Station | Latitude (°S) | Longitude (°E) | Salinity | *Θ* (°C) | $\delta^{18}O$ (‰) | $\delta^{13}C$ (‰) |
|---|---|---|---|---|---|---|
| 20 | 59.68 | 29.99 | 33.717 | 1.8669 | – | 0.88 |
| 21 | 59.02 | 30 | 33.7054 | 1.8109 | – | 0.75 |
| 22 | 58.35 | 29.97 | 33.5976 | 2.1938 | −0.46 | – |
| 23 | 57.68 | 29.99 | 33.7095 | 2.1798 | – | 0.78 |
| 26 | 55.68 | 30 | 33.9342 | 2.8325 | −0.44 | 1.04 |
| 27 | 55.01 | 30 | 33.8169 | 2.3613 | – | 1.36 |
| 29 | 53.68 | 29.98 | 33.9538 | 2.7055 | – | 0.86 |
| 30 | 53.01 | 30 | 33.8815 | 3.1221 | −0.51 | – |
| 31 | 52.33 | 30.02 | 33.8802 | 4.177 | – | 1.19 |
| 32 | 51.64 | 29.97 | 33.8812 | 4.6461 | −0.28 | 1.32 |
| 34 | 51 | 29.97 | 33.8913 | 4.6703 | −0.47 | 1.21 |
| 36 | 50.35 | 29.99 | 33.8451 | 3.1573 | −0.27 | – |
| 38 | 49.68 | 30.02 | 33.8755 | 4.5363 | −0.35 | 0.99 |
| 40 | 49 | 30.01 | 33.8919 | 6.3907 | – | 1.23 |
| 42 | 48.03 | 30 | 34.1661 | 8.3457 | −0.24 | 1.74 |
| 43 | 47.51 | 29.98 | 34.2679 | 8.8479 | – | 1.18 |
| 44 | 47.01 | 30 | 34.3512 | 10.1607 | −0.1 | 1.14 |
| 45 | 46.67 | 30.02 | 34.2965 | 9.93 | – | 1.32 |
| 46 | 46.34 | 29.98 | 34.5306 | 10.8762 | – | 1.61 |
| 47 | 46 | 29.99 | 34.4394 | 10.8862 | – | 1.26 |
| 48 | 45.68 | 29.99 | 34.6698 | 11.5325 | −0.03 | 1.33 |
| 49 | 45.38 | 30 | 34.4968 | 10.8949 | – | 1.47 |
| 50 | 45.01 | 29.98 | 34.4389 | 10.7013 | – | 1.18 |
| 51 | 44.52 | 29.98 | 34.4487 | 12.0471 | – | 1.6 |
| 52 | 44.01 | 29.96 | 34.4794 | 12.315 | 0.04 | 1.56 |

**Table 2 :** CFC-12, oxygen-18 and carbon-13 data for CIVA1 seawater samples. Each sample is listed by station number and depth, together with its potential temperature (θ) and salinity (S)

| Depth (m) | *Θ* (°C) | *S* | F12 (pmol/kg) | $\delta^{18}O$ (‰) | $\delta^{13}C$ (‰) |
|---|---|---|---|---|---|
| *Station 5 (68.67°S 29.96°E)* | | | | | |
| 10.1 | −1.0749 | 33.7513 | 2.94 | −0.24 | −1.05 |
| 20.6 | −0.1286 | 33.8975 | 2.84 | −0.46 | 1.35 |
| 39.1 | −0.3232 | 33.9091 | 2.82 | −0.38 | 1.24 |
| 60.7 | −1.6306 | 34.1131 | 2.60 | −0.48 | 0.91 |
| 80.1 | −1.7271 | 34.1751 | 2.47 | −0.49 | – |
| 100.3 | −1.7986 | 34.2010 | 2.53 | −0.53 | 0.83 |
| 198.4 | −1.5708 | 34.2888 | 2.38 | −0.30 | 0.71 |
| 325.5 | −0.8186 | 34.4444 | 1.67 | −0.31 | 0.57 |
| 399.3 | 0.1062 | 34.5601 | 0.99 | −0.31 | 0.38 |
| 498.5 | 0.6585 | 34.6434 | 0.55 | −0.17 | 0.35 |
| 697.1 | 0.6859 | 34.6785 | 0.34 | −0.25 | 0.31 |
| 998.8 | 0.4346 | 34.6827 | 0.21 | – | 0.31 |
| 1345.8 | 0.1750 | 34.6735 | 0.18 | −0.10 | 0.32 |
| 1748.2 | −0.0280 | 34.6678 | 0.18 | −0.15 | 0.25 |
| 1996.0 | −0.1251 | 34.6670 | 0.20 | – | 0.29 |
| 2496.4 | −0.2797 | 34.6622 | 0.28 | −0.23 | – |
| 3021.7 | −0.4232 | 34.6590 | 0.38 | −0.08 | 0.29 |
| *Station 6 (68.01°S 30.00°E)* | | | | | |
| 10.2 | 0.2009 | 33.9122 | 2.92 | −0.21 | 0.97 |
| 19.9 | 0.1145 | 33.9158 | 2.93 | −0.53 | 1.21 |
| 40.0 | −0.1182 | 33.9307 | 2.86 | −0.44 | 1.27 |
| 60.7 | −1.7257 | 34.2924 | 2.50 | −0.51 | 0.86 |
| 81.0 | −1.7582 | 34.3304 | 2.50 | −0.11 | 0.71 |
| 100.6 | −1.7636 | 34.3487 | 2.47 | −0.16 | 0.80 |
| 199.7 | −0.5536 | 34.4732 | 1.52 | 0.07 | 0.60 |

| | | | | | |
|---|---|---|---|---|---|
| 324.4 | 0.7518 | 34.6407 | 0.46 | 0.04 | 0.17 |
| 403.2 | 0.8128 | 34.6642 | 0.42 | −0.03 | −0.02 |
| 698.8 | 0.7136 | 34.6916 | 0.23 | 0.08 | 0.26 |
| 998.8 | 0.4484 | 34.6879 | 0.18 | −0.15 | 0.08 |
| 1346.3 | 0.2066 | 34.6780 | 0.13 | −0.13 | 0.34 |
| 1747.9 | −0.0171 | 34.6713 | 0.15 | −0.15 | 0.37 |
| 1996.4 | −0.1300 | 34.6672 | 0.19 | – | 0.33 |
| 2497.6 | −0.2729 | 34.6630 | 0.24 | −0.25 | 0.38 |
| 2997.6 | −0.3780 | 34.6601 | 0.36 | −0.07 | 0.41 |
| 3495.9 | −0.4769 | 34.6562 | 0.41 | −0.06 | 0.41 |
| 3681.3 | −0.5667 | 34.6538 | 0.40 | −0.01 | – |
| *Station 8 (66.99°S 29.98°E)* | | | | | |
| 10.6 | 0.6460 | 33.8657 | 2.89 | 0.19 | – |
| 20.2 | 0.6406 | 33.8655 | 2.84 | −0.47 | – |
| 40.0 | −1.505 | 34.2558 | 2.46 | −0.52 | – |
| 61.0 | −1.6737 | 34.3407 | 2.35 | −0.45 | – |
| 80.8 | −1.7041 | 34.3543 | 2.36 | −0.55 | – |
| 100.0 | −1.6465 | 34.3737 | 2.24 | −0.40 | – |
| 201.0 | 0.7616 | 34.6069 | 0.61 | −0.18 | – |
| 322.1 | 1.1479 | 34.6803 | 0.29 | −0.27 | – |
| 397.5 | 1.1609 | 34.6970 | 0.22 | −0.22 | – |
| 493.7 | 1.1169 | 34.7074 | 0.16 | 0.08 | – |
| 699.7 | 0.8876 | 34.7082 | 0.15 | −0.12 | – |
| 997.1 | 0.5854 | 34.6986 | 0.09 | −0.24 | – |
| 1300.3 | 0.2866 | 34.6845 | 0.16 | −0.23 | – |
| 1299.9 | 0.2877 | 34.6836 | 0.15 | −0.37 | – |
| 1595.7 | 0.1155 | 34.6753 | 0.13 | −0.40 | – |
| 1993.8 | −0.0865 | 34.6692 | 0.25 | −0.24 | – |
| 2490.9 | −0.2596 | 34.6639 | 0.29 | 0.00 | – |
| 3193.9 | −0.4247 | 34.6577 | 0.39 | −0.37 | – |
| 3697.2 | −0.5206 | 34.6547 | 0.42 | −0.44 | – |

| | | | | | |
|---|---|---|---|---|---|
| 4065.9 | −0.6265 | 34.6518 | 0.36 | −0.48 | – |
| 4065.7 | −0.6255 | 34.6508 | 0.36 | −0.56 | – |
| *Station 10 (66.01°S 29.99°E)* | | | | | |
| 13.2 | 0.8639 | 33.8424 | 2.86 | −0.56 | 0.81 |
| 23.3 | 0.8255 | 33.8495 | 2.84 | −0.61 | – |
| 82.4 | 0.4151 | 34.5224 | 1.09 | 0.10 | – |
| 102.0 | 0.8490 | 34.5760 | 0.65 | −0.21 | – |
| 202.8 | 1.5142 | 34.6852 | 0.20 | −0.12 | – |
| 324.3 | 1.4360 | 34.7080 | 0.14 | −0.16 | – |
| 399.1 | 1.3432 | 34.7120 | 0.17 | −0.34 | – |
| 500.3 | 1.2390 | 34.7171 | 0.11 | −0.10 | – |
| 698.2 | 1.0239 | 34.7164 | 0.11 | −0.21 | – |
| 998.1 | 0.6925 | 34.7047 | 0.11 | −0.34 | – |
| 1350.8 | 0.3953 | 34.6916 | 0.11 | −0.32 | – |
| 1350.3 | 0.3963 | 34.6908 | 0.09 | −0.32 | – |
| 1495.7 | 0.3028 | 34.6841 | 0.07 | −0.33 | – |
| 1995.4 | 0.0335 | 34.6748 | 0.11 | −0.22 | – |
| 2495.4 | −0.1756 | 34.6665 | 0.17 | −0.39 | – |
| 2994.9 | −0.3338 | 34.6613 | 0.27 | −0.39 | – |
| 3495.1 | −0.4408 | 34.6601 | 0.22 | −0.34 | – |
| 3998.4 | −0.5312 | 34.6553 | 0.37 | −0.37 | – |
| 3998.0 | −0.5321 | 34.6552 | 0.30 | −0.58 | – |
| 4477.0 | −0.6604 | 34.6524 | 0.23 | −0.44 | – |
| *Station 14 (63.68°S 30.00°E)* | | | | | |
| 11.0 | 1.0260 | 33.8285 | 2.87 | – | 0.96 |
| 20.8 | 0.7816 | 33.8316 | 2.89 | −0.46 | 1.10 |
| 40.5 | −0.8856 | 34.0561 | 2.76 | −0.55 | 1.07 |
| 60.2 | −1.5886 | 34.1637 | 2.69 | −0.41 | 0.01 |
| 79.9 | −1.6670 | 34.1966 | 2.62 | −0.57 | 1.03 |
| 99.5 | −1.0753 | 34.2850 | 2.22 | −0.32 | 0.79 |
| 202.0 | 1.3446 | 34.6453 | 0.35 | −0.02 | 0.02 |

| | | | | | |
|---|---|---|---|---|---|
| 324.4 | 1.3472 | 34.6891 | 0.20 | −0.21 | 0.23 |
| 399.3 | 1.3442 | 34.7070 | 0.16 | −0.33 | 0.19 |
| 498.7 | 1.1963 | 34.7095 | 0.15 | −0.17 | 0.26 |
| 691.6 | 1.0014 | 34.7124 | 0.11 | −0.07 | 0.38 |
| 998.0 | 0.6657 | 34.7026 | 0.09 | −0.07 | 0.19 |
| 1347.9 | 0.3994 | 34.6928 | 0.09 | −0.27 | 0.18 |
| 2495.2 | −0.1687 | 34.6669 | 0.11 | −0.38 | 0.25 |
| 3493.5 | −0.4415 | 34.6596 | 0.14 | −0.44 | 0.64 |
| 3994.2 | −0.5385 | 34.6572 | 0.15 | −0.41 | 0.39 |
| 3995.0 | −0.5386 | 34.6568 | 0.14 | −0.41 | 0.30 |
| 4491.9 | −0.6271 | 34.6545 | 0.08 | −0.37 | – |
| 5092.8 | −0.7216 | 34.6514 | 0.08 | −0.40 | 0.40 |
| *Station 18 (61.00°S 30.00°E)* | | | | | |
| 11.3 | 1.7759 | 33.6881 | 2.83 | −0.36 | 0.88 |
| 20.9 | 1.6254 | 33.7183 | 2.85 | −0.49 | – |
| 80.0 | −1.6200 | 34.1229 | 2.74 | −0.39 | – |
| 100.1 | −1.6305 | 34.1397 | 2.66 | −0.03 | – |
| 200.0 | 1.2090 | 34.5679 | 0.62 | 0.04 | – |
| 324.4 | 1.5217 | 34.6755 | 0.23 | 0.05 | – |
| 398.9 | 1.5356 | 34.7015 | 0.17 | −0.14 | – |
| 498.8 | 1.4363 | 34.7135 | 0.10 | −0.03 | – |
| 698.1 | 1.2098 | 34.7208 | 0.08 | 0.03 | – |
| 998.9 | 0.8452 | 34.7100 | 0.10 | 0.01 | – |
| 1346.3 | 0.5005 | 34.6957 | 0.09 | 0.01 | – |
| 1348.3 | 0.5003 | 34.6947 | 0.07 | 0.09 | – |
| 1495.7 | 0.3958 | 34.6901 | 0.07 | −0.16 | – |
| 1994.7 | 0.1193 | 34.6790 | 0.08 | −0.05 | – |
| 2494.0 | −0.1077 | 34.6706 | 0.09 | −0.22 | – |
| 2995.5 | −0.2888 | 34.6626 | 0.10 | 0.05 | – |
| 3495.4 | −0.4173 | 34.6600 | 0.08 | −0.42 | – |
| 3993.6 | −0.5189 | 34.6565 | 0.13 | −0.46 | – |

| | | | | | |
|---|---|---|---|---|---|
| 5228.2 | −0.7164 | 34.6515 | 0.10 | −0.40 | – |
| *Station 22 (58.35°S 29.97°E)* | | | | | |
| 9.7 | 2.1938 | 33.5976 | 2.80 | −0.47 | 1.41 |
| 19.9 | 2.1963 | 33.5974 | 2.78 | −0.46 | 1.46 |
| 40.4 | 2.1712 | 33.6051 | 2.76 | −0.39 | 1.43 |
| 62.4 | −0.2850 | 33.9609 | 2.95 | −0.52 | 1.24 |
| 82.4 | −0.6427 | 34.0512 | 2.89 | −0.43 | 0.78 |
| 101.5 | −0.3753 | 34.1183 | 2.76 | −0.13 | 0.83 |
| 201.7 | 0.6828 | 34.3620 | 1.57 | −0.02 | 0.51 |
| 320.1 | 1.4822 | 34.5507 | 0.58 | −0.20 | 0.30 |
| 396.6 | 1.6254 | 34.6269 | 0.34 | 0.13 | 0.22 |
| 497.7 | 1.8556 | 34.6953 | 0.13 | −0.09 | 0.31 |
| 696.3 | 1.7796 | 34.7376 | 0.07 | – | 0.32 |
| 994.9 | 1.3741 | 34.7341 | 0.05 | −0.10 | 0.30 |
| 1349.8 | 0.9444 | 34.7215 | 0.09 | −0.09 | – |
| 1349.3 | 0.9464 | 34.7208 | 0.05 | −0.05 | 0.27 |
| 1494.2 | 0.7931 | 34.7122 | 0.06 | −0.18 | 0.27 |
| 1998.2 | 0.3760 | 34.6897 | 0.07 | −0.18 | 0.17 |
| 2497.0 | 0.0873 | 34.6759 | 0.08 | −0.28 | – |
| 3000.1 | −0.1513 | 34.6696 | 0.07 | −0.07 | 0.33 |
| 3496.3 | −0.3267 | 34.6598 | 0.11 | −0.22 | 0.32 |
| 3998.1 | −0.4552 | 34.6574 | 0.11 | −0.18 | 0.42 |
| 5371.4 | −0.7105 | 34.6495 | 0.11 | −0.42 | 0.36 |
| *Station 26 (55.68°S 30.00°E)* | | | | | |
| 10.2 | 2.8325 | 33.9342 | 2.67 | −0.50 | 1.04 |
| 19.4 | 2.8249 | 33.9352 | 2.67 | −0.44 | 1.48 |
| 38.7 | 2.8278 | 33.9362 | 2.67 | −0.41 | 1.48 |
| 60.0 | 2.4319 | 33.9566 | 2.71 | −0.48 | 1.33 |
| 79.8 | 0.8511 | 34.0314 | 2.75 | −0.21 | 1.23 |
| 100.0 | 0.6233 | 34.0809 | 2.58 | −0.02 | 1.10 |
| 199.9 | 1.4017 | 34.2946 | 1.27 | 0.04 | 0.69 |

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|---|---|---|---|---|---|
| 322.6 | 1.9119 | 34.4610 | 0.57 | 0.03 | 0.43 |
| 392.3 | 2.0951 | 34.5489 | 0.29 | 0.16 | 0.30 |
| 503.4 | 2.1331 | 34.6271 | 0.15 | −0.05 | 0.31 |
| 699.1 | 2.0807 | 34.7022 | 0.07 | 0.07 | 0.28 |
| 995.4 | 1.8621 | 34.7517 | 0.00 | – | 0.34 |
| 1343.8 | 1.4918 | 34.7541 | 0.04 | 0.12 | 0.33 |
| 1745.6 | 0.9319 | 34.7202 | 0.06 | – | 0.35 |
| 2244.9 | 0.4002 | 34.6911 | 0.07 | 0.09 | 0.26 |
| 2994.6 | −0.0833 | 34.6703 | 0.08 | – | 0.28 |
| 3495.2 | −0.2934 | 34.6633 | 0.09 | 0.12 | 0.31 |
| 3994.5 | −0.4334 | 34.6585 | 0.11 | – | 0.36 |
| 5441.6 | −0.7160 | 34.6503 | 0.10 | −0.06 | 0.35 |
| *Station 32 (51.64°S 29.97°E)* | | | | | |
| 10.9 | 4.6461 | 33.8812 | 2.46 | −0.27 | 1.32 |
| 20.2 | 4.6394 | 33.8824 | 2.38 | −0.24 | 1.32 |
| 37.7 | 4.6391 | 33.8815 | 2.47 | −0.42 | 1.59 |
| 60.9 | 4.6214 | 33.8822 | 2.37 | −0.23 | 1.69 |
| 79.2 | 3.9949 | 33.9012 | 2.44 | −0.20 | 1.51 |
| 99.3 | 2.9470 | 33.9513 | 2.58 | −0.27 | 1.26 |
| 200.9 | 2.7721 | 34.1327 | 1.88 | −0.12 | 0.99 |
| 325.9 | 2.4452 | 34.2137 | 1.31 | −0.23 | 0.79 |
| 398.6 | 2.4088 | 34.2755 | 0.91 | −0.07 | 0.67 |
| 499.8 | 2.3705 | 34.3515 | 0.57 | −0.11 | 0.62 |
| 700.5 | 2.4456 | 34.5183 | 0.21 | 0.01 | 0.43 |
| 996.9 | 2.3759 | 34.6628 | 0.05 | 0.05 | 0.39 |
| 1345.0 | 2.2820 | 34.7661 | 0.04 | −0.05 | – |
| 1349.1 | 2.2678 | 34.7643 | 0.03 | 0.05 | 0.43 |
| 1496.9 | 2.2403 | 34.7791 | 0.00 | 0.03 | 0.43 |
| 2012.0 | 1.6977 | 34.7807 | 0.00 | 0.03 | 0.51 |
| 2404.7 | 1.3461 | 34.7611 | 0.03 | −0.04 | 0.42 |
| 2746.6 | 1.2286 | 34.7657 | 0.00 | 0.01 | 0.54 |

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|---|---|---|---|---|---|
| 2994.3 | 0.8648 | 34.7290 | 0.00 | −0.08 | 0.46 |
| 3495.4 | 0.3224 | 34.6895 | 0.06 | 0.02 | 0.36 |
| 4854.7 | −0.3832 | 34.6611 | 0.08 | −0.19 | 0.50 |
| *Station 42 (48.03°S 30.00°E)* | | | | | |
| 7.3 | 8.3457 | 34.1661 | 2.16 | −0.28 | 1.74 |
| 18.2 | 8.3456 | 34.1642 | 2.17 | −0.24 | 1.74 |
| 40.0 | 8.3484 | 34.1660 | 2.16 | −0.40 | 1.74 |
| 58.3 | 8.3495 | 34.1671 | 2.16 | −0.23 | 1.73 |
| 76.9 | 8.5443 | 34.3887 | 2.07 | – | 1.50 |
| 97.7 | 8.2066 | 34.4798 | 2.01 | −0.11 | – |
| 198.5 | 6.4745 | 34.3083 | 2.07 | −0.29 | 1.30 |
| 323.4 | 5.3758 | 34.2373 | 1.42 | −0.27 | 1.18 |
| 399.0 | 5.1701 | 34.2882 | – | −0.29 | 1.04 |
| 499.0 | 4.7635 | 34.3022 | 1.11 | −0.35 | 1.19 |
| 698.3 | 3.2969 | 34.2365 | 1.01 | −0.32 | 0.89 |
| 1097.6 | 2.8633 | 34.4643 | 0.22 | – | 0.56 |
| 1351.0 | 2.5481 | 34.5625 | 0.08 | −0.21 | 0.44 |
| 1744.4 | 2.3917 | 34.6950 | 0.00 | −0.20 | – |
| 1992.1 | 2.2862 | 34.7487 | 0.05 | – | 0.45 |
| 2244.3 | 2.1168 | 34.7731 | – | −0.02 | – |
| 2745.4 | 1.7741 | 34.7923 | 0.04 | 0.01 | – |
| 2993.6 | 1.5461 | 34.7783 | 0.05 | 0.01 | 0.42 |
| 3498.3 | 0.9699 | 34.7333 | 0.00 | 0.00 | 0.33 |
| 3993.9 | 0.5506 | 34.7090 | 0.04 | −0.09 | – |
| 5060.8 | −0.2095 | 34.6668 | 0.09 | – | 0.32 |
| *Station 52 (44.01°S 29.96°E)* | | | | | |
| 9.8 | 12.3150 | 34.4794 | 1.82 | 0.03 | 1.56 |
| 19.4 | 12.2968 | 34.4783 | 1.87 | 0.04 | 1.59 |
| 39.7 | 12.0453 | 34.4526 | 1.95 | 0.02 | 1.56 |
| 61.0 | 11.8357 | 34.6558 | 1.86 | −0.12 | – |
| 82.1 | 10.0045 | 34.6431 | 1.86 | −0.13 | – |

| | | | | | |
|---|---|---|---|---|---|
| 100.5 | 9.2985 | 34.5982 | 1.89 | 0.09 | – |
| 197.4 | 7.9160 | 34.4974 | 1.75 | 0.09 | 0.96 |
| 323.3 | 6.3703 | 34.3396 | 1.62 | −0.18 | 1.07 |
| 398.5 | 5.8962 | 34.3536 | 1.32 | −0.02 | 1.04 |
| 499.0 | 5.1576 | 34.3321 | 1.09 | −0.05 | 0.79 |
| 698.7 | 4.0819 | 34.3287 | 0.80 | −0.18 | 0.79 |
| 1098.2 | 2.7701 | 34.4644 | 0.25 | −0.17 | 0.49 |
| 1345.5 | 2.6602 | 34.5998 | 0.12 | −0.07 | – |
| 1347.4 | 2.6561 | 34.6007 | 0.11 | – | 0.40 |
| 1748.2 | 2.4683 | 34.7234 | 0.00 | −0.03 | 0.27 |
| 2244.9 | 2.2081 | 34.7934 | 0.00 | 0.08 | 0.58 |
| 2995.4 | 1.6311 | 34.7894 | 0.00 | 0.00 | 0.58 |
| 3496.4 | 1.0783 | 34.7521 | 0.00 | −0.03 | 0.44 |
| 4497.9 | 0.1862 | 34.6903 | 0.00 | – | 0.37 |
| 5002.0 | −0.1482 | 34.6705 | 0.09 | −0.18 | 0.40 |
| 5440.7 | −0.2290 | 34.6660 | 0.09 | −0.15 | – |

### The oxygen isotope composition

In the uppermost surface waters, the $\delta^{18}O$ values and salinities show latitudinal gradients (Fig. 4). North of the Subantarctic Front to the Polar Front, $\delta^{18}O$ values decrease from 0.0‰ to −0.4‰ and salinities drop from 34.7 to 33.9 due to dilution by atmospheric precipitations. In the antarctic zone, the $\delta^{18}O$ values of AASW remains around −0.45‰ while salinities are in the range 33.6–33.9 due to the melting of sea ice. At the AD, a slight drop in the $\delta^{18}O$ values to −0.6‰ associated with a very small salinity decrease is probably indicative of a very weak contribution from continental ice melting. South of 69°S, the decrease of $\delta^{18}O$ value which is associated with a salinity increase marks the effect of sea-ice freezing.

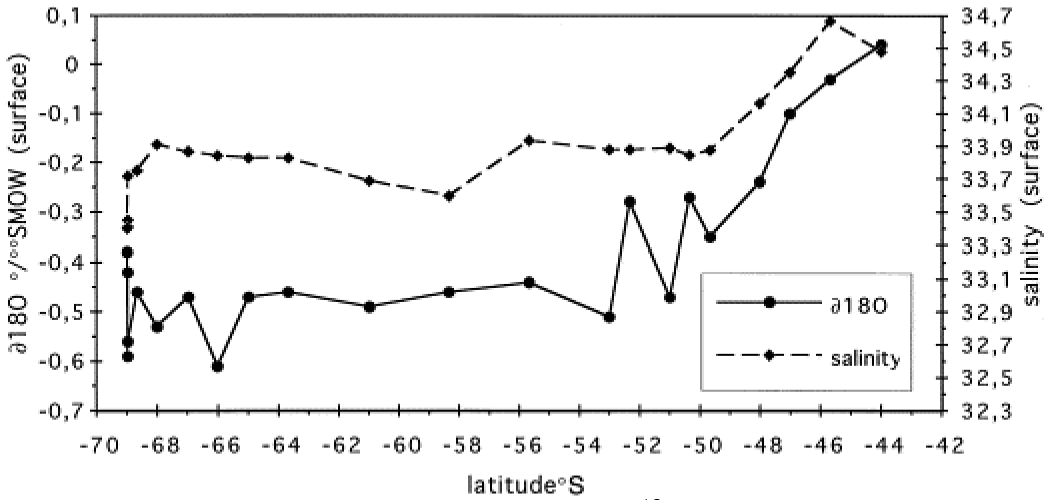


Fig. 4. Latitudinal variations of observed $\delta^{18}O$ and salinity values in the uppermost surface waters of the Southern Ocean.

On the $\delta^{18}O$–S diagram (Fig. 5), the signal of Winter Waters (WW) is well defined by its salinity (34.15 to 34.30) and $\delta^{18}O$ value (−0.56‰ to −0.40‰). The other water masses are also differentiated by their $\delta^{18}O$–S parameters: $-0.15‰<\delta^{18}O<-0.35‰$ and $34.22<S<34.34$ for AAIW; $-0.18‰<\delta^{18}O<0.15‰$ and $34.70<S<34.80$ for CDW, the $^{18}O$ and salinity enrichments being due to the influence of North Atlantic Deep Water (NADW) in the northern part of the section; $-0.28‰<\delta^{18}O<-0.42‰$ and $34.64<S<34.68$ for AABW. This diagram shows a grouping of waters identified as CSBW (Continental Shelf Bottom Water) which have the same salinity as AABW (S=34.66) but higher $\delta^{18}O$ values (−0.2 to 0.0‰).

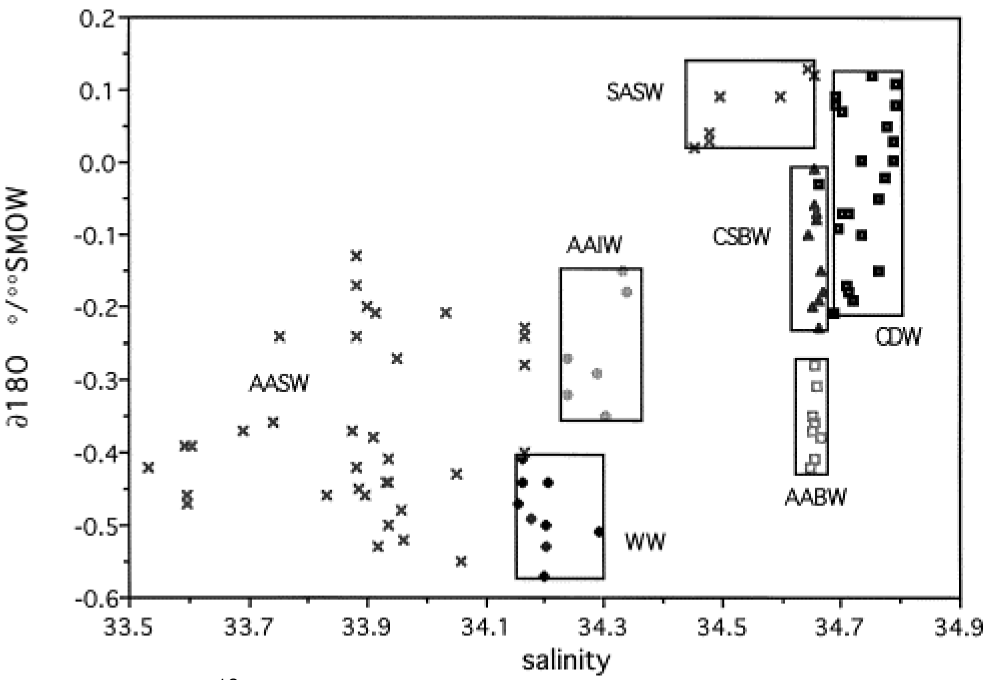


Fig. 5. The $\delta^{18}O$/salinity relationship in the water masses of the Southern Ocean. The following water masses have been identified: AASW, Antarctic Surface Water; SASW, SubAntarctic Surface Water; WW, Winter Water; CDW, Circumpolar Deep Water; AABW, Antarctic Bottom Water; CSBW, Continental Shelf Bottom Water.

The vertical distributions of δ$^{18}$O values along the 30°E section (Fig. 6) follows rather well the general pathways of the main water masses. The AAIW, characterized by δ$^{18}$O values between −0.2 and −0.3‰ when it sinks at the Polar Front, is advected northward at a depth of about 800 m. The core of CDW is well recognized by δ$^{18}$O values close to 0.0‰ between 2000 and 3000 m; the upwelling of this water mass at the antarctic divergence is marked by the raising of the δ$^{18}$O=0‰ isoline at immersion depths of about 1000 m. The AABW, characterized by δ$^{18}$O values around −0.4‰, lies below 3500 m. Along the southern margin of Antarctica, a lense of bottom water with maximum values of δ$^{18}$O≈0.1‰ is observed between 2500 m and 4000 m. This water mass corresponding to the CSBW, which is not differentiated by its temperature and salinity characteristics, has also been identified by a relative maximum in the CFC-12 concentrations. There is no evidence of local formation of deep water in this area so two hypothesis may be put forward: (1) the water mass comes from the East and corresponds to bottom waters formed near Prydz Bay, (2) the water is formed in the Weddell sea and acquires an intermediate density between the WSBW and the CDW; then, following the topography, this water flows back to the Weddell basin by the Enderby basin. However, further physical measurements would be necessary for a better understanding of the origin and circulation of this deep water mass in this area.

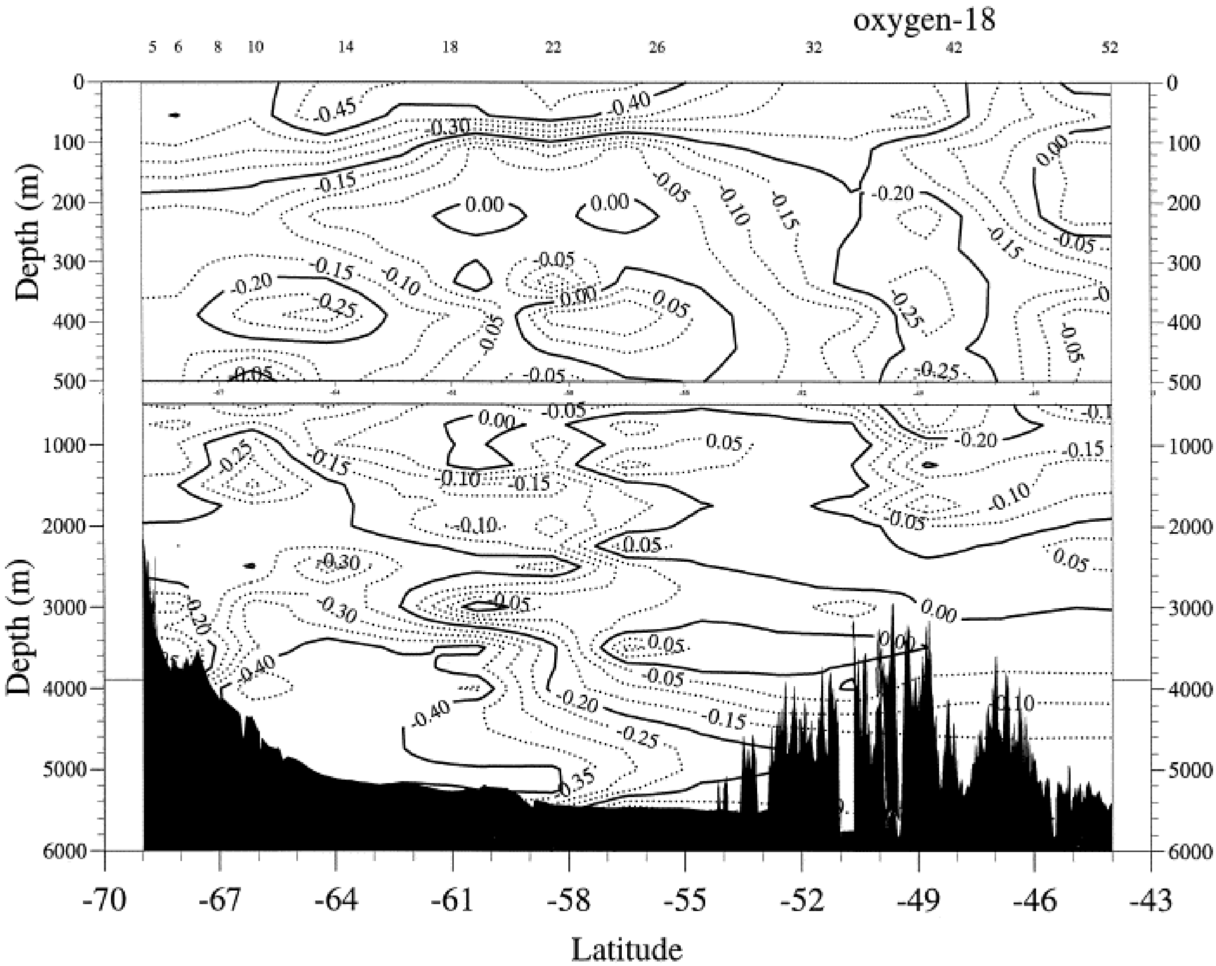


Fig. 6. Latitudinal distribution of the δ$^{18}$O values.

**The carbon isotope composition**

The variations of $\delta^{13}C$ values in the uppermost surface waters (Fig. 7) follow the main frontal oceanic structures. Strong oscillations are observed north of the Polar Front, separating the $^{13}C$-rich waters (1.15‰<$\delta^{13}C$<1.6‰) of the polar front and subantarctic zones from the $^{13}C$-depleted waters (0.5‰<$\delta^{13}C$<0.9‰) of the antarctic zone. The major drop of $\delta^{13}C$ values down to 0.5‰ characterizes the antarctic divergence and is due to the upwelling of $^{13}C$-depleted waters.

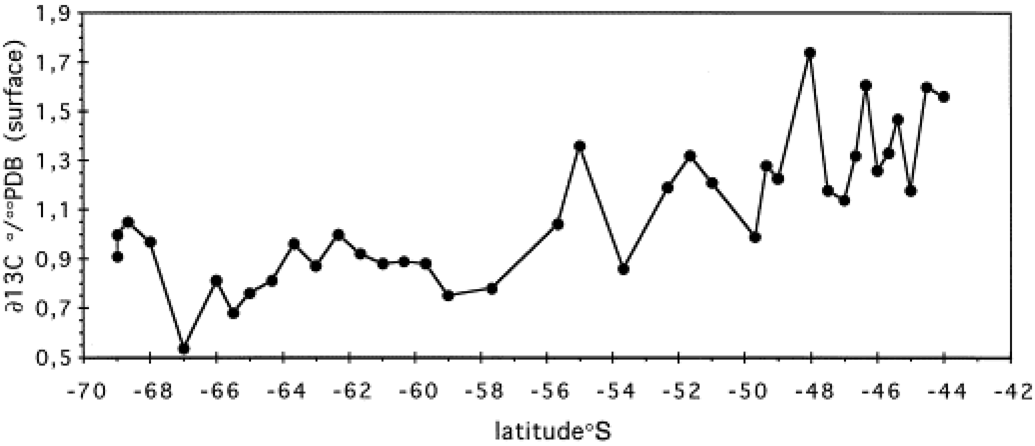


Fig. 7. Latitudinal variations of $\delta^{13}C$ of $\Sigma CO_2$ in the uppermost surface waters of the Southern Ocean.

Along the 30°E meridional section, the $\delta^{13}C$ values exhibit strong latitudinal and vertical variabilities (Fig. 8). In the subantarctic and polar front zones, the $\delta^{13}C$ values decrease to ≈0.6‰ at 1000 m due to organic matter remineralization; the $\delta^{13}C$ values then remain close to 0.4‰ downward in the water column. The progressive upwelling of $^{13}C$-depleted CDW (0.3 to 0.4‰) at the antarctic divergence is responsible for the decrease of about 0.7‰ in surface waters between the subantarctic and the antarctic zone. Around 4000 m, a local maximum of $\delta^{13}C$ values (0.45 to 0.5‰) is observed and corresponds with a local CFC-12 maximum; identifying a deep lense of better ventilated water.

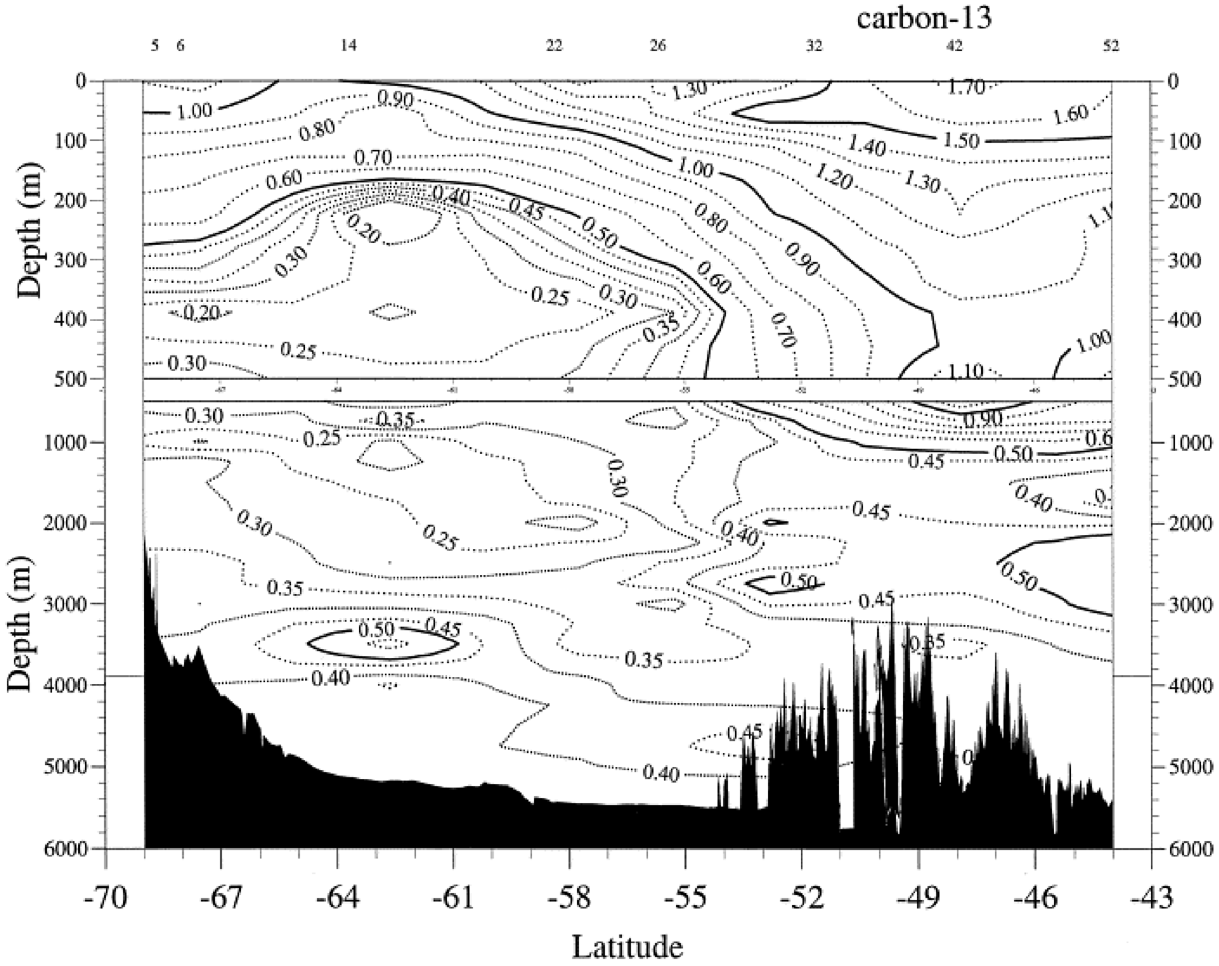


Fig. 8. Latitudinal distribution of the $\delta^{13}C$ values of $\Sigma CO_2$.

## Conclusions

The distributions of $\delta^{13}C$, $\delta^{18}O$ and CFC-12 along the meridian 30°E follow the general pathways of the main water masses described by temperature and salinity sections. The AASW and SASW are well discriminated by the uppermost $\delta^{18}O$ and $\delta^{13}C$ surface values and their mixing occurs in the PF-SAF zone. The sinking of AAIW north of the SAF and the upwelling of CDW at the AD are also well identified by the distribution of these tracers.

These tracers give also new information on the circulation of the water masses in this area. A relative maximum of CFC-12 appears around 4000 m between 66°S and 56°S and is correlated with maximum $\delta^{13}C$ values; both observations indicate a higher ventilation rate than in the surrounding deep waters. Along the continental margin of Antarctica, the bottom waters, between 2500 and 4000 m, are identified by relatively high $\delta^{18}O$ values ($-0.2‰<\delta^{18}O<0‰$) and relatively high CFC-12 concentrations, indicating that this water mass is well ventilated, newly formed and does not come from the downwelling of the superficial waters. This water mass which is not identified by the temperature and salinity parameters may originate either from the Weddell Sea or from Prydz Bay. An extensive study of this region, including physical measurements and geochemical tracer data, would give information on the extension of this newly formed water mass and provide more details on its origin.

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