

## How much deep water is formed in the Southern Ocean?

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**Abstract.** Three tracers are used to place constraints on the production rate of ventilated deep water in the Southern Ocean. The distribution of the water mass tracer  $\text{PO}_4^*$  ("phosphate star") in the deep sea suggests that the amount of ventilated deep water produced in the Southern Ocean is equal to or greater than the outflow of North Atlantic Deep Water from the Atlantic. Radiocarbon distributions yield an export flux of water from the North Atlantic which has averaged about 15 Sv over the last several hundred years. CFC inventories are used as a direct indicator of the current production rate of ventilated deep water in the Southern Ocean. Although coverage is as yet sparse, it appears that the CFC inventory is not inconsistent with the deep water production rate required by the distributions of  $\text{PO}_4^*$  and radiocarbon. It has been widely accepted that the major part of the deep water production in the Southern Ocean takes place in the Weddell Sea. However, our estimate of the Southern Ocean ventilated deep water flux is in conflict with previous estimates of the flux of ventilated deep water from the Weddell Sea, which lie in the range 1-5 Sv. Possible reasons for this difference are discussed.

### 1. Introduction

No consensus exists regarding the locations or rates at which deep water is being produced in the Southern Ocean. The best documented sources lie along the margins of the Weddell Sea [Carmack, 1973; Gill, 1973; Carmack and Foster, 1975; Foster and Carmack, 1976; Killworth, 1977; Foster and Middleton, 1980; Foldvick et al., 1985; Gordon et al., 1993; Fahrbach et al., 1995]. Sources of dense bottom water have been identified at other locations around the perimeter of Antarctica, including the Ross Sea, the Adelic coast, and off Enderby Land [Jacobs et al., 1970; Gordon and Tcherina, 1972; Mantyla and Reid, 1983], but there appears to be general acceptance that it is within the Weddell Sea that about 80% of the Antarctic water which ventilates the deep global ocean originates [e.g., Foldvick and Gammelsrød, 1988].

Previous estimates of the production rate of ventilated deep waters (i.e., those which have recently exchanged gases with the atmosphere) in the Weddell Sea have been relatively low. The distribution of tritium suggests a production rate of between 2 and 3.5 sverdrups (Sv); 1 Sv =  $10^6 \text{ m}^3/\text{s}$  for surface ventilated water [Michel, 1978; Weiss et al., 1979; Bayer and Schlosser, 1991; Schlosser et al., 1991]; mass balance equations that link the rate

of ice shelf melting to rate of bottom water formation yield a production rate of 5 Sv [Weiss et al., 1979], while direct current meter measurements [Fahrbach et al., 1995] suggest that the rate at which cold bottom water leaves the Weddell Sea is < 5 Sv.

Our approach to this puzzle is to make use of a property that is able to trace the contribution of newly ventilated waters from the Antarctic perimeter to the global deep ocean. Our primary aim here is not (as has been the goal of most previous work focusing on this problem) to estimate the fluxes of narrowly defined, well-recognized water masses but rather to assess the contribution made by recently ventilated waters from around the entire Antarctic perimeter to the global deep water pool.

### 2. $\text{PO}_4^*$ Distribution

It is our judgment that the best means of estimating the relative contributions of deep waters of northern and southern origin to the global deep ocean is through the use of the quasi-conservative water mass tracer,  $\text{PO}_4^*$  [Broecker et al., 1985]. If the ratio of oxygen utilization to phosphate remineralization in a water parcel that has left the sea surface is known, then a correction can be made for this effect. The "corrected" deep sea phosphate distributions can then be used as a tracer of water mass circulation.  $\text{PO}_4^*$  is strictly conservative to the extent that the  $-\text{O}_2:\text{P}$  ratio is constant in the deep oceans. To make this correction, we use the revised Redfield  $-\text{O}_2:\text{P}$  ratio of 175:1 [Broecker et al., 1985; Takahashi et al., 1985], which recent work [e.g., Anderson and Sarmiento, 1994] suggests is indeed a good approximation for respiration throughout the deep sea.  $\text{PO}_4^*$  is defined as

$$\text{PO}_4^* = \text{PO}_4 + \text{O}_2/175 - 1.95 \mu\text{mol/kg}$$

where 175 is the average molar Redfield ratio of  $\text{O}_2$  consumption to phosphate remineralization in the deep sea and 1.95 is an arbitrary constant (explained by Broecker et al., [1985]). The reason we opt for  $\text{PO}_4^*$  is that the difference of  $1.22 \mu\text{mol/kg}$  between the  $\text{PO}_4^*$  for deep water formed in the North Atlantic ( $0.73 \pm 0.07 \mu\text{mol/kg}$ ) and ventilated deep water formed in the Weddell Sea ( $1.95 \pm 0.07 \mu\text{mol/kg}$ ) is ~20 times the range in this property for

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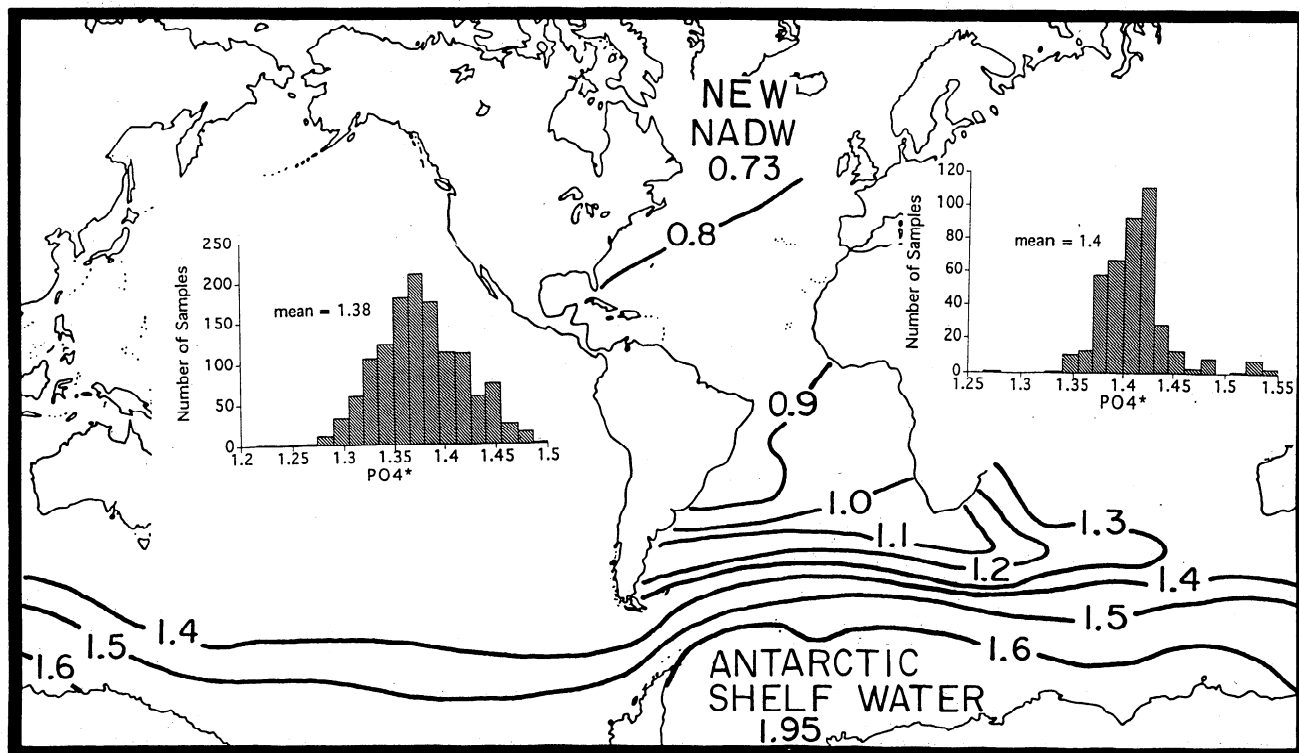
each of the end-members. We refer to the source waters as North Atlantic Deep Water (NADW) and Southern Ocean ventilated water. The term "ventilated water" is used because we are interested only in that water which has recently contacted the atmosphere, thereby renewing its oxygen and taking on chlorofluorocarbons.  $\text{PO}_4^*$  is unique in that it allows evaluation of the contribution of surface waters from around the Antarctic perimeter to the global deep water pool. Southern Ocean surface waters are the only waters in the world ocean able to attain the very high oxygen concentrations (because of their very cold temperature and hence enhanced  $\text{O}_2$  solubility) and the high phosphate concentrations (due to low nutrient utilization) necessary for a  $\text{PO}_4^*$  value as high as 1.9 to 2.0  $\mu\text{mol/kg}$ . The high  $\text{PO}_4^*$  value of deeper water masses in the Southern Ocean is a direct reflection of the contribution from these high-oxygen, high- $\text{PO}_4^*$  surface waters.

The global distribution of  $\text{PO}_4^*$  shows a large dynamic range, with a minimum in the North Atlantic and a maximum in the Southern Ocean (the two locations in which deep water production is taking place in the world ocean today). The global distribution of  $\text{PO}_4^*$  is here used to make a direct assessment of the contribution made by Southern Ocean ventilated water to the global deep pool. If the northern and southern end-members were blended together in equal proportions, the mix would have a  $\text{PO}_4^*$  value of  $(1.95+0.73)/2$  or 1.34  $\mu\text{mol/kg}$ , a value very close to the average of 1.39  $\mu\text{mol/kg}$  for deep water in the Indian and Pacific Oceans (see Figure 1). To create this mixture in the circumpolar current by blending of the two source waters would require that the flux of Southern Ocean ventilated water which enters the global deep ocean be roughly equal to the flux of NADW which leaves the Atlantic. This has important implications regarding the role of the Southern Ocean in ventilating the world's deep oceans.

During its traverse down the Atlantic, NADW entrains northward penetrating Antarctic Bottom Water (AABW). This mixture joins the circumpolar current south of Africa, creating a cross-circumpolar gradient in  $\text{PO}_4^*$  ranging from 1.05  $\mu\text{mol/kg}$  along the upper northern boundary to 1.65  $\mu\text{mol/kg}$  along the southern boundary (Figure 2). As the circumpolar current passes through the Indian and Pacific sectors of the Southern Ocean, these injections of new water are blended so that upon reaching the Drake Passage, a nearly uniform mix with a  $\text{PO}_4^*$  value of about 1.4  $\mu\text{mol/kg}$  has been generated. Bottom waters entering the Pacific and Indian Oceans have a slightly higher component of NADW and hence slightly lower  $\text{PO}_4^*$  values.

A few words must be said about the selection of the end-member compositions. For the North Atlantic, all deep waters north of 55°N and deeper than 1500 m have  $\text{PO}_4^*$  values close to 0.73  $\mu\text{mol/kg}$ . No trend with temperature is seen (see Figure 3). In the Southern Ocean a value of 1.67  $\mu\text{mol/kg}$  was adopted in earlier studies as characteristic of all deep waters formed in the Weddell Sea [Broecker *et al.*, 1985]. However, as shown in Figure 3,  $\text{PO}_4^*$  shows a strong temperature dependence in the Southern Ocean, a direct reflection of mixing between ventilated deep waters forming in the Southern Ocean and the Circumpolar Deep Water (CDW) flowing through the Drake Passage. Extrapolation of this mixing line to -1.8°C (taken to be the mean temperature of the cold surface and near-surface waters in the Southern Ocean) yields a  $\text{PO}_4^*$  value of about 1.95  $\mu\text{mol/kg}$ . As shown in Figure 4, surface waters with this  $\text{PO}_4^*$  value were observed by Schroeder *et al.* [1994] along the southeastern margin of the Weddell Sea. Surface waters with a similar  $\text{PO}_4^*$  range were also found along the Ross Ice Shelf [Jacobs *et al.*, 1989].

At this point we must alert the reader to the consequences of assigning the average  $\text{PO}_4^*$  value of 1.95 observed in the Weddell



**Figure 1.** Contours of  $\text{PO}_4^*$  at 3 km depth. The values for northern and southern source waters are 0.73 and 1.95  $\mu\text{mol/kg}$ , respectively. As shown by the histograms, the values for the Pacific and Indian Oceans are extremely uniform.

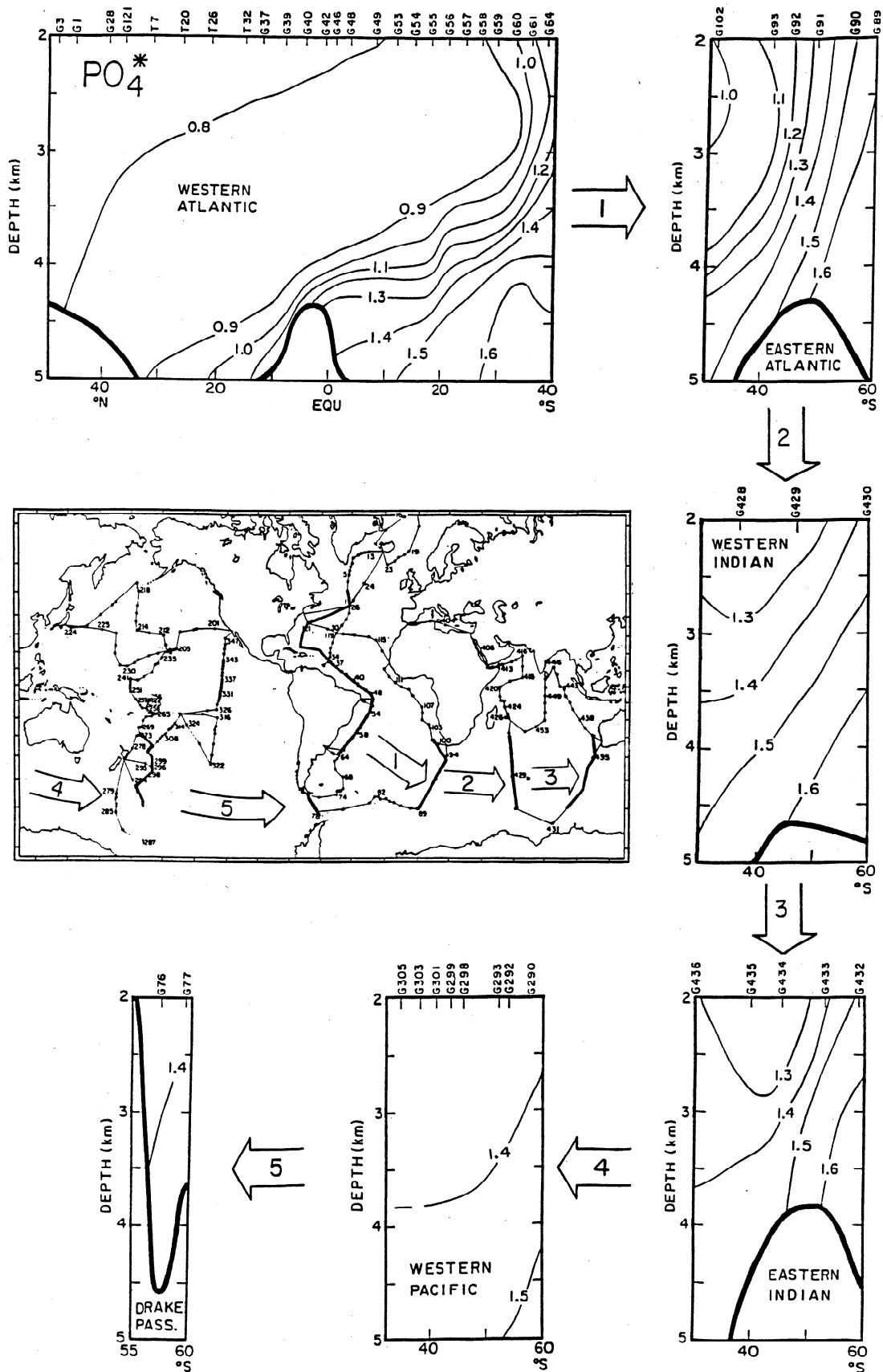
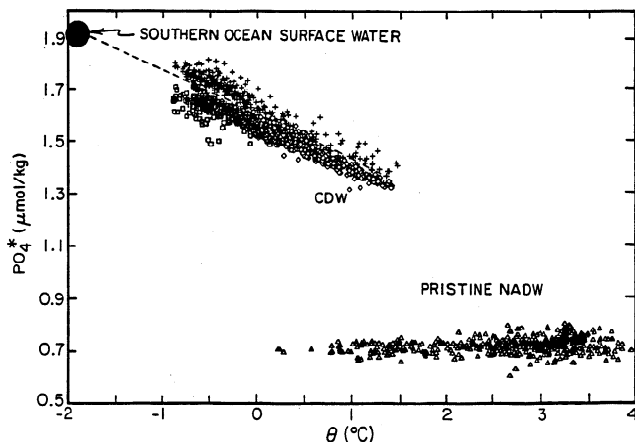


Figure 2. Sections showing the distribution of PO<sub>4</sub>\* with depth in the western Atlantic Ocean and in five crossings of the Antarctic Ocean. Also shown are the locations of stations occupied during the Geochemical Ocean Sections Study (GEOSECS) expeditions.



**Figure 3.**  $\text{PO}_4^*$  values for all GEOSECS [Bainbridge, 1981; Broecker et al., 1982; Weiss et al., 1983] and Transient Tracers in the Ocean (TTO) [Ostlund and Grall, 1987] water samples from  $> 1500$  m north of  $55^\circ\text{N}$  in the Atlantic Ocean (triangles) and for all waters deeper than 2000 m in the Antarctic at GEOSECS stations 79 through 90 in the Atlantic sector and 430 through 432 in the Indian sector (squares). Also shown are the  $\text{PO}_4^*$  values from the World Ocean Circulation Experiment (WOCE) sections A-12 and A-21, obtained during the R/V *Meteor* 11/5 expedition, for all depths  $> 2000$  m (stations 102 through 179 (see map in Figure 6)), and for water samples from  $> 2000$  m in the Pacific sector obtained during the WOCE S4 expedition along  $67^\circ\text{S}$ , (stations 682 through 794).

Sea, Ross Sea, and the Pacific sector to all surface waters around the Antarctic perimeter. If there are surface waters with  $\text{PO}_4^*$  values  $< 1.95$   $\mu\text{mol/kg}$  which contribute to the export flux of dense bottom waters, then the contribution of these ventilated Antarctic waters to the global deep water pool would have to exceed that of the rate of NADW outflow from the Atlantic. For example, if the mean  $\text{PO}_4^*$  value for Southern Ocean surface waters was 1.67  $\mu\text{mol/kg}$  (as proposed by Broecker et al. [1985]), then in order to explain the average  $\text{PO}_4^*$  value of 1.39  $\mu\text{mol/kg}$  of the deep Pacific and Indian waters, the flux of ventilated deep water from the Southern Ocean would have to be about twice that of the deep Atlantic outflow.

Dense waters with  $\text{PO}_4^*$  values significantly higher than 1.95  $\mu\text{mol/kg}$  have yet to be found in the Antarctic region. The highest phosphate concentrations found in waters around the Antarctic perimeter are about 2.4  $\mu\text{mol/kg}$  (Figure 5), and the oxygen content of waters at  $-1.8^\circ\text{C}$  and 100% saturation is about 350  $\mu\text{mol/kg}$ . It is clearly demonstrated (Figure 5) that an upper attainable limit of about 2.3  $\mu\text{mol/kg}$  can be placed on the  $\text{PO}_4^*$  values in Southern Ocean surface waters. However, bearing in mind that most data from the shelf waters in the Ross and Weddell Seas show  $\text{PO}_4^*$  values of  $< 2$   $\mu\text{mol/kg}$  and that it is in these two areas that the bulk of deep water formation is thought to be occurring, we maintain that our end-member value of 1.95 must be close to the average for Southern Ocean ventilated waters, which ultimately contribute to the global deep water pool. As the phosphate concentration in these waters lies in the range 2.0-2.1  $\mu\text{mol/kg}$ , a  $\text{PO}_4^*$  value of 1.95  $\mu\text{mol/kg}$  requires  $\text{O}_2$  contents in the range 306-324  $\mu\text{mol/kg}$ . These values correspond to 84 and 89% saturation with atmospheric  $\text{O}_2$ . As upwelling deep waters carry about 210  $\mu\text{mol/kg}$   $\text{O}_2$  (i.e., 57% saturation), the extent of  $\text{O}_2$  equilibration with the atmosphere lies in the range 62-74%. As we shall discuss later, this places important

constraints on the CFC-based estimate of deep water formation rates in the Southern Ocean.

If ocean ventilation is at steady state, if the bulk of NADW produced in the North Atlantic makes it around the tip of Africa rather than being recirculated within the Atlantic basin, and if the dominant inputs to the deep ocean come from the northern Atlantic (NADW) and the Southern Ocean, then the following conclusions are inescapable. First, the Southern Ocean ventilated water and NADW sources make nearly equal contributions to the deep ocean pool, and second, their fluxes must be nearly the same. The volumetric inventory of  $\text{PO}_4^*$  in the deep Pacific and Indian Oceans requires the former conclusion. But for the latter to be correct, the residence times in the deep sea of waters from these two inputs must also be roughly the same. The fact that both are injected into the rapidly homogenized circumpolar current demands that once mixed, they share a common residence time. Of course, as NADW has a prehistory of about 200 years in the Atlantic, this equality applies only to the postblending period.

What about the steady state caveat? This concept is sacred to our field, and as immense complications may result from non-steady-state behavior, we tend to avoid thinking about such a possibility. But, models have clearly demonstrated that the possibility of non-steady-state behavior looms large [e.g., Winton and Sarachik, 1993; Rahmstorf, 1995], and we must therefore keep an open mind on the subject.

### 3. Radiocarbon Distribution

The distribution of radiocarbon in the deep sea is treated in three different ways in order to obtain an estimate of NADW flux. The first approach is to analyze the radiocarbon budget for the entire deep ocean, the second is to look at the budget for the deep Atlantic alone, and the third is to consider the budget for the entire deep sea minus the Atlantic.

For each of these three approaches the flux of NADW was calculated below 2200, 1900, and 1600 m in order to give an indication of sensitivity of our estimates to the choice of the cutoff depth. The radiocarbon measurements from the Geochemical Ocean Sections Study (GEOSECS) [Ostlund and Stuiver, 1980; Ostlund et al., 1980; Stuiver and Ostlund, 1980], Transient Tracers in the Ocean (TTO) [Ostlund and Grall, 1987], South Atlantic Ventilation Experiment (SAVE) [Ostlund and Grall, 1992], and World Ocean Circulation Experiment (WOCE) expeditions (R. Key, unpublished data, 1996) were used to obtain average  $\Delta^{14}\text{C}$  values for ocean basins below various depth horizons. We also obtained ocean basin volumes based on a smoothed topography of the Hamburg model.

All three approaches (outlined below and in Tables 1 and 2a, b, c) lead to the same conclusion: on the century to millennial timescale the production rate of NADW (and hence also of Southern Ocean ventilated water) must have averaged about 15 Sv.

#### 3.1. The Entire Deep Sea

We obtain an estimate of the flux of NADW by assuming steady state conditions, i.e., that the number of radiocarbon moles decaying in the deep sea each year must be resupplied by particulate rain and with the influx of new deep waters. We assume that the only deep waters resupplying these radiocarbon moles are NADW and Southern Ocean ventilated water; the contribution from other possible sources such as the downward mixing of intermediate waters is discussed later.

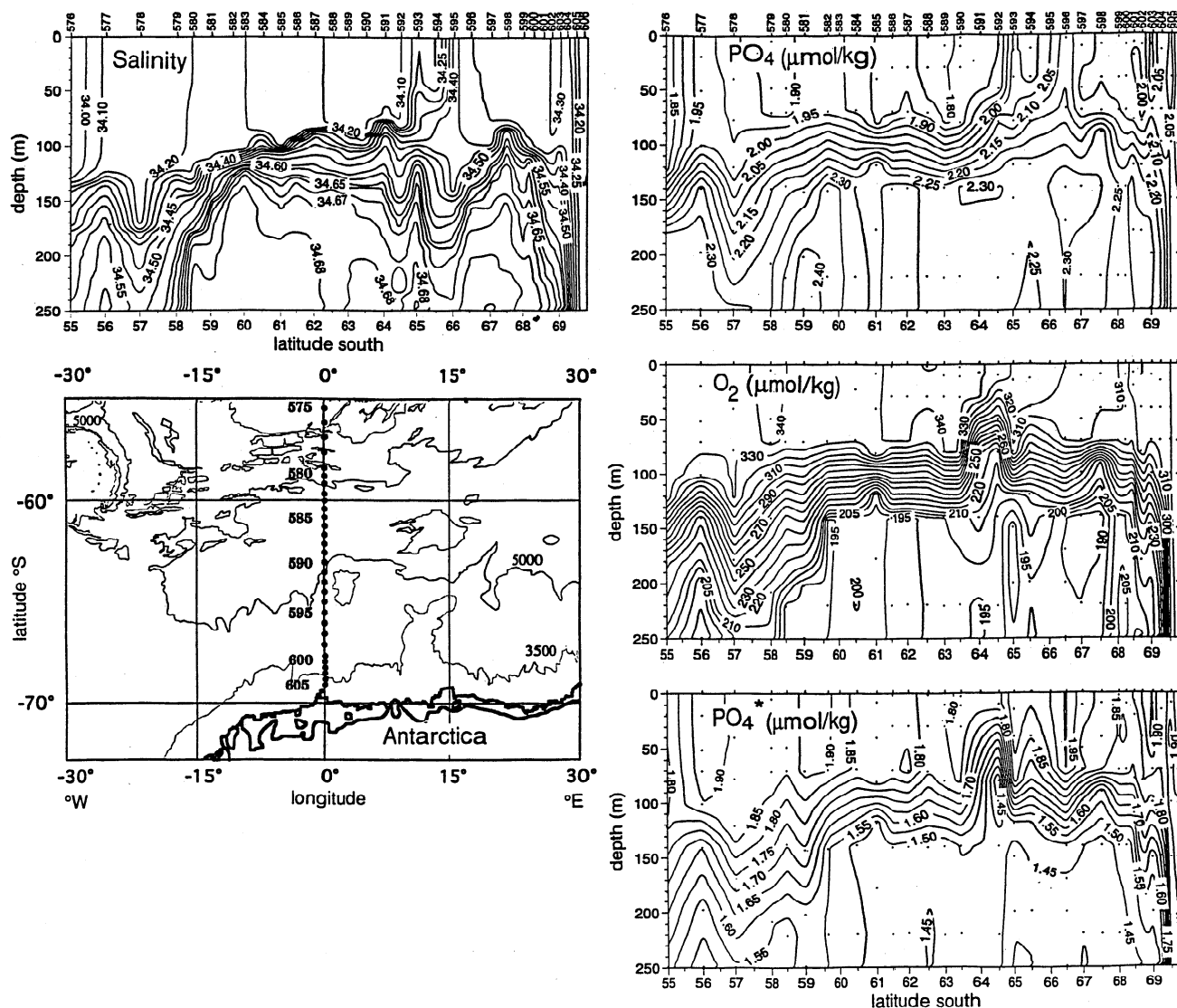


Figure 4. Section obtained from the German R/V *Polarstern* in May-June 1992.

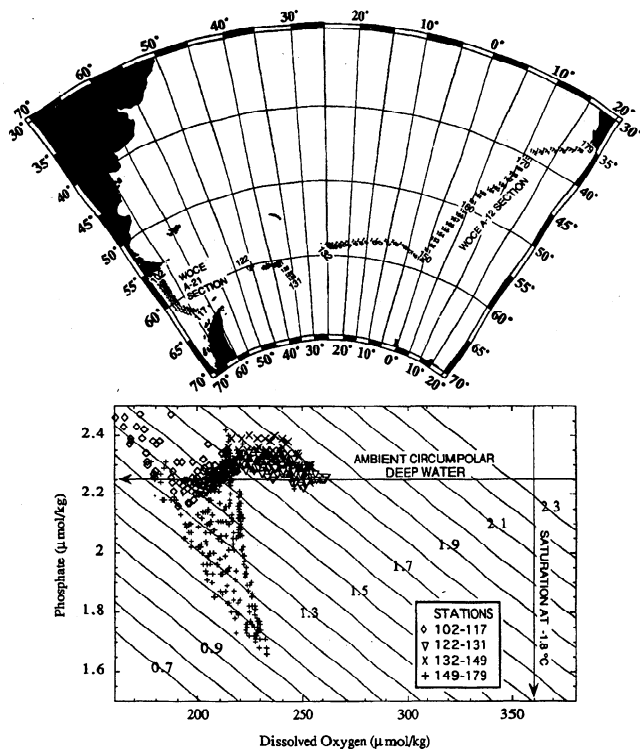
The difference of 110‰ between the  $^{14}\text{C}/\text{C}$  ratio of newly formed NADW ( $\Delta^{14}\text{C} = -67\text{‰}$ ) and that of mean deep seawater ( $\Delta^{14}\text{C} = -177\text{‰}$ ) is about 3 times the difference of 37‰ between surface waters in the Weddell Sea ( $\Delta^{14}\text{C} = -140\text{‰}$ ) and mean deep seawater, as summarized in Table 1. Thus, if these two fluxes are equal (as is required by the  $\text{PO}_4^*$  distribution), NADW must supply about 3 times as many moles of radiocarbon as does Southern Ocean ventilated water. For depths below 2000 m this requires a flux of about 15 Sv (see Table 2a). It should be noted that we assume that the old deep water displaced by the input of new deep water has an average  $\Delta^{14}\text{C}$  value equal to that of the entire deep sea.

### 3.2. The Deep Atlantic

In this approach the ventilation times and hence the fluxes of new bottom water are derived by calculating the average amount of radiocarbon lost by decay (initial  $\Delta^{14}\text{C}$  minus measured  $\Delta^{14}\text{C}$ ) during the residence of the water in the deep Atlantic. It has been shown by Broecker *et al.* [1991a] that the north to south decrease in  $^{14}\text{C}/\text{C}$  along any given isopycnal horizon in the North Atlantic is mainly the result of mixing between southern circumpolar wa-

ter (relatively low  $\Delta^{14}\text{C}$ ) and NADW (relatively high  $\Delta^{14}\text{C}$ ). Using the distribution of  $\text{PO}_4^*$ , Broecker *et al.* [1991a] isolate the smaller contribution of radiocarbon and show that at any given site the  $\Delta^{14}\text{C}$  deficiencies are nearly constant with depth for waters below 2000 m but that there is a strong west to east gradient. Deficiencies range from near zero along the western margin to more than 30‰ along the eastern margin (see Figure 6).

The average radiocarbon-produced deficiency of water in the deep North Atlantic (calculated using the data presented by Broecker *et al.* [1991a]) is 18‰, which corresponds to a mean residence time of 161 years. However, when the post-Maunder-minimum decrease of atmospheric  $\Delta^{14}\text{C}$  [Stuiver and Quay, 1981] is taken into account, this time has to be increased by 10-15% [Broecker *et al.*, 1991b] to about 180 years. The total ventilation rate required to flush the deep Atlantic below 2000 m once every 180 years is about 22 Sv (see Table 2b). Most estimates of the contribution of AABW to this total range from 4 to 7 Sv [Rintoul, 1991; Schmitz and McCartney, 1993]. Hence the distribution of radiocarbon in the Atlantic sends us a similar message as for the entire deep ocean; the production rate of NADW is between 15 and 18 Sv.



### 3.3. "Remainder" (Entire Deep Ocean Outside the Atlantic)

The consideration of the remainder of the deep sea may appear redundant; in a sense it is inherent in the previous calculations. But there is one aspect which remains to be explored: What fraction of the deep water generated in the north Atlantic is exported to the circumpolar current, and what fraction recirculates within the Atlantic? This is an important consideration because our estimate of deep water production rate in the Weddell Sea obtained using the distribution of  $\text{PO}_4^*$  is actually matched to the flux of NADW around the tip of Africa (i.e., to the export flux rather than production flux).

**Figure 5.** Contours illustrate the dependence of  $\text{PO}_4^*$  on the concentrations of phosphate and dissolved oxygen in newly formed deep water. As shown, the maximum achievable  $\text{PO}_4^*$  value in the Southern Ocean is about  $2.3 \mu\text{mol/kg}$ . This value would require that the surface water be saturated in oxygen at its freezing point and have an amount of phosphate equal to that in ambient deep water. Deep water formed in the Weddell Sea has about 93% of the  $\text{PO}_4$  content in ambient deep water and about 86% of the dissolved oxygen content of saturated surface water at the freezing point of seawater. As shown in Figure 5, surface waters with  $\text{PO}_4^*$  values higher than  $2.0 \mu\text{mol/kg}$  have rarely been observed.

**Table 1.** Values Used in Radiocarbon Calculations

	Values
$\Delta^{14}\text{C}$ for particulate matter <sup>a</sup>	-70‰
$\Delta^{14}\text{C}$ for newly formed NADW	-67‰
$\Delta^{14}\text{C}$ for Weddell Sea surface waters <sup>b</sup>	-140‰
$\Delta^{14}\text{C}$ for entire deep sea (mean deep seawater)	-177‰
$\Delta^{14}\text{C}$ difference between NADW and mean deep seawater	110‰
$\Delta^{14}\text{C}$ difference between Weddell Sea surface waters and mean deep seawater	37‰
$\Delta^{14}\text{C}/\text{C}$ excess for newly formed NADW	$(0.933-0.823) \times (1.18 \times 10^{-12})$
$\Delta^{14}\text{C}$ of NADW at the tip of Africa	-87‰
$\Delta^{14}\text{C}$ of "mix" in circumpolar current	-114‰
$\Delta^{14}\text{C}$ for deep sea outside the Atlantic	-193‰
$\Delta^{14}\text{C}$ excess for input water	79‰
$\Sigma\text{CO}_2$ in the north Atlantic	2.2 m mmol/kg
$\Sigma\text{CO}_2$ for entire deep sea	2.3 m mmol/kg
Area of entire ocean at 2000 m	$3.2 \times 10^{14} \text{ m}^3$
Particulate flux	$0.5 \text{ mol/m}^2\text{yr}^{-1}$
Mean lifetime of $^{14}\text{C}$	8266 years
Number of $^{14}\text{C}$ moles added to the deep sea each year by particulates <sup>c</sup>	20
Number of $^{14}\text{C}$ moles added to deep sea outside the Atlantic each year by particulates	15

For this table,  $\Delta^{14}\text{C}$  values were obtained using the Hamburg model to obtain volume-weighted averages of the radiocarbon measurements made as a part of the Geochemical Ocean Sections Study (GEOSECS), South Atlantic Ventilation Experiment (SAVE), Transient Tracers in the Ocean (TTO) and World Ocean Circulation Experiment (WOCE) programs. NADW is North Atlantic Deep Water.

<sup>a</sup> About  $1.6 \times 10^{14}$  mol of carbon reach the deep sea each year in particulate form [Broecker and Peng, 1982]. This particulate matter is assumed to consist of equal amounts of  $\text{CaCO}_3$  ( $\Delta^{14}\text{C} = -50\text{‰}$ ) and organic material ( $\Delta^{14}\text{C} = -90\text{‰}$ ). This difference in  $\Delta^{14}\text{C}$  values is due to photosynthetic fractionation.

<sup>b</sup> The  $^{14}\text{C}$  value we have assigned to surface waters in the Weddell Sea is not as tightly constrained as the other  $\Delta^{14}\text{C}$  values in this table. Recent work by Berkman and Forman [1996] suggests a  $\Delta^{14}\text{C}$  value of -150‰ for Antarctic surface waters. This difference of 10‰ will change our flux estimates for NADW by < 1 Sv.

<sup>c</sup> The number of  $^{14}\text{C}$  mol added to the deep sea each year as particulate rain =  $(1.6 \times 10^{14}) \times (\Delta^{14}\text{C}/\text{C})_{\text{excess}}$ .

**Table 2a.** Radiocarbon-Based Ventilation Rate Estimates for the Entire Deep Sea

Depth Limit m	Mean $\Delta^{14}\text{C}$ , ‰	Volume, $10^{15}\text{m}^3$	$^{14}\text{C}$ resupplied, <sup>a</sup> mol/yr	$^{14}\text{C}$ Supplied by NADW plus Southern Ocean Ventilated Water, mol/yr	$^{14}\text{C}$ supplied by NADW, <sup>b</sup> mol/yr	Flux of NADW, <sup>c</sup> Sv
2192	-178	662	179	159	120	13
1879	-177	767	207	187	140	16
1605	-176	861	233	213	160	18

<sup>a</sup> The number of radiocarbon moles in the entire deep sea =  $(\Sigma\text{CO}_2) \times (1.18 \times 10^{-12}) \times (\text{volume}) \times (1 + \Delta^{14}\text{C})$ . The number of moles decaying each year = number of moles in the deep sea/mean lifetime.

<sup>b</sup> NADW is assumed to supply 3 times the number of moles supplied by Southern Ocean ventilated water (see text).

<sup>c</sup> Flux of NADW = (number of moles supplied by NADW) /  $(\Sigma\text{CO}_2) \times (^{14}\text{C}/\text{C})_{\text{excess}}$ .

**Table 2b.** Radiocarbon-Based Ventilation Rate Estimates for the Deep Atlantic

Depth Limit, m	Volume, <sup>a</sup> $10^{15}\text{m}^3$	Deep Water Flux, <sup>b</sup> Sv	NADW Flux, <sup>c</sup> Sv
2192	116	20	15
1879	136	24	19
1605	154	27	22

<sup>a</sup> The southern cutoff of the deep Atlantic is taken to be 30°S.

<sup>b</sup> Flux required to flush the deep Atlantic every 180 years = volume/ventilation time.

<sup>c</sup> The northward flux of AABW is taken to be 5 Sv (see text).

**Table 2c.** Radiocarbon-Based Ventilation Rate Estimates for the Deep Sea Minus the Atlantic

Depth Limit, m	Volume, $10^{15}\text{m}^3$	Total Flux, <sup>a</sup> Sv	Flux of NADW, <sup>b</sup> Sv
2192	546	27	13.5
1879	631	31	15.5
1605	706	34	17

<sup>a</sup> Total flux = (volume of deep sea minus Atlantic) / (age difference between "mix" and mean deep sea outside the Atlantic).

<sup>b</sup> Passing around the tip of Africa into the deep circumpolar current.

It was shown in the previous section that the flux of NADW around the tip of Africa and the production rate of Southern Ocean ventilated water must be about equal. This third approach enables us to determine whether or not recirculation of waters within the Atlantic basin is important. The flux of NADW as it rounds the tip of Africa is estimated by calculating the age difference between the "mix" of these two end-members and the deep ocean minus the Atlantic. Assuming a mean residence time of 180 years for water in the deep Atlantic [Broecker et al., 1991b] leads to the conclusion that "pure" NADW has a  $\Delta^{14}\text{C}$  value of about -87‰ by the time it rounds the tip of Africa. We take the  $\Delta^{14}\text{C}$  value of surface waters in the Weddell Sea to be -140‰; hence the  $\Delta^{14}\text{C}$  for the mix is -114‰, as summarized in Table 1. It should be noted that because of the entrainment of waters entering the South Atlantic from the circumpolar region the actual  $\Delta^{14}\text{C}$  value for the mix is closer to -125‰. But, as it is the NADW contribution we are after, we exclude the contribution from this recirculated Southern Ocean water. Taking the average  $\Delta^{14}\text{C}$  of deep waters outside the Atlantic to be -193‰, the mix has a 79‰ higher  $^{14}\text{C}/\text{C}$  ratio. This requires a total flux of about

30 Sv (15 Sv from NADW and 15 Sv from Southern Ocean surface waters). We conclude from this that the radiocarbon budget appears to require that a major fraction of the deep water formed in the northern Atlantic makes its way around Africa into the circumpolar current.

In the first and third of these approaches we have neglected the contribution of intermediate waters to the deep water radiocarbon inventory. Because of its uniformity with depth in the Pacific and Indian Oceans it is not possible to use  $\text{PO}_4^*$  to gauge the extent of intermediate water contribution to the deep ocean pool (Figure 7). Rather, we turn to salinity. The relationship between salinity and  $\text{PO}_4^*$  suggests that this contribution averages about 30%. However, because the  $\Delta^{14}\text{C}$  value of the intermediate water is close to that for ventilated surface waters in the Weddell Sea (Table 3), the impact of mixing with intermediate waters on the deep sea radiocarbon budget is much smaller than the volumetric contribution. In order to account for the effect of downward mixing of intermediate waters, NADW and Southern Ocean ventilated water flux estimates by the first and third methods should be reduced by about 10%.

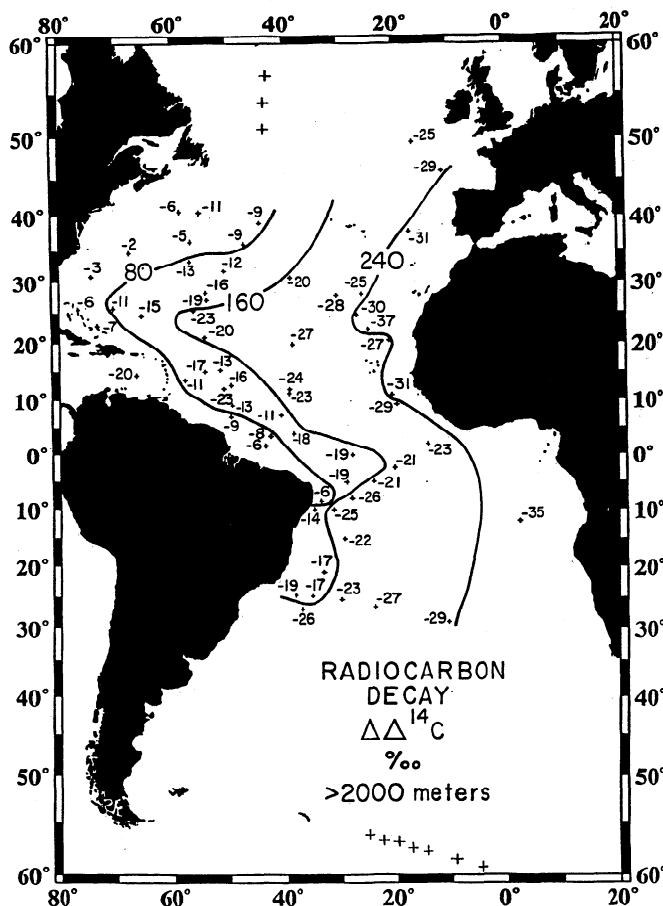


Figure 6. Map showing the average deficiencies of  $^{14}\text{C}$  created by radioactive decay in the Atlantic Ocean at depths > 2 km. These deficiencies were obtained using  $\text{PO}_4^*$  to separate the contributions of northern and southern end-member water [Broecker et al., 1991a].

4. Chlorofluorocarbons

A check on the above deep water production estimate can be obtained from the inventory of chlorofluorocarbons (CFCs) in the deep Southern Ocean. New deep waters descending into the abyss carry with them CFC-11 and CFC-12 concentrations acquired from the atmosphere through surface water gas exchange. Further, on the timescale of this anthropogenic invasion few of the CFCs are returned to the atmosphere or exported northward from the circumpolar current; hence it is safe to assume that they remain in the deep water column south of  $45^\circ\text{S}$  at depths > 1000 m and  $\sigma_\theta > 27.7$ . Taking this volume to be  $1.67 \times 10^{17}\text{m}^3$  (~12% of the world ocean), then for a ventilation rate of 15 Sv as of 1990 and an assumed surface water concentration equal to 70% of the saturation value, the mean CFC-11 concentration in this volume would be 3.0% of the saturation surface value at that time.

Because of the spatial and temporal sparsity of CFC observations (Figure 8) it is not possible to calculate directly the mean CFC saturation level for the deep waters around Antarctica. Therefore we were forced to follow a less direct path. First, using the 22-layer version of the Hamburg large-scale geostrophic ocean general circulation model (LSG OGCM) [Maier-Reimer et al., 1993], we simulated the CFC uptake process. We obtained for 1990 an average concentration of 4.1% of the saturation value for the waters south of  $45^\circ\text{S}$ , below 1000 m and with  $\sigma_\theta > 27.7$ .

The next step was to compare section by section (see Figure 8) the simulated CFC inventory with observations. As shown in Figure 9, the model yields inventories ranging from 0.2 to 8 times the observed section means for deep water. When taken together, the model yields a value 30% lower than the observed inventory for the aggregate of the Atlantic sections and 120% higher than the observed values for the Pacific. As no CFC data are yet available for the Indian Ocean sector of the Southern Ocean, we are forced to assume that its inventory lies in between those for the Atlantic and Pacific sectors. The model then yields 1.6 times more CFC than is observed. Correcting for this overestimate, we

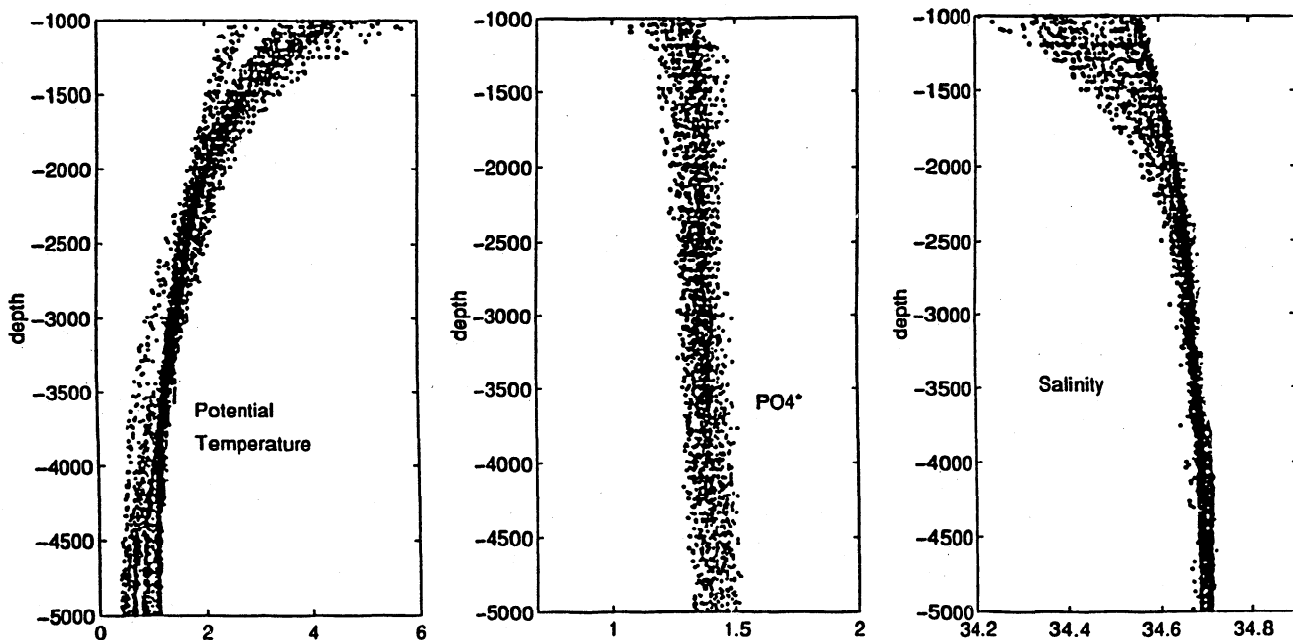


Figure 7. Plots of GEOSSECS data from the Pacific Ocean, to illustrate the uniformity of  $\text{PO}_4^*$  in waters below 1000 m depth, and the larger range in potential temperature and salinity (see also table 3). It is because of this remarkable uniformity with depth that  $\text{PO}_4^*$  can be used to separate the relative contributions of northern and southern component water; when considering the deep salinity and potential temperature budgets, the downward mixing of intermediate waters must also be taken into account.



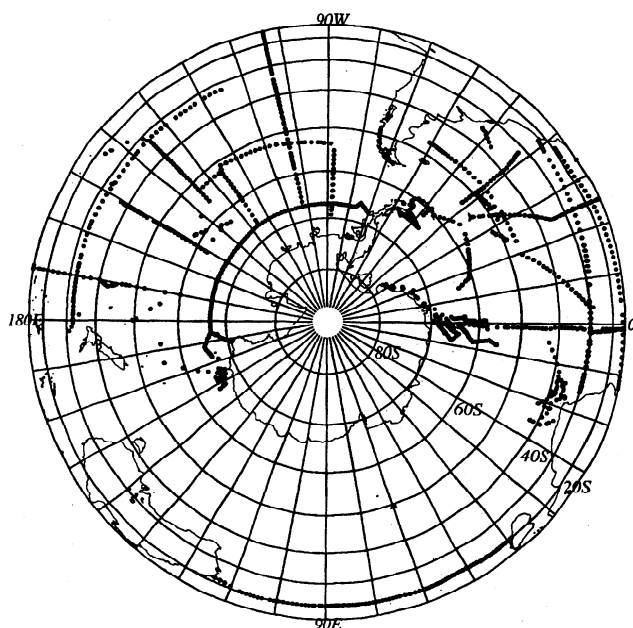
**Table 3.** Composition of Intermediate Waters of Southern Origin

GEOSECS Station Number	Latitude, °S	$\theta$ , °C	$S$ , ‰	Depth, m	SiO <sub>2</sub> , μmol/kg	PO <sub>4</sub> <sup>*</sup> , μmol/kg	Δ <sup>14</sup> C, ‰
<i>Atlantic</i>							
60	33	2.7	34.47	1386	52	1.45	-134
93	42	3.0	34.51	1293	62	1.45	-138
<i>Pacific</i>							
303	38	3.8	34.25	1348	53	1.40	-143
322	43	2.9	34.44	1403	59	1.40	-143
<i>Indian</i>							
428	38	3.1	34.47	1418	54	1.37	-131
435	39	3.1	34.45	1369	59	1.45	-144

Here  $\theta$  is potential temperature and  $S$  is salinity.

can use the model results to estimate the overall inventory of CFCs in the deep Southern Ocean. The result is 2.6% of the surface saturation concentration. This value is 0.85 times the one-box model value mentioned above, suggesting a ventilation flux of 13 Sv.

We are the first to admit that this CFC-based estimate is subject to a large error. It is known that ocean model calculations of deep water CFC concentrations are inherently sensitive to a number of factors, including the assumed degree of surface water CFC saturation [cf. England *et al.*, 1994]. Under partial sea ice cover it is known that some regions of the ocean are undersaturated by as much as 40% [Schlosser *et al.*, 1991]. It is especially important to recognize that because of grid spacing limitations in the model the local shelf edge and subsurface mixing processes which are believed to be responsible for the bulk of deep water formation in the Weddell Sea [e.g., Foster *et al.*, 1987] cannot be correctly simulated. Instead, the model parameterizes this process as if it were open ocean convection occurring over a much wider geographic area.

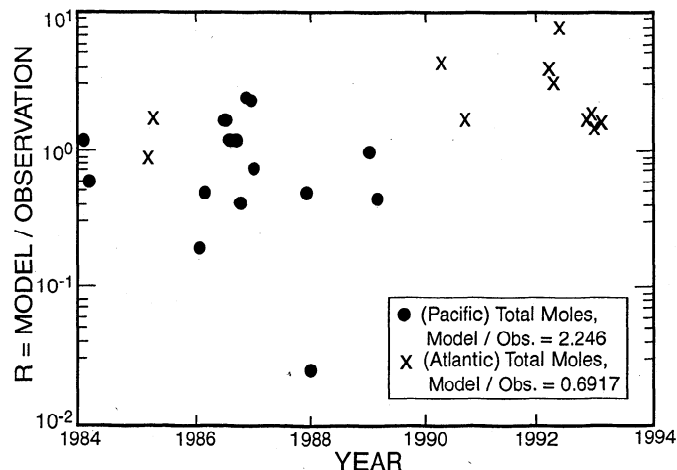


**Figure 8.** Map showing the locations of the stations for which data was available for use in calculating the CFC inventory in the deep Antarctic.

However, despite the large uncertainty associated with the our CFC-based ventilation estimate, the above result does appear to rule out the ventilation rate estimates of a few sverdrups suggested for the Weddell Sea as typifying the entire Southern Ocean. Clearly, when a more complete picture of the CFC distribution in the Antarctic becomes available, it will be possible to greatly narrow the uncertainty in the estimate of the mean deep ventilation rate for the last decade.

## 5. Discussion

Our result presents an enigma when compared with previous studies employing transient tracers, which suggest that the production rate of ventilated deep water in the Weddell Sea alone does not exceed 5 Sv. If the comparatively low values of between 2 and 5 Sv for the production rate of ventilated water in the Weddell Sea are correct, then the remainder (at least 10 Sv) must be supplied by deep water production at other locations in the Southern Ocean. One possibility is that there be a significant addition of deep water from the Ross Sea into the Pacific sector. While surface waters in this region have PO<sub>4</sub><sup>\*</sup> values as high as those in the Weddell Sea, the average PO<sub>4</sub><sup>\*</sup> value for waters below 1500 m at 67°S in the Pacific sector is only 1.51 μmol/kg. But as these waters have a lower silica content (~112 μmol/kg) than ambient circumpolar deep water (~125 μmol/kg), they must

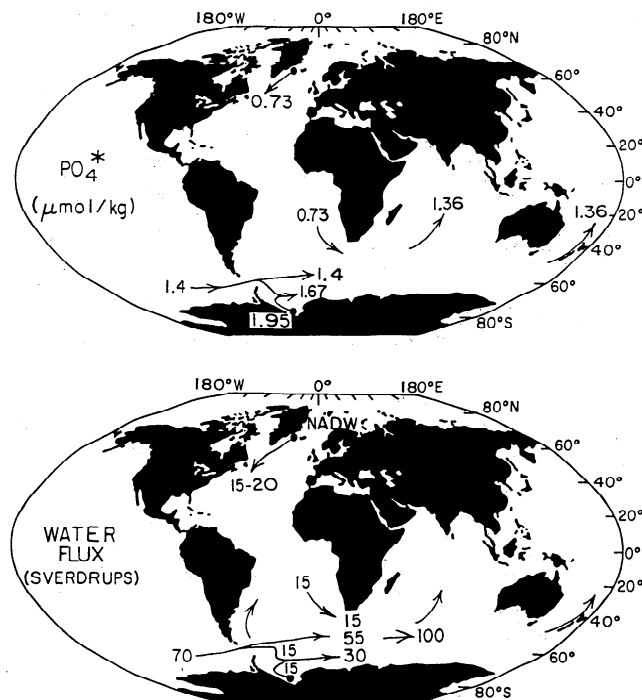


**Figure 9.** Plot of the ratio of the CFC inventory obtained using the Hamburg model to the observed inventory along each of the sections shown in Figure 8.

contain a component of ventilated deep water produced in the Pacific sector of the Southern Ocean. The high  $\text{PO}_4^*$  values generated in southernmost deep waters by output from the Weddell Sea persist only through the Indian Ocean. They appear to have been largely mixed into the ambient circumpolar deep water by the time the Pacific sector is reached. If major additions of new deep water are added in the Pacific sector, they must have  $\text{PO}_4^*$  values similar to those in ambient circumpolar deep water. Further, if there are deep waters produced in the Southern Ocean with a value comparable to the ambient for circumpolar deep water then, in order to account for the deep Pacific and Indian  $\text{PO}_4^*$  values, a Southern Ocean deep water production rate substantially higher than our estimate would be required.

Alternatively, the bulk of the estimated 15 Sv may indeed be produced in and exported from the Weddell Sea. Perhaps the methods used to estimate the current production capture only a fraction of the total ventilated deep water flux. Previous estimates of the ventilation of the ocean by the formation of Weddell Sea Bottom Water (WSBW) were based on the assumption that it is entrained into Weddell Sea Deep Water (WSDW), which is shallow enough to leave the Weddell basin. However, other water masses can leave the Weddell embayment and feed into the CDW. *Whitworth et al.* [1994] point out that shelf water from the northwestern Weddell Sea feeds into the Weddell-Scotia Confluence, from where it can be entrained into CDW. WSDW with a high contribution of freshly ventilated shelf water most probably leaves the Weddell Sea at a depth shallower than 2000 m through the Powell basin, as this layer is skimmed off between the northern tip of the Antarctic Peninsula and the southern slope of the South Orkney Islands [*Fahrbach et al.*, 1995]. That deep water was forming in the southwestern Weddell Sea is evident in data obtained during the *Polarstern* cruises in 1992 and 1996, which hint at an inflow of recently ventilated water into the Weddell Sea from the east. Deep water formation has also been recently reported by *Foster* [1995] at Wilkes Land and by *Park et al.* [1993] off Adelie coast. However, these scenarios are not able to fully account for the difference between this and previous ventilated deep water flux estimates.

Another way to explain the discrepancy would be to propose that the deep water production in the Southern Ocean over the past two decades has been much smaller than that averaged over the last several hundred years and that the present conditions are non-steady-state. Repeated hydrographic sections and moored instruments in the Weddell Sea have revealed a continuous increase in the temperature of bottom waters between 1990 and 1995 of about  $0.01^\circ\text{K/yr}$  (*E. Fahrbach et al.*, manuscript in preparation, 1996). This correlates with an increase of the Warm Deep Water (WDW) temperature at the Greenwich Meridian of up to  $0.5^\circ\text{K}$  between 1984 and 1992. Despite the short duration of available time series, they suggest that there may be variations in the formation rate of bottom waters. A possible mechanism suggested by *O. Nost et al.* (manuscript in preparation, 1996) is that huge stranded icebergs on the Berkner shelf may have inhibited the formation of a polynya off the Filchner depression since the late 1980s. The polynya is thought to be necessary to produce the high-salinity shelf water, which in turn is required to induce the outflow of ice shelf water from the Filchner depression. However, the available CFC data for deep waters in the Southern Ocean suggest that the production rate of ventilated deep water in the Southern Ocean over the last two decades is not atypical of the long-term average; the deep water CFC inventory appears to be consistent with a ventilation rate of about 15 Sv.



**Figure 10.** One scenario showing the  $\text{PO}_4^*$  values and fluxes for waters ventilating the deep sea. Note that the flow around the tip of Africa does not include the contribution of waters of southern origin entrained into the southward flowing NADW. Rather, the  $\text{PO}_4^*$  and water flux values are for the pure NADW component of this mixture. Also note that in this scenario all the Southern Ocean ventilated water is assumed to form in the Weddell Sea. As discussed in the text, this assumption may well not hold. Rather, a sizable fraction of the water ventilating the deep Southern Ocean may be produced in other sectors of the perimeter of the Antarctic continent.

Our approach to the problem of assessing the importance of the Southern Ocean ventilated water contribution to the global pool has differed from previous methods. By assigning an average  $\text{PO}_4^*$  value to the surface waters around the Antarctic perimeter, it has been possible to assess the relative contributions of NADW exiting the Atlantic and Southern Ocean ventilated water to the world's deep oceans. It should be noted that the surface water in the Weddell Sea which eventually makes its way into the global deep ocean is believed to entrain a substantial amount of intermediate and deep water [e.g., *Carmack and Foster*, 1975]. We recognize that if the commonly accepted surface:deep ratio of 1:3 is correct, then the total outflow of deep waters (newly ventilated plus entrained) from the Southern Ocean will be significantly greater than our estimate of the contribution of Southern Ocean ventilated water.

## 6. Conclusions

Our analysis of the  $\text{PO}_4^*$  data for the ocean deep waters and their sources suggests that the amount of deep water produced in the North Atlantic, which makes it around the southern tip of Africa to join the circumpolar current, is roughly equal to the amount of ventilated deep water produced along the margins of Antarctica or in Southern Ocean polynyas. The deep sea radiocarbon budget indicates that in order to resupply the radiocarbon

moles decaying in the deep sea each year, about 15 Sv of NADW are required. Thus the combined use of  $\text{PO}_4^*$  and radiocarbon distributions leads to the conclusion that if the ocean is in steady state, about 15 Sv of recently ventilated waters from around the Antarctic perimeter must join the circumpolar current (see Figure 10) and subsequently enter the deep Pacific and Indian Oceans.

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