Broecker Brief

What fraction of the ocean's deep water is formed in the Northern Atlantic?

Synte Peacock, Martin Visbeck and I published papers claiming that the deep Pacific and Indian Oceans received about half of their water from the northern Atlantic. More recently Gebbie and Huybers and Khatiwala and Primeau published papers suggesting that only about one quarter of this water came from the northern Atlantic. Why the large difference?

My read is that B-P-V assumed that the dominant mode of Southern Ocean ventilation is advective and that it takes place along the margin of the Antarctic continent and in polynyas formed in the winter sea ice surrounding Antarctica. In contrast, G-H and K-P assume that ventilation occurs primarily along isopycnal horizons which outcrop in the Southern Ocean. As the areas of the G-H and K-P Southern Ocean surface boxes are far larger than the areas from which direct advection occurs, these authors exclude our advective contribution.

B-P-V assume that the advective component has a PO_4^* of 1.95. We obtained this value both by extrapolating the PO_4^* - Θ relationship to the freezing point of sea water (Figure 1) and from direct observations in the Weddell and Ross Seas (Figure 2). The 1.95 PO_4^* value is that expected for water upwelling in the Southern Ocean if when cooled to the freezing point about 65 percent O_2 replenishment occurs and if little of its PO_4 is consumed (see Table 1).

Using the 1.95 value to characterize the southern component, and 0.73 to characterize the northern component, a 55 – 45 mix has a PO_4^* value of 1.4. This is the value observed in the water deeper than 1.5 km in Pacific and Indian Oceans and also for the deep water passing through the deep Drake Passage.

It is important to note that there are no waters in the interior of the deep Southern Ocean which have PO_4^* values greater than about 1.7 (see Figure 3). If this value were assigned to the water ventilating the Southern Ocean, then a 70-30 mixture of southern and northern component would be required ($0.3 x 0.73+0.7 x 1.70 \cong 1.4$). The dependence of this fraction on the choice of the PO_4^* value characterizing is shown in Figure 4.

In a sense the choice of the PO_4^* value for deep water produced in the Southern Ocean is the basis for difference between B-P-V on one hand and G-H and K-P on the other. Of course G-H and K-P do not base their analysis on PO_4^*. Rather, they employ a wide range of properties and include additional source waters. As their result is based on a complex deconvolution, it is difficult to come to grips with it. A more transparent means of establishing the relative contribution of these two sources is needed. This is why I turn to PO_4^*.

In the past I have suggested that the radiocarbon budget of the deep sea be used to constrain the ventilation flux from the Southern Ocean (see Table 2 for sample budget). Of the 220 moles per year of ^{14}C undergoing radiodecay in the deep sea, about 20 moles/yr are resupplied by particle rain. At 16 Sverdrups NADW supplies about 130 moles/yr. This leaves about 70 to be supplied from the Southern Ocean. The problem is that there is a large uncertainty in the small differences between the ^{14}C to C ratio in mean deep water and that in the water supplied by ventilation in the Southern Ocean. This problem becomes even larger when the uncertainty in the flux of NADW is taken into account. Were it 19 Sverdrups instead of 16, the NADW would supply 155 moles ^{14}C per year leaving only 35 for the Southern Ocean. An example budget is shown in Table 2. Although these uncertainties can perhaps be reduced, the existence of the H-bomb ^{14}C overlay will remain a major source of uncertainty.

Another approach is to use the inventory of CFCs in the Southern Ocean to constrain the rate of ventilation. As I remember, the result was quite small, only about 6 Sverdrups. If the northern Atlantic supplies only one quarter of the water ventilating the Indian and Pacific Ocean, then the Southern Ocean must account for most of the rest. This would mean that about 45 Sverdrups of deep water would have to be produced in the Southern Ocean. On the other hand, if half the deep water ventilating the deep sea was produced in the northern Atlantic, then the required Southern Ocean flux would be reduced to more like 20 Sverdrups. In either case, the CFC-based estimate falls far short.

So how do we go about narrowing this very large range in Southern Ocean ventilation rates?

Table 1. Expected PO_4^*

Upwelled PO_4 = 2.2 μmol/kg

Upwelled O_2 = 210 μmol/kg

Saturation O_2 = 360 μmol/kg

Assume

1) No PO_4 utilization
2) 65% O_2 resaturation

Then

$$PO_4^* = 2.2 + \frac{0.65\ (360-210)+210}{175} - 1.95 = 1.95\ \mu\text{mol/kg}$$

Table 2. Example ^{14}C budget for the deep ocean.

Loss via Radiodecay	
Volume of deep sea	$8 \times 10^{17} m^3$
Mean ΣCO_2	2.3 moles/m^3
Mean $\Delta^{14}C$	-175‰
Mean $^{14}C/C$	1.0×10^{-12}
Amount of ^{14}C in deep sea	1.8×10^{6} moles
Amount decaying	220 moles/yr
Gain of Radiocarbon from North Atlantic	
Flux	16 Sverdrups
Flux	$6 \times 10^{14} m^3/yr$
ΣCO_2	2.1 moles/m^3
$\Delta^{14}C$	-67‰
$^{14}C/C$-$^{14}C/C$ mean deep sea	0.13×10^{-12}
Input ^{14}C to deep sea	130 moles/yr
Gain of Radiocarbon from Southern Ocean	
Flux	45 Sverdrups
Flux	$17 \times 10^{14} m^3 yr$
ΣCO_2	2.2 moles/yr
$\Delta^{14}C$	-154‰
$^{14}C/C$-$^{14}C/C$ mean deep sea	0.025×10^{-12} ??
Input ^{14}C to deep sea	70 moles/yr
Gain of Radiocarbon by Particle Flux	
Carbon flux	0.5 moles/m^2yr
$\Delta^{14}C$	-70‰
$^{14}C/C$-$^{14}C/C$ mean deep sea	0.126×10^{-12}
Input ^{14}C to deep sea	20 moles/yr
Total Gain of Radiocarbon	220 moles/yr

Fraction NADW = $\frac{16}{45+16}\ x\ 100 = 26‰$

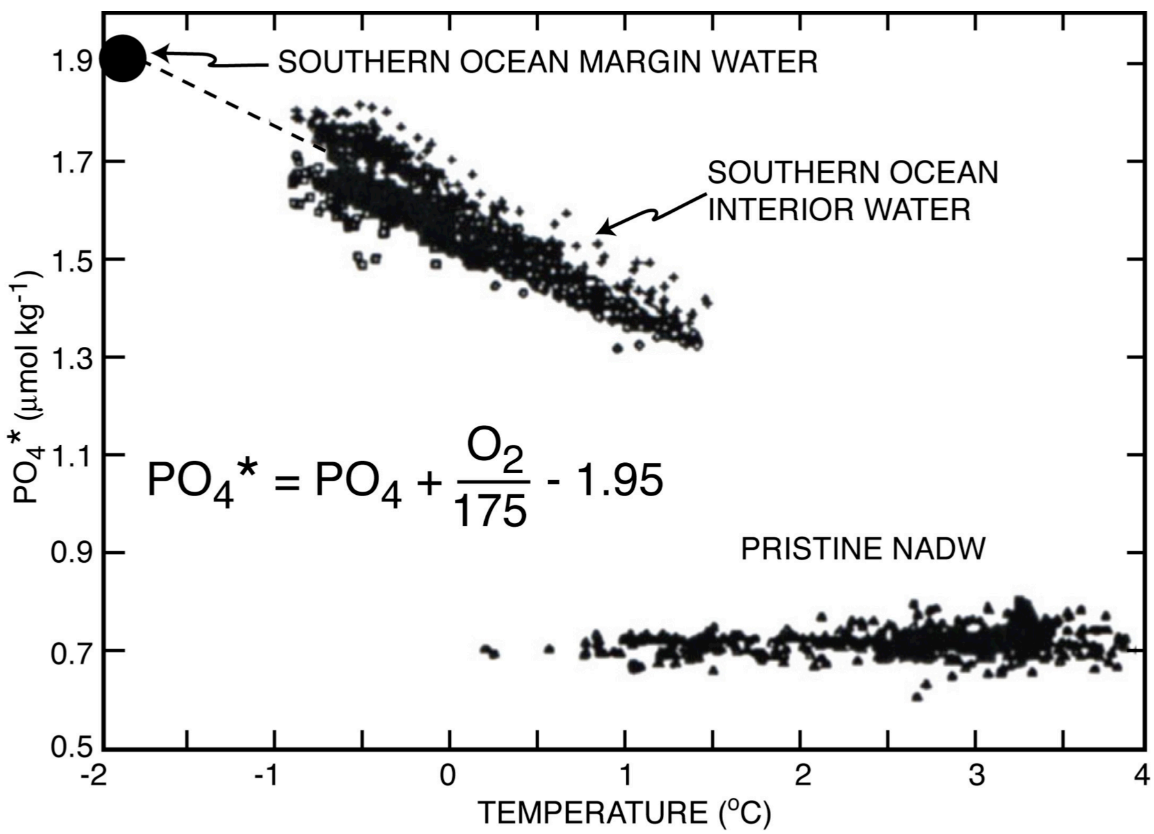

Figure 1. Plots of PO_4^* versus potential temperature for various brands of deep water formed in the northern Atlantic and in the Southern Ocean (based on measurements made as part of the GEOSECS expeditions). Note that all contributors of NADW have PO_4^* value within the measurement error of 0.73 μmol/kg. The Southern Ocean PO_4^* is obtained by extrapolating the observed PO_4^* - temperature trend to sea water's freezing point. As shown in Figure 2, this extrapolated value is consistent with that observed in Weddell and Ross Sea surface waters.

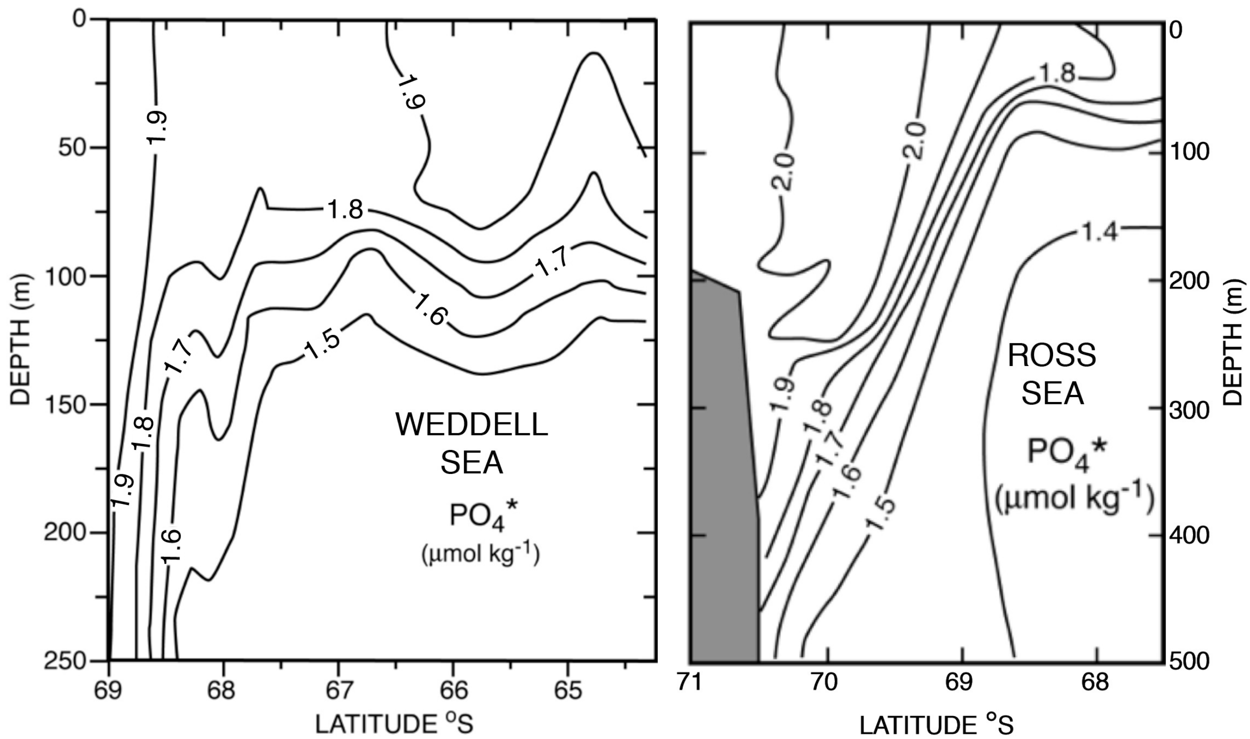

Figure 2. PO_4^* sections extending out from the Antarctic continent for the Weddell and Ross Seas. As can be seen, water with a value of 1.95 is descending in a narrow margin-hugging plume.

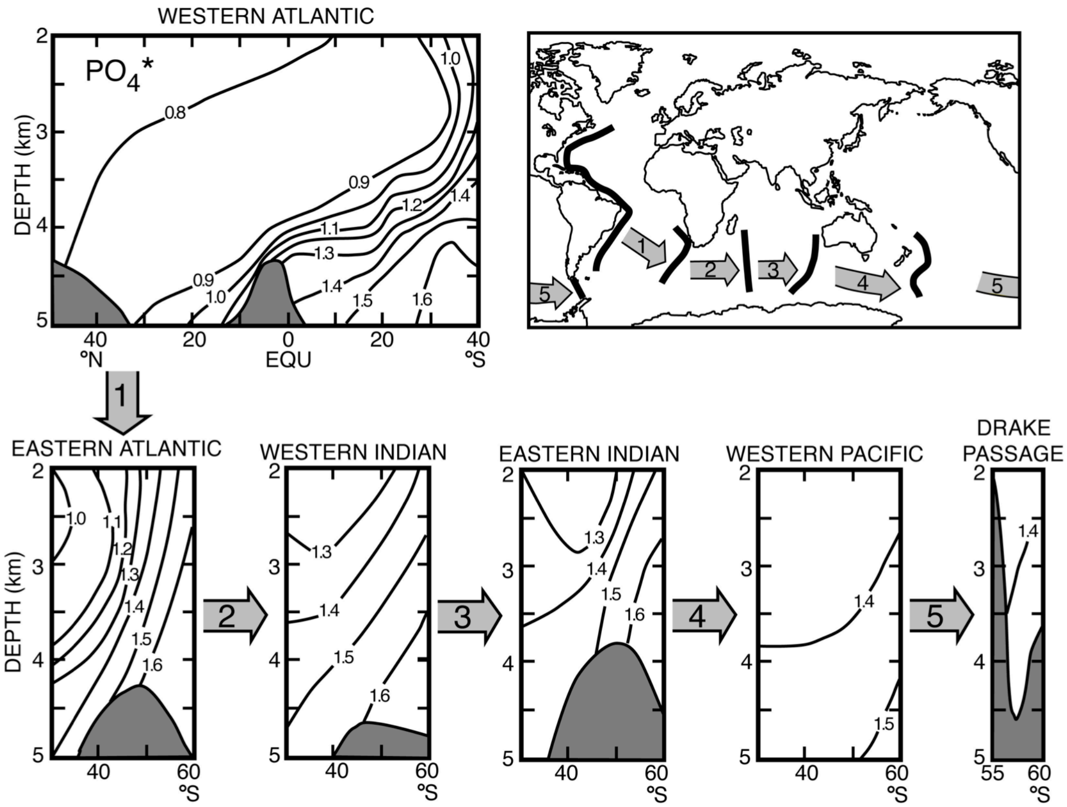

Figure 3. PO_4^* sections for the western Atlantic and for a series of quadrants of the Southern Ocean. The PO_4^* values for the interiors of the deep Pacific and Indian Oceans are very uniform at close to 1.4 μmol/kg. Note that the low PO_4^* waters entering the Southern Ocean from the Atlantic and the high PO_4^* waters generated in the Southern Ocean are blended by the time they reach the Drake Passage.

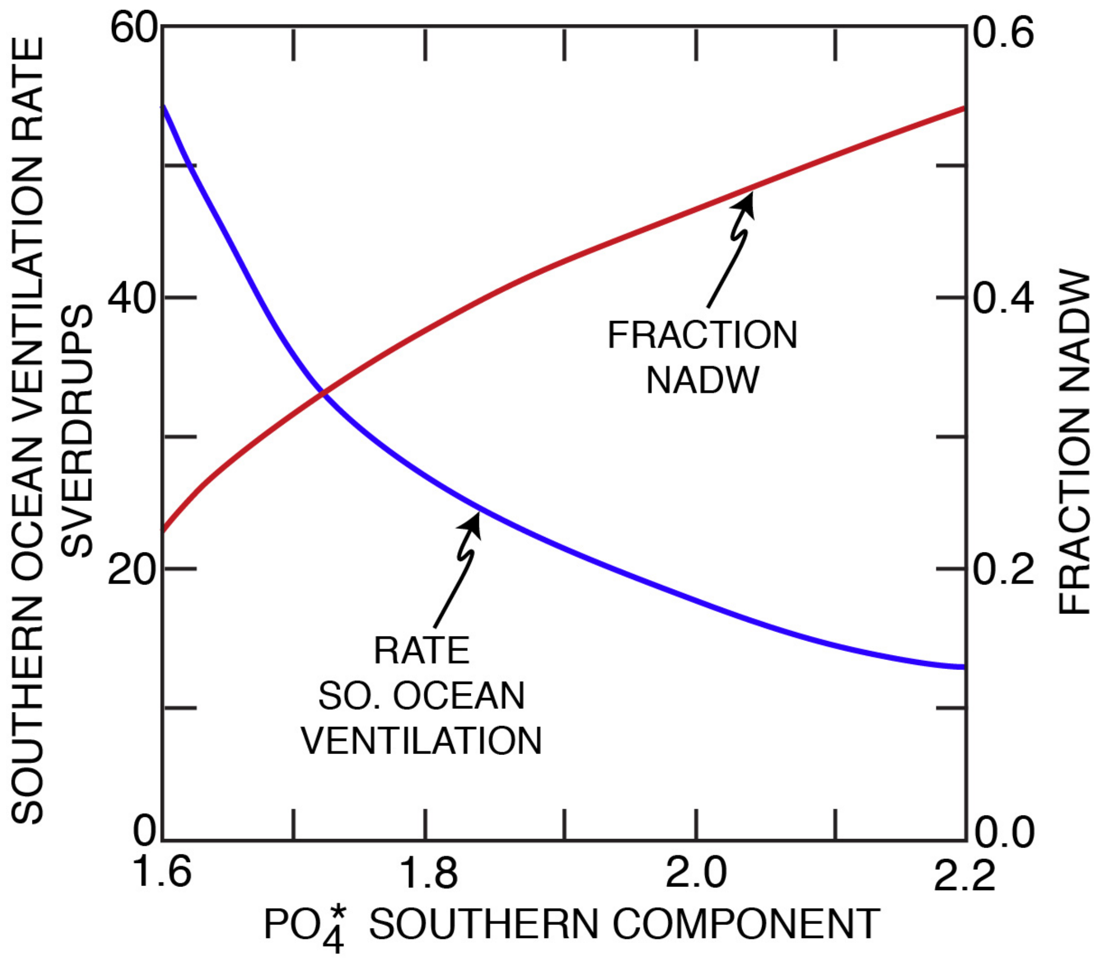

Figure 4. Rate of ventilation of the deep Southern Ocean as a function of the PO_4^* value for the source water. Also shown is the corresponding fraction of NADW in the water ventilating the deep Pacific and Indian Oceans.