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Interocean exchange of water masses

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Abstract. A new method for calculating water mass transport between different ocean basins from the velocity fields obtained by numerical models is presented. The method is applied to the velocity field of the Southern Ocean simulated by a primitive equation model (fine resolution Antarctic model). With this method it is possible to judge whether a water mass has been ventilated or not, to estimate how many times it has circled around Antarctica, and to calculate the time it has spent in the Southern Ocean. Calculations have also been undertaken revealing to what extent the changes of temperature, salinity, and density have been caused by mixing and by ventilation. Two major ways to redistribute the water through the Southern Ocean are identified. The first one redistributes 53% of the water and involves an unventilated direct exchange between the oceans, the second one redistributes 33% by going around Antarctica. It is found that, on average, the water mass makes six circuits before the water is ventilated and subsequently driven to the north by the Ekman transport. A heat transport study is carried out for the Atlantic, showing that the northward heat transport into the Atlantic comes 85% from the Indian Ocean and the rest from the Drake Passage.

1. Introduction

The three world oceans communicate with each other through the Southern Ocean, where the heat and the salt is redistributed between the oceans. A simplified view of this was illustrated by *Broecker* [1991], by the so-called conveyor belt, and by *Gordon* [1986]. These studies of the interocean exchange of the water masses in the Southern Ocean were based on looking at different water masses and their characteristics. The number of different water masses and the relatively strong mixing in the Antarctic Circumpolar Current make it almost an art to judge the origin of the water and to estimate their volume transport.

A debate has also developed about whether the northward heat transport into the Atlantic from the Southern Ocean comes from the Indian Ocean in the "warm water path" [*Gordon*, 1986] or from the Drake Passage in the "cold water path" [*Rintoul*, 1991]. *Gordon* [1986] argues that the global thermohaline cell (conveyor belt) associated with the North Atlantic Deep Water (NADW) formation is closed primarily by the warm water path: NADW leaving the Atlantic upwells uniformly into the thermocline of the Indian and Pacific Oceans. The water that upwells in the Pacific flows then through the Indonesian Sea and across the Indian Ocean and finally returns into the Atlantic in the Agulhas Current. *Gordon* estimates that the cold water path does not contribute more than 25% of the northward heat transport. The cold water path is found, on the other hand, by *Rintoul* [1991] to dominate completely the warm water path, with northward waters equally split between the surface layers and the intermediate and bottom water.

The traditional method in studying water masses, whether it has been with numerical models or observations, has been by defining them by their properties, in particular, by their temperature and salinity. In this study we will use a new method, which defines the water masses on water particle trajectories, instead of temperature and salinity. The great advantage with this method is that we can follow a water mass from one ocean to another, even when it changes properties. The trajectories are calculated from a velocity field. The velocity field as well as the temperature and salinity fields we use in this study have been obtained by a primitive equation model.

A short description of the primitive equation model is presented in section 2. A presentation of the method of how to calculate the volume transport with water particle trajectories is described in section 3. The volume transport between the oceans obtained with the method are presented in section 4. The heat transport into the Atlantic is calculated in section 5, followed by a discussion and summary in section 6.

2. Fine Resolution Antarctic Model

The velocity, temperature, and salinity fields that are used in this study come from the fine resolution antarctic model (FRAM). For a more complete description, see *FRAM Group* [1991]. The model is based on the Bryan-Cox-Semtner ocean model [*Bryan*, 1969; *Semtner*, 1974; *Cox*, 1984] and covers the Southern Ocean from 24°S to Antarctica at a resolution of 0.25° in the north-south direction and 0.5° in the east-west direction. The model was initialized as a cold (-2°C), saline (36.69‰), motionless fluid, and for the first 6 years of the model run the temperature and salinity fields were dynamically relaxed to the annual mean *Levitus* [1982] data. For the first 2 years and 160 days the relaxation time was 180 days in the top 140 m and 540 days in the deeper levels. From then to 6 years the relaxation time was 360 days throughout the model ocean. After 6 years, relaxation conditions for the temperature and salinity were retained in the surface layer to reflect the exchange of heat and fresh water with the atmosphere. An alternative method would have been mixed boundary conditions, where instead of a surface relaxation to the sea surface salinity, one imposes a surface flux of fresh water. But at the

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time of the run there were no available fresh water flux data close to Antarctica. The FRAM group therefore opted for a relaxation to the *Levitus* [1982] sea surface salinity and temperature.

During the first 2 years the model was run without any surface wind stress forcing. During the next 6 months the wind stress field was increased linearly to the *Hellerman and Rosenstein* [1983] annual mean wind stress field. This was then used until the end of the 6-year spin-up period. For the rest of the run the *Hellerman and Rosenstein* [1983] monthly wind stress field was used.

FRAM ran for a total period of 16 model years, of which the last 6 have been chosen for detailed analysis. Although the potential energy of the model dropped slightly during the analysis period, it otherwise appears to be in a statistically steady state, with a well-developed eddy field and regular seasonal variations.

During the analysis period (year 10 to 15), data from the model were archived at monthly intervals. The results presented in the paper are calculated by making a time average over the whole of this archived data.

3. Volume Transports With Water Particle Trajectories

Water particle trajectories have been calculated from the velocity field and the convective stability fields simulated by FRAM. Since the calculation of the trajectories are carried out on a time-independent velocity field, it is possible to find an exact solution of the trajectories to the time-averaged field. See appendix for details of the water particle trajectory calculation. Time-dependent calculations of trajectories used in other studies [e.g. *Böning and Cox*, 1988; S. Drijfhout, tracing the conveyor belt in the Hamburg L56 ocean general circulation model, submitted to *Journal of Geophysical Research*, 1994] present the obvious advantage of its time dependence but are much more time consuming. They are therefore not possible to use in the present study since we here need a considerable amount of trajectories in order to quantify the transports.

The water particles are introduced at the open boundary (25°S) of the model and followed until they leave the model domain. By following a water particle, it is, of course, not possible to say anything about the mass or volume transport. If two water particles enter the basin next to each other, they will eventually diverge, no matter how close they are when they enter. Nevertheless, if several water particles are let in close enough to each other, they should be able to indicate tendencies for different possible water routes. To test this, trajectories have been calculated for water particles let in at all the zonal-vertical grid boxes at the open northern boundary with southward velocities. We then presume the volume of the water particles is conserved during their travel all the way until they exit the Southern Ocean at the northern open boundary. We can test the credibility of this method by recalculating the northward velocity at the northern boundary where the water particles exit.

This is done by first calculating the volume transport in through the open boundary for each trajectory:

$$V_n = (v_{i,k}\, \Delta x \Delta z_K)/N$$

where $v_{i,k}$ is the meridional velocity at the northern boundary for the considered grid box, which has the zonal-vertical area $\Delta x \Delta z_K$, i denotes the discretized longitude and k the discretized depth, and N is the number of subboxes or trajectories introduced per grid box.

In this study we have set the number of subboxes to $N = 441$ at 20°S. The numerical model has a resolution of 720 zonal grids and 32 vertical levels (including land points). This would give a total amount of 10,160,640 (720 x 32 x 441) trajectories, but with land points excluded the number of trajectories is reduced to 5,569,141. The zonal distance is 2398 m between each trajectory and a vertical distance varying between 1 m at the surface of the ocean and 11 m at the bottom of the ocean.

In order to validate this method, it is possible to recalculate the meridional velocity at the northern boundary indirectly from the water particle trajectories, so that if the assumption that the sum over the number of trajectories from each model box conserves the transport, the recalculated meridional velocity should be the same as the meridional velocity directly obtained from FRAM. This recalculated northward velocity is obtained by summing up the volume transports from all the trajectories exiting the model domain through the same grid box:

$$\bar{v}_{i,k} = \sum_n (V_n / \Delta x \Delta z_K)$$

where n are the trajectories exiting through the i,k grid box. To get the southward velocity, we follow the water particles backward from the point they exit to the point where they enter. By comparing the original velocity $v_{i,k}$ with the recalculated velocity $\bar{v}_{i,k}$, it is possible to validate this method of calculating the volume transport with water particle trajectories.

Figure 1 shows a schematic illustration of a recalculation of the northward velocity from two water particle trajectories. All the zonal-vertical boxes are divided into 16 subboxes ($N = 16$), through which we have water particles entering if the box velocity is southward (i.e., out of the paper). To recalculate the northward velocity in the center box ($i = 2$, $k = 2$), we calculate the transport from the two trajectories and divide by the area of the center box ($\Delta x \Delta z_{k=2}$):

$$\bar{v}_{i=2,k=2} = -\frac{v_{i=1,k=1}\, \Delta x \Delta z_{k=1} + v_{i=3,k=3}\, \Delta x \Delta z_{k=3}}{N\, \Delta x \Delta z_{k=2}}$$

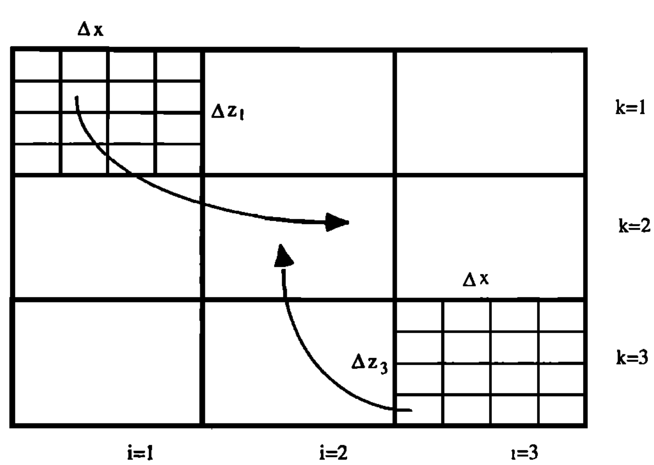


Figure 1. Schmetic illustration of two water particle trajectories entering the model domain through the meridional-vertical boundary and exiting through the same box, where the northward velocity can be recalculated.

This recalculated northward velocity ($\bar{v}_{i=2,k=2}$) can now be validated by comparing it with the actual velocity ($v_{i=2,k=2}$).

The recalculated meridional velocity $\bar{v}_{i,k}$ at the open boundary is presented in Figure 2a, and can be validated by comparing it with the original meridional velocity $v_{i,k}$ calculated by the numerical model shown in Figure 2b. The difference between the two velocity fields is presented in Figure 2c. The recalculated velocity compares very well everywhere except at the Indian and Atlantic western boundaries. The corresponding transport to these differences can be seen by calculating the water volume exchange between the three world oceans through the Southern Ocean (Figure 3). All the three oceans should have a net zero transport since the Bering Straight and the Indonesian Sea are both closed. The Pacific receives 1 Sv (1 Sv = 10^6m^3/s) too much, and the Indian Ocean exports 1 Sv more than it receives. This gives a measurement of the accuracy of the method compared with the FRAM data.

4. Interocean Water Transports

The interocean exchange of water in Figure 3 gives us only a very broad view. These interocean exchanges have been broken down into different paths, depending on how and where they go. Table 1 presents these different paths of all routes associated with a transport of more than 0.5 Sv. The distinction is made between water particles that go directly from one ocean to the other (dir) and those that go around Antarctica at least once (indir). A further distinction is made between routes where the water is ventilated (vent) and those where the water is not ventilated (unvent). A water particle is defined as ventilated if it reaches the surface layer at least once during its travel through the model domain.

The water masses do not follow isopycnals or isotherms and will therefore change temperature, salinity, and density depending on the paths of the water particle trajectories. The changes in temperature, salinity, and density can be due to air-sea interaction and to mixing. The unventilated routes are only due to mixing since the trajectories do not outcrop. The ventilated routes, on the other hand, change their properties also due to air-sea interaction.

Direct Unventilated Routes

The most important paths are those that carry water directly from one basin to the other without being ventilated. This accounts for 55% of the water mass exchange between the basins in the Southern Ocean. The water transport that does not contribute to the interocean water exchange (i.e., water going in and out through the open boundary in the same ocean) is even more dominated by the unventilated direct path (75%) which is mainly due to the strength of the subtropical gyres. Figure 4 shows a schematic illustration of these routes.

Typical trajectories for the most important routes are presented in Figures 5a - 5f. Figure 5a shows unventilated water going directly from the Atlantic into the Indian. With an average σ_0=27.6 kg/m^3 at the entry in the Atlantic at 25°S it is likely to represent some of the North Atlantic Deep Water. The transport is 4 Sv, and the water increases its density by 0.1 kg/m^3 due to cooling of 1.7°C. It is also interesting to notice that almost all the water exits the basin just to the east of Madagascar, whether it comes from the Brazil current, the mid-ocean ridge, or close to Africa.

Figure 5b shows unventilated water going directly from the Atlantic into the Pacific with a transport of 2 Sv. This water is lighter (σ_0=27.0 kg/m^3) than the water going into the Indian Ocean, but during their journey the water particles gain 0.3 kg/m^3. The gain in density is a result of the cooling of 4.9°C, despite the freshening of 0.6 practical salinity units (psu). This salinity change is present in all the paths between the Atlantic and the Pacific, which is due to the fresher water in the

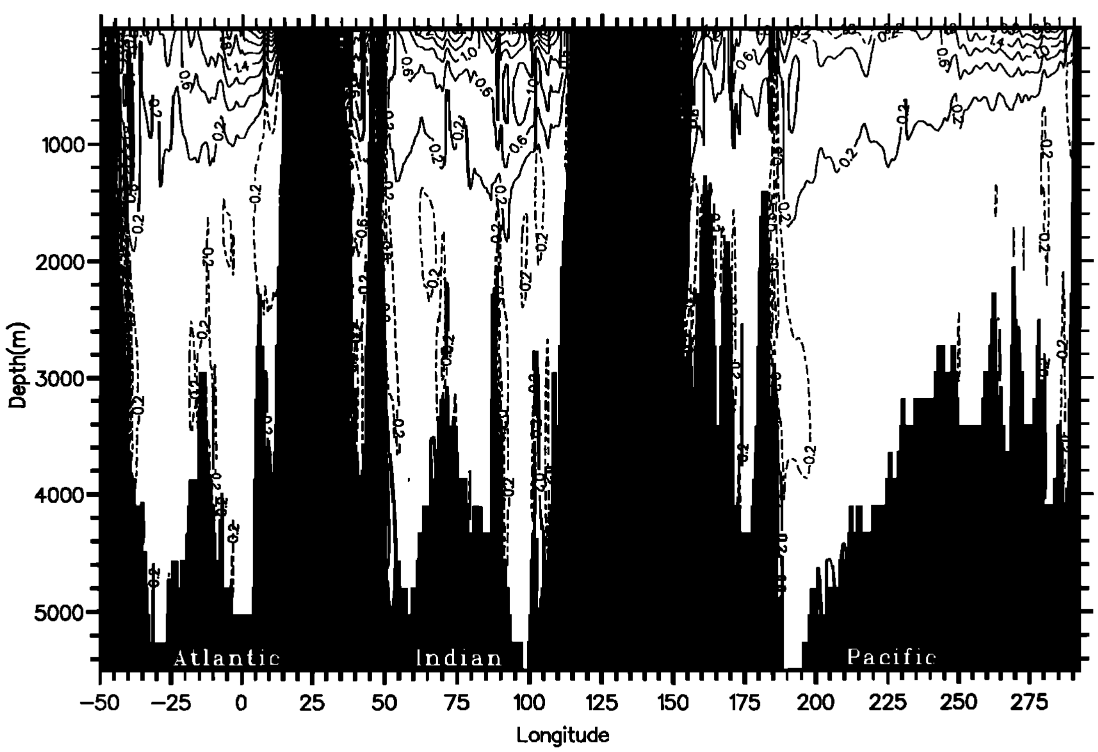


Figure 2. The meridional velocity (centimeters per second) at 25°S (a) directly calculated by the numerical model, (b) recalculated from the trajectories, and (c) the difference between the two.

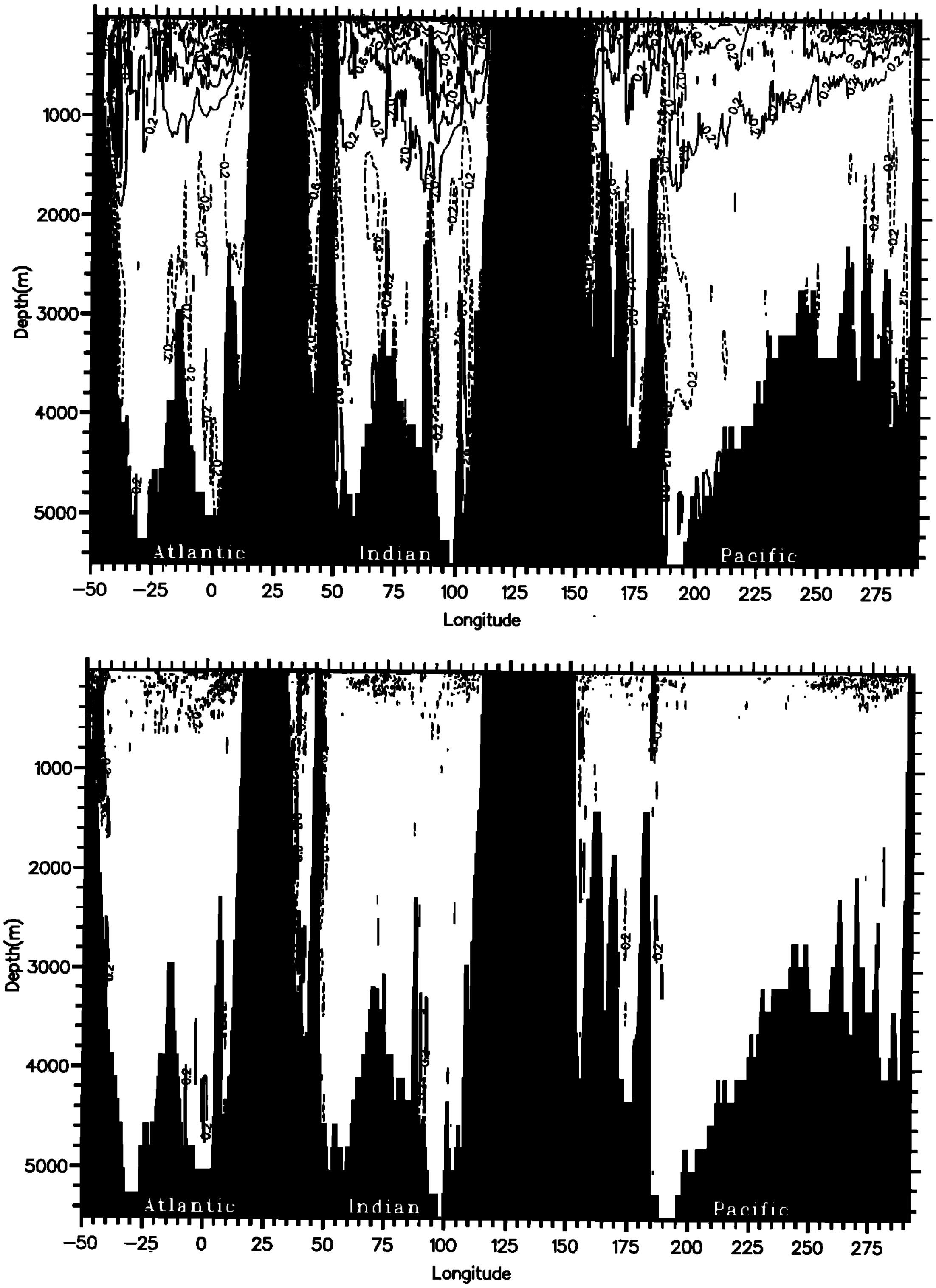


Figure 2. (continued)

Pacific. It is important to emphasize that the salinity decrease is due to higher precipitation in the Pacific than in the Atlantic. The water that travels in the unventilated paths decreases its salinity by mixing with water that is already in the Pacific.

The water path from the Indian to the Atlantic is presented in Figure 5c. It carries 21 Sv of warm water (12.3°C) from the Indian into the Atlantic and is the major component of the so-called warm water path discussed in section 5. The westward route from the Pacific into the Indian results in another (small) contribution to the warm water path discussed below and the eastward one to the cold water path, both shown in Figure 5d. These two paths together carry just over 1 Sv.

Figure 5e shows the path transporting 3 Sv that goes directly from the Indian to the Pacific. This water is dense and unventilated and comes from the eastern Indian Ocean. It exports the coldest water from the Indian Ocean and gets even colder during its journey around Australia. It travels north into

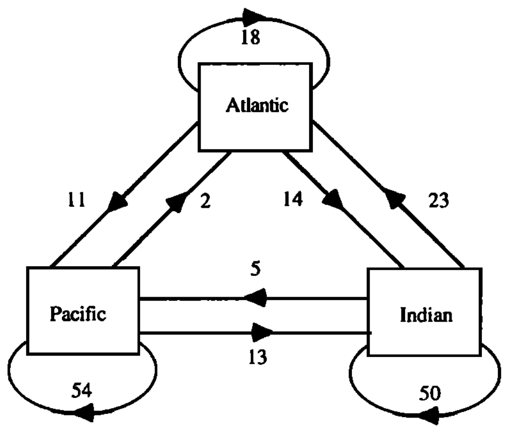


Figure 3. Transports of water between the three world oceans through the Southern Ocean. The transport here is independent of the path. Note that the Atlantic imports 1 Sv too much and the Indian Ocean exports 1 Sv too much. The units are in sverdrups.

the Pacific, either close to Australia in a deep western boundary current or trapped by the western boundary in the deep Southwest Pacific Basin.

The westward path of water direct from the Pacific to the Indian Ocean shown in Figure 5f leaves the Pacific by the East Australian Current, goes around Australia in the Great Australian Bight, and then goes north into the Indian Ocean. This route transports 7 Sv of the lightest (27.2 kg/m^3) and warmest (6.3°C) water that the Pacific exports. It is unclear how physical this route is and to what extent this path is a replacement of the transfer of water from the Pacific to the Indian Ocean through the Indonesian Seas, which is not represented in the FRAM model.

Indirect Ventilated Routes

The second most important route contributes 26% (18 Sv) of the interocean water exchange in the Southern Ocean. This route represents the water that makes at least one circuit around Antarctica and is ventilated at least once. We say that the water is ventilated if the water reaches the surface layer at least once during its travel through the Southern Ocean. The water will make, on average, 4.6 ± 2.3 circuits until it is ventilated and then driven in the Ekman layer out north from the Southern Ocean into the different oceans, resulting in a total of 6.5 ± 3.8 circuits before exiting the open boundary at 24°S. Figure 6 shows a schematic illustration of these paths, and Figure 7 shows a selection of typical water particle trajectories. The time the water particles spend in the Southern Ocean before they are ventilated tends to depend on the incoming density at the open boundary (Figure 8). The densest water spends, on average, a longer time going around Antarctica before being ventilated than does the lighter water. The water rises to the surface in a gradual spiral around Antarctica, where the denser water reaches the surface farther south than the lighter water (Figure 9).

The northward Ekman transport has a maximum of 32 Sv at 45°S. These 32 Sv must, by continuity, upwell to the surface

Table 1. Results of Computations of the Interocean Mass Exchanges

	V, Sv	Circuits	σ, kg/m^3	$\Delta\sigma$	T, °C	ΔT	S, ‰	ΔS	t, years
				From the Atlantic Into the Atlantic, Indian, or Pacific Oceans					
Atlantic	18	0.1±1.5	27.1±0.9	-0.1±0.6	7.8±7.0	0.2±4.5	35.0±0.5	-0.1±0.4	31±75
unvent dir	14	-0.2±0.6	27.3±0.7	0.0±0.3	5.9±5.5	0.1±2.6	34.9±0.4	-0.1±0.2	19±40
vent dir	3	-0.2±0.6	25.9±0.7	0.0±0.9	17.2±5.5	0.3±6.7	35.6±0.6	0.0±0.5	20±56
vent indir	1	5.8±3.9	27.0±1.1	-0.7±1.7	8.7±8.4	4.8±13.1	35.2±0.6	0.1±0.9	258±186
Indian	14	3.0±3.5	27.5±0.8	-0.3±1.1	5.5±6.0	1.3±8.3	35.0±0.4	-0.1±0.4	154±156
unvent dir	4	0.2±0.1	27.6±0.5	0.1±0.4	4.2±4.2	-1.7±3.7	35.0±0.3	-0.2±0.3	84±82
unvent indir	4	2.7±2.0	27.6±0.6	-0.1±0.8	4.5±4.7	-0.3±6.5	35.0±0.3	-0.2±0.3	120±113
vent indir	5	6.1±3.6	27.3±0.9	-0.9±1.3	6.5±6.9	6.3±9.3	35.1±0.4	0.0±0.5	247±189
Pacific	11	4.3±4.2	27.2±0.8	-0.5±1.2	7.6±6.7	0.7±8.7	35.1±0.4	-0.6±0.6	191±173
unvent dir	2	0.6±0.3	27.0±0.8	0.3±0.5	9.3±6.7	-4.9±4.9	35.2±0.4	-0.6±0.6	85±74
unvent indir	3	2.7±2.9	27.1±0.8	0.1±0.8	9.0±6.8	-3.8±6.6	35.2±0.4	-0.6±0.6	126±117
vent indir	5	7.0±4.0	27.4±0.8	-1.2±1.0	5.7±6.1	5.9±7.8	35.0±0.4	-0.4±0.5	276±187
				From the Indian Into the Atlantic, Indian, or Pacific Oceans					
Atlantic	23	-0.6±1.1	26.4±0.8	0.1±0.7	12.8±5.2	-0.2±4.5	35.0±0.3	0.0±0.2	17±49
unvent dir	21	-0.7±0.8	26.5±0.7	0.0±0.5	12.3±.4.6	0.1±3.6	35.0±0.3	0.0±0.2	13±35
vent dir	2	-0.6±0.8	25.2±1.2	0.8±1.4	18.0±6.8	-2.8±8.5	35.1±0.2	0.1±0.4	31±62
Indian	50	0.2±1.1	26.6±1.2	0.4±0.7	10.3±8.2	-2.3±4.7	35.0±0.3	-0.1±0.2	32±77
unvent dir	40	0.0±0.1	26.9±1.0	0.3±0.6	8.1±7.1	-2.0±3.8	34.9±0.3	-0.1±0.2	25±52
vent dir	8	0.0±0.1	24.8±0.4	0.9±1.0	21.4±1.9	-4.8±5.9	35.4±0.1	-0.1±0.2	16±48
vent indir	1	6.1±3.4	27.0±1.0	-0.6±1.2	8.1±6.4	5.1±7.9	34.9±0.2	0.2±0.3	323±193
Pacific	5	2.3±3.8	27.1±0.8	0.0±1.0	7.0±6.0	-1.1±6.9	34.9±0.2	-0.2±0.4	185±166
unvent dir	3	0.0±0.3	27.3±0.6	0.3±0.4	5.9±5.4	-3.5±4.1	34.9±0.2	-0.2±0.3	113±92
vent indir	2	6.6±3.8	27.0±0.9	-0.8±1.1	8.0±6.2	3.9±7.8	34.9±0.2	-0.3±0.4	323±191

Table 1. (continued) Results of Computations of the Interocean Mass Exchanges

	V, Sv	Circuits	σ, kg/m^3	Δσ	T, °C	ΔT	S, ‰	ΔS	t, years
From the Pacific Into the Atlantic, Indian, or Pacific Oceans									
Atlantic	2	3.0±4.2	27.4±0.4	-0.9±0.9	3.8±3.0	8.1±7.3	34.6±0.1	0.6±0.5	222±205
unvent dir	1	-0.3±0.7	27.4±0.3	-0.5±0.6	3.9±2.0	4.4±4.6	34.6±0.1	0.2±0.2	106±114
vent indir	1	6.5±3.9	27.5±0.5	-1.3±0.9	3.8±3.9	11.7±7.4	34.7±0.2	0.9±0.6	350±215
Indian	13	2.9±3.7	27.3±0.5	-0.6±0.8	4.9±3.6	4.6±6.6	34.6±0.2	0.2±0.3	186±207
unvent dir	7	0.0±0.2	27.2±0.3	0.0±0.3	6.3±2.6	0.4±2.6	34.6±0.1	0.0±0.2	43±40
unvent indir	2	4.1±3.5	27.5±0.4	-0.6±1.1	3.4±3.2	4.7±8.3	34.6±0.1	0.3±0.3	252±195
vent indir	5	6.3±3.6	27.5±0.5	-1.2±0.8	3.4±3.6	9.9±5.9	34.7±0.2	0.4±0.2	340±210
Pacific	54	0.9±2.7	26.5±1.2	0.1±0.7	10.8±8.7	-0.4±4.8	35.0±0.4	-0.1±0.2	80±145
unvent dir	37	0.0±0.1	26.6±1.1	0.3±0.4	9.9±8.1	-1.9±2.6	35.0±0.4	-0.1±0.2	42±76
vent dir	9	0.0±0.1	24.9±0.6	0.3±0.7	21.4±4.0	-1.5±3.9	35.6±0.3	-0.1±0.2	10±34
unvent indir	2	4.1±3.5	27.5±0.3	-0.3±0.8	3.7±2.7	1.8±5.8	34.6±0.1	0.0±0.3	244±163
vent indir	7	6.6±3.9	27.5±0.5	-1.3±0.8	3.5±3.6	8.4±5.8	34.7±0.2	0.0±0.4	345±202

The numerical values of the main quantities characterizing the interocean mass transports (including standard deviations) for routes more than 0.5 Sv are shown. V is volume transport, σ is density, Δ is the difference between entry and exit values, T is temperature, S is salinity, and t is the average time the water particles spend in the Southern Ocean. For σ, T, and S the original values are given, i.e., the values they have as they enter the Southern Ocean. "Vent" is water ventilated at least once, "unvent" is water never ventilated, "dir" is direct transport of water from one ocean to another, i.e., less than one circuit around Antarctica, and "indir" is water that has gone at least once around Antarctica.

of the ocean farther south. This could be compared with the estimated amount of ventilated water in the water particle trajectories, which is 33 Sv.

Two Minor Routes

There are two other minor types of routes. The ventilated one that makes less than one circuit around Antarctica (vent

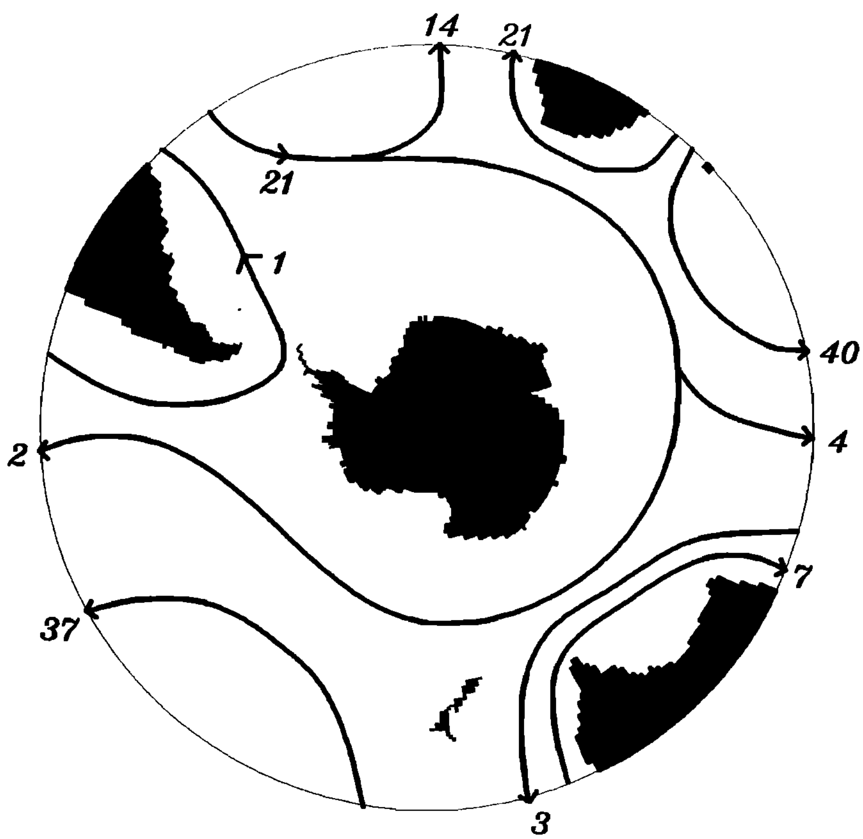


Figure 4. Schematic illustration of the "unventilated direct" ocean routes, with at least 1 Sv that is neither ventilated nor goes around Antarctica. Units are in sverdrups.

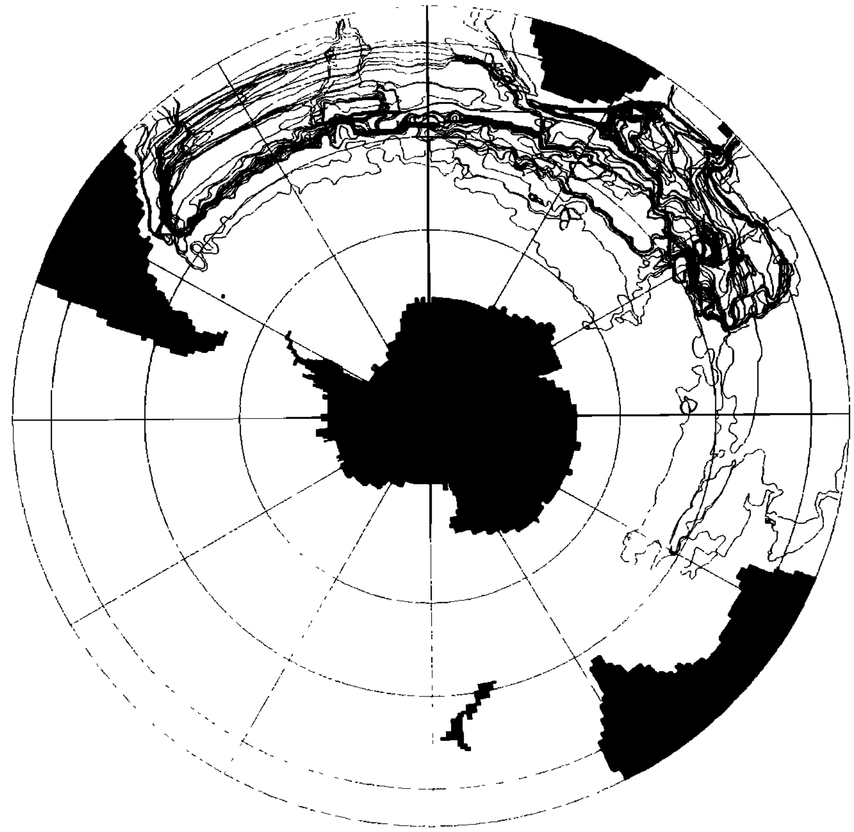


Figure 5. Typical chosen trajectories representing the direct unventilated routes in the Southern Ocean that go less than one circuit around Antarctica and never reach the surface layer (a) from the Atlantic to the Indian, (b) from the Atlantic to the Pacific, (c) from the Indian to the Atlantic, (d) from the Pacific to the Atlantic, going either west or east, (e) from the Indian to the Pacific, (f) from the Pacific to the Indian and from the Atlantic to the Atlantic, and (g) from the Indian to the Indian and from the Pacific to the Pacific. Units are in sverdrups.

dir) is important for the subtropical gyre circulation within the oceans but contributes only with 5% of the interocean exchange. The unventilated one that goes at least once around Antarctica (unvent indir) contributes 14%. This route is mainly water coming from the Atlantic, making just over one circuit around Antarctica and then traveling north into the Indian Ocean (4 Sv) or up north into the Pacific (3 Sv). This route has very much the same characteristics as the direct unventilated one.

Water Masses Defined by Temperature and Salinity

A more traditional subdivision of the water masses is based on their salinity and temperature characteristics. We have used here definitions of the water masses based on *Emery and Meincke* [1986].

The North Atlantic Deep Water (NADW) is defined as water with temperatures between 1.5 and 4°C and salinities between 34.4 and 35.0 psu. The southward transport from the Atlantic into the Indian Ocean and the Pacific versus the temperature is illustrated as the solid line in Figure 10. The NADW is easily detected as a well-isolated water mass with temperatures from 1 to 4°C, with a peak around 2.6°C.

Eleven Sv of the NADW go into the Indian Ocean, of which 4 Sv go directly and the rest (7 Sv) circle an average 4.7 ± 2.6 times around Antarctica before exiting through the open boundary in the Indian Ocean. Another 7 Sv of the NADW go into the Pacific, of which only 1 Sv goes directly in and the rest (6 Sv) make 5.9 ± 3.6 circuits around Antarctica before exiting through the Pacific open boundary. There is 1 Sv that circles five times around Antarctica and then goes back north in the Atlantic. There is finally 10 Sv of NADW in the Atlantic Subtropical Gyre. They will, on average, warm up by 0.8°C, so that when the water returns north into the Atlantic, only 5 Sv will still be classified as NADW and the rest becomes Antarctic Intermediate Water (AAIW).

Table 2 summarizes the conversions of the NADW. Ten Sv of the 29 Sv that enter as NADW will remain as such. Of the remaining 19 Sv, 11 Sv change temperature and salinity in the deep ocean by mixing and 8 Sv by mixing and air-sea interaction. Only 5 of the 19 Sv of the interocean exchange of NADW both enter and exit as NADW, and they are all destined for the Indian Ocean. Seven Sv of the NADW warm up to become the South Indian Central Water (SICW). Five Sv warm up to become the South Pacific Central Water (SPCW), and 2 Sv cool down, probably by mixing with the Antarctic Bottom Water (AABW) and exit through the Pacific. A selection of 100 trajectories of the unventilated NADW that both enters and exits as such, as a function of temperature and salinity, is illustrated in Figure 11. Despite that all the changes are due to diffusion, since these trajectories never outcrop, the change is enough for most of the trajectories to change water mass definition.

The AAIW is defined as waters with temperatures between 2 and 6°C and salinities between 33.8 and 34.8 psu, so it overlaps therefore the definition of the NADW. The only inter-

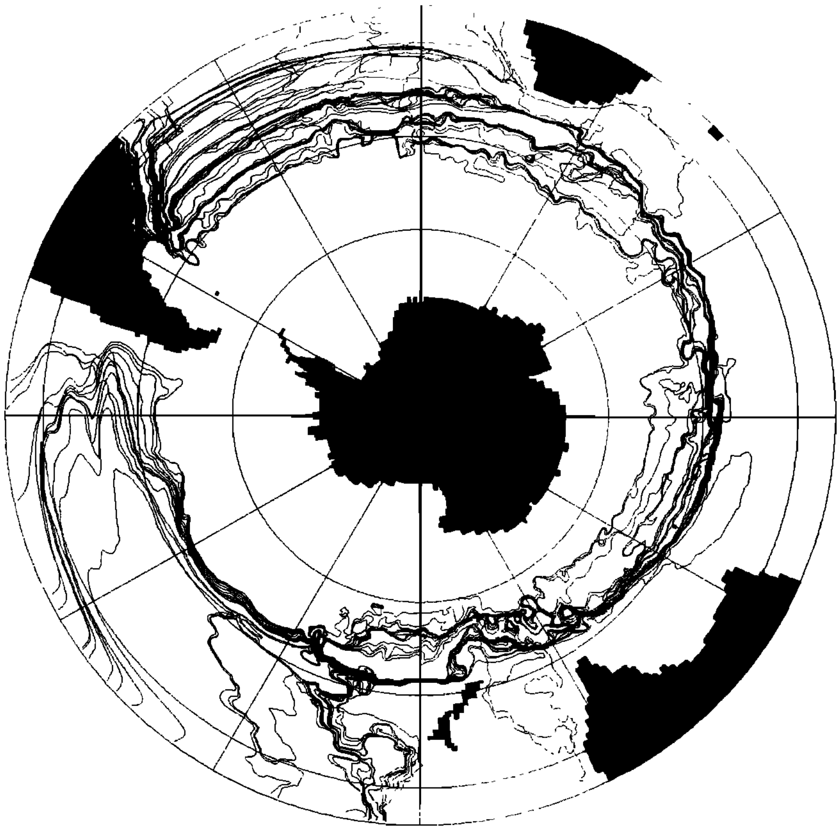
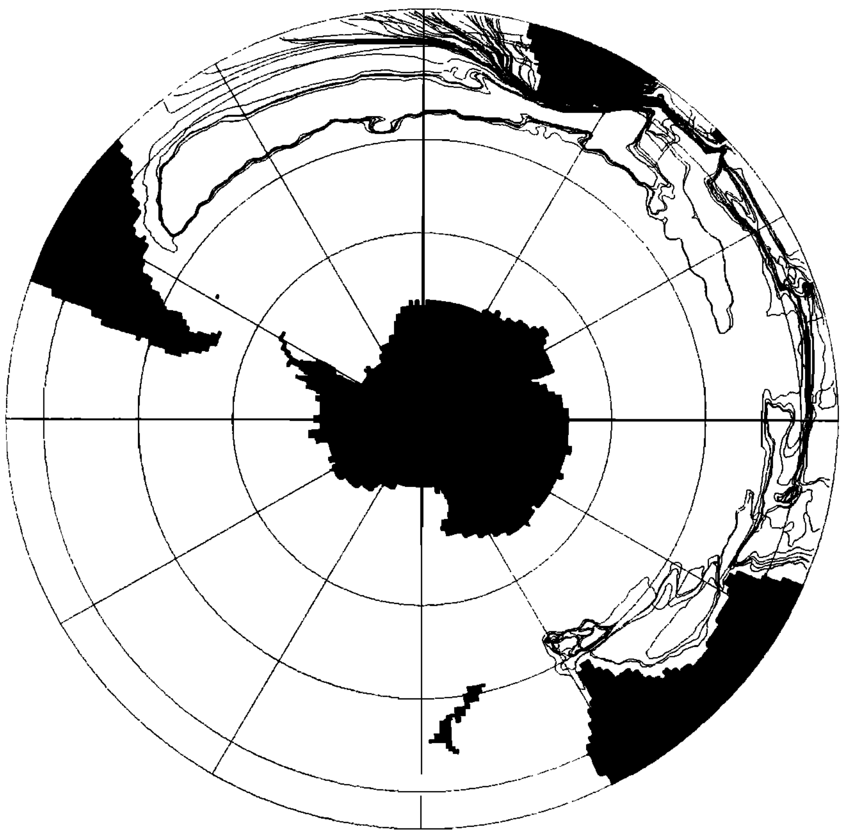


Figure 5. (continued)



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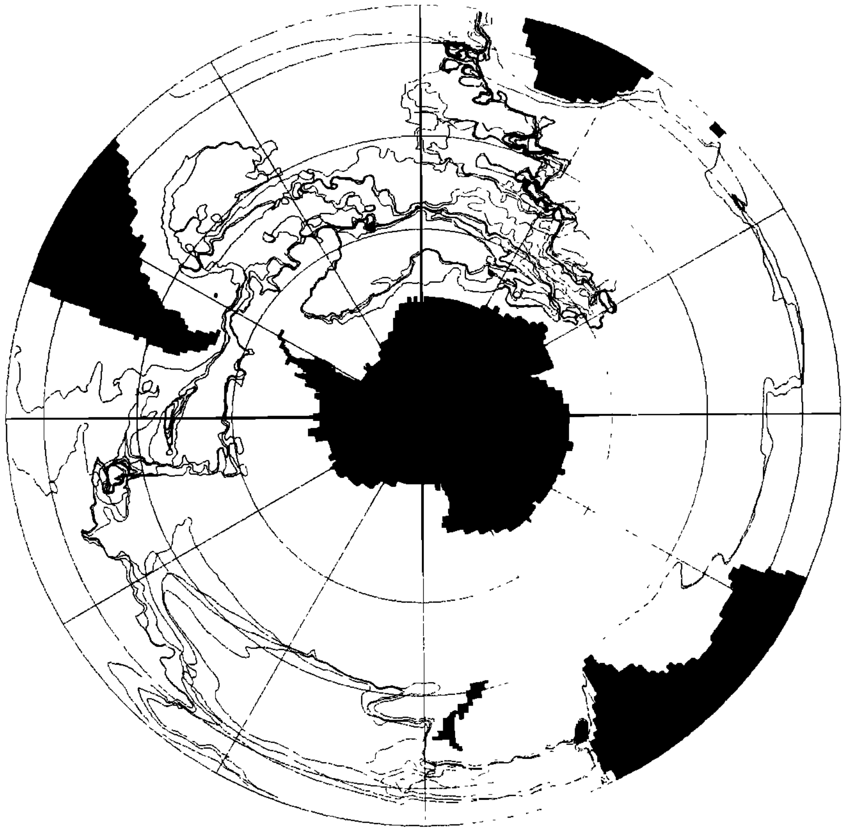

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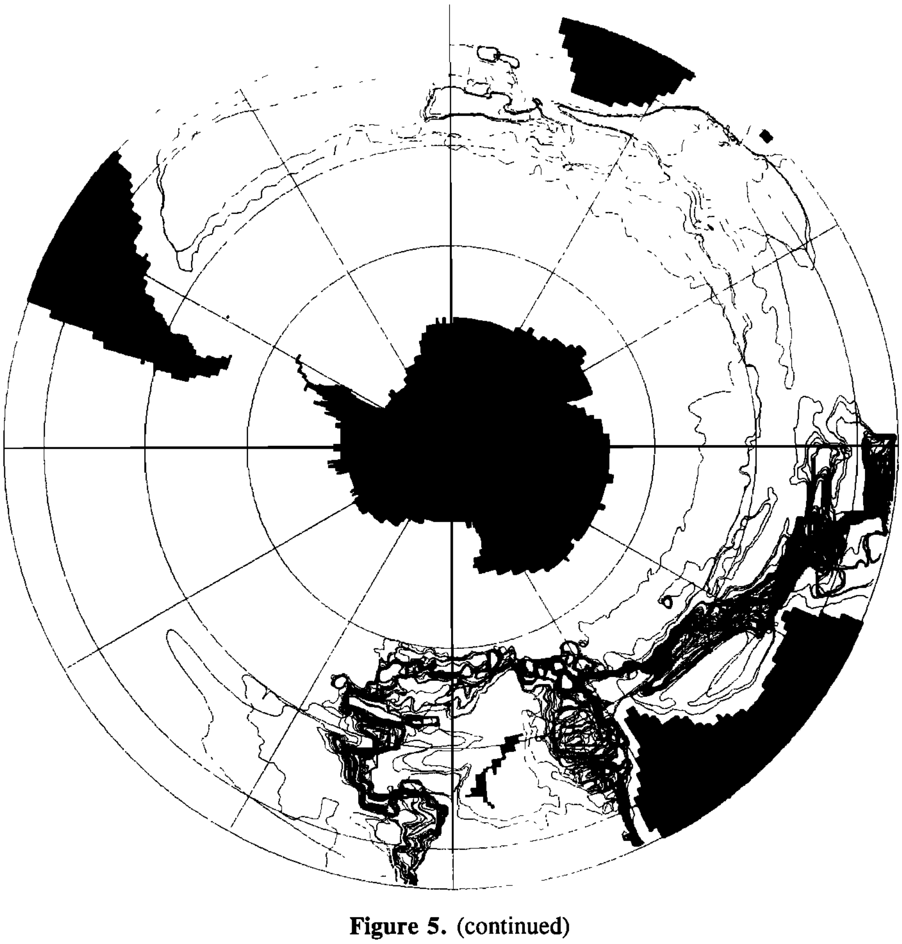

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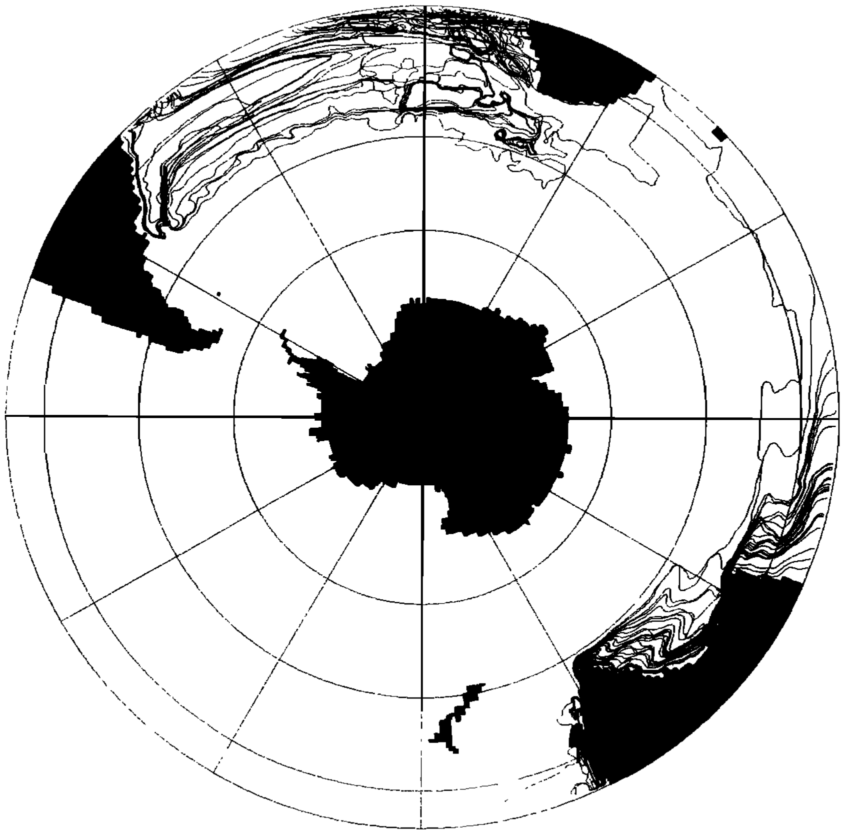

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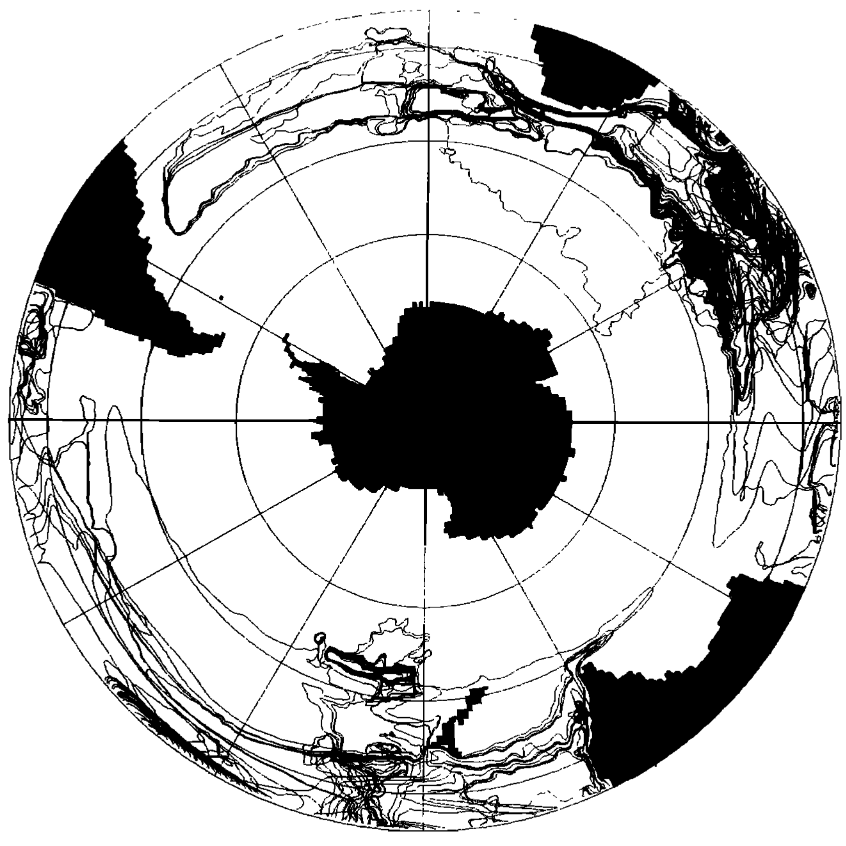

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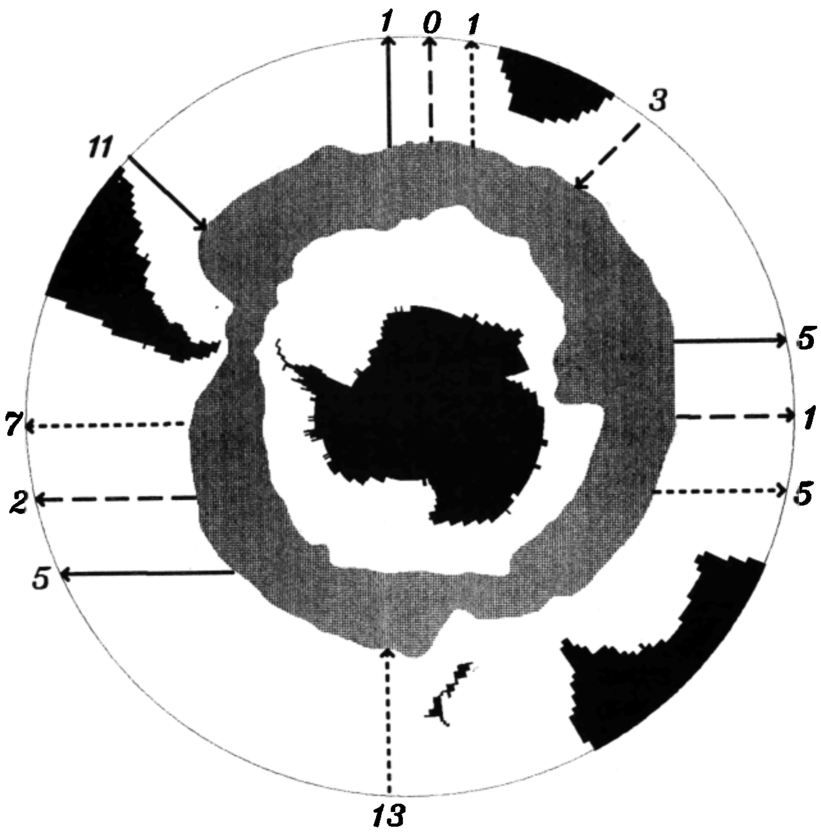

Figure 6. Schmetic illustration of the ventilated routes (numbered) which go around Antarctica at least once and, on average, five times before they are ventilated and then driven rapidly north by the Ekman transport. The solid lines represent water originating from the Atlantic, the long-dashed lines from the Indian Ocean, and the short-dashed lines from the Pacific. Units are in sverdrups.

ocean exchange of waters that arrive as AAIW is 2 Sv from the Atlantic to the Indian, of which 1 Sv goes directly without going around Antarctica. In the Subtropical gyres there is, however, a significant amount of AAIW: 5 Sv in the Atlantic, 13 Sv in the Indian, and 5 Sv in the Pacific.

The SICW can be defined as waters with temperatures between 8.0 and 25.0°C and salinities between 34.6 and 35.8 psu, and it has a very similar definition to the South Atlantic Central Water (temperatures between 5 and 18°C and salinities between 34.3 and 35.8 psu). Almost all the transport (19 out of 23 Sv) from the Indian to the Atlantic corresponds to this water mass. But only 1 out of 5 Sv of the water that goes from the Indian Ocean to the Pacific is SICW. There is 5 Sv of SPCW (temperatures between 6 and 24°C and salinities between 34.4 and 36.4 psu) going from the Pacific into the Indian, of which 4 Sv go south of Australia and 1 Sv circles in the ACC seven times before entering the Indian Ocean.

5. Heat Transport Into the Atlantic

The heat transport in the South Atlantic is dominated by the southward NADW and its northward return flow. The NADW upwells in the Southern Ocean, the Indian, and the Pacific. There are two routes by which the water can return to the Atlantic, as follows: the cold water route from the Drake Passage and the warm water route in which water is introduced to the Atlantic Ocean south of Africa [*Gordon*, 1986].

Two ways of defining the cold/warm water routes have been used in this study. The first one defines the warm water route as all the water that originates from the northern open boundary in the Indian and the Pacific and that goes into the Atlantic without going through Drake Passage. The second definition considers only the NADW and its possible return flows, which fits more the *Gordon* [1986] definition of the cold/warm water paths.

First Definition of the Warm/Cold Water Paths

The warm water path that goes west from the Indian Ocean into the Atlantic Ocean carries 23 Sv of warm water, which has a mean temperature of 12.8°C when coming in and 12.6°C when exiting the Atlantic and is the major component of the so-called warm water path, which transfers heat into the Atlantic. The unventilated part (21 Sv) is presented in Figure 5c. The quantification of the heat transport from the Indian into the Atlantic is not straightforward. We can estimate a heat loss of 0.02 PW (PW = 10^{15}W) of the water mass when it goes around Africa by multiplying the volume transport by the temperature difference between the exit and the entry in the Southern Ocean.

There is also a small contribution (1 Sv) of water going west from the Pacific through the Indian and then north into the Atlantic. This is illustrated in Figure 5d by the trajectories that go westward. This is all the water that goes into the Atlantic from the Indian and the Pacific but does not go through Drake Passage.

It is not possible to calculate the exact amount of heat that this warm water route brings into the Atlantic since the tem-

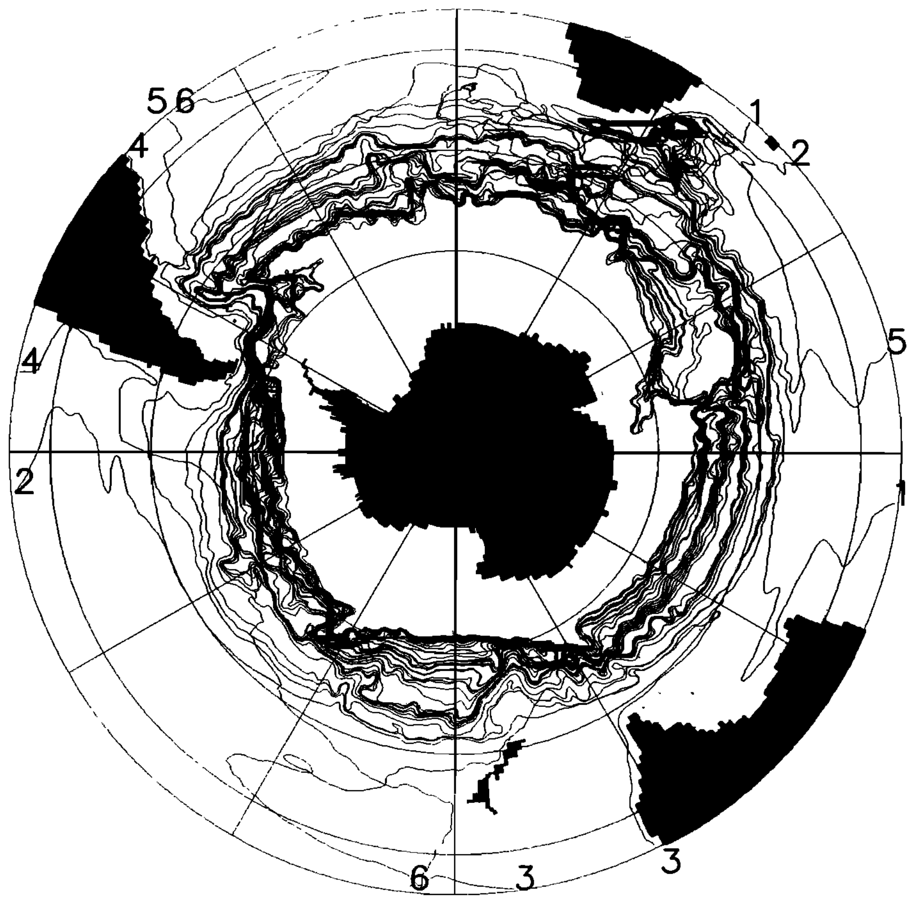

Figure 7. A selection of eight typical water particle trajectories (numbered) that go around Antarctica five to six times before being ventilated and then rapidly driven north by the Ekman transport (i.e., the ventilated indirect route).

perature of the return flow is unknown. It is, however, possible to calculate the maximum and the minimum by taking the coldest and the warmest of the return flow that goes from the open boundary in the Atlantic to the open boundaries in the Indian and the Pacific. The warm water path transports V_{tot} 24.1 Sv, with an average temperature T_w of 12.5°C.

The total amount of volume transport that could be the return flow of the warm water route, coming in from the Atlantic and exiting the Indian or the Pacific, is 24.8 Sv. The temperature division of this transport is defined as $\partial V/\partial T$ (illustrated in Figure 10 by the solid curve), where V is the volume transport and T is the temperature. In order to find the coldest and the warmest possible return flows, we integrate from the coldest temperature up to the temperature TW or from the warmest down to the temperature TC, so that

$$V_{tot} = \int_{-\infty}^{TW} \frac{\partial V}{\partial T} dT = \int_{TC}^{\infty} \frac{\partial V}{\partial T} dT$$

This is illustrated by the short-dashed curve in Figure 10. The maximum heat transport can now be calculated as

$$H_{max} = cV_{tot}T_w - c\int_{-\infty}^{TW} \frac{\partial V}{\partial T}\, TdT$$

The minimum heat transport can be estimated in a similar manner by integrating the return flow over the warmest part of the volume transport illustrated by the long-dashed curve in Figure 10. This gives a warm water route contribution with between 0.62 and 0.69 PW or between 85% and 95% of the total heat transport (0.73 PW). The cold water route (i.e., water coming from Drake's Passage) contributes the rest, which is between 0.04 and 0.11 PW.

Warm/Cold Water Paths Based on NADW

The disadvantage of the previous definition of the warm water path is that it includes water that is not part of the conveyor belt that redistributes heat and salt between the north Atlantic and the Indian and Pacific Oceans. In order to eliminate water that is not part of the conveyor belt, it is possible to define the heat transport in the warm water path as the difference between the NADW and the northward transport that originates from the Indian or the Atlantic without going through Drake Passage.

The NADW is a well-defined water mass in Figure 10, with temperatures between 1.0 and 3.7°C. This water mass corresponds to 18.9 Sv of southward water, with an average temperature of 2.8°C. The coldest 18.9 Sv of the 24.1 Sv going westward from the Pacific and the Indian into the Atlantic has an average temperature of 11.1°C and the warmest, 14.3°C. The resulting heat transport due to the warm water path based on the NADW is therefore between 0.65 and 0.90 PW or between 89% and 123% of the total heat transport, which is 0.73 PW. This estimate of the total meridional heat transport

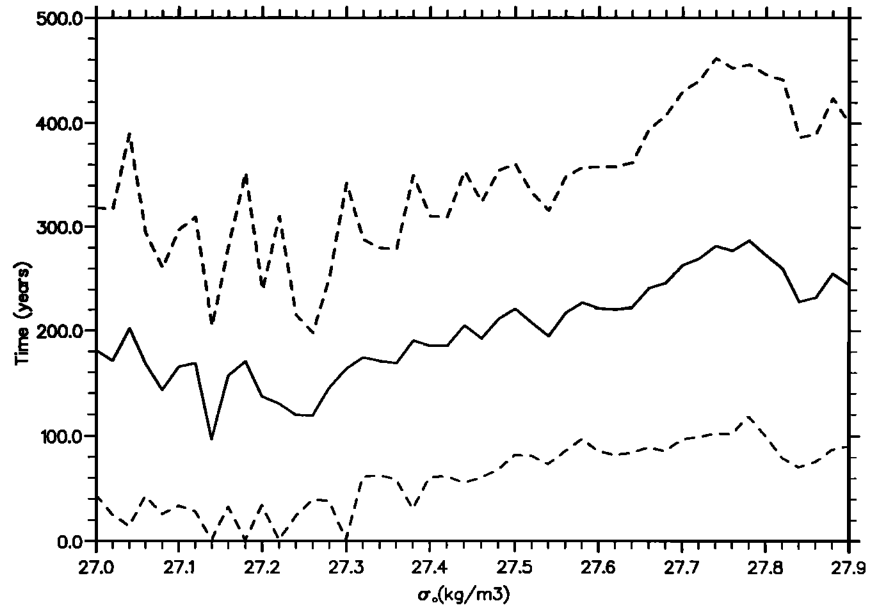

Figure 8. The average time the ventilated water particles spend in the deep ocean before they are ventilated, as a function of their initial density when entering through the open boundary at 25°S. The time is counted from the instant the enter through the open boundary until they are ventilated. The dashed lines represent the standard deviation.

by FRAM lies within the very broad range of estimates of other investigators with a minimum of 0.04 to a maximum of 1.15 PW. See *Rintoul* [1991] for a review of these values.

Indirect Cold Water Path via the Indian Ocean

The above calculation does not take account that some of the water in the warm water path coming from the Indian into the Atlantic has been heated up before arriving at the Indian. If this water comes from the Drake Passage, then it can be classified as being part of the cold water path, or at least to some extent. Since we do not know where exactly the water comes from, we are once again reduced to estimate a maximum/minimum importance of this indirect cold path.

The transport of water from the Drake Passage to the open boundary in the Indian is 17.8 Sv, with an average temperature of 10.7°C, which is just under the total amount of NADW (18.2 Sv). The maximum possible importance of this cold water

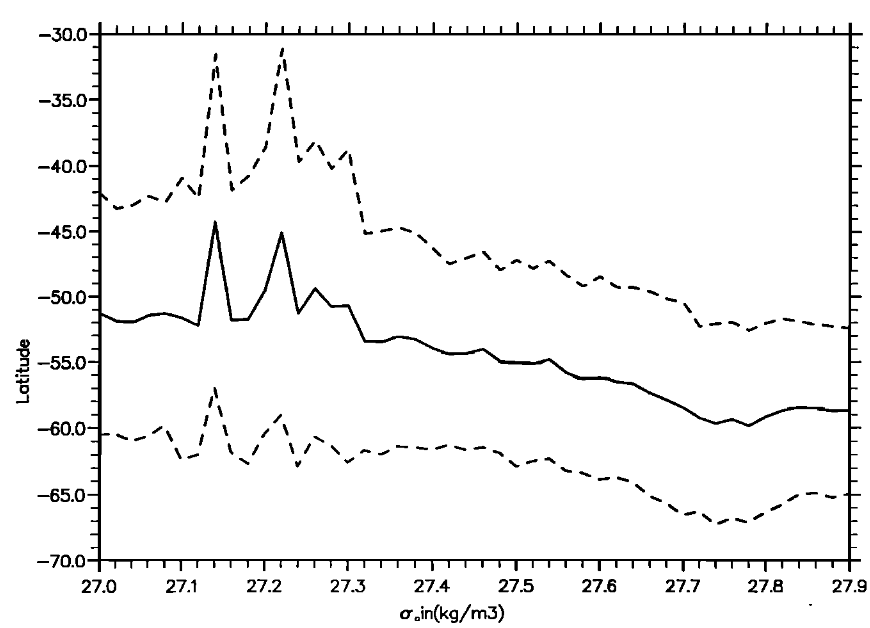

Figure 9. The average latitude at which the ventilated water particles reach the surface layer as a function of the initial density of the particles when entering through the open boundary at 25°S. The dashed lines represent the standard deviation.

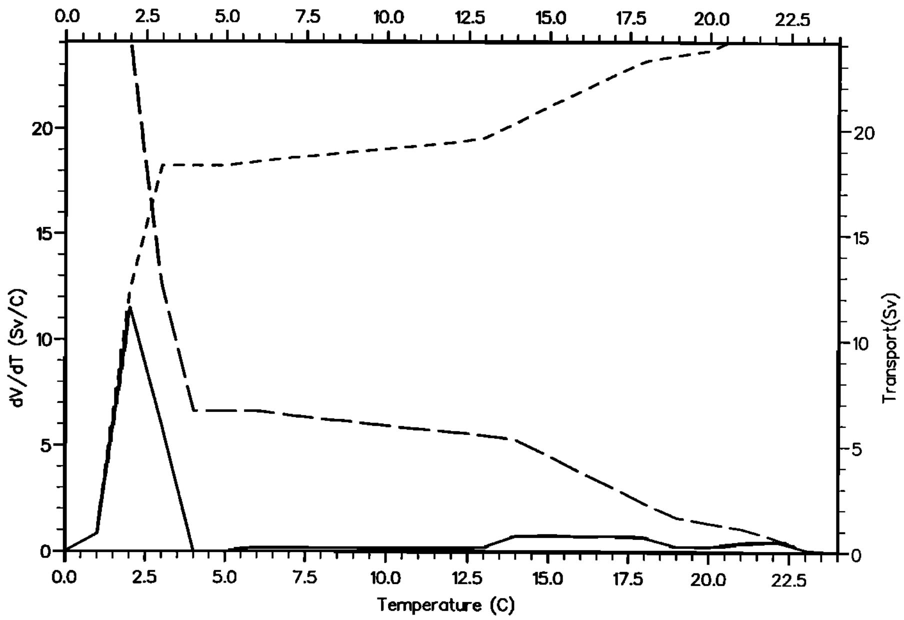

Figure 10. The temperature division of the North Atlantic Deep Water (NADW) transport that goes into the Indian Ocean and the Pacific (solid line). Units are in sverdrups per degree Celsius. Integration of the transport (sverdrups) from the coldest temperature (short-dashed line) and from the warmest temperature (long-dashed line) is made to a temperature so that the transport equals the 24.1 Sv of the warm water path.

path is if all this water goes up in the Atlantic. The heat transport of the indirect cold water path H_{ic} is then simply

$$H_{ic} = cV_{ic}(T_{ic} - T_{NADW})$$
$$= 4.3 \times 10^{-3} \times 18.0(10.6 - 2.8) = 0.60\,\mathrm{PW}$$

The heat transport of the "pure" warm water path would then be between 0.05 and 0.35 PW.

All these heat transports are due to the mean flow. The heat transport due to the eddies and the diffusive heat flux cannot be included in this study. The eddy heat transport in the Atlantic has been compared with that found in the rest of the model, revealing that the Aghulas Retroflection and the Brazil-Falkland Current Confluence regions account for all the eddy transport of 0.3 PW [*Stevens and Thompson*, 1994]. It is however small (0.01 PW) at the open boundary where the trajectories start and end.

The results agree qualitatively with those of *Gordon* [1985], who estimated the volume transport from the Indian Ocean to the Atlantic to be 14 Sv and the corresponding heat transport to be between 0.02 PW and 0.47 PW, depending on the temperature of the return flow. *Gordon* [1986, p.5037] argues that "The cold water route, Pacific to Atlantic transport of Subantarctic water within the Drake Passage, is of secondary importance, amounting to perhaps 25% of the warm water route transport."

Rintoul [1991] argues for the dominance of the cold water path over the warm water path and for a smaller northward heat transport (0.25 PW) in the Southern Atlantic. S.R. Thompson et. al. (The importance of interocean exchange south of Africa in a numerical model, unpublished manuscript, 1995) estimated using a different method, but with the same data set as ours (FRAM mean simulation), that the heat transport between South Africa and a zero stream function point located at 21°E, 41°S is 0.55 PW.

6. Discussion and Summary

In this paper we have studied the interocean water exchange in the Southern Ocean with a new method based on water particle trajectories. The method has been able to give us a much more detailed view of the water cycle than the classical studies of water masses and passive tracers. Individual water

Table 2. Transport of NADW from the Atlantic Ocean

Into	Enters as NADW	Exits and Enters as NADW	Changes by Mixing and Ventilation	Changes by Mixing
Atlantic	10	5	0	5
Indian	12	5	4	3
Pacific	7	10	4	3
Global	29	10	8	11

All values are in sverdrups.

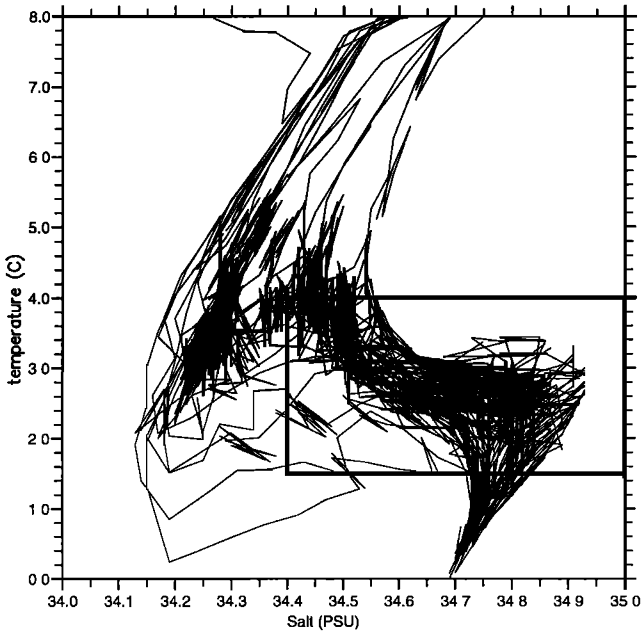

Figure 11. The 100 randomly chosen trajectories of the unventilated NADW that both enters and exits, as such, as a function of temperature and salinity. The inside box illustrates the limits of NADW.

particle trajectories show an almost chaotic behavior. It is not before a sum over a considerable amount of trajectories is used that it is possible to talk about water masses and their routes.

It has been shown that the interocean water exchange takes place basically through two different types of processes. One is a direct transport from one ocean to another without ventilation. The other process is characterized by circling around Antarctica until it is ventilated and then rapidly driven north by the wind stress in the Ekman layer.

The time the water particles spend in the Southern Ocean varies with the distance they travel. The water particles going in the ventilated indirect water route will thus tend to spend much more time in the Southern Ocean than those going in the unventilated direct route. The time spent in the Southern Ocean varies with a standard deviation of the same order as the mean (Table 1). The ventilated route, for instance, takes from the moment it enters the Southern Ocean until it is ventilated, an average 243 of years, but with a standard deviation of 162 years.

The biggest density changes occurs in the ventilated route when the particle is in the surface layer. However, the density changes in the unventilated routes are important. The unventilated route with the largest change is in the indirect one from the Atlantic to the Pacific, which has a cooling of 5.8°C. This may not involve a very high diffusion since the trajectories take, on average, 86 years to travel. But the question remains whether the model has a realistic diffusion or not. Most numerical models have an artificially high diffusion in order to solve the western boundary current. FRAM does not need this due to its high resolution. The temperature and salinity fields are, however, sensitive to how the model is spun-up. FRAM, as all other high-resolution models, cannot be spun-up to a perfect thermohaline equilibrium with today's computer facilities since it would require 100 times longer integration.

This study supports strongly the warm water route since it has been possible to quantify the importance of the cold and warm water routes. The warm water route carries in this study between 92 and 102% of the northward heat transport into the Atlantic.

A weakness of this study is that the Indonesian archipelago is closed and that there is consequently no Indonesian throughflow. It is therefore not clear how this affects the FRAM model simulation. It would be interesting to use this method with a global data set with the different straits open in the future. Another weakness of the present method is that it does not include the seasonal variability. It should be possible to include this, but it would complicate considerably the calculations of the water particle trajectories. The path through each grid box would have to be solved numerically.

The resolution of the numerical model (FRAM) itself is crucial to get a realistic interocean exchange of water masses. S.R. Thompson et al. (unpublished manuscript, 1995) have used a model similar to FRAM, but with a much coarser horizontal resolution (4° x 2°). The coarser model did not produce any eddies in the Aghulas Retroflection zone. Without these eddies there is no mechanism to transport mass and heat from the Indian to the Atlantic and, consequently, the whole interocean exchange of water changes. It is also possible that a model with finer resolution than FRAM would change the circulation. It is, however, unlikely that the warm water path becomes much stronger than in FRAM since it already dominates completely the cold water path in FRAM.

The use of traditional water masses seems to be a doubtful method to trace the interocean exchange of water masses. Only 10 of the 29 Sv of the NADW that enter at 24°S in the Atlantic will remain as such. Another valuable study would be to compare results obtained through this method with results from other methods such as integrating the model with passive tracers.

Appendix

The solution for the trajectory paths is obtained by calculating the trajectory analytically through each grid box of the model, where the velocity field in this study is the FRAM time-averaged data set. We start with finding an expression for the zonal velocity. This is obtained by first averaging

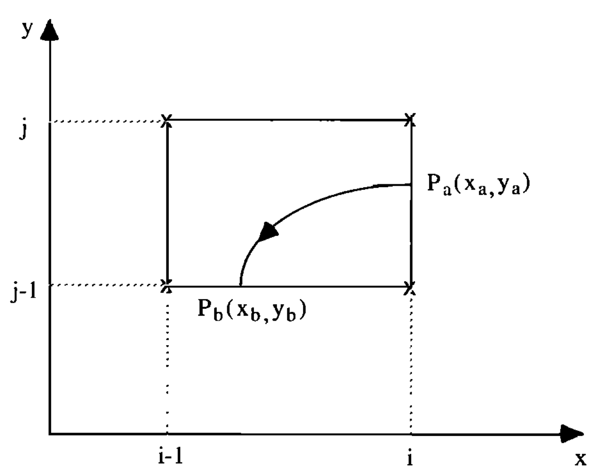

Figure A1. Illustration of the trajectory path through one grid box, where the model velocities are at the four corners of the box.

meridionally and then interpolating zonally the zonal velocity between the four corners of the grid box shown in Figure A1:

$$u(x) = \frac{1}{2}\left(u_{i-1,j} + u_{i-1,j-1}\right) + \frac{x - x_{i-1}}{2\Delta x}\left(u_{i,j} + u_{i,j-1} - u_{i-1,j} - u_{i-1,j-1}\right) \quad \text{(A1)}$$

by using $u(x)=dx/dt$ we can rewrite (A1) as a differential equation

$$\frac{dx}{dt} + \alpha x + \beta = 0 \quad \text{(A2)}$$

where

$$\alpha = \frac{u_{i-1,j} + u_{i-1,j-1} - u_{i,j} - u_{i,j-1}}{2\Delta x}$$

$$\beta = \frac{x_{i-1}\left(u_{i,j} + u_{i,j-1} - u_{i-1,j} - u_{i-1,j-1}\right)}{2\Delta x} - \frac{1}{2}\left(u_{i-1,j} + u_{i-1,j-1}\right)$$

The differential equation (A2), together with the boundary conditions $x(t_a)=x_a$ and $x(t_b)=x_b$, have the solutions:

$$x_b = \left(x_a + \frac{\beta}{\alpha}\right)\exp\left[-\alpha\left(t_b - t_a\right)\right] - \frac{\beta}{\alpha}$$

or

$$t_b = t_a - \frac{1}{\alpha}\log\left[\frac{x_b + \beta/\alpha}{x_a + \beta/\alpha}\right]$$

The calculation is repeated similarly for the meridional and vertical velocities, which will determine the meridional and the vertical displacements. The lowest of the 3 time values (t_b) defines which side of the box is attended by the particle. These are exact solutions to the velocity fields.

The convection is parameterized so that when a water particle enters a convectively unstable water column, it will take a random depth within this column. The convection field is calculated from the time-averaged density field in FRAM.

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