On Convection and the Formation of Subantarctic Mode Water in the Fine Resolution Antarctic Model (FRAM)

Joachim Ribbe & Matthias Tomczak

The Flinders University of South Australia

Abstract

We investigate the formation of Subantarctic Mode Water (SAMW) in the Fine Resolution Antarctic Model (FRAM). FRAM velocity fields are applied to advect an ideal tracer in an off-line diffusion and advection model of the Southern Ocean, and the results from two computational experiments are reported. In the first of our experiments, the tracer was released to the south of the Antarctic Polar Front (APF), in the second experiment to the north of the front. In this manner, we obtain insight into the SAMW formation process and the relative importance of convection, downwelling, vertical mixing and subduction in FRAM.

The modelled tracer distribution was not in a steady state; however, good overall agreement was found between the modelled and the observed climatological distribution of ventilated water. The formation of SAMW in the model is found to be only weak for the southeast Pacific Ocean. In contrast, Indian Ocean SAMW is ventilating the Indian Ocean thermocline and is advected eastward into the Pacific Ocean. We give a quantitative estimate for the amount of Antarctic and subantarctic surface water found north of the APF and find that its contribution to ventilated water in the upper thermocline is significant.

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1. Introduction

In the mid-latitude regions of the southern hemisphere oceanic convection leads to the formation of Subantarctic Mode Water (SAMW). McCartney (1977, 1982) described the regional distribution of SAMW from observations and identified a thermostad spanning the upper 400-500 m of the water column north of the Subantarctic Front (SAF) as a reminiscence of its formation process. He verified that SAMW is a major contributor to the formation of Central Water and suggested that the only area where SAMW contributes to Antarctic Intermediate Water (AAIW) is the remote southeast region of the Pacific Ocean. The densest SAMW is found here, and the observed temperature and salinity values are close to those of AAIW.

England et al. (1993) investigated the formation of AAIW in a low resolution ocean general circulation model (OGCM) and were able to reproduce McCartney's observations. SAMW was identified as a direct precursor of AAIW in the eastern South Pacific and western South Atlantic Oceans, while less dense varieties of SAMW were found in the South Indian Ocean. Low resolution OGCMs generally fail in resolving individual fronts of the Antarctic Circumpolar Current (ACC) or observed mesoscale features characteristic of the Southern Ocean circulation (Bryden, 1983). Despite these limitations, the models are routinely applied in global climate change studies or investigations into the oceanic uptake of anthropogenic environmental tracers (IPCC, 1992; England et al., 1994). The impact of compromises made in model developments are not known in full detail. This is in particular the case for the Southern Ocean which is an important link for both the global carbon cycle, and the wind and thermohaline driven circulation (Broecker, 1991).

In this paper, we investigate the formation of SAMW and its ventilation pathway within a high resolution OGCM. The Fine Resolution Antarctic Model (FRAM) was developed to overcome some of the shortcomings of low resolution OGCM (The FRAM Group, 1991). It sharpened dynamical fronts and developed mesoscale activity in reasonable agreement with observations. Both aspects are particularly important for the zonal transport of oceanic properties and the interoceanic property exchange. To date, the evaluation and analysis of the FRAM results has found good agreement with the observational data base (The FRAM Group, 1991; Saunders & Thompson, 1992; Stevens & Killworth, 1992; Thompson, 1993: Quartly & Srokosz, 1993; Döös & Webb, 1994; Stevens & Thompson, 1994; Feron, 1995; Grose et al., 1995; Döös, 1995; Lutjeharms & Webb, 1995). FRAM was integrated for 16 model years only, however, Saunders & Thompson (1992) found that the model approached a near thermodynamic equilibrium with a density field very close to climatology. No study into the explicit formation of water masses in FRAM has been carried out so far. Studies by Döös (1995) and Stevens & Stevens (1996) were concerned about the actual circulation of water mass between ocean basins. Döös (1995) study was also limited in that regard that it used a Lagrangian method to track the interoceanic flow and excluded any mixing process in his model.

The formation of SAMW in the Southern Ocean represents an important and fast removal mechanism for atmospheric properties on annual to decadal time scales. Naturally occurring gases like oxygen, nitrogen or the greenhouse gas carbon dioxide (CO_2) are being exchanged between the ocean and atmosphere in an attempt to maintain an equilibrium distribution between the two reservoirs. CO_2 derived from the burning of fossil fuel causes a disturbance of the natural equilibrium. Anthropogenically produced atmospheric substances like chlorofluorocarbons or bomb radionuclides like carbon-14 have been observed to have penetrated the global ocean to an average depth of several hundred metres (Bullister, 1989; Broecker et al., 1995). On annual to decadal time scales, these upper SAMW forming layers of the ocean are important buffers for the natural and anthropogenic disturbances of the atmospheric CO_2 concentration and carry the signal of atmospheric temperature fluctuations into the deep ocean. Subducted water advected with the ACC may have already contributed to the recent temperature increase observed in the Tasman Sea (Bindoff & Church, 1992).

The quantities of the oceanic uptake are not fully known due to our limited understanding of the underlying physical mechanisms. There is indication that the oceanic processes controlling the removal of tracer enriched surface water are more important for the magnitude of the oceanic uptake than the exchange mechanism between the atmosphere and ocean (Watson, 1993). The replacement processes for surface water are controlled by the interior ocean dynamics, its large scale wind and thermohaline driven circulation, and the subsequent formation of water masses.

The focus of this paper is on the formation of SAMW and the identification of the involved mechanisms in FRAM. Its pathways within the model is studied and compared with the observational data base of the Southern Ocean. An off-line tracer model utilising the velocity fields of FRAM was applied for this purpose. The model represents a solution to the three dimensional advection and diffusion equation only, and the approach can be interpreted as an analysis of FRAM and its representation of some aspects of the large scale global thermohaline circulation. Section 2 of this paper describes the method and processes of convection, downwelling and vertical mixing which operate within the tracer model, and in Section 3 our results are shown.

The results of two experiments for an ideal oceanic tracer are presented. The experiments have identical model parameters but differ in their initial surface distribution. This is controlled by the location of the 2^{o} C isotherm, taken to represent the approximate northern boundary of the Antarctic zone (the Antarctic Polar Front, or APF). In the first experiment, the tracer was released to the south, in the second one to the north of the boundary. As will be shown in detail in Section 3, SAMW formation in FRAM is characterised by convection, downwelling and subduction north of the APF. South of the APF only vertical mixing removes surface water properties into the interior of the modelled ocean domain. With the exemption of the Weddell Sea and Ross Sea which are characterised by weak convection within the model, no regions of enhanced ventilation are located. The experimental design allows us to quantify cross frontal tracer transport in FRAM which is found to be significant. The obtained tracer distributions are transient; however, they resemble clearly the observed distribution of ventilated water in the mid-latitudes of the Southern Ocean, ie. SAMW of which oxygen is an indicator in the real ocean.

In this paper, we present a global view of the SAMW formation process in FRAM. Future work will report on the sensitivity of the tracer model results, particularly for those of the southeast Indian Ocean to the chosen model parameters and include a quantification of the SAMW formation process (Ribbe & Tomczak, 1996).

2. Methodology

a) The tracer model

The tracer model of the Southern Ocean is based upon the three dimensional advection and diffusion equation used in FRAM for the scalar quantities temperature and salinity (eg. Semtner, 1986). FRAM is a three dimensional high resolution primitive equation model. It was developed for the Southern Ocean domain south of 24^{o} S with a horizontal and vertical resolution of 0.25^{o} in latitudinal and 0.5^{o} in longitudinal direction. There are 32 vertical levels ranging from 20.7 m at the surface to 233 m thickness in the bottom layer, and the model has been described in detail in the literature (eg. The FRAM Group, 1991). The integration of FRAM over a period of 16 years resulted in a complete simulated description of the velocity, temperature and salinity fields for the Southern Ocean and the model was found to be close to a dynamic and thermodynamic equilibrium (Saunders & Thompson, 1992) A mean velocity, temperature and salinity field was derived as an average from the accumulated 72 monthly data sets of years 11 - 16 of the FRAM integration (de Cuevas, 1994; pers. comm.). This data set is referred to as the FRMEAN data set. Although FRAM is quasi eddy resolving, it was expected that the average fields would be in a steady state in a statistical sense with only a minor time dependent fraction.

A copy of the original FRAM code for the advection and diffusion equation was obtained (D. Stevens, pers. comm.), converted into CM5 FORTRAN for parallel processing and integrated at the South Australian Centre for Parallel Processing in Adelaide, Australia. The tracer model is identical to FRAM with the exemption that it does not solve the complete set of primitive equations. Instead, it utilises the FRAM velocity field to calculate the advection terms and the tracer model is therefore referred to as an off-line model.

The tracer equation has been integrated for various initial surface distributions of an idealised tracer to study the effect of convection, downwelling, vertical mixing and subduction in FRAM. These physical processes comprise the removal mechanisms for surface water and introduced tracer quantities within the model. Since we use FRAM velocity, temperature and salinity fields as input data for the off-line tracer model some analysis of how the model represents these removal mechanisms is required. We define this mechanisms here based upon their relative lengths scales and discuss them in the following sections. A more detailed description of the actual FRAM circulation, and the distribution of temperature and salinity can be found in the literature (eg. Webb et al., 1991).

b) Convection in FRAM

Oceanic convection is a vertical mixing process, however, it is being differentiated from small scale vertical mixing due to the involved lengths scales. Convection results in an instantaneous homogenisation of the water column which can extend far into the deep ocean, and is for example the cause of the thermostad observed by McCartney (1977, 1982) north of the SAF. Primitive equation models such as FRAM are hydrostatic models and include convection through a convective adjustment scheme (eg. Bryan, 1969). At each time step the water column is tested for static stability, and any unstable situation is adjusted for by averaging adjacent vertical temperature and salinity values until a stabile density profile is simulated.

During the FRAM integration temperature and salinity fields were stored after application of the standard Bryan (1969) convective adjustment procedure. After it was applied regions which were statically unstable have no vertical density differences. These regions can subsequently be identified from the stored temperature and salinity fields and a convective mask is derived from the mean density field by identifying vertically homogenised water (Dr. D. Stevens, pers. comm.). Any tracer included in the FRAM integration would have undergone the same adjustment procedure as temperature and salinity and therefore, the procedure is applied in the off-line tracer model at each time step.

The maximum penetration depth of surface originating convection is presented in Figure 1. Most convection in FRAM is found in the mid-latitudinal region, with only weak convection observed close to the Antarctic continent (a known observation made for low resolution OGCMs in general, eg. Toggweiler, 1989). Convection at the higher latitudes is primarily a result of an increase in salinity due to the formation of sea ice and subsequent brine rejection. Only few observations of the temperature and salinity values for the higher latitudes exist, most were made during the austral summer causing a bias toward summer conditions in the forcing temperature and salinity fields of FRAM. Sea ice formation and convection do, however, occur mostly during the austral winter for which no direct observations exist; hence, convection is under-represented in FRAM for the high latitudes.

In the mid-latitudinal regions, most convection is related to oceanic heat loss and results in the formation of SAMW (McCartney, 1977, 1982). The large scale anticyclonic circulation of the subtropical regions moves warm surface water from the tropics along the western branches of the gyres into the mid-latitudes. Subsequently, it is advected across the ocean toward the east and looses heat along its path to the atmosphere. Regions of maximum heat loss coincide with maximum convection depths (England et al., 1993; Hirst & Godfrey, 1993). This convection type is observed to occur mostly during winter time. At other times, a seasonal thermocline insulates the deeper winter water which is subducted northward into the permanent thermocline (Some isolated observations of convection events that continued throughout the year were reported by Heath, 1981).

The correlation of increased heat loss and maximum convective depths seems to hold well for the Pacific Ocean (eg. England et al., 1993). A similar overlap is not as well established for the southeast Indian Ocean. Figures shown by Hirst & Godfrey (1993), for example, show convection also for regions of actual heat gain. This apparent discrepancy can be explained by a northward directed Ekman transport (Ribbe & Tomczak, 1996). At the surface, cold dense water is advected northward making the water column unstable. A similar suggestion has been made by England et al. (1993) to explain some mis-match in their correlation of heat loss and convection.

The mid-latitudinal convection simulated within the model is deepest for the southeast Indian Ocean. It is found to be extremely weak in the southeast Pacific Ocean where in the real ocean the densest varieties of SAMW and AAIW were observed (McCartney, 1977, 1982). The cause for the weakened convection in the model is most likely that identified by England et al. (1993). FRAM is a primitive equation model forced to Levitus climatology. Its temperature and salinity observations are biased toward summer conditions which effect the density structure of the Southern Ocean.

In the southeast Indian Ocean, mid-latitudinal convection in FRAM is most likely under represented. Hirst & Godfrey (1993) investigated the ocean's response to a closed Indonesian Passage and no throughflow. Convection in the southeast Indian Ocean is weakened in the no through flow case. Less heat is transported from the Pacific Ocean into the Indian Ocean and therefore, less cooling occurs to generated convection in the surface layer. FRAM does not include the Indonesian Passage and heat is not advected from the Pacific Ocean westward. It is likely that the inclusion of a throughflow in FRAM would have resulted in even more convection as that already observed for FRAM's southeast Indian Ocean (Ribbe & Tomczak, 1996).

In both experiments discussed in Section 3, the computed convective mask is applied at each time step. This is certainly a limitation of our model as we do not account for any seasonal variation in convection. This would also require the use of seasonal cycles of the circulation. Such an approach, however, would have been far beyond our available computational resources considering the vast data to be stored on-line to integrate the off-line tracer model. In this paper, it is not our intention, however, to quantify the exact formation rate of SAMW within FRAM, but to demonstrate the involved mechanisms, identify likely pathways and locate it formation sites. To attempt the former, the consideration of seasonal variability would certainly be more accurate.

c) Downwelling and subduction in FRAM

Downwelling is the second physical mechanism for the removal of surface water and introduced tracer quantities. In primitive equation models, the vertical component of the advection is diagnosed from the horizontal velocity components. FRAM's vertical circulation in the sub-surface layer is in general agreement with the expected pattern for the global thermohaline circulation (Figure 2a). Westerly winds driving the ACC cause a northward Ekman drift of the surface water toward the subtropical gyres. The advected water is replaced by upwelling of mostly North Atlantic Deep Water (NADW). Vertical velocities are positive south of approximately 44^{o}S, the region of NADW upwelling. North of 44^{o}S, vertical velocities are generally negative indicating downwelling. This is in agreement with expected Ekman pumping velocities (Figure 2b) observed for the subtropical regions and calculated from the Sverdrup relation $\rho \cdot w = curl(\tau)$, where ρ is density, w vertical velocity and τ the wind stress. Largest downwelling velocities are indicated for the eastern Indian Ocean. Downwelling is characteristic for some regions close to the Antarctic Continent as a consequence of easterly winds and an associated southward transport of surface water. Upwelling is shown along the western continental coasts.

An estimate of the length scale for the vertical transport by downwelling is obtained considering an average vertical velocity of the order of 10^{-6} m/s. Such a velocity displaces a tracer by approximately 32 m in one year. Water which is removed from the surface by downwelling as well as convection is spreading subsequently into the permanent thermocline by subduction, ie. northward flow along isopycnal surfaces. As such subduction is part of the advection field of which the vertical component is shown in Figure 2. We refer to subduction in this paper as the northward flow of ventilated water into the permanent thermocline.

d) Eddy diffusivity in the tracer model

During year 11 to 16 of the FRAM integration, the model was integrated with a combination of harmonic, ie. Laplacian and biharmonic friction coefficients for both horizontal eddy viscosity and diffusivity. This dampened high frequency motion in FRAM, but in conjunction with a small Laplacian coefficient allowed for the development of mesoscale features. The off-line tracer model utilises a mean circulation derived from FRAM which is assumed to be in a steady state in a statistical sense with only a minor time dependent fraction. We did not consider biharmonic friction in the tracer model and horizontal mixing was parameterised through a conventional harmonic mixing coefficient only. A larger horizontal coefficient, however, was required to guarantee computational stability of the model. This may be attributed to the small but time dependent fraction remaining in the mean data set which is particular large in areas where the modelled circulation is characterised by significant mesoscale activity. The coefficient of $1.0 \cdot 10^3$ m^2/s applied in the tracer model is within the range of those chosen in other model applications.

In the vertical, a larger Laplacian mixing coefficient than usual was chosen to avoid computational instability due to possible two grid point waves in regions of the eastern subtropical Indian Ocean with extreme large vertical velocity. Maximum vertical velocities w were found to be in the range of $3\text{-}4 \cdot 10^{-6}$ m/s down to layer 10 with a layer thickness Δz of 156 m. The vertical diffusion coefficient K_V chosen with $2 \cdot 5 \cdot 10^{-4}$ m^2/s fulfils the Reynolds stability criteria defined as $2 > w \cdot \Delta z / K_V$ (Weaver & Sarachik, 1990).

The lengths scale z for the penetration of a tracer due to vertical mixing K_v over the period T of one year is given by $z=(T \cdot K_v)^{1/2}$. A typical Laplacian mixing coefficient applied to parameterise vertical mixing in ocean models and in this paper of the order of 10^{-4} m^2/s results in a penetration depth of 56 m in one year. Throughout the paper, the term vertical mixing refers to small scale vertical diffusion. While convection is a vertical mixing process itself, the underlying length scales of several hundred metres are quite distinct from those of small scale vertical mixing. Convection is dominant over vertical transport mechanism such as downwelling and vertical mixing.

e) Experimental design

In Section 3, the results of two tracer experiments are presented. The parameter settings for both experiments are summarised in Table 1. As mentioned previously, the only difference is in the initial tracer distribution. In experiment one, the tracer was introduced south of the 2^{o} C isotherm where it was set to an arbitrary value of 100 units at the surface (layer 1) only. Everywhere else the concentration was set to zero. In the second experiment, the tracer was set to 100 units north of the 2º C isotherm, again at the surface (layer 1) only. No extra tracer quantities were released into the model domain during the integration. At the northern model boundary, no tracer influx was specified and the flux out of the model domain was determined by the concentration within the interior. The 2º C isotherm was taken to represent the approximate position of the APF and is indicated in Figure 1. The model was integrated for a period of 5 years with a time step of 14,400 s.

The resulting tracer distribution is not in equilibrium but is to be thought of as transient. To obtain a steady state distribution, the model would have to be integrated for hundreds of years, requiring also the specification of a tracer influx at the northern boundary; otherwise, the model domain would be cleared of the tracer as no further input after initialisation occurs. But the obtained tracer distributions allow us to identify regions of enhanced removal of surface water. They are analysed to identify regions of SAMW formation and its subsequent pathway within the model. The 5 year time scale for integrating the model is long enough to identified regions of enhanced ventilation within the model. However, much of the flow along the northern model boundary is directed northward and ventilated water leaves the model domain. An accurate capture of the recirculation of SAMW within the subtropical gyres is with the present model configuration not possible and therefore, the integration time was limited to 5 years.

Potentially there are many possible experiments which can be conducted using an idealised tracer (see also Stevens & Stevens, 1996). Our aim is to investigate the ventilation of the upper water column within the model. We introduce an idealised tracer as a marker or dye of water which is removed from the surface by convection, downwelling and vertical mixing. It is an indicator of ventilated water. In the real ocean, oxygen is a real tracer of water which only recently was in contact with the atmosphere and therefore, is useful to identify the location of SAMW in the real ocean. Locations in which both tracer distribution show the existence of ventilated water and maxima in their distribution lead to conclusions about the formation site and pathway of SAMW within FRAM and the tracer model. The configuration of the model experiments with tracer input to the north and south of the APF allows us to quantify the contribution made by Antarctic and subantarctic surface water to ventilated water north of the APF.

3. Results

While it is clear that convection, downwelling, vertical mixing and subduction all contribute to the removal of water from the surface layer and the renewal of water masses in the layers below, their relative importance for the formation of known oceanic water masses is still an open question. In the southern hemisphere this is particularly true for

AAIW, which has been shown by some (McCartney, 1977) to be formed in a localised region of the southeast Pacific Ocean, while others (Piola & Georgi, 1982; Emery & Meincke, 1986; Piola & Gordon, 1989) maintain that its formation is a circumpolar phenomenon occurring along the APF and therefore requiring some amount of cross-frontal mixing within the Subantarctic Zone. It is possible and indeed likely that both processes contribute to the replenishment of AAIW; but quantitative information is lacking. Both concepts have in common the formation of SAMW as a precursor of AAIW.

The analysis of McCartney (1977) and England et al. (1993) shows maximum convection depths in excess of 600 m near southern Chile. Because FRAM convection depths do not exceed 400 m, FRAM cannot be of much assistance to the debate about AAIW formation. But an analysis of SAMW in FRAM data can contribute to our understanding of the relative roles of convection, downwelling, vertical mixing and subduction in the formation of water masses above the level of AAIW in FRAM. In particular, the experimental design of the tracer experiments advances our understanding of the contribution made by cross-frontal property transport to SAMW and subsequently AAIW characteristics in the real ocean.

The results of our experiments are discussed by presenting examples of the horizontal tracer distribution from the approximate depth range of the observed SAMW ventilation pathway of 300 to 500 m depth. This is followed by a discussion of two meridional sections from the Indian Ocean and the Pacific Ocean which intersect with regions of convection. In this paper, we are not showing any graphics which depict the horizontal FRAM circulation used in the tracer model to calculated the advection terms. The presented tracer distributions as such are reflecting the circulation pattern. The interested reader is referred to the FRAM atlas (Webb et al, 1991) and the references given above for more detailed information on the circulation in FRAM.

Horizontal Distribution

We present our results for the horizontal tracer distribution with the purpose to establish a clear view of the ventilation pathway taken by SAMW in FRAM. This is achieved by analysing the tracer distribution from experiment one for model layers 8 (290 m) and 10 (532 m) at the end of each simulated year (Figure 3). Contours are given in intervals of 0.5 (layer 8) and 0.1 (layer 10) units and the density of shading increases with the concentration. At the begin of this integration, the tracer was released to the south of the APF which is indicated in Figure 1. After the first year, the tracer distribution in model layer 8 (Figure 3a) is characterised by a homogeneous distribution for most of the model domain. Exemptions are locations characterised by maximal concentrations in the Ross Sea, Weddell Sea, the southeast Indian Ocean between approximately 40^{o}-60^{o} E and 90^{o}-

120^{o} E, and in the extreme southeast Pacific Ocean, Drake Passage and the southwest Atlantic Ocean. The locations of the maxima are in proximity to the location of surface originating convection (Figure 1) leading to the conclusion that their primary cause is indeed convection. The most pronounced tracer maximum, however, is found in the southeast Indian Ocean indicating that the ventilation process within the model due to convection is most vigorous at this location.

In the following years, the tracer concentrations south of the APF gradually increases due to a combination of convection, downwelling, and vertical mixing of tracer quantities away from the surface layer. The effect of downwelling as the dominant mechanism is particularly evident close to the Antarctic continent where in its proximity the tracer concentration has increased to above 2 units after 5 years. Within the Weddell Sea and Ross Sea, the concentration is above 3 units due to the weak convection (Figure 1) which occurs in addition to downwelling and vertical mixing. Further north away from the continent the concentration decreases. This area is dominated by upwelling (Figure 2) and only small scale vertical mixing acts in displacing the tracer vertically. North of the APF, the tracer has propagated furthest to the north in the Indian Ocean indicating a more vigorous ventilation than that modelled for the Pacific and Atlantic Ocean.

A similar presentation of the ventilation process for model layer 10 at 532 m (Figure 3b) reveals the pathway taken by convectively displaced surface water in the mid-latitudes. Maximum convection extends only into model layer 8 of the southeast Indian Ocean. Below that layer, vertical mixing and downwelling are the only vertical transport mechanism. This increases the ventilation time scale of this layer compared to those above. It takes a period of two years to significantly increase tracer concentrations in the mid-latitudes and in proximity to the Antarctic continent. Ventilated water as characterised through an elevated tracer concentration is leaving the southeast Indian Ocean and moves with the flow of the ACC south of New Zealand into the Pacific Ocean or is moving northward into the permanent thermocline of the Indian Ocean. There is also a weak tracer maximum in proximity to the extreme southern landmass of the south American continent which is a result of local convection and vertical mixing.

The influence of Antarctic and subantarctic surface water upon the tracer concentration north of the APF is evident from this experiment. No tracer was released into the surface north of the front. The presented distributions with tracer maxima north of the front indicate that the tracer was transported across the front into regions characterised by enhanced oceanic tracer uptake due to mid-latitudinal convection, vertical mixing and downwelling.

In the second tracer experiment, the idealised tracer was released to the north of the APF and the tracer distribution is presented for model layers 8 and 10 in Figure 4 after 5 years of integrating the model. In both layers any distinct maximum in the tracer concentration within the mid-latitudinal regions is absent. The concentration gradually increases away from the APF northward and reaches maxima in the centres of the subtropical gyres. The tracer quantities removed from the surface layer by downwelling and mixing in the subtropics and north of any regions characterised by convection are more significant than those removed by convection. This indicates that the ventilation of the permanent thermocline in the subtropics is controlled by the two former mechanisms rather than by convection of the mid-latitudes and subsequent subduction northward into the permanent thermocline. Although the main tracer flow is northward some tracer quantities have been transported across the APF southward.

A better quantitative presentation of the ventilation strength of Antarctic and subantarctic surface water is obtained by combing the results from experiment one and two. This allows us to present the percentage contribution made by tracers originating in the south to the total tracer concentration simulated to the north of the APF. We obtain this total by summing the tracer concentrations in respective model layers from experiment one and two at the end of the 5 year integration. In Figure 5, we presented as an example the contribution made by southern surface water to the combined tracer concentration of experiment one and two for model layers 8 (at 290 m in Figure 5a) and 10 (at 532 m in Figure 5b). We already have learnt (Figure 3) that mid-latitude convection is extreme in the southeast Indian Ocean and that convectively removed surface water flows either eastward or is subducted northward into the permanent thermocline. The tracer distribution presented in Figure 5 indicates that surface water marked by an introduced idealised tracer, and which originates south of the APF (the grey shaded area represents the initial tracer distribution in the surface layer), contributes significantly to ventilated water north of the APF. In the convection regions of the southeast Indian Ocean is makes up 30-60 per cent, further north its contribution diminishes and contributes less than 10 percent to ventilated water. Its contribution is more significant for ventilated water of the south Indian Ocean but is less for the Pacific and Atlantic oceans, and its contribution to ventilated water in layer 10 is less than in layer 8. This indicates that the main pathway of southern surface water is above the model depth of 532 m.

The existence of mid-latitudinal convection in the model allows us to draw some comparison with the distribution of SAMW in the real ocean which is known to be produced by convection. While within the model the idealised tracer marks ventilated surface water and its pathway, oxygen plays such a role in the real ocean. McCartney (1982) identified a thermostad north of the SAF as an indication of SAMW formation. He observed maximum penetration depths of approximately 600 m. At this depth, SAMW is characterised by an oxygen maximum.

In Figure 6, we presented an oxygen climatology of the Southern Ocean for depths of 500 and 600 m (Olbers et al., 1992). Note that the northern boundary of the observational data base is at 30^{o}S, some 650 km south of the northern limit of the model data at 24^{o}S. The presence of recently ventilated water can be derived from the distribution of the oxygen. In the mid-latitudinal regions, the oxygen concentrations are generally maximal with values above 5.5 ml/l (500 m) and 5.75 ml/l (600 m). Highest values are observed in the southeast Indian Ocean and the southeast Pacific Ocean with concentrations of more than 6.0 ml/l and 6.5 respectively. Based upon McCartney's (1982) analysis we identify this maxima to be associated with formation regions of SAMW. In the southeast Indian Ocean, the oxygen distribution in both layers also exhibits a distinct meridional front at approximately 100^{o} E and north of 47^{o} S, indicating northward directed flow away from the SAMW formation site in the southeast Indian Ocean.

There is good agreement in the distribution of recent ventilated water within the model and the real ocean. This is particularly valid for the Indian Ocean, and we know about the likely causes for the disagreement between modelled and observed data in the south Pacific Ocean. These seem to be intrinsic problems associated with the forcing of OGCMs to Levitus climatology. In the southeast Indian Ocean, however, the location of the oxygen maxima and the indicated northward directed pathway of ventilated water corresponds well with the results obtained from the tracer model.

Our analysis leads us to the conclusion that FRAM includes the formation mechanisms for SAMW. From the application of our tracer model, however, we are not able to derive any information about the correct temperature and salinity (T/S) signature of SAMW in FRAM. Toggweiler (1989) found a type of SAMW in a low resolution OGCM and concluded that the model was able to present water only with *similar* T/S characteristics to those identified by McCartney (1982) as SAMW. He was reluctant to identify it as SAMW. In the future a similar analysis may be required for FRAM and be included in a detailed description of the 72 monthly FRAM climatology applied in this paper.

Vertical Distribution

In this section, the tracer distributions from experiment one and two along two meridional sections are discussed in association with the cross-sectional FRAM velocity component. The sections are located at 110^{o} E in the Indian Ocean (Figure 7) and at 100^{o} W in the Pacific Ocean (Figure 8). Both intersect regions of convective activity (sections are indicated in Figure 1). Data of the final tracer distribution (end of year 5) are presented down to a depth of 800 m only which corresponds to the approximate penetration depth of the tracer during the integration.

In Figure 7, the main path of the ACC is located between 47^{o} to 53^{o} S. The SAF in the north and the APF in the south are the boundaries confining the main transport of the

ACC and are associated with the two cores with velocity above 10 cm/s and 15 cm/s. The positions of the fronts identified here from the cross-sectional velocity maxima are in proximity to positions derived from temperature and salinity climatology (eg. Tomczak & Godfrey, 1994). To the south of the main ACC path, one or two other velocity cores are observed. The existence of these additional fronts to the south of the APF has been confirmed recently through the re-evaluation of both the observed (Olbers et al., 1991) and modelled (FRAM) temperature and salinity data base by Sparrow et al. (1995).

The vertical tracer distribution presented in Figure 7 for the southeast Indian Ocean indicates that tracer transport across the fronts occurred in both model experiments. The SAF centred at approximately 47^{o} S constitutes an obvious boundary. Convection occurs north of the SAF, the region of SAMW formation. In experiment one (Figure 7b), the tracer is transported to the north within the Ekman layer, then vertically homogenised down to approximately 350 m in the region of convection and subducted in a northward direction into the permanent thermocline of the Indian Ocean. The vertical penetration of the tracer in proximity to the Antarctic continent is not caused by convection. No convection occurs in the model at this location. The isolines are almost horizontal due to isotropic vertical diffusion. However, they exhibit some northward slope towards the surface predominantly due to upwelling in the northern part of the Antarctic Zone, and as a result of the tracer loss in the surface layer caused by a northward directed Ekman Drift. In experiment two (Figure 7c), cross-frontal southward directed tracer transport occurs by lateral diffusion. Down to a depth of approximately 400 m the isolines are almost vertically orientated, except at the surface where the Ekman Drift rapidly removes the tracer northward.

We plotted again the percentage contribution of tracers (Figure 7d) to the total tracer concentration (sum of experiment 1 and 2) which originated in the surface layer south of the APF (experiment 1). This is interpreted as the contribution of Antarctic and subantarctic surface water to ventilated water within the model. It constitutes more than 90 per cent of ventilated water in the south of the APF were the tracer was introduced. The remainder fraction of less than 10 percent is ventilated by water which originates at the surface north of the APF. However, to the north of the APF Antarctic and subantarctic surface water makes up a large proportion of ventilated water above 500 m with a contribution of 40 to 60 percent in regions of convection between approximately 42^{o} to 50^{o} S (see Figure 1). Further north its influence is weakening, but still contributes with around 10 percent to ventilated water above 400 m at 30^{o} S.

In Figure 8, we present the corresponding analysis for the meridional section located at 100^{o} W in the southeast Pacific Ocean. At 100^{o} W, the locations of the two main ACC fronts are approximately 54^{o} S (SAF) and 61^{o} S (PF). This region is characterised by weaker convection compared to the Indian Ocean (Figure 1), and therefore reduces the ventilation capacity of water which originates here. The contribution of southern surface water to ventilated water north of the frontal system of the ACC (Figure 8d) is much less compared to the situation simulated for the southeast Indian Ocean.

4. Conclusion

We present an analysis of downwelling, vertical mixing, convection, and subduction which lead to the formation of SAMW within FRAM. Like many OGCMs, FRAM does not produce AAIW in significant quantities. This is mostly due inaccurate forcing in the temperature and salinity climatology and correspondingly low convection in proximity to the Antarctic continent. However, much convection is simulated by FRAM in the mid-latitudinal range. A convection and velocity field derived from FRAM was applied in two ideal tracer experiments to investigate the ventilation of the upper thermocline in FRAM.

The results of our experiments indicate that Antarctic and subantarctic surface water contributes significantly to ventilated water north of the APF. In comparing our modelled data with an oxygen climatology good agreement is found in the distribution of maxima and pathways of ventilated water. This is in particular true for the southeast Indian Ocean, and we conclude that FRAM presents the processes leading to SAMW formation correctly. We are able to provide a quantitative estimate of cross-frontal tracer transport, ie. the contribution made by Antarctic and subantarctic surface water to ventilated water north of the APF. Our model experiments suggest that cross-frontal property transport may be significant in contributing to the temperature and salinity characteristics of SAMW and possible AAIW in the real ocean. In particular, we do not support either of the two contradicting proposals made by McCartney (1977, 1982) and Piola and Georgi (1982), but conclude that the most likely mechanism for the formation of SAMW and AAIW is a combination of both ideas.

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7. List of Figures

Figure 1: Maximum depth [m] of surface generated convection. The depth is derived as an average from 72 monthly FRAM temperature and salinity data sets. Indicated are the location of the 2^o C surface isotherm chosen as the approximate northern boundary of the Antarctic zone and the two meridional sections at 110^o E and 100^o W discussed in section 3.

Figure 2: (a) Vertical velocity near the surface [$\cdot 10^{-6}$ m/s] based upon the FRMEAN data set. Downwelling is found generally north of 44^o S, upwelling dominates the domain south of 44^o S in agreement with the global thermohaline circulation, (b) Ekman pumping velocity [$\cdot 10^{-6}$ m/s] derived from the FRAM winds and using the Sverdrup balance. Downwelling regions are shaded.

Figure 3: Tracer distribution from (top) year 1 to (bottom) year 5 and from experiment one with tracer input south of the Antarctic Polar Front from; (a) for model layer 8 at 290 m and (b) for model layer 10 at 532 m. Contours are given in intervals of 0.5 (layer 8) and 0.1 units (layer 10), and shading increases with the tracer concentration.

Figure 4: Tracer distribution in (a) model layer 8 at 290 m and (b) model layer 10 at 532 m at the end of the model integration (year 5) and from experiment two with tracer input north of the Antarctic Polar Front. Contours are given in intervals of 1 unit, and shading increases with the concentration.

Figure 5: Contribution of surface water [%] originating south of the Antarctic Polar Front to ventilated water at the end of the model integration (year 5); (a) model layer 8 at 290 m and (b) model layer 10 at 532 m. Grey shaded area represents the initial surface distribution of the tracer in experiment 1.

Figure 6: (a) Oxygen [ml/l] climatology (Olbers et al. 1992); (a) layer 15 at 500 m depth, and (b) layer 16 at 600 m depth.

Figure 7: (a) Meridional section of the cross-sectional velocity [cm/s] at 110^o E in the Indian Ocean, westward directed flow is shaded; (b) tracer distribution from

experiment one (tracer input south of the Antarctic Polar Front); (c) tracer distribution from experiment two (tracer input north of the Antarctic Polar Front); and (d) the contribution [%] of southern surface water to ventilated water. Presented is the final tracer distribution, ie. after completion of the model run (end of year 5).

Figure 8: (a) Meridional section of the cross-sectional velocity [cm/s] at 100^{o} W in the Indian Ocean, westward directed flow is shaded; (b) tracer distribution from experiment one (tracer input south of the Antarctic Polar Front); (c) tracer distribution from experiment two (tracer input north of the Antarctic Polar Front); and (d) the contribution [%] of southern surface water to ventilated water. Presented is the final tracer distribution, ie. after completion of the model run (end of year 5).

Table 1: Parameter settings for two the tracer experiments with initial distribution north or south of the 2^{o} C isotherm.

Model Variables	Settings
Advection	FRMEAN Data Set
Horizontal Diffusivity	$1.0 \cdot 10^3$ [m^2/s]
Vertical Diffusivity	$2.5 \cdot 10^{-4}$ [m^2/s]
Time Step	14,400 [s]
Northern Boundary	No flux in, but out allowed
Initial Distribution	100 into surface at t = 0
Total Run Time	5 years
Convection	FRMEAN Data Set

Table 1: Parameter settings for two tracer experiments. The initial distribution is controlled by the location of the 2^o C isotherm which coincides with the approximate position of the Antarctic Polar Front. Experiment 1 with input south of the Antarctic Polar Front , Experiment 2 with input north of the Antarctic Polar Front.