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The importance of interocean exchange south of Africa in a numerical model

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Abstract. A fine resolution numerical model of the Southern Ocean (the Fine Resolution Antarctic Model (FRAM)) has been used to investigate the way in which heat is supplied to the South Atlantic. The heat budget in the model is compared with other estimates and is found to be broadly realistic. The temperature structure in the Atlantic, and therefore the meridional heat transport, depend heavily on the input of heat from the Indian Ocean via the Agulhas Retroflection region. FRAM is compared with three models which do not exhibit a significant input of heat from the Indian Ocean. These models also have a lower equatorward heat transport in the South Atlantic. Horizontal resolution affects the amount of Agulhas transfer with coarser resolution leading to lower heat transport in the Atlantic, a result which has implications for ocean models used in climate simulations.

1. Introduction

It is now generally accepted that the South Atlantic carries heat toward the equator (see *Rintoul* [1991, Figure 9] for a summary of estimates of meridional heat transport in the South Atlantic), forming part of what has been termed a "global conveyor belt" [*Broecker*, 1991]. The northern section of this conveyor belt consists of a northward flow of relatively warm shallow water in the North Atlantic which enters high-latitude regions where deep convection occurs, with the return flow occurring at depth as North Atlantic Deep Water (NADW). Such a system requires a source of heat at its southern end. The debate over the way in which the conveyor belt is completed hinges on the relative importance of two proposed paths. The Warm Water Path (WWP), suggested by *Gordon* [1986], is based on NADW leaving the Atlantic, upwelling in both the Pacific and Indian Oceans, then flowing westward (with water from the Pacific entering the Indian Ocean through the Indonesian Passages), and completing its circuit back into the Atlantic via the Agulhas Retroflection zone. Gordon concludes that the Cold Water Path (CWP) is less important, carrying around 25% of the heat of the WWP. The CWP requires heat to be supplied from the south. According to *Rintoul* [1991], Intermediate Water entering the South Atlantic through Drake Passage exits to the north, gaining heat from the atmosphere in a broad outcropping region. In this case, no significant role is played by leakage of water from the Indian Ocean into the Atlantic via the Agulhas region. The model of *Semtner and Chervin* [1992] indicates that both routes may play an important part, whereas *Gordon et al.* [1992] propose a scheme in which the CWP makes an excursion into the Indian Ocean and passes into to Atlantic via the Agulhas region.

There is substantial evidence for the existence of leakage of water from the Indian Ocean into the South Atlantic via the Agulhas Retroflection region. This takes the form of altimetric data [*Gordon and Haxby*, 1990], hydrographic survey [*Gordon et al.*, 1992, *van Ballegooyen et al.*, 1994], and model integrations such as the Fine Resolution Antarctic Model (FRAM) [*Stevens and Thompson*, 1994]. *Gordon et al.* [1992] suggest that the salt input may be important in preconditioning the northward flowing waters for deep convection once they reach high latitudes. However, the effect, on a global scale, of the input of warm, salty water into the South Atlantic has not been conclusively established.

This paper describes the way in which heat is supplied to the South Atlantic in a numerical model of the Southern Ocean (FRAM) and makes comparisons with other models and observations. Section 2 contains a description of FRAM and the meridional heat trans-

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ports within it, with comparisons being made with observations. The heat and water mass budgets of the model South Atlantic are examined in detail. Section 3 compares the FRAM results to those of two models of the South Atlantic which have been used to address the question of heat supply to the conveyor belt: an inversion carried out by *Rintoul* [1991] and a model reported by *Matano and Philander* [1993]. In section 4, a coarse resolution version of FRAM is investigated to see how horizontal resolution affects the behavior of the model in this region. At present, models used in climate studies are of coarse resolution because of the enormous CPU requirements of long integrations. Therefore differences in representation of the global conveyor belt due to model resolution are of interest to climate modelers.

2. The Fine Resolution Antarctic Model

In this section the heat transports in FRAM are described and the degree of realism of the integration will be discussed using comparisons with estimates made by other authors for the meridional transport in the southern oceans.

FRAM is a high-resolution numerical model of the Southern Ocean south of 24°S. The model is based on those of *Cox* [1984] and *Semtner* [1974] with a resolution of 1/2° in the east-west direction, 1/4° in the north-south direction, and 32 levels in the vertical, ranging from 20 m thick near the surface to around 230 m at depth. For the first 6 years of integration the model was operated in robust diagnostic mode using a relaxation to temperature and salinity values based on those of *Levitus* [1982]. A more detailed description of the model and these first 6 years of integration can be found in the paper by The FRAM Group [1991]. According to *Lutjeharms and Webb* [1995], FRAM represents the Agulhas region with remarkable success although the eddies are too large and too intense. However, *Stevens and Thompson* [1994] estimate that the effect is compensated by the lower frequency of eddy shedding.

A previous study of the heat and freshwater transport within this model dealt with a single model snapshot, that is, the state of the model ocean at the end of the diagnostic phase [*Saunders and Thompson*, 1993]. The transport of volume, heat, and fresh water was examined at 60°S and near 30°S in all three oceans. In general, the results were argued as being realistic. The analysis revealed that at 30°S the heat flux was determined largely by the overturning component. At 60°S the heat transport was found to be dominated by large-scale meanderings of the Antarctic Circumpolar Current (ACC). The authors also indicated that the model underestimated the production of abyssal water, with inadequacies in the *Levitus* [1982] analysis field and the lack of seasonal buoyancy forcing identified as likely causes. While this work has the advantage of dealing with the model in a state as close as it was to get to the Levitus climatology, there are disadvantages in using the output for this single instant in time.

The work presented here involves analysis of mean and transient processes in the last 6 years of the 16 year model integration. During this phase, relaxation to *Levitus* [1982] values in temperature and salinity occurred only in the upper level and the surface was forced by the mean monthly wind stress fields of *Hellerman and Rosenstein* [1983]. Although the model temperature and salinity fields were found to be drifting, the authors feel that the state of the model ocean is sufficiently close to that of the Levitus data to merit a study of the transports. An added benefit over the previous study is that in its prognostic phase, the model was allowed to develop a more energetic eddy field. Furthermore, the unphysical deep sources and sinks of heat and salt that are a feature of the robust diagnostic method are no longer present in the prognostic phase. The model output at this stage consists of the full temperature, salinity, and velocity fields for each end of month, that is, an average is obtained from a time series of 72 model realizations.

The zonally integrated meridional heat transport (see Figure 1) lies in the range of -0.1 to -0.3 PW (where negative values indicate a southward transport) north of 60°S, which appears low compared to other estimates. For example, *Carissimo et al.* [1985] predicted a poleward transport in the ocean of around 2 PW at 60°S by calculating the transport as the residual of the heat transport estimated for the total ocean-atmosphere system and for the atmosphere alone. More recently, using an atmospheric climatology developed from European Centre for Medium-Range Weather Forecasts (ECMWF) analyses and Earth Radiation Budget Experiment (ERBE) satellite data, *Trenberth and Solomon* [1994] found a poleward transport of around 0.2 PW at

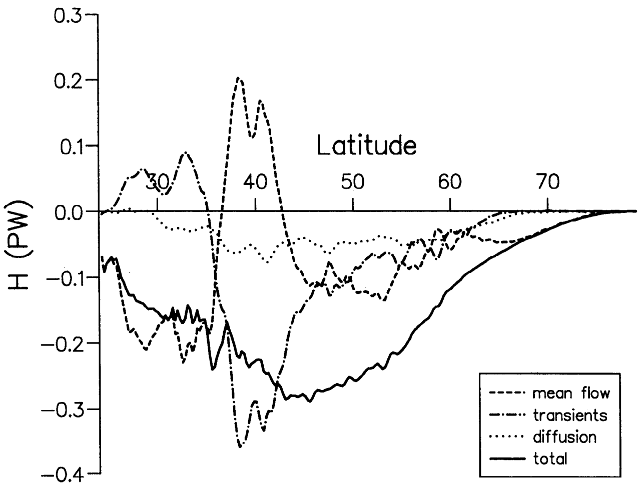

Figure 1. Zonally integrated meridional heat transport in FRAM decomposed into total (solid curve), mean (dashed curve), and transient (dot-dashed curve) advective components and diffusive (dotted curve) heat transport.

60°S. Using surface flux estimates on the other hand, *Hastenrath* [1982] arrived at a figure of 0.65 PW poleward at 60°S. *Russell et al.* [1985] used a model of the atmosphere to infer transports in the oceans and obtained a value of 0.2 PW at 60°S. *DeSzoeke and Levine* [1981] quote a value for heat transport across the polar front (average latitude 53°S) of 0.3 PW calculated from estimates of average heat loss of the ocean surface south of the polar front. The huge spread of these estimates indicates how poorly the total meridional transport is known, particularly in the Southern Ocean.

The heat transports in three major ocean basins have also been calculated separately using the 6-year FRAM climatology. The total time mean meridional heat transport can be decomposed as follows

$$\begin{aligned} a\cos\phi\,\rho C_p \int\int \overline{v\theta} dz d\lambda &= a\cos\phi\,\rho C_p \int\int \overline{v}\overline{\theta} dz d\lambda \\ &+ a\cos\phi\,\rho C_p \int\int \overline{v'\theta'} dz d\lambda \end{aligned}$$

where a is the radius of the Earth, C_p is the heat capacity, θ is the potential temperature, v is the meridional velocity, ϕ is the latitude, and λ is the longitude. Time mean quantities have a bar over them, while a prime indicates deviation about the mean. Thus the first term on the right-hand side is a measure of the heat transported by the mean flow, and the second term represents the so-called eddy or transient heat transport.

The Indian Ocean basin transports a large amount of heat (0.9 PW) poleward. Almost all of this transport is due to the mean flow in which the dominant term is the overturning circulation, consisting of warm shallow water moving south and colder deep water moving north. The Atlantic exhibits similar characteristics in that the transport is dominated by the overturning, but in this case the transport of heat is around 0.6 PW to the north. This is because the surface and intermediate water is flowing north with a return flow of NADW. Another difference is that the transient processes are significant in the Atlantic basin, where they carry heat to the north. There is only a small net transport of heat in the Pacific basin (0.1 PW northward). Again, the mean flow dominates, but this time the overturning and gyre components are in opposite directions and almost cancel. These heat transports can be compared with the summary of estimates given by *Macdonald* [1993]. Although Macdonald's Tables 1 to 3 show a wide range of estimates of the heat transport in the three main basins, there is clearly a large equatorward heat transport in the South Atlantic, an even larger poleward heat transport out of the Indian Ocean, and a small heat transport in the Pacific. Comparison with the results from the diagnostic phase of FRAM [*Saunders and Thompson*, 1993, Table 6] reveals that the model heat transports have changed slightly. Each basin carries a smaller poleward (or larger equatorward) heat transport, resulting in a reduced total meridional transport as the model moves slowly away from its state at the end of the diagnostic phase.

Calculation of heat transport is a straightforward matter in cases where the net mass transport is zero but becomes ambiguous when this is not the case [*Montgomery*, 1974]. This zero mass (in the model calculations, volume) transport condition is met for circumpolar sections and, in the case of the model, any section between Australia, South America, and Africa (the model is constrained to allow no net flow out of the open boundary of each basin, which is equivalent to specifying no net flow through the Bering Strait and the Indonesian Passages). For zonal transports such as that between the Indian and Atlantic Oceans, however, the definition of heat transport becomes less obvious.

An unambiguous estimate of heat transport in the zonal flow south of South Africa can be made by noting that there is a point in the model at approximately 41.5°S where the mean transport stream function crosses zero. This allows a zero mass transport section to be constructed between the African coast and this "0 Sv" point. This point is to the south of the Agulhas current and its retroflection and as such enables an estimate to be made of the transport of heat in the Agulhas current region. Zonal heat transports are calculated thus

$$\begin{aligned} &a\rho C_p \int\int \overline{u\theta} dz d\phi \\ &\quad = a\rho C_p \int\int \overline{u}\overline{\theta} dz d\phi + a\rho C_p \int\int \overline{u'\theta'} dz d\phi \end{aligned}$$

where u is the zonal velocity.

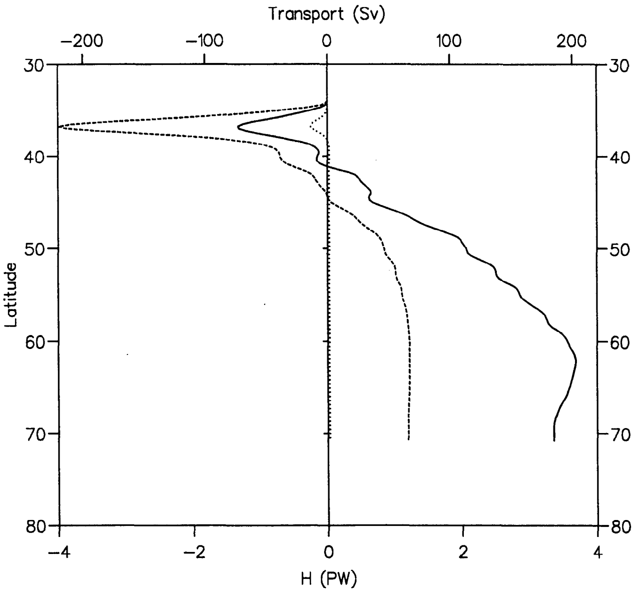

Figure 2. Zonal temperature advection and volume transport integrated along 21°E from Africa to Antarctica in FRAM, with positive values being toward the east. The solid line represents volume transport in Sverdrups, the dashed line is total (mean and transient) temperature advection (converted to petaWatts), and the dotted line shows the transient contribution.

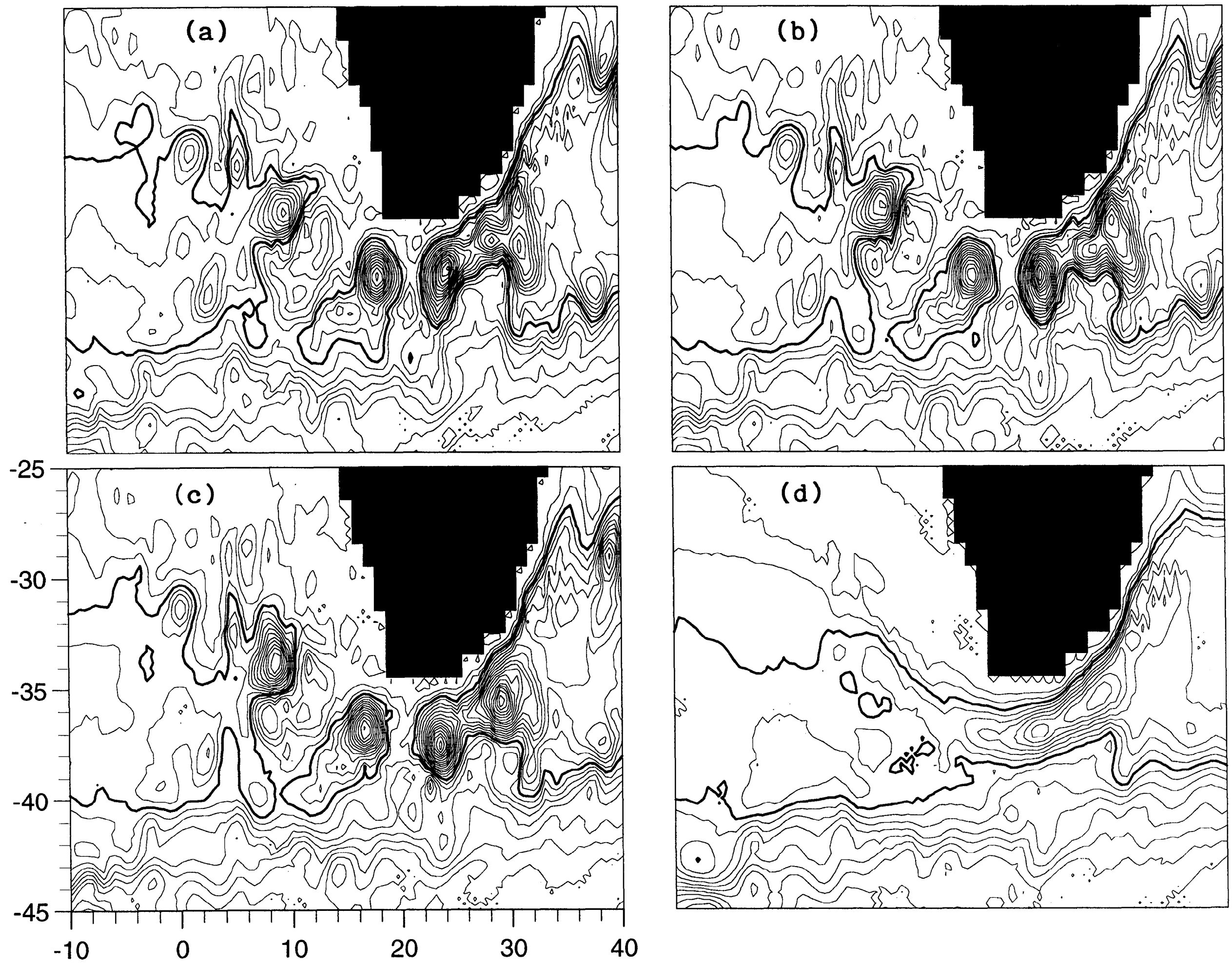

Figure 3. The barotropic stream function in FRAM for (a) model day 5810, (b) model day 5820, (c) model day 5830, and (d) a 6-year time mean. The contour interval is 10 Sv and the -30 Sv contour is highlighted.

Figure 2 shows the zonal heat and volume transport accumulated along a meridional section starting at the African coast at 21°E and extending southward to Antarctica. This demonstrates that at the latitude where the stream function returns to zero, the accumulated heat transport has a value of 0.51 PW toward the west. *Gordon* [1985] estimates a heat input into the South Atlantic of between 0.23 and 0.47 PW from the Indian Ocean, depending on whether the outflow from the Indian Ocean is replaced by South Atlantic thermocline water or much colder NADW (or some combination of the two).

It is interesting to note that while there is a transport of 0.51 PW across the Agulhas section, the majority of this transport occurs in the mean flow and not in the transient component as one would expect if eddies are responsible. Nevertheless, the eddies play an important role in the transport of heat between basins. Figure 3 shows how the flow between the basins has a mean component due to the eddies. For the instantaneous fields (Figures 3a, 3b and 3c) there is no connection between the -30 Sv contour (highlighted) in the two basins. However, when the mean field is calculated (Figure 3d), the connection is clear. This is because, although the net westward velocity across an eddy is zero, the eddy itself moves westward as can be seen in Figure 3.

Van Ballegooyen et al. [1994] have made an estimate of the heat flux from the Indian Ocean into the Atlantic due to the Agulhas rings by estimating the heat anomaly of eddies observed in a hydrographic survey. They estimate a flux due to the eddies of only 0.045 PW. They tentatively identify this figure with the "specific estimate of the eddy heat flux" in FRAM, that is, the $\overline{u'\theta'}$ component which, as mentioned above, is not necessarily correct. Their estimate could be low for two reasons: the fact that conditions in the Agulhas Retroflection region during the period of the cruise were atypical [*Shannon et al.*, 1990] and the method of estimating the heat transport due to an eddy by referring the temperature in each layer to the ambient temperature for the layer outside of the eddy. A meaningful estimate of the heat transport can only be made if the temperature of the return flow is known, and this return flow does not necessarily occur in the same layer. Because of the limited domain of the model we cannot state exactly how the return flow occurs in FRAM. However, we will present a series of calculations which show that an important heat exchange between the Indian and Atlantic Oceans occurs in the Agulhas region.

In constructing heat budgets for time varying data sets, matters are simplified if volume domains are fixed. Quantities such as heat storage and surface exchange become meaningless if the volume of ocean for which they are calculated varies. However, the total advective transport of heat between, for example, Africa and the mean position of the 0 Sv point on 21°E is not the same as the mean value of a time series of transports between Africa and the instantaneous position of the 0 Sv point. Let $\overline{\phi}_0$ be the mean latitude of the 0 Sv point and the instantaneous latitude of the 0 Sv point be $\phi_0(t) = \overline{\phi}_0 + \phi_0(t)'$, where an overbar indicates a time mean and a prime indicates variation about the mean value. Now the total heat transport between Africa and the time varying 0 Sv point is

$$\overline{H}_{\text{total}} = \overline{H}_{\overline{\phi}_0} + a\rho C_p \overline{\int_{\overline{\phi}_0}^{\phi_0'} \int u\theta dz d\phi}$$

where the first term on the right-hand side represents the result presented previously (that is, with a fixed 0 Sv point) and the second term is the contribution due to correlations between the latitude of the 0 Sv point and the heat transport. This quantity was found to have a value of 0.06 PW to the west, or around 10% of the total; therefore the fixed volume approach has been retained for heat budget calculations.

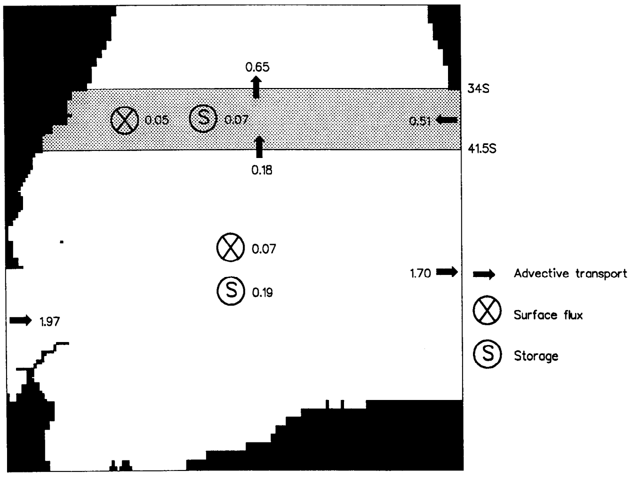

Figure 4. Heat budget for the South Atlantic in FRAM. Solid arrows represent advection, crossed circles represent surface flux, and S represents storage. Positive values of storage and surface flux indicate heat gains by the ocean. Diffusive transports across these sections are small and are not shown.

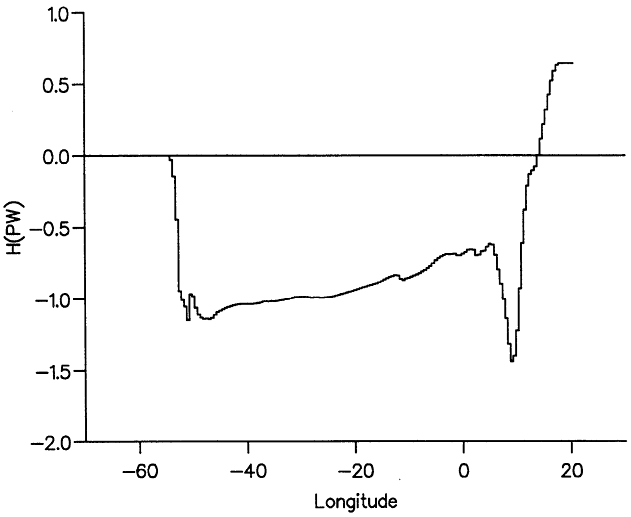

Figure 5. West to east accumulation of the heat transport across 34°S in FRAM.

This transport across 21°E does not prove the existence of the WWP in FRAM, as the possibility remains that the heat transport in the Agulhas region is simply recirculated, either returning to the Indian Ocean or entering the ACC without forming part of the conveyor belt. In order to find the most likely scenario it is necessary to study the heat budget for the entire South Atlantic.

Figure 4 shows the heat budget for the South Atlantic in FRAM, including advective and diffusive fluxes, surface fluxes arising from the "relax to Levitus" term, and heat storage due to the model not having reached thermodynamic equilibrium. The volume of ocean under consideration is bounded by the section at 21°E, a transatlantic section at 34°S, and one across Drake Passage. A further section is shown from the 0 Sv point on the 21°E section across the Atlantic to the South American coast at 41.5°S, forming the southern face of a smaller "box" through which any oceanic heat transport (be it associated with the CWP or WWP) must pass before taking part in the conveyor belt. This box is shown as the shaded region in Figure 4. At face value, Figure 4 appears to favor the WWP for the supply of heat to the conveyor belt. The 0.64 PW crossing 34°S (the figure of 0.6 PW quoted earlier relates to the basin as a whole, north of 34°S) seems to be fed largely by the heat transport in the Agulhas region, with less than 0.2 PW entering from the south. However, these are net transports and do not preclude the possibility of large, partly canceling, transports in opposing directions.

Although we are not attempting to state exactly the path taken by individual water particles in transporting heat (see *Döös* [1995] for efforts in this direction), Figure 5 reveals that the net northward transport of heat appears to arise from a large northward component in the eastern section of the basin, precisely at the longitudes at which the Agulhas eddies cross the section.

The way in which the heat transport in the eastern basin dominates compares well with recent results from transatlantic section A11 [*Saunders and King*, 1995]. The WOCE one-time section, occupied in January 1993, crossed the western South Atlantic at 45°S, and on reaching the mid-ocean ridge, turned northeast to reach the African continent at 30°S. The heat flux across the section was found to be 0.5 ± 0.1 PW equatorward and due entirely to the circulation within the subtropical gyre in the eastern basin. Accumulation of both the hydrographic and modeled volume transports shows that there is a point near the mid-ocean ridge at which the volume transport returns to zero. Because of this, the heat transport across the A11 section can be considered as arising from contributions in the western and eastern basins. Not only do the estimates of total meridional heat transport agree very well between model and hydrography (0.56 PW in the model, 0.5 ± 0.1 PW from A11), but in both cases the eastern basin dominates. This lends weight both to the model realism and to the suggestion that heat input into the South Atlantic occurs in the eastern basin.

Returning to the model heat budget, the storage terms are significant, demonstrating the fact that FRAM has not reached equilibrium. This unwelcome feature of the integration was unavoidable partly due to the computational expense of running such a large code. Nevertheless, *Saunders and Thompson* [1993] have shown that during the spin-up period, although the storage and restore to *Levitus* [1982] terms were initially large, the decay in these quantities appeared to have minimal effect on the meridional heat transport. That is, when the temperature field is close to that of Levitus and the velocity field appears to be realistic, then the correlation of these two fields contains useful information. The main problem here is associated with the lack of seasonal heat and freshwater forcing. The surface level temperature and salinity fields were relaxed toward values derived from the annual mean Levitus data, which lead to a lack of winter conditions associated with intermediate and deep water formation. This means that water mass formation cannot be correctly represented, which must play a large part in the model warming. Also, any correlation between the seasonal wind forcing and seasonal variations in the shallow temperature structure will not be correctly modeled (see section 5 for discussion of this problem). These problems lie outside the control of modelers to a certain extent. Spatial coverage in the Levitus fields is uneven when taking the annual mean, and attempting to force the model with seasonal data will amplify this problem, especially in winter at high latitudes. Thus the FRAM results have been used to study heat transport even though the model did not reach equilibrium, as they represent some of the most comprehensive calculations available at the time. Furthermore, the model remained close to the state described by the mean Levitus fields (indeed, in such a short time it could not be expected to deviate far) in a way in which its eventual equilibrium state may not have.

3. Comparison With Other Models

Although the FRAM integration appears to exhibit a significant direct communication between the Indian and Atlantic Oceans, other models do not. In this section we will investigate the similarities and differences between FRAM, an inverse model described by *Rintoul* [1991], and a model integration carried out by *Matano and Philander* [1993].

Using hydrographic sections at 32°S, across the ACC at Drake Passage, and south of Africa at 0° and 30°E, as well as a section across the northern extent of the Weddell Sea, *Rintoul* [1991] applied the inverse method of Wunsch to estimate the exchanges of mass and heat between the South Atlantic and its neighboring basins. He found that his data gave a northward heat transport in the conveyor belt of 0.25 ± 0.12 PW with no direct input from the Indian Ocean and that forcing his model to carry a larger conveyor belt heat transport, or to allow an influx of Indian Ocean water in the Agulhas region, led to an unrealistic circulation in the rest of the model domain with an overvigorous overturning in the Atlantic and a near reversal of the Brazil Current. A large equatorward heat flux in the Atlantic also led to an unrealistic circulation in the work of Macdonald [1993], who used the same method with a different set of hydrographic sections. The Brazil Current in FRAM shows no reversal; indeed, it has a very strong poleward transport of 51 Sv at 37°S [*Stevens and Thompson*, 1994] which is larger than the 19-22 Sv estimated by *Gordon and Greengrove* [1986] using a reference level of 1400-1500 m but smaller than the 70 Sv referred to deeper levels [*Zemba and McCartney*, 1988; *Peterson*, 1990].

As the ACC crosses the South Atlantic in *Rintoul's* [1991] calculation, it "loses" 0.25 ± 0.18 PW. This is not due to a general cooling of the waters of the ACC; rather, it is due to the formation of deep and bottom waters at high latitudes. FRAM shows similar behavior. From Figure 4 it can be seen that, as it crosses 21°E, the ACC (south of the 0 Sv contour) carries 0.26 PW less than it does on entering the basin.

Figure 6 shows the water mass budget for the ACC and the Atlantic section of the conveyor belt in FRAM, calculated using the definitions given by *Rintoul* [1991]. Table 1 shows the effect that the Atlantic has on the ACC in terms of water mass conversion, with positive values representing a net formation of a particular water mass. Water mass changes are calculated by taking the difference between the transport through Drake Passage and that across 21°E (for FRAM) or the 0° and 30°E sections (for Rintoul's work) for each layer. The first column of FRAM results is calculated using the transports between Antarctica and Africa at 21°E, whereas, for the column headed FRAM2, the ACC is considered

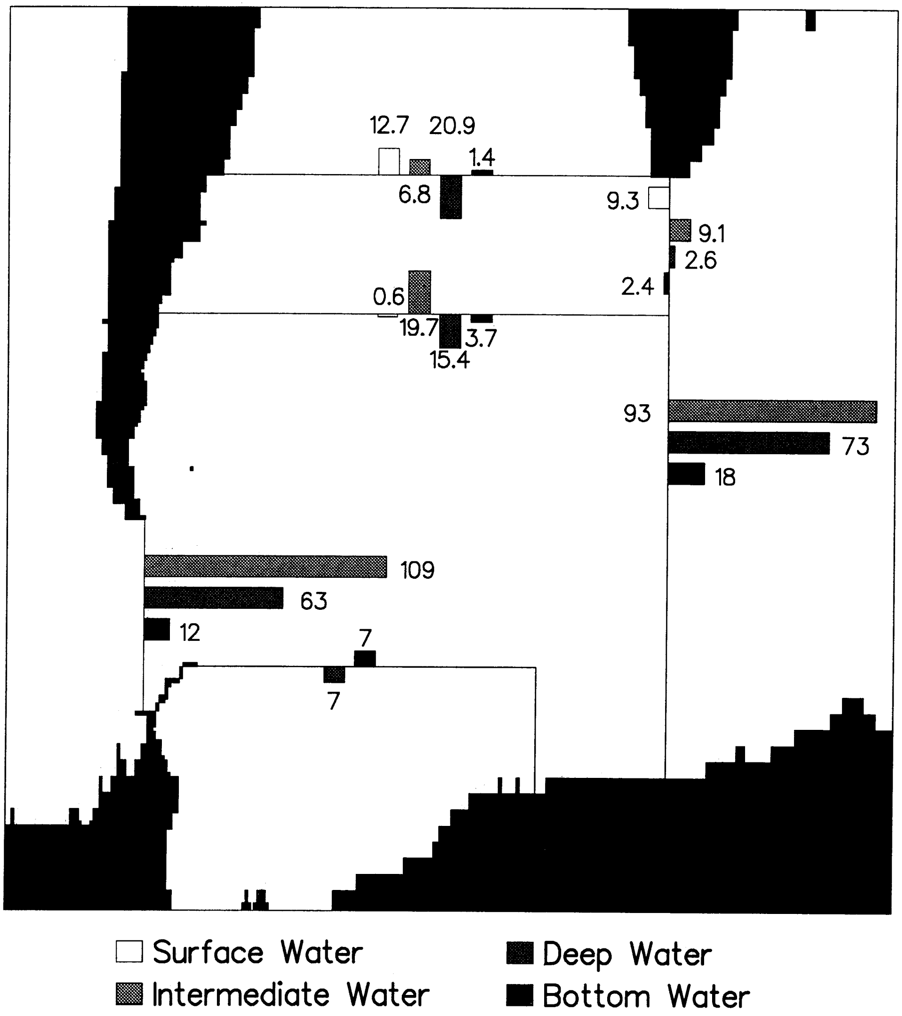

Figure 6. South Atlantic water mass budget for FRAM. Units are Sverdrups.

to extend only as far north as the time varying 0 Sv point on the 21°E section. The two sets of results are presented in order to suggest a range of values for the transport in each layer: the 0 Sv point does not strictly define the boundary of ACC waters, but neither can the westward flow in the Agulhas region be considered part of the ACC.

Although the transports in the ACC are larger in FRAM (in *Rintoul*'s [1991] inversion the ACC was constrained to have a transport of $130 \pm 13 Sv$ in the ACC) as shown in Figure 6, Table 1 shows that the pattern of conversion of water masses is similar in the two models. The Atlantic converts Intermediate Water (IW) to Deep Water (DW) and Bottom Water (BW) in both models. Another similarity between the models is in the apparent conversion of DW to BW in the Weddell Sea. The word apparent is used because, as has already been mentioned, production of BW is poorly represented in FRAM; thus the transports out of the Weddell Sea are of water "left behind" by the initialization. This probably accounts for FRAM exporting less BW than Rintoul's model.

Where the two models differ, however, is in the heat transport in the conveyor belt and in the transfer of water from the Indian Ocean into the Atlantic. Further evidence for the domination of Agulhas input over CWP influence is given by considering the section at 41.5°S. The CWP depends on the conversion of IW to SW via outcropping in the South Atlantic. Figure 6, however, shows that there is very little net transport of SW across the southern face of the "box" at 41.5°S. This low net transport actually arises because there is very little water of this density range crossing the section in either direction. Calculating the total surface heat flux into the box (not including the western boundary current and Agulhas ring areas which are losing heat to the atmosphere) reveals that only 0.06 PW is available to any outcropping IW; thus the CWP appears not to be very important in FRAM. FRAM appears to support similar water mass conversion in the South Atlantic to *Rintoul*'s [1991] models, but additionally, a significant leakage of SW from the Indian Ocean augments the northward transport in the conveyor belt.

Matano and Philander [1993] have used the mean

Table 1. Water Mass Changes for the ACC as It Passes Through the Atlantic

Water Mass	Rintoul	FRAM 1	FRAM 2
Surface Water ($\sigma_0 < 26.80$)	4	-9	0
Intermediate Water ($\sigma_0 \geq 26.80$ and $\sigma_2 < 32.36$)	-14	-7	-16
Deep Water ($\sigma_2 \geq 32.36$ and $\sigma_3 < 41.66$)	7	13	10
Bottom Water ($\sigma_3 \geq 41.66$)	3	3	6

Values are given in Sverdrups. Positive values represent a gain. The definition of the layers follows *Rintoul* [1991], with the 13 layers divided into four water masses according to direction of flow and density. FRAM 1 refers to the calculation carried out using the full 21°E section, whereas in the FRAM 2 case, the 0 Sv point was taken as the northern limit of the ACC.

Levitus [1982] data in a similar way to FRAM in a study of the heat and mass balance of the South Atlantic. They employed a limited area Cox-Bryan model with resolution between 1/2 and 1° horizontally and 15 levels in the vertical and initialized it using the annual mean Levitus climatology. They state that by limiting the integration time they allow the model to adjust dynamically to the wind forcing and topography but avoid changes in the density field due to thermodynamic adjustment. They find that the Atlantic transports 0.19 PW northward at 30°S and that the CWP plays a large role. However, they also point out that divergence of heat in their model may be too large, perhaps resulting in too great a conversion of intermediate water to surface water. This points to the need for alternative sources of heat, such as the WWP.

FRAM has several advantages over this model. Because of the open ocean boundaries at Drake Passage and between Africa and Antarctica, *Matano and Philander* [1993] needed to prescribe the mass transport stream function, as well as temperature and salinity for water flowing in through these boundaries. As FRAM includes the other oceans within its domain, exchanges between them can be studied and the interbasin exchange can be measured directly. Second, FRAM uses an open boundary condition at its northern boundary [*Stevens*, 1991] rather than the solid one employed by Matano and Philander. The solid northern boundary at 20°S could probably affect the strength of the overturning circulation near 30°S in which intermediate and surface waters flowing north are balanced by a poleward flow of NADW. The size of the equatorward heat transport is closely related to the strength of this circulation. In Matano and Philander's model this circulation is weaker than that found by *Rintoul* [1991] and FRAM [see *Saunders and Thompson*, 1993]. Furthermore, FRAM has a higher horizontal and vertical resolution enabling it to begin to represent eddies, which appear to play a role in transporting heat between the Indian Ocean and the Atlantic.

4. Comparisons With a Low-Resolution Model

In order to assess the impact of the Agulhas current system and the associated rings on the heat budget of the South Atlantic, FRAM has been compared with a coarse resolution integration of the same region (henceforth referred to as CRAM).

CRAM has a horizontal resolution of 4° east-west and 2° north-south (giving a grid size of approximately 220 km at 60°S) but has an identical vertical level distribution to FRAM. It was initialized in a similar way to FRAM. The value of horizontal viscosity A_h was increased in order to resolve the western boundary layer to the same extent as it was resolved in FRAM, according to *Munk* [1950], that is

$$L \propto \left(\frac{A_h}{\beta}\right)^{\frac{1}{3}}$$

where L is the width of the boundary layer and β is the northward gradient of the coriolis parameter. The value of A_h used in CRAM was 8×10^4 m^{2}s^{-1} compared with 2×10^2 m^{2}s^{-1} for FRAM. There is no equivalent theory governing choice of the coefficient of horizontal diffusivity κ_h. Current practice seems to be to use the smallest value without allowing numerical instability to become a problem. High values of κ_h lead to a rapid decline in the strength of the ACC (due to diffusive flattening of density gradients across the current). Another consequence of using high values of κ_h in CRAM was the failure of the model to represent the southward transport of NADW. The coefficient of horizontal diffusivity κ_h was determined by trial and error until the overturning stream function (that is, the vertical integration of the zonally integrated meridional velocity field) in each basin matched approximately those in FRAM. With $\kappa_h = 10^3$ m^{2}s^{-1} the overturning circulation found in Figure 7b compares well with the FRAM circulation (Figure 7a) albeit with a slightly weakened overturning in the Atlantic.

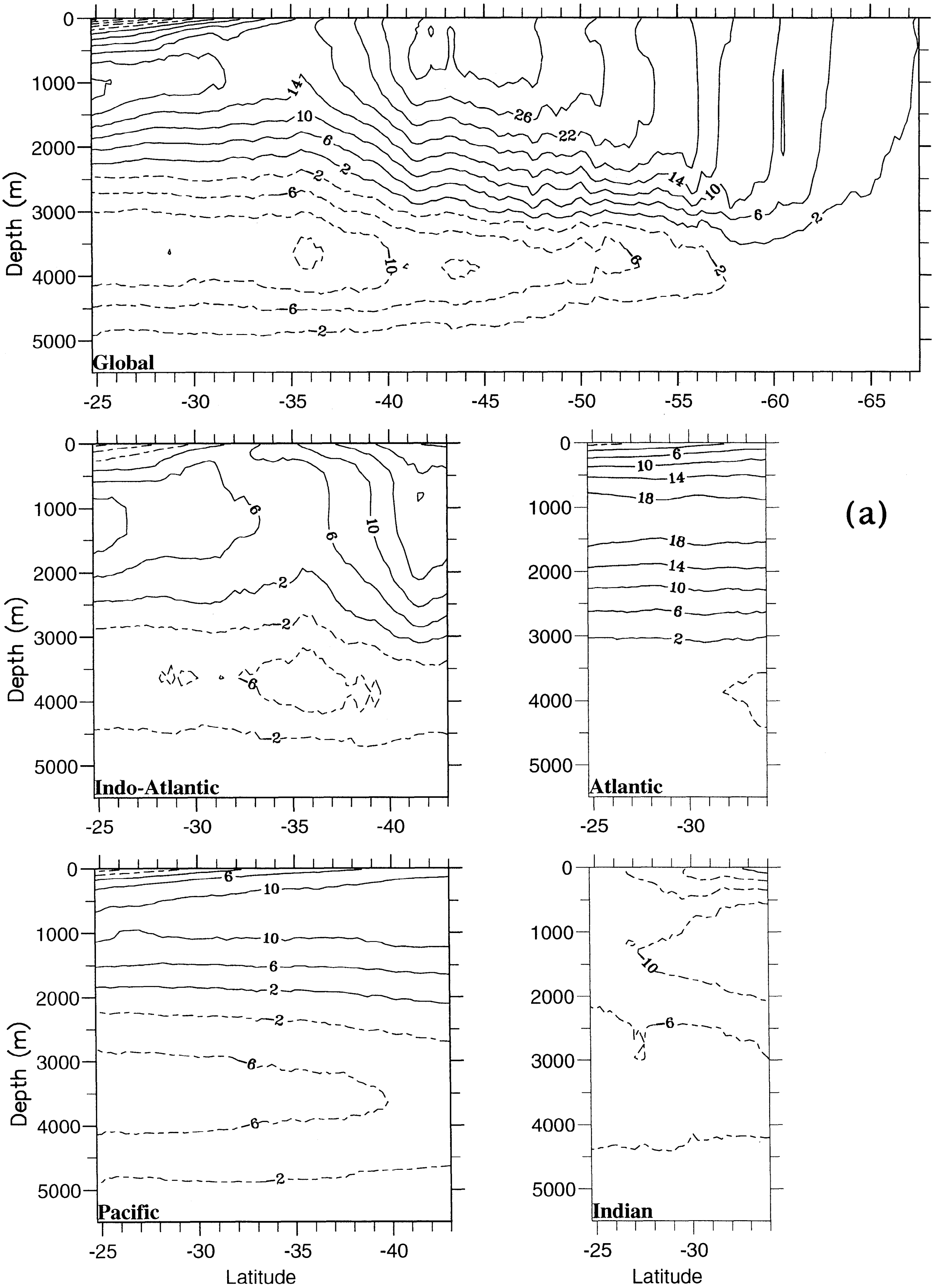

Figure 7. Mean overturning stream function in (a) FRAM and (b) CRAM. The larger panels show the global integration, whereas the smaller panels represent individual basins.

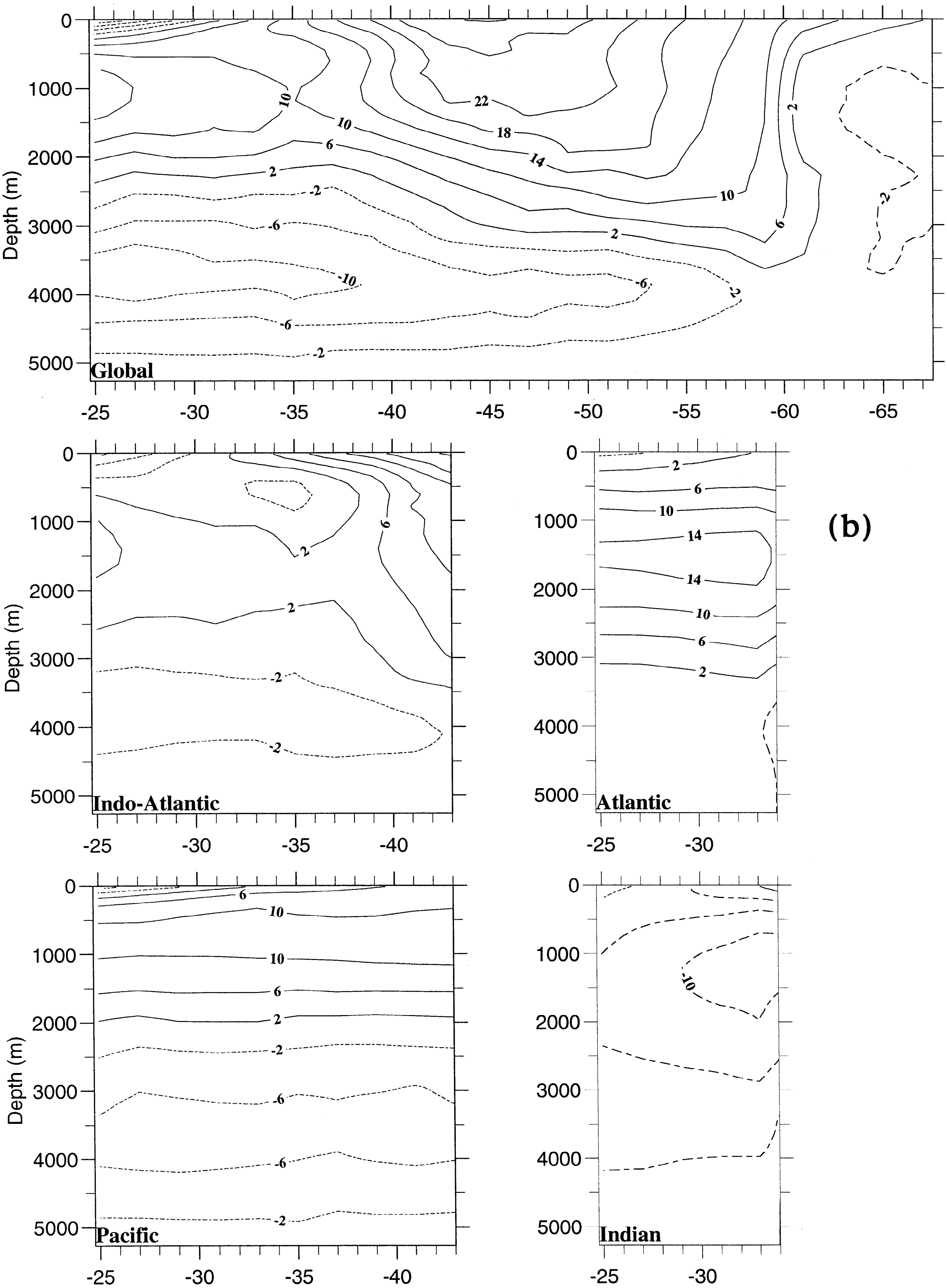

Figure 7. (continued)

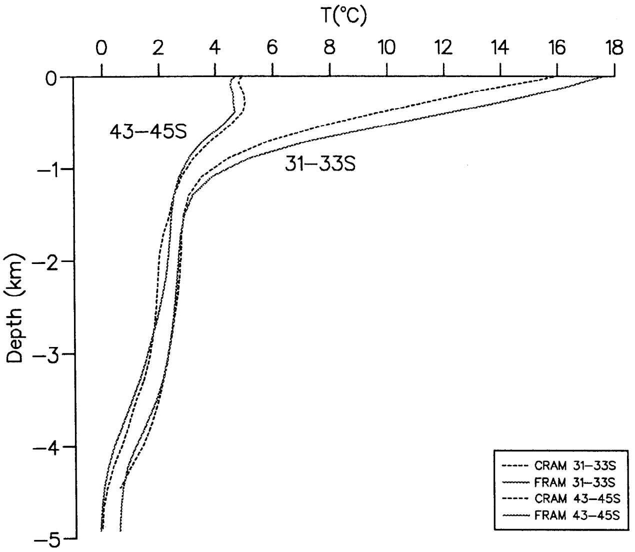

Figure 8. Zonal mean temperature in FRAM and CRAM for regions to the north and south of the shaded box in figure 4.

Having established a coarse resolution integration with roughly the same circulation as its fine resolution counterpart, but obviously lacking any of the mesoscale processes found in the latter, it is interesting to look at some of the differences between the models. Figure 8 shows the Atlantic basin-wide mean temperature for the 10- to 16-year period of the integration for regions north and south of the shaded region shown in Figure 4. The temperature in the top 1500 m to the north of the box is clearly lower in CRAM than in FRAM, but this is not due to a lower temperature at similar depths in waters to the south; that is, the lower shallow and intermediate water temperatures are not a general feature of the coarse resolution integration. Furthermore, the difference in temperature cannot be explained by changes in surface heat flux (which arises from the relaxation to the *Levitus* [1982] temperature field near the surface): due to the lower surface temperatures in the Atlantic in CRAM, the model actually receives more heat from the atmosphere than FRAM in this region (8.7 $\mathrm{Wm^{-2}}$ for CRAM compared with 5.5 $\mathrm{Wm^{-2}}$ for FRAM).

In addition to the fact that the overturning circulation in the Atlantic is weaker in CRAM, because of the lower temperature of the northward flowing component, the meridional advective heat transport is much reduced (0.24 PW compared to 0.64 PW in FRAM). The increased diffusive fluxes in CRAM only serve to reduce the northward transport even more with a southward transport of 0.13 PW across the 33°S section. By examining the mass transport in layers of constant temperature we found that FRAM has 22.0 Sv of water flowing northward above the southward flowing NADW. The transport weighted mean temperature of this warm arm of the conveyor belt is 11.6°C. In CRAM this flow is reduced to 15.3 Sv at a mean temperature of 8.0°C. An estimate of the relative contributions to the reduction in the meridional heat transport in the Atlantic can be made by noting that 22 Sv $\times(11.6-8.0)$°C = 79.2 Sv°C (= 0.3 PW) difference is caused by the reduced temperature in CRAM, while $(22.0-15.3)$ Sv ×11.6°C = 77.7 Sv°C difference is due to the weaker northward flow; that is, each makes a similar contribution.

Thus it appears that the cooling of the northward flowing arm of the conveyor belt is due largely to a lack of heat input in the Agulhas region. The heat transport between the two basins is only 0.02 PW (compared with 0.51 PW in FRAM). Due to the coarse resolution, the complex behavior south of Africa is not represented: the Agulhas rings are not resolved and there appears to be very little exchange of water from the Indian Ocean into the Atlantic. Confirmation of the reduced interocean exchange is provided using a method based on water particle trajectories [*Döös*, 1995]. In FRAM, 24 Sv of water enters through the open boundary in the Indian and Pacific Oceans and takes the WWP around Africa before leaving the model through the open boundary in the Atlantic. In CRAM this transport is reduced to 5 Sv.

In another CRAM integration, the model temperature and salinity fields were relaxed (using a 1-year relaxation constant) toward those found in FRAM at the beginning of year 10. After 10 years integration, the relaxation was switched off (except at the surface) and the model was allowed to develop for a further 6 years. Figure 9 shows the time evolution of the temperature of the top 1500 m for regions to the north and south of the shaded box in Figure 4. The temperature in FRAM to the north of the box remains reasonably steady, whereas the temperature in CRAM for the same region falls off rapidly (reaching values close to those found in the previous CRAM integration within 2 years). For the region south of the box, however, the two models appear

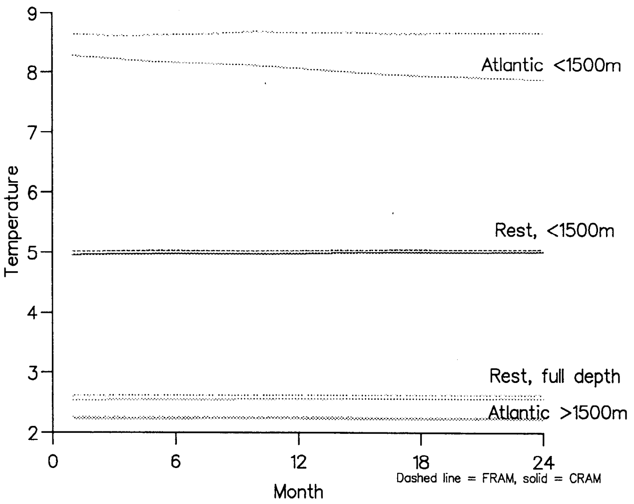

Figure 9. Temperature evolution of the South Atlantic for FRAM (dashed lines) and for the second CRAM integration (solid lines).

to evolve in an almost identical fashion. The rate of decrease in the temperature of the top 1500 m of the Atlantic in CRAM is equivalent to a missing heat input of around 0.3PW. From Figure 9 we can see that this is probably an underestimate of the effect of the missing Agulhas region heat input, as the relaxation toward the FRAM state has failed to maintain the temperature in the Atlantic during the 10 years of spin-up leading up to the beginning of the period shown in Figure 9. It would seem likely that if the two curves had started from the same point, the temperature in CRAM would have decreased even more quickly toward its equilibrium value.

A repeat of the water mass analysis was made for the South Atlantic in CRAM, again using the layer definitions employed by *Rintoul* [1991]. Rather than a westward flow of SW into the Atlantic from the Agulhas Retroflection region as found in FRAM, there is a small eastward flux (0.6 Sv). There is, however, a small westward flux (1.6 Sv) of IW in this region. The layer transports across 34°S in the Atlantic reflect these changes, with a large reduction in SW exported northward from the southern South Atlantic. There is an increase in the net amount of IW flowing north, but it is not enough to compensate for the deficit of SW.

5. Discussion

Surface forcing in the FRAM integration took the form of relaxation of the surface temperature and salinity values toward the annual mean values given by *Levitus* [1982] with a relaxation timescale of 1 year. In an attempt to estimate the effect of the lack of seasonality in this forcing scheme, the seasonally varying Levitus values were substituted for model values in the top level and the heat transports were recalculated for the 10- to 16-year period of the run. While there were significant differences in the heat transports, these were found not to be due to any seasonal correlations between the temperature and velocity fields. The main cause was large differences in the mean temperature: due to the weak forcing, large temperature deviations from the Levitus values developed. Large areas of the surface in the South Atlantic were 3 to 4°C cooler than the Levitus values, with extreme differences of almost 10°C near strong frontal regions.

The weak relaxation had been chosen so as not to dampen development of the eddy field, and relaxation toward the annual mean fields was used because this was the best that was available at the time the model was being developed.

Further experiments with the coarse model showed that reducing the relaxation timescale to 1 month reduced the differences from the Levitus values and caused an increase in the meridional heat transport in the Atlantic to 0.39 PW compared with 0.24 PW using the 1-year timescale. However, the heat input through the surface required to maintain the temperature in level 1 increased dramatically. For the area of the South Atlantic where the surface cooling occurred, between 47°S and 35°S, the surface heat flux increased from the 0.14 PW found in CRAM to 0.40 PW (equivalent to 33 Wm^{-2}). This is higher than the values of 0-20 Wm^{-2} for the annual mean net downward heat flux in this area calculated by *Esbensen and Kushnir* [1981], but the sparsity of data in this region makes their estimates rather uncertain. Thus it appears that the Atlantic conveyor belt heat transport in the model could largely be maintained through surface heat fluxes in the South Atlantic (as stated by *Cai and Greatbatch* [1995]). However, the FRAM integration shows that in the absence of a direct CWP, it is possible for the heat to be supplied via the Agulhas Retroflection region (whether it be in the form of the WWP or via the detour of the CWP described by *Gordon et al.* [1992]).

To summarize, transfer of water from the Indian Ocean into the Atlantic via the Agulhas region appears to be an important mechanism for supplying heat to the South Atlantic in FRAM. We cannot categorically state whether the conveyor belt is supplied via the WWP or CWP (because we cannot know whether water supplied to the South Atlantic would eventually take part in convection at high latitudes and return as NADW). However, the large input of heat into the South Atlantic from the east and the fact that the heat transport in the conveyor belt drops when these eddies are not present suggest that the WWP is important.

One could argue that the question of whether FRAM supports the CWP or WWP is academic, since, even though we have tried to verify the model against observations and other models, FRAM is only a model. However, the main result of this study is to point out that in a high-resolution model, there is a transfer of heat into the South Atlantic in the Agulhas Retroflection region, which has a major impact on the amount of heat transport in the conveyor belt. Decreasing the resolution of the model leads to the near extinction of the transfer and consequently a lower equilibrium temperature in the South Atlantic. The dependence of the strength of the meridional heat transport in the South Atlantic on model resolution is of particular concern in the use of ocean models for climate studies.

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