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The origin of Intermediate and Subpolar Mode Waters crossing the Atlantic equator in OCCAM

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[1] The origin of the intermediate waters that cross the equatorial Atlantic as part of the return flow for North Atlantic Deep Water was studied in a high resolution global ocean model using a Lagrangian particle following technique. Most of these waters are subducted in the southeast Indian Ocean. Less than twenty percent comes directly from Drake Passage without looping into the Indian Ocean; the majority being provided by Agulhas leakage. Most of the intermediate waters that subduct in the South Atlantic do not follow the South Atlantic/Indian Ocean supergyre, but remain within the Antarctic Circumpolar Current, and gradually transform into Circumpolar Deep Water by diapycnal mixing. **Citation:** Drijfhout, S. S., J. Donners, and W. P. M. de Ruijter (2005), The origin of Intermediate and Subpolar Mode Waters crossing the Atlantic equator in OCCAM, *Geophys. Res. Lett.*, *32*, L06602, doi:10.1029/2004GL021851.

1. Introduction

[2] Extending northward from the Subantarctic Front (SAF) a layer of low salinity is found in the Atlantic, Pacific and Indian Oceans, at a depth of 800 to 1000 meters. In the Atlantic this layer of Antarctic Intermediate Water (AAIW) can be traced up to 30°N [*Talley*, 1996]. Until recently [*Reid*, 1989; *Larqué et al.*, 1997], the possibility of direct northward flow of AAIW along the western boundary was still left open. *Boebel et al.* [1997] addressed this by analyzing direct observations of moored current meters and neutrally buoyant floats, concluding that no evidence existed for direct northward flow between 40°S and 30°S. The emerging picture was, that AAIW, either entering the South Atlantic via Drake Passage or by being formed [*Piola and Gordon*, 1989] at the Brazil-Malvinas Confluence from its primary precursor Subantarctic Mode Water (SAMW) [*McCartney*, 1977], was advected within the South Atlantic with the wind-driven gyre until it reached the Santos bifurcation [*Schmid et al.*, 2000], where part of it returned southward to recirculate within the subtropical gyre, and another part followed the northern route to cross the Atlantic equator.

[3] Such a picture was consistent with the view of *Rintoul* [1991] that AAIW entering the South Atlantic via Drake Passage is the major contributor to the North Atlantic Deep Water (NADW) return flow, challenging the warm water route described by *Gordon* [1986]. In an update, *Gordon et al.* [1992] stressed the role of AAIW, but argued that most AAIW flows in the Indian-Atlantic supergyre [*de Ruijter*, 1982]. Feeding the Agulhas Current it could return to the South Atlantic by Agulhas leakage. This was supported by several model studies [*Speich et al.*, 2001; *Donners and Drijfhout*, 2004]. Corroborating the theory of *McCartney* [1977], it was found that SAMW and AAIW feature rather close origins: they follow similar flow patterns and seem to be governed by similar dynamics. Typically, about 1 Sv of SAMW and AAIW flows from Drake Passage to the Atlantic equator by directly folding from the South Atlantic Current into the Benguela Current, while some 5–6 Sv of these water masses are provided by Agulhas leakage; the rest being made up by warmer water coming from the Indian Ocean.

[4] The Southwest Atlantic is no self-evident source region for the SAMW and AAIW that cross the equator when they are mainly provided by Agulhas leakage from the Indian Ocean. Observational data are too sparse and non-synoptic to give an unequivocal answer to the origin of a water mass. Therefore, we will study the origin of these waters by a Lagrangian analysis of a high-resolution, global ocean model. In the ocean model the origin of water masses can be traced exactly, but the model may be biased. Therefore, we regard the model results as a hypothesis for the real world, which can be further tested within an observational program.

2. Methods

[5] Data have been employed from the global ocean model OCCAM [*Webb et al.*, 1997]. The model uses an eddy-permitting resolution of 1/4°, and employs 36 depth levels, with 16 layers in the upper kilometer. It is initialized with temperature and salinity from the Levitus 1994 climatology. For more details on the model, and the construction of the seasonal mean and eddy-induced velocity fields we used in this study, we refer to *Drijfhout et al.* [2003] and *Donners and Drijfhout* [2004].

[6] To estimate subduction sites and pathways of subducted water masses, a three-dimensional Lagrangian trajectory technique was used. The tracing technique was originally developed by *Döös* [1995] and *Blanke and Raynaud* [1997]. Velocities were linearly interpolated between seasonal means with the technique of *de Vries and Döös* [2001] for the use with time-dependent flows.

[7] To find the sources of a specific water mass trajectories were started from the Atlantic equator and backtraced in

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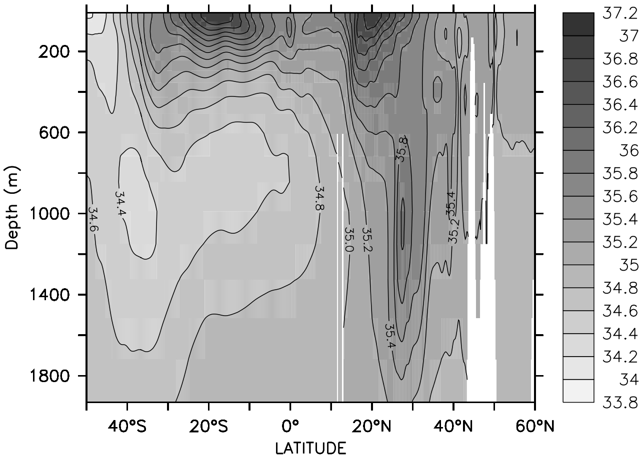

Figure 1. Model generated salinity in the upper 2000 m along approximately 25°W, showing the northward spread of low salinity, intermediate water in the Atlantic. The topography is denoted in white.

time until they entered the interior ocean through the winter mixed layer base. This site, where the water mass properties are set just prior to subduction, is the origin of the water mass. The fate of subducted water masses is found by tracing trajectories forward after they enter the interior through the base of the mixed layer. Because of the particle seeding being proportional to the transport across an initial surface or section, the results can be quantified. Each particle represents a transport of at most 10^{-3} Sv. To obtain a quantitative picture of the Lagrangian subduction ten thousands of particle trajectories have been calculated. The accuracy of the total transports is within 0.1 Sv. This Lagrangian analysis of subduction follows the method of *Blanke et al.* [2002].

3. Results

[8] Figure 1 shows a vertical section of salinity along 25°W in the South Atlantic. North of the equator, the section follows a curve that ends east of Iceland. The exact course of the section is not relevant here. It almost coincides with the sections discussed by *Tsuchiya et al.* [1992, 1994] and *Talley* [1996]. As we use the climatology of a three-year average, the model field is somewhat smoother than the fields derived from a quasi-synoptic hydrographic section. The main characteristics, however, are strikingly similar. There is a minimum salinity layer which subducts poleward of the Subantarctic Front at 45°S. Surface values fall below 34.0 psu. A salinity layer with minimum values of 34.36 psu extends to 1000 m depth and as far north as the Brazil Current Front at 32°S. Equatorward from 32°S the salinity minimum is found at about 800 m depth and gradually becomes more saline; at the equator the salinity minimum has become 34.6 psu. Northward of the equator the salinity minimum can be traced until about 20°N. Apparently, in the model, propagation of the salinity minimum layer in the Atlantic is still very close to the observations, and the same holds for its T,S-characteristics and the large-scale density field, although the T,S-characteristics are slightly biased to saltier and warmer.

[9] The salinity minimum layer is associated with intermediate water, especially AAIW. *Donners et al.* [2005] found that SAMW and AAIW follow similar flow patterns. Therefore, we define Intermediate Water (IW) by $26.6 < \sigma_0 < 27.3$, a density range that encompasses both water masses. This rather broad range may include some other thermocline water masses. It was motivated by choosing the largest volume that still features homogeneous origins and flow characteristics.

[10] The origin of IW that crosses the Atlantic equator was traced with a Lagrangian calculation. There is 6.1 Sv of IW that crosses the equator northward; about 40% of the upper branch of the Atlantic Meridional Overturning Cell (MOC). Of this 6.1 Sv, 1.0 Sv was subducted in the South Atlantic. Figure 2 shows the subduction sites of the IW that crosses the Atlantic equator. The majority, 3.9 Sv originates from the southeast Indian Ocean. *McCarthy and Talley* [1999] showed that the dominant mode of ventilation for the Indian Ocean is Southeast Indian SAMW (SEISAMW). It appears that in the model this mode water is the main contributor to the cross-equatorial intermediate flow in the Atlantic. This can be understood, as the major part of the intermediate water flow (re)enters the South Atlantic by Agulhas leakage, while the direct connection between Drake Passage and the Atlantic equator, with the South Atlantic Current folding into the Benguela Current, is of the order of 1 Sv only [*Donners and Drijfhout*, 2004].

[11] The spread of SEISAMW in the Indian Ocean was suggested by the map of potential vorticity at its core layer [*McCarthy and Talley*, 1999]. South of Australia the SEISAMW spreads westward. Beyond the west cape it follows a more northerly route, whereafter it seems to become entrained into the South Indian subtropical gyre, heading toward Madagascar. This pathway almost exactly coincides with the main route of Tasman leakage, described by *Speich et al.* [2002], which was found with the same Lagrangian trajectory technique as has been used here. It was also found that it is mainly IW that follows this route. So, IW at the Atlantic equator is mainly ventilated as

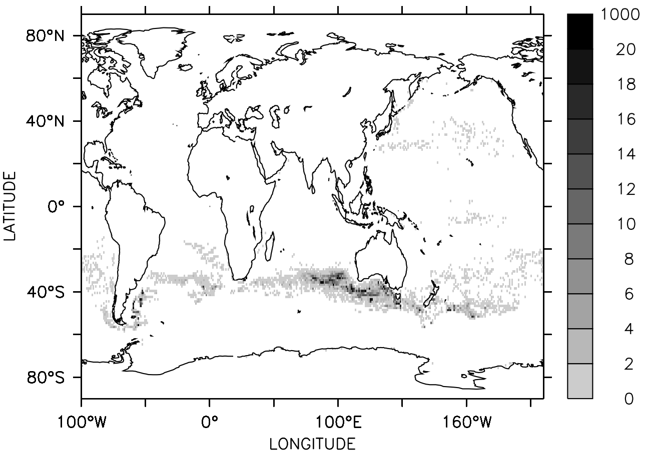

Figure 2. Subduction sites of the intermediate waters that cross the Atlantic equator northward and that form part of the global overturning circulation (THC). The subduction sites were found by backtracing water particles that cross the Atlantic Equator until they 'hit' the winter mixed layer. Mass fluxes are denoted in mSv per 1° × 1° gridbox.

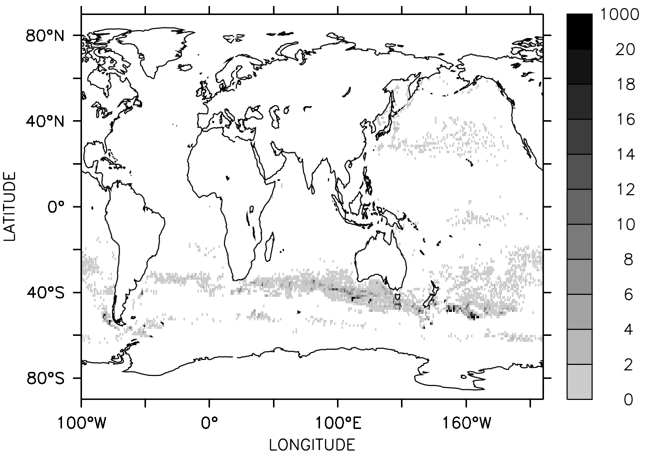

Figure 3. Final subduction sites of South Atlantic intermediate water before it is transformed into deep water, after re-emergence in the mixed layer. The sites were obtained by forward tracing water particles. Note that this IW does not take part in the MOC.

SEISAMW following the pathways of Tasman leakage. It should be noted that along this route the waters gradually densify through diapycnal mixing. As a result, IW is lighter at its formation sites than when it crosses the equator; most of its subducts as SAMW in the class $26.6 < \sigma_0 < 27.0$. At deeper σ-levels the southwest Indian Ocean is more directly ventilated [*McCarthy and Talley*, 1999], but this mode of AAIW apparently recirculates in the Indian-Atlantic supergyre and is ultimately transformed into CDW instead of taking part in the NADW return flow.

[12] If the source regions of IW that crosses the equator are mainly in the southeast Indian Ocean, the question arises what the fate is of the IW that subducts in the South Atlantic. It appears that 11.6 Sv of IW subducts in the South Atlantic. Of this 11.6 Sv, only 3.7 Sv ultimately crosses the Atlantic equator as part of the northward upper branch of the MOC. The remaining 7.9 Sv is advected downstream with the Antarctic Circumpolar Current and gradually mixes with denser waters to form deep water, mainly CDW. Of the 3.7 Sv that crosses the Atlantic equator, 1.5 Sv re-emerges and re-subducts as TW and 2.2 Sv crosses the Atlantic equator as IW. Of this 2.2 Sv, 1.6 Sv re-emerged and was re-subducted outside the Atlantic basin. This implies that of the South Atlantic IW 68% transforms to deep water; 13% transforms to TW which crosses the Atlantic equator; 14% transforms to other varieties of IW, mainly SEISAMW, which thereafter cross the Atlantic equator: 5% directly feeds the NADW return flow as South Atlantic IW. Figure 3 shows, after re-emergence in the mixed layer, the last subduction site before the South Atlantic IW is transformed to deep water. Most transformation to deep water takes place in the Southern Ocean forming CDW, but some transformation also occurs in the tropical and North Pacific. 4.7 Sv IW re-emerges and re-subducts before it transforms to deep water, while 3.2 Sv directly mixes with denser water after being subducted in the South Atlantic.

[13] This result suggests that a series of water mass transformation events occurs within the circulation loop associated with NADW export and its return flow. In OCCAM most NADW upwells poleward of the ACC and is advected with the Ekman flow into the basins north of the ACC. Most of this water enters the South Pacific and flows back through the Indonesian passages and south of Australia. IW favors the latter route and final subduction takes place in the SE Indian Ocean. However, some 40% of the SEISAMW directly loops from the ACC into the Indian Ocean, after crossing the Atlantic, with prior subduction in the southwest of the basin.

4. Discussion and Conclusions

[14] Two model deficiencies could severely impact the picture sketched above. Firstly, the model is not yet in steady state, and model drift may affect subduction rates and subduction pathways. *Donners and Drijfhout* [2004] tested transport time series of IW and TW in the South Atlantic, but found no significant trend. Drift might spuriously increase the apparent diapycnal mixing of water masses in the model. This could bias the fate of South Atlantic IW toward a transformation into more CDW. But the excess of IW subduction in the South Atlantic with respect to IW crossing the Atlantic equator necessitates a large fraction of it to transform into CDW. For instance, *Sloyan and Rintoul* [2001] estimate a total IW to CDW conversion of 31.7 Sv for the World Ocean. This suggests that our finding that the main fraction of South Atlantic IW is transformed into CDW is not unrealistic. Also, excessive diapycnal mixing might bias the IW source regions to those where lighter water masses subduct. This would not affect the importance of SEISAMW as a source for the IW that crosses the equator, but might lead to underestimation of the AAIW formation sites in the southwest Atlantic and Indian Ocean.

[15] Drift also affects the water mass characteristics of the IW considered here. Figure 4 shows a theta-salinity diagram which compares the 25°W and 100°E Levitus and OCCAM data at 30°S. The model data feature too warm and saline

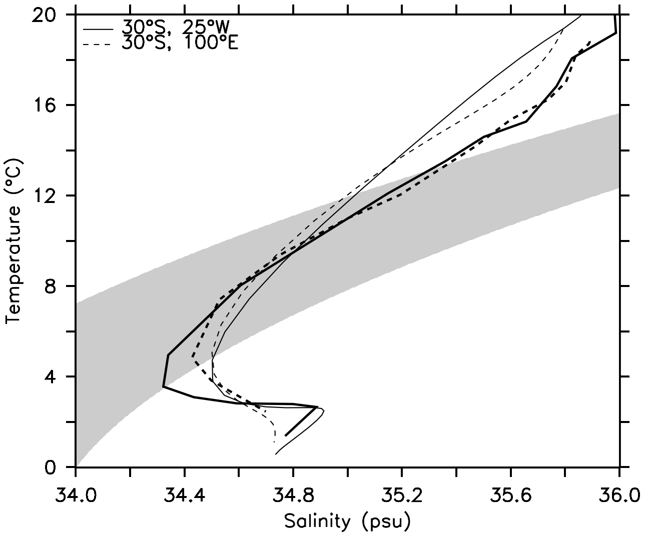

Figure 4. The temperature-salinity diagram for two locations (both at 30°S), one in the South Atlantic and one in the South Indian Ocean. The thin lines are annual mean data from the OCCAM model, the thick lines are data from the Levitus climatology. The density range for the IW is indicated by the grey area.

intermediate water, thermocline water and SAMW is too cool and too fresh. The bias in IW characteristics is associated with a northward bias of density fronts in the ACC [*Donners et al.*, 2005]. The increased heat gain and evaporation resulting from relaxating to Levitus data compensate each other in density. As a result there is no density bias associated with IW formation in OCCAM and we assume that the effect on the circulation is small.

[16] A second model deficiency is a too weak water mass transformation due to relaxing to surface climatologies of temperature and salinity [*Fox and Haines*, 2003]. This model error will tend to produce too weak subduction rates. Also, in reality the IW formed at high-latitudes is subject to very intense and very variable forcing that is completely omitted in the model and which impact is unclear besides a further underestimation of subduction. *Karstensen and Quadfasel* [2002], for instance, estimate larger subduction rates in the South Atlantic as we find with our model, but they also find a larger export of these subducted water masses to the other ocean basins. As the MOC in OCCAM is of realistic strength, a larger subduction rate of South Atlantic IW would necessitate a larger fraction of it to be converted into CDW, opposing a possible bias due to drift. By and large, we may conclude that these model deficiencies are likely to underestimate the total subduction rates of IW all over the World Ocean, but that there are no simple arguments which suggest that the qualitative picture that emerges from these model results is wrong. However, caution should be taken when interpreting these model results and it seems more appropriate to regard them as a possible behavior of the real ocean.

[17] In summary, our main conclusions are that most IW crossing the Atlantic equator is formed in the southeast Indian Ocean, being dominantly SEISAMW. The fate of South Atlantic IW is mainly a transformation into CDW. The largest fraction that crosses the Atlantic equator as IW has re-emerged elsewhere, and was re-subducted, mainly in the southeast Indian Ocean. Most of the South Atlantic IW that directly flows to the Atlantic equator without being re-subducted in other basins is transformed and re-subducted in the South Atlantic as TW.

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References

Blanke, B., and S. Raynaud (1997), Kinematics of the Pacific Equatorial Undercurrent: An Eulerian and Lagrangian approach from GCM results, *J. Phys. Oceanogr.*, *27*, 1038–1053.

Blanke, B., S. Speich, G. Madec, and R. Maug (2002), A global diagnostic of interior ocean ventilation, *Geophys. Res. Lett.*, *29*(8), 1267, doi:10.1029/2001GL013727.

Boebel, O., C. Schmid, and W. Zenk (1997), Flow and recirculation of Antarctic Intermediate Water across the Rio Grande Rise, *J. Geophys. Res.*, *102*, 20,967–20,986.

de Ruijter, W. P. M. (1982), Asymptotic analysis of the Agulhas and Brazil Current systems, *J. Phys. Oceanogr.*, *12*, 361–373.

de Vries, P., and K. Döös (2001), Calculating Lagrangian trajectories using time-dependent velocity fields, *J. Atmos. Oceanic Technol.*, *18*, 1092–1101.

Donners, J., and S. Drijfhout (2004), The Lagrangian view of South Atlantic interocean exchange in a global ocean model compared with inverse model results, *J. Phys. Oceanogr.*, *34*, 1019–1035.

Donners, J., S. S. Drijfhout, and W. Hazeleger (2005), Water mass transformation and subduction in the South Atlantic, *J. Phys. Oceanogr.*, in press.

Döös, K. (1995), Interocean exchange of water masses, *J. Geophys. Res.*, *100*, 13,499–13,514.

Drijfhout, S. S., P. de Vries, K. Döös, and A. C. Coward (2003), Impact of eddy-induced transport on the Lagrangian structure of the upper branch of the thermohaline circulation, *J. Phys. Oceanogr.*, *33*, 2141–2155.

Fox, A. D., and K. Haines (2003), Interpretation of water mass transformations diagnosed from data assimilation, *J. Phys. Oceanogr.*, *33*, 485–498.

Gordon, A. L. (1986), Interocean exchange of thermocline water, *J. Geophys. Res.*, *91*, 5037–5046.

Gordon, A. L., R. F. Weiss, W. M. Smethie, and M. J. Warner (1992), Thermocline and Intermediate Water communication between the South Atlantic and Indian oceans, *J. Geophys. Res.*, *97*, 7223–7240.

Karstensen, J., and D. Quadfasel (2002), Formation of Southern Hemisphere thermocline waters: Water mass conversion and subduction, *J. Phys. Oceanogr.*, *32*, 3020–3038.

Larqué, L., K. Maamaatuaiahutapu, and V. Garçon (1997), On the Intermediate and Deep Water flows in the South Atlantic Ocean, *J. Geophys. Res.*, *102*, 12,425–12,440.

McCarthy, M. C., and L. D. Talley (1999), Three-dimensional isoneutral potential vorticity structure in the Indian Ocean, *J. Geophys. Res.*, *104*, 13,251–13,267.

McCartney, M. S. (1977), Subantarctic Mode Water, in *A Voyage of Discovery: George Deacon 70th Anniversary Volume*, edited by M. Angel, pp. 103–119, Elsevier, New York.

Piola, A. R., and A. L. Gordon (1989), Intermediate Waters in the southwest South Atlantic, *Deep Sea Res., Part A*, *36*, 1–16.

Reid, J. R. (1989), On the total geostrophic circulation of the South Atlantic Ocean: Flow patterns, tracers, and transports, *Prog. Oceanogr.*, *23*, 149–244.

Rintoul, S. R. (1991), South Atlantic interbasin exchange, *J. Geophys. Res.*, *96*, 2675–2692.

Schmid, C., G. Siedler, and W. Zenk (2000), Dynamics of Intermediate Water circulation in the subtropical South Atlantic, *J. Phys. Oceanogr.*, *30*, 3191–3211.

Sloyan, B. M., and S. R. Rintoul (2001), Circulation, renewal and modification of Antarctic Mode and Intermediate Water, *J. Phys. Oceanogr.*, *31*, 1005–1030.

Speich, S., B. Blanke, and G. Madec (2001), Warm and cold water routes of an OGCM thermohaline conveyor belt, *Geophys. Res. Lett.*, *28*, 311–314.

Speich, S., B. Blanke, P. de Vries, S. Drijfhout, K. Ds, A. Ganachaud, and R. Marsh (2002), Tasman leakage: A new route in the global ocean conveyor belt, *Geophys. Res. Lett.*, *29*(10), 1416, doi:10.1029/2001GL014586.

Talley, L. D. (1996), Antarctic Intermediate Water in the South Atlantic, in *The South Atlantic: Present and Past Circulation*, edited by G. Wefer et al., pp. 219–238, Springer-Verlag, New York.

Tsuchiya, M., L. D. Talley, and M. S. McCartney (1992), An eastern Atlantic section from Iceland southward across the equator, *Deep Sea Res., Part A*, *39*, 1885–1917.

Tsuchiya, M., L. D. Talley, and M. S. McCartney (1994), A western Atlantic section from South Georgia Island (54°S) northward across the equator, *J. Mar. Res.*, *52*, 55–81.

Webb, D. J., A. C. Coward, B. de Cuevas, and C. S. Gwilliam (1997), A multiprocessor ocean general circulation model using message passing, *J. Atmos. Oceanic Technol.*, *14*, 175–183.

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