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Meridional heat transport across the Antarctic Circumpolar Current by the Antarctic Bottom Water overturning cell

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[1] The heat transported by the lower limb of the Southern Ocean meridional overturning circulation is commonly held to be negligible in comparison with that transported by eddies higher in the water column. We use output from one of the first global high resolution models to have a reasonably realistic export of Antarctic Bottom Water, the OCCAM one twelfth degree model. The heat fluxed southward by the deep overturning cell using the annual mean field for 1994 at 56S is 0.033 PW, but the 5-day mean fields give a larger heat flux (0.048 and 0.061 PW depending on calculation method). This is more than 30% of previous estimates of the total heat flux. Eddies and other transients add considerably to the heat flux. These results imply that this component of meridional heat flux may not be negligible as has been supposed. **Citation:** Heywood, K. J., and D. P. Stevens (2007), Meridional heat transport across the Antarctic Circumpolar Current by the Antarctic Bottom Water overturning cell, *Geophys. Res. Lett.*, *34*, L11610, doi:10.1029/2007GL030130.

1. Introduction

[2] The lower limb of the meridional overturning circulation of the Southern Ocean is likely to play a role in transporting heat meridionally. Cold Antarctic Bottom Water flows on average northward at the sea bed, and is replaced by warmer, saltier circumpolar water flowing southward that forms its source. Both provide a poleward heat transport and an equatorward freshwater transport. However, across the Southern Ocean, the heat transport by this deep cell is commonly held to be negligible, in comparison with the meridional heat transport effected by eddies [*de Szoeke and Levine*, 1981; *Gille*, 2003]. Integrating along a circumpolar path close to the Polar Front of the Antarctic Circumpolar Current, *de Szoeke and Levine* [1981] used a hydrographic climatology to calculate that the mean advective geostrophic heat flux across this path was indistinguishable from zero at 0.00 ± 0.23 PW (1 PW = 1×10^{15} Watts). They suggested that eddy heat fluxes must therefore be responsible for the remaining 0.45 PW required to close the heat budget of the Southern Ocean atmosphere-ocean system.

[3] *Thompson* [1993] verified that the eddies carried the bulk of the mean poleward heat transport by replicating the analysis of *de Szoeke and Levine* [1981] for the output of the first eddy-permitting model of the Southern Ocean, FRAM. The mean meridional geostrophic flow and hence heat transport across the Polar Front (or any similarly defined streamline) was, as expected, small. *Thompson* [1993] also integrated the meridional heat flux along lines of constant latitude rather than lines of constant vertically-averaged temperature (as *de Szoeke and Levine* [1981] require) to obtain similar values for the total heat transport (~0.15 PW). He was able to do this because FRAM, as a rigid lid model, constrained the meridional volume flux at all latitudes to be zero. He found that the mean flow played a significant role in transporting heat across 55.25S (about half of the total), because the Antarctic Circumpolar Current generally carries warmer water south (at longitudes where it flows south) and cooler waters north (at longitudes where it flows north).

[4] *Sun and Watts* [2002] addressed the issue of meridional heat flux in the Southern Ocean by analysing a historical climatology in streamfunction space. They conclude, like *Thompson* [1993], that the mean geostrophic flows carry a significant heat flux across a latitudinal circle (ranging from 0.140 ± 0.010 PW at 56S, through 0.095 ± 0.009 PW at 58S, to 0.082 ± 0.008 PW at 60S), whereas across a streamline the heat flux is negligible (0.001 ± 0.001 PW). However, their calculation considers only the baroclinic geostrophic flow relative to 3000 m. Crucially, they do not include the velocity field below 3000 m, and are therefore unable to include the contribution made by the lower limb of the meridional overturning circulation.

[5] Here we focus on the contribution to the meridional heat flux of the Antarctic Bottom Water overturning cell. This has been previously overlooked for a variety of reasons. In climatology, it is easier to assume a reference depth of 3000 m in order to apply streamfunction techniques. In numerical models, it is still a challenge to form and export a realistic volume of Antarctic Bottom Water, requiring a realistic sea ice model, reasonable surface forcing particularly in winter, high horizontal and vertical resolution, and realistic bottom topography to allow the northward escape of the bottom water when formed. The recent development of such a model (described in section 2) has allowed us, for the first time, to determine whether the heat flux carried across the Southern Ocean by the Antarctic Bottom Water overturning cell is indeed negligible.

2. Model Output and Method

[6] We use output temperature and velocity fields from the 1/12 degree version (run 401) of the Ocean Circulation and Climate Advanced Modelling Project (OCCAM) model run by the National Oceanography Centre, Southampton [*Coward and de Cuevas*, 2005]. The model has 66 levels of varying thicknesses ranging from 5 m near the surface to

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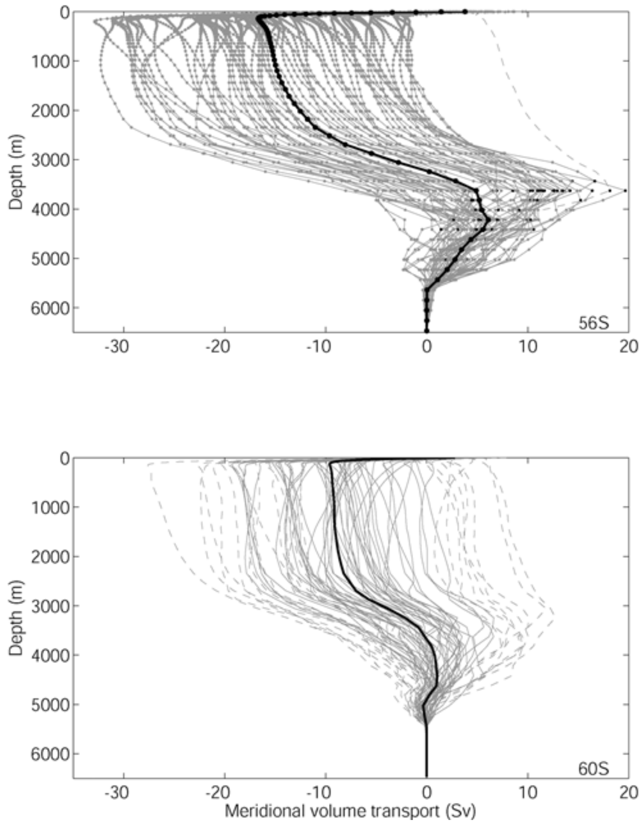

Figure 1. Zonally integrated meridional volume transport in Sverdrups (10^6 m^3 s^{-1}) at (top) 56S and (bottom) 60S, accumulated by model layer from the deepest layer. Positive values indicate equatorward transport. Grey lines indicate each 5-day mean field; the heavy black line indicates the annual mean field, both for 1994. Dots in Figure 1 (top) mark model layers. Small black dots denote the total export of Antarctic Bottom Water for each 5-day field. Note that this is a free surface model so the total meridional volume transport is not zero. Dashed lines denote those 5-day fields that do not have a zero crossing depth at the top of the lower limb of the overturning circulation, and that therefore cannot be used to calculate the heat transport.

200 m in the deep ocean. It includes sea ice and is forced by surface winds, heat and freshwater fluxes derived from the National Centers for Environmental Prediction (NCEP) global reanalysis, starting in 1985. OCCAM is a free surface model, thus the meridional ocean volume flux may vary, allowing for a flux of water through the atmosphere. Here we analyse the year 1994, chosen since it is the tenth year into the integration. We extracted 5-day mean fields, and the annual mean fields, at three lines of latitude spanning the zonally-unconstrained Antarctic Circumpolar Current, 56S, 58S and 60S, chosen to be consistent with the analysis of *Sun and Watts* [2002].

[7] Heat transports across a section can only be calculated unambiguously if the net volume flux across the section is zero [*Montgomery*, 1974]. This is not generally the case, either in reality or in a free surface model. The studies discussed above get around this problem either by using a rigid lid model (e.g., FRAM) or by integrating around Antarctica in a variety of imaginative ways in either models or historical climatology. We however address the issue in a different way, since we are particularly interested in the heat transported by the Antarctic Bottom Water cell. In the Southern Ocean, if the zonally-averaged meridional volume transport is accumulated upwards from the sea bed, there will (usually) be a zero crossing depth. This indicates the top of the Antarctic Bottom Water cell, the lower limb of the overturning circulation. At this depth, the net meridional volume transport is zero, and a heat transport can be calculated for the lower cell.

[8] We calculate the zero crossing depth of the zonally integrated meridional volume transport, interpolating between layer mid-depths to find the crossing depth to the nearest 0.1 m. The corresponding heat transport at this zero crossing point is determined. The zero crossing depth z_0 for each time t is the value which satisfies the equation

$$\int_{-H}^{z_0(t)} \int_0^{2\pi} \mathrm{v\,a}\cos\varphi\ \mathrm{d}\lambda\ \mathrm{d\,z} = 0.$$

[9] Here H is the maximum ocean depth, λ is longitude, ϕ is latitude, z is depth, a is the radius of the earth used in the model (6370 km), v is the meridional velocity. Once z_0 is found, the heat Q fluxed by the lower limb of the overturning circulation is determined for each 5-day-average field by

$$\mathrm{Q} = \rho\ \mathrm{C_p} \int_{-H}^{z_0(t)} \int_0^{2\pi} \mathrm{v}\ \vartheta\ \mathrm{a}\ \cos\varphi\ \mathrm{d}\lambda\ \mathrm{dz},$$

where ρ is the model ocean reference density, C_p the specific heat capacity, and ϑ the potential temperature. The annual average of the 5-day-fields is then the mean of these values of Q. Alternatively we restrict the calculation to below the depth of the annual-mean Antarctic Bottom water overturning cell, by using a time-mean value of z_0, to assess the influence of variations in the zero crossing depth.

[10] Export of Antarctic Bottom Water is determined for each zonally and vertically integrated field as the maximum northward cumulative transport in the lower layer.

3. Results

[11] For some output fields at each latitude there is no zero crossing depth in volume transport at any depth; these 5-day fields must be omitted from the subsequent analysis since the heat flux is not meaningful. At 56S (Figure 1, top) there is only one such 5-day field (shown dashed) so we can be confident that the results are robust. However at 58S and 60S (the latter is shown in Figure 1, bottom) there are a large number of 5-day fields that must be omitted: 20 out of 73. Some of these are fields with a large northward transport of bottom water and northward transport at all depths, others are fields with no northward transport of bottom water at all. The results for these latitudes are therefore not robust using the 5-day fields with varying zero crossing depth and are not discussed further. However the annual average fields for both latitudes do have a zero crossing depth and heat transports for these will be calculated. Note that where the full depth values are shown, they do not include the variable thickness of the top layer of the free surface model, since this does not affect the fluxes of the Antarctic Bottom water cell. The apparently large meridio-

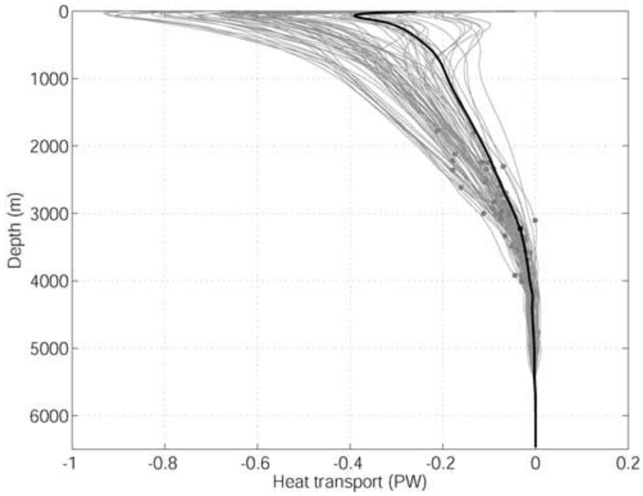

Figure 2. Zonally integrated meridional heat transport in Peta-Watts (10^{15} J s^{-1}) at 56S accumulated by model layer from the deepest layer. Positive values indicate equatorward heat flux. Grey lines indicate each 5-day mean field; the heavy black line indicates the annual mean field, both for 1994. Dots mark the depth of the zero crossing for the corresponding volume transport profile, therefore indicating the heat fluxed by the lower limb of the Southern Ocean overturning circulation.

nal volume fluxes implied at the surface in Figure 1 are partially compensated by the varying thickness of the uppermost grid box.

[12] Zonally averaged meridional volume fluxes, accumulated from the bottom, indicate that the zero crossing depth is typically at about 3000 m (Figure 1). This is the depth to which *Sun and Watts* [2002] made their calculations of heat fluxed by the upper water column. The corresponding heat fluxes are shown in Figure 2; strictly speaking these are only meaningful values of heat flux at the zero crossing depth for the volume flux, but we show the whole profile for context. Table 1 summarises the mean meridional heat and volume fluxes effected by the Antarctic Bottom Water cell for the three latitude bands.

[13] The heat transported by the Antarctic Bottom Water cell correlates highly with the depth at which the zero volume transport occurs (Figure 3, top). There is also a strong correlation (r^2 = 0.70) with the volume of the Antarctic Bottom Water export (Figure 3, middle). These correlations are expected, since a relatively large column of water is likely to transport more heat, as well as volume, than a thinner layer, and the greater the volume flux of Antarctic Bottom Water, the more heat it is able to transport. There is a large amount of variability in the heat flux during the year (Figure 3, bottom). If we test robustness of the annual mean of the 5 day fields by calculating the heat flux for the first and second halves of the year, we find values of 0.056 and 0.066 PW respectively, compared with the whole year of 0.061 PW. We assign an uncertainty of ±0.008 PW to the values quoted in Table 1, representing this temporal variability and methodological inaccuracies in determining the zero crossing depth. This does not take into account any bias due to uncertainty in the representation of Antarctic Bottom Water production in the model; we suspect that the model underestimates the volume flux, and therefore the heat transport, of Antarctic Bottom Water.

[14] The zero crossing depth varies by some 3000 m (Figures 1 and 3); sometimes it will not capture all the water with properties of Antarctic Bottom Water, and sometimes it will include water not associated with the Antarctic Bottom Water cell. This is associated with barotropic variability. By confining the time-varying analysis to the depth of the time-mean Antarctic Bottom Water overturning cell, a further non-ambiguous heat transport can be calculated (Table 1).

[15] The same method should be equally applicable for determining freshwater fluxes. However, the meridional volume flux and the meridional salt or freshwater flux are highly correlated since the difference in salinity between the southward flowing Warm Deep Water, and northward flowing Antarctic Bottom Water, is very small. The calculations of freshwater flux are not robust because they depend critically on the determination of the zero crossing depth, which is not well defined in a model with 200 m model layer thicknesses. We do not discuss these further, but note that when model vertical resolution is an order of magnitude better, these calculations should be revisited.

4. Discussion

[16] Use of a high resolution model, OCCAM, has enabled us to show that at least two processes are critical to accurately describe the heat transport across the Southern Ocean. These are improved export of Antarctic Bottom Water (without which the contribution carried by the lower limb of the overturning circulation is bound to be negligible) and inclusion of eddies and other transients (without which the contribution carried by the lower limb of the overturning circulation is substantially smaller).

Table 1. Meridional Volume and Heat Fluxes Carried by the Antarctic Bottom Water Overturning Cell Across Latitudinal Circles in the Southern Ocean[a]

Latitude Circle	Total AABW Northward Volume Transport Derived From the Mean of 5-Day Fields, Sv	Mean AABW Cell Overturning Strength Derived From Annual Mean Field, Sv	Heat Flux Derived From the Mean of 5-Day Fields, PW	Heat Flux Derived From Annual Mean Field, PW	Heat Flux Derived From 5-Day Fields But Confined to Depth of Annual Mean Cell, PW
56S	7.96	6.09	0.061	0.033	0.048
58S	-	1.00	-	0.004	0.007
60S	-	1.04	-	0.009	0.012

[a]Values of heat fluxes are in Peta-Watts (10^{15} J s^{-1}) and are derived from output of the 1/12 degree OCCAM model for the year 1994. Values are not calculated for the mean of the 5-day fields for 58S and 60S because more than a quarter of the fields do not have a zero crossing depth in volume transport.

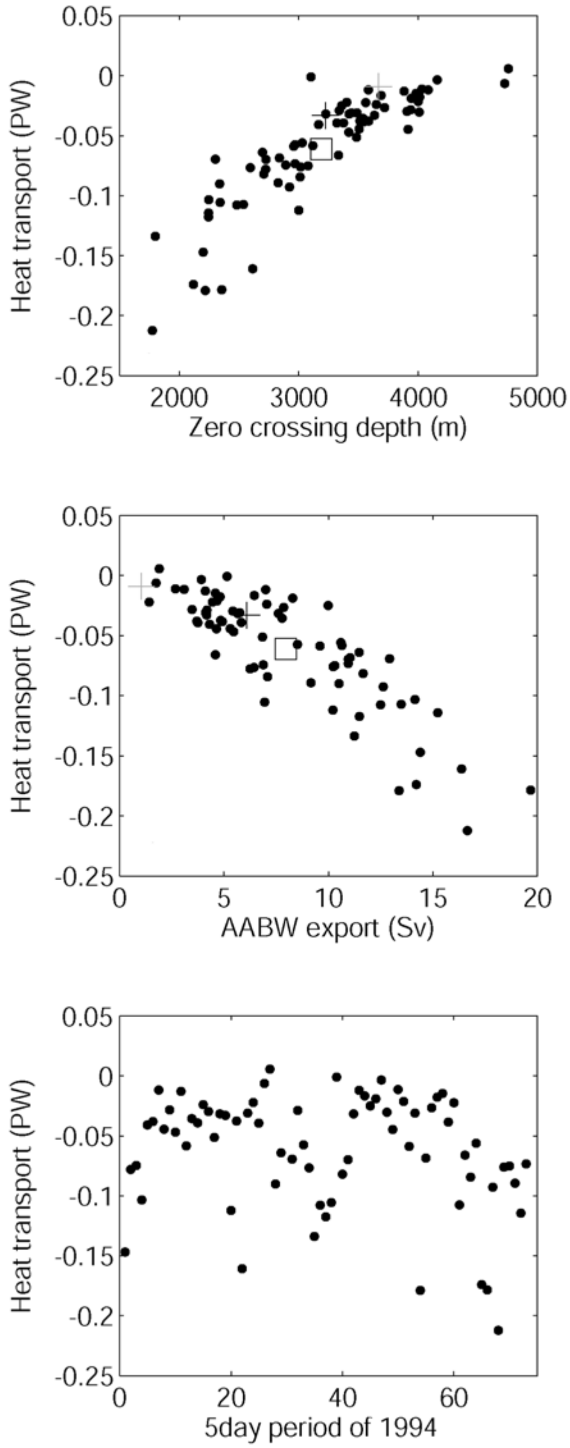

Figure 3. Dependence of heat transported by the lower limb of the Southern Ocean overturning circulation on (top) the zero crossing depth of the volume transport; (middle) the maximum Antarctic Bottom Water northward volume transport; and (bottom) time of each 5-day mean field in 1994. Values are in Peta-Watts (10^{15} J s^{-1}) at 56S for each 5 day mean field (black dots). In the top and middle panels, the mean of all 5-day fields is indicated by the black square, and values calculated from the annual mean fields for 56S (black cross) and 60S (grey cross) are also shown.

[17] Using the annual mean field for 1994 yields a value for the Antarctic Bottom Water export of 6.1 Sv at 56S. This is probably still a factor of two smaller than most observational estimates of the export of this water mass from the Antarctic [e.g., *Naveira Garabato et al.*, 2002]. Values further south across the Antarctic Circumpolar Current are even smaller, indicating that the enhanced northward transport to the north is achieved by entrainment of waters above, and that the rate of Antarctic Bottom Water formation in the OCCAM model is too small. Therefore the values for the heat flux deduced from the model are likely to be a lower bound on the oceanic values, and are likely to converge on reality as improvements to model representation of the processes of Antarctic Bottom Water formation are made. Such improvements are likely to include representation of the processes on the Antarctic continental shelf, better sea ice models, more accurate high latitude surface heat fluxes and wind fields, and higher-resolution ocean bathymetry.

[18] When calculating the contribution of the deep water masses, using the 5 day mean fields rather than the annual mean field is critical. Variations in temperature and velocity are correlated, so use of the annual mean does not give a true picture of the overturning, because it does not include the effect of eddies and other transients. Including this contribution doubles (at least) the heat fluxes, even though the volume of Antarctic Bottom Water exported is only increased by one third. Restricting the calculation to the depth of the time-mean Antarctic Bottom Water cell also leads to an additional (although smaller) contribution from eddies and other transients.

[19] The use of annual mean, coarse resolution fields is one reason why previous estimates of the heat flux effected by the Antarctic Bottom Water cell were deemed negligible. We do not expect heat fluxes to increase greatly if even higher frequency output were available, since 5 days is likely to be shorter than the typical eddy time scale. The use of 5-day mean fields excludes the possible aliasing effect highlighted by *Jayne and Tokmakian* [1997].

[20] The OCCAM model results are sufficient to conclude that the heat transported by the deep overturning cell does make a significant contribution to the total heat transport across latitude circles. The values obtained including transient effects are between 34 and 44% of the estimates obtained by *Sun and Watts* [2002] for the upper water column using historical data (our 0.048 and 0.061 PW at 56S, compared with their 0.14 PW). If we take the total water column heat flux estimates by *Thompson* [1993] in FRAM (a rigid lid model) of 0.15 PW at 55.25S as a reasonable figure, then our value using the 5-day fields would be some 30–40% of this.

[21] For further comparison, our method also can provide the heat fluxed by the upper limb of the overturning circulation, by determining the heat transported between the two zero crossings at the top and bottom of the upper limb of the Southern Ocean overturning (this excludes the substantial northward heat flux carried by the bulk of the northward flowing near-surface Ekman layer, since this usually lies above the uppermost zero crossing, and is also influenced by the variable sea surface height that we do not take into account). At 56S, the poleward heat effected by the upper limb of the overturning is 0.4 PW for the mean of the 5-day fields, and 0.26 PW for the annual mean field. Thus

the heat transported by the lower limb is 10–15% of that carried by the upper limb. These values are larger than the 0.15 PW calculated by *Sun and Watts* [2002] because their value applies to the complete upper 3000 m, including the near-surface, northward heat transport.

[22] Thus the use of high temporal resolution output, including the effects of eddies and other transients, is adding considerably to the heat fluxed poleward by the Antarctic Bottom Water overturning cell. The results imply that this component of the meridional heat flux, although small, may not be as negligible as has been supposed.

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