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The Antarctic Circumpolar Current and the oceanic heat and freshwater budgets

by Daniel T. Georgi[1] and John M. Toole[2]

ABSTRACT

Hydrographic sections that span the Antarctic Circumpolar Current are used to estimate the zonal heat and freshwater transports south of Africa, New Zealand and America. These in turn are used to calculate the exchanges of heat and freshwater between the three major oceans. It is found that both the Atlantic and Pacific lose heat and gain freshwater and that these differences are supplied by a corresponding gain of heat and loss of freshwater in the Indian Ocean. Our results also indicate that the three oceans exchange less heat and freshwater with one another than is suggested by studies based on large-scale integration of air-sea exchanges. As the absolute velocity field is not uniquely known, the magnitude of the calculated losses and gains is sensitive to the choice of a reference level and the horizontal structure of the barotropic transport. In addition, the presence of baroclinic eddies introduces uncertainties into the calculated heat and salt transports. Because of the large relative errors associated with the salt transport calculations, no definitive conclusion is reached for the interoceanic freshwater exchanges. However, the signs of the interoceanic heat transports appear to be well determined.

Finally, estimates of air-sea exchanges in the Southern Ocean are combined with the heat and freshwater divergences to calculate the meridional fluxes across 40S. These meridional transports are in general much smaller than those obtained by other investigators employing different methods.

1. Introduction

The role of the oceans and the atmosphere in the global redistribution of heat and freshwater has been treated with increasing frequency in recent literature. Satellite measurements have been used to estimate the meridional heat transport accomplished by the atmosphere-ocean system (Vonder Haar and Suomi, 1971) while these measurements coupled with atmospheric observations have been used to estimate the total oceanic heat transport (e.g., Vonder Haar and Oort, 1973; Trenberth, 1979). Several approaches have been employed to estimate meridional heat fluxes for the Atlantic, Indian, and Pacific Oceans, including the direct method (Bryan, 1962) which balances western boundary volume transports and interior Sverdrup

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and Ekman transports on zonal sections (e.g., Bennett, 1978; Bryden and Hall, 1980), inverse methods (e.g., Wunsch, 1980; Fu, 1981; Roemmich, 1981), and integration with respect to latitude of the net exchange of heat across the air-sea interface between lateral boundaries (e.g., Hastenrath, 1980; Bunker, 1981).

The global oceanic heat and freshwater budgets deduced from integrations of the air-sea exchanges suggest that there are non-zero net exchanges over the three individual ocean basins. For example, the heat budget computation of Hastenrath (1980) shows the Pacific Ocean northward of 60S to gain heat at the rate of 119 × 10^{13}W, while the Atlantic Ocean for the same latitude range loses 106 × 10^{13}W. Provided that there is no net storage of heat or freshwater in the oceans, then such imbalances in the heat and freshwater budgets of the individual oceans must be compensated for by interoceanic transports.

Certainly, the Antarctic Circumpolar Current (ACC) in the Southern Ocean provides the most efficient vehicle for transporting heat and freshwater between the three oceans. Other minor exchanges do occur outside of the Southern Ocean: 1 to 2 × 10^6m^3/s of water pass from the Indian to the Pacific Ocean through the Indonesian Archipelago between southeast Asia and Australia (Wyrtki, 1961); another 1 to 2 × 10^6m^3/s of water pass through the Arctic Ocean from the Pacific to the Atlantic Ocean (Aagaard and Greisman, 1975). However, these exchanges are minor in comparison to the 127 ± 24 × 10^6m^3/s volume transport of the ACC (Fandry and Pillsbury, 1979).

As the three major ocean basins are, in effect, closed northward of the Southern Ocean, interoceanic heat and freshwater exchanges must be associated with variations in the zonal temperature and salinity transports of the ACC. The topographic constrictions imposed by the presence of Africa, Australia, and South America, provide natural boundaries between the ocean basins and make ideal sites to estimate interoceanic heat and freshwater transports.

Since there are only minor exchanges of water between the Atlantic, Indian, and Pacific Oceans north of the large Southern Hemisphere continents, continuity requires that the volume transport of the ACC be nearly equal south of America, Africa, and Australia. Interoceanic heat and freshwater exchanges must, therefore, be associated with the variations in temperature, salinity, and the velocity distributions across the ACC; subject, however, to the constraint that the integrated volume transport through each passage be the same. For example in the Hastenrath (1980) scheme mentioned above, the waters of the ACC need to be nearly 2.5°C warmer in the Drake Passage than south of Australia to account for the implied heat flux divergence.

In the following analysis, the direct method is employed to compute the zonal heat and freshwater transport from hydrographic sections that span the ACC. Due to the indeterminancy of the geostrophic equations, additional information is required to obtain the absolute velocity fields necessary to compute the interoceanic transports. The continuity condition for the ACC provides a constraint on the total volume transport south of Africa and south of New Zealand.

In the Drake Passage, the total volume transport has been well documented with extensive current meter and hydrographic measurements (Neal and Nowlin, 1979). Bryden and Pillsbury (1977) calculated the time- and space-averaged flow in the Drake Passage at 2700 dbar to be 1.56 ± 1.44 cm/s. By combining this estimate with the integrated baroclinic transport, they arrived at a total flow of $139 \pm 36 \times 10^6 m^3/s$. Fandry and Pillsbury (1979) analyzed the same data, but used additional information on correlation length scales and estimated the total transport and variability to be somewhat less ($127 \pm 24 \times 10^6 m^3/s$).

The current meter observations coupled with the hydrographic observations have demonstrated that the ACC is strongly baroclinic (Nowlin *et al.*, 1977; Bryden and Pillsbury, 1977). Estimates of the integrated baroclinic transport with respect to the bottom are well within the transport bounds computed with the combined current meter and hydrographic data. It seems reasonable, therefore, to use density observations and geostrophy with a deep reference level to infer the zonal velocity structure of the ACC. Furthermore, if it is assumed that the hydrographic sections used to infer the structure of the ACC are representative of the mean conditions, then the net air-sea exchanges in the individual oceans can be estimated from the divergences of the heat and salt transports of the ACC between sections separating the major ocean basins.

Therefore, in the following section, we have computed geostrophic velocities and the zonal heat and salt transports assuming a zero velocity surface at the sea floor. A second calculation using a shallower reference level is discussed as part of an error analysis (Section 3). Finally, we combined the results from the direct computations with estimates of air-sea exchange for the Southern Ocean and compute meridional fluxes of heat and freshwater across 40S (Section 4). These meridional fluxes are compared with other recent estimates obtained by other investigators using other methods.

2. Zonal transports and divergences of heat and salt

Good hydrographic sections (Fig. 1), suitable for geostrophic transport calculations, are available from the Drake Passage (Nowlin *et al.*, 1976), south of Africa (Jacobs and Georgi, 1977), and south of New Zealand (Gordon, 1975; McCartney, unpublished data). These data have been used to calculate baroclinic volume transports relative to the deepest common level of adjacent station pairs (generally within 50 m of the bottom) and relative to 2500 dbar.

The volume transports calculated relative to the deepest observations for the two sections from the Drake Passage (Table 1) agree well with the estimates based on the current meter observations (Bryden and Pillsbury, 1977; Fandry and Pills-

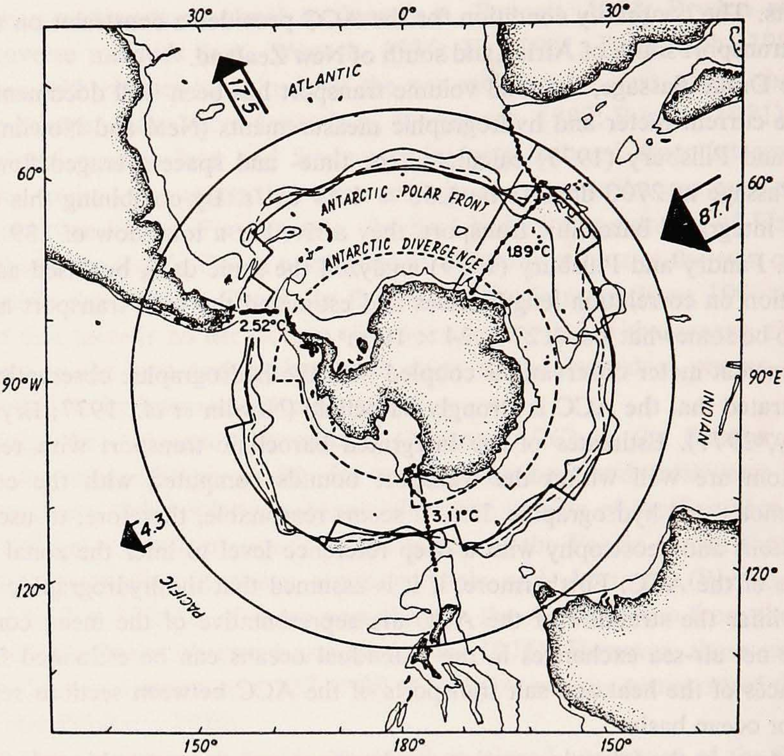

Figure 1. Location of the hydrographic sections used to calculate heat and freshwater divergences. The average temperatures from Table 1 are indicated next to the section locations. Also shown are the position of the Antarctic Polar Front (dashed line), the location of the circumpolar salinity minimum at 200 m (shaded area) after Gordon *et al.* (1978), the schematic polar front and Antarctic Divergence. The magnitudes and direction of the meridional heat fluxes across 40S from Table 3 are indicated with large arrows.

bury, 1979). The estimates for south of Africa and south of New Zealand are also within the expected range of transport for the Drake Passage. However, the two sections south of New Zealand do not reach the Antarctic Continent. Both sections terminate south of the midocean ridge system but appear to encompass the major portion of the ACC. The summer section south of New Zealand (Gordon, 1975) has been extended toward Antarctica by using data collected on previous cruises (Jacobs and Amos, 1967; Jacobs *et al.*, 1970). The baroclinic volume transport for this "combined" section (Table 1) is only $2 \times 10^6 m^3/s$ larger than that of the original section, as is to be expected since the isotherms and (and isopycnals) within the extension slope steeply only in the relatively shallow zone over the continental slope.

It should also be noted that the sections south of New Zealand are located downstream of the East Australian Current (EAC). The poleward transport of the EAC

Table 1. Volume transports, weighted mean-potential temperatures and salinities for the Antarctic Circumpolar Current. (Baroclinic transports calculated relative to deepest common level.)

A.

Location	Volume transport $[10^6 m^3/s]$	θ [°C]	S [‰]
Drake Passage			
Section II	137	2.52 ± .34	34.446 ± .087
Section V	121	2.52 ± .29	34.442 ± .074
South of Africa	140	1.89 ± .65	34.418 ± .139
South of New Zealand			
Summer	123	3.16 ± .54	34.447 ± .106
Combined	125	3.11 ± .61	34.447 ± .120
Winter	113	2.96 ± .58	34.434 ± .113

B.

Net gain of	Heat $[10^{13} W]$	Freshwater $[10^6 m^3/s]$
Atlantic Ocean:	−33.5 ± 33.8 (−106)	.103 ± .605 (−.342)
Indian Ocean:	64.8 ± 46.3 (6)	−.107 ± .677 (−.376)
Pacific Ocean:	−31.7 ± 37.5 (119)	.004 ± .547 (.719)

Note: Section B shows the net heat and freshwater gains for the 3 oceans. Given in parentheses are the heat gains for the oceans north of 60S from Hastenrath (1980) and the oceanic freshwater gains due to Southern Ocean exchanges according to Baumgartner and Reichel (1975).

appears to be highly variable, and often there is no evidence of a current at all (Thompson and Veronis, 1980). Thus, there is reason to believe that the net volume transport of the EAC is negligible and, hence, the circulation around New Zealand small and the volume transport of the ACC south of New Zealand similar to that south of Australia. Nevertheless, the estimated zonal heat and freshwater divergences for the Pacific may be in error because of eddy heat and freshwater transports associated with the EAC. These errors are discussed in Section 3c.

As the calculated geostrophic velocity fields satisfy the total volume transport constraint, they were combined with the observed temperature and salinity data to estimate the zonal heat and salt transports. Volume-transport-weighted mean potential temperatures and salinities (Table 1) were then obtained by dividing the property transport by the total volume transport. The differences between the mean properties in the Drake Passage, south of Africa, and south of New Zealand, are a measure of the changes in heat and salt content that the ACC undergoes in traversing each of the three oceans. Since the ACC transports water eastward around Antarctica, temperature and salinity differences have been formed by subtracting the volume-transport-weighted mean values of the western section from those of the eastern section. As the transport estimates obtained by using the deepest common level agree well with the Drake Passage estimates, the temperature differences can be converted to heat transport divergences by simply multiplying the differences by the total volume transport ($127 \times 10^6 m^3/s$), mean density and the heat capacity. Similarly, freshwater transports are estimated from the salinity differences and the mean salinity and volume transport of the ACC.

The temperature change undergone by the ACC in the Atlantic corresponds to a net heat loss of $33.5 \times 10^{13} W$ and a freshwater gain of $.103 \times 10^6 m^3/s$ (Table 1). The Pacific loses almost the same amount of heat as the Atlantic, but evaporation, precipitation, and runoff appear to be well balanced. The Indian Ocean on the whole gains heat and loses freshwater.

The magnitudes of the calculated heat and freshwater losses for the three oceans are generally much smaller than those obtained by integration of sea surface exchanges (Table 1). For example, in the Atlantic, the sign of the calculated heat loss agrees with Hastenrath's (1980) estimate, but the loss is only one-third as large. Hastenrath's study indicates that the Indian Ocean gains virtually no heat while the Pacific gains large amounts of heat which are exported to the Atlantic Ocean. In contrast, these results indicate that the ACC loses heat in the Pacific Ocean and gains large amounts of heat in the Indian Ocean.

Baumgartner and Reichel (1975, Fig. 17) give a schematic presentation for the freshwater exchanges between the oceans. Their scheme indicates that the exchanges in the Northern Hemisphere are small, and, thus, only the Southern Hemisphere exchanges are listed for comparison in Table 1. Only in the Indian Ocean does the sign of the exchange agree with that calculated by Baumgartner and Reichel (1975). Our calculated Pacific freshwater gain is virtually zero. The exchange for the Atlantic, though small, is opposite to that found by Baumgartner and Reichel (1975).

3. Error analysis

There are several sources of error which could influence the results of the previous section. A discussion of the major errors follows.

a. Zonal eddy fluxes. In addition to the heat transport divergence resulting from the temperature change of the ACC, there can also be a contribution to the total heat flux divergence due to the divergence of zonal-eddy heat flux. In the Drake Passage, the magnitude of the eastward eddy heat flux due to low-frequency motions is much less than that of the poleward heat flux of $.7 \times 10^4 W/m^2$ (Bryden, 1979) and is not significantly different from zero. Even if the zonal eddy heat flux per unit area in the Drake Passage, south of Africa, and New Zealand were $0(10^4 W/m^2)$, the resulting heat flux divergences would be more than an order of magnitude smaller than those calculated from the large-scale temperature change of the ACC.

b. Sampling errors. The data used in calculating heat, freshwater and volume transports can introduce errors through spatial aliasing resulting from coarse station spacing and through aliasing of seasonal and interannual variability of the ACC.

The presence of baroclinic eddies (Bryden, 1981) and zonal jets (Nowlin *et al.*, 1977) in the circumpolar current has been well documented. The observed horizontal scale of these features, 0(50 km), is much less than the width of the ACC, and their presence does not affect the computed volume transports. However, their presence does introduce uncertainties into the calculated property transports. Generally, the spacing of the hydrographic stations does not fully resolve such features. Even if all such features were fully resolved, their presence would cause the given section to deviate from the mean hydrographic conditions. These uncertainties can presumably be estimated from the eddy statistics available from the Drake Passage current meter data in a manner similar to that used by Bennett (1978). We have, however, chosen to estimate these errors directly with the hydrographic data.

For a uniform current embedded in a region of constant horizontal temperature gradient, the volume-transport-weighted temperature is linearly related to the cross-current distance. In the ACC, temperature decreases toward the south, and the transport weighted temperatures for individual station pairs decrease monotonically towards Antarctica. A measure of the uncertainty in the volume-transport-weighted temperature is then given by the departure of an individual station pair's weighted temperature from a simple linear trend. As there is considerable meridional structure that is resolved by the typical station spacing, we have computed the deviations (in a least-squares sense) for groups of stations from each section in the ACC. Generally, the standard deviation of the residuals is less than .2°C. The residuals decrease 30 to 50 percent when a quadratic model for the weighted temperature structure is used, which suggests that much of the smaller transport structure is resolved by the typical station spacing.

To obtain uncertainty estimates for the section mean properties, the uncertainty per station pair has been multiplied by the square root of the number of independent station pairs on the section. The estimates for the uncertainties in volume-transport-weighted mean temperatures and the heat transport divergences are given in Table 1. Estimates for the uncertainties of the volume-transport-weighted salinities and the freshwater divergences were arrived at in a similar manner.

Even though the tabulated uncertainties (sampling errors) are only a measure of the uncertainty due to the presence of baroclinic eddies and the smaller scale velocity structure of the ACC, the total uncertainty (excluding uncertainties due to the barotropic velocity field) may be significantly less. We have used seven hydrographic sections made during the International Southern Ocean Studies (ISOS) in the Drake

Passage to compute volume-transport-weighted mean temperatures and salinities. The mean temperature for the seven sections was 2.44 ± .07°C, and the mean salinity was 34.431 ± .012‰. Unfortunately, repeated sections do not exist for the regions south of New Zealand or south of Africa that would permit us to carry out a similar analysis; however, we feel the magnitudes of these error bounds are more representative than those given in Table 1.

These standard deviations (± .07°C and ± .012‰) include not only the eddy noise, but the property transport variability of the ACC as well. Temporal variability of the ACC transports could introduce significant errors into the calculations, since the hydrographic data used for these calculations are not synoptic. Although the sections were collected over a five year period, only summer sections have been used to compute the divergences listed in Table 1.

The small error bounds computed from the seven ISOS sections imply that there is little interannual variability in the heat and freshwater transports. Additional evidence exists which suggests that the time scale of the ACC baroclinic transport is much longer than five years. Whitworth (1980) has investigated the variability of the baroclinic transport in the upper 2500 dbar assuming a zero geostrophic velocity at 2500 dbar. He found that the baroclinic transport was 78.7 ± 13.2 × $10^6 m^3/s$ for 16 summer sections and 70.6 ± 14.5 × $10^6 m^3/s$ for 6 winter sections. Transport variations of this magnitude may simply reflect too coarse sampling over the rough topography in the Drake Passage; however, the direct current measurements do indicate that real transport variations occur. Wearn and Baker (1980) suggest these fluctuations are barotropic and, therefore, are not reflected in the baroclinic transport estimates. These results are consistent with Clarke's (1981) analytical model of the wind driven ACC, which predicts that the time scale of baroclinic transport fluctuations is many decades. In terms of our calculations, this suggests that the sections separated in time by five years can be considered synoptic.

Seasonal variations in property transports also exist. However, if the difference in the volume-transport-weighted temperatures for the summer and winter section south of New Zealand are representative of other sections, this variability does not appear to be large enough to change the signs of the heat fluxes given in Table 1.

c. The East Australian Current. As the hydrographic sections which divide the Indian and Pacific Ocean are located south of New Zealand, the effect of any poleward heat flux through the Tasman Sea would appear in this analysis as a heat gain in the Indian Ocean sector. Thus, a large poleward heat transport through the Tasman Sea would reconcile our results with those of Hastenrath (1980). Although the EAC may be weakly developed, Thompson and Veronis (1980) suggested that intense eddies in the Tasman Sea may give rise to a substantial poleward heat transport. If one assumes that all the heat gained by the circumpolar current between 20E and New Zealand (40.6 × 10^{13}W, Table 3) is carried south from the Pacific

Table 2. As in Table 1, except baroclinic transports are calculated relative to 2500 dbar.

Location	Volume transport [$10^6 m^3/s$]	θ_1 [°C]	S_1 [‰]	θ_2 [°C]	S_2 [‰]
Drake Passage					
Section II	77	3.06	34.334	1.64	34.598
Section I	76	2.92	34.359	1.58	34.610
South of Africa	47.4	2.90	33.966	1.60	34.658
South of New Zealand					
Summer	76.2	3.90	34.346	1.97	34.606
Combined	82.5	3.62	34.367	1.39	34.634
Winter	69.5	3.65	34.320	1.87	34.608

Note: subscript 1 refers to volume-transport-weighted mean properties and subscript 2 to areal-weighted mean properties.

Net gain of	Heat [10^{13} W]	Freshwater [$10^6 m^3/s$]
Atlantic Ocean:	−22.7	.143
Indian Ocean:	40.6	−.226
Pacific Ocean:	−18.0	.081

Ocean through the Tasman Sea, then there would need to be an average poleward heat flux of $8 \times 10^4 W/m^2$. This calculated flux is five to ten times as large as the poleward heat flux observed in the Drake Passage ($.7 \times 10^4 W/m^2$, Bryden, 1979; $1.7 \times 10^4 W/m^2$, Sciremammano, 1980). The poleward heat flux in the Drake Passage has been attributed to baroclinic instability which releases energy associated with horizontal density gradients (Bryden, 1979; Wright, 1981). However, as the north-south density gradient is considerably less in the ACC south of the Tasman Sea than in the Drake Passage (Fig. 2a, Gordon *et al.*, 1978), such a large poleward heat flux is unlikely to occur in the Tasman Sea.

d. The reference level. Because of the large meridional temperature and salinity gradients associated with the ACC, it is not possible to simply separate the baroclinic and barotropic heat transports as can be done with midlatitude zonal hydrographic sections (Bryden and Hall, 1980). Thus, to test the sensitivity of the results to the choice of the reference level and the ratio of the baroclinic to barotropic transport, the calculations were repeated using a shallower reference level (2500 dbar). This reduces the baroclinic transport through each section and requires a nonzero barotropic component to be added to achieve the observed $127 \times 10^6 m^3/s$ volume transport of the ACC. Of course, the horizontal structure of the barotropic transport is not known. Hence, we simply added a horizontally nonvarying barotropic transport to each section to achieve the desired total volume transport. The total property transports were then obtained by multiplying the barotropic transports by the areal-weighted mean properties and summing with the baroclinic contribution (Table 2). Even though the baroclinic volume-transport-weighted mean properties of the "combined" section south of New Zealand are virtually identical to those for the northern portions of the transect, the areal-weighted properties are significantly different. The changes are much larger than the summer/winter differences observed in the northern portions of the crossings because of the large volume of cold saline waters in the Ross Sea. Since the surface waters are moving faster than the deep waters, the baroclinic property transports still dominate the total property transports. Even south of Africa, where the baroclinic transport decreases markedly and comprises only 37 percent of the total transport, the baroclinic heat transport (relative to 0°C) still accounts for 52 percent of the section total.

The reduction in the baroclinic and the increase in the barotropic transport of the ACC reduce the magnitude of the heat exchanges between the three oceans by approximately 33 percent (Table 2). The Indian Ocean still gains heat while the Atlantic and Pacific lose heat. However, the calculated freshwater fluxes are all larger than they were with the deeper reference level. The freshwater flux into the Atlantic is increased by 40 percent, and the Pacific freshwater input is increased nearly 20-fold to 57 percent of the Atlantic value. The freshwater loss in the Indian Ocean doubles to compensate for the increased gains in the Atlantic and Pacific Oceans.

The addition of a uniform barotropic flow does not alter the basic conclusion that the Indian Ocean gains the heat that is lost in the Atlantic Ocean. However, if a meridionally varying barotropic flow is superimposed on the baroclinic flow (referenced to the deepest common level, Table 1), it is possible to reduce the zonal heat transport south of New Zealand to equal that south of Africa. The ACC would then gain in the Pacific the heat it loses in the Atlantic Ocean, as suggested by Hastenrath (1980). By adding a westward directed barotropic flow to the northern half of the "combined" section and an equal but eastward-flowing barotropic transport to the southern half of the section, it is possible to decrease the heat transport and not alter the total volume transport. Since the areal-weighted mean potential temperature is 2.366°C for the northern half of the "combined" section (cross-sectional area of 4204. km^2) and .425°C for the southern half (cross-sectional area 4218. km^2), a barotropic recirculation of $80 \times 10^6 m^3/s$ is required. This would reduce the eastward transport in the northern half of the section to $23 \times 10^6 m^3/s$ and increase the transport in the southern half to $102 \times 10^6 m^3/s$. Such a distribution of transport appears to be inconsistent with observations of surface currents based on drifting-buoy data (Fig. 1, Garrett, 1980).

Clearly, the structure of the unknown barotropic velocity field is most problematic and can introduce sizeable uncertainties in the calculated heat and freshwater divergences. Although other errors can be sizeable as well, the above analysis and in particular the results from the repeated sections in the Drake Passage give us confidence that the sign of the interoceanic heat divergences are well determined.

The same cannot be concluded for the freshwater divergences. Since the divergences are small, the sampling errors and other interoceanic freshwater transports (e.g. currents through the Arctic Ocean and the Indonesian Archipelago; sea ice and iceberg transports) are important. We conclude, subject to the errors above, that there are no significant interoceanic freshwater transports. A far more detailed study appears necessary to resolve the sign of the interoceanic freshwater fluxes.

4. Meridional fluxes

Meridional estimates of heat and freshwater fluxes are often obtained by integrating the net exchanges of heat and freshwater across the air-sea interface of the major oceans. Traditionally, the integration is carried out from a northern boundary or latitude circle, where the meridional fluxes are known or specified. When this method is used to estimate the meridional fluxes for Southern Ocean latitudes, the integration may span more than 90° of latitude (e.g., Hastenrath, 1980). Hence, rather large uncertainties may result (Wunsch, 1980).

If it is assumed that the computed heat and freshwater divergences (Table 1) represent the integrated exchanges of heat and freshwater for the entire ocean, then estimates of meridional transport can be obtained by subtracting the contribution due to air-sea exchanges between Antarctica and a given latitude circle from that divergence. Thus, it is necessary to estimate the net exchange of heat and freshwater between the atmosphere and the Southern Ocean. This is difficult because of the scarcity of data and the complications introduced by the large variations in seasonal sea-ice cover (Gordon, 1981). The Southern Ocean can be subdivided into a set of oceanographic regions for which one expects similar air-sea exchanges (Fig. 1). For the sake of comparison, we will accept and extrapolate to the whole of the Southern Ocean some published values of air-sea exchanges for three regions; the area south of the Antarctic Divergence, the region between the Divergence and the Antarctic Polar Front, and the area north of the Front and south of 40S.

In general, if the Southern Ocean loses heat and gains freshwater due to air-sea interactions, then the meridional transports of heat and freshwater will be given by the sum of our tabulated values (Tables 1 or 2) and a poleward heat transport and an equatorward freshwater transport. South of the Antarctic Divergence we assume a value of oceanic heat loss of $-35 \mathrm{W/m^2}$ from Gordon (1981), a value sufficient to convert $20 \times 10^6 \mathrm{m^3/s}$ of Circumpolar Deep Water into Antarctic Bottom Water; and a flux of $10 \mathrm{W/m^2}$ for the waters between the Divergence and the Polar Front, which corresponds to a conversion of $30 \times 10^6 \mathrm{m^3/s}$ of Circumpolar Deep Water into Antarctic Surface Water; and a value of $-15 \mathrm{W/m^2}$ for the region north of the Polar Front and south of 40S both from Taylor *et al.* (1978). Integrating these surface exchanges and combining with the oceanic heat loss estimates (Table 1 or 2) yields the values of meridional transport across 40S given in Table 3. Similarly,

Table 3. Meridional transports of heat calculated from the divergences given in Tables 1 and 2 and the air-sea exchanges south of 40S.

Latitude	Atlantic	Indian	Pacific	Reference
	Poleward Heat Flux [10^{13} W]			
28S to 32S	−41	98	—	Bunker (see note)
	−115	49	192	Hastenrath, 1980
	−16 to −18	−46 to −176	17 to 116	Bennett, 1978
	−40	—	0	Bryan, 1980
	−66 to −88	—	—	Fu, 1981
	—	—	26 to 11	Roemmich, 1981
40S	−17.5	87.7	−4.3	Table 1
	−6.7	63.5	8.9	Table 2
	−40.0	36.0	—	Bunker (see note)
43S	—	—	42 to −15	Bennett, 1978
	—	—	12 to 5	Roemmich, 1981
60S	−106	6	119	Hastenrath, 1980

Note: The Atlantic Ocean heat flux values are from Bunker (1981) and the Indian Ocean values are from preliminary data compiled by the late A. F. Bunker.

using values of precipitation plus runoff minus evaporation consistent with the water mass conversions above and the estimates of Albrecht (1960) (35 cm/yr south of the Divergence; 70 cm/yr between the Divergence and the Polar Front; and −50 cm/yr north of the Polar Front) yields the meridional freshwater transports given in Table 4.

While these estimates are crude, there is reasonable agreement between the various estimates listed in Table 3 for the South Atlantic and Indian Oceans. It is particularly reassuring that the sign of the heat transport for the South Atlantic is the same for all investigations even though the heat flux is equatorward and contrary to the global requirement that the oceans transport heat poleward.

The largest disagreements are associated with the South Pacific meridional flux estimates. Hastenrath's (1980) estimate indicates an extremely large poleward heat flux across 30S, while the estimates of Bennett (1978) (which change sign depending on the assumed width of the western boundary current) and the estimates of Roemmich (1981) (which are not significantly different from zero) indicate that the meridional heat fluxes at 28 and 43S are small. We find that a small meridional heat flux in the South Pacific is consistent with the calculated heat transport divergences of the ACC in the Pacific sector. Only the combination of a small poleward

Table 4. Meridional transports of freshwater calculated from the divergences given in Tables 1 and 2 and the air-sea exchanges south of 40S.

Latitude	Atlantic	Indian	Pacific	Reference
	Poleward Freshwater Flux			
	[10^6 m^3/s]			
30S	−.552	−.519	.504	Stommel, 1980
40S	.021	−.183	−.054	Table 1
	.061	−.302	−.023	Table 2
60S	−.521	−.538	.786	Stommel, 1980

heat flux and a net oceanic heat loss to the atmosphere in the Pacific sector of the Southern Ocean can explain the decrease in the mean temperature of the ACC.

The data of Baumgartner and Reichel (1975) yield a large poleward freshwater flux in the South Pacific (Stommel, 1980), contrary to our findings. However, Reed and Elliot (1981) suggest that the Baumgartner and Reichel (1975) study overestimates precipitation over the ocean which results in an excessively large poleward freshwater transport in the South Pacific. Although the works of Dorman and Bourke (1979, 1981) tend to support the results of Baumgartner and Reichel (1975), large meridional poleward freshwater fluxes appear to be inconsistent with the observed changes in ACC salinities. Because of the large uncertainties associated with our freshwater calculations, no definitive conclusions should be drawn.

5. Summary

This study demonstrates how the ACC property transport divergences can be used to assess both the integrated effect of the net air-sea exchanges and the interoceanic exchanges of heat and freshwater. The technique relies primarily on oceanographic observations and can serve as a fundamental check on estimates of oceanic transports of heat and freshwater deduced from large-scale integration of air-sea exchanges. Our results for the Atlantic Ocean agree with most published results; however, the results for the Indian and Pacific Oceans differ appreciably. We note, however, that the magnitudes of the losses and gains calculated with the hydrographic data are smaller than those obtained by integrating the sea-air exchanges.

Perhaps the largest drawback to this method is the lack of knowledge of the barotropic velocity structure and the lack of the oceanographic data needed to determine annual average sections and investigate seasonal effects. The results from our study suggest that a monitoring experiment in the Drake Passage and south of Africa and/or New Zealand in conjunction with repeated hydrographic sections could yield valuable information on the oceanic adjustments to climate change.

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