Transport of Freshwater by the Oceans

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ABSTRACT

The global distribution of freshwater transport in the ocean is presented, based on an integration point at Bering Strait, which connects the Pacific and Atlantic oceans via the Arctic Ocean. Through Bering Strait, 0.8 $\times 10^6$ m^3 s^{-1} of relatively fresh, 32.5 psu, water flows from the Pacific into the Arctic Ocean. Baumgartner and Reichel's tabulation of the net gain of freshwater by the ocean in 5° latitude intervals is then integrated from the reference location at Bering Strait to yield the meridional freshwater transport in each ocean. Freshwater transport in the Pacific is directed northward at nearly all latitudes. In the Atlantic, the freshwater transport is directed southward at all latitudes, with a small southward freshwater transport out of the Atlantic across 35°S. Salt transport, which must be considered jointly with the freshwater transport, is northward throughout the Pacific and southward throughout the Atlantic (in the same direction as the freshwater flux) and is equal to the salt transport through the Bering Strait. The circulation around Australasia associated with the poorly known Pacific–Indian throughflow modifies the above scenario only in the South Pacific and Indian oceans. A moderate choice for the throughflow indicates that it dominates the absolute meridional fluxes of freshwater and salt in these oceans. The global freshwater scheme presented here differs markedly from earlier interpretations and suggests the need for a careful assessment of the treatment of ocean freshwater and salt transports in inverse, numerical, and climate models.

1. Introduction

There are so few absolute transport values in oceanography that one ought to make as much use of them as possible. A case in point is the transport through the Bering Strait. Recently, on the basis of long-term measurements, Coachman and Aagaard (1988) reported that a flow of 0.8 $\times 10^6$ m^3 s^{-1} of relatively fresh seawater leaves the North Pacific through the Bering Strait and enters the Arctic Ocean. Here we utilize this transport along with Baumgartner and Reichel's (1975) estimates for the air–sea exchange of freshwater and for coastal runoff to derive the distribution of the meridional transport of freshwater in the global ocean.

Freshwater transport in the ocean can be a puzzling subject, with much confusion arising simply out of differences in what is meant by the term "freshwater transport." In the following analysis, freshwater transport applies to that part of a seawater flux that is pure water. Since oceanic salinities are typically 35 psu, only 3.5% of the oceanic mass transport is salt transport, with the remaining 96.5% being freshwater transport. The need to make this point on semantics arises from the common use of the term freshwater transport for what is really a relative transport or a divergence of freshwater in an oceanic volume. "Freshwater anomaly" or "freshwater fraction" is commonly used in budgets of confined seas, where one can choose a reference salinity. Here we are interested in the global ocean freshwater budget and use a definition of freshwater transport free of any implicit assumptions concerning the salt budget.

The ocean exchanges freshwater with the atmosphere via evaporation at the surface of the ocean and precipitation, both terrestrial and marine. Because of this exchange, the steady-state mass divergence in oceanic volumes will not be precisely zero. For an oceanic basin, the changes in the zonally integrated meridional

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transport are related to the surface fluxes as follows (ignoring small-scale mixing processes):

$$\frac{d}{dy}\iint \rho v\,dxdz = \int F(x, y)dx, \tag{1}$$

where x, y, and z are the zonal, meridional, and vertical coordinates, respectively, v is the meridional oceanic velocity, and ρ the density of seawater. Here $F(x, y)$ is the net gain of mass at the ocean surface due to precipitation, evaporation, and land runoff—P, E, and R, respectively. Hence, $F(x, y) = P - E + R$.

Because there is no significant atmospheric pathway for salt, the long-term divergence of salt in an oceanic volume in a steady state must always be zero. This does not imply that there is no salt flux across oceanic sections, only that for any given volume of ocean the ingoing and outgoing fluxes are exactly equal; that is,

$$\frac{d}{dy}\iint \rho v S\,dxdz = 0, \tag{2}$$

where S is the salinity of seawater. The freshwater balance is the difference between (1) and (2):

$$\frac{d}{dy}\iint \rho v(1 - S)dxdz = \int F(x, y)dx. \tag{3}$$

In (1) through (3) the left-hand side denotes the divergence of the meridional fluxes in the ocean. Hence, the surface mass exchange is the difference between the incoming and outgoing advective fluxes. The oceanic advective fluxes may themselves dwarf the air–sea exchanges, making the surface fluxes appear negligible, a small difference between large numbers. However, one should keep two things in mind: 1) the surface fluxes drive the thermohaline circulation and 2) the surface freshwater flux has implications for the salt budget of oceanic volumes.

It is useful to note the relationships between the freshwater flux and salt flux for flows of varying complexity. That is, we can separate the velocity and salinity fields into section averages $\bar{v}$, $\bar{S}$, and spatially varying components $v'(x, z)$, $S'(x, z)$, and let the overbar represent the section average (or equally well, a time average) such that

$$\bar{S} = \frac{\int S(x, z)dxdz}{\int dxdz}, \quad S'(x, z) = S(x, z) - \bar{S}; \tag{4}$$

similarly for $\bar{v}$ and v'. Neglecting density variations, the salt flux across a section can be written

$$\rho(\bar{v}\bar{S} + \overline{v'S'}) \tag{5}$$

and the freshwater flux is

$$\rho(\bar{v} - \bar{v}\bar{S} - \overline{v'S'}). \tag{6}$$

We see that the freshwater flux is equal to the negative salt flux only in the case where $\bar{v} = 0$. This may apply to the two-layer flows found in straits connecting enclosed basins (and only where there is no net mass gain or loss in the basin due to runoff and evaporation). For the throughflows connecting the major ocean basins and for sections across the basins, $\bar{v} \neq 0$ and the more general expression must be used. Note that $\rho\overline{v'S'}$, as defined here, represents the salt flux across a section due to all scales of flow beyond uniform advection, such as the large-scale horizontal and vertical circulations associated with the wind-driven gyres and thermohaline circulations, and also includes mesoscale eddy fluxes.

2. Freshwater transport for each ocean

For ocean mass and freshwater transports, we take the Bering Strait as a reference point for the integration of (1). Coachman and Aagaard (1988) have recently reported that long-term measurements in the Bering Strait show that 0.8 (±0.1) × 10^6 m^3 s^{-1} flow from the Pacific into the Arctic Ocean with an average salinity of 32.5. Thus, there is a northward transport of mass through the Bering Strait of 0.821 × 10^9 kg s^{-1} (0.8 × 10^6 m^3 s^{-1} × 1026 kg m^{-3}) and a net northward freshwater transport of 0.794 × 10^9 kg s^{-1} [= 0.821 × 10^9 kg s^{-1} × (1 − 0.0325)]. For the net gain or loss of freshwater by the ocean, Baumgartner and Reichel's (1975, Table XXXV) compilation of the air–sea freshwater exchange and runoff from the coasts in 5° latitude bands is used. In the North Atlantic the more recent estimates of Schmitt et al. (1989, from here on, SBD) are also presented. (Refer to Fig. 2 for the demarcation of the various ocean basins.)

The flow of water from the Pacific to the Indian oceans through the Indonesian archipelago is initially ignored for simplicity in interpretation. The impact of the Pacific–Indian throughflow (PIT) will be discussed later.

For the Pacific, a straightforward integration of Baumgartner and Reichel's values southward from the reference transport through Bering Strait yields the freshwater transport as a function of latitude (Fig. 1a). The resulting Pacific freshwater transport is northward for all latitudes north of 45°S, which is taken to be the southern boundary of the Pacific.

For the Atlantic, the net precipitation and runoff over the Arctic Ocean is added to the Bering Strait freshwater transport and is used as the northern boundary value for the Atlantic at 65°N. Integration southward of Baumgartner and Reichel's values then yields the freshwater transport as a function of the latitude for the Atlantic (Fig. 1b). The Atlantic freshwater transport is southward at all latitudes. The more recent estimates of the air–sea fluxes by SBD show enhanced evaporation over the Atlantic, resulting in almost zero net meridional freshwater flux at 35°S, which is the southern boundary of the Atlantic.

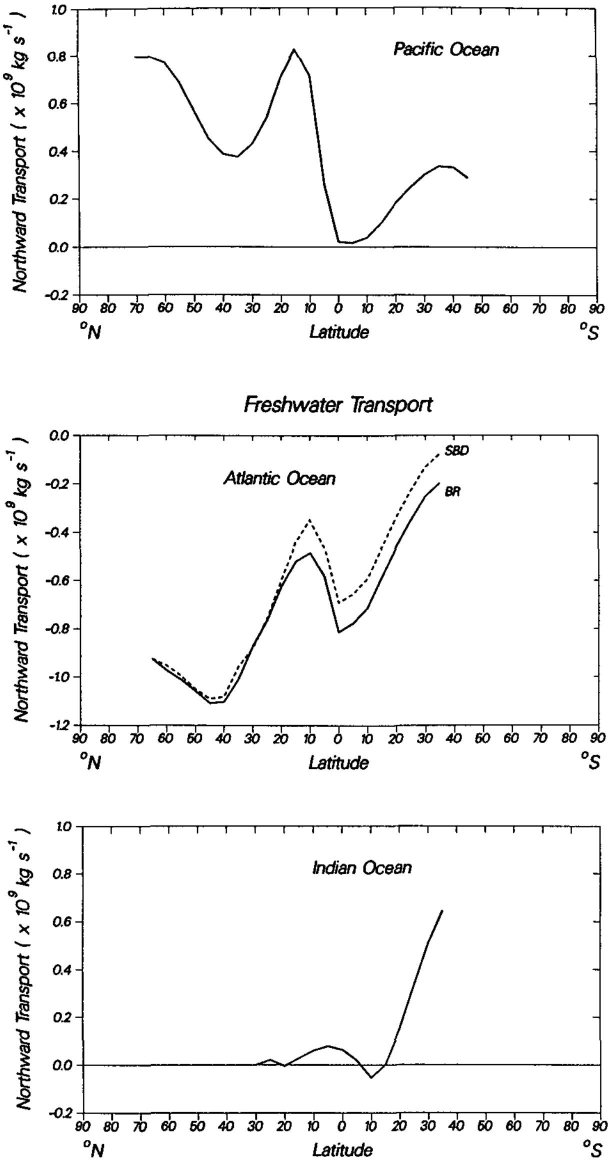


FIG. 1. Northward transport ($\times 10^9$ kg s^{-1}) of freshwater as a function of latitude for the (a) Pacific, (b) Atlantic, and (c) Indian Oceans. The effect of the Pacific–Indian throughflow is not included in this figure.

For the Indian Ocean, zero freshwater transport at the northern land boundary at about 35°N is used as a starting point. Then, integration of Baumgartner and Reichel's values southward from this reference point yields freshwater transport as a function of latitude for the Indian Ocean (Fig. 1c). The Indian Ocean freshwater transport is northward at nearly all latitudes.

The meridional freshwater transports across each latitude (Fig. 2a) can be summed over the three oceans to derive the global ocean freshwater transport as a function of latitude. In the Atlantic, the SBD values have been used. The freshwater flux of the PIT in the Indian Ocean cancels that in the South Pacific Ocean, and so does not affect the global integration. For comparison, Peixóto and Oort's (1983) independent estimates of the meridional water vapor transport in the atmosphere are also plotted in Fig. 3. The sum of the ocean and atmosphere freshwater transports must equal the meridional freshwater flow over land due to rivers and groundwater runoff, which is generally considered to be small (e.g., the discharge of the Mississippi at 30°N is less than 2% of the flux carried by the Atlantic at that latitude). The atmospheric transports appear to be a bit smaller than the ocean freshwater transports and to peak at slightly lower latitudes. Overall, however, the compensation between the ocean and atmosphere freshwater transports determined from two quite independent methods is comforting and illustrates the complementary transports of freshwater by the ocean and atmosphere.

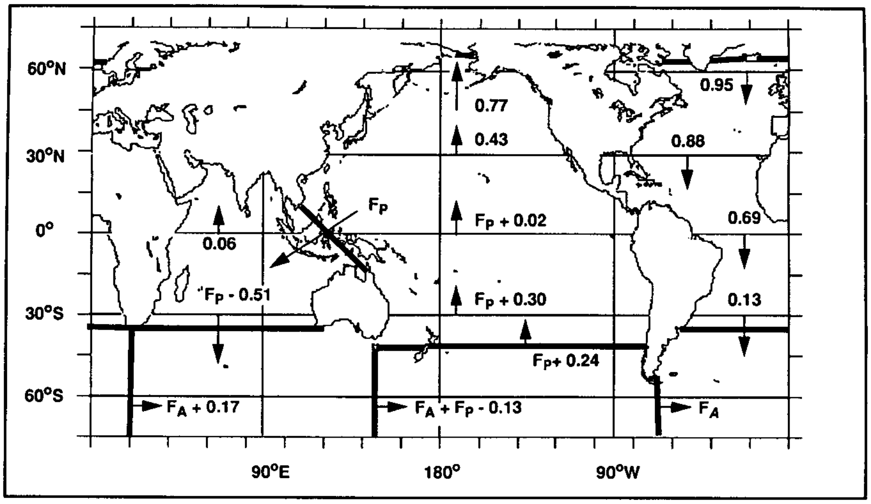
It is worth noting that this water cycle with nearly balancing meridional water transports in the atmosphere and ocean carries a substantial amount of the meridional heat transport required to balance the global radiation budget. Because the atmospheric transport is of water in its gaseous phase, its heat content is higher than the compensating ocean transport by the latent heat of evaporation equal to 2.5×10^6 J kg^{-1}. Thus, for example, in subtropical latitudes between 20° and 40°N, the northward atmospheric and compensating southward oceanic freshwater transport of order 0.6×10^6 m^3 s^{-1} carries 1.5×10^{15}W of heat northward as well. While such heat transport is commonly considered to be part of the atmospheric energy transport, this latent heat transport is really the result of the combined atmosphere–ocean water cycle.

3. Salt transport

The flow through the Bering Strait carries 26.7 ($\pm$ 3.3) $\times 10^6$ kg s^{-1} ($= 0.8 \times 10^6$ m^3 s^{-1} $\times$ 0.0325 $\times$ 1026 kg m^{-3}) of salt northward out of the Pacific into the Arctic and then into the northern Atlantic. To maintain salt conservation, an equal amount of salt must enter the Pacific from the south and migrate northward, all the way to the Bering Strait. In the South Pacific a northward salt flux associated with the PIT will also be present. Similarly, 26.7×10^6 kg s^{-1} of salt must be transported southward through the Atlantic and across its southern boundary at about 35°S and eventually make its way back into the Pacific Ocean (Fig. 2b). Usually, it is assumed that such salt is transported by a small net mass transport. In this analysis, however, places exist where the net mass transport is near zero and yet the salt flux is significant. For example, across 35°S in the Atlantic there is only a small net mass transport of 0.1×10^9 kg s^{-1} (SBD). Such a small net mass transport in an ocean with a salinity of about 35 psu can advect only 3.5×10^6 kg s^{-1} of salt poleward. Salt conservation demands a salt flux of 26.7 ($\pm$3.3) $\times 10^6$ kg s^{-1} across 35°S in the Atlantic, and

FRESHWATER TRANSPORT IN THE WORLD OCEAN

(x 10^9 kgs^{-1})



SALT TRANSPORT IN THE WORLD OCEAN

(x 10^6 kgs^{-1})

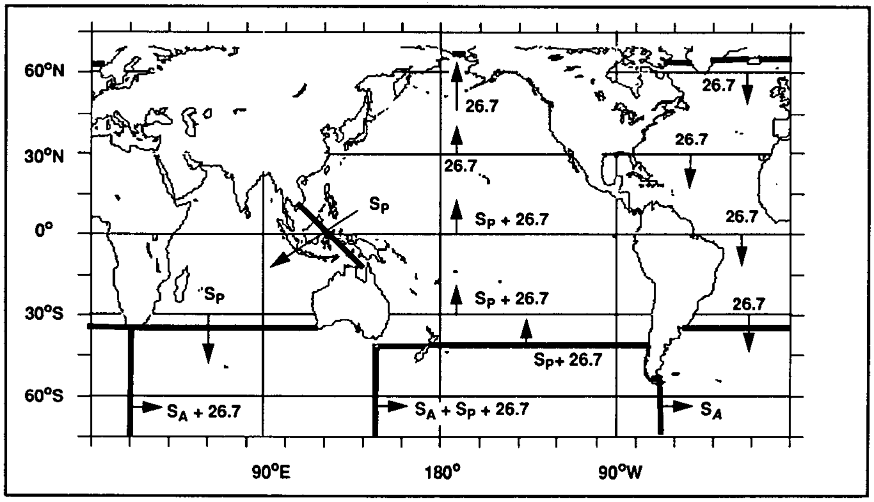


FIG. 2. Global distribution of (a) the meridional freshwater transport ($\times 10^9$ kg s^{-1}) in the ocean, and (b) the meridional salt transport ($\times 10^6$ kg s^{-1}). Here F_P and F_A refer to the freshwater fluxes of the Pacific–Indian throughflow and the Antarctic Circumpolar Current in Drake Passage, respectively. Similarly, S_P and S_A represent the respective salt fluxes.

so a circulation must exist that carries salty water poleward and fresher water equatorward with little net mass transport. This salt transport without a net mass transport, which we call $\rho \overline{v'S'}$, must carry the remaining 23.2 × 10^6 kg s^{-1} of salt southward.

4. The effect of the Pacific–Indian throughflow

In the above analysis the presence of the mass flux from the Pacific Ocean to the Indian Ocean via the Indonesian passages, the Pacific–Indian throughflow, has been ignored. The size of the PIT volume flux is controversial, with estimates ranging from 1 to 20 ($\times 10^6$ m^3 s^{-1}) (Gordon 1986). The effect of the PIT on the above scenario is as follows. In the Indian Ocean, the freshwater flux of the PIT will appear as a large downward displacement of the freshwater curve in Fig. 1c for latitudes south of the throughflow passages (~10°S). The South Pacific curve is also modified by

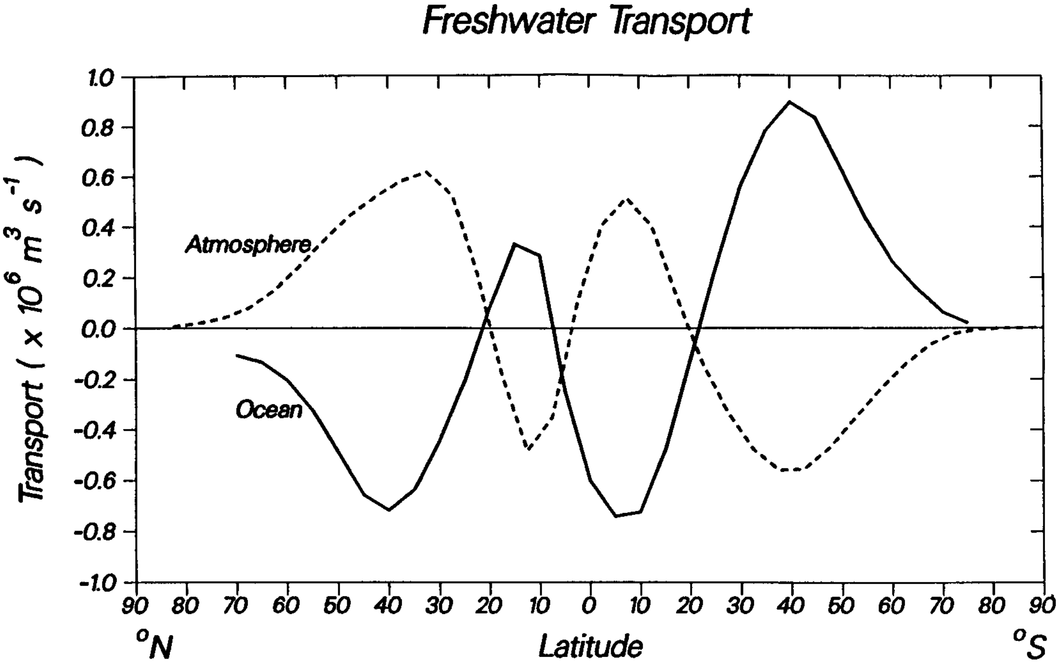


FIG. 3. Northward transport ($\times 10^6$ m^3 s^{-1}) of freshwater as a function of latitude in the ocean (solid line) and the atmosphere (dashed line). Ocean transport at each latitude is the sum of the individual ocean transports in Fig. 1. Atmospheric transport is calculated from Peixóto and Oort's (1983, Table 1) water-vapor flux divergence values.

the PIT, with the PIT freshwater flux appearing as a northward flux from the southern limit of the Pacific Ocean until 5°N, where the PIT is believed to exit to the Indian Ocean. Hence, the curve in Fig. 1a will be displaced upward. A moderate choice of 5×10^6 m^3 s^{-1} for the PIT dwarfs the ocean transports in Fig. 1 and the small mass exchanges with the atmosphere.

The PIT provides one mechanism by which the ocean circulation can balance the salt convergence caused by atmospheric fluxes. It is illustrative to estimate the size of the PIT by performing a mass and salt budget for the Pacific Ocean, say between 45°S and the Bering Strait, as was carried out by Piola and Gordon (1989). The mass balance for this volume of ocean can be written as

$$M_{45} + \int\int_{45}^{\mathrm{BS}} (P - E + R)dxdy = M_{\mathrm{BS}} + M_P, \quad (7)$$

where M_{45} is the mass entering the volume northward across 45°S, M_{BS} and M_P are the mass fluxes leaving via the Bering Strait and the PIT, and $P - E + R$, the net gain of mass at the surface. The salt budget is

$$M_{45}\bar{S}_{45} + \rho\overline{v'S'}_{45} = M_{\mathrm{BS}}\bar{S}_{\mathrm{BS}} + M_P\bar{S}_P.$$

Note that the $\overline{v'S'}$ terms for the Bering Strait and the PIT are being ignored. Since both flows are believed to be unidirectional, these terms will be small.

Eliminating M_{45}, we have an expression for the mass transport of the PIT:

$$M_P = \frac{-M_{\mathrm{BS}}(\bar{S}_{45} - \bar{S}_{\mathrm{BS}}) + \bar{S}_{45}\int\int_{45}^{\mathrm{BS}} (P - E + R)dxdy - \rho\overline{v'S'}_{45}}{\bar{S}_{45} - \bar{S}_P}. \quad (8)$$

Hence, the salt convergence due to the PIT, equal to $M_P(\bar{S}_{45} - \bar{S}_P)$, and the Bering Strait transport $M_{\mathrm{BS}}(\bar{S}_{45} - \bar{S}_{\mathrm{BS}})$, is balanced by the salt divergence due to the mass gain from the atmosphere and the $\overline{v'S'}$ term across 45°S.

If we assume that $\rho\overline{v'S'}_{45}$ is negligible, then we can estimate M_P. Using Coachman and Aagaard's (1988) values for the Bering Strait, Baumgartner and Reichel's values for $P - E + R$, setting $\bar{S}_{45} = 35.0$ and choosing a reasonable value for the mean salinity of the PIT, say 34.5 (J. Toole, personal communication), we have

$$M_P = \frac{(-0.821)(35.0 - 32.5) + 35.0(0.509)}{35.0 - 34.5}$$
$$= 31.5(10^9 \text{ kg s}^{-1}). \quad (9)$$

This value for the PIT is far larger than any other estimates and is unacceptable. Hence, given the $P - E + R$ estimates available, one is led to conclude that the $\rho\overline{v'S'}_{45}$ is of importance in the salt balance of the Pacific, and that it is not possible to ignore such terms in box models involving large oceanic volumes. Hall and Bryden (1982) also found the $\overline{v'S'}$ term to be large in the salt budget for the Atlantic north of 24°N. Note that $\bar{S}_{45} = 35$ is the maximum salinity found in the *Scorpio* section at 43°S in the Pacific (Reid 1973), and that the real section average is no doubt lower, indicating that M_P estimated via (9) will be even larger. To reduce the size of the PIT required for salt balance, $\rho\overline{v'S'}_{45}$ must be positive; i.e., there must be a northward mass-compensated salt flux across 45°S in the Pacific.

Piola and Gordon (1984) perform a salinity budget for the upper layer of the Pacific and Indian oceans and include one element of $\rho\overline{v'S'}_{45}$, a vertical overturning cell in these oceans (i.e., deep inflow, upwelling, and outflow into the upper layers). At 45°S in the Pacific, their circulation implies a small southward $\rho\overline{v'S'}_{45}$ flux, and salt balance is achieved through a moderate M_P of 14×10^6 m^3 s^{-1} with a much lower salinity of 33.55. In their scheme the salt budget of the Pacific is balanced with a PIT with a low salinity rather than a large size. The subject may remain controversial until direct measurements of the throughflow's size and salinity become available.

5. Discussion

The Pacific Ocean as a whole gains a great deal of freshwater from the atmosphere and coastal runoff, a total of 0.887×10^6 m^3 s^{-1} of freshwater according to Baumgartner and Reichel (1975). Much of this gain occurs in the tropical zone between 0° and 15°N. The Atlantic and Indian oceans lose large amounts of freshwater in net evaporation to the atmosphere, 0.543×10^6 m^3 s^{-1} in the Atlantic and 0.441×10^6 m^3 s^{-1} in the Indian. [The additional gain of freshwater of 0.095×10^6 m^3 s^{-1} in the Arctic maintains the global ocean freshwater balance in Baumgartner and Reichel's (1975) analysis.] Thus, the Indian and Atlantic oceans are evaporative basins, while the Pacific has a net gain of freshwater.

It is important to account for the Arctic link between the Pacific and Atlantic oceans. If the Bering Strait freshwater transport were neglected (i.e., assumed zero or negligible), then the air–sea exchanges demand that the freshwater transport in the North Pacific be southward, with a net export of freshwater to the Antarctic Circumpolar Current (ACC) via the South Pacific or Indian oceans. The Atlantic freshwater transport would be northward at all latitudes, with the supply coming from the south via the ACC. This is the global freshwater scheme put forward by Baumgartner and Reichel (1975) and adopted by Stommel (1980). They assume that the Bering Strait freshwater transport is about 0.1×10^6 m^3 s^{-1}, based on the salinity contrast between the Bering Strait water and the Atlantic, rather than the total (absolute) transport. However, this implicitly assumes that the flow replenishing Bering Strait water from the Pacific is seawater. This is an unjustified assumption, since high precipitation over the Pacific is capable of providing the compensating mass flux as pure freshwater (see Fig. 1a). The required salt flux can be made up by mass-compensated flows $\rho\overline{v'S'}$ in the Pacific, as previously discussed.

By accounting for the total flow through the Bering Strait, our global oceanic freshwater scheme (anticipated in Stigebrandt 1984) contrasts dramatically with Baumgartner and Reichel's. The North Pacific exports essentially all of its atmospheric freshwater gain northward through the Bering Strait. The Atlantic exhibits southward freshwater transport at all latitudes: it is carrying the freshwater gained in the Pacific, which comes through the Bering Strait and the Arctic into the northern Atlantic. While the southward freshwater transport decreases southward to balance the net evaporation over the Atlantic, there is still an export of freshwater (though small) from the Atlantic evaporative basin to the Antarctic circumpolar region.

Citing only the freshwater transport can be misleading. For example, the freshwater transports reported here across 45°S in the Pacific, Indian, and Atlantic oceans appear initially to be in remarkable agreement with Georgi and Toole's (1982) estimates of freshwater input into the Antarctic circumpolar region. Based on estimates of salinity of the Antarctic Circumpolar Current south of New Zealand, in Drake Passage, and south of Africa, Georgi and Toole found that the circumpolar current neither gains nor loses any freshwater in the Pacific, that it gains freshwater in the Atlantic, and that it loses freshwater in the Indian Ocean. They were surprised by these results because the Pacific overall gains so much freshwater from the atmosphere and from runoff that they had expected a decrease in salinity in the ACC across the Pacific. Also, since the Atlantic is a net evaporative basin, they had expected an increase in salinity across the Atlantic. At first glance, the fresh water transport reported here across 35°S (Fig. 1) seems to confirm Georgi and Toole's unexpected results: in the Pacific the freshwater transport is small, in the Atlantic the freshwater transport is indeed directed southward across 35°S, and in the Indian Ocean the freshwater transport is northward.

For a comparison with our scenario, consider the budget in the Atlantic sector of the ACC since it is unaffected by the PIT. The above discussion has ignored the salt transport across 35°S, which is crucial for a meaningful comparison. Due to the Bering Strait flow, the Atlantic sector of the Antarctic Circumpolar Current has a net gain of salt of 26.7×10^6 kg s^{-1} from the Atlantic north of 35°S. The Atlantic Ocean exports both freshwater and salt to the ACC. A complete budget for the Atlantic sector of the ACC, including both freshwater and salt transports then would still indicate that the salinity of the ACC should increase across the

Atlantic from Drake Passage to south of Africa, contrary to Georgi and Toole's findings. Thus, Georgi and Toole's results are still surprising, even though their estimates of freshwater input into the Atlantic–Antarctic sector are consistent with the freshwater transports reported here. Because of problems of interpretation such as this, it is essential that both freshwater and salt transports be considered in any comparison of the freshwater transports reported here with other existing estimates.

There are large errors in determining the freshwater balance for the ocean, and integrating even a small bias error over the vast area of the ocean could lead to large errors in freshwater transports. Baumgartner and Reichel (1975) present a long discussion of the problems and possible solutions in making better estimates of the global water balance. The most severe problem is that of estimating evaporation and precipitation over the ocean. Evaporation estimates from bulk formulas are considered to have uncertainties of ±25% (Bretherton et al. 1982). Precipitation estimates are even more uncertain, with order-of-magnitude differences between existing analyses over large areas of the tropical and subtropical ocean (e.g., Reed and Elliot 1979; Dorman and Bourke 1981). If one assumes optimistically an error of only ±30% in $P - E + R$, then in the Atlantic the accumulated error from a southward integration from 65°N is $\pm 0.42 \times 10^9$ kg s^{-1} at the equator and $\pm 0.60 \times 10^9$ kg s^{-1} at 35°S. With errors of this size, it is clear that many aspects of the scenario presented here are tentative. For example, the sign of the freshwater flux in the South Atlantic is not resolved. We regard the scheme for the global freshwater flux presented here as a starting point and hope that more accurate estimates of the surface fluxes become available.

One new approach to improving our understanding of the water balance for the ocean is to determine the oceanic freshwater convergence or divergence directly from oceanographic observations, in particular from zonal transoceanic hydrographic sections. Hall and Bryden (1982) estimated the freshwater transport across the 24°N section in the North Atlantic, Toole and Raymer (1985) estimated the freshwater transport across 32°S in the Indian Ocean, and Roemmich and McCallister (1989) estimated freshwater transports across 24°N, 35°N, and 47°N in the Pacific. All are in reasonable agreement with Baumgartner and Reichel's tabulation of the gain or loss of freshwater by the ocean. Georgi and Toole's (1982) estimates of freshwater exchange in the Antarctic circumpolar region are in the same spirit, but their results are not consistent with Baumgartner and Reichel's tabulation, as discussed above. With analyses for the freshwater transports across other zonal hydrographic sections, particularly in the South Atlantic and South Pacific, it may soon be possible to make a meaningful comparison of direct estimates of the freshwater divergence in the ocean with indirect estimates of the net gain of freshwater by the ocean such as those by Baumgartner and Reichel (1975).

Analyses of the zonal hydrographic sections across the South Pacific and South Atlantic have generally used constraints of zero meridional mass and salt transports in diagnostic inverse calculations of the meridional circulation across these sections (Fu 1981; Wunsch et al. 1983; Rintoul 1988). The estimates of net meridional mass transport found here are small for subtropical and subpolar latitudes in the South Atlantic, and so the constraints of zero mass transport across a section are reasonable ones. There should, however, be a salt transport of 26.7×10^6 m s^{-1} across these South Pacific and Atlantic latitudes according to the analysis presented above. Since this is a sizeable salt flux, the constraints of no meridional salt transport used in the inverse calculations appear to be inconsistent with the salt budgets of the Pacific and Atlantic oceans. Instead, constraints on the salt transport across these sections, such that 26.7×10^6 m s^{-1} of salt is transported southward in the Atlantic and northward in the Pacific, would be more appropriate.

6. Conclusions

Freshwater transport in the ocean is accompanied by a salt transport, and these two fluxes must be considered together in order to obtain a consistent global scenario. The oceanic circulation that achieves these fluxes may be complex and not well modeled by the simple uniform advection of mass with an assigned bulk property. In this presentation, more complex mass-compensated circulations are deduced to be important in the South Atlantic and South Pacific oceans, where large meridional salt fluxes must occur with nearly no net volume flux. Given the importance of the ocean in the hydrological cycle, oceanic freshwater transports are receiving increasing attention (Broecker et al. 1990) and yet we have found some confusion in the literature regarding the definition of oceanic freshwater transport. Most estimates, such as those reported here, are based upon surface fluxes, are subject to large errors, and require an integration reference point. Here we have used the Bering Strait as an integration point. Independent estimates of oceanic freshwater transports can be obtained directly from oceanographic observations and compared with the indirect estimates presented here. Studies based upon direct ocean observations are also able to reveal the mechanisms of heat and freshwater transport in the ocean and may shed light upon how they are linked to the air–sea fluxes.

The oceanic freshwater pathway from the Pacific to the Atlantic Ocean through the Bering Strait provides a mechanism that competes with the "conveyor belt" described by Broecker (1987), in which the burden of balancing the freshwater budget of the evaporative North Atlantic is placed upon the exiting salty North Atlantic Deep Water and its fresher return flow. It would be interesting to see if the circulation patterns in World Ocean models that address the thermohaline circulation, such as Semtner and Chervin (1991), are changed by the inclusion of the Bering Strait pathway.

Finally, we note that the increased importance accorded to the Bering Strait as the reference point in our budget raises interesting climatological issues. The high-latitude North Atlantic contains areas of deep convection and bottom water formation that are key elements of the global thermohaline circulation. Deep convection is quite sensitive to surface salinity variations; low upper-layer salinities can cap off the deep waters, effectively insulating them from atmospheric cooling (Lazier 1980). The Bering Strait is only 50 m deep and is known to have been a land bridge during the ice ages. Did the cutoff of this freshwater source provide a negative feedback to glaciation by allowing North Atlantic salinities to increase and thus make the North Atlantic more prone to deep convection? What would be the time scale of such a "freshwater oscillation?" How would the ocean circulation adjust to accommodate the global changes in freshwater and salt transport made necessary by closure of the strait? These and other questions can only be addressed when models begin to take proper account of the freshwater and salt transports through straits that connect the major ocean basins.

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