FRESHWATER TRANSPORT AND CLIMATE

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Introduction

The ocean is the largest reservoir of water on the planet, consisting of 96% of the total available surface water (**Figure 1**) and it covers 75% of the earth's surface. It is no surprise then that the majority of water cycling through the atmosphere derives from the ocean: about 12.2 Sv (1 Sverdrup = $1\times10^{6}\,m^{3}\,s^{-1}$) precipitates over the oceans compared to only 3.5 Sv over land (**Figure 1**), while 13.5 Sv evaporates from the oceans compared to 2.2 Sv of evapotranspiration over land. Total runoff into the global oceans is around 1.3–1.5 Sv, which must be balanced in the long term by a slightly higher total evaporation than precipitation over the oceans.

In the following the term transport is used to refer to processes within the ocean and atmosphere, while the term flux is used for processes between these media.

At any point on the ocean's surface, the total fresh water flux is often a small residual between the two nearly equal and opposite fluxes of precipitation and evaporation. These fluxes between the ocean and atmosphere have quite different spatial patterns, and together create a rich structure in the mean annual fresh water flux at the ocean surface (**Figure 2**). The main sources of atmospheric water vapour are the subtropical oceans under the atmospheric high-pressure belts; the main atmospheric water sinks are the tropical convergence zones (particularly the eastern Indian Ocean/western Pacific) and the polar oceans. Since runoff is a relatively small component of the global fluxes, the transport of moisture within the atmosphere from surface sources to sinks is compensated by an equal and opposite ocean transport of fresh water. The atmosphere's poleward transport of moisture also carries latent heat, and this heat transport comprises as much as 1.5 PW (1.5×10^{15} W) of the total of 4 PW of poleward atmospheric energy transport. The compensating ocean fresh water transport is therefore a fundamental parameter in the planetary energy budget.

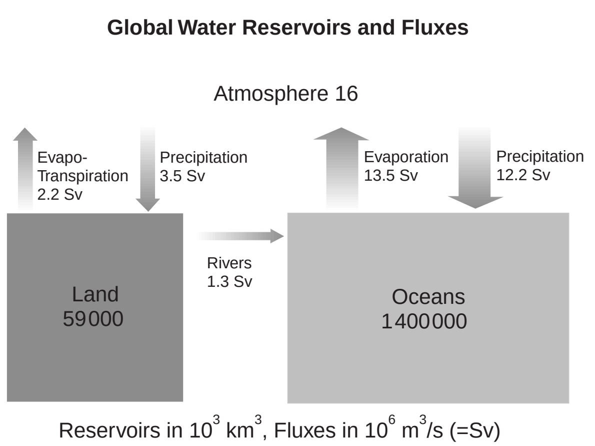

Figure 1 Global water reservoirs and fluxes. (Adapted with permission from Schmitt, 1995.).

Surface fresh water fluxes impact on the oceans in several ways. They change the salinity of surface waters, imprinting them with properties characteristic of their formation regions. For example, intermediate waters formed in the subpolar regions where excess precipitation occurs are traceable far from their source regions because of their low salinity. Fresh water inputs from runoff or excess precipitation can also profoundly influence local air–sea interaction: the formation of fresh light surface layers can suppress convective mixing and thus isolate warmer, saltier deep waters from atmospheric cooling. Such mechanisms are observed in ocean models that display strong sensitivity to fresh water forcing, especially at high latitudes where deep convective mixing occurs that renews the near-bottom waters in the ocean. Changes in high-latitude fresh water forcing of the Atlantic are suspected to have changed the global thermohaline circulation in the past. The sensitivity of ocean models to changes in fresh water forcing is also manifest in the slowing down of the modeled global ocean thermohaline circulation when high-latitude precipitation increases under greenhouse-gas forcing.

Primarily because of the difficulty of measuring rainfall rates over the oceans, estimates of surface fresh water fluxes have been, to date, too uncertain to constrain model behavior well. In the realm of atmospheric modeling, the lack of a reliable benchmark against which to compare the models' moisture transport is a difficulty – the differences among models are often smaller than those among observations. Atmospheric models often overestimate the poleward transport of moisture compared to estimates based on direct observations. However, these

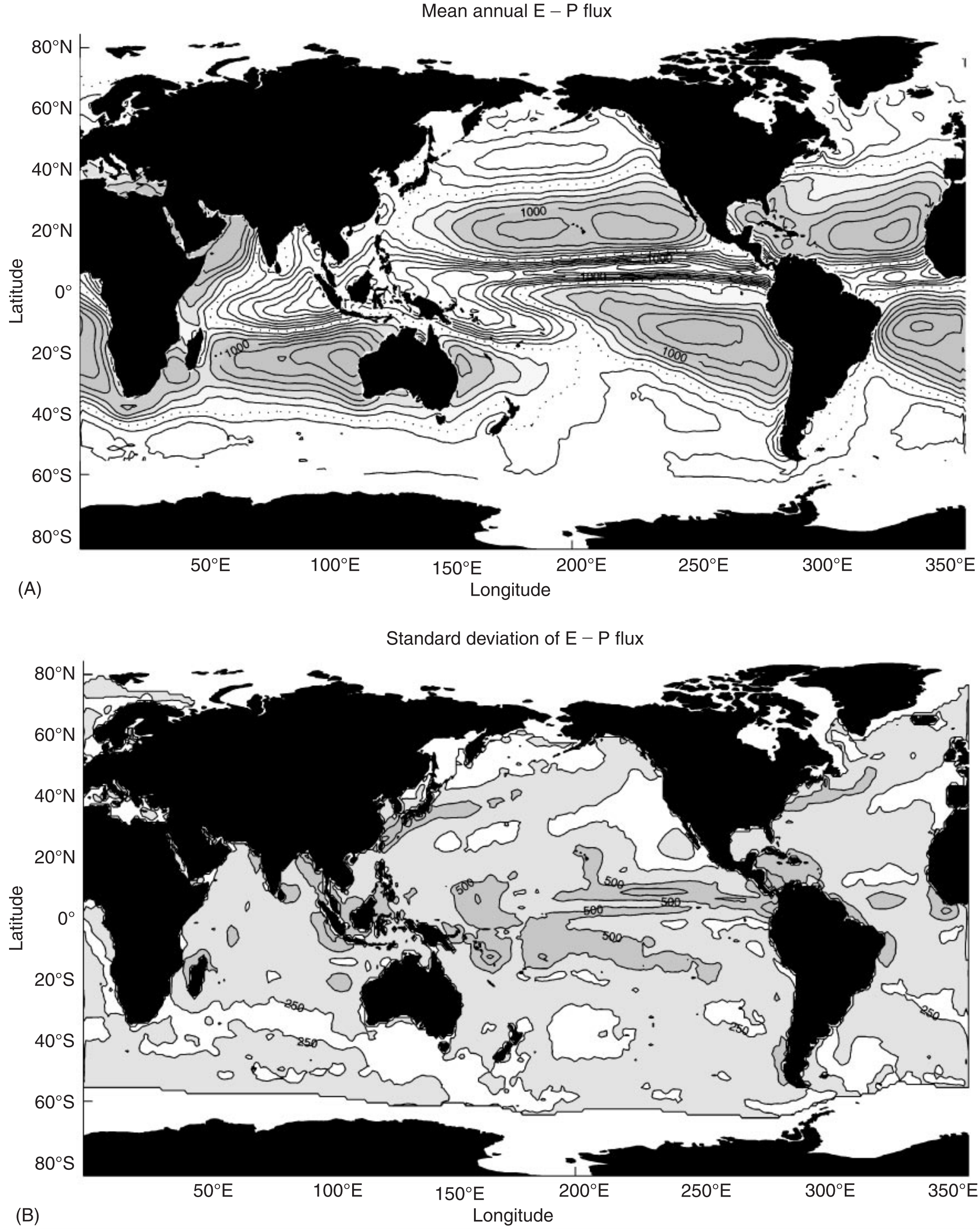

Figure 2 (A) Average mean annual fresh water flux out of the ocean (mm y^{-1}). The zero line is dotted. (B) Standard deviation of 10 estimates of the above showing where the uncertainties are largest. The contour interval is 250 mm y^{-1} in both (A) and (B). (Reproduced with permission from Wijffels, 2001.)

observations are mostly made over the land, with very few made over the oceans that cover the majority of the surface area of the planet.

When forced with observed air–sea fresh water fluxes, ocean models can drift off to unrealistic states, and it has been difficult to distinguish the cause: either inaccurate model physics or errors in the forcing fields. To avoid this problem (and because fresh water forcing has been considered less important compared to thermal forcing) the practice of forcing the model's surface salinity field back to an observed surface salinity field has become the convention in ocean modeling. Such a flux formulation for salinity is physically unjustifiable. The resulting surface flux and salinity fields in the model are unrealistic. This prevents the use of salinity (the next most commonly observed quantity after temperature), to identify and correct physical errors in ocean models.

Methods of Fresh Water Flux and Transport Estimation

In the past, most estimates of ocean fresh water transport derive from surface observations (ship and island) of rainfall rates and parameters (such as wind speed and temperature) used to estimate evaporation. The resulting surface fresh water flux fields can be integrated over the surface area of ocean basins, runoff from the continents added, and the result compared with estimates of ocean fresh water transport based on ocean measurements at specific locations.

Surface Fluxes

In recent years, many new estimates of both atmospheric and surface moisture fluxes have appeared. They are based on the development of data-assimilating atmospheric general circulation models and the availability of new satellite datasets that can be used to deduce evaporation, precipitation, and the net moisture content of the atmospheric column.

Estimates based on data-assimilating atmospheric models have several difficulties, as described by Trenberth and Guillemont in 1999. First, the model output often does not obey total mass conservation making budget calculations difficult. Second, there is a lack of atmospheric profile data over the oceans; the assimilation of scant island station data into these models produces 'bulls eyes' in the surface flux fields, indicating differences between the models and observations.

Estimates of evaporation at the surface rely on empirical relations between the flux and parameters based on either radiometric data measured from satellites or marine meteorological measurements such as wind speed, relative humidity, and sea surface temperature. Though constantly improving, these flux formulas, which are required to apply under all conditions, suffer small biases. When accumulated over large areas such as ocean basins, these flux biases can dominate the totals. The accuracy of the ship-based measurements can also be poor and vary between vessels. Precipitation is particularly challenging to estimate over the ocean because it is sporadic in both time and space. Here, satellite estimates may be the only way to progress, but these also rely on empirical algorithms that require 'tuning.'

The range (as measured by the standard deviation) of current estimates of the mean annual surface fresh water flux (**Figure 2B**) is globally about $250\,\mathrm{mm\,y^{-1}}$, which if integrated over the surface area of the Pacific Ocean north of 30°S adds up to 1 Sv of fresh water transport, which is as large as the natural transport. The largest uncertainty occurs over the tropics and the area affected by mid-latitude storm tracks, as well as a region in the Southeast Pacific off Chile. These are all regions where precipitation is high, thus confirming that the main uncertainty in the total water flux derives from precipitation estimates.

Direct Estimates of Ocean Fresh Water Transport

Ocean fresh water transports can be directly estimated in the same way as those of heat: by examining the flux budgets of volumes of ocean enclosed by long hydrographic lines. The technique is reliant on being able to determine the steady-state portion of the velocity and the salinity field.

For a volume of ocean enclosed by a hydrographic section, salt conservation applies in the steady state, as the transport of salt through the atmosphere and in runoff is negligible:

$$\iint \rho S v \,\mathrm{d}x\,\mathrm{d}z = T_{\mathrm{I}}^{\mathrm{S}} \qquad [1]$$

where ρ is the *in situ* density, S the salinity (e.g., 0.035), v the cross-track velocity (into the volume) and x the along-track distance. $T_{\mathrm{I}}^{\mathrm{S}}$ represents the total salt transport associated with the interbasin exchange, such as the flow through Bering Strait or the Indonesian Throughflow.

Mass conservation is written as

$$\iint \rho v \,\mathrm{d}x\,\mathrm{d}z + [P - E + R] = T_{\mathrm{I}}^{\mathrm{M}} \qquad [2]$$

where E, P, and R are the net fluxes into the surface of the ocean volume of, respectively, evaporation, precipitation, and runoff, and $T_{\mathrm{I}}^{\mathrm{M}}$ the interbasin mass transport. The fresh water part of the above total mass transport is just

$$\iint \rho v(1 - S)\mathrm{d}x\,\mathrm{d}z + [P - E + R] = T_{\mathrm{I}}^{\mathrm{M}} - T_{\mathrm{I}}^{\mathrm{S}} \qquad [3]$$

The $P - E + R$ eqn [3] is not a useful approach because the mass transport across an ocean section has uncertainties that are larger than the fresh water transport. However, the errors in the total salt and mass transports across a section are strongly correlated, and these errors can be largely canceled through defining an areal average salinity and its deviation for the section:

$$\bar{S} = \frac{\iint S \,\mathrm{d}x \,\mathrm{d}z}{\iint \mathrm{d}x \,\mathrm{d}z}; \qquad S' = S - \bar{S} \qquad [4]$$

For simplicity, we also assume that the interbasin transport of salt occurs at a known salinity, S_{I}, so that the associated salt transport is just $T_{\mathrm{I}}^{\mathrm{S}} = S_{\mathrm{I}} \times T_{\mathrm{I}}^{\mathrm{M}}$. Combining eqns [1], [2] and [4], the surface fresh water flux can now be written as a simple product of the salinity deviation and the velocity field:

$$[P - E + R] = \frac{T_{\mathrm{I}}^{\mathrm{M}} S'_{\mathrm{I}} - \iint \rho v S' \,\mathrm{d}x \,\mathrm{d}z}{\bar{S}} \qquad [5]$$

Here the first term on the right is referred to as the 'leakage' term associated with the total cross-section transport (the interbasin exchange) and the second term is due to correlations of salinity and velocity across the section, which effect a fresh water transport. In practice, v is found from density and wind-stress measurements using the geostrophic and Ekman assumptions, and often inverse techniques, while S is directly measured along ocean sections.

Deriving error estimates for the product of eqn [5] is challenging, since the statistics of the vS' term are not well known. Simple scaling arguments were used by Wijffels to show that the expected uncertainty in the direct transport estimates based on eqn [5] might be 0.17 Sv outside of the tropics, but as large as 0.3 Sv in the tropics because of uncertainties in the near-surface wind-driven component. Going beyond the simple scaling argument requires simultaneous time-series of both velocity and salinity over basin scales, measurements that are not likely to be available in the short term.

Comparison of Direct and Indirect Transport Estimates

Runoff from the continents must be added to the surface $E - P$ fluxes integrated over the ocean basins in order to predict the ocean transport of fresh water. Despite attempts to catalog the runoff of major rivers, there are few global estimates of runoff. Here Baumgartner and Riechel's 1975 compilation is utilized, which roughly agrees with the runoff deduced from recent atmospheric analyses. The lack of global runoff datasets makes assessing the errors in the runoff fluxes difficult and adds uncertainty to estimates of ocean fresh water transport.

All three major ocean basins exchange large amounts of sea water through linking passages: the Southern Ocean, the Indonesian Archipelago, and Bering Strait. As these sea water exchanges are much larger than the fresh water exchanges through the atmosphere, it is simpler to present only the divergent part of the ocean fresh water transport (in contrast to the full transports reported by Wijffels and colleagues in 1992). This is equivalent to removing an unknown constant equal to the Pacific–Indian Throughflow for the Indian and South Pacific Oceans, and the Bering Strait flow in the North Pacific and Atlantic. Only the divergence part of the fresh water transport relative to the entrances of the Bering and Throughflow straits (South of Mindinao in the Philippines) will be presented below.

While the size and salinity of the Bering Strait flow are relatively well known, those of the Pacific–Indian Throughflow are not. Hence, investigators have had to make assumptions about them in order to generate an estimate of the fresh water divergence over the South Pacific and Indian Oceans – that is, to calculate the 'leakage' term in eqn [5]. As direct estimates for the long-term average Throughflow range between 5 and 10 Sv, it remains a large source of uncertainty in the freshwater budgets of the South Pacific and Indian Oceans.

Basin Balances

Most direct transport estimates derive from single-section or regional analyses of long hydrographic lines, many of which were completed during the World Ocean Circulation Experiment during the 1990s. To date, few truly global syntheses have been made and so we report Wijffels' year 2000 compilation. The divergent part of the ocean fresh water transport in the three major ocean basins is shown in **Figure 3**.

According to the surface flux estimates, the Indian Ocean north of 30°S undergoes net evaporation; that is, the ocean circulation must import fresh water to the Indian basin, from which the atmosphere exports it. Only two latitudes are currently constrained by direct ocean transport estimates in this basin: 32°S and 18°S, shown by the location of the vertical bars in **Figure 3A**. Over the large evaporative zone between latitudes 15° and 40°S, the indirect transport estimates are fairly consistent

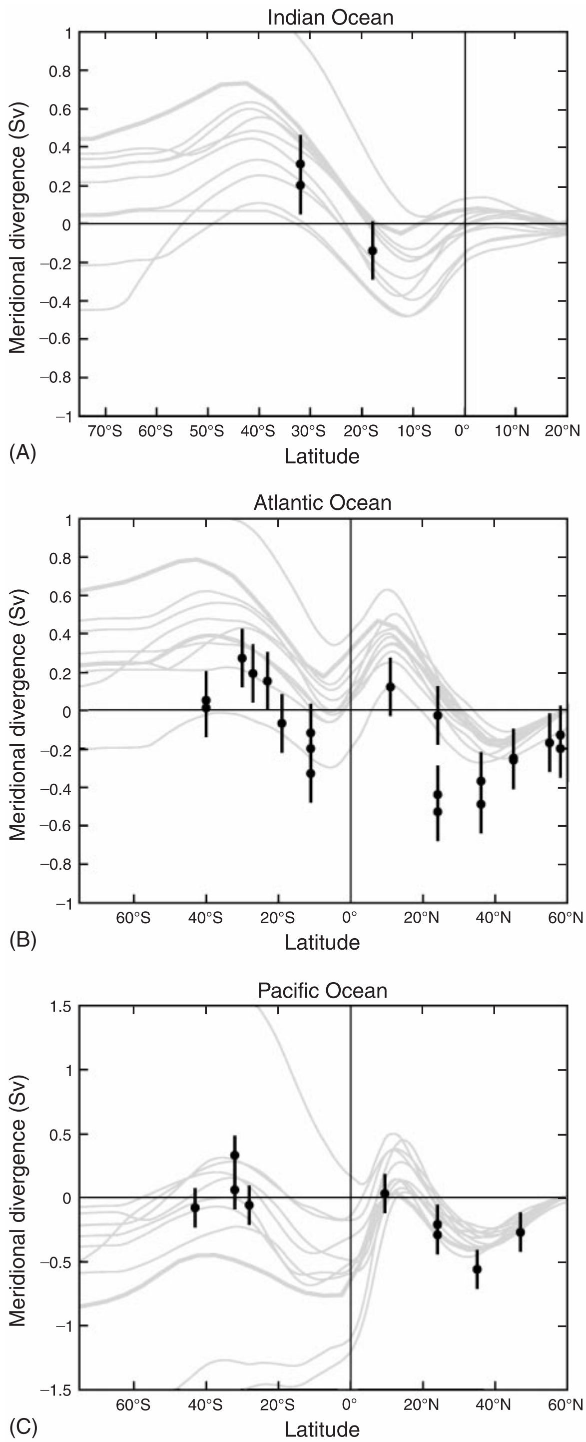

Figure 3 The divergent part of the ocean fresh water transport (Sv) in each ocean basin. Indirect estimates based on surface flux climatologies and atmospheric analyses are shown as gray continuous lines while direct ocean estimates at discrete latitudes are shown in black with error bars. The 'classical' climatology of Baumgartner and Reichel used by Wijffels *et al.* in 1992 is shown as the thicker gray line. (A) Indian Ocean relative to 30°N; (B) Atlantic/Arctic relative to Bering Strait; and (C) Pacific transport relative to Bering Strait and the Throughflow channels off Mindanao. (Adapted with permission from Wijffels, 2001.)

(they have similar slopes) and are also in reasonable agreement with the direct estimates. It is in the regions of high precipitation north of 10°S and south of 40°S that the transport curves diverge, confirming again the large differences between estimates of precipitation over the ocean. The reader may note in particular the 0.5 Sv variability in the net fresh water divergence north of 18°S, where the monsoons are active.

The Atlantic Ocean is the best-covered by direct transport estimates (**Figure 3B**), which are remarkably consistent, except for those at 24°N, which are from three occupations of a trans-ocean section spanning 30 years. Nearly all of the major transport maxima are delineated by the direct estimates. Again, the indirect estimates diverge most strongly over regions of high precipitation in the tropics and polar regions. When integrated over the Atlantic between 40°S and Bering Strait (we have included the entire Arctic Ocean in the Atlantic), the indirect transport divergences range between 1.0 and 0.0 Sv, while, surprisingly, the direct estimates indicate very little net fresh water divergence over the basin. This difference could be due to an underestimate of runoff to the Arctic/Atlantic as well as an underestimate of $P - E$ to the basin.

Problems with biases in the indirect transport estimates are even more pronounced in the Pacific Ocean owing to its huge size (**Figure 3C**). Indirect transport estimates vary wildly over the South Pacific, where *in situ* atmospheric data and marine observations are very scarce. Here again, despite the different assumptions made to close the ocean mass balance, Throughflow sizes and different data sets, the direct ocean fresh water transport estimates are quite consistent, and show much less scatter than the indirect estimates. Remarkably, despite a 25 years' difference between section occupations, two direct estimates of the fresh water divergence made near 30°S are indistinguishable.

Interbasin Exchange

One of the first attempts to deduce the exchange of fresh water between ocean basins was made by Baumgartner and Reichel. Lacking 'control' points for the nondivergent part, they assumed zero fresh water transport across the Atlantic equator, and could thus integrate runoff and surface fluxes to deduce the ocean transport. Using new estimates of transport through Bering Strait, Wijffels *et al.* in 1992 also used the Baumgartner and Reichel climatology to predict the ocean fresh water transport. They deduced that the Pacific received an excess of precipitation and runoff over evaporation of

0.5 Sv, which was then redistributed through the Indonesian Throughflow, Bering Strait, and Southern Ocean to the more evaporative Atlantic and Indian Oceans.

The new direct ocean estimates indicate a quite different interocean fresh water exchange. **Figure 3C** shows that the fresh water divergence over the Pacific between Bering Strait and 30°S is near zero: there is a net balance of evaporation, precipitation, and runoff over that basin. Direct transport estimates for the Atlantic/Arctic also suggest a net divergence of fresh water that is much smaller than previously thought. The new direct estimate of a 0.24 Sv convergence between Bering Strait and 30°S in the Atlantic is roughly half that predicted by Baumgartner and Reichel (**Figure 3B**), while the direct estimates at 40°S indicate almost no net divergence over the Atlantic/Arctic. The Indian Ocean direct transport estimates, however, remain consonant with net excess evaporation over precipitation over that basin (**Figure 3A**).

Since the Pacific Ocean and Atlantic/Arctic Oceans cannot be the source of the excess ocean fresh water required to supply the Indian deficit, only one possibility remains: excess precipitation and ice melt over the Southern Ocean. The newly available direct estimates imply a fresh water source of about 0.5 Sv south of 30°S, highlighting the importance of the Southern Ocean in the global ocean fresh water balance.

Mechanisms of Ocean Fresh Water Transport

In 1981 Stommel and Csanady pointed out that ocean heat and fresh water transport is related to the rates of conversion of water from one temperature–salinity class to another. They went further and attempted to model this process with salinity as a simple function of temperature. Recent analyses of fresh water transports across ocean sections and in general circulation models showed this assumption to be wrong, though the underlying idea remains powerful, as it links surface fluxes to water mass inventories and exchanges in temperature–salinity space. Stommel and Csanady's approach has also been recast in terms of density classes of water, which expresses the competition between surface fluxes and interior ocean mixing in controlling exchange between density classes. The challenge in analysing ocean sections will be in distinguishing the water mass conversion at the surface from that due to internal mixing. Use of the fresh water fluxes will be critical.

How and which elements of the circulation achieve the ocean fresh water transport is also of great interest. The definition of a tracer transport mechanism across an ocean section is still, however, somewhat *ad hoc*. In their pioneering work in 1982, Hall and Bryden chose to form zonal averages (and deviations) of velocity and properties on pressure surfaces. They termed the resulting products the 'overturning' component of tracer transport, while the residual (associated with the correlation of velocity and tracer at a pressure level) was termed the 'horizontal' or gyre component. A similar decomposition can be carried out within density layers and, as density is largely determined by temperature, more closely relates back to Stommel and Csanady's suggestion. Fresh water divergence is also achieved by the interbasin flows, the 'leakage' term in eqn [5]. Unfortunately, few detailed decompositions of the ocean fresh water transport across hydrographic lines are available; those that are, however, reveal interesting mechanisms and cases where different circulation components can provide canceling fresh water transports.

For example, at 10°N in the Pacific, the small net fresh water divergence over the Pacific relative to Bering Strait is due to a balance between three major mechanisms: (1) net export of very fresh water through Bering Strait to the Arctic; (2) a northward fresh water transport by a shallow meridional circulation where the northward Ekman transport in the upper 100 m is fresh and there is a compensating salty southward thermocline flow (100–300 m); (3) southward fresh water transport is achieved by a 300–450 m deep horizontal gyre where salty South Pacific waters flow north in the eastern Pacific and fresh intermediate water flows south in the western Pacific. The deep and bottom water circulations in the low-latitude Pacific achieve little net fresh water transport.

In the Indian Ocean a large net evaporation of 0.31 Sv is estimated to occur north of 32°S. Three mechanisms act to import this fresh water to the ocean basin: (1) a leakage term associated with the inflow of fresh Indonesian Archipelago waters that are evaporated and leave across 32°S as salty thermocline waters; (2) upwelling of deep and intermediate waters and their export as saltier thermocline waters; and (3) horizontal inflow of fresh Antarctic intermediate water in the east that leaves as saltier intermediate water in the west. This latter transport mechanism was also found to be an important fresh water transport mechanism at 32°S in the Pacific. It is likely that the recirculation of subtropical mode and intermediate waters between the Southern Ocean and the Southern Hemisphere subtropical gyres may be the single most important mechanism for balancing the large net flux (0.57 Sv) received by the ocean south of 30°S from the atmosphere and ice flows.

The ability of ocean general circulation models to reproduce the estimated fresh water transports and their mechanisms will be a stringent test of the models' realism. In ocean-only models, surface-flux forcing will determine the net equilibrium transports (unless the problematic relaxation boundary conditions are used), but internal model physics will determine how this transport is achieved. It is also noteworthy that the fresh water transports effected by the subtropical gyres through the vS' term in eqn [5] is not accounted for in simple box models of the global thermohaline circulation, which allow only a single salinity and temperature to represent the major water mass pools. Such models must fold this upper-ocean gyre transport into the deep-water component of the global thermohaline circulation, confusing the role of fresh water forcing as a control on the circulation. More detailed studies of how the ocean transports fresh water are required to isolate the relative roles of the shallow wind-driven gyres and the deep circulation in balancing the surface forcing.

Global Budgets

Direct ocean transport estimates are available in all ocean basins at five latitude bands, which allows the total global meridional fresh water transport to be examined. Since few of the major rivers flow meridionally, the zonally integrated meridional ocean transport of fresh water is largely equal and opposite to that in the atmosphere. Therefore, these estimates can be compared with direct estimates of atmospheric moisture transport or those produced by atmospheric general circulation models (**Figure 4**). Based on a comparison with Oort and Piexoto's 1983 global atmospheric estimates, international model intercomparison studies concluded that most atmospheric models overestimate the poleward transport of moisture. Direct ocean measurements are still too sparse to shed conclusive light on this issue. In the northern hemisphere high latitudes, the direct estimates agree better with Oort and Piexoto's than those from Atmospheric Model Intercomparison Project (AMIP), while in the tropics and southern hemisphere the opposite is true. To more usefully constrain the total meridional moisture transport in the atmosphere, more direct ocean fresh water transport estimates are needed as well as a better estimate of their errors – those shown in Figure 4 are based on simple scale arguments and so are rather conservative.

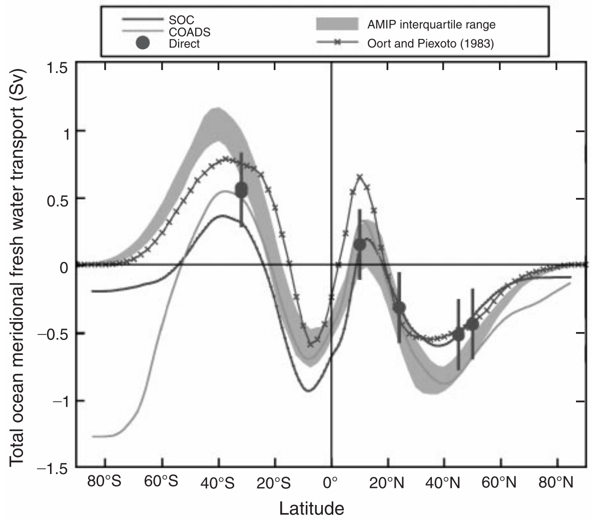

Figure 4 Various estimates of the total ocean meridional fresh water transport (Sv). Estimates based on ocean data are shown as black circles; thin lines are indirect estimates based on two recent surface flux climatologies with the Baumgartner and Reichel's 1975 continental runoff added. Gray shaded is the interquartile range for the atmospheric models participating in AMIP. Oort and Piexoto's 1983 direct atmospheric estimate is marked as x-x. The two surface flux climatologies are as follows. SOC: Josey SA, Kent EC, Oakley D and Taylor PK (1996) A new global air-sea heat and momentum flux climatology. *International WOCE Newsletter* 24: 3–5. COADS: da Silva AM, Young C and Levitus S (1994) *Atlas of Surface Marine Data*, vol. 1: *Algorithms and procedures*. NOAA Atlas NESDIS 6. (Reproduced with permission from Wijffels, 2001.)

Future Directions

Despite many new estimates of surface fresh water fluxes over the oceans having been made, their use in assessing atmospheric models and forcing ocean models will depend on the accuracy of their basin-wide integrals. These can only be assessed by fresh water transport estimates from ocean data. Direct ocean fresh water transports are not as well reported or analyzed as their companion heat transports. While most estimates are fairly consonant with each other and with error estimates based on simple scaling arguments, others are quite anomalous. Without a detailed breakdown of the mechanisms making up these transports, tracking down the source of these differences is next to impossible.

There may be enormous potential in the idea of 'tuning' surface flux products by using direct ocean estimates to remove flux biases. This might in turn lead to products that are accurate enough to directly force ocean climate models with confidence, and thus allow meaningful use of salinity as an ocean model diagnostic.

Monitoring for changes in ocean fresh water storage may also now be feasible with the availability of salinity sensors that are stable over long deployments on floats and buoys.

Estimates of ocean fresh water transport will remain reliant on transport-resolving temperature–salinity sections, until such time as data-assimilating ocean models are sufficiently accurate to capture the essential ocean fresh water transport mechanisms.

See also

Abrupt Climate Change. Deep Convection. Elemental Distribution: Overview. Heat and Momentum Fluxes at the Sea Surface. Heat Transport and Climate. Inverse Models. Satellite Remote Sensing SAR. Thermohaline Circulation. Upper Ocean Heat and Freshwater Budgets.

Further Reading

Baumgartner A and Reichel E (1975) *The World Water Balance*. New York: Elsevier.

Hall MM and Bryden HL (1982) Direct estimates and mechanisms of ocean heat transport. *Deep-Sea Research* 29: 339–359.

Oort AH and Peixoto's JP (1983) Global angular momentum and energy balance requirements from observations. *Advances in Geophysics* 25: 355–490.

Schmitt R (1995) The ocean component of the global water cycle. *Review of Geophysics* (supplement) 1395–1409.

Schmitt R (1999) The ocean's response to the freshwater cycle. In: Browning KA and Gurney RJ (eds). *Global Energy and Water Cycles*. Cambridge: Cambridge University Press.

Stommel HM and Csanady GT (1980) A relation between the TS curve and global heat and atmospheric water transports. *Journal of Geophysical Research* 85: 495–501.

Trenberth KE and Guillemot C (1999) Estimating evaporation-minus-precipitation as a residual of the atmospheric water budget. In: Browning KA and Gurney RJ (eds). *Global Energy and Water Cycles*. Cambridge: Cambridge University Press.

Wijffels SE, Schmitt RW, Bryden HL and Stigebrandt A (1992) Transport of freshwater by the oceans. *Journal of Physical Oceanography* 22: 155–162.

Wijffels SE (2001) Ocean transport of freshwater. In: Church J, Gould J and Siedler G (eds). *Ocean Circulation and Climate*. London: Academic Press.