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HEAT TRANSPORT AND CLIMATE

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Introduction

It has long been recognized that the ocean plays a significant role in determining the Earth's climate through its interaction with the atmosphere. Since it is the radiation from the sun heating the Earth which drives motion in both these fluid regimes, an understanding of climate and how it evolves is necessarily based upon an understanding of how energy is transported within, and exchanged between, the ocean and the atmosphere.

The Earth receives energy from the sun in the form of short-wave (ultraviolet, visible, and infrared) radiation. Due to the shape and tilt of the Earth, and simple geometry, the intensity of this incoming solar radiation is greatest near the equator and least (but not zero) near the poles (**Figure 1**). The same is true of the intensity of the outgoing long-wave (infrared) radiation returning to space. However, the equator to pole difference is far less for the outgoing radiation (about 50 $\mathrm{Wm^{-2}}$) than for the incoming (>200 $\mathrm{Wm^{-2}}$). Therefore, equatorward of about 35°, the Earth experiences a net warming, while poleward of this latitude, it experiences a net cooling. Because the distribution of incident solar radiation over the Earth is both spatially and temporally uneven, the two systems work together in advecting and exchanging energy to produce an equilibrium, which is why the equatorial regions do not become steadily warmer and the polar regions do not become steadily colder.

To maintain the balance, the ocean–atmosphere system carries a maximum of $\sim$5–6 PW of energy poleward (**Figure 2**). Whether it is the atmosphere or the ocean which is the dominant contributor to this poleward transfer and at what latitudes, is a source of continued debate and further research. However, because the heat capacity and density of the atmosphere are so much less than those of water, the top 2.5 m of the ocean holds as much heat as the entire depth of the atmosphere. It would only take a temperature change of 0.01°C to change the ocean heat content by 1 PW. It is then not surprising that available estimates clearly suggest that the oceanic heat budget is a major component of the climate system, supporting at least half the poleward transfer of energy at some latitudes.

Historically, estimates of oceanic heat transport have presented a broad range of values, but more recently, there appears to be some convergence both in direct estimates (especially in the North Atlantic), as well as in indirect estimates. Satellite data and numerical models now allow us to look at some aspects of ocean heat transport variability, and together the various methods give a broad view of how the oceans contribute to the poleward transfer of energy.

Basic Theory

Estimates of meridional oceanic heat transport derived from observations (i.e., direct estimates) are usually computed from the data using the following formula:

$$\int \rho(T,S,a)c_p\Theta(T,S,a)v(a)\,\mathrm{d}a \qquad [1]$$

where, a is a function of horizontal distance and pressure such that the integral is taken over a vertical slice of the ocean, ρ is density, T is temperature, S is salinity, c_p is specific heat at constant pressure (in practice taken as a single value calculated at a standard T and S), Θ is the potential temperature, and v is the absolute velocity.

Note, however, that what is generally referred to as oceanic heat transport is actually the transport of internal energy. The internal energy is part of the total energy, E, whose transport per unit mass

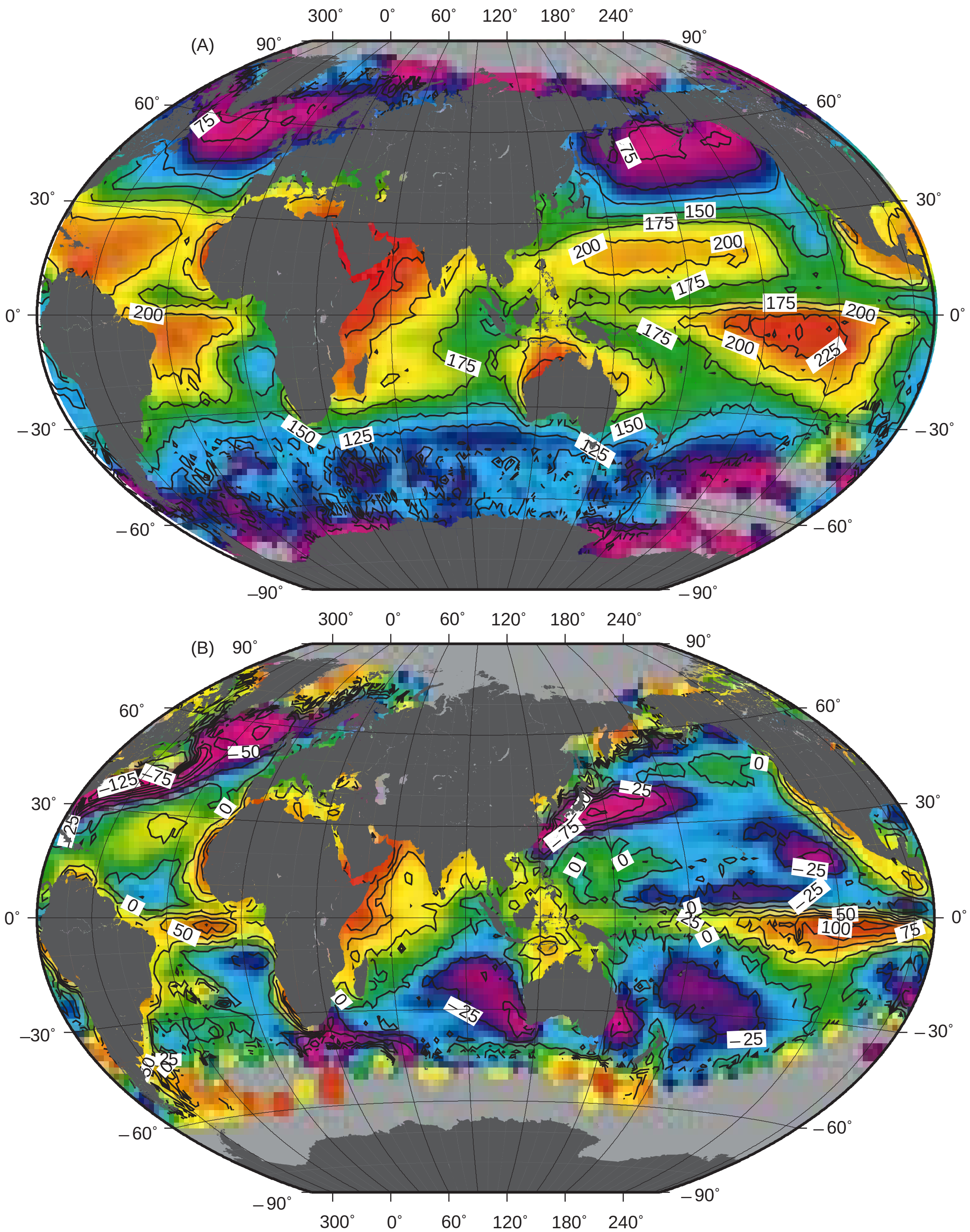

Figure 1 (A) Annual average incoming solar radiation at the ocean surface. (B) Annual average net heat flux into (positive) and out of (negative) the ocean. Values are in units of W m^{-2}. The data set was compiled by Z. Wu and computed by a bulk formula method using the Comprehensive Ocean Atmosphere Data Set (COADS).

across a section is defined as:

$$\int \rho E v \, \mathrm{d}a = \int \left(U + \tfrac{1}{2}c^2 + \varphi + \alpha p\right)\rho v \, \mathrm{d}a \qquad [2]$$

where the first term on the right hand side, U, represents the internal energy per unit mass, the second term the kinetic energy, the third the gravitational potential energy and the last term the work

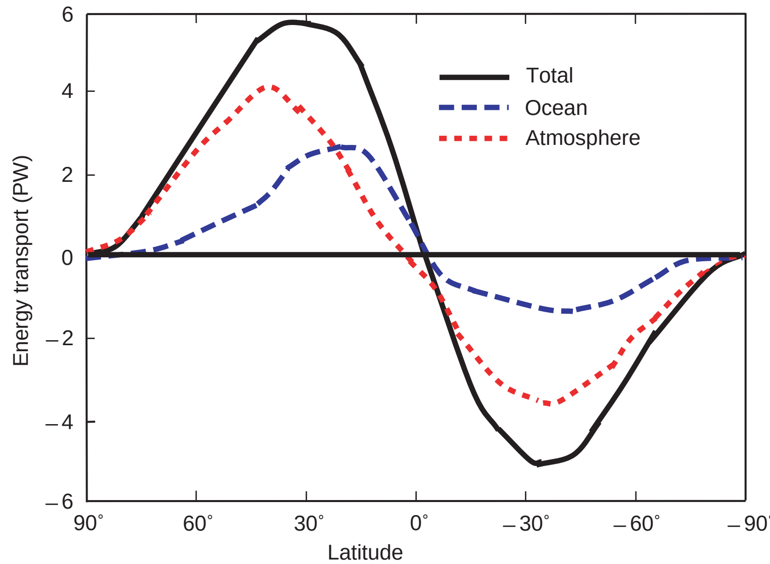

Figure 2 Schematic illustrating the relative contributions of the atmosphere and oceans to the total poleward heat flux.

done by the pressure force. In a concise and illuminating note, Warren (1999) showed that the heat transport derived from observations $\int \rho c_p \Theta v \, da$ not only approximates the internal energy transport to within a few percent, but also approximates the total energy transport to within about 0.1%. So with the caution and understanding that heat is no more a property of water than is cold, we shall continue to use, as has been done in the past, the term 'heat transport' synonymously with the term 'energy transport', and shall take estimates of heat transport to be equivalent to estimates of total energy transport.

Units

Meridional ocean heat transport estimates are generally quoted in units of PW, where 1 PW = 10^{15} W = 10^{15} Joules s^{-1}. Mass transport is quoted in Mt s^{-1} (megatonnes per second, where 1 Mt s^{-1} = 10^9 kg s^{-1} which for fresh water is equivalent to 10^6 m^3 s^{-1}). The Gulf Stream carries about 100 Mt s^{-1} of water. As a reference, the Amazon river carries about 0.2 Mt s^{-1}, while the Mississippi has a transport of only 0.02 Mt s^{-1}. Throughout, negative mass and heat transport values are to be interpreted as southward, and positive values as northward.

Methods of Estimation

There are three main types of estimates of oceanic heat transport: direct, indirect, and model. Model estimates are discussed in light of variability in a later section. Indirect methods come from two sources, those derived from bulk formulae and those which take the oceanic heat transport as the residual of top of the atmosphere radiation budget and the atmospheric heat transport. Direct estimates are based on ocean circulation and temperature observations.

Bulk Formula Methods

Bulk formula methods rely upon estimates of the exchange across the air–sea interface. They are used to estimate ocean heat flux divergence. Air–sea exchange occurs in various guises including short- and long-wave radiation, latent and sensible heat, precipitation, momentum, and gas exchange. Direct estimates of these transfers over large areas of the ocean and extensive periods of time are often impractical. Instead equations (bulk formulae) are used which estimate the exchanges through other measurable quantities, both atmospheric and marine, along with empirical coefficients.

Over the years, bulk formula coefficients, the formulae themselves, the data to which they are applied, and the method of application have all been improved. Nevertheless, the resulting estimates of surface energy fluxes still retain uncertainties and biases of the order of 30 Wm^{-2}. For regional analyses of surface exchanges this level of uncertainty may be acceptable (see **Figure 1**). However, integrating these estimates to derive ocean heat transport divergence produces errors as large as 0.5 PW in the North Atlantic and >1 PW in the North Pacific; uncertainties which are as large or larger than the estimates themselves.

Residual Methods

Residual methods take the oceanic heat transport to be what is left over after subtracting the atmospheric energy transport (computed by integrating the surface heat flux) from the top of the atmosphere radiation balance (incoming minus outgoing). The latter, which these days is usually determined from satellite data, is considered to be good to the order of 10 W m^{-2}. The former, which is calculated from the observational network of rawinsondes, is less certain. It has tended to produce ocean heat transports which are large compared with both direct observations and estimates coming from numerical models which assimilate atmospheric data.

Even improved techniques in the application of the residual method produce surface heat flux estimates which are uncertain by as much as 30 W m^{-2} over land. Although these techniques are thought to be more accurate over the open ocean, traditionally, the residual method only produced estimates of oceanic heat transport across global latitudinal circles, thereby implying that the ocean estimates would be contaminated by the uncertainties over land. Recently, however, improvements in technique have allowed estimates of the atmospheric energy transport to be made over the oceans only, thereby avoiding the issue of contamination. Such residual methods still produce an overall warming of the oceans, but the resulting ocean heat transport uncertainties are not only lower (e.g., 0.7 PW for a maximum transport of 2.7 PW at 20°N), but are also consistent, as shown below, with recent direct observations.

Direct Methods

The third method of estimating oceanic heat transport is directly, through the use of hydrographic observations. To estimate the meridional transport across a line of latitude, temperature (T) and salinity (S) measurements are taken across the entire breadth of an ocean basin near the desired latitude, at a variety of longitudes and depths. T and S are used to determine the elements of eqn. [1], which is solved as a discrete sum over the area sampled by the data. Although this appears to be a relatively simple procedure, it is complicated by the uncertainties involved in computing the absolute velocity, v.

T and S can be used to calculate the geostrophic velocity profiles perpendicular to a pair of stations, but only relative to a specified reference level. To obtain an estimate of the absolute velocity profile two things are needed: (1) an estimate of the velocity at the reference level and (2) an estimate of the wind-induced transport. A variety of methods have been used to determine the former. Most apply some set of constraints (based on preconceived ideas or prior knowledge about the distributions of water mass properties and circulation) either formally or informally, to arrive at an educated guess as to what the reference level velocities should be. More recently direct observations of the absolute velocity at a single level have been used.

The second necessary component of an absolute velocity field is an estimate of the wind-induced mass (Ekman) transport across the section. There are a number of estimates of the wind field available, most of these use observations assimilated into numerical models. At some latitudes, particularly where the temporal variance in the wind field is large (e.g., the tropics) or where there is a scarcity of data (e.g., the Southern Ocean) the resulting estimates of Ekman mass transport often differ.

An additional complication is that although the wind effect is surface intensified, assumptions about the depth to which its effects penetrate are also a factor in determining the heat transport. Since water temperatures almost always decrease with depth, an assumed shallow penetration will be associated with a greater average temperature than a deeper penetration, thereby increasing the estimated heat transport. In certain regions of the ocean the annual average surface temperature may be a more appropriate choice than a synoptic depth averaged temperature.

Given all the various choices in both indirectly and directly estimating the oceanic heat transport, one of the most significant advances of the last decade has been the effort made to include some estimate of the uncertainty in the final numbers. This inclusion now makes it possible to determine whether or not the various techniques produce consistent solutions. **Figure 3** illustrates how some of these estimates compare. It is interesting to note that many, although not all, of the more recent estimates are consistent within their present levels of uncertainty. Only in the Southern Ocean is there any uncertainty in the sign of oceanic heat transport, and at most latitudes the estimates are significantly different from zero.

Heat Transport: Circulation and Water Mass Formation

In comparing estimates of oceanic heat transport the issue of mass conservation should be kept in mind. Eqn [1] is not particularly useful if the associated mass transport across a section, $\int \rho v \, da$, is not zero.

Note that if the mass transport is nonzero, a change in units of Θ will change the estimate of heat transport. Because there is some net flow between each of the major ocean basins, as well as a freshwater flux at the ocean's surface and boundaries, there are few, if any places where the net mass transport across a line of latitude is truly zero (**Table 1**).

To circumvent this issue, in the Atlantic and North Pacific, the small net meridional mass transport (~ 1 Mt s^{-1}) is usually considered negligible compared with its uncertainty. The same assumption is made about the freshwater exchange. In the South Pacific and South Indian Ocean, either individual basin values are combined to obtain a mass balance, or a separate term accounting for the flow through the Indonesian Archipelago is calculated. Heat transport estimates which assume a zero net mass transport through either of these two basins individually should be treated with caution. To compare estimates where mass conservation can not be assumed (e.g., across the Antarctic Circumpolar Current) the usual technique is to base the estimates on a 0°C reference and call them temperature transports. Heat transport occurs because waters of

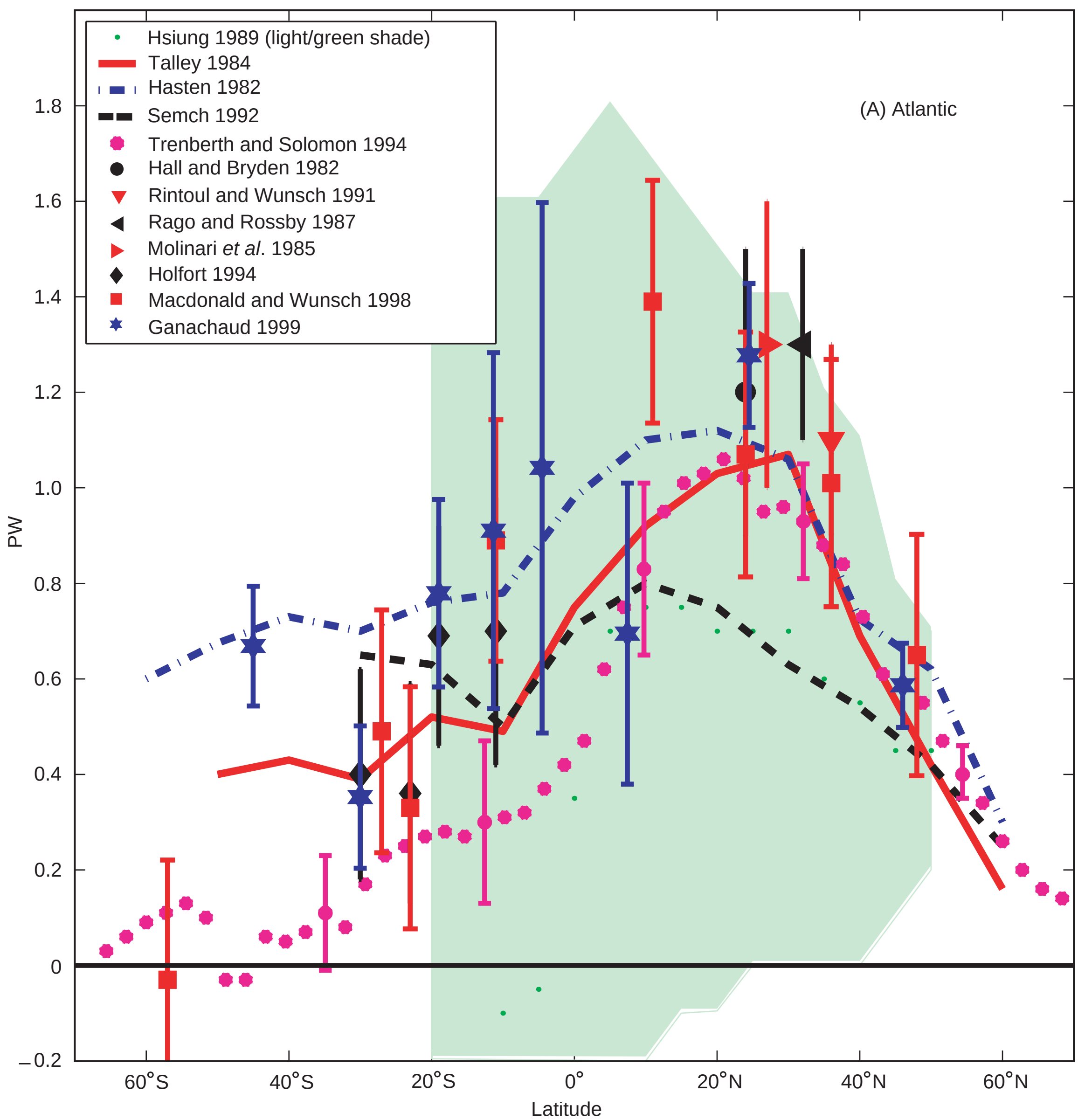

Figure 3 Estimates of northward meridional heat transport within the (A) Atlantic Ocean, (B) Indo-Pacific Ocean, and (C) World Ocean. (Figure (C) adapted with permission from Ganachaud and Wunsch, 2000). Note, the Semtner and Chervin values are derived from the recent POCM-4B integration used by Jayne (1999). The shaded regions (Hsiung et al., 1989) illustrate the seasonal range of the reported estimates.

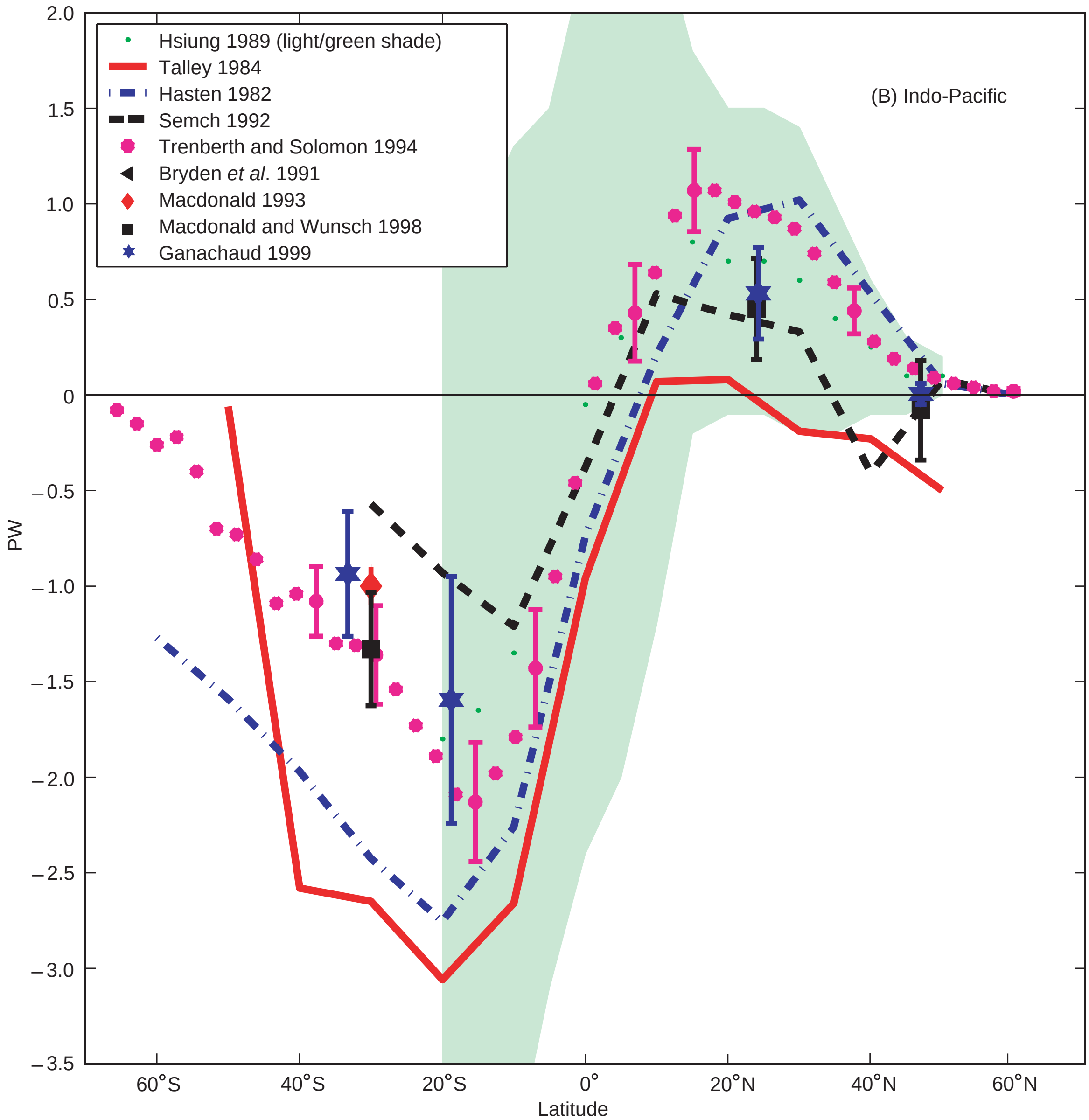

Figure 3 *Continued*

different temperature are flowing at different rates throughout the water column and across basins. Therefore, oceanic heat transport estimates are inextricably linked to the underlying circulation. A heat transport estimate cannot be understood without a knowledge of the associated mass transport.

Generally speaking, the mass transport of surface waters in the Atlantic is northward. The ocean gains energy (heat) in the tropics and loses it in the subtropics and polar regions (**Figure 4**). As these surface waters cool, they become more dense and eventually sink (**Figure 5**). The resulting North Atlantic Deep Waters (NADW) flow southward, meet with bottom waters formed around Antarctica (AABW), and flow within the Antarctic Circumpolar Current into the Indian and Pacific Basins. Here, they mix with surrounding warmer water masses, upwell, and eventually return to the Atlantic to begin the process again. In all the ocean basins, except the South Atlantic, the net oceanic heat transport is poleward, as expected. In the South Atlantic, the ocean gains energy from the atmosphere and relatively warm surface waters are transported equatorward to replenish the deep-water formation sites in the northern hemisphere. Balancing the mass budget, the colder deep waters return southward and result in a net equatorward heat transport. Note that in the South Pacific, although the pattern appears similar,

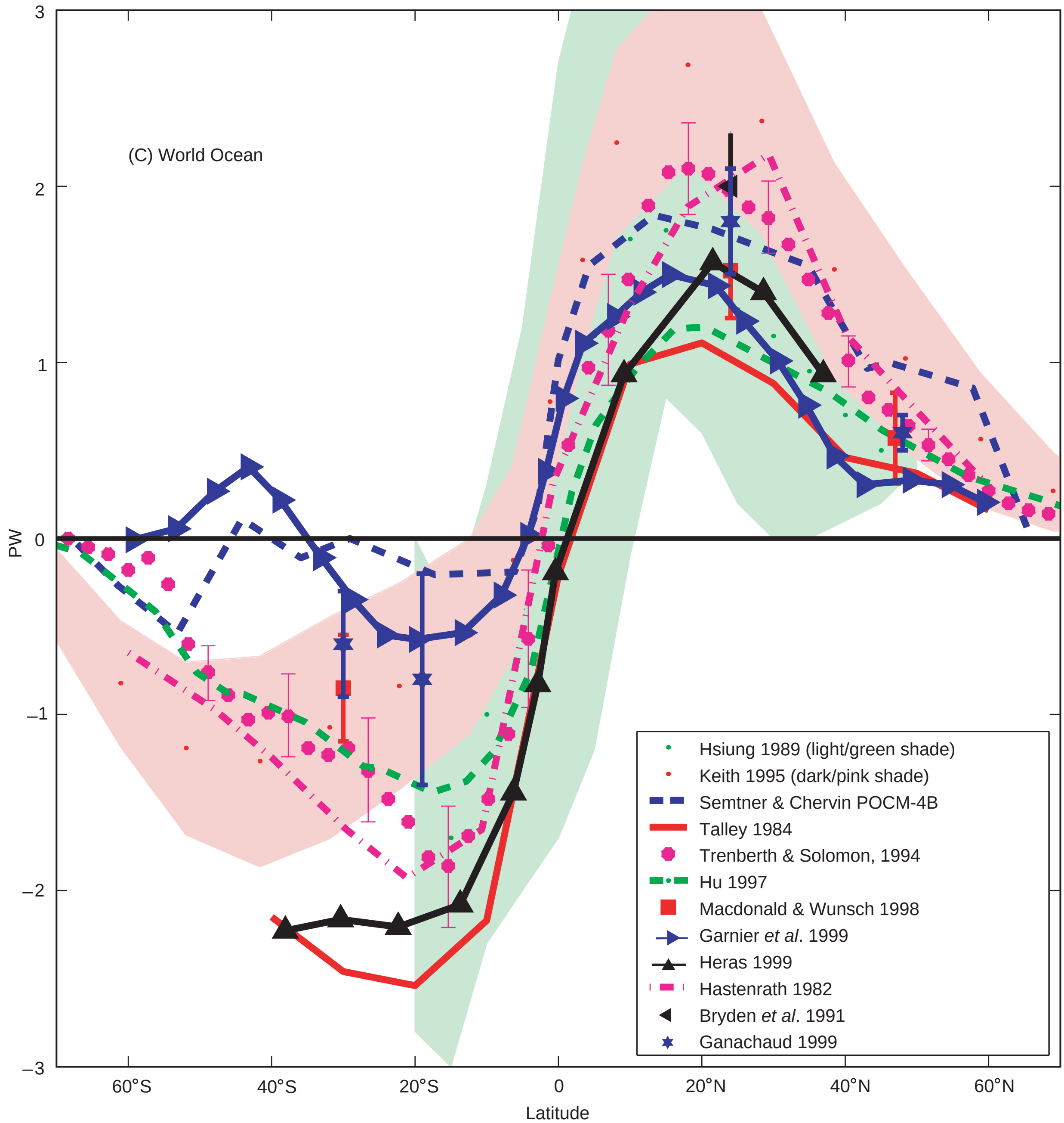

Figure 3 *Continued*

to balance mass the Indian and Pacific Basins should be viewed together.

Overlaid on top of the thermohaline (density driven) (also known as global overturning) circulation, is the wind-driven circulation which is responsible for the characteristic cyclonic and anti-cyclonic gyre patterns of the surface currents. The winds also strongly affect evaporation (cooling), as well as upwelling processes, and therefore, also directly contribute to water mass transformation and heat transport. Whether and how the two components can be separated is still debated.

Latitude 24°N in the Atlantic can be used as the location for an example of how a direct estimate of meridional ocean heat transport might be broken up into component pieces. At this latitude, the mass transport balance is between the water flowing northward through the Florida Straits (~ 30 Mt s^{-1}) and the water flowing southward in the interior basin (**Figure 6**). In the Florida Straits, the water is

Table 1 One set of direct estimates of mass, heat, and temperature transports

Atlantic latitude	Net mass transport ($Mt\,s^{-1}$)	Heat/Θ transport (PW ± 0.3)	Pacific latitude	Net mass transport ($Mt\,s^{-1}$)	Heat/Θ transport (PW ± 0.3)
48°N	-1.0 ± 1.3	0.7	47°N	0.6 ± 1.4	-0.1
36°N	-1.1 ± 1.1	1.0			
24°N	-1.0 ± 1.2	1.1	24°N	0.6 ± 1.3	0.5
11°N	-1.0 ± 1.9	1.4	10°N	0.8 ± 1.7	0.4
11°S	-1.1 ± 1.2	0.9			
23°S	-0.7 ± 1.1	0.3			
27°S	-0.7 ± 1.2	0.5	28°S	9.5 ± 6.8	0.0
			43°S	9.4 ± 7.0	0.3
Indian latitude	**Net mass transport ($Mt\,s^{-1}$)**	**Heat/Θ transport (PW ± 0.3)**	**Between Antarctica and**	**Net mass transport ($Mt\,s^{-1}$)**	**Heat/Θtransport (PW ± 0.4)**
18°S	-8.6 ± 6.5	-1.5	S. America	141.1 ± 3.4	1.4
32°S	-8.1 ± 6.6	-1.3	S. Africa	143.7 ± 4.7	1.2
			Australia	151.0 ± 7.9	1.7

The Ekman component is included. In the early 1990s, it was found to be possible, by combining data taken over about 25 years, to obtain estimates over the few complete latitudinal circles shown here, thereby circumventing the mass conservation issue. Note that the temperature transport estimates at approximately 48°N, 24°N, and 30°S in each of the ocean basins can be taken together to obtain a zero net mass transport and an estimate of net ocean heat transport. The extensive effort of the World Ocean Circulation Experiment in the last decade has allowed such complete latitude estimates to be made over more synoptic time frame (see **Figure 4**). (values from Macdonald, 1998).

relatively warm with 24 Mt s^{-1} at temperatures >12°C and a temperature transport of about 2.3 PW. In the interior basin, the warmest waters near the surface are flowing southward and are partially balanced by a northward Ekman transport of about 5 Mt s^{-1}. The Ekman temperature transport is in the order of 0.4 PW. A small layer at about 1000 m (Antarctic Intermediate Water, AAIW) flows northward. The thick deep layer is NADW, formed in northern polar regions. It flows southward, while a much smaller layer of AABW flows northward. The interior geostrophic temperature transport is of the order of -1.6 PW. Summarizing, there is a strong warm flow in the Florida Straits balanced by a deeper return flow in the interior, resulting in a mass balance and a net poleward heat transport of about 1.1 PW.

In this instance, the northward meridional heat transport is the result of a warm northward surface flow and a deep cold return flow (i.e., a vertical temperature gradient and deep overturning). The Ekman component is fairly small compared with the geostrophic components. In other basins (e.g., the North Pacific) the heat transport is mainly accomplished through horizontal temperature gradients, and at some latitudes (e.g., the tropics), the Ekman component is as large or larger than the geostrophic component.

As the energy balance between the ocean and atmosphere is set across their interface, where the exchange of energy is associated with changes in the surface water properties, the exchange of energy with the atmosphere, and the advection of energy within the oceans can be considered in terms of the creation and movement of water masses. For instance, in the example just given: the extremely cold bottom waters formed in Atlantic polar regions are preconditioned by the loss of heat through evaporation within the Gulf Stream and so are associated with the formation of so-called mode waters in the subtropics. The vertical overturning and formation of deep and intermediate depth water masses within the North Atlantic are thought to be responsible for as much as three-quarters of the northward heat transport within the basin.

Often the amount of water being transformed is of less importance to the heat budget than the temperature change it involves. Although their formation rates are similar, AAIW is thought to contribute more to the meridional transport of heat than AABW, because during formation it undergoes a change in temperature three times as great as does AABW. Considering water mass formation in all the ocean basins, shallow, intermediate, and deep overturnings each support approximately one-third of the global meridional heat transport.

Ocean Heat Transport Variability

Investigation into the time dependency of oceanic heat transport is in its infancy, but it is a subject of

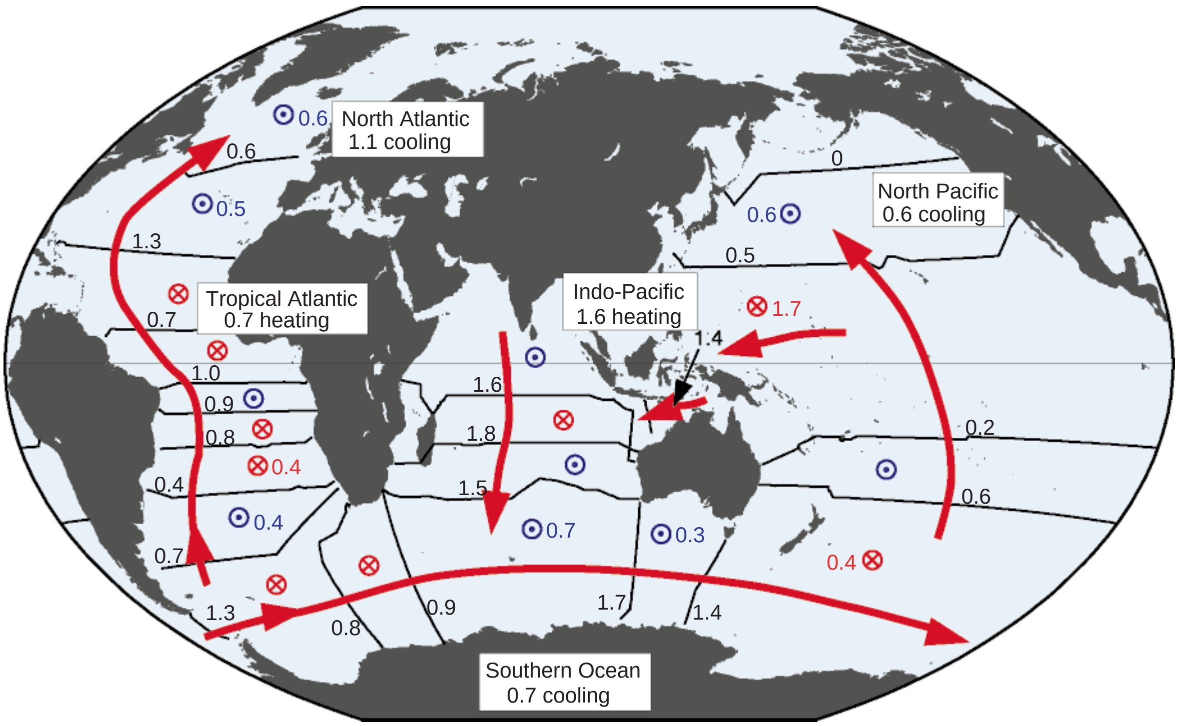

Figure 4 Estimates of northward meridional ocean heat/temperature transport and heat transport divergence. Thin black lines indicate the location of the hydrographic sections used to compute the transport values. Estimated uncertainties are in the range of 0.1 PW at high latitudes to 0.5 PW at low latitudes (in the tropics). The direction of the heat transport divergence between the sections is shown by arrowheads, blue circles with dots (oceanic loss of heat to the atmosphere, cooling) and arrowtails, circles with x's (oceanic gain of heat from the atmosphere). Divergence values are only indicated where the computed estimates are significantly different from zero. The values in the labeled boxes indicate the divergence integrated over entire ocean basins. (Adapted with permission from Ganachaud and Wunsch, 2000.)

great interest not only to those investigating climate evolution, but also to those interested in phenomena occurring on shorter time-scales, e.g., seasonal, inter-annual, and decadal.

All discussion thus far has been based upon estimates of the time-mean oceanic heat transport. In the case of direct estimates, the ergodic assumption has been used, i.e., the assumption that an average in space is equivalent to an average in time. This assumption has been necessary because: (1) direct ocean observations have traditionally been made one basin at a time, (2) it can take as long as 3 months (an entire season) to acquire the data at a single latitude across a basin the size of the Pacific, and (3) direct observations are undoubtedly aliased by various scales of variability (eddies, waves, and atmospheric disturbances, etc.) Nevertheless, it appears (**Figure 3**) that actual time-mean estimates made through residual methods are consistent, within the given uncertainties, with observed spatial-mean estimates. Given this state of affairs, what if anything can be said about the temporal variability of oceanic heat transport and how it might affect estimates of the time-mean?

Given the reasons cited above, it is fairly obvious why direct observations of temporal changes in heat transport have not been possible as yet. For the most part studies of temporal variability have been made through the indirect techniques and through numerical modeling studies. Indirect methods have suffered from the large uncertainties discussed in the previous section. Until quite recently, numerical studies were hampered by either a lack of resolution or a lack of global continuity. However, with increased computer power the ability of numerical models to adequately represent both the oceans and the atmosphere has allowed investigation into the dynamics governing time-dependent circulation.

Historically, the seasonal cycle is the temporal mode which has been the subject of most study. Early investigations using the residual method reported seasonal variations in the tropics of about 7 ± 4 PW, a value larger than the estimated total poleward heat transport in the ocean–atmosphere system. Recent model results find a somewhat smaller seasonal cycle of the order of 4.5 PW. It has also been found that annual variations in Ekman heat transport are as large as the mean Ekman

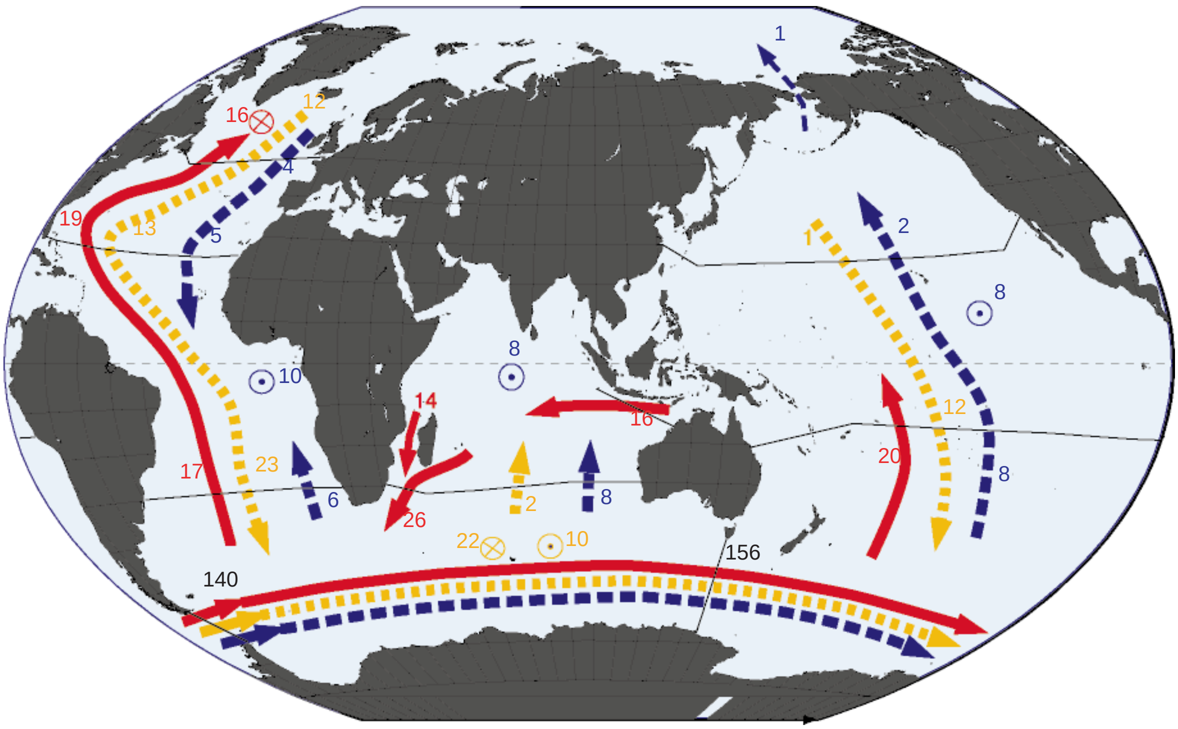

Figure 5 Estimates of meridional mass transport indicating the circulation underlying the heat transport estimates shown in **Figure 4**. The solid (red) line represents shallow and/or relatively warm waters. The dotted (yellow) line represents intermediate to deep waters. The dashed (blue) lines represent bottom and/or cold waters. Note, the arrows do not correspond to oceanic currents, but rather represent the coast-to-coast integration of those currents. The circles with dots represent upwelling due to mass divergence. The circles with x's represent downwelling due to mass convergence. The convergence/divergence values are given for each of the major ocean basins and their positions are not indicative as to where such processes actually occur within the basins. All units are Mt s^{-1}. (Adapted with permission from Ganachaud and Wunsch, 2000.)

transport. Recent estimates suggest an annual variation in Ekman heat transport of approximately 8 PW.

The question is whether a large seasonal variation in the wind-induced or total heat transport necessarily invalidates direct, hydrographic estimates of

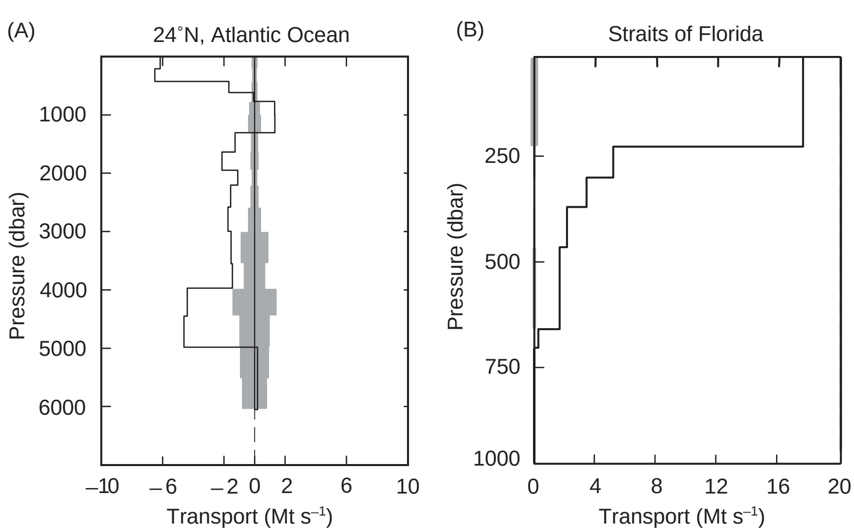

Figure 6 Profiles of mass transport across 24°N and the Florida Straits (~ 26°N) in the Atlantic. The shaded regions represent the 1σ uncertainty on the transport estimates.

mean heat transport. The answer appears to be no. First the seasonal variation of total heat transport is dominated by the variability in winds. Temperature fluctuations are of secondary importance. While the time-mean Ekman transport is returned at fairly shallow depths and warm temperatures, a modeling study published by Jayne in 1999 confirmed the idea that much of the seasonal variation of Ekman mass transport is compensated for by a depth-independent return flow. The adjustment is fast, taking place in an inertial period (12 h at the poles, 1 day at mid-latitudes and infinite at the equator). Because this adjustment is independent of depth, it is not measurable by hydrographic surveys. So, as long as time mean winds are used to balance mass and compute heat transport from directly observed fields, the estimates will not be affected by the large wind-induced seasonal signal. This result is important because it implies that 'mean' ocean heat transports calculated from long-running hydrographic surveys or combinations of surveys taken in different seasons (as in **Figures 4** and **5**, and **Table 1**) are an adequate representation of the time mean.

The contribution to the heat transport due to noncancelling variations in velocity and temperature is called the eddy heat transport. Although the eddy contribution to heat transport in the atmosphere is dominant, this does not appear to be the case in the ocean. Satellite and current meter observations indicate that ocean eddy heat transport is small. However, in a few places, in particular near the equator and strong currents, it is significant. Direct estimates at 24°N in the Atlantic found the eddy contribution to be somewhere between 1% and 20% of the total ocean heat transport. Model estimates of the variance in the geostrophic portion of the heat transport place the uncertainty due to mesoscale eddies at between 0.2 and 0.4 PW at mid-latitudes. The variance is higher near the equator, particularly in the Pacific. The higher resolution of more recent hydrographic surveys has been introduced partly to help minimize such aliasing issues.

Variations in ocean heat transport on time scales longer than a year (decadal and centennial) have yet to be adequately studied. Recent studies of hydrographic data do appear to indicate that changes in the ocean temperature fields can occur on decadal time scales, but this does not necessarily indicate a change in the ocean heat transport. Modeling studies are presently hampered by the inability to combine ocean and atmosphere on eddy resolving scales, with model run duration long enough to study longer timescales. Coarser model runs are possible, but there are issues associated with the parameterization of sub-gridscale processes which still need to be overcome.

Conclusions

Improvements have been made on many fronts in recent years which have brought us to the point where direct and indirect estimates of mean ocean heat transport appear to be converging and are consistent to within their respective estimates of uncertainty. The globally integrated net heat transport within the oceans is poleward, as it is in the atmosphere, moderating temperatures at all latitudes in the presence of uneven heating through solar radiation.

Studies of temporal variability in heat transport indicate that although hydrographic observations of the 'mean' heat transport are subject to a 0.2–0.4 PW variance due to the eddy field, they can adequately represent time mean quantities. These direct estimates are not affected by the large seasonal variation in the wind-induced heat transport.

Goals for the future will include obtaining more direct estimates of ocean heat transport around complete latitudinal circles and more study of the temporal variability of ocean heat transport on various scales using models, indirect, and direct methods. Comparison of model-estimated variability to observed estimates remains a necessary check on the validity of model solutions, both on global and regional spatial scales, and on short- and long-term temporal scales.

Glossary

Hydrography, Hydrographic station, Hydrographic section Historically hydrography has meant the scientific study of the physical conditions of water systems. Here the term hydrographic station means the set of measurements of oceanic physical conditions such as temperature, salinity, oxygen, and nutrients usually taken at various depth intervals at a specific latitude and longitude in the ocean. A hydrographic section is a set of such stations taken from a particular ship during a particular cruise.

Geostrophic velocity The velocity which results when the Coriolis force acting on moving water is balanced by the horizontal pressure gradient force. Geostrophic velocities are a function of density. Wind-induced Ekman transports are ageostrophic and therefore, do not produce a signal in the density field.

Potential temperature *In situ* temperature corrected for heating by compression (i.e., the removal of pressure effects).

Rawinsonde A radiosonde (i.e., an instrument, usually flown on a balloon, which gathers and transmits meteorological data) used to observe the velocity and direction of upper-air winds and tracked by a radio direction-finding instrument or radar.

Salinity An expression of the mass of dissolved solids in sea water per unit mass.

Thermohaline circulation That part of the ocean circulation which is due to density differences. Density differences arise from temperature (thermo) and salinity (haline) differences which occur throughout the oceans due to varying patterns of heating, cooling, evaporation, and precipitation.

Water mass Body of water which is identified by a certain set of property characteristics (i.e., not by topographic boundaries). These properties are most often temperature, salinity, and oxygen and nutrient concentrations.

Wind-driven circulation That part of the ocean circulation which is driven by the winds. The wind acts as a frictional force on the sea surface. As the wind transfers its energy to the ocean it can not only create waves, but it can also create surface currents. The convergence and divergence of these currents can in turn create regions of upwelling deep waters and downwelling surface waters.

See also

Ekman Transport and Pumping. Heat and Momentum Fluxes at the Sea Surface. Thermohaline Circulation. Wind Driven Circulation.

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HEAVY METALS

See **TRANSITION METALS AND HEAVY METAL SPECIATION**

HISTORY OF OCEAN SCIENCES

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Oceanography is the scientific study of the ocean, its inhabitants, and its physical and chemical conditions. Since its emergence as a recognized scientific discipline, oceanography has been characterized less by the intellectual cohesiveness of a traditional academic discipline than by multidisciplinary, often large-scale, investigation of a complex and forbidding environment. The term 'oceanography' was not applied until the 1880s, at which point it still competed with such alternatives as 'thassalography' and 'oceanology'. In many countries, 'oceanography' now encompasses both biological and physical traditions, but this meaning is not universal. In Russia, for instance, it does not include biological sciences; the umbrella term remains 'oceanology'.

Before scientists studied the ocean as a geographic place with an integrated ecosystem, they addressed