Ocean Heat Transport

Lecture for Introduction to Physical Oceanography
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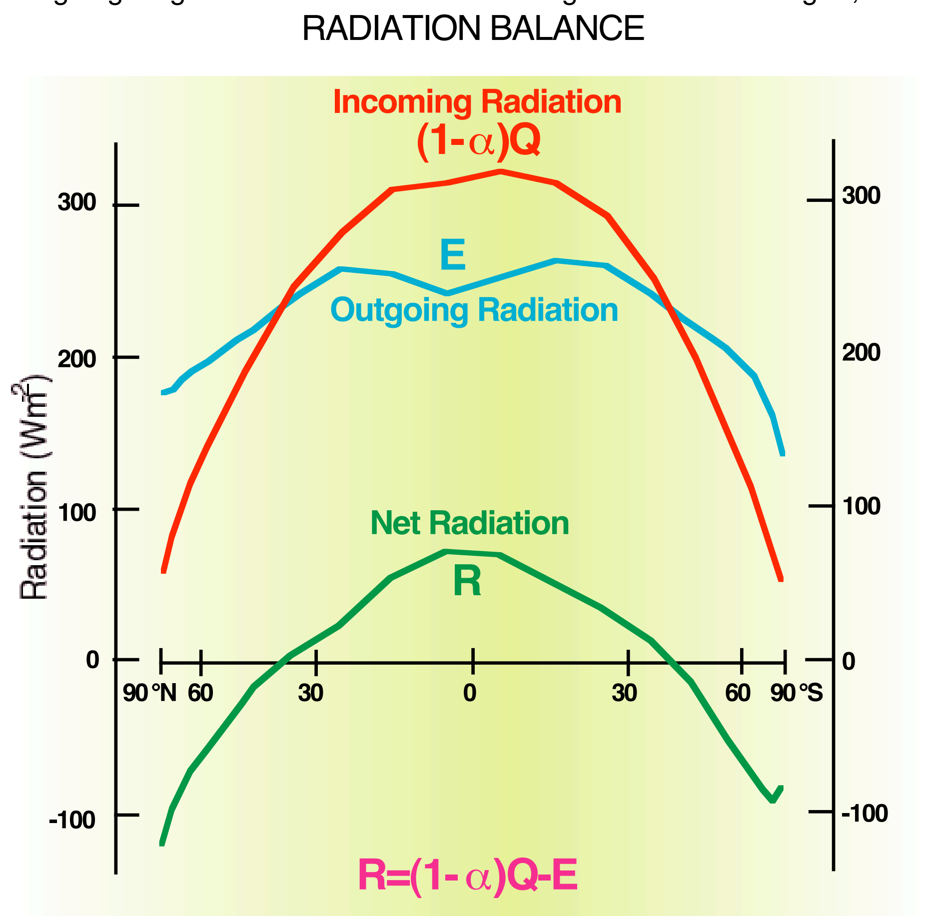
Introduction

One of the important aspects of the thermohaline circulation or Conveyor Belt in the Atlantic Ocean is that the northward flowing warm upper waters compensated by southward flowing cold deep waters transports a substantial amount of heat northward through the Atlantic. It is often said that the thermohaline circulation keeps the northern North Atlantic relatively warm. For example, the surface waters at 70°N off the coast of Norway remain above 5°C even in late winter. And Russia's only year-round ice-free port on the ocean is Murmansk, around Finland on the Arctic Ocean. Closer to home, the ocean waters west of the U.K. and Ireland remain greater than 7° to 10°C in winter ensuring reasonable wintertime temperatures over the U.K. By one account, the waters west of the U.K. and Ireland are about 8°C warmer than they would be without ocean currents.

While these are qualitative examples of the effect of the thermohaline circulation in the Atlantic Ocean, it is possible to estimate the amount of heat that is given up by the ocean to warm the atmosphere regionally and the amount of heat in total that is transported northward through the Atlantic Ocean. Here we will examine the magnitude of the ocean heat flux and transport.

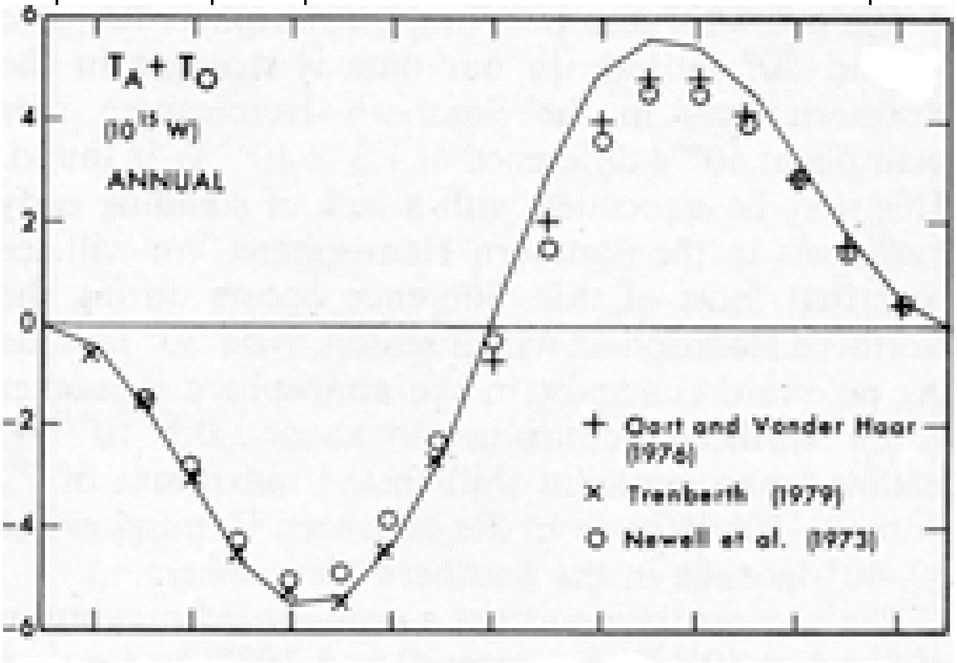
Global Heat Balance

The earth's Radiation Balance can be summarised as a balance between incoming solar radiation and outgoing long-wave radiation: The incoming radiation is "sunlight", shortwave



radiation, some of which is reflected back to space. The percentage of energy reflected is called the albedo, α, and the albedo is higher over lighter areas like snow and lower over darker areas like the ocean. The incoming radiation arrives at the earth at the rate of 1367 W m^{-2}, which is the solar constant. On average over the earth's surface and over a day, one-quarter of this energy 342 W m^{-2} reaches the top of the atmosphere, the average albedo is about 0.3 so on average the incoming solar radiation taken up over the earth's surface is about 240 W m^{-2}. To maintain the earth's temperatures at near constant values, an equal amount of energy must radiate back to space. The outgoing radiation is "black body" radiation which is proportional to the 4th power of the temperature at the top of the atmosphere. The temperature at the top of the atmosphere is relatively constant so the outgoing black body radiation is relatively uniform over the earth's surface. Most of the incoming radiation occurs in the tropical and equatorial regions of course, so there is more incoming radiation than outgoing radiation for latitudes less that 35°; and there is more outgoing radiation than incoming radiation in subpolar and polar regions. As a result to maintain the heat budget at each latitude, the ocean + atmosphere must transport heat poleward away from tropical regions toward polar regions; and the maximum ocean + atmosphere heat transport occurs at a latitude of about 35°.

Ocean + Atmosphere Transport required to balance the Radiation Balance at top of Atmosphere



Carissimo, Oort and Vonder Haar (1985)

Which is more important, ocean or atmosphere? During the 1980's and early 1990's, we had a situation in which oceanographers thought the atmosphere more important while the meteorologists thought the ocean more important. A key issue has been to estimate the ocean heat transport to try to settle this controversy.

How do we estimate ocean heat transport? There are 3 methods:

1) Traditional method of bulk formula estimates.
2) Residual method - subtract atmospheric heat transport from total ocean-atmosphere transport required by radiation balance.
3) Direct method - use ocean velocity and temperature to calculate $\rho C_p \int vT dx dz$ across a line of latitude.

Bulk formula

Estimate Air-Sea heat exchange locally at the sea surface: $Q = R + E + S$
where

Radiation = Incoming Solar – Outgoing Infrared

Solar - depends on latitude, season of year, time of day, amount of cloudiness

Infrared - depends on air and sea temperatures, water vapour pressure and cloudiness

Latent Heat Flux

$$E = \rho C_E (q_s - q_{10}) U_{10}$$

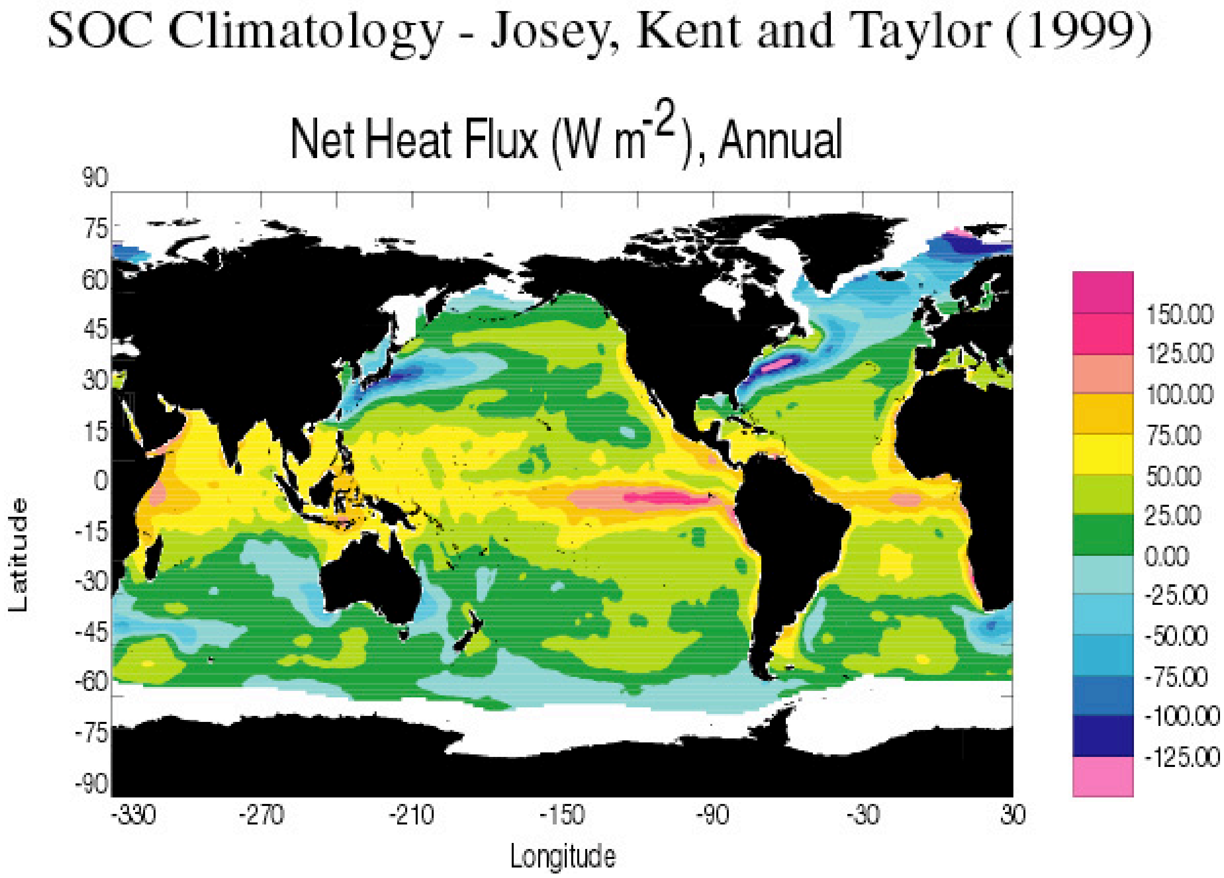
q_s and q_{10} are mixing ratios for air in contact with salt water: q_s is effectively the saturation specific humidity at T_{10}; q_{10} is the atmospheric specific humidity at the 10 m temperature; U_{10} is wind speed at 10 m.

Sensible Heat Flux

$$S = \rho C_H c_p (T_s - T_{10}) U_{10} ;$$

T_s and T_{10} are temperatures of the water at sea surface and air at 10 m.

C_E and C_H are exchange coefficients, sometimes taken to be constant sometimes varying with wind speed, and even with stability conditions. These exchange coefficients are determined from research experiments in which the fluxes are measured and then the coefficients are chosen so that the bulk formula give similar air-sea fluxes. There are many arguments (and uncertainties) over the size of these exchange coefficients and how they vary under different conditions. Maps of air-sea heat exchange calculated from bulk formula applied to ship observations of air and sea temperatures, humidity, cloudiness and wind speed show areas where heat is gained or lost by the ocean. Heat gain by the ocean is concentrated in the vast tropical oceans. Substantial heat losses (ocean to atmosphere) occur particularly over western boundary currents like the Gulf Stream where there is cold continental air over warm water coming from the tropics. But also, there is a substantial heat loss to the atmosphere over

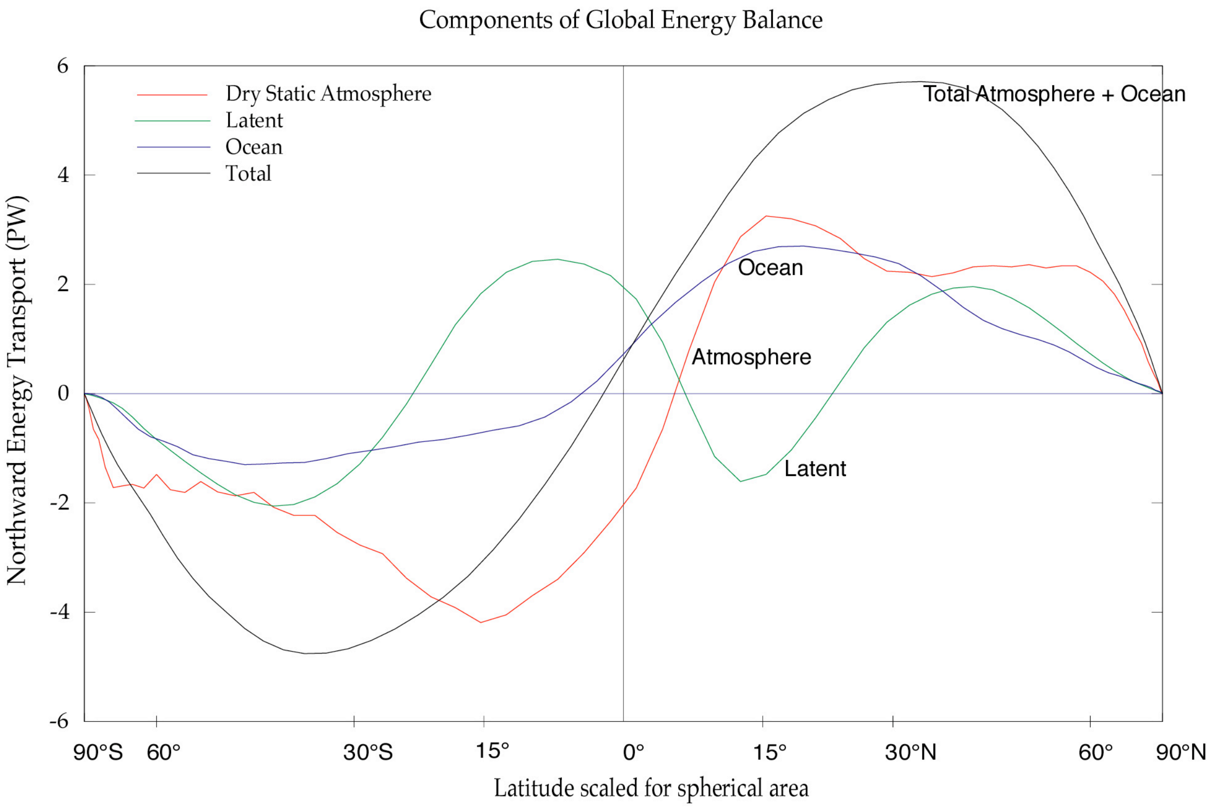


the subpolar North Atlantic due to the northward penetration of warm ocean waters which continue to lose heat to the atmosphere "keeping Europe warm".

The continuing problem with the Bulk Formula method is uncertainty over the size of the coefficients and the form of the parameterisations. 30W m^{-2} remains a typical overall bias in global net heat gain by ocean in state-of-the-art compilations despite years of effort to refine the data and the parameterisations. Here at SOC, we have probably the world's leading group on bulk formula estimates of air-sea heat, water and momentum exchanges (Web Page: http://www.soc.soton.ac.uk/JRD/MET/)

Residual Method

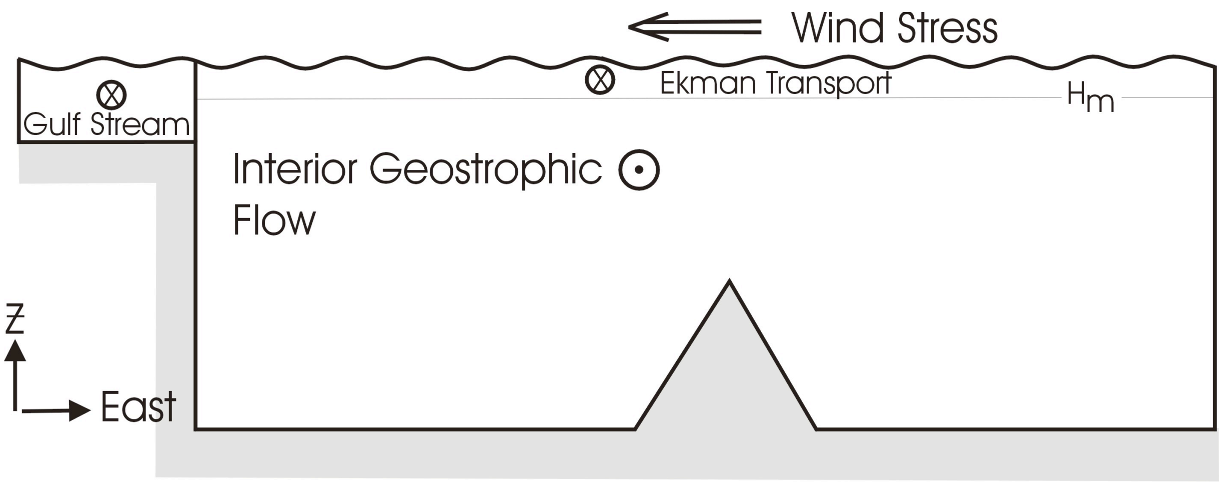
This approach caused controversy 20 years ago when it was first used because any errors in radiation requirements or in atmospheric energy transport led to huge uncertainties in ocean heat transport. Now with the advancement of atmospheric circulation models, the results appear to be much more realistic (Trenberth and Caron, 2001), but there is still some uncertainty about how well the atmospheric moisture transport is resolved by the circulation models and the moisture transport contributes substantially to the meridional heat transport as seen in the figure below. In fact, one can argue that the moisture transport or latent heat transport is a joint process by the ocean and atmosphere since the water carried northward by the atmosphere must be returned southward by the ocean and vice versa. The figure below suggests that the ocean transport, atmospheric transport and the latent heat transport contribute about equally to the maximum transport at about 35°N. One problem with the residual method is that one gets little idea on the ocean processes that contribute to ocean heat flux because it is a residual calculation that does not actually look at the ocean or use any ocean measurements.



Bryden and Imawaki (2001, Figure 3) based on values from Keith (1995)

Direct Method

Powerful techniques were initiated 25 years ago to directly estimate ocean heat transport, concentrating on latitudes of expected largest ocean heat transport ~25°N. The procedure is to determine western boundary current (WBC) transport and its temperature, the Ekman transport and SST, and then to require mid-ocean geostrophic mass transport to balance WBC + Ekman transport. It is relatively simple to determine geostrophic heat transport once overall mass transport is set. Sample calculation is shown schematically here:



We can measure the Gulf Stream flow and temperature in Florida Straits easily because it is a confined area only 75 km wide. Wind stress is available from climatologies like the SOC flux climatology or from atmospheric analysis centres, so we can estimate the Ekman transport. The interior geostrophic flow can be estimated from measurements of the temperature, salinity and density distributions across the North Atlantic. The geostrophic flow is adjusted with a reference level velocity so that the southward interior geostrophic transport balances the northward Gulf Stream and Ekman transports. Both simple and complicated methods have been used to determine the reference level velocity and its distribution across the section, but the overall heat transport seems to be relatively insensitive to the method used. Once the mass transport is balanced, the heat transport is just

$$\int \rho C_p v \theta dxdz$$

But one must be absolutely sure that $\int vdxdz = 0$, i.e. that mass is conserved.

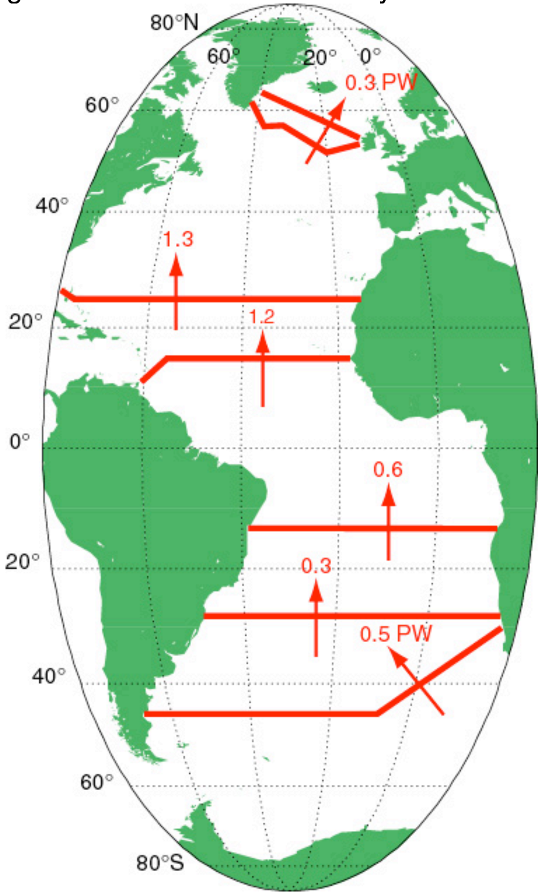
The northward heat transport across 25°N in the Atlantic Ocean is estimated to be 1.3 PW (petawatts). A petawatt is 10^{15} watts, or a megagigawatt. We hear of big power plants being 1 gigawatt (10^9 watts). So we are saying the North Atlantic Ocean power plant is equivalent to a million gigawatt power plants in terms of the heat it transfers form the ocean to the atmosphere.

Fresh water transport can be done in a similar manner. Once the circulation is established so that v is given across the entire section and mass is "conserved", it is generally straightforward to multiply v by any property "C" to determine C transport.

$$\int \rho v C dxdz$$

CO_2 has been used as well as NO_3, PO_4, SiO_2. The principal problem is to determine the circulation, which is difficult. The advantage of the Atlantic 25°N section is the long time series measurements of Gulf Stream transport through Florida Straits which then establishes the size of the geostrophic return transport in mid ocean.

Other latitudes and oceans are more difficult because the western boundary current transport must be carefully determined so as to define the size of the mid-ocean flow. The WOCE field programme was carried out from 1990 to 1998 with a major goal to make the measurements necessary to determine ocean heat and freshwater transports. From the WOCE measurements, the pattern of Atlantic heat transport has been reasonably well established with northward transport of 0.5 PW across the southern boundary increasing to a maximum of 1.3 PW at about 25°N as the subtropical and tropical ocean gains heat from the atmosphere, and then decreasing northward as the northward flowing warm waters lose their heat to the atmosphere. This is the effect of the thermohaline circulation or Conveyor Belt.



Bryden and Imawaki (2001)

With end of WOCE field programme, a major analysis effort is underway to determine heat transport and its variability in all ocean basins. SOC scientists are also involved with a number of new sections in the Indian, Pacific and Atlantic Oceans, some of them repeats of earlier sections so we can look at decadal changes in ocean circulation and water mass properties. In fact, we went across the southern Indian Ocean in March-April 2002 in an attempt to measure the circulation and fluxes across the southern boundary between South Africa and Australia to assess the basin-scale heat, freshwater and biogeochemical budgets for the Indian Ocean. As part of the Rapid programme to calibrate the moored array estimates of meridional overturning circulation, we repeated the 25°N transatlantic section for its 5th occupation in April-May 2004. And we are going to make a transatlantic across 36°N in the Atlantic Ocean in May 2005 to fill in the obvious gap in the WOCE Atlantic survey in the above figure.

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