

MERIDIONAL ATMOSPHERE AND OCEAN HEAT TRANSPORTS

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1. INTRODUCTION AND METHODS

Radiative processes continually act to cool the high latitudes and warm the low latitudes of planet Earth, and it is only the poleward energy transport by the atmosphere and the oceans that serves to offset this. Early studies that tried to apportion how much each component contributed, first estimated the required poleward heat transport from satellite measurements, then computed the atmospheric transports from observations, and finally computed the ocean transports as residuals. Moreover, this was done using zonal means (Vonder Haar and Oort, 1973; Oort and Vonder Haar, 1976; Trenberth, 1979; Masuda, 1988; Carissimo et al., 1985; Savijärvi, 1988; Michaud and Derome, 1991). This procedure not only assumes that the atmospheric transports are correct, it also assumes they are correct over both land and ocean, yet subsequent analyses (e.g., Trenberth and Solomon, 1994) have found that there are implied subterranean transports in land areas, whereas physical constraints ensure that any such transports must be tiny as they can arise only from surface and ground water flows plus conduction. As estimates of direct global ocean heat transports emerged (Bryden, 1993), it became apparent that the atmospheric transports were likely to have been underestimated.

The studies of Vonder Haar and Oort (1973), Oort and Vonder Haar (1976) for the Northern Hemisphere (NH) and Trenberth (1979) for the Southern Hemisphere (SH), as well as those from Carissimo et al. (1985) and Savijärvi (1988) made use of radiosonde data, but the uncertainties in the atmospheric heat transports are substantial because of lack of observations over the oceans. The uncertainties are apparent at 70°S in the Carissimo et al. and Savijärvi results, for instance, where there is no ocean but their residuals imply a large poleward heat transport by the ocean. Moreover, use of global analyses (Masuda, 1988) indicated larger estimates of poleward atmospheric transport apparently because radiosondes fail to pick up the substantial heat transports over the oceans. However, there has been a steady trend of increases in the magnitude of the poleward energy transports in both hemispheres as atmospheric analyses have improved, and this has continued with the recent reanalyses. Thus the poleward ocean transports inferred using residual methods have decreased over time.

We have computed new results of meridional ocean and atmosphere heat transports based upon energy balance computations of the atmosphere, adjusted to fit physical constraints, using the reanalyses from National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR). The approach used is to estimate the atmospheric energy transports directly from analyses of measurements within the atmosphere. The analysis focuses on the period from February 1985 to April 1989 when there are reliable top-of-the-atmosphere (TOA) radiation data from Earth Radiation Budget Experiment (ERBE). We compute monthly means of all quantities and combine the average monthly means over the ERBE period to produce an annualized mean. Then we compute the net surface heat fluxes as a residual and use those to infer the ocean heat transports.

We make several adjustments to the fluxes so that physical constraints are satisfied in order to provide the best estimates of values in the real world. The constraints are the estimates of long-term changes in heat storage, the transports at the northern and southern limits of our integration and the requirement that the TOA radiation balance the divergence of atmospheric energy over land. The details along with the surface fluxes are given in Trenberth et al. (2001). Implied ocean transports are compared with those from direct ocean measurements and from coupled models as well as derived results from ECMWF in Trenberth and Caron (2001). Results of the zonal means of the quantities from this study are available online at <http://www.cgd.ucar.edu/cas/catalog/ohts/>.

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2. RESULTS

In Figure 1 we present the mean northward atmospheric energy transports from NCEP as a function of month, as this allows a comparison with those for the NH of Oort and Vonder Haar (1976). The latter featured peak northward transports of 5.0 PW in December at 63°N, values exceeded 4 PW from about mid November to the end of February and were less than 2 PW in summer. Figure 1 shows that the maximum poleward transports occur in winter of both hemispheres and exceed 8 PW in the NH, with values much greater throughout the year than those in Oort and Vonder Haar (1976). The peak poleward transport in the SH is not quite as large as in the north, but the annual cycle is much smaller.

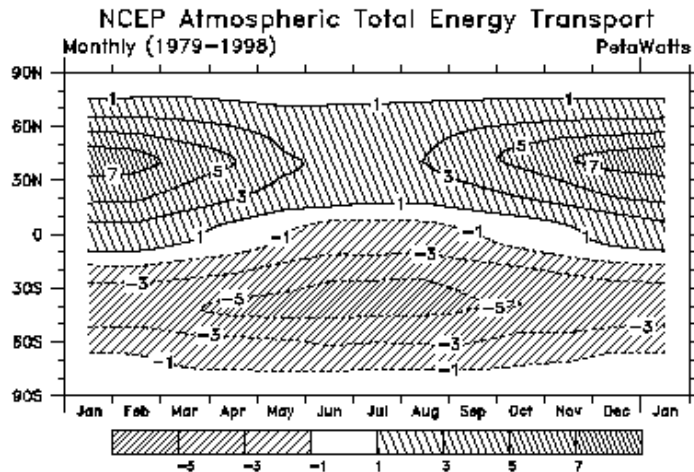


Figure 1-The average zonal mean annual cycle of northward atmospheric energy transports for 1979-1998 is shown in PW.

Over land, there is negligible subterranean heat transport, which allows an evaluation of errors in the implied surface fluxes and they are found to be largest over complex and high topography (Trenberth et al., 2001). Therefore, it is desirable to compute the ocean transport separately based upon the implied surface fluxes over just the ocean.

The implied zonal mean ocean transports, adjusted as in Trenberth and Caron (2001), are computed starting at 65°N where there is a minimum of ocean available to transport heat northward. Estimates are that the transport through the Bering Strait is 0.2×10^{13} W, and in the North Atlantic 1.4×10^{14} W (Aagaard and Greisman, 1975). Therefore, we use 0.14 PW at 65°N as the starting point of our integration in the Atlantic. While integration of the surface fluxes readily partitions the contributions by basin, the result can not necessarily be interpreted as a heat transport unless the mass budget is closed. The Indian and Pacific Ocean partition is confounded by the Indonesian Throughflow, so that ocean mass flow in each basin is not closed, and only their sum is meaningful as a heat transport.

Because computed heat storage changes are fairly small and tend to cancel when integrated over about 30° latitude, and there is not an adequate global ocean analysis available to assess local tendencies in heat storage, we have ignored changes in ocean heat storage, except for the systematic warming trends. There is evidence that a systematic warming of the global oceans is occurring (Levitus et al., 2000) because of changes in atmospheric composition, with a magnitude of 0.3 W m^{-2} overall. Integrated over the oceans, this would contribute to an apparent transport at 68°S of -0.1 PW which also provides the magnitude of this adjustment on the implied heat transports. To treat it as a change in heat storage, we subtract the 0.3 W m^{-2} from the surface fluxes uniformly throughout the ocean, consistent with the global nature of the changes shown in Levitus et al. (2000).

Because we began the integration from the north and the global oceans are a closed system, any accumulated bias shows up as the imbalance at the southern-most latitude, taken as 68°S owing to seasonal ice cover. Coupled ocean models (Boville and Gent, 1998, Gordon et al., 2000) have northward ocean heat transports at 68°S which average -0.1 ± 0.05 PW. Hence we require that the total northward heat transport must tend to -0.1 PW at 68S. Further we assume that the main errors arise over the southern oceans south of 30°S, because they are so sparsely observed. This is also compatible with the NCEP problems revealed in Trenberth et al. (2001) and the analysis of Josey et al.

(1999). The computed total northward heat transport at 68°S has an imbalance of -0.1 PW for NCEP-derived product and thus an adjustment was imposed on the Pacific Ocean of 2 W m^{-2} from 30 to 68° S because the sign of the error was the same as that in the Pacific. Rather than performing a formal error analysis, we use the empirical estimate of errors and we have plotted error bars in Figure 2 assuming random errors of 30 W m^{-2} over 1000 km scales, which approximately takes the spatial coherence into account, but which is probably a slight overestimate in the NH.

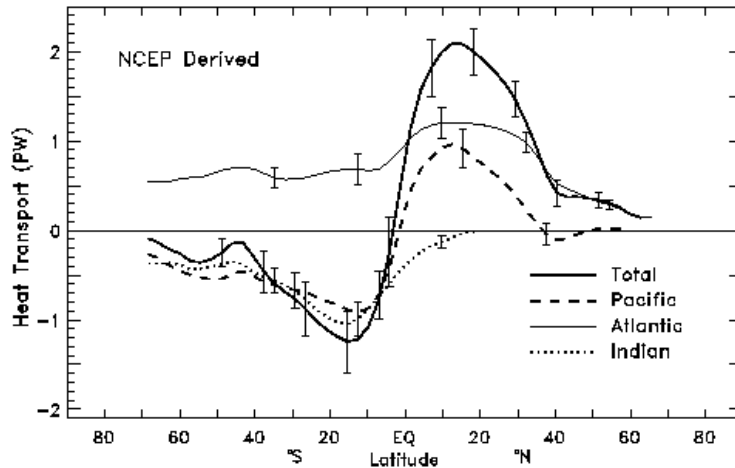


Figure 2-Implied zonal annual mean ocean heat transports based upon the surface fluxes for February 1985 to April 1989 for the total, Atlantic, Indian and Pacific basins for NCEP atmospheric fields in PW. One standard error bars are indicated by the dashed curves.

To show the relative roles of the atmosphere and ocean transports, Figure 3 presents the required transport RT , along with the adjusted derived ocean transport (OT) from the NCEP reanalyses, and the atmospheric transport (AT) as their difference. The differences from raw values are -0.2 PW near 40°N for AT , growing to ~ -0.4 PW from 0 to 60°S. Aside from the changes at the northern and southern boundaries, which are small, the differences exist mainly from the implied adjustments over land, plus the small ocean adjustments south of 30°S. A spurious downward surface flux into the land in the NH (Trenberth et al., 2001) results in lower adjusted northward AT throughout the globe.

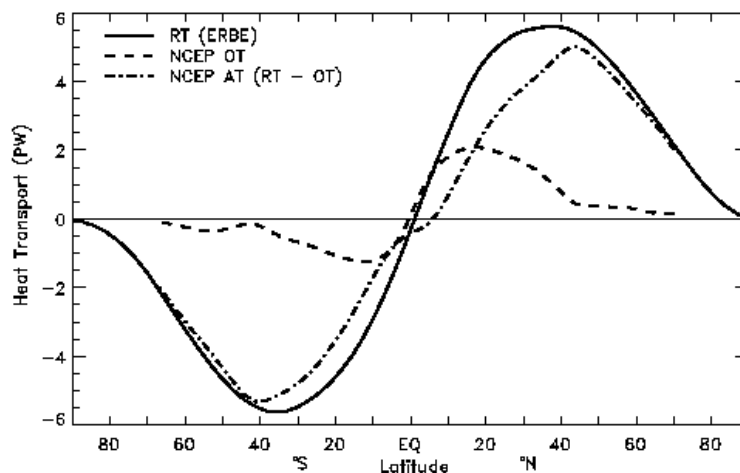


Figure 3-The required total heat transport from the TOA radiation RT is compared with the derived estimate of the adjusted ocean heat transport OT (dashed) and implied atmospheric transport AT from NCEP/NCAR reanalyses in PW.

North of 45°N the inferred OT is quite small. The peak AT value is 5.0 ± 0.14 PW at 43°N and with similar values near 40°S, much larger than previous estimates. At 35° latitude, which is very close to where the peak total poleward transport in each hemisphere occurs, the total atmospheric transport

accounts for 78% of the total in the NH and 92% in the SH. Generally a much greater portion of the required poleward transport is contributed by the atmosphere than the ocean compared with previous estimates. It is only from the equator to 17°N that the poleward ocean transports exceed those from the atmosphere.

Reasonable agreement is obtained with direct ocean transports when the results from NCEP/NCAR reanalyses based upon residually-derived (not model-generated) methods are used, and this suggests that improvements have occurred and convergence is to the true values. It is important to note that while the ocean heat transports and surface fluxes derived from the TOA radiation plus the atmospheric transports (the indirect method) have improved substantially and mostly agree with the independent estimates, the same cannot be said for the atmospheric NWP model surface fluxes computed with bulk parameterizations, which contain substantial biases. The NWP models have not yet been improved to satisfy the global energy budgets in the same way that the best coupled climate models have, highlighting the fact that weather prediction is constrained by the specification of the SSTs and the models do not have to get the SST tendencies correct to produce excellent weather forecasts.

Acknowledgments

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