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ANNUAL OCEANIC HEAT TRANSPORTS COMPUTED FROM AN ATMOSPHERIC MODEL

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ABSTRACT

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Mean annual estimates of the oceanic poleward energy transport are obtained using a global atmospheric general circulation model. The computations are carried out by using the atmospheric model to determine the net annual heat flux into the ocean on an $8° \times 10°$ grid. Assuming no net annual heat storage, the annual surface heat fluxes into any zonal band must be accompanied by a corresponding meridional heat transport in the ocean. Heat is transported northward at all latitudes in the Atlantic Ocean and is transported poleward in both hemispheres in the Pacific Ocean. To account for the net northward transport throughout the Atlantic, heat is transported into the Atlantic from the Indian and Pacific basins. The results are compared with several recent direct and indirect calculations of oceanic meridional heat transports.

1. INTRODUCTION

There have been many recent studies devoted to determining the contribution of the oceans to the global poleward transport of heat. Since a poleward transport of heat by the atmosphere and oceans is required to maintain a global steady state heat balance, it is important to know the relative contributions of each in order to understand climate and climatic variations. Bryan (1982) has written a comprehensive review of recent studies of oceanic heat transports.

Four different methods have been used to calculate oceanic heat transports. These include direct methods based on hydrographic data, indirect methods based on surface heat flux calculations, residual methods based on

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satellite and atmospheric data, and heat transports calculated from numerical ocean models. Direct methods have been used to estimate the poleward heat transport across given latitudes. Most of these calculations have been for the Atlantic Ocean. Among these are the studies of Bryan (1962), Bennett (1978), Fu (1981), Roemmich (1980), Bryden and Hall (1980) and Wunsch (1980). Bryden (1979) made a global estimate at 60°S.

Oceanic heat transports in the tropics were computed by the indirect method in a series of papers by Hastenrath (1977a, 1977b, 1980) and Hastenrath and Lamb (1980). These computations of the oceanic transports were based on long term heat flux calculations determined from 60 years of ship observations. Net radiation and sensible and latent heat fluxes at the air–sea interface were used to obtain annual values of net heat gain or loss. By assuming no net heat storage over an annual cycle, the net annual oceanic heat transport was computed. Hastenrath (1980) also extended his results to the global ocean by using the surface heat flux data of Budyko (1963) outside the tropics. Other calculations using this indirect method have been made by Bryan (1962) and Sellers (1965).

The residual method used by Vonder Haar and Oort (1973) and Oort and Vonder Haar (1976) combined radiation data from satellites with climatological atmospheric data to compute Northern Hemisphere oceanic transports as a residual. Trenberth (1979) used the radiation values of Stone (1978) to obtain similar values for the Southern Hemisphere. Both of these studies obtained oceanic heat transports at low latitudes that were larger than most of those calculated using the direct methods. The final method of computing oceanic heat transports used numerical ocean models to calculate the poleward heat transport. This method was used by Bye (1979) and Bryan and Lewis (1979).

The purpose of this paper is to use a new method to compute global oceanic heat transports. The method is essentially the same as the indirect method. However, rather than using climatological surface heat fluxes calculated from a large number of observations such as those compiled by Budyko (1963) and Bunker (1976), the present method is based on surface heat flux data generated by an atmospheric general circulation model. These fluxes are then averaged over one year and integrated for each ocean basin from north to south to obtain the meridional heat transport as a function of latitude. Values for the global ocean and for each basin are computed and compared with values calculated by some of the other methods. In addition, the heat transported between the oceans near Antarctica is computed as a residual.

2. THE ATMOSPHERIC MODEL

Model II of the atmospheric general circulation model described by Hansen, et al. (1982) was used to obtain the surface heat fluxes. This three dimensional climate model has $8° \times 10°$ horizontal resolution and nine vertical layers. Arakawa's scheme B is used for the dynamics. Source terms include a comprehensive radiation package and parameterizations of condensation and surface interaction. At the surface, grid boxes are divided into land and ocean fractions with surface fluxes calculated separately. The ocean surface temperatures are climatologically specified from the Robinson and Bauer (1982) data set. The climatological ocean ice coverage for the Southern Hemisphere is from Alexander and Mobley (1976) and the Northern Hemisphere ice coverage is from Walsh and Johnson (1979).

The surface sensible heat flux of Model II could be unrealistic for the separate fractions of mixed grid points since the ground and water temperatures are separate but the atmospheric temperature is a single composite for the whole grid box. The same applies to the surface latent heat flux. The existence of mixed grid points would also cause problems if one wanted to incorporate a dynamical ocean model. For these reasons, a non-fractional version of Model II in which each grid box is either all land or all water is used. This version of the model was integrated for a simulated year and many diagnostics relevant to oceanic heat transports were saved. Some of these diagnostics will be discussed and compared to observations.

Figure 1 shows the net radiational heating at the top of the atmosphere from the satellite observations of Stephens et al. (1981) and those computed by the model. As functions of month and latitude, the model's radiation agrees quite well with the observed features. However, the model's net radiation at the top of the atmosphere is not in balance. When averaged over the globe for an entire year, there is a net downward flux of 5.1 W m^{-2}. Of that imbalance, approximately half goes into the surface where it is absorbed by the specified ocean and the rest is lost in the atmosphere through conversion to kinetic energy and computer truncation.

Figure 2 shows the divergence of static energy flux as computed by the model and compiled by Oort and Vonder Haar (1976) from Northern Hemisphere observations. The divergence of static energy flux is the sum of the divergences of geopotential energy, sensible heat, and latent heat and the work that is converted to kinetic energy. Regions of negative divergence indicate areas into which heat is transported by the atmosphere. The main disagreements are that for all seasons the model does not converge enough heat near the North Pole, and that the model does not simulate the high positive divergences observed at 50°N from November through March. It should be noted that the calculations here are based on a one year run of the

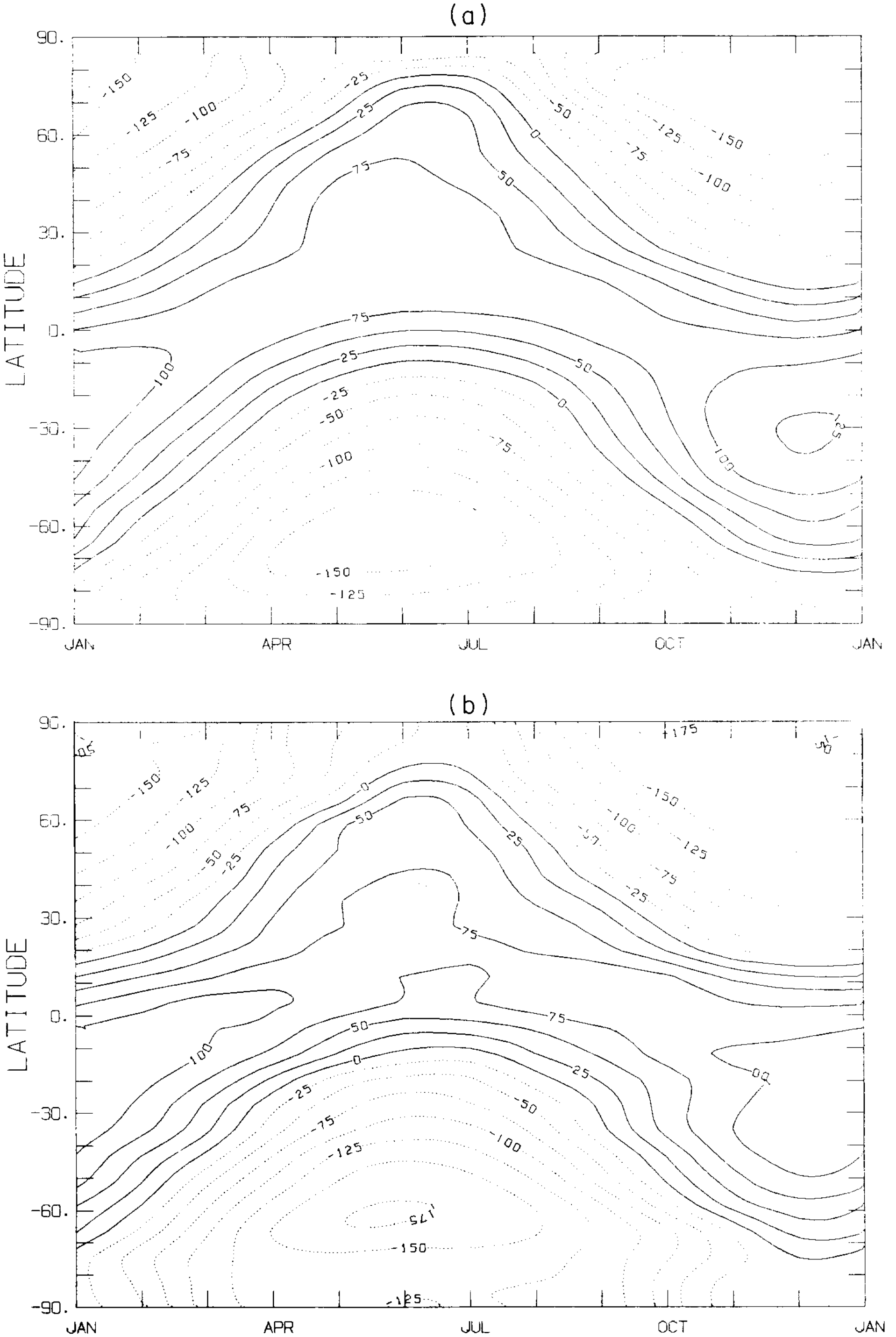

Fig. 1. Net radiational heating at the top of the atmosphere: (a) satellite observations of Stephens et al. (1981); (b) generated by the climate model. Units are W m^{-2}.

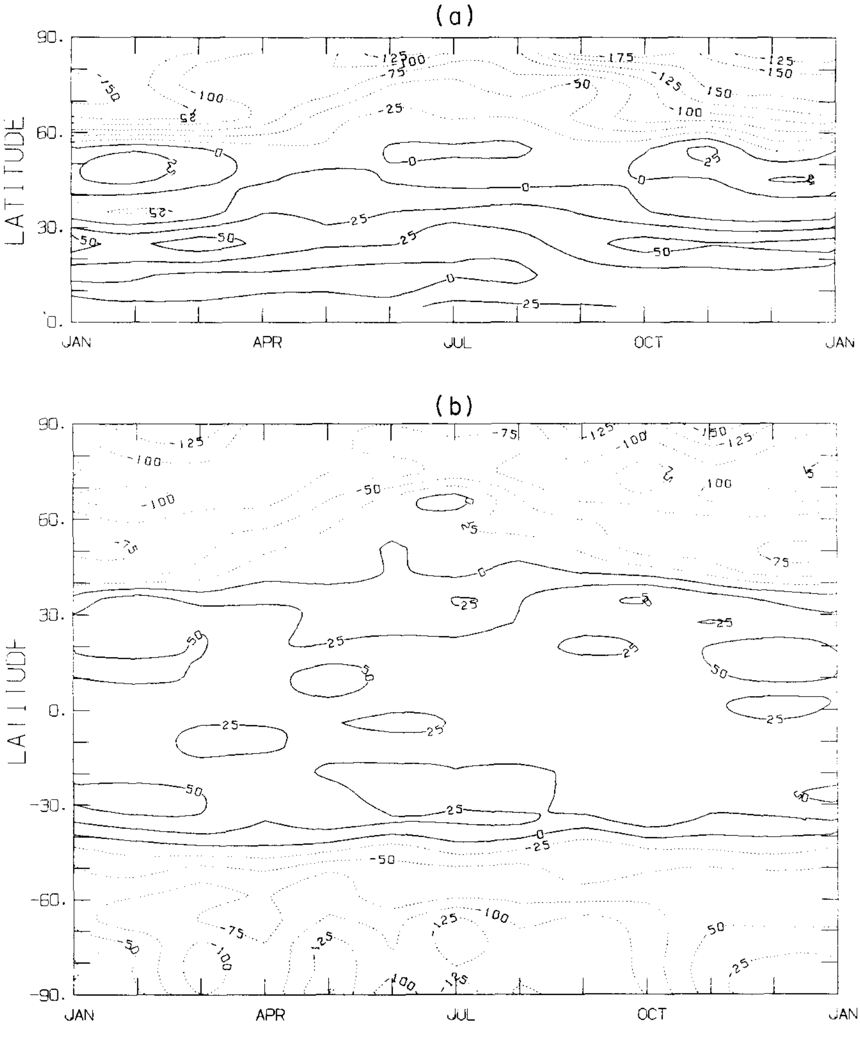

Fig. 2. Divergence of atmospheric static energy flux: (a) observations compiled by Oort and Vonder Haar (1976) for the Northern Hemisphere; (b) generated by the climate model. Units are W m^{-2}.

atmospheric model, and do not necessarily represent the model's climatology.

The final diagnostic to be compared with observed values is the model's surface heat fluxes. This comparison is of particular importance to the present study since the oceanic heat transports are calculated from the surface heat fluxes over the oceans. These heat fluxes are comprised primarily of the net radiation balance and the sensible and latent heat fluxes at the surface. Figure 3 shows the monthly variations of the model's computed heat fluxes and the corresponding Northern Hemisphere observed values of Oort and Vonder Haar (1976) which were calculated as a residual. Negative values indicate fluxes of heat into the atmosphere. The model reproduces the general features of the observed variations; however, it does not reproduce the maximum winter heat flux into the atmosphere at 50°N, shows too great a winter heat loss at high latitudes, and shows too little heat flux into the ground north of 75° during the summer. When averaged over the globe for

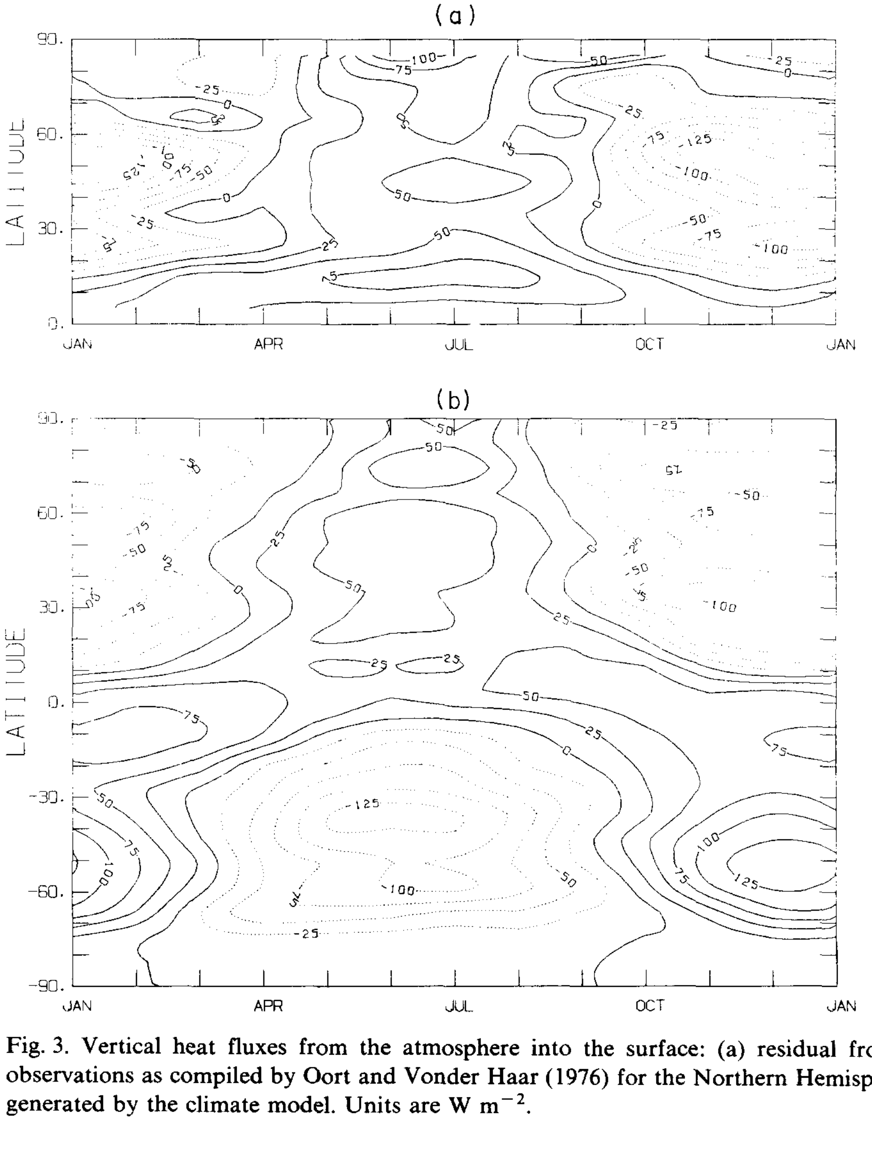

Fig. 3. Vertical heat fluxes from the atmosphere into the surface: (a) residual from other observations as compiled by Oort and Vonder Haar (1976) for the Northern Hemisphere; (b) generated by the climate model. Units are W m^{-2}.

an entire year, the model yields a net downward heat flux into the surface of 2.7 W m^{-2}.

3. CALCULATION OF THE ANNUAL OCEANIC NORTHWARD TRANSPORT OF HEAT

Each of the vertical heat flux components into the ocean and ocean ice is calculated from the climate model. The equation for the balance of these fluxes as a function of time for each grid point is given by

$$\mathrm{VF} = \mathrm{SR} - \mathrm{TR} - \mathrm{SH} - \mathrm{LH} + \mathrm{PR} \tag{1}$$

where VF is the net vertical heat flux into the ocean, SR is the net downward solar radiation, TR is the net upward thermal radiation, SH is the upward sensible heat flux, LH is the upward latent heat flux from evaporation (negative for dew), and PR is the precipitation heat flux (negative for snow). Ignoring the effects of rivers and assuming that the planet is near equilibrium, the long term global average vertical heat flux into the ocean and ice should be zero. The method of calculating the oceanic heat transports from the climate model also requires that that value be zero. However, when integrated over the one year run of the climate model,

$$[\overline{\mathrm{VF}}] = \int_{\text{year}} \int_{\substack{\text{ocean}\\ +\text{ice}}} \mathrm{VF}\, \mathrm{d}A\, \mathrm{d}t \Big/ \int_{\text{year}} \int_{\substack{\text{ocean}\\ +\text{ice}}} \mathrm{d}A\, \mathrm{d}t = 4.0\ (\mathrm{W\ m^{-2}}), \tag{2}$$

where the brackets represent an annual average and the overbar a spatial average. This excess of 4.0 W m^{-2} into the oceans and ice can be caused by inaccurate representations of physical processes, inaccurate clouds, inaccurate albedoes, or inaccurate ocean surface temperatures or ice coverage. It cannot be attributed to the climate model's inter-annual variability. Integrating over the model's one year run, the surface fluxes over land are essentially zero. Thus $[\overline{\mathrm{VF}}] = 4.0$ over the ocean corresponds to 2.7 over the whole globe.

To correct this problem of excess heat into the ocean, a constant factor x was used to modify the solar radiation term to insure that

$$\int_{\text{year}} \int_{\substack{\text{ocean}\\ +\text{ice}}} (\mathrm{x} \cdot \mathrm{SR} - \mathrm{TR} - \mathrm{SH} - \mathrm{LH} + \mathrm{PR})\, \mathrm{d}A\, \mathrm{d}t = 0. \tag{3}$$

The necessary factor for the one year run was 0.9776. Solar radiation was chosen for this normalization because it always has the same sign, radiation is sensitive to the clouds which are not well known, the model's radiation is not in balance at the top of the atmosphere, and modifying sensible or latent heat would require changes in the radiation if the atmosphere is in

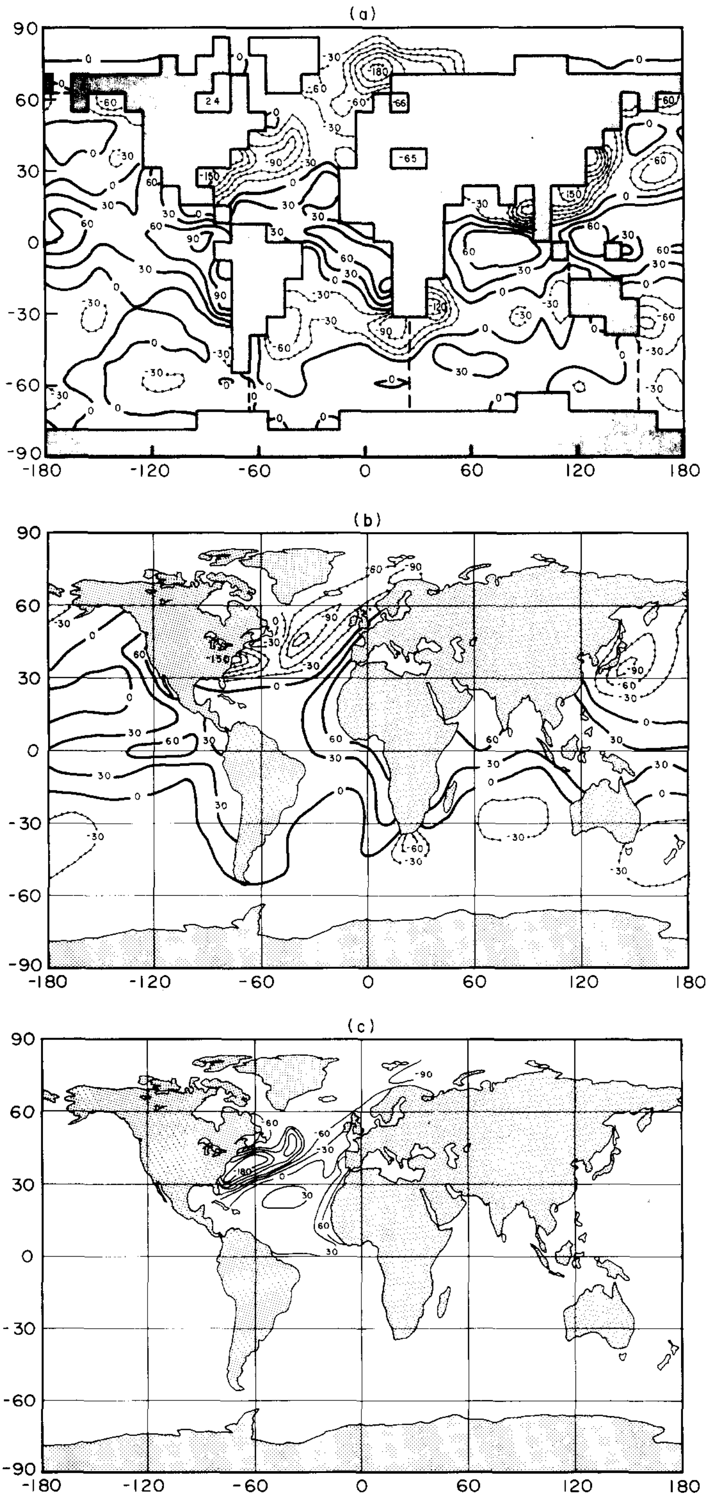

Fig. 4. Annual vertical heat fluxes at the surface: (a) generated by the climate model after normalizing with the solar radiation (The heavy dashed lines delineate the ocean basins); (b) observations of Budyko (1963); (c) observations of Bunker (1976) for the North Atlantic. Units are W m^{-2}.

equilibrium. The normalized vertical flux is denoted by

$$VF^x = x \cdot SR - TR - SH - LH + PR \tag{4}$$

The annual average $[VF^x]$, is shown in Fig. 4. The figure also shows comparisons with the global heat fluxes of Budyko (1963) and the North Atlantic values of Bunker (1976).

Assuming that there is no net annual heat storage in the oceans, the oceanic heat transports can be calculated from VF^x. The equation

$$Q_\phi = -\int_\phi^{90°N} [VF^x] \, dA \tag{5}$$

is used to determine the northward transport, Q_ϕ (in Watts), across a particular latitude. Equation 5 is calculated separately for each of the three ocean basins and for each latitude; the integration being performed over a particular basin north of that latitude. When the integration is extended to Antarctica, that residual is interpreted as a transport between ocean basins. Figure 4 shows the global grid used for the calculations. The heavy dashed lines show the boundaries assumed for the ocean basins. We are ignoring transport through the Bering Strait and the straits between Malaysia and Australia. The neglect of transport through the latter straits may be a poor assumption since the recent results of Godfrey and Golding (1981) indicate that the transport from the Pacific into the Indian Ocean north of Australia may be an order of magnitude greater than previously thought.

4. RESULTS

Figure 5 shows the annual oceanic heat transport for each of the three ocean basins and for the global ocean. The global transport is characterized by a poleward transport of heat in both hemispheres with maximum poleward transports between 20° and 30°. The Pacific Ocean shows the same pattern as the global transport while the Atlantic Ocean shows a net northward transport of heat at all latitudes. The northward transport of heat in the Northern Hemisphere portion of the Indian Ocean is suspect due to the very large heat fluxes at the model grid point to the east of India. These large heat fluxes occur because the air temperatures over the high topography on the adjacent land masses produce artificially large sensible and latent heat fluxes over the ocean.

The heat transport in the Pacific Ocean shows a net southward transport of heat across the equator. The maximum poleward transport at 20–25°S is probably due to the strong upwelling areas in the eastern Pacific where significant absorption of solar radiation occurs. Unlike the Atlantic, the Pacific Ocean exhibits similar characteristics in both hemispheres; absorp-

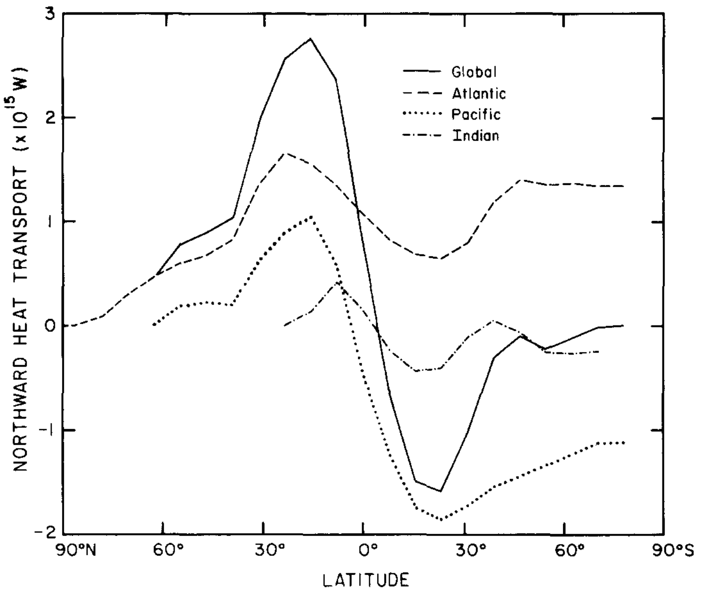

Fig. 5. Annual oceanic heat transports for the ocean basins and the global ocean as generated by the climate model.

tion of solar radiation in equatorial latitudes and subsequent poleward transport in each hemisphere. The residual of 1.1 PW (PW = petawatt = 10^{15} W) at the Antarctic continent indicates that heat is transported out of the Pacific. Some of this excess heat is originally absorbed in the Northern Hemisphere.

Figure 5 shows that the net transport of heat in the Indian Ocean is northward north of the equator and southward south of the equator with a maximum at 20°S. Hastenrath and Lamb (1980) show a maximum southward transport of 0.5 PW at 10–20°S, which agrees well with the value of 0.4 PW obtained from the climate model. The transport out of the Indian Ocean is about 0.25 PW, which indicates that the Pacific Ocean contributes about four times more than the Indian Ocean to the net flow of heat into the Atlantic basin.

Figure 6 shows that the annual oceanic heat transport for the Atlantic Ocean is northward at all latitudes. In both hemispheres there is a net transport of heat into the region poleward of 30°. In the North Atlantic this poleward transport is accomplished by a northward transport of heat absorbed in equatorial regions, while in the South Atlantic, the heat transported to high latitudes comes from other ocean basins. Between 60°S and 25°S, a portion of the heat transported northward is released to the atmosphere. Between 25°S and 25°N, heat is absorbed by the ocean and trans-

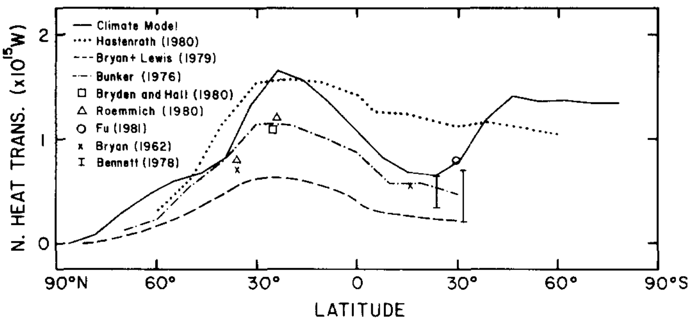

Fig. 6. Annual Atlantic Ocean heat transports generated by the climate model and comparisons with other studies. The Bunker (1976) and Bryan and Lewis (1979) transports are taken from Bryan (1982).

ported northward. North of 25°N the heat transported northward is released to the atmosphere. The 0.4 PW transported north of 60°N is somewhat larger than that found by Aagaard and Greisman (1975).

The Atlantic Ocean heat transports calculated from the climate model are consistent with values computed by other direct and indirect methods as shown in Fig. 6. The transports calculated by the indirect method using the climatological heat fluxes of Bunker (1976) and Hastenrath (1980) bracket the transport calculated from the climate model. The transports calculated from the numerical ocean model of Bryan and Lewis (1979) are considerably smaller, particularly in the region of maximum transport in the Northern Hemisphere. The climate model transports are also in reasonable agreement with the direct calculations of Bryan (1962), Fu (1981) and Bennett (1978) in the Southern Hemisphere and with Bryan (1962) and Roemmich (1980) at 36°N. The maximum northward transport of the climate model at 24°N, however, appears to be considerably higher than the 1.2 PW value calculated by Roemmich (1980) at 24°N and the 1.1 PW value of Bryden and Hall (1980) at 25°N.

The solid curve in Fig. 7 shows the global oceanic heat transport determined from the climate model. Also included in Fig. 7 are Northern Hemisphere computations of Oort and Vonder Haar (1976) and Southern Hemisphere computations of Trenberth (1979) using residual methods, global computations of Hastenrath (1980) using the indirect method, a direct computation of Bryden (1979) at 60°S and the global values from the numerical ocean model of Bryan and Lewis (1979). The present computations are the first global computations based on heat balances that are computed in a consistent and uniform manner at all latitudes. The curves in Fig. 7 are all similar although the maximum values differ. The present calculations are consistent with those of Trenberth (1979) and Bryan and

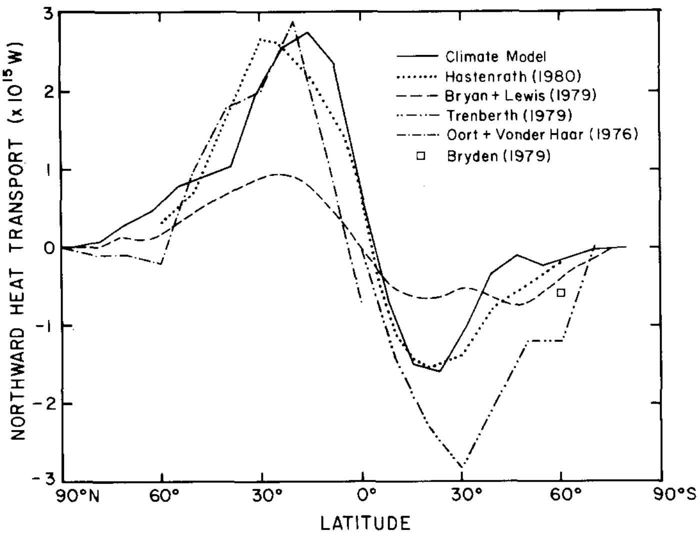

Fig. 7. Annual global oceanic heat transports generated by the climate model and comparisons with other studies.

Lewis (1979) in showing a secondary maximum poleward of 40°S. The location of this maximum, however, is different for each of the methods of calculation. The climate model also yields much smaller transports between 40°S and 60°S than the other methods of calculation.

The net transport of heat out of each ocean basin is calculated by obtaining the value of the transport at the Antarctic continent for each ocean basin. Figure 5 shows a transport of 1.35 PW into the Atlantic Ocean, 1.1 PW out of the Pacific and 0.25 PW out of the Indian Ocean. Direct computations of these transports by Georgi and Toole (1982) yield values of 0.34 PW into the Atlantic Ocean, 0.32 PW into the Pacific Ocean and 0.65 out of the Indian Ocean. The different results for the Pacific and Indian Oceans may be due partially to the different choice of boundaries between these two basins. This boundary is south of Australia in the present study and south of New Zealand in the Georgi and Toole (1982) study.

It is important to emphasize the advantages and limitations of the present method. One major advantage is the ability to compute global heat fluxes in a consistent manner for all regions. The daily fluxes are combined to give an annual average. Other studies using heat fluxes from surface observations do not have good coverage of all oceanic regions. A disadvantage of the present method is that the climate model itself contains many parameterizations and approximations. In particular, the error bars on the surface heat fluxes are not well known, the cloud patterns produced by the model may lead to errors in the radiation and severe topography adjacent to ocean grid points may yield poor heat fluxes over the ocean.

5. CONCLUSIONS

The annual oceanic heat transports for each of the three ocean basins and the global ocean have been calculated using radiation and heat flux data at the air–sea interface. These data were obtained as diagnostics from a one year simulation of an atmospheric general circulation model on an $8° \times 10°$ grid. Since the climate model (GCM) did not reach equilibrium, the net annual heat input to the global ocean was not equal to zero. The solar radiation was modified to insure no net annual heat flux into the ocean. One of the principal advantages of this method is that the model is internally consistent, updates values daily and is not based on long term averages or isolated ship reports that must be smoothed spatially and temporally in data sparse regions.

The results show northward transport of heat throughout the Atlantic Ocean, a result which is consistent with other studies. Hence, heat must be transported into the Atlantic from the Pacific and Indian Oceans. The heat transports calculated from the diagnostics of the climate model are in good agreement with estimates using other methods, although the maximum transports found here appear to be somewhat too large, particularly with respect to many of the estimates from the direct methods. Further improvements in the climate model, such as better cloud parameterizations and better calculations of oceanic heat fluxes adjacent to land masses are likely to produce more accurate values of the oceanic heat transports, although the qualitative description given here may not be significantly changed.

It is interesting to note that the oceanic heat transports calculated from the atmospheric model and the transports calculated from the ocean model of Bryan and Lewis (1979) bracket most of the other calculations with which they have been compared. This is due to both of these models transporting too little heat into high latitudes, which for the model used here will require a larger oceanic transport to compensate for the low poleward atmospheric transport.

Calculations of the oceanic heat transports would be a useful diagnostic for future climate and atmospheric general circulation models. These calculations would help to provide more information about the nature of ocean heat transport, and the comparisons with many of the recent calculations using other methods would prove useful as a GCM comparison diagnostic.

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