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# New Estimate of Annual Poleward Energy Transport by Northern Hemisphere Oceans

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## ABSTRACT

Recent measurements of the earth's radiation budget from satellites, together with extensive atmospheric energy transport summaries based on rawinsonde data, allow a new estimate of the required poleward energy transport by Northern Hemisphere oceans for the mean annual case. In the region of maximum net northward energy transport (30–35N), the oceans transport 47% of the required energy ($1.7\times10^{22}$ cal year$^{-1}$). At 20N, the peak ocean transport accounts for 74% at that latitude; for the region 0–70N the ocean contribution averages 40%.

## 1. Introduction

Poleward energy transport by ocean currents plays an important role in climate on earth and has been a subject of study for many years. Bryan (1962) provides a synopsis of the estimates based on surface heat budget studies (Budyko, 1958; Albrecht, 1960; Sverdrup, 1957). In addition, he demonstrates a method for oceanic transport calculations based on hydrographic data as an extension of earlier work by Jung (1952). The inadequacies of the former method are shown by Bryan to result primarily from the fact that the transport is calculated as a small residual of two large quantities, the net radiation gain of the ocean surface and the net energy loss (to the atmosphere) due to latent and sensible heat exchange. Unfortunately, global availability of hydrographic data is probably not yet extensive enough to use the second technique for global ocean transport estimates; an additional difficulty is the ambiguity in the choice of reference level.

The present study uses a third, indirect approach based entirely upon measurements. Satellite data on the net radiation budget of the earth-atmosphere system (Vonder Haar and Suomi, 1971) are now available over sufficient time periods (data from the years 1962–70 are used in this study) to allow a firm estimate of the "mean annual" energy exchange between earth and space. In addition, rawinsonde data from the MIT General Circulation Library for the 5-year period May 1958 through April 1963 give a matching data set for which Oort (1971) has calculated the energy transport in the atmosphere.

## 2. Method of calculation

The energy balance for a polar cap north of a certain latitude $\phi$ (°N) can be written in the form (compare Starr, 1951)

$$\partial E/\partial t = \mathrm{AT}+\mathrm{OT}+\mathrm{RF}+\mathrm{HF}, \tag{1}$$

where

$\partial E/\partial t$ rate of change with time of the total energy in a polar cap north of latitude $\phi$ (°N). The important components of the total energy are the internal energy, potential energy, latent heat, and kinetic energy of the atmosphere, ocean and cryosphere (snow and ice) contained in the polar cap.

AT atmospheric energy flux into polar cap across latitude $\phi$(°N) (area S1)

$$=\int_{S1}\int \rho(c_vT+gz+Lq+c^2/2+p/\rho)v\,dx\,dz$$

OT oceanic energy flux into polar cap across latitude $\phi$(°N) (area S2)

$$=\int_{S2}\int \rho(c_v'T+gz+c^2/2+p/\rho)v\,dx\,dz$$

RF net radiational flux into polar cap at top of the atmosphere (area S3)

$$=\int_{S3}\int Q\,dx\,dy$$

HF energy flux into polar cap at the surface of the solid earth (area S4)

$$=\int_{S4}\int Q'\,dx\,dy$$

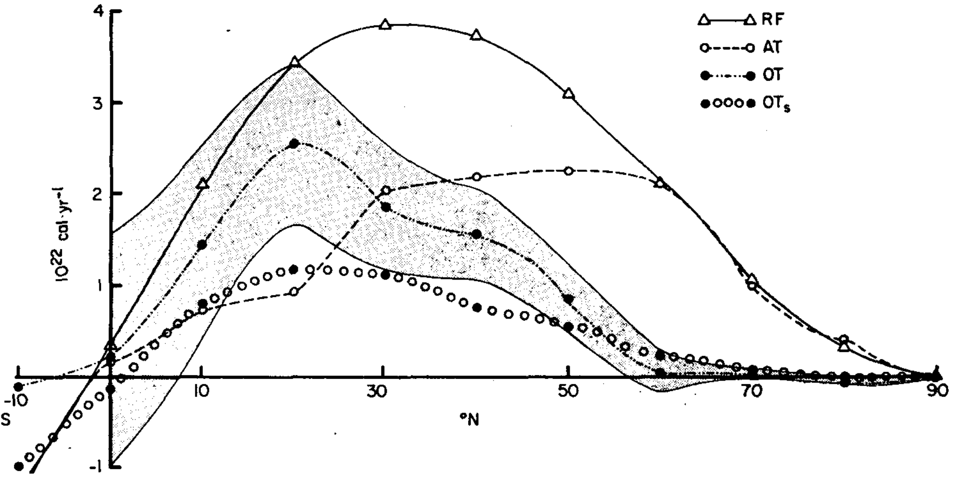

FIG. 1. Variation of net energy transport with latitude over the Northern Hemisphere: RF, total required energy transport inferred from satellite measurements; AT, measured energy transport by the atmosphere; OT, ocean energy transport derived from the present study; $OT_s$, ocean energy transport according to Sellers (1965). Uncertainty in the OT values is denoted by the shading. Minus values indicate net transport to the south.

Other symbols used are:

| | |
|---|---|
| $c$ | wind (current) velocity |
| $c_v(c_v')$ | specific heat at constant volume in atmosphere (ocean) |
| $g$ | acceleration resulting from gravity |
| $L$ | heat of condensation |
| $p$ | pressure |
| $q$ | specific humidity |
| $Q$ | net flux of radiation at top of atmosphere |
| $Q'$ | net flux of energy at surface of solid earth |
| $T$ | temperature |
| $v$ | northward component of wind (current) |
| $z$ | height |
| $\rho$ | density |

For a period of a year the energy storage[1] in the atmosphere-ocean-cryosphere system ($\partial E/\partial t$) and the energy exchange with the solid earth (HF) are probably small compared to the remaining terms on the right-hand side of (1) and will be neglected. Thus, on a mean annual basis we assume an approximate balance of the form

$$AT+OT+RF=0. \qquad (2)$$

From satellite measurements we have an estimate of the net radiational heating (RF) which under the assumptions used in deriving (2) must be equal to the net northward energy flow into the polar cap. The atmospheric measurements supply an estimate of AT. Therefore, the oceanic transport (OT) can be computed from (2) as a residual. Fig. 1 shows the total energy flux from radiation requirements, the atmospheric flux, and the deduced oceanic flux as a function of latitude. The numerical values are presented in Table 1. Sellers' (1965) values for atmospheric ($AT_s$) and oceanic ($OT_s$) transports based on the most recent surface energy budget estimates [including Budyko's (1963) estimates] are also tabulated.

## 3. Error estimates

The atmospheric energy flux was computed for five different years. This enabled us to estimate the error of the 5-year mean value of AT by calculating the standard deviation of the mean, $S=\sigma(X)/(N-1)^{\frac{1}{2}}$, where $n=5$. Twice the standard deviation of the mean indicates the 95% confidence limit and we assume that the instru-

TABLE 1. Poleward energy transport in the Northern Hemisphere for the mean annual case: units ($\times 10^{22}$ cal year$^{-1}$); minus indicates net southward transport.

| Latitude | RF* | AT† | OT | $AT_s$‡ | $OT_s$‡ | $\frac{OT}{RF}$ (%) |
|---|---|---|---|---|---|---|
| 90N | 0 | 0 | 0 | 0 | 0 | — |
| 80N | 0.32 | 0.37 | −0.05 | 0.25 | 0 | — |
| 70N | 1.14 | 1.10 | 0.04 | 1.18 | 0.09 | 3.5 |
| 60N | 2.15 | 2.11 | 0.04 | 2.14 | 0.26 | 2 |
| 50N | 3.10 | 2.24 | 0.86 | 2.82 | 0.57 | 28 |
| 40N | 3.76 | 2.20 | 1.56 | 3.10 | 0.79 | 41 |
| 30N | 3.88 | 2.03 | 1.85 | 2.60 | 1.15 | 48 |
| 20N | 3.49 | 0.91 | 2.58 | 1.34 | 1.19 | 74 |
| 10N | 2.14 | 0.72 | 1.42 | 0.42 | 0.81 | 66 |
| EQ | 0.33 | 0.13 | 0.20 | −0.07 | −0.16 | 60 |
| 10S | −1.54 | −1.44 | −0.10 | −0.66 | −1.00 | 6.5 |

* The values of RF are slightly different from those reported by Vonder Haar and Suomi (1971), since the measurements from the 13 seasons of that study have been augmented by 4 more measurement seasons (see Vonder Haar, 1972).

† The values of AT are slightly different from those reported earlier by Oort (1971). The present values represent the mean of 5 years analyzed separately. In the earlier study the same 5-year data set was analyzed but as one sample.

‡ Values of $AT_s$ and $OT_s$ as given by Sellers (1965).

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[1] Variability in ocean energy storage, presently under study in terms of temperature anomalies, is not well known but most probably lies within the error limits of this study.

ment plus sampling error of the atmospheric transport is not larger than this value. Error estimates are given in Table 2. From Vonder Haar (1968) and Vonder Haar and Suomi (1971), error analysis of the satellite measurements showed a maximum probable bias error of ±0.01 cal $\mathrm{cm}^{-2}$ $\mathrm{min}^{-1}$ in mean annual zonal values of the net radiation $Q$. The cumulative effect of such an error in the required transport (RF) values derived from the satellite measurements increases equatorward from the beginning point of integration at $\phi = 90\mathrm{N}$ (Table 2). The law of propagation of independent errors was used to obtain the estimate of error in the derived ocean transport $E_{\mathrm{OT}} = (E^2_{\mathrm{RF}} + E^2_{\mathrm{AT}})^{\frac{1}{2}}$. This error[2] is indicated by the shading in Fig. 1.

Table 2. Probable error in measurements and estimates of poleward energy transport in the Northern Hemisphere for the mean annual case: units ($10^{22}$ cal $\mathrm{year}^{-1}$).

| Latitude | $E_{\mathrm{RF}}$ | $E_{\mathrm{AT}}$ | $E_{\mathrm{OT}}$ |
|---|---|---|---|
| 90N | — | — | — |
| 80N | ±0.02 | ±0.12 | ±0.12 |
| 70N | ±0.08 | ±0.06 | ±0.10 |
| 60N | ±0.18 | ±0.10 | ±0.21 |
| 50N | ±0.32 | ±0.16 | ±0.34 |
| 40N | ±0.48 | ±0.10 | ±0.49 |
| 30N | ±0.67 | ±0.16 | ±0.68 |
| 20N | ±0.88 | ±0.08 | ±0.88 |
| 10N | ±1.10 | ±0.12 | ±1.10 |
| EQ | ±1.33 | ±0.10 | ±1.33 |
| 10S | ±1.56 | ±0.24 | ±1.58 |

## 4. Discussion of results

Between 10–50N the ocean transports derived in the present study are significantly greater than those previously derived. In the region of maximum net northward energy transport by the ocean-atmosphere system (30–35N), the ocean transports 47% of the required energy ($1.7 \times 10^{22}$ cal $\mathrm{year}^{-1}$). At 20N, the peak ocean transport accounts for 74%; for the region 0–70N the ocean contribution averages 40%. Both the absolute magnitude of the ocean transport and the relative role of the oceans significantly exceed earlier estimates.

The total transport value (RF) derived directly from satellite measurements is also greater than earlier (pre-satellite) estimates (Houghton, 1954). Vonder Haar (1968) pointed out that the increased required energy transport stemmed primarily from a lower albedo in tropical regions than was estimated before satellite data became available. Vonder Haar and Hanson (1969) showed that the increased net gain of energy in the tropics was corroborated by the few available measurements of direct solar energy reaching the tropical ocean surfaces. In fact, they showed that the extra energy entering the tropical zones was primarily absorbed in the oceans. Independent checks of the satellite values (1962–66) on the annual scale have just recently been possible using Nimbus 3 radiation budget measurements during 1969–70 (Vonder Haar *et al.*, 1972; Raschke *et al.*, 1972). These data, from a totally different radiometer system, confirm the earlier satellite results of a lower planetary albedo (0.29–0.30), an increased net energy gain, and an increased required transport. In addition, the atmospheric transport values used in this study are somewhat smaller than earlier values compiled by Sellers (see Table 1). Thus, the absolute value of the ocean transport must be greater since the overall requirement is greater and the atmosphere transports less.

These new ocean values show that not only the absolute amount, but also the relative role of the oceans, are greater than previously believed. They are shown to transport on the average 40% of the total required. Peak net transport values for the ocean (20N) apparently exceed the flat atmospheric maxima between 30–50N. Location of the ocean peak is the same as that shown by Sellers, but the transport value is more than 50% larger. Note that the curves indicate the need for a small net northward energy transport across the equator by the oceans.

In recent years large numerical models have been used to simulate the circulation of the atmosphere and the ocean. As they pass from the development phase they offer great promise for numerical experimentation. A measure of their representativeness is gained by comparison of their computed values of basic circulation parameters with the observed values. Comparison of the recent values of ocean transport computed in a joint ocean-atmosphere model run for the annual case (Bryan, 1969; Manabe, 1969) shows that the total Northern Hemisphere transport calculated by the model is less than the results of this study (but in agreement with previously accepted values). Furthermore, the latitude of maximum transport by oceans was calculated in the model to be about 38N, which is not in agreement with our results or any others. Wetherald and Manabe (1972) have recently run another joint atmosphere-ocean model in which seasonal variations of insolation were allowed. Reduced snow cover in the high-latitude summer lessened the annual gradient of net radiation to space and also the meridional transport of energy by ocean currents. Thus, this recent experiment caused the ocean value to deviate even further from our result. At this point it should be mentioned that the models presently used to simulate the combined atmosphere-ocean system are highly idealized and cannot be expected to give very reliable results for the ocean transport. For example, in the model horizontal sub-grid scale and vertical mixing strongly affect the oceanic

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[2] The error shown for the tropics and subtropics results primarily from the cumulative satellite error. It is definitely a worst-case estimate for this region since independent information [Vonder Haar and Suomi (1971) from measurements; London and Sasamori (1971) from calculations] show no *net* energy transport required across the equator. Thus, our transport integration could begin at 0° rather than 90°.

heat transport. Unfortunately, it is not known what value one should use for the mixing coefficient.

In summary, the estimates of ocean transport obtained in the present study are greater than previously believed, are derived from two new extensive data sets that have been checked and will be continuously updated in the years to come, and are timely in view of the renewed interest in the influence of the ocean on weather and climate. Our results suggest that air-sea interaction in mid-latitudes may be even more significant than presently acknowledged.

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