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# On the mean meridional transport of energy in the atmosphere and oceans as derived from six years of ECMWF analyses

By RÉJEAN MICHAUD[1] and JACQUES DEROME, *Centre for Climate and Global Change Research and Department of Meteorology, McGill University, Montréal, Canada H3A 2K6*

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ABSTRACT

The global ECMWF analyses for the period 1981–86 are used to compute the mean meridional transport of moist static energy in the atmosphere. The results show that the recurring changes made to the analysis procedure over the years have led to a significant increase in the transport due to the mean meridional circulation in the tropics. Compared to the earlier radiowind data based results of Oort and Peixóto, the use of analyses resulting from the data assimilation system leads to larger poleward transports; these amount to about $4 \times 10^{15}$ W (compared to $3 \times 10^{15}$ W) near 45° of latitude in both hemispheres in the annual mean. The subtraction of the mean atmospheric transport from the total ocean-atmosphere transport implied by the Nimbus 7 ERB NFOV net radiation flux at the top of the atmosphere leads to a maximum annual northward ocean heat transport of $3.2 \times 10^{15}$ W at 20°N. This value exceeds by $1 \times 10^{15}$ W or more the values obtained using surface marine data and bulk aerodynamic formulae in previous studies.

## 1. Introduction

It is well-known that the atmospheric temperature difference between the polar and the tropical regions does not reflect an atmosphere in radiative-convective equilibrium. The maintenance of the observed atmospheric pole-equator temperature difference is achieved through a poleward heat transport within the ocean-atmosphere fluid system, both components of the system playing a role as they interact through the surface energy fluxes. In this study we concentrate on that part of the meridional transport accomplished by the atmosphere, but we also draw some conclusions on the oceanic energy transport.

The meridional heat transport by the atmosphere has been studied by Oort and Peixóto (1983) and Savijärvi (1988) using 10 years (1963–73) of upper air radiowind data and ship observations (Oort, 1983) and, using different analyses or periods of the FGGE year data, by a number of investigators such as Lorenc and Swinbank (1984, ECMWF and UKMO analyses for July 1979), Boer (1986, ECMWF and GFDL analyses for July 1979), Holopainen and Fortelius (1986, ECMWF and GLA analyses for February 1979) and, more recently, Masuda (1988, ECMWF and GFDL analyses for the entire FGGE year). The results of Oort and Peixóto and Savijärvi differ because the latter used dynamical constraints related to the vorticity budget to replace in the original Oort data set the observed divergent wind field, which is likely unreliable in the midlatitude free atmosphere. The differences among the results based on the various FGGE analyses reflect to some extent the differences between the data assimilation systems used to obtain the analyses. (A description of the components of the assimilation systems can be found in a review paper by Bourke et al., 1985.)

The mean meridional atmospheric heat transports computed with the FGGE analyses are likely to lead to somewhat different results from those of Oort and Peixóto (1983) and Savijärvi (1988),

[1] *On leave from the Laboratoire de Météorologie Dynamique du CNRS, Paris, France.*

mainly because of the specific characters of the analysed fields over the oceans. Oort used a spatial interpolation method to fill the data gaps while assimilation systems rely on a global model forecast, the so-called first guess. Also, the interannual atmospheric fluctuations appear as a second likely cause for differences between the above mentioned 10-year average studies and the FGGE year studies.

In this study, we use 6 years (1981–86) of ECMWF analyses to compute the mean meridional fluxes of dry static energy and latent heat by the atmosphere. The results over the years bring out the impact of the recurring changes made to the assimilation system. This is mainly true for the tropics where the mean meridional circulation plays a dominant role as the assimilation system updates were often aimed at improving this circulation. For example, the introduction of a diabatic initialisation procedure in September 1982 modified the mean meridional circulation, as did in 1985 the major modifications of the humidity-related parameterizations through the close link of that circulation with the latent heat release. The reader can find lists of the assimilation system changes in Bengtsson and Shukla (1988, Tables 2 and 3) or Trenberth and Olson (1988, Table 1). Also, Fig. 10 of Bengtsson and Shukla and Fig. 13 of Trenberth and Olson clearly illustrate the effects of changes in the data assimilation on the analyzed mean meridional circulation in the tropics. The present study can be expected to give a meaningful insight into the true interannual variability of the transports in the middle and high latitudes, as the rotational wind and the temperature fields seem to have been relatively reliably analyzed over the years. These variables do not seem to have undergone large changes due to the modifications of the assimilation system, in contrast to the irrotational wind and humidity fields (A. Hollingsworth pers. com., Trenberth and Olson, 1988).

A better knowledge of the mean meridional heat transport by the atmosphere is valuable not only in itself, but also for the assessment of the meridional heat transport by the oceans. Three methods have been used to determine the latter. One method uses the net surface heat flux computed with bulk aerodynamic formulae and surface marine observations (e.g., Hastenrath, 1982; Hsiung, 1985; Oberhuber, 1988). Knowing the vertical heat fluxes at the ocean surface and assuming a steady state without internal heat sources, it is then possible to deduce the horizontal transport of heat within the ocean. A variant of this method has been employed by Simonot and Le Treut (1987), who used the surface energy fluxes predicted for day one by the ECMWF operational model instead of those computed from marine observations. A second method makes use of longitude-depth oceanographic cross sections to compute directly the oceanic meridional flux of heat, as done, for example, by Bryden and Hall (1980); these calculations are summarized in a review paper by Bryan (1982). Both methods, using either bulk aerodynamic formulae or sparse oceanic data, continue to lead to considerable uncertainties in the determination of the meridional heat transport by the oceans. A third method was developed by Vonder Haar and Oort (1973) and adopted by Carissimo et al. (1985), Savijärvi (1988) and Masuda (1988). With this approach, satellite measurements are used to obtain the net radiative heat flux at the top of the atmosphere, and atmospheric data to compute the atmospheric meridional heat transport. Assuming that the atmosphere-ocean system is in thermal equilibrium, it is then possible to obtain, as a residual, the ocean heat transport required to maintain that equilibrium. It is clear that an improvement in our knowledge of the atmospheric meridional heat transport will reduce the uncertainties in the ocean transports inherent in this approach.

In the present study, we use the analyses of the last year of our ECMWF data set, namely 1986, and the total ocean-atmosphere meridional heat transport implied by the most recent radiative measurements published by Hartmann et al. (1986, Nimbus 7 ERB NFOV) to obtain a new estimate of the annual mean ocean heat transport. Masuda (1988) used the same radiative measurements and the ECMWF FGGE "main" (old) IIIb analyses (e.g., Bengtsson, 1983) which, despite the larger amount of available observations for the FGGE year, suffer from the forecast model and initialisation deficiencies of that time. It is because of these deficiencies that the ECMWF decided to re-analyze part of the FGGE data, and in particular Special Observing Periods data (January, February, May, and June 1979) with the assimilation system of 1985 (e.g., Uppala, 1986).

The knowledge of the meridional heat transport by the atmosphere can also be used in the verification of atmospheric general circulation models. (A review of the observational studies relevant to the verification of these models was provided by Holopainen, 1982). This knowledge may shed some light on the nature of a given model climate drift. It may be possible, for example, to show whether the model deficiencies are associated with an erroneous mean meridional circulation, with erroneous longitudinal stationary eddies or with erroneous transient eddies in the circulation. Naturally, it must be realized that all these parts of the flow are coupled, and hence one should not treat them as independent possible causes of a model deficiency. Nevertheless, the comparison of the various components of the meridional heat flux in the model and atmosphere may provide some insight in the analysis of the model defects and hence lead to model improvements.

## 2. The energy equation

When considering sufficiently long time periods during which no noticeable change of the mean atmospheric state has developed (for example the winter or the summer seasons), the time-averaged energy sources or sinks that may have been active during such time periods must have given rise to an export of energy from or an import of energy into these regions to counterbalance the former gain or loss of energy by the atmosphere. We study here the meridional transport of energy by the atmosphere (i.e., the meridional component of this export or import of energy) expressed as a horizontal transport of dry static energy and latent heat.

Using isobaric coordinates, the horizontal equation of motion, the thermodynamic equation, the mass continuity equation and the moisture equation take the form:

$$\frac{d\boldsymbol{V}}{dt} = -f\boldsymbol{k} \times \boldsymbol{V} - \nabla\phi + \boldsymbol{F}, \tag{1}$$

$$\frac{dc_p T}{dt} - \frac{RT}{p}\omega = \dot{Q}, \tag{2}$$

$$\nabla \cdot \boldsymbol{V} + \frac{\partial \omega}{\partial p} = 0, \tag{3}$$

$$\frac{dq}{dt} = S, \tag{4}$$

where the various symbols are:

| | |
|---|---|
| $\boldsymbol{V}$ | the horizontal wind vector |
| $f$ | the Coriolis parameter |
| $\boldsymbol{k}$ | the unit vertical vector |
| $\phi$ | $gz$, where $z$ is the geopotential height of a pressure surface |
| $\boldsymbol{F}$ | the friction force |
| $c_p T$ | the enthalpy |
| $\omega$ | the vertical velocity $dp/dt$ |
| $\dot{Q}$ | the diabatic heating rate |
| $q$ | the specific humidity |
| $S$ | the source or sink of humidity. |

The total energy (kinetic, internal, potential and latent energies) of an atmospheric column of unit horizontal area extending from the bottom to the top of the atmosphere can be written as

$$E = \int_0^{p_s} (V^2/2 + c_v T + \phi + Lq)\, dp/g$$
$$= \int_0^{p_s} (V^2/2 + c_p T + Lq)\, dp/g, \tag{5}$$

where $L$ is the latent heat of condensation, and the enthalpy in the column has been obtained as the sum of the internal and potential energies with the use of the hydrostatic approximation and the condition that $p\phi \to 0$ as $p \to 0$.

The tendency equation for $E$ can be obtained by taking $\boldsymbol{V} \cdot (1) + (2) + L \times (4)$. Using (3) to rewrite the various terms in a flux form the resulting equation takes the form

$$\frac{\partial}{\partial t}\int_0^{p_s} (V^2/2 + c_p T + Lq)\, dp/g$$
$$= -\int_0^{p_s} \nabla \cdot [(V^2/2 + c_p T + Lq)\boldsymbol{V}]\, dp/g$$
$$- \int_0^{p_s} \nabla \cdot (\boldsymbol{V}\phi)\, dp/g + \mathscr{F}_T - \mathscr{F}_B. \tag{6}$$

The first integral on the right is seen to be the convergence of the horizontal flux of $E$. The second integral, which results from the mechanical work done by the pressure force, takes the form of a convergence of a horizontal flux of potential energy. The $\mathscr{F}_T$ and $\mathscr{F}_B$ terms represent the net downward flux of energy at the top and bottom of the atmosphere, respectively, and appear as a result of the vertical integration of the energy equation.

When (6) is averaged over a season the left-hand side is negligibly small, so that $\mathscr{F}_T - \mathscr{F}_B$ must balance the divergence of the horizontal atmospheric transports represented by the two integrals on the right-hand side. In the present study we compute the horizontal atmospheric energy fluxes in these two integrals; we then use information on the vertical radiative fluxes at the top of the atmosphere from Hartmann et al. (1986) to obtain $\mathscr{F}_T$ and compute $\mathscr{F}_B$ as a residual. We assume that over a sufficiently long period of time (one season) the land masses are in thermal equilibrium without any required horizontal transport within them, so that the lower boundary fluxes take place entirely over the oceans. Having $\mathscr{F}_B$, it is then a simple matter to compute the ocean transport required to maintain a thermal equilibrium within the oceans.

We are concerned with the zonally-averaged form of (6), in which case only the meridional transports are of interest. The meridional flux of kinetic energy is negligibly small in comparison with those of sensible heat, latent heat and potential energy and need not to be computed (Oort and Peixóto, 1983).

We resolve the meridional transport of the various scalars of interest into transports due to the stationary and transient structures of the flow. Moreover, the transport by the stationary part of the flow is expressed as the sum of the fluxes associated with the mean meridional circulation and with the standing longitudinal eddies.

Using the symbols $[(\ )]$, $(^-)$, $(\ )^*$ and $(\ )'$ to represent the zonal average, the time-mean and the departures from the zonal and time means, respectively, of the quantity ( ), the time-averaged zonal mean meridional transport of a scalar $X$ takes the form

$$\overline{[vX]} = [\bar{v}][\bar{X}] + [\bar{v}^*\bar{X}^*] + \overline{[v'X']}, \qquad (7)$$

the right-hand side representing the fluxes by the mean meridional circulation, the stationary eddies and the transient eddies, respectively.

## 3. The data set

The original data set was composed of initialised analyses at 12 hour intervals on a global 2.5° by 2.5° latitude-longitude grid. We used the horizontal wind components, the temperature, the geopotential height and the relative humidity at the seven standard pressure levels 1000, 850, 700, 500, 300, 200 and 100 hPa on a reduced time-space grid. In the interest of economy, we used data at 36-h intervals on a grid with 5.0° of longitude and 2.5° of latitude. Because of the time correlation that exists between synoptic observations, our 36-h sampling period is adequate. In fact, for a given computational effort, it is preferable to use a longer time series and a longer sampling interval than the opposite since highly correlated data do not add much information to the estimate of time means. For the same reason, the reduction of the number of grid points in the longitudinal direction should also have a minor impact as a similar variety of longitudinal-dependent phenomena is likely to be captured.

Our study uses data from the six-year period 1981 through 1986. The computations are performed for each "meteorological season" independently, namely, December through February, March through May, June through August and September through November. Moreover, since the divergent wind and moisture fields have been quite sensitive to the numerous changes made to the parameterization schemes of the data assimilating model, as well as to the analysis and to the initialisation techniques during that time period, the various years are treated independently. We thus have 6 years of data for each season, except for the winter season for which we have the 5 years December 1981–February 1982 to December 1985–February 1986.

The top of the atmosphere was chosen to be 50 hPa in order that the 100 hPa data level be at mid-layer. The surface pressure required as the lower boundary of our vertical integrals was obtained by extrapolation using the hydrostatic approximation and a constant temperature in the layer in which the orographic surface is located. The orographic height, in turn, was computed for the given horizontal resolution of 5.0° × 2.5° by area averaging the data from a 1/6 degree resolution topographic field.

Our initial computations of the energy transports revealed unphysical seasonally-averaged vertically integrated divergent horizontal mass fluxes for the various seasons, as these mass fluxes would remove a substantial fraction of the air from some regions and would accumulate it in others in the time interval of a season. Spurious divergent horizontal mass fluxes were also noted in the FGGE data sets (e.g., Boer, 1986; Masuda, 1988) and the energy computations were made after their removal. Corrections were applied to the horizontal velocity vector at each available time and for each layer, by subtracting the corresponding mass-weighted fraction of the seasonally-averaged vertically integrated divergent component of the horizontal velocity. The latter component was obtained from the gradients of the potential function associated with the divergence field, i.e., $\nabla^2\Phi = D$. Here, as in the entire study, the computations used finite differences on the sphere.

## 4. Atmospheric transports

*4.1. The seasonal mean transports*

Figs. 1a and 1b display the mean meridional moist static energy ($c_p T + Lq + \phi$) transports for the two seasons December-January-February (DJF) and June-July-August (JJA), for the first and last year (only the corresponding solid line is reliable in the tropics) of our data set. The curves for the other years are not drawn. In the tropics they would be located between the curves that are displayed; in fact, in that region the results from the various years evolved monotonically from the results of the first year (DJF-82, JJA-81) to those of the last year (DJF-86, JJA-86). This progression evidently results from the recurring changes made to the assimilation system during the 1981–1986 period.

The shape of the total transport curves (all motions) shown in Figs. 1a and 1b implies a flux divergence between about 40°S and 40°N, and hence an export of moist static energy poleward from that latitude band. During the Northern Hemisphere winter (NHW), the "meteorological equator", defined here as the latitude of zero flux, is located near 10°S while during the Northern Hemisphere summer (NHS) it is located at a more northerly latitude, near 15°N.

In both seasons and both hemispheres, the transient eddies are the dominant contributor to the mid-latitude poleward transport of energy, followed in importance by the standing eddies. It should also be noted that the Ferrel cell transports energy equatorward (except possibly in JJA in the NH, where it is negligibly weak).

In the NH the transports by the transient and stationary eddies are seen to be very much stronger in winter than in summer. In the Southern Hemisphere (SH), on the other hand, the contrast between the two seasons is much weaker. It is worth noting that if we average the winter and summer total transports, the magnitude of the SH maximum is found to be similar to that of the NH, namely, about 4 PW (1 PW = $10^{15}$ W).

The main discrepancy between the two total flux curves in the first and last year of our data set (solid vs dashed curves in Figs. 1a and 1b) is found in the tropics and is clearly associated with the near absence of the transport due to the mean meridional circulation in the 1981–82 data. The ECMWF data assimilation system of that time could only produce weak divergent circulations in the tropics as an adiabatic initialisation procedure was then in use. The introduction of a diabatic initialisation in September 1982 allowed the system to retain a large fraction of the analyzed information in the tropics (e.g., Wergen, 1988). In addition, the modifications made to the ECMWF forecast model from 1981 to 1986 improved the first-guess fields used in the data assimilation procedure. This is of particular significance in the tropics where reliable observations to modify the first-guess fields are not abundant. Fig. 12 of Wergen (1988) displaying the ECMWF FGGE "main" (old) and "final" (new) analyzed zonal mean meridional and vertical velocities for May 1979 illustrates quite well the superiority of the 1985 data assimilation system over that of the early 1980s.

Figs. 2 and 3 display the transports of dry static energy and latent heat, respectively (in the same format as in Fig. 1). These two figures are better illustrations of the changes over the years in the tropical heat transports based on the ECMWF analyses. Indeed, while the modifications of the meridional transport of moist static energy in the tropics appeared moderate in Fig. 1, the differences between the 1981–82 and 1985–86 result in Figs. 2 and 3 are seen to be major ones in the low latitudes. We note that the horizontal divergence or convergence of the transport of dry static energy in the tropics, as indicated by a positive or a negative local slope, and which should have taken place to counterbalance the local diabatic heating

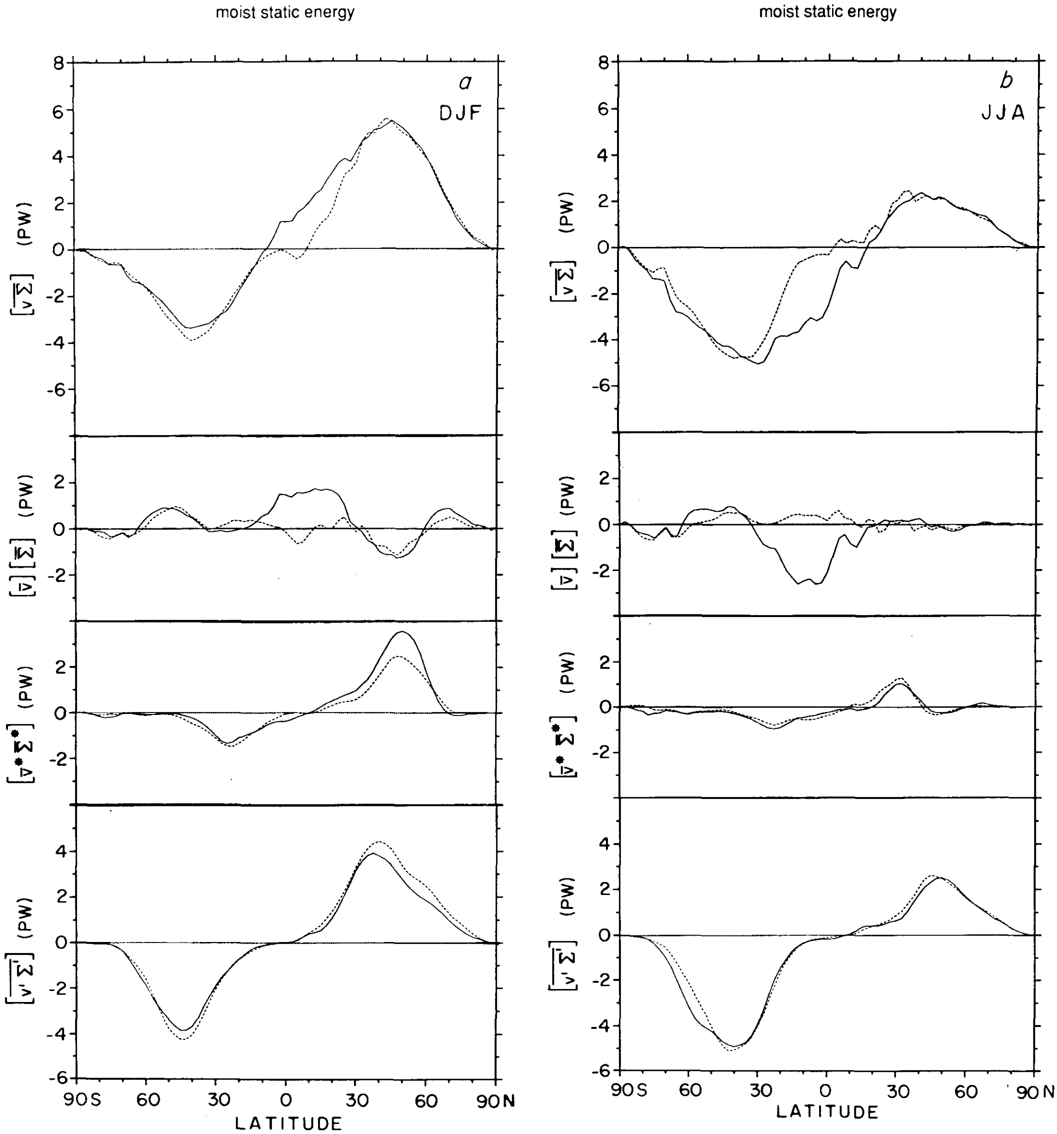


*Fig. 1.* Zonally and vertically integrated meridional transport of moist static energy by (top to bottom) the total flow, the mean meridional circulation, the standing eddies and the transient eddies, in units of 1 PW = $10^{15}$ W. Panel (a) is for DJF of 1981–82 (dashed) and 1985–86 (solid), while panel (b) applies to JJA of 1981 (dashed) and 1986 (solid).

or cooling (Section 2), depicts a very different situation for the 1986 data and the 1981 data. The 1986 fluxes of dry static energy (Fig. 2) imply a strong loss of energy (60–75 W/m$^2$) between about the 20° latitude in the summer hemisphere and the 10° latitude in the winter hemisphere and a pronounced gain of energy (40–60 W/m$^2$) in the winter hemisphere between this latter latitude and the 30° latitude, as a result of divergence and convergence of the transport by the mean meridional circulation. The total latent heat transport shown in Fig. 3, on the other hand, is seen to be such that the flux converges (leading to a release of latent heat) in those latitudes where the dry static energy

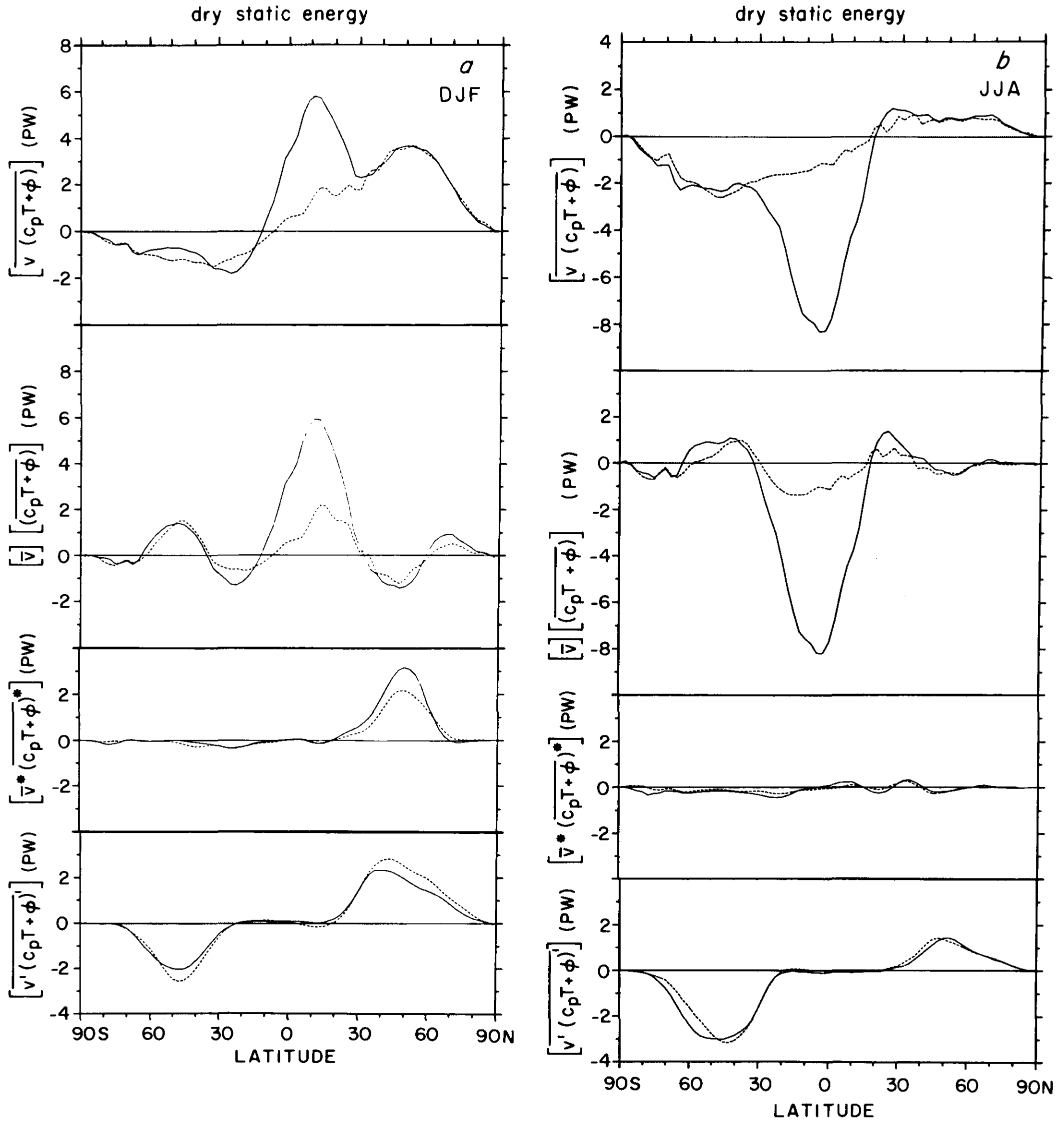


*Fig. 2.* As in Fig. 1 but for the transport of dry static energy.

flux diverges, while it diverges (implying a net evaporation) in the latitudes where the dry static energy converges. As a result, the total transport of heat (the moist static energy, Fig. 1) by the tropical atmosphere is relatively small and essentially shows that heat is extracted from the 20°–0° latitude band of the summer hemisphere and carried towards the subtropical latitudes (20°–30°) of the winter hemisphere by the mean meridional circulation. This process was not detectable in the 1981–82 data.

As we have already discussed, the evolution in the quality of the ECMWF analyses between 1981 and 1986 is the result of not only the introduction of a diabatic initialisation procedure in September 1982 but also, and likely to a large extent, of the modifications made to the forecast model. Probably the most important changes relevant to

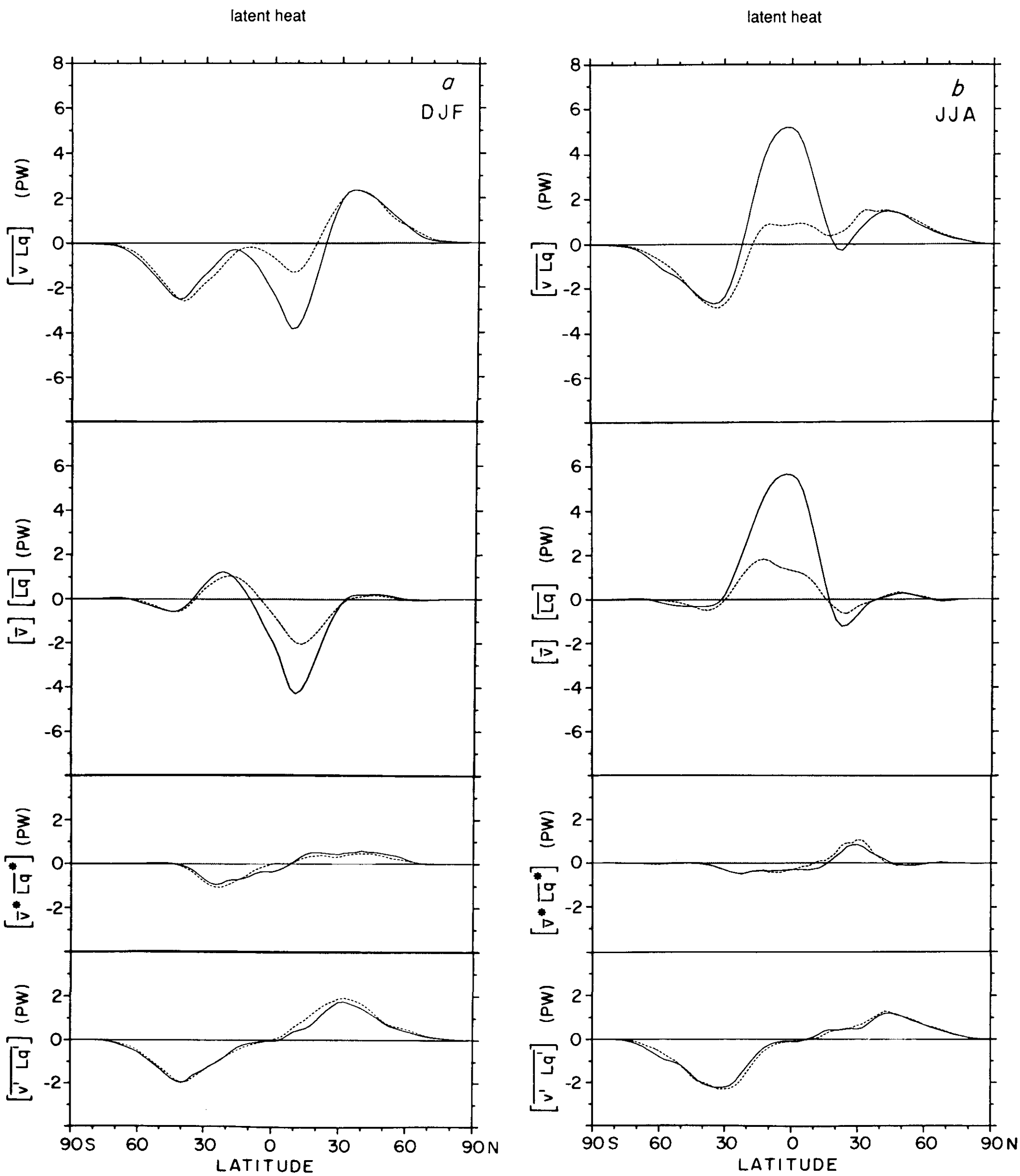


*Fig. 3.* As in Fig. 1 but for the transport of latent heat.

our study took place in May 1985 and included the introduction of a parameterization of shallow cumulus convection, a modification to the parameterization of deep cumulus convection, and a new cloud scheme. Because good quality observations of tropical moisture are scarce, the tropical moisture analyses tend to be strongly dependent on the first guess fields provided by the forecast model (Tiedke et al. 1988, Trenberth and Olson 1988). The vertical motion and the divergent component of the horizontal wind were also substantially affected by the model changes due to the close link with the latent heat release. The changes led to the enhancement of the whole hydrological cycle, including the moisture supply from the surface to the subtropical boundary layer (Tiedke et al., Trenberth and Olson). Figs. 17 and 18 of Bengtsson and Shukla (1988) show the impact on the latent heat flux at the ocean surface, in particular the increased fluxes over the trade wind regions (from 60–80 W/m$^2$ to 120–150 W/m$^2$). These larger fluxes are also implied in our data set as the divergence of humidity is strongly increased in the trade wind latitudes from JJA 1984 to JJA 1985 (figures not shown).

*4.2. The interannual variability*

As the evolution in the data assimilation procedure in use at the ECMWF from 1981 through 1986 has had a major impact on the tropical analyses, it is impossible with our data set to comment on the true interannual fluctuations in the meridional energy transport in those latitudes. In the mid and high latitudes, on the other hand, the transports are dominated by the non-divergent or irrotational component of the wind (transient and stationary eddies, rather than the mean meridional circulation), which has been much less

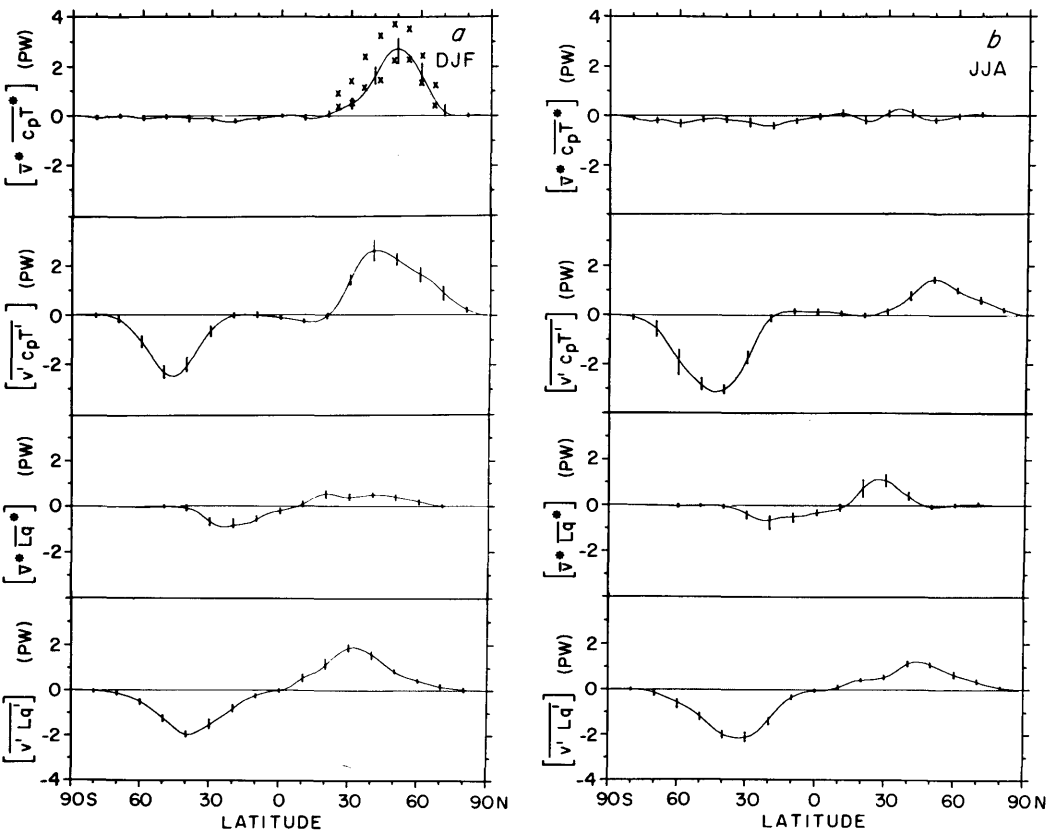


*Fig. 4.* Zonally and vertically integrated transport of (top to bottom) sensible heat by the stationary eddies, sensible heat by the transient eddies, latent heat by the stationary eddies, and latent heat by the transient eddies, in units of PW. The curves give the average over the 5 DJF periods from December 1981 through February 1986 (a) and over the 6 JJA periods from June 1981 to August 1986 (b). The vertical bars represent the extreme values over the five periods used in the average. In the top diagram of Fig. 4a, similar results from Oort (1977) using a 5-year radiowind data set are indicated by crosses but for the January-mean interannual variability.

affected by the modifications made to the assimilation system. This argument is supported by the fact that an examination of the eddy transports for the various years does not reveal a gradual evolution from one year to the next, as is the case for the fluxes by the mean meridional circulation in the tropics. Instead, the eddy transports for the various years are distributed approximately randomly about their mean over the years. Thus, for the eddy transports, it is meaningful to compute the time average and to examine the spread in the transport values obtained over the years, as a rough measure of the variability of the fluxes from year to year.

Figs. 4a and 4b show the sensible and latent heat transports by the stationary and transients eddies, respectively, for both the DJF and JJA seasons. The curves correspond to the time-averaged transport, while the vertical bars give the extremes over the years. We note that it is thc NHW stationary eddy transport of sensible heat that exhibits the largest interannual variability. The range in the transport maximum is about $\frac{2}{5}$ of the averaged transport (1 PW compared to 2.5 PW), a large fluctuation considering that we are looking at the seasonal mean of a vertically integrated and zonally averaged quantity. This result can be compared to that obtained by Oort (1977) using a 5-year (1958–1963) radiowind data set; the corresponding extremes over the years for the month of January are indicated by crosses in Fig. 4a. Those results are in close agreement with ours, as a reduction factor of about $\frac{2}{3}$ should be applied to the interannual fluctuations of monthly-means to take into account the influence of the averaging interval (this conclusion has been drawn by visual inspection of monthly and seasonal interannual fluctuations of the total eddy fluxes in Oort 1977). The other transports exhibit a weaker interannual variability of their seasonal mean, except the transport of the sensible heat by the transients in the SH during JJA, which also varies considerably near 60°S. The few seasonal interannual fluctuations given by Oort (1977) for the NH (not shown) agree well with those computed in the present study.

### 4.3. *The annual mean transport*

Fig. 5 compares various estimates of the annual mean northward transport of moist static energy. The solid curve applies to our results for the period December 85–November 86 (all 12 months), while the long dashed curve refers to Oort and Peixóto's (1983) calculations for the period 1963–1973 and the short dashed curve applies to the calculations of Masuda (1988) using ECMWF FGGE analyses.

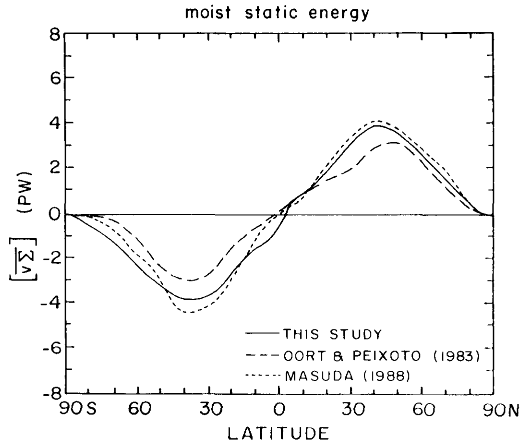


*Fig. 5.* The solid line gives the zonally and vertically integrated transport of moist static energy obtained in the present study for the period December 1985 through November 1986 as a function of latitude, in units of PW. The long-dashed curve refers to the corresponding results obtained by Oort and Peixóto (1983) for the period 1963–1973. The results obtained by Masuda (1988) using the FGGE-ECMWF "main" (old) analyses (short-dashed curve) are also shown. The last two curves were redrawn from the corresponding referenced papers.

Compared to Oort and Peixóto's results, the December 85–November 86 curve mainly displays larger maximum poleward transports in both hemispheres with values of 4 PW rather than 3 PW. The lower maxima obtained by Oort and Peixóto are undoubtedly due to the use of the radiowind data which, except for some island stations, are all located over continents. The interpolation of the radiowind data over the oceans probably leads to less developed transient structures than those given by the data assimilation procedure. As the transport at the latitudes of the maxima is mainly carried out by the transient eddies, one can expect weaker transports with Oort and Peixóto's analysis procedure. We note finally that our results exhibit a small southward cross-equatorial transport of moist static energy. It is essentially due to a more pronounced cross-equatorial transport during summer than during winter (that in turn results from a more poleward meteorological equator during summer than during winter).

The December 85–November 86 curve does not depart much from the FGGE year curve which is based on an additional amount of observational data but a deficient data assimilation procedure. Besides the moderate differences in the maximum poleward transports in midlatitudes, which can probably be explained by the naturally occurring interannual variability, the main differences appear in the vicinity of the equator with a smaller positive slope (source of moist static energy) in the FGGE analyses than in the December 85–November 86 analyses. The weak mean meridional circulation in the tropics in the FGGE "main" analyses (e.g., Wergen, 1988) is responsible for this weak flux divergence with the FGGE data. The transports based on the FGGE analyses show some similarity with our results for 1981–82 (Fig. 1) where the total transport divergence fails to display a source of moist static energy in the 10°S–10°N latitude band.

The individual contributions of the dry static energy and the latent heat (Fig. 6) bring out the

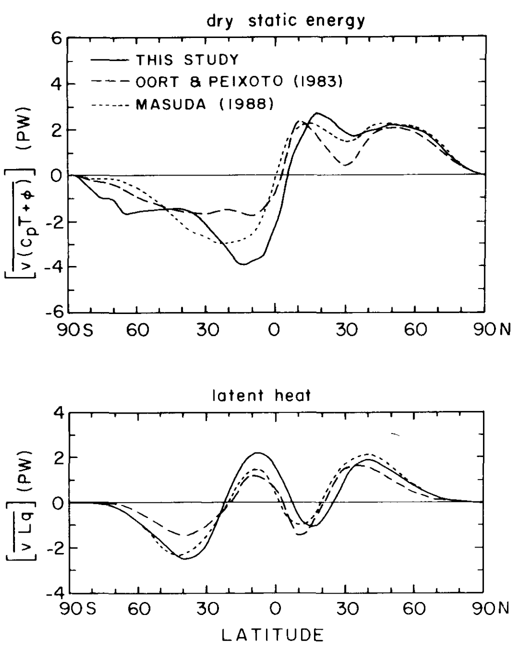


*Fig. 6.* As in Fig. 5 but for dry static energy and latent heat, respectively.

differences between the ECMWF FGGE "main" analyses and the December 85–November 86 analyses. The 1985–86 analyses display a larger hydrological cycle in the SH tropical latitudes, which are mainly ocean covered. We note that the SH trade winds bring much more moisture equatorward than the NH trades in the 1985–86 data. This may reflect to a certain extent a further modification made to the humidity analyses in March 1986 (e.g., Illari, 1989). The large southward transport of dry static energy at 10°S merely reflects the large transport of potential energy aloft in conjunction with the well-developed mean meridional circulation transport of JJA 1986 (Fig. 2b), to which the enhanced hydrological cycle has most likely contributed.

## 5. The required ocean transport

As discussed in the introduction and after the presentation of equation (6), given the net vertical radiative energy flux at the top of the atmosphere and the meridional energy flux by the atmosphere, it is possible to compute the oceanic energy flux required to maintain a steady state in the atmosphere-ocean system. The results of such a calculation are presented in this section.

Fig. 7 shows the total atmosphere-ocean energy transport required to balance the vertical flux of radiative energy at the top of the atmosphere, from three different sources. The dotted curve is from Ellis and Vonder Haar (1976), the dashed curve from Campbell and Vonder Haar (1980) and the solid curve refers to Nimbus 7 ERB NFOV instruments; the three curves are redrawn from Hartmann et al. (1986). While all three curves agree rather well in the SH, they show some appreciable differences in the NH, where the maximum values range from less than 5 PW for the earliest study by Ellis and Vonder Haar, to almost 6 PW for the latest study by Hartmann et al.

The ocean heat transport obtained by subtracting the atmospheric contribution from the total ocean-atmospheric transport is displayed as the solid curve in Fig. 8. The long-dashed curve refers to the results of Carissimo et al. (1985) and the short-dashed curve to those of Savijärvi (1988), both based on the radiation curve of Campbell and Vonder Haar. While both studies used the atmospheric transports inferred from the original

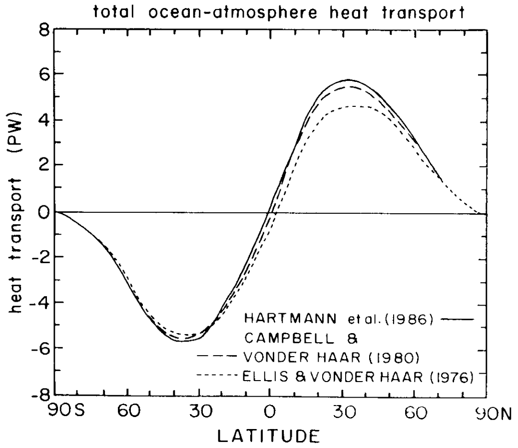


*Fig. 7.* The meridional flux of energy by the combined atmosphere-ocean system, as derived from the net vertical flux of energy at the top of the atmosphere. The dotted curve is from Ellis and Vonder Haar (1976), the dashed curve from Campbell and Vonder Haar (1980) and the solid curve from Nimbus 7 ERB NFOV measurements (Hartmann et al., 1986). The first and third curves were redrawn from Hartmann et al., while the second was drawn using the tabulated values given by Carissimo et al. (1985).

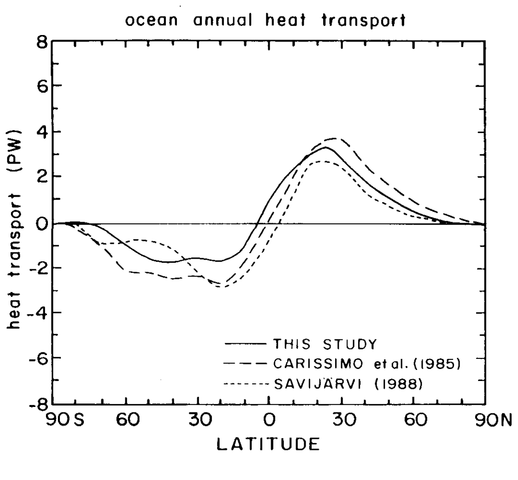


*Fig. 8.* The meridional flux of energy by the oceans derived from the net vertical radiation flux at the top of the atmosphere and the meridional flux by the atmosphere. The long-dashed curve is from Carissimo et al. (1985), the short-dashed curve is from Savijärvi (1988), while the solid curve applies to the present study. The last curve was obtained from the solid curves in Figs. 5 and 7.

Oort (1983) data set, Savijärvi modified those data for the wind in the midlatitude free atmosphere. Our own results are based on the Nimbus 7 ERB NFOV measurements and the atmospheric transports of the present study (Fig. 5, solid curve, for the period December 1985–November 1986). As the latter showed a southward cross-equatorial transport in the atmosphere, an opposite cross-equatorial transport is found in the oceans (Fig. 8) to balance the total atmosphere-ocean transport (Fig. 7) that nearly vanishes at the equator. Over the atmospheric data sparse SH, the discrepancies between the various curves are considerable; our results lead to the smaller poleward transport with values less than 2 PW. On the other hand, our maximum northward ocean-heat transport reaches a value of 3.2 PW at 20° N. At the same latitude Carissimo et al. obtained 3.5 PW and Savijärvi 2.7 PW. A larger range of values is found at 30° N where Carissimo et al.'s values exceeds the two other values by almost 1 PW. This difference results from their relatively small atmospheric transport due to the transient and stationary eddies of the midlatitudes. The modified Oort radiowind data set of Savijärvi leads to considerably larger atmospheric transports and, as a residual, to a smaller ocean transport in the NH midlatitudes. Although our computations yield NH northward transports that are smaller than those of Carissimo et al., our maximum ocean flux still exceeds by 1 PW or more the values derived from the heat flux estimates at the air-sea interface. Hastenrath (1982), for example, obtained a maximum of 2.2 PW, Hsiung (1985) a maximum of 1.7 PW and Oberhuber (1988) a maximum of 1.6 PW.

In view of the uncertainties inherent in all estimates of the oceanic meridional every transport, it is difficult to make a definitive statement as to which is the most reliable. It is worth noting, however, that our results fall in an intermediate range between those cited above. As they are based on atmospheric data analyzed by state-of-the-art assimilation techniques and the most recent published radiation data, they should provide a reasonable estimate of the ocean transport.

## 6. Conclusion

The ECMWF data set for the period 1981 to 1986 has been used to compute the seasonal mean meridional moist static energy transport by the atmosphere. Owing to the recurring changes made to the assimilation system during this period, it has not been possible to study the interannual variability of the meridional heat transport in the tropics and subtropics. The present study does show, however, that the most recent initialised fields of the data set reconstruct a well-developed mean meridional circulation transport in the tropical and subtropical areas. It is not quite clear how close the latter circulation is to reality, but it would seem likely that the transports associated with it for the months DJF-86 and JJA-86 obtained in the present study are quite reasonable. Further modifications to the assimilation system are still being introduced, however, as efforts are made to eliminate known model deficiencies (e.g., Arpe, 1988).

The recurring changes made to the analysis and initialisation procedure at ECMWF during the period 1981 to 1986 do not seem to have had a major impact on the meridional heat transports by the rotational wind component, i.e., the transports by the stationary and transient eddies in the middle and high latitudes. It is thus possible to obtain from our calculations a crude estimate of the interannual variability of the corresponding mean-seasonal meridional heat transports. We have found that only the transport of enthalpy by the stationary eddies (which is sizeable only during the NH winter) displays a noteworthy interannual variability, in agreement with the results of Oort's (1977) study using a 5-year (1958–1963) radiowind data set. The maximum value of this transport near 50° N ranges from 2.0 to 3.0 PW over the 5 winter seasons of our data set.

The subtraction of the annual mean atmospheric transport from the total ocean-atmosphere transport implied by the most recent observed net radiation budget at the top of the atmosphere leads to a maximum northward heat transport of 3.2 PW at 20° N in the oceans. At this latitude, the ocean transport is only slightly smaller (3.2 versus 3.5 PW) than that obtained by Carissimo et al. (1985) using atmospheric transports based on Oort's (1983) radiowind and ship observations. These radiowind-based transports, however, appear too small in the middle latitudes and lead to an excessive residual oceanic transport, which reaches a maximum at 30° N, a latitude at which this study shows a northward heat transport that is decreasing northward.

There are still large differences between the oceanic transport inferred in this study and those resulting from the various studies using surface marine data and bulk aerodynamic formulae. The latter lead to a maximum poleward transport of about 2 PW in the NH. The difference of 1 PW between the maximum northward oceanic transport inferred by the two methods is likely to be within the range of uncertainty of each method. For example, when Fortelius and Holopainen (1990) examined the net radiation measurements at the top of the atmosphere over land from Nimbus 7 ERB NFOV instruments, and the moist atmosphere heat sources/sinks implied by the ECMWF FGGE "final" (re-analyzed) analyses for February and July 1979, they found significant local discrepancies between the two estimates of atmospheric total energy sources/sinks. This suggests that the determination of the oceanic mean meridional heat transport using the residual method first proposed by Vonder Haar and Oort (1973) still displays some uncertainty; it should be reduced by further modifications of the assimilation system (e.g., Morcrette, 1990).

## 7. Acknowledgments

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