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Mean meridional transport of energy in the earth-atmosphere system using NMC global analyses and ERBE radiation data

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ABSTRACT

Recently processed data from the Earth Radiation Budget Experiment (ERBE) provides an incentive to continue investigations addressing the energy transport of the earth-atmosphere system. Within this study, we compare the top-of atmosphere ERBE net radiation measurements and derived energy transports thereof with computed transports derived from the daily global analyses of the National Meteorological Center (NMC). The period of study is for the year March 1985–February 1986, and the results are divided into the annual and seasonal averages. The basic result is that most features depicted in the calculation of meridional energy transports within the atmosphere are physically realistic. Mean motions dominate in the tropics, with contributions by both the Hadley and Ferrel Cells evident. Comparisons between these ERBE/NMC results and published results of similar studies aid the evaluation process. The greatest differences are found in the tropics, where the mean transports derived from NMC analyses are somewhat smaller than expected due to a weak Hadley Cell circulation.

1. Introduction

Detailed satellite measurements from the Earth Radiation Budget Experiment (ERBE, see Barkstrom et al., 1989) have provided both daily and monthly-averaged values of longwave and shortwave radiation fluxes. The use of these values as earth-atmosphere "top-side-truth" has become an important aspect of various diagnostic investigations of atmospheric circulations (e.g., Hartmann et al., 1986 and Ramanathan, 1987). Over the course of a year, the Earth is in an approximate state of radiative balance; the low latitudes receive more energy than the polar regions and, together, atmospheric and oceanic circulations transport excess heat from the tropics to the polar regions. Satellite measurements provide accurate estimates of the net radiation of the Earth-atmosphere-ocean system, and when a sufficiently long period of time is considered, integration of the net radiation provides a measure of the necessary mean meridional transport of energy. In this study, recently processed data from the ERBE experiment provides an incentive to continue the examination of Earth-atmosphere energy transports.

Since the advent of satellite data, it has been possible to assess the total energy transport required for radiative balance, however, the partition of this transport into the atmospheric and oceanic components is difficult to complete. One such partition can be obtained by utilizing the equations of energy conservation in the Earth-atmosphere system. The net energy transport of the Earth-atmosphere system obtained from satellite measurements can be compared to atmospheric energy transports obtained from meteorological analyses, and the residual results in an estimate of the energy transport by the oceans. This method,

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was first described by Oort and Vonder Haar (1976), and later evaluated by Bretherton et al. (1982) for the CAGE experiment. It is referred to in the literature as the satellite/atmosphere method, or the column budget technique, and has been used in a number of investigations for both zonally averaged energy transports (e.g., Carissimo et al., 1985; Masuda, 1988; and Michaud and Derome, 1991) as well as for regional energy budgets (e.g., Alexander and Schubert, 1990).

Estimates of the mean meridional heat transport by the ocean described by the column budget method exceed those obtained using other approaches, such as the surface heat balance (e.g., Hastenrath, 1982). The accuracy of this method for obtaining oceanic energy transports is difficult to determine and has been an issue of much debate. Lorenc and Swinbank (1984) used analyses produced from two different assimilation systems, found differences smaller than 10 W m^{-2}, and were optimistic about the method. In similar studies, Boer (1986) and Holopainen and Fortelius (1986) found larger differences and concluded that the method was not yet accurate enough for oceanographic purposes. The accuracy of the column-budget technique for calculating mean meridional ocean heat transports is clearly dependent on the specific data assimilation method used to produce the atmospheric analyses.

Over the past two decades, a number of studies have used various approaches to provide estimates of atmospheric energy transports. Several studies were completed using radiosonde data. For example, Newell et al. (1974), Oort and Vonder Haar (1976), Oort (1983) and Oort and Peixóto (1983) used long time series of data to study the atmospheric energy budget for zonally averaged conditions. Savijärvi (1988) used an improved 10-year station data set (Oort, 1983) in which the observed mid-latitude divergent wind field was recomputed using dynamical constraints imposed from vorticity balance. Savijärvi (1988) noted that while improved energy statistics were obtained, aerological data sets suffer from a lack of observations over the oceans.

Atmospheric analyses from data assimilations produced in conjunction with numerical weather prediction have also been used in investigations of atmospheric energy transports. In these assimilations, a 6-h forecast is used as a first-guess (or background) and allows the transport of information from data-rich to data-sparse areas. A number of energy budget studies benefitted from the global assimilations produced with data from all or part of the First GARP Global Experiment (FGGE) year. Boer (1986), Holopainen and Fortelius (1986), and Masuda (1988) are each an example of studies in which energy transports were calculated using analyses produced by two different data assimilation systems. In each case, comparisons illustrated that differences in the energy transports were obtained when using different assimilation systems, even though the input data was identical, or nearly so. Recently, Michaud and Derome (1991) completed a study on the mean meridional transport of energy using the European Centre for Medium-range Weather Forecasts (ECMWF) global analyses for the period 1981–86. Their results demonstrated that changes to both the assimilation system and the model parameterizations are clearly reflected in the energy transports, particularly in the tropics.

Until energy transports can be computed with accuracy, interannual variations cannot be examined. Absent from the previously cited energy transport studies has been the use of the NMC global analyses, which provides motivation for this study. It is our intent to further investigate mean meridional atmospheric energy transports calculated using the NMC global analyses, and to compare them with similar calculations published in recent years, particularly those of Michaud and Derome (1991) for the ECMWF global analyses from 1986. Additionally, we feel that the net radiation obtained from the ERBE satellites is of improved quality, and we use the earliest validated ERBE data (March 1985 through February 1986, see Barkstrom et al., 1989) as top-side-truth to examine the latitudinal relationship of the net radiation to the horizontal energy transports on both a seasonal and an annual basis. The ERBE data are used to obtain the net annual meridional energy transports and represent the same period as those derived from the NMC analyses. Using the column budget technique, the residual provides an estimate of the energy transport by ocean circulations. It is our intent to focus on the atmospheric transports and their seasonal variation and not to quantify the accuracy of the column budget technique. Our results provide incentive for an extended study, currently in progress. The energy equations and the data are described in Sections 2 and 3. In

Section 4, results are presented and are compared to those of previously cited studies. Concluding remarks are given in Section 5.

2. Energy transport equations

The energy balance is used to investigate the zonally-averaged meridional transport within the earth-atmosphere system. As given by Oort and Vonder Haar (1976), the total energy in an atmosphere-ocean column can be expressed as:

$$S_A + S_O = -\nabla \cdot (F_A + F_O) + R_{net} \tag{1}$$

where S_A and S_O represent storage within the atmosphere and ocean, respectively, $F_A + F_O$ is the sum of the net horizontal energy flux into and out of the column, and R_{net} is the net radiation at the top of the atmosphere. The focus of this study is limited to mean meridional energy transports and, therefore, we consider a zonally averaged form of (1).

For an annual average, the storage is negligibly small and, by eq. (1), any net flux of energy through the top of a column is balanced by the horizontal flux of energy into or out of that column. The vertically integrated, mean meridional flux by atmospheric motions is:

$$F_A = \frac{1}{g} \int_{p_t}^{p_s} [\overline{(c_p T + Lq + \Phi)\, v}]\, dp, \tag{2}$$

where the total energy is defined as the moist static energy, or the sum of sensible heat ($c_p T$), latent heat (Lq), and potential energy (Φ). The small contribution to the total energy by kinetic energy (Oort and Peixóto, 1983) has been neglected. The overbar represents a time average, the brackets a zonal average, and v is the meridional component of the horizontal wind.

According to Gruber (1970), analyses from wind data do not generally conserve atmospheric mass. Similarly, analyses produced by 4-D data assimilation systems do not satisfy the necessary condition of mass conservation (Masuda, 1988). In the present study, using NMC analyses, erroneous mass transport was found to adversely affect the transport calculations, and here we correct the spurious mass flux at all latitudes by subtracting the mean divergent wind from the horizontal wind at each level.

The atmospheric energy transports are further partitioned by making use of the time mean and its deviation (denoted by an overbar and a prime) as well as a zonal average and its deviation (denoted by brackets and an asterisk). In this manner, the mean meridional transport of any scalar quantity, X, is expressed as:

$$[\overline{Xv}] = [\bar{X}][\bar{v}] + [\bar{X}^* \bar{v}^*] + [\overline{X'v'}] \tag{3}$$

the sum of transports by mean motions, and standing and transient eddies (Newell et al., 1974).

For this study, vertical integrals were calculated up to 100 mb using the trapezoidal rule. Divergences were computed using centered finite differences with a 1–2–1 smoother applied for plotting purposes. Annual results describe the average of the twelve consecutive months (March 1985 through February 1986), and the four seasonal means are averages of March–April–May, June–July–August, September–October–November, and December–January–February.

3. Data

Global analyses used in this study were prepared by the NMC Global Data Assimilation System, which is described by Dey and Morone (1985) and Kanamitsu (1989). In the 4-dimensional assimilation, a 6-h forecast produced by NMC's global model is used as a first-guess (background) field for the analyses. This insures that the analyses in data-sparse regions are dynamically realistic, although they are dependent on the dynamical and physical characteristics of the forecast model. Global initialized analyses for the period were available for each day at 1200 UTC and had a resolution of 2.5° latitude by 2.5° longitude. Analysis parameters include temperature, horizontal wind and geopotential height at 10 mandatory pressure levels (1000–100 mb) and relative humidity at the lowest 6 mandatory pressure levels (1000–300 mb).

A calculation of the time mean fields using only the 1200 UTC analyses could result in a diurnal bias. It is important to note that the analysis system in use during the period of study, March 1985 through February 1986, was different from

NMC's present configuration, although no major changes or implementations occurred during the period of study. Since 1985, changes have occurred within NMC's data assimilation system as well as the medium-range (global) forecast (MRF) model, as shown in Caplan and White (1989). In April of 1985, an 18-layer model with an extensive physics package (MRF85) replaced a 12-layer model (Spectral) with limited physics in that the physics were representative of a daily mean. This Spectral model continued to provide the first guess for the analyses of the MRF85 and since neither the forecast nor the analysis contained a diurnal cycle, we feel that the use of once daily analyses does not have a strong effect on the calculated energy transports. The analyses were subject to an initialization procedure to assure dynamic balance and at this time, the initialization had an adverse effect particularly in the tropics, where the divergent circulations were reduced (White, 1988).

Nearly 5 years of ERBE data starting from November 1984 have been processed and are archived at the National Space Science Data Center (see Barkstrom et al., 1989, for details). In order to produce highly accurate ERBE data, NASA employed a multi-satellite system with a dedicated Earth Radiation Budget Satellite (ERBS) and two sun-synchronous NOAA satellites (NOAA-9 and NOAA-10). With an inclination of 57°, ERBS precessed 4.95° west in the ascending node, such that over the course of approximately one month it sampled all local times in every region. By combining ERBS data with that of either or both NOAA satellites, global coverage is insured and diurnal variations are accounted for.

On board each of the satellites are two types of instruments: scanning radiometers and non-scanning radiometers. The scanning radiometer package consists of three channels, namely the total spectral, the longwave and the shortwave channels. The non-scanner radiometer package has four channels: total spectral and shortwave for both Wide-Field-of-View (WFOV) and Medium-Field-of-View (MFOV). All seven channels were subject to inflight calibration which insures that the accuracy of each is maintained.

For our study period of March 1985 through February 1986, net radiation data are available from the ERBE S-4 products measured by ERBS and NOAA-9. The S-4 data sets were designed to support research on the radiation budget's climatology. Data from the scanning radiometers were employed for this study as the resolution was comparable with that of the meteorological fields. We utilize monthly mean data that are mapped at a 2.5° latitude by 2.5° longitude horizontal resolution. The fluxes and the resulting values of net radiation are averaged to provide seasonal and annual means.

If a period of sufficient length is considered, such that the energy storage can be ignored, the net radiation for the period can be integrated to obtain the net meridional transport. A boundary constraint is imposed such that the net meridional transport is zero at each pole. However, without corrective measures during this integration, systematic errors can accumulate and result in a net meridional transport of energy at a pole. In this study, a value of 6.11 W m^{-2} would be obtained after the integration for the annual mean. In a similar calculation using 5 years of Nimbus-7 data (December 1978 to November 1983), Smith and Smith (1987) used a correction term of 4.3 W m^{-2}. In order to remove this cumulative bias, the global mean net radiation is subtracted from each latitudinal value before the integration.

4. Results

In this section, we describe results obtained for the annual and seasonal energy transports. Where appropriate, we compare our results to those of previous studies. These comparisons can serve to provide a cursory estimate of the errors present in the calculations and help to evaluate the regions for which we are most confident in the energy transports. It should be noted that in all meridionally averaged diagrams, the abscissa is proportional to the sine of the latitude.

4.1. Annual mean meridional transports

Fig. 1 depicts all components of the annual mean northward energy transports computed for this study. The net or total transport derived from ERBE radiation data is symmetric about the equator, with maxima of 5.70 PW and 5.67 PW (where PW = 10^{15} W) at 35° North and South respectively. The computed atmospheric transports are also quite symmetric about the equator, with the tropics as an exception. Maxima in atmospheric transports of 4.3 PW and 3.9 PW

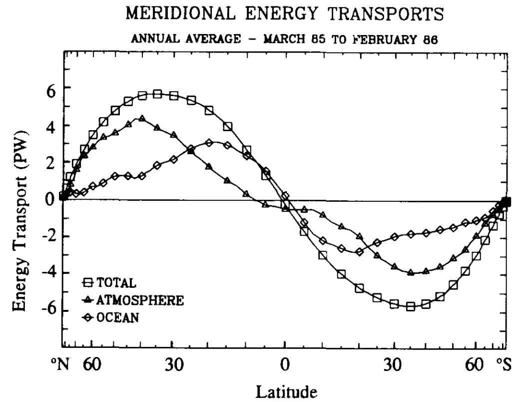

Fig. 1. The annual mean meridional energy transport for the earth-atmosphere, derived from ERBE net radiation (□), the atmospheric component of the meridional energy flux, derived from NMC analyses (△), and the residual, or the oceanic component of the transport (◇) in PW for the period March 1985 through February 1986. Positive values denote northward transport.

occur at 40° N and 37.5° S. The least amount of symmetry is evident in the transport by oceanic circulations, derived as the residual. Maxima transports are located much closer to the equator (3.1 PW at 17.5° N and 2.8 PW at 17.5° S) and transports decrease more rapidly with latitude in the Northern Hemisphere.

The ERBE results of net transport are quite similar to those obtained by Hartmann et al. (1986), who used Nimbus 7 ERB NFOV measurements. Smith and Smith (1987) calculated net transport using five years of Nimbus 7 data and obtained slightly larger peak values of just over 6 PW in the Northern Hemisphere and just less than 6 PW in the Southern Hemisphere. Hartmann et al. (1986), Masuda (1988), and Michaud and Derome (1991) have compared energy transports derived from satellite measurements. They note differences as great as 1.5 PW in the Northern Hemisphere and 0.5 PW in the Southern Hemisphere. Here, we do not show comparisons between our scanner results and those previously published as differences between the ERBE scanner results and the Nimbus 7 NFOV results (Hartmann et al., 1986) are quite small, particularly in the Southern Hemisphere.

The values of total atmospheric transport of moist static energy calculated from the NMC analyses are comparable to those obtained by Michaud and Derome (1991) using ECMWF analyses from 1986, as well as to results obtained using FGGE analyses (e.g., Masuda, 1988), and are nearly 1 PW greater than those of Oort and Peixóto (1986) who used radiosonde data which did not adequately depict atmospheric circulations over oceanic regions. The NMC analyses result in transports that are less symmetric, with a 0.4 PW difference in the hemispheric maxima. The greatest differences are found in the tropics where the NMC analyses result in transports in which the meridional variation is quite small between 5° north and south of the equator. This would imply a rather weak divergence of energy where a more significant amount is expected (to be shown later). Both the 1986 ECMWF results (Michaud and Derome, 1991) and those depicted in Fig. 1 indicate a small southward cross-equatorial transport, which would imply a thermal equator north of 0°.

The total atmospheric transport calculated from the NMC analyses (from Fig. 1) was calculated as the sum of contributions by mean motions, and standing and transient eddies. Eddy circulations dominate in the midlatitudes, with the transient eddies contributing the most to the energy transports. Transports by standing eddies are larger in the Northern Hemisphere than in the Southern Hemisphere due to contributions by the planetary waves, while the converse is true of transient eddies. The transport of moist static energy by mean motions, which is expected to dominate in the tropics, is instead greatest in the mid-latitudes. This is, at least in part, due to the reduction of tropical meridional circulations by the initialization, as well as the limited physics with the Spectral model producing the first guess. In Michaud and Derome (1991), various energy transport results obtained using ECMWF analyses for 1981 are compared to those for 1986. An increase in the transport by mean motions within the tropics with greater divergence (transports vary with latitude) was noted in a comparison of the 1986 results to 1981 results. These comparisons illustrated that the introductions of a diabatic initialization and an improvement to the convective parameterization scheme within the ECMWF model increased the transports in the tropics. The transport within the tropics derived from NMC analyses is between the 1981 and 1986 ECMWF results of Michaud and Derome.

In Fig. 2, the total annual atmospheric transport

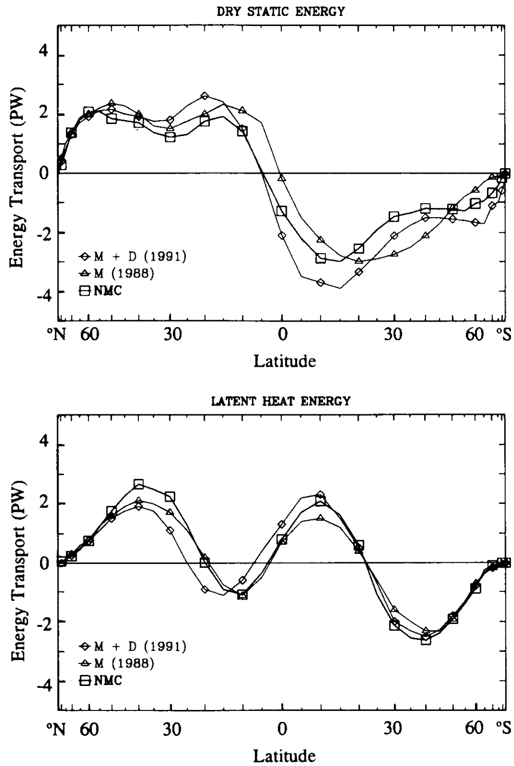

Fig. 2. The annual mean meridional atmospheric transport of dry static energy (upper panel) and latent heat energy (lower panel) derived from NMC analyses for the period March 1985 through February 1986 (□), and similar results (redrawn) from Michaud and Derome (1991) using ECMWF analyses for 1986 (◇) and from Masuda (1988) using ECMWF analyses of FGGE IIIb data (△) in PW. Positive values denote northward transport.

is partitioned into the contributions by dry static energy ($c_p T + \Phi$, upper panel) and by latent heat energy (Lq, lower panel). Results are shown for the NMC analyses (bold lines) and for results from the ECMWF operational analyses (Michaud and Derome, 1991) and from the original ECMWF analyses for the FGGE year (Masuda, 1981). In this figure, as well as others illustrating comparisons, the cited results have been redrawn and plotted at 5° intervals. Thus, the comparison results in figures that are, in most cases, less smooth than the originals.

Results of dry static energy transport for all three studies are comparable in magnitude poleward of 35° N. All curves depict two maxima, with one located near 50° where the transport of sensible heat, particularly by transient eddies, dominates and a second near 15°, where the transport of geopotential energy by mean motions dominates. A large transport aloft of potential energy in the region bounded by 30° North and South is expected, but the NMC analyses result in transports that are smaller than those of the other two studies. Although a difference of nearly 1 PW is apparent, it should be noted that Holopainen and Fortelius (1986) found differences of 2 PW when comparing dry static energy transports derived from two different analyses of FGGE IIIb data for the month of February. In the Southern Hemisphere tropics, NMC transports lie between those of the two comparisons. Throughout the Southern Hemisphere the NMC results and the 1986 ECMWF results exhibit a similar shape, in which the transport remains nearly constant in the midlatitudes. The FGGE analyses result in a transport that decreases steadily with latitude from the maxima at 20° and is similar to that obtained by Savijärvi (1988, not shown) who used 10 years of modified radiosonde data. Trenberth (1984) noted that circulations in the Southern Hemisphere during the FGGE year were different than climatology, which may also contribute to the shape of the profile.

The transport of latent heat is well resolved by all analyses using analyzed data, with a poleward transport in midlatitudes, and an equatorward transport in the tropics forced by the lower branch of the Hadley Cell. Differences are greatest in the tropics but also fairly large in the Northern Hemisphere midlatitudes. Using the radiosonde data, Savijärvi (1988) showed magnitudes of latent heat transports at most latitudes as nearly half of those shown in Fig. 2. It is likely that a lack of radiosonde data over the oceans contributed to the decreased magnitudes.

It will be illustrated in the next section that for both the dry static energy and the latent energy, the differences illustrated in Fig. 2 can be almost completely attributed to differences in the transports by mean motions. Although a Hadley Cell is resolved by the NMC analyses, its strength particularly in the upper-level divergent flow is less than that of the 1986 ECMWF analyses used by Michaud and Derome (1991). Trenberth and Olsen (1988) also documented that during the period of study, March 1985 through February 1986, the NMC Hadley Cell was weaker than the ECMWF Hadley Cell.

The energy flux divergences of both dry static energy and latent energy are depicted in the top panel of Fig. 3. The two curves represent $[Q]$, the vertically integrated and zonally averaged diabatic heating, and $L[E-P]$, the vertically integrated and zonally averaged evaporation minus precipitation. Both profiles are dynamically realistic and are similar to those of Savijärvi (1988), who calculated separate profiles for June–July–August and December–January–February. The curve for $[Q]$ shows maximum heating in the tropics, and a secondary maximum near 40° N. Cooling is evident in the subtropics and polar regions, as well as the Southern Hemisphere mid-latitudes. Within the tropics and subtropics the diabatic heating is nearly offset by the $L[E-P]$ profile. The negative values in the tropics are a result of precipitation in excess of evaporation, with the converse true in the subtropics. The total atmospheric energy flux divergence is shown in the lower panel. This profile is often compared to that of the net radiation, and one would expect positive values in the tropics and subtropics with negative values elsewhere. Here, the effect of the weak meridional variation of the total atmospheric transport is most apparent. The divergence is greater than 25 W m^{-2} for most of the tropics, but it decreases to nearly zero just south of the equator. This is yet another indicator of underestimated tropical circulations within the NMC analyses of this time period.

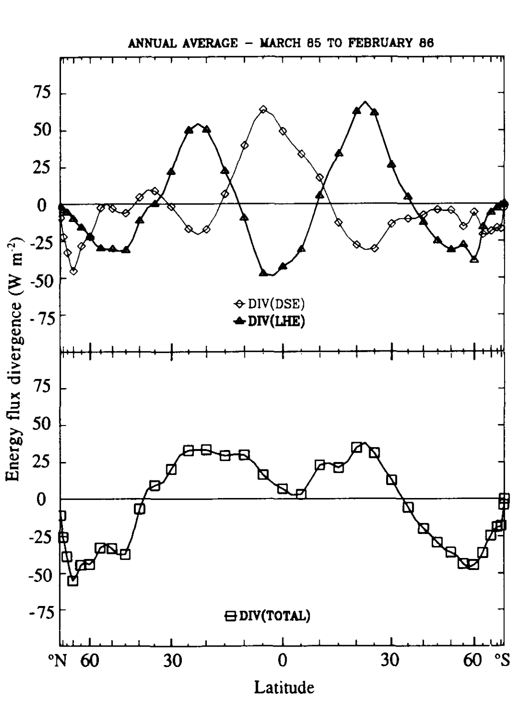

Fig. 3. Upper panel: vertically integrated and zonally averaged divergence of dry static energy flux or $[Q]$ (△), and latent heat energy flux, or $L[E-P]$ (◇); and, lower panel: the total atmospheric flux divergence (□) from NMC analyses for the period March 1985 through February 1986 in W m^{-2}.

Finally, in Fig. 4, we compare the heat transport by the oceans, computed as a residual, to other results obtained using the column-budget method (Michaud and Derome, 1991 and Savijärvi, 1988). Because this profile is a residual, it contains errors from both the total and the atmospheric transport calculations. In addition, for many latitudes the oceanic transport is the small residual of two large terms. Fig. 4 illustrates that the NMC results and those obtained using the ECMWF 1986 analyses (Michaud and Derome, 1991) are similar, except that the ERBE/NMC values are larger north and just south of the equator, where atmospheric transports are small. Both curves show a single Northern Hemisphere maximum near 25° N with a steady decrease in transport poleward and equatorward, such that the transport in the Northern Hemisphere subtropics exceeds that in the

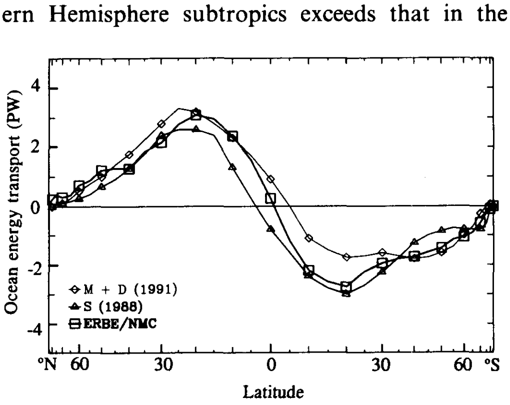

Fig. 4. The annual mean meridional energy transport by the ocean computed as a residual using ERBE data and NMC analyses for the period March 1985 through February 1986 (□), and similar results (redrawn) from Michaud and Derome (1991) using ECMWF analyses for 1986 (◇) and from Savijärvi (1988) using modified GFDL 10-year radiosonde (△) data in PW. Positive values denote northward transport.

Southern Hemisphere. The distribution of the transport is quite different between the three curves in the Southern Hemisphere. The results from Michaud and Derome (1991) depict two maxima, a distribution which has also been indicated by ocean models (Meehl et al., 1982). In the NMC/ERBE results, a second maxima is not present although the transports remain above 1.5 PW to 50° S. The results from Savijärvi (1988) exhibit the greatest values in the Southern Hemisphere tropics with a large decrease such that the values are the smallest by 40° S. The values shown in Fig. 4 are all somewhat less than those obtained by Carissimo et al. (1985) who employed atmospheric transports derived by Oort and Peixóto (1983) using radiosonde data. On the other hand, all curves in Fig. 4 depict transports that are larger than those obtained from the surface energy budget (e.g., Hastenrath, 1982; Hsiung, 1985) or from ocean models (Han, 1984), which had maxima near 2 PW in both hemispheres. In Masuda (1988, Fig. 14), a more complete comparison of the annual mean heat transport by the oceans is presented. Although differences in magnitudes of ocean transports vary, most of the recent studies do agree on the distribution of the ocean transports within the two hemispheres.

4.2. *Seasonal transports*

The mean seasonal total atmospheric transports are shown in Fig. 5. For all seasons, transient

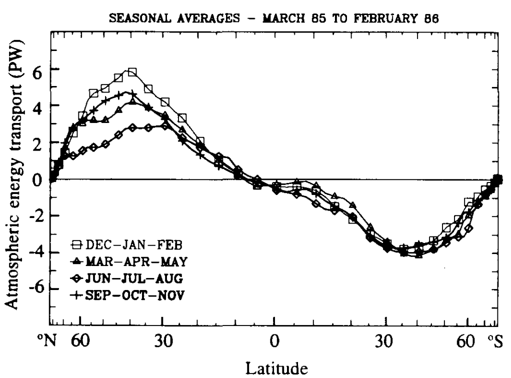

Fig. 5. The mean meridional atmospheric energy transport using NMC analyses for: March through May 1985 (△); June through August 1985 (◇); September through November 1985 (+); and December 1985 through February 1986 (□) in PW. Positive values denote nothward transport.

eddies are the dominant component of the midlatitude poleward transports (not shown). Despite the fact that the maximum transports for the annual results are approximately equal for each hemisphere, the variation within each hemisphere differs considerably. The Northern Hemisphere winter (DJF) has poleward transports which are nearly double those for the Northern Hemisphere summer (JJA) due to a strong contribution by standing waves in Northern Hemisphere winter. Contrast in the Southern Hemisphere is much smaller, but the circulations there may not be adequately sampled. As in the annual case, the transports within the tropics are small and exhibit weak meridional variation. The small southward cross-equatorial transport that was evident in the annual results is present in all seasons.

The seasonal extremes of all components of dry static energy transport and latent heat transport were examined and compared to those for the 1986 ECMWF analyses as computed by Michaud and Derome (1991). For the December–January–February results, the analyses represent the same time period, and differences between the two curves could be an indication of the errors within the ECMWF and NMC analyses. For the June–July–August results, the transports represent two different years (1985 and 1986), and interannual variations may play a rôle in the observed differences.

For the transport of dry static energy, the salient features are dynamically realistic and consistent with those of other studies (as an example see Fig. 2, Michaud and Derome, 1991). For the transport of dry static energy by the total motions, the greatest poleward transport occurs in the winter hemisphere with an extraction of heat from the summer hemisphere. Differences between the NMC results and the ECMWF 1986 results are the largest between 30° N and S. These differences are explained by discrepancies in the transport by mean motions. The NMC analyses produce transports whose magnitude is over 2 PW less than that of the 1986 ECMWF analyses. However, both analyses depict transport by both the Hadley Cells and, to a lesser extent, the Ferrel Cells. Encouraging results are noted in the transport by standing and transient eddies as the profiles are very similar. Both curves show that the transport by the transient eddies, which is dominated by midlatitude cyclones, is largest in the winter hemisphere.

Transport by standing eddies is almost negligible for all locations with the exception of the Northern Hemisphere midlatitudes in winter.

Meridional transports of latent heat energy are illustrated in Fig. 6. In contrast to dry static energy, there is better agreement in the transport by mean motions, but larger differences in the transport by the eddy terms. As latent heat transport is maximized near the surface, the agreement in the mean transport indicates that the differences in mean meridional circulations of the two analyses are the largest aloft. Transient eddies dominate the transport in the midlatitudes, and the contrast in the Southern Hemisphere for the JJA profiles could, as least in part, be a product of interannual variations. Michaud and Derome (1991) found that the interannual variation tend to be largest for transports by stationary eddies, but

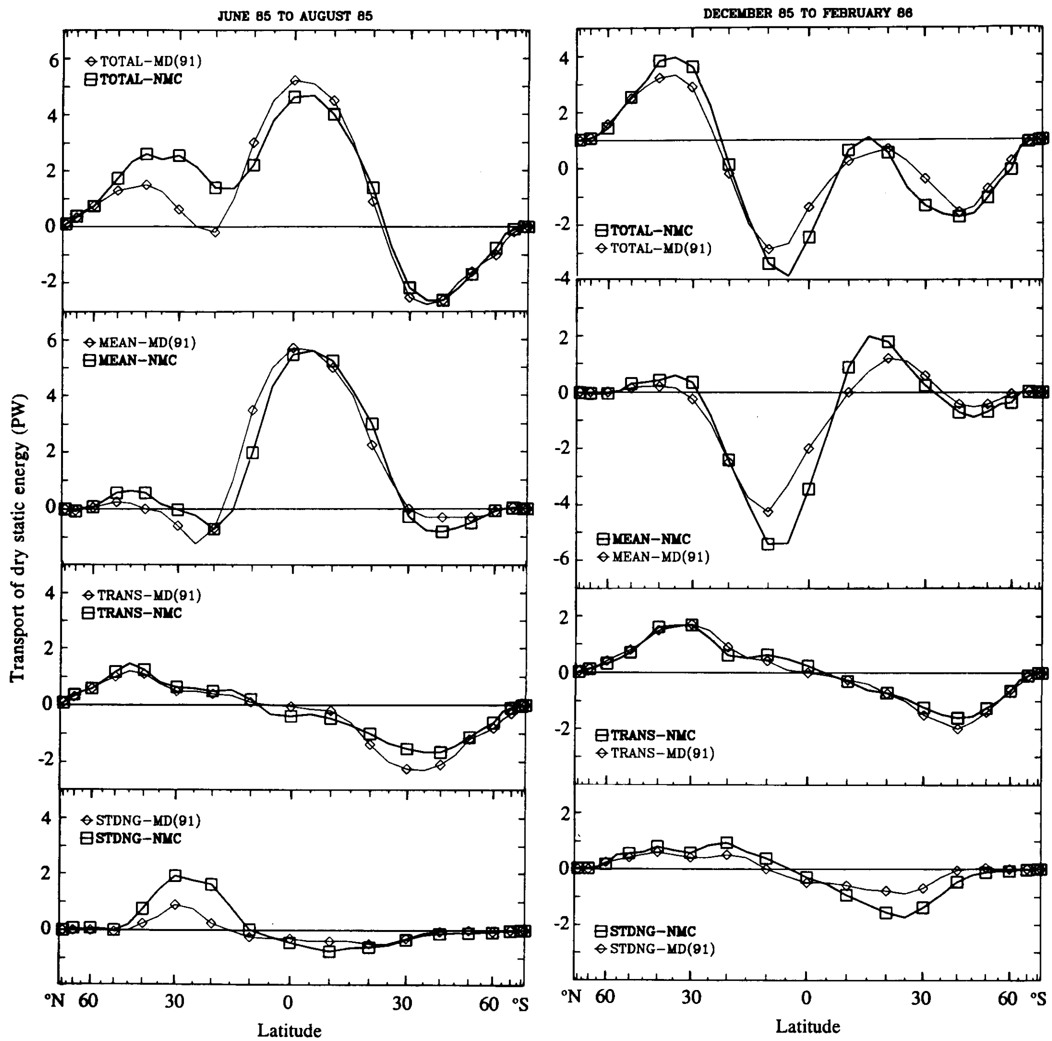

Fig. 6. Meridional transport of latent heat energy by the total flow, mean motions, transient eddies and standing eddies for the period June 1985 through August 1985 (left panel) and December 1985 through February 1986 (right panel) using NMC analyses (□), and similar results (redrawn) from Michaud and Derome (1991) using ECMWF analyses for 1986 (◇) in PW. Positive values denote nothward transport.

it is doubtful that interannual variations could explain the large difference in Northern Hemisphere summer. Masuda (1988) noted a similar difference when comparing transports derived from two independent FGGE analyses and Oort's (1983) results. He noted that a difference in the moisture transport by monsoon circulations was responsible which could be a possible explanation for the differences noted in (his) Fig. 9, but further study would be necessary.

Fig. 7 illustrates the zonally averaged net radiation for the four seasons. The profiles for December–January–February and June–July–August are nearly reversed, such that positive net radiation is located from 15° in the winter hemisphere to 70° in the summer hemisphere. Maximum positive values are somewhat higher in the Southern Hemisphere summer and are just over 100 W m^{-2}. For the winter and summer seasons, the magnitude of the negative radiation values is the largest. The profiles for the remaining two seasons are similarly reversed, the maximum values are decreased, and positive values range from 20° in the fall hemisphere to 50° in the spring hemisphere. For an individual month or season, radiative balance can not be assumed. In addition, storage terms which are negligibly small on an annual basis can not be ignored. Therefore, it becomes difficult to accurately assess the monthly or seasonal total net transport of energy from the ERBE net radiation observations. The atmospheric storage can be calculated, but it is considerably smaller than the oceanic rate of heat storage which is poorly known. Also, in addition to the oceanic heat storage, the heat exchange at the surface would be necessary to estimate the seasonal energy transports by the oceans, which are not addressed by this study.

As a comparison to the seasonal variation of net radiation, the distribution of the zonally averaged source/sink terms are obtained by differentiating the atmospheric transports, as shown in Fig. 8. Larger positive values are expected in the tropics (Savijärvi, 1988) but are not obtained because of the near zero slope of the transport curve. The seasonal variation and the range is much less than that of the net radiation, with the greatest variation found in the Northern Hemisphere mid-latitudes. This suggests that the oceanic energy transports, and the storage terms, are apt to exhibit significant seasonal variations. Recent studies appear to support this suggestion. The annual cycle of the oceanic transport of heat has recently been examined for the Atlantic basin using both oceanographic observations (Molinari et al., 1990) and oceanographic models (Böning et al., 1991). Molinari et al. (1990) calculated the mean annual flux at 26.5°N to be 1.21 ± 0.34 PW which agreed with other estimates of the quantity. The annual cycle, however, was somewhat different. Using a model for the same location, Böning et al. (1991) found a somewhat smaller annual range of the meridional heat transport. It varied from 0.44 PW to 0.80 PW, depending on the mean wind

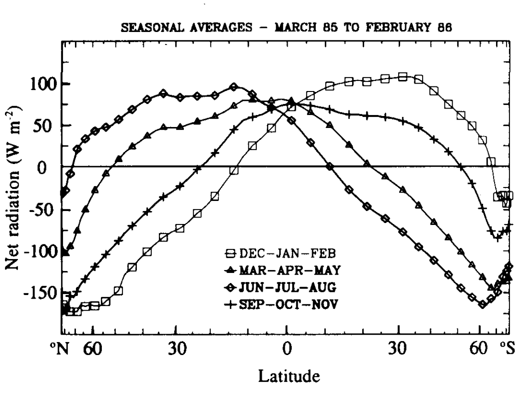

Fig. 7. Net radiation (W m^{-2}) versus latitude from ERBE data for the periods: March through May 1985 (△); June through August 1985 (◇); September through November 1985 (+); and December 1985 through February 1986 (□).

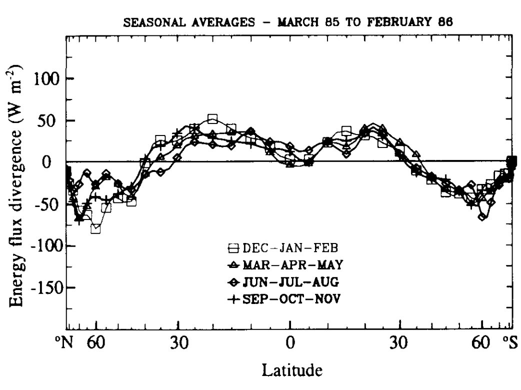

Fig. 8. The vertically integrated and zonally averaged total atmospheric flux divergence (W m^{-2}) for the periods: March through May 1985 (△); June through August 1985 (◇); September through November 1985 (+); and December 1985 through February 1986 (□).

stress employed. It must be emphasized, that these studies were for a limited area and if all ocean basins were considered, the range could be greater. A paucity of data restricts the study of direct oceanic heat flux studies. The oceanic heat storage has also been studied using both observations (Levitus, 1987) and models (Gallimore and Houghton, 1990), and estimates of the annual range of the zonal mean exceed 100 W m^{-2} for both hemispheres.

5. Concluding remarks

This study of meridional energy transports was motivated by the availability of recently processed ERBE scanner data, and an objective to evaluate the NMC global analyses. In this study, the satellite measurements represented the same period as the NMC analyses. Comparisons to published results of similar studies help to evaluate the findings of this study, provide an idea of the errors within the atmospheric analyses, and establish the usefulness of investigations of energy transport.

Most features depicted in the calculation of meridional energy transports within the atmosphere are physically realistic. Mean motions dominate in the tropics, with contributions by both the Hadley and Ferrel Cells evident. Standing and transient eddies dominate the midlatitude transport. Comparisons of the annual average of the mean meridional atmospheric transport reveal a weaker divergent circulation in the tropics of the NMC analyses than what is analyzed by the 1986 ECMWF analyses. The partitioning of the transport into contributions by dry and moist processes, and also the divergence of these contributions, helped to document the weak upper level divergent flow in the tropics. Therefore, it is apparent that a certain degree of error remains in the global analyses, particularly in the tropical circulations where data is sparse. Elsewhere, results are comparable, and it is encouraging to document the agreement in the transports by standing and transient eddies in the midlatitudes.

Transport by oceanic circulations continues to remain to be somewhat uncertain. Disagreements within results obtained by the column-budget method are a product of differences in the atmospheric global analyses. When compared to profiles obtained from oceanographic data or models, the column-budget results are generally 1 PW larger. However, the information on the distribution of energy transport within the oceans obtained by all methods is qualitatively similar. Transports within Northern Hemisphere subtropics are greater than that of the Southern Hemisphere, but the magnitude of the transport remains greater at higher latitudes in the Southern Hemisphere. Although the column-budget method is, most likely, still unable to provide a definitive measure of oceanic transport, we feel that as the accuracy of atmospheric analyses has continued to improve, so has the usefulness of this method.

Seasonal variation of the meridional atmospheric energy transport was shown to be considerably greater in the Northern Hemisphere than in the Southern Hemisphere. Although this is undoubtedly a result of a larger seasonal cycle in Northern Hemisphere circulations, the extent to which the lack of data in the Southern Hemisphere contributes to this result is unknown. An evaluation of the atmospheric seasonal variation to that of the net radiation indicates that both energy transports and heat storage within the oceans may have a considerable variation.

In conclusion, we feel that the knowledge of energy transports can be used successfully in the evaluation and verification of general circulation models, and continuation of this study is ongoing. Michaud and Derome (1991) illustrated that improvements made to both the ECMWF initialization scheme and the model's cumulus parameterization resulted in improvements in the transport of energy within the tropics. Since the period of study of this project (March 1985 through February 1986), a number of improvements have been implemented in NMC's data assimilation system and global forecast model (see Kanamitsu et al., 1991). Trenberth and Olsen (1988) found improved agreement between the Hadley Cells of the NMC and ECMWF analyses after May of 1986, when a physics package was introduced to the NMC analysis cycle. Most recently, a new method of data assimilation, the Statistical Spectral Interpolation (SSI) scheme (Parrish and Derber, 1992) was implemented in May of 1991. We expect that as we continue to examine the energy transports with both the ERBE data and the NMC analyses, improvements within the global analyses will be evident. The reanalysis effort of the Climate Data Assimilation System (Kalnay and Jenne, 1991) should allow the study of interannual variations without the effect of model discontinuities. Finally, NMC's development of a coupled atmosphere-ocean model, in progress, should help to resolve the role of the oceans in the annual transport of energy and its seasonal variation.

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REFERENCES

Alexander, M. A. and Schubert, S. D. 1990. Regional Earth-atmosphere energy balance estimates based on assimilations with a CGM. *J. Climat.* **3**, 15–31.

Barkstrom, B., Harrison, E., Smith, G., Green, R., Kibler, J., Cess, R. and the ERBE Science Team, 1989. Earth Radiation Budget Experiment (ERBE) Archival and April 1985 Results. *Bull. Amer. Meteor. Soc.* **70**, 1254–1262.

Boer, G. J. 1986. A comparison of mass and energy budgets from two FGGE datasets and a GCM. *Mon. Wea. Rev.* **114**, 885–902.

Böning, C. W., Döscher, R. and Budich, R. G. 1991. Seasonal transport variation in the western subtropical North Atlantic: Experiments with an Eddy-resolving model. *J. Phys. Oceanogr.* **21**, 1721–1289.

Bretherton, F. B., Burridge, D. M., Crease, J., Dobson, F. W., Kraus, E. B. and Vonder Haar, T. H. 1982. *The "CAGE" experiment. A feasibility study WCP-22.* WMO Secretariat, Geneva, 95 pp.

Caplan, P. M. and White, G. H. 1989. Performance of the National Meteorological Center's medium-range model. *Wea. Forecasting* **4**, 391–400.

Carissimo, B. C., Oort, A. H. and Vonder Haar, T. H. 1985. Estimating the meridional energy transports in the atmosphere and ocean. *J. Phys. Oceanogr.* **15**, 82–91.

Dey, C. H. and Morone, L. L. 1985. Evolution of the National Meteorological Center Global Data Assimilation System: January 1982–December 1983. *Mon. Wea. Rev.* **113**, 304–318.

Gallimore, R. G. and Houghton, D. D. 1990. Simulation of ocean temperature and heat storage from a GCM coupled to a variable depth upper ocean. *J. Phys. Oceanogr.* **20**, 1312–1332.

Gruber, A. 1970. The energy budget over the Florida Peninsula when a convective regime dominates. *J. Appl. Meteor.* **9**, 401–416.

Han, Y.-J. 1984. A numerical world ocean general circulation model, Part II: A baroclinic experiment. *Dyn. Atmos. Oceans* **8**, 141–172.

Hartmann, D. L., Ramanathan, V., Berroir, A. and Hunt, A. 1986. Earth radiation budget data and climate research. *Rev. Geophys.* **24**, 439–468.

Hastenrath, S. 1982. On meridional heat transports in the world ocean. *J. Phys. Oceanogr.* **12**, 922–927.

Holopainen, E. and Fortelius, C. 1986. Accuracy of estimates of atmospheric large-scale energy flux divergence. *Mon. Wea. Rev.* **114**, 1910–1921.

Hsiung, J. 1985. Estimates of global oceanic meridional heat transport. *J. Phys. Oceanogr.* **12**, 1405–1413.

Kalnay, E. and Jenne, R. 1991. Summary of the NMC/NCAR reanalysis workshop of April 1991. *Bull. Amer. Meteor. Soc.* **72**, 1897–1904.

Kanamitsu, M. 1989. Description of the NMC Global Data Assimilation and Forecast System. *Wea. Forecasting* **4**, 335–342.

Kanamitsu, M., Alpert, J. C., Campana, K. A., Caplan, P. M., Deaven, D. G., Iredell, M., Katz, B., Pan, H.-L., Sela, J. and White, G. H. 1991. Recent changes implemented into the global forecast system at NMC. *Wea. Forecasting* **6**, 425–435.

Levitus, S. 1987. Rate of change of heat storage of the world ocean. *J. Phys. Oceanogr.* **17**, 518–528.

Lorenc, A. C. and Swinbank, R. 1984. On the accuracy of general circulation statistics calculated from FGGE data, a comparison of results from two sets of analyses. *Quart. J. Roy. Met. Soc.* **110**, 915–942.

Masuda, K. 1988. Meridional heat transport by the atmosphere and the ocean. *Tellus* **40A**, 285–302.

Meehl, G. A., Washington, W. M. and Semter, A. J. Jr. 1982. Experiments with a global ocean model driven by observed atmospheric forcing. *J. Phys. Oceanogr.* **12**, 301–312.

Michaud, R. and Derome, J. 1991. On the mean meridional transport of energy in the atmosphere and oceans as derived from six years of ECMWF analysis. *Tellus* **43A**, 1–14.

Molinari, R. L., Johns, E. and Festa, J. F. 1990. The annual cycle of meridional heat flux in the Atlantic Ocean at 26.5° N. *J. Phys. Oceanogr.* **20**, 476–482.

Newell, R. E., Kidson, J. W., Vincent, D. G. and Boer, G. J. 1974. *The general circulation of the tropical atmo-*

sphere and interactions with extratropical latitudes, vol. 2. The MIT Press, Cambridge, Mass., 371 pp.

Oort, A. H. and Vonder Haar, T. H. 1976. On the observed annual cycle in the ocean-atmosphere heat balance over the Northern Hemisphere. *J. Phys. Oceanogr.* **6**, 781–800.

Oort, A. H. 1983. Global atmospheric circulation statistics. *NOAA Prof. Paper no. 14*, U.S. Government Printing Office, Washington, DC, 180 pp and microfiches.

Oort, A. H. and Peixóto, J. P. 1983. Global angular momentum and energy balance requirements from observations. *Advances in geophysics*, vol. 25. Academic Press, 355–489.

Parrish, D. F. and Derber, J. C. 1992. The National Meteorological Center's spectral statistical-interpolation analysis system. *Mon. Wea. Rev.* **120**, 1747–1763.

Ramanathan, V. 1987. The role of earth radiation budget studies in climate and general circulation research. *J. Geophys. Res.* **92**, 4075–4095.

Savijärvi, H. I. 1988. Global energy and moisture budgets for rawindsonde data. *Mon. Wea. Rev.* **116**, 417–430.

Smith, E. A. and Smith, M. R. 1987. Interannual variability of the tropical radiation balance and the role of the extended cloud systems. *J. Atmos. Sci.* **44**, 3210–3234.

Trenberth, K. E. 1984. Interannual variability of the southern hemisphere circulation: Representativeness of the year of the Global Weather Experiment. *Mon. Wea. Rev.* **112**, 108–123.

Trenberth, K. E. and Olson, J. G. 1988. *Intercomparison of NMC and ECMWF global analyses.* NCAR Tech. Note NCAR/TN − 301 + STR.

White, G. H. 1988. Systematic Performance of NMC Medium-range forecasts 1985–88. *Preprint, 8th Conference on Numerical Weather Prediction.* Amer. Meteor. Soc., Baltimore, 466–471.