Covariability of Components of Poleward Atmospheric Energy Transports on Seasonal and Interannual Timescales

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ABSTRACT

Vertically integrated atmospheric energy and heat budgets are presented with a focus on the zonal mean transports and divergences of dry static energy, latent energy, their sum (the moist static energy), and the total (which includes kinetic energy), as well as their partitioning into the within-month transient and quasi-stationary components. The latter includes the long-term mean and interannual variability from 1979 to 2001 and, in the Tropics, corresponds to the large-scale overturning global monsoon and the embedded Hadley and Walker circulations. In the extratropics, it includes the quasi-stationary planetary waves, which are primarily a factor in the Northern Hemisphere winter. In addition to the mean annual cycle, results are presented for the interannual variability. In the extratropics, poleward transports of both latent and dry static energy reinforce one another. However, the results highlight strong cancellations between the transports of latent and dry static energy in the Tropics as moisture is converted into latent heat, and also between quasi-stationary and transient components in the extratropics. Hence the total energy transports and divergences are fairly seamless with latitude and the total interannual variability is substantially less than that of the components. The strong interplay between the transient and quasi-stationary waves in the atmosphere highlights the symbiotic relationship between them, as the stationary waves determine the location and intensity of the storm tracks while the transient disturbances help maintain the stationary waves. These results highlight that observationally there is a very strong constraint that the global energy budget places on atmospheric dynamics.

1. Introduction

For many years, after some semblance of an atmospheric observing system was put in place following the huge growth in aviation after World War II, there was considerable interest in the atmospheric energetics. Comprehensive reviews by Lorenz (1967) and Peixoto and Oort (1992) describe the growth in understanding as observations became sufficiently abundant to provide insights into the processes involving atmospheric energy in various forms, and their transport and conversion of one form to another. At the same time, theoretical developments helped frame the diagnostics by focusing on available energy. The most detailed studies originated from the Planetary Circulations Project under Victor P. Starr and focused on the Northern Hemisphere statistics based on station rawinsonde data. Extensions into the Tropics occurred with the works of Newell et al. (1972, 1974). The great advantage of the station data approach was to stay close to the capabilities of the data, and only at the end stage was there an attempt to map the resulting statistics and compile zonal means. The substantial disadvantages were missing data and the huge gaps between stations over the oceans, limiting the potential applications in the Southern Hemisphere, and the difficulty in dealing with unobserved quantities, notably the field of vertical motion and the divergent wind. Yet the latter are important because they are closely linked to the diabatic processes that force the climate system.

While global operational atmospheric analyses overcame the problems with spatial and temporal gaps, and over time improved the depiction of the vertical motion component, they were impossible to use for climate purposes owing to the huge discontinuities in time as the inevitable improvements were incorporated into the analyses (Trenberth and Olson 1988). Reanalyses of the atmosphere using a constant analysis system have partly addressed this concern, but still leave considerable noise from the continuing changes in the observing system. Nevertheless, considerable progress has been made to the point where it has been possible to reconcile the top-of-the-atmosphere (TOA) satellite measurements of the energy balance, with those in the atmosphere and ocean to within observational uncertainties (Trenberth and Caron 2001). It is therefore appropriate to reex-

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amine aspects of the breakdown of the atmospheric transports into the main components.

Trenberth and Caron (2001) presented results on the atmospheric heat budget based upon National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) and European Centre for Medium-Range Weather Forecasts (ECMWF) reanalyses and found that the estimates of the total poleward atmospheric transports in different studies have increased over time. The total net required transport was computed from the TOA net radiation measured from satellites of the absorbed solar radiation (ASR) and the outgoing longwave radiation (OLR). The atmospheric transports were estimated from the global analyses of observations (Trenberth and Solomon 1994; Trenberth et al. 2001; Trenberth and Caron 2001). Their difference, the inferred ocean transports, are now in quite good agreement with direct estimates from within the ocean. Results were superior for the NCEP–NCAR reanalyses and, in large part, this appears to be because the moisture transports and latent heating implied by the ECMWF 15-yr reanalysis (ERA-15) associated with the hydrological cycle, are too strong (Trenberth et al. 2002a). Trenberth and Caron (2001) find that at 35° latitude the atmospheric transport accounts for 78% of the total in the Northern Hemisphere and 92% in the Southern Hemisphere. The ocean contributes significantly to the poleward heat transport in the Tropics. Generally a much greater portion of the required poleward transport is contributed by the atmosphere versus the ocean than found in previous estimates, and this has consequences for the inferred role of the Gulf Stream in climate (Seager et al. 2002).

Therefore the atmospheric heat budget is analyzed in some detail. Section 2 briefly discusses the datasets used. The physical background and mathematical expressions for the transports and their components are given in section 3. We are interested in the vertically integrated heat budget to simplify at least one dimension of the problem, and in this paper the focus is on the zonal means. The breakdown of the total atmospheric transports and their divergences into the components of the dry static energy, latent energy, kinetic energy, and moist static energy is examined. Their variation over the mean annual cycle is considered, with a focus on the zonal means as well as the partitioning into the within-month transient and quasistationary components. The latter includes the long-term mean and interannual variability and, in the Tropics, corresponds to the large-scale overturning global monsoon and the embedded Hadley and Walker circulations (Trenberth et al. 2000). In the extratropics, it includes the quasi-stationary planetary waves, which are primarily a factor in the Northern Hemisphere winter. The interannual variability and relationships among the various components are also examined. The results are presented in section 4 and discussed in section 5. A companion paper (Trenberth and Stepaniak 2003, this issue) focuses on the degree to which the transports are continuous with latitude in spite of the rather different mechanisms for transport within the atmosphere, especially between the Tropics and midlatitudes. Thus it further examines the spatial structure of the transports and their divergences, how they end up to be so seamless, and the implications for atmospheric dynamics.

2. Methods and data

The overall energy transports derived from the NCEP–NCAR reanalyses (Kalnay et al. 1996) were deemed the best of those available (Trenberth and Caron 2001) because they are most consistent with the overall heat budget based upon TOA and ocean measurements. Hence we use those reanalyses from 1979 to 2001 to examine the components. A description of the data processing and archive is given in Trenberth et al. (2001). The computations were performed in model coordinates at full resolution using 4-times-daily analyses in order to produce vertically integrated quantities. The NCEP system is based on a numerical weather prediction model with T62 spectral resolution and 28 sigma levels in the vertical with five of those levels in the atmospheric boundary layer. At the TOA we use the Earth Radiation Budget Experiment (ERBE) measurements of radiation (Trenberth 1997).

The atmospheric transports vector $\mathbf{F}_A$ is split into rotational and divergent parts, and the focus is on the divergent component of the transports because of its link to the diabatic forcings. The transports and components are also split into those associated with the time mean circulation, given by the overbar, and the transients, given by the prime, so that $h = \overline{h} + h'$ for example. The transients are defined to be the within-month variability and the intermonthly and interannual variability are included in the long-term mean covariability terms.

3. Physical framework

The notation used for the mass weighted vertical integral of M is

$$\tilde{M} = \int_0^\infty \rho M \, dz = \frac{1}{g}\int_0^{p_s} M \, dp. \tag{1}$$

The total mass of atmosphere is p_s/g and that of moisture, as precipitable water, is $w = \tilde{q}$. Energy in the atmosphere is considered in the form of kinetic energy K_E, internal energy I_E, potential energy P_E, and latent energy L_E and the total energy $A_E = P_E + I_E + K_E + L_E$ is conserved in the absence of forcings.

The kinetic energy per unit mass $k = \frac{1}{2}(u^2 + v^2)$ when vertically integrated becomes $K_E = \tilde{k}$. The internal energy $I_E = \widetilde{c_v T}$ combines with potential energy $P_E = \tilde{\Phi}$ to give, after some manipulation,

$$P_E + I_E = \widetilde{c_pT} + \tilde{\Phi}_s = S_H + \Phi_s\frac{p_s}{g}, \qquad (2)$$

where the sensible heat $S_H = \widetilde{c_pT}$ and the latent energy $L_E = \widetilde{Lq}$. Hence the total atmospheric energy $A_E = \widetilde{c_pT} + \tilde{\Phi}_s + \tilde{k} + \widetilde{Lq}$. Note, however, that the dry static energy (DSE) $s = c_pT + gz$ and moist static energy (MSE) $h = s + Lq$, when vertically integrated, give $D_E = \widetilde{c_pT} + \tilde{\Phi}$ and $M_E = D_E + L_E$: M_E and D_E are not components of the total energy, rather their relevance arises when transports are considered.

The kinetic energy and the thermodynamic equations can be combined as

$$\frac{\partial(K_E + P_E + I_E)}{\partial t} = -\nabla\cdot(\mathbf{F}_K + \mathbf{F}_{S_H} + \mathbf{F}_\Phi) + Q_1 - Q_f \qquad (3)$$

or written as

$$\frac{\partial(K_E + S_H + \tilde{\Phi}_s)}{\partial t} = -\nabla\cdot(\mathbf{F}_K + \mathbf{F}_{D_E}) + Q_1 - Q_f. \qquad (4)$$

The moisture equation gives

$$\frac{\partial L_E}{\partial t} = -\nabla\cdot\mathbf{F}_{L_E} - Q_2 \qquad (5)$$

and the total energy

$$\frac{\partial A_E}{\partial t} = -\nabla\cdot\mathbf{F}_A + Q_1 - Q_f - Q_2, \qquad (6)$$

where

$\mathbf{F}_K = \widetilde{\mathbf{v}k}$	kinetic energy flux
$\mathbf{F}_\Phi = \widetilde{\mathbf{v}\Phi}$	geopotential flux
$\mathbf{F}_{S_H} = \widetilde{\mathbf{v}c_pT}$	sensible heat flux
$\mathbf{F}_{L_E} = \widetilde{\mathbf{v}Lq}$	latent energy flux
$\mathbf{F}_{D_E} = \widetilde{\mathbf{v}s} = \mathbf{F}_{S_H} + \mathbf{F}_\Phi$	dry static energy flux
$\mathbf{F}_{M_E} = \widetilde{\mathbf{v}h} = \mathbf{F}_{D_E} + \mathbf{F}_{L_E}$	moist static energy flux
$\mathbf{F}_A = \mathbf{F}_{M_E} + \mathbf{F}_K$	total energy flux
$Q_2 = L(\tilde{P} - \tilde{E})$	column latent heating
$Q_1 - Q_f = R_T - R_s + H_s + \widetilde{LP}$	diabatic atmospheric heating
$= R_T + F_s + Q_2,$	

and Q_f is the frictional heating; R_T and R_s are the net downward radiation at the TOA and the surface, respectively; H_s is the sensible heat flux at the surface; and $F_s = LE_s + H_s - R_s$ is the net upward flux at the surface. Note that Q_1, which comes from the thermodynamic equation, includes the frictional heating Q_f and hence $Q_1 - Q_f$ is the diabatic heating from radiation and latent and sensible heating.

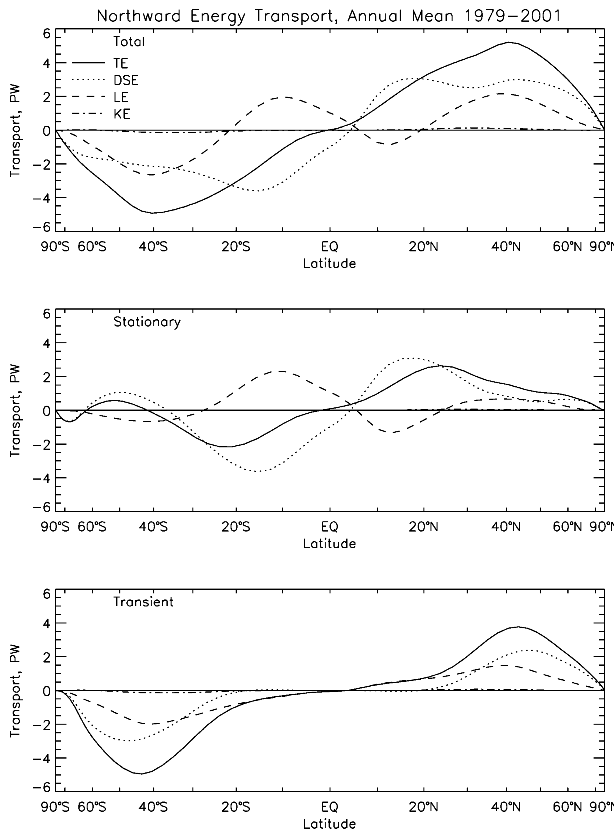

FIG. 1. Annual and zonal mean for 1979–2001 northward energy transport for the (top) total atmospheric energy, (middle) quasi-stationary component, and (bottom) transient component, showing the total, dry static, and latent and kinetic energy components; in PW. The coordinate is latitude (ϕ) plotted as $\sin\phi$ so that values properly depict the area.

As shown in Trenberth et al. (2002a), the kinetic energy component is small, although not negligible. Consequently the atmospheric energy transports predominantly correspond to the moist static energy transports. The difference between the total energy and the quantity transported arises from the pressure work term in the thermodynamic equation and the conversion of kinetic to internal energy.

4. Results for the zonal mean energy budget

a. Time means

Figure 1 presents the northward energy transport annual mean from 1979 to 2001 as the total energy (TE) and breakdown into the contributions from transients (within month) and the quasi-stationary component (which includes the long-term mean). The latter includes the contributions from the mean overturning, and the Hadley cell and monsoonal contributions are dominant

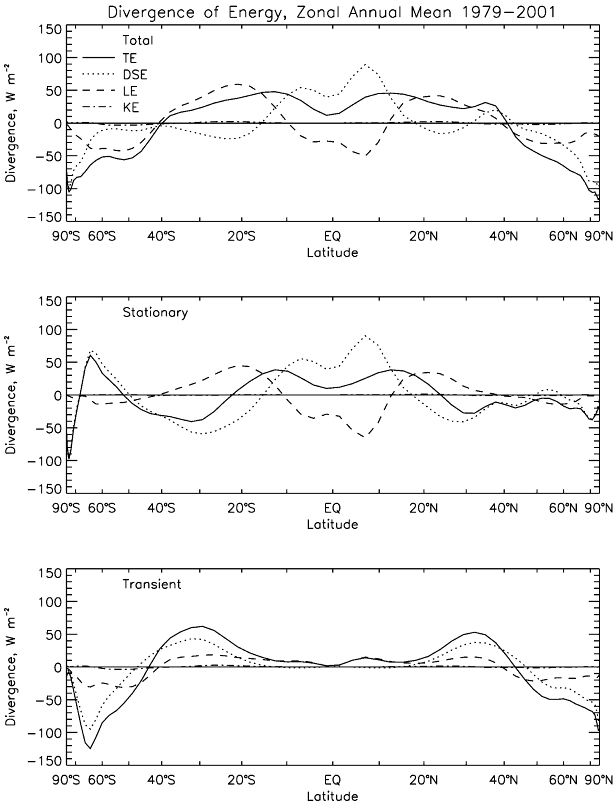

FIG. 2. Divergence of the annual mean for 1979–2001 northward energy transport zonally integrated for the (top) total atmospheric energy, (middle) quasi-stationary component, and (bottom) transient component, with the curves showing the total, dry static, and latent and kinetic energy components. Values are in W m^{-2}.

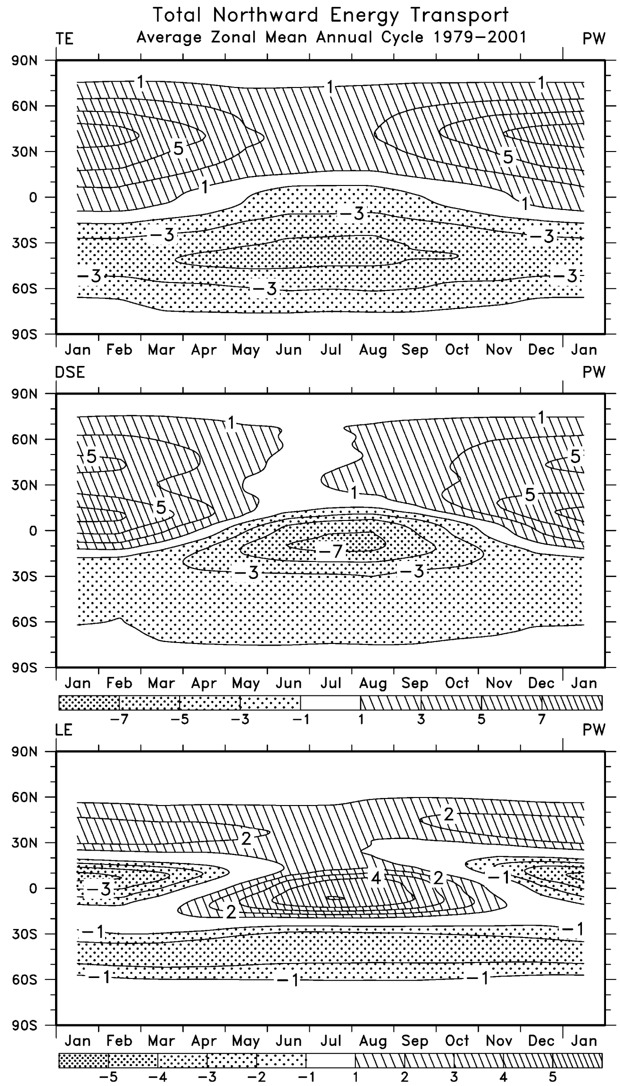

FIG. 3. Total zonal mean northward energy transport for 1979–2001 for the mean annual cycle, in PW. Shown are the atmospheric energy transports for the (top) TE, (middle) DSE, and (bottom) LE, with shadings given in the keys. The contour interval is 1 PW in the bottom panel but 2 PW in the top two panels.

in the Tropics. Note how smoothly the TE transport varies, somewhat like a sine curve from pole to pole, but this is not the case for the breakdown into the contributions from the DSE and the latent energy (LE). In the Tropics, the crossover between the characteristic DSE and LE transports in each hemisphere occurs at about 7°N, the time mean location of the intertropical convergence zone (ITCZ), although the TE transport crosses zero slightly south of the equator. Low-level moisture transports in the Hadley circulation toward the ITCZ give rise to the LE transports in the opposite direction to those of both the TE and the DSE. In the extratropics, the contributions from the transient energy transports dominate in both hemispheres, with LE predominant in the subtropics to about 35° latitude but with the DSE dominant at high latitudes. As KE contributions are tiny for the northward transports, the total energy transported meridionally is closely aligned with that of the MSE.

The zonal mean divergences of the atmospheric transports can be presented as either zonal integrals or zonal means. The latter are given in watts per square meter and are of interest for comparing regions, but profiles as a function of latitude can be misleading because of the need to account for the convergence of meridians and hence smaller areas as the poles are approached. Rather than plotting integrals, a sinϕ coordinate is chosen to better reflect the areas involved so that areas under the curves can be compared visually.

The divergence of the atmospheric transports also varies remarkably smoothly with latitude (Fig. 2). The total can be characterized as looking roughly like a cosine curve, but with a distinct minimum near the equator amid otherwise positive values from 40°N to 40°S and negative values that reach maxima poleward of 80° latitude in each hemisphere (but the zonal integrals tend to zero as the meridians converge on the pole). The equatorial minimum is associated with the cold tongue in sea surface temperatures (SSTs), especially in the

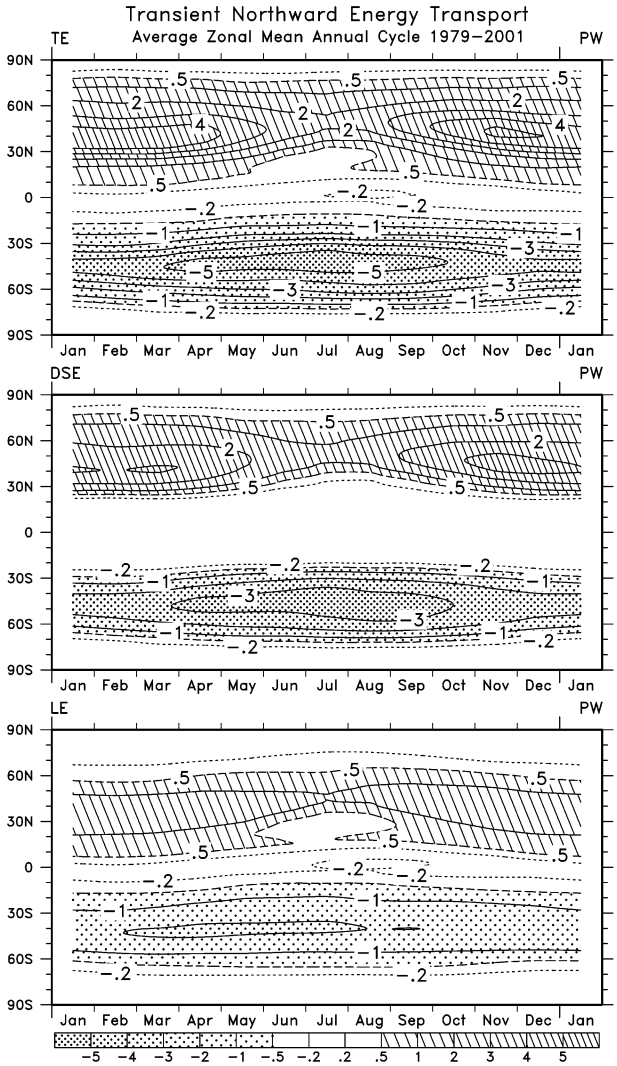

FIG. 4. Zonal mean northward energy transport by the transient eddies for 1979–2001 for the mean annual cycle, in PW. Shown are the atmospheric energy transports for the (top) TE, (middle) DSE, and (bottom) LE, with shadings given in the key. The contour interval varies but the same key applies to each panel.

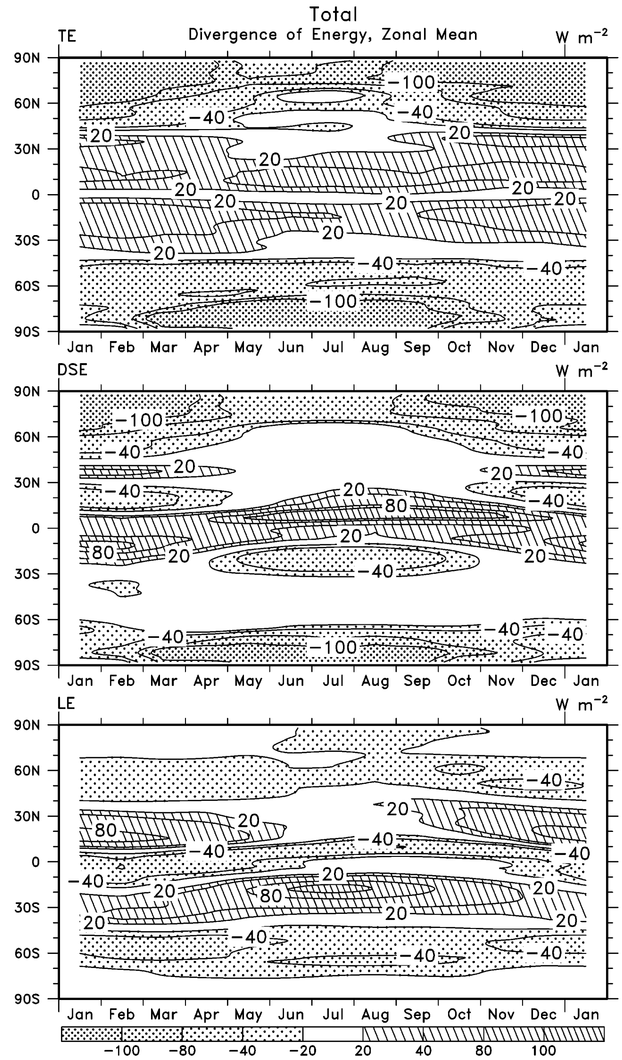

FIG. 5. Total divergence of zonal mean northward energy transport for 1979–2001 for the mean annual cycle, in W m^{-2}. Shown are the (top) TE, (middle) DSE, and (bottom) LE, with shadings given in the key. The contour interval is in the key.

Pacific (see Trenberth and Stepaniak 2003). In the Tropics, the relatively uniform total divergences are made up of strongly positive values of DSE and negative LE equatorward of 10° latitude, but negative DSE mostly poleward of 15° latitude. These features are evident in the quasi-stationary component (Fig. 2) where it is seen that the DSE divergence is negative from about 15° to 50° latitude in both hemispheres while the LE component is positive. In marked contrast the DSE and LE transient contributions are of similar sign except with the LE displaced somewhat equatorward, as is expected in storm tracks (Trenberth 1991). It is noteworthy that the zone where the quasi-stationary component of the DSE is negative is also where the transient component is positive, enabling the total energy to appear so featureless and produce relatively seamless poleward transports.

A new, but perhaps partly fallacious, result in this breakdown is the substantial quasi-stationary component in the Southern Hemisphere, which is not fully reproducible in the ERA-15 reanalyses. Previous analyses (e.g., van Loon 1979) have often used geostrophic flow to estimate transports in the Southern Hemisphere and therefore would not capture ageostrophic influences. In both reanalyses, there is a distinctive katabatic drainage of cold air from Antarctica at low tropospheric levels, leading to a direct circulation in the low troposphere and a poleward heat transport south of 62°S. A consequence is that the cold air spreads out over the Southern Ocean between the coast (near 70°S) and 50°S and results in very large surface fluxes of heat into the atmosphere immediately off the coast (Fig. 2) that exceed

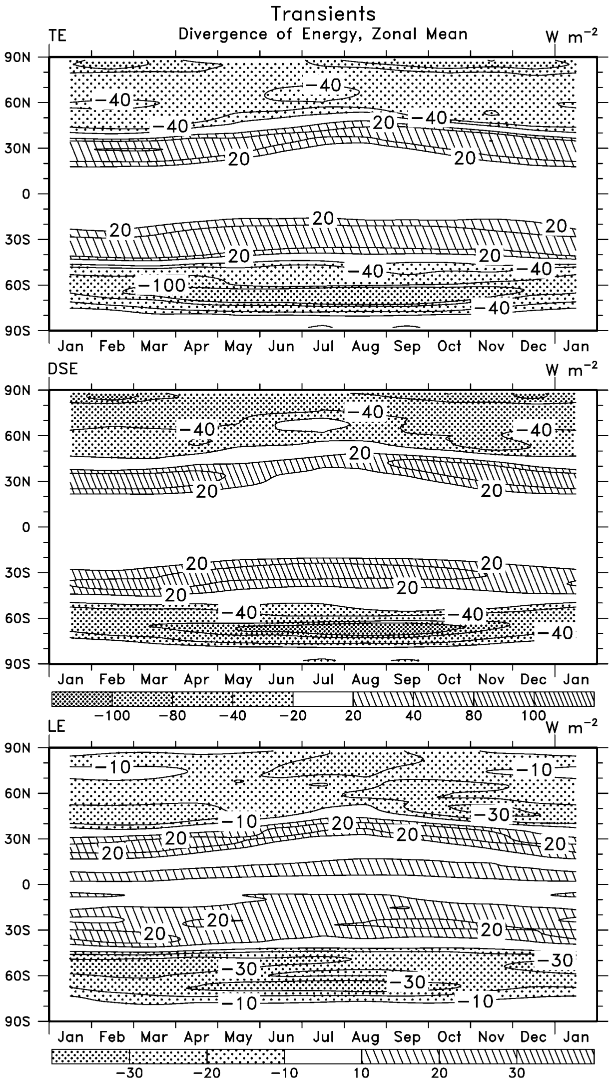

FIG. 6. Divergence of zonal mean northward energy transport by the transient eddies for 1979–2001 for the mean annual cycle, in W m^{-2}. Shown are the (top) TE, (middle) DSE, and (bottom) LE, with shadings given in the keys. The contour interval is 20 W m^{-2} in the top two panels and 10 W m^{-2} in the bottom panel.

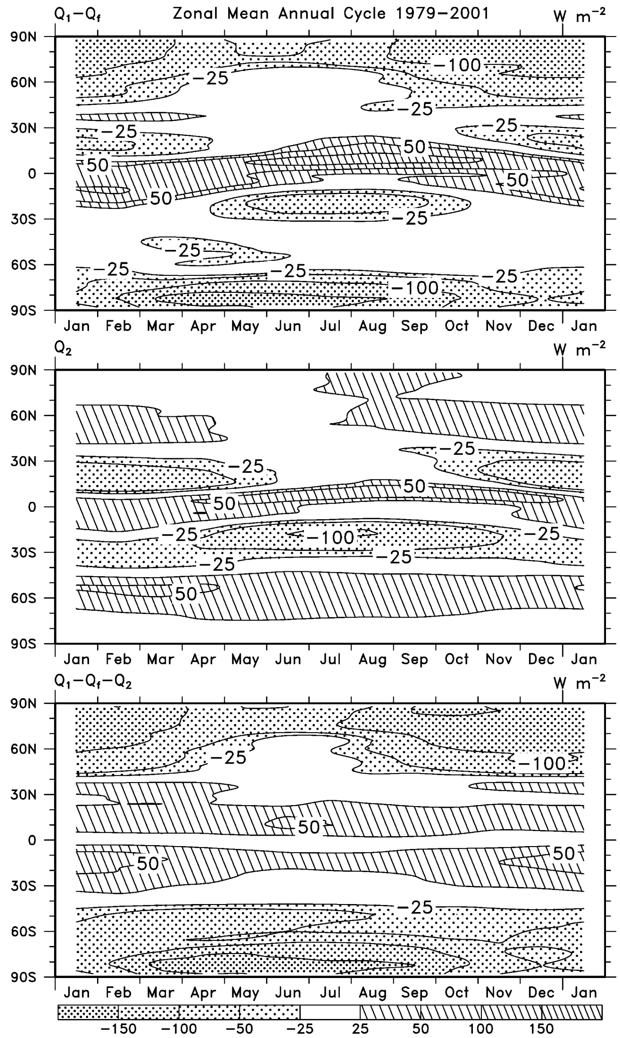

FIG. 7. Zonal mean heating components for 1979–2001 for the mean annual cycle, in W m^{-2}. Shown are the (top) diabatic heating $Q_1 - Q_f$, (middle) column latent heating Q_2, and (bottom) total column atmospheric heating $Q_1 - Q_f - Q_2$, with shadings given in the key. The contour interval varies but the same key applies to each panel.

100 W m^{-2} in places. The large heat flux into the atmosphere helps drive an equatorward quasi-stationary transport of energy between about 60° and 40°S (Fig. 1). Such a pattern appears to be somewhat enhanced by the way ice cover was treated in the reanalyses and the T62 resolution, which places the coastal stations around Antarctica as high as several hundred meters above their correct location. A comparison of surface temperatures with those at coastal stations reveals much colder values in winter in the NCEP–NCAR reanalyses by >10°C at some stations (F. Bryan 2002, personal communication). The Southern Ocean winds are about 1 m s^{-1} more equatorward in the NCEP–NCAR versus ERA-15 reanalyses and the coastal katabatic drainage, although present in both, extends much farther offshore in the NCEP–NCAR reanalyses.

The mean annual cycle of the northward energy transports is given for the TE and its DSE and LE components (Fig. 3) and the corresponding transients (Fig. 4). The much greater seasonality in the Northern Hemisphere is well known. The TE transport of over 7 PW in winter months, with ~5 PW from DSE and ~2 PW from LE, drops to about 2 PW in summer. Seasonal variations in the extratropics of the Southern Hemisphere are much less. However, the large seasonal variations in both DSE and LE (of opposite sign) in the Tropics associated with the monsoons are readily apparent. Seasonal variations in the transient component are not as pronounced in the Northern Hemisphere, although the maximum in November–December (Trenberth 1991; Chang et al. 2002), rather than midwinter, is apparent. Note the penetration of the transient poleward heat transports to regions equatorward of 20°N and 15°S. This is important in the dynamics of the Hadley circulation, as described in Trenberth and Stepaniak (2003).

The corresponding zonal mean divergences of the energy transports are given in Figs. 5 and 6. The divergence of the DSE by the quasi-stationary component reveals the monsoonal migration of the precipitation and latent heating, given by positive values of DSE, in the deep Tropics from south of the equator from December through March to north of the equator the rest of the year. The signature is seen in the quasi-stationary LE by convergence in the same locations. Although the oceanic ITCZ remains in the Northern Hemisphere year round, the development of the monsoons over the Amazon, Africa, and northern Australia dominate the zonal mean. Meanwhile the main convergence of DSE and divergence of LE occurs in the subtropics of the winter hemisphere (Trenberth et al. 2000). A unique feature in the Northern Hemisphere winter from December through March is the region of divergence of DSE near 40°N, which is associated with the quasi-stationary waves that are much weaker and more barotropic in the Southern Hemisphere. Note how the strong seasonality in the DSE and LE components is greatly reduced for the TE (top panel, Fig. 5), demonstrating the cancellation and inverse covariability. The seasonality of the divergence of transient DSE transports (Fig. 6) is greater in the Northern Hemisphere and is accompanied by divergence of LE at slightly lower latitudes in both hemispheres, as is typical of storm tracks (Trenberth 1991), because moisture is concentrated in warmer climes.

The mean annual cycle of various heating terms, computed as residuals, is given in Fig. 7. The diabatic heating in the atmosphere $Q_1 - Q_f$ mean annual cycle reveals the seasonal migration of the monsoonal heating, which exceeds 100 W m^{-2}, and the poleward cooling in the winter hemisphere of $>$50 W m^{-2} balanced by subsidence warming in the downward branch of the Hadley circulation. This zone is quite distinctive and separate from the more general cooling region poleward of 45° latitude in each hemisphere. In the Tropics and subtropics, the middle panel showing Q_2 reveals that latent heating due to precipitation accounts for a major part of the diabatic heating. Recall that this quantity is proportional to $P - E$ and hence the surface evaporation is subtracted from the precipitation-induced diabatic heating. Moreover, the excess of evaporation over precipitation in the winter hemisphere subtropics largely matches the zones of the diabatic cooling, suggesting the link between strong solar heating of the surface with radiative cooling in the atmosphere where the skies are clear in the subsiding branch of the Hadley circulation. The bottom panel gives the net column heating in which the surface latent heat flux is included, and is the relevant quantity that drives the atmospheric energy transports. Values are quite modest in the Tropics although they consistently exceed 25 W m^{-2} from about 5° to 35° latitude, while remaining negative at high latitudes year round.

For a few months we have recomputed the energy transports after separating the velocity into rotational and divergent components (not shown). In all cases, the transport is dominated by the rotational component. The divergent wind transport is largest in the vicinity of high topography (Himalayas, Rockies, Andes, Antarctica, and Greenland) in both quasi-stationary and transient transports, but with very strong cancellation.

b. Variability

The time series of zonal mean anomalies, as departures from the 1979–2001 means, for divergences of DSE, LE, and the TE are given in Fig. 8, while Fig. 9 presents the quasi-stationary and transient contributions to TE. These reveal several points of considerable interest: 1) The divergence of latent energy variations is mainly confined to lower latitudes, 2) in the tropical regions the LE and DSE features tend to be similar but opposite in sign so that the TE divergence has much smaller variations, 3) the quasi-stationary and transient components are both substantial outside of the Tropics, and 4) there is also strong cancellation between the quasi-stationary and transient components so that their sum, TE divergence, has much smaller variations—about half the standard deviations of the quasi-stationary and transient components. Therefore, before discussing these further, we present the annual and zonal mean standard deviations of the various energy components in Figs. 10 and 11, and cross-correlation matrices of several of these variables in Fig. 12.

Figure 10, which shows the annual cycle of standard deviations of northward energy transports for the TE, DSE, and LE in the left panels, illustrates that the LE and DSE components can vary by 0.6 PW in the Tropics, but the TE varies by roughly half of this, ~0.3 PW. The LE is not much of a factor poleward of 40° latitude, however. Transient components (Fig. 10, right panels) follow a rather different pattern. The TE variations are larger than either component, showing that they tend to reinforce each other, although with the transient LE mainly important from 15° to 50° latitude. The quasi-stationary component standard deviation (not shown) can be inferred as the difference in variance between the two figures. Hence the quasi-stationary component variance dominates the Tropics. In the Northern Hemisphere extratropics in winter, the transient variance is greater than the total, and hence the quasi-stationary component must cancel part of it.

Figure 11 shows the standard deviation of the divergence of the energy transports from the same variables and reinforces the comments just made. Divergences exceeding 90 W m^{-2} in the northern regions from October to March by transient eddies are reduced to barely

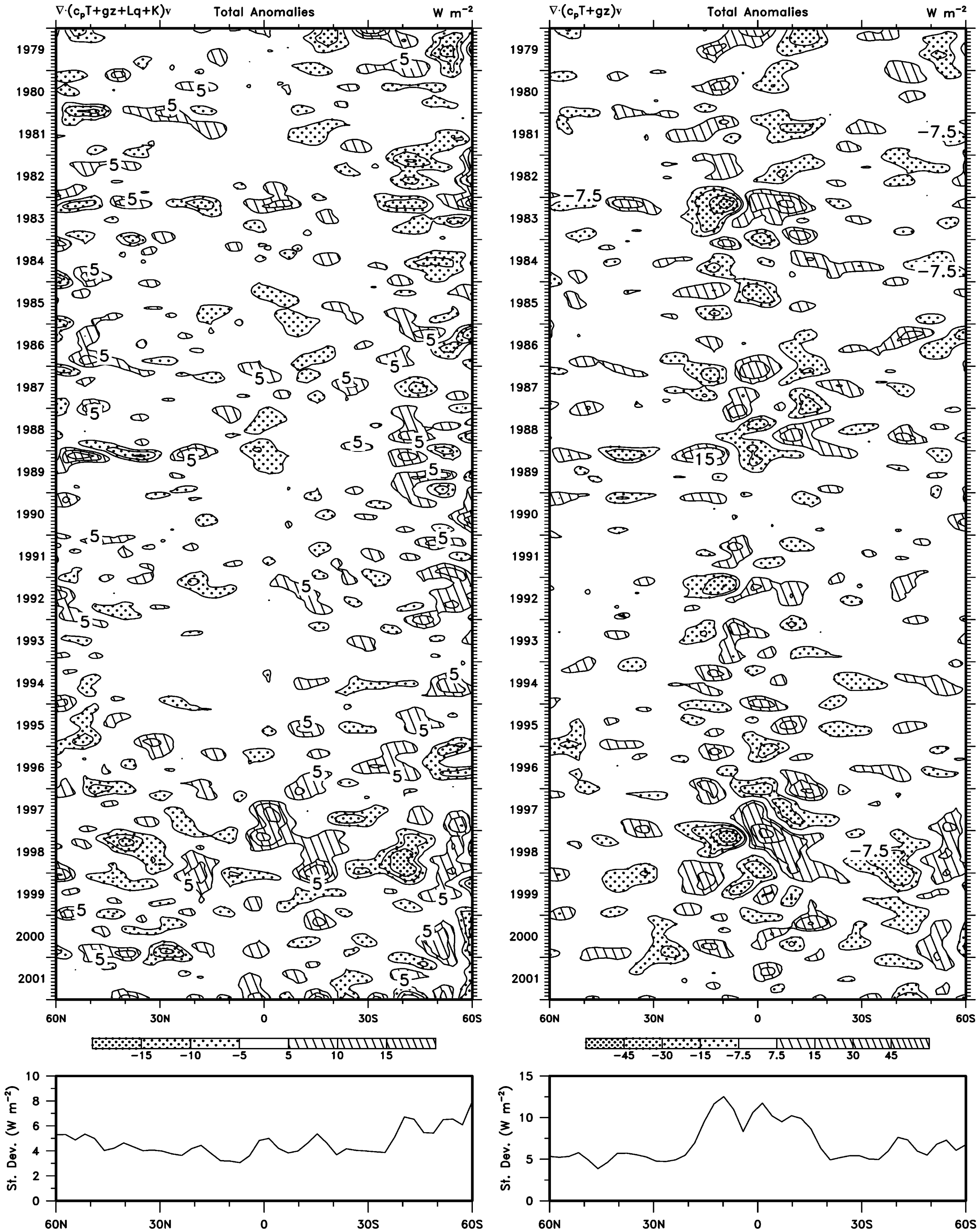

FIG. 8. Time series of zonal mean divergence of northward transport of (left) TE, and (middle) DSE and (right) LE. The time series have been smoothed with a 1/12(1–3–4–3–1) filter that removes less than 3-month fluctuations. Units are W m^{-2} and shading as in the key.

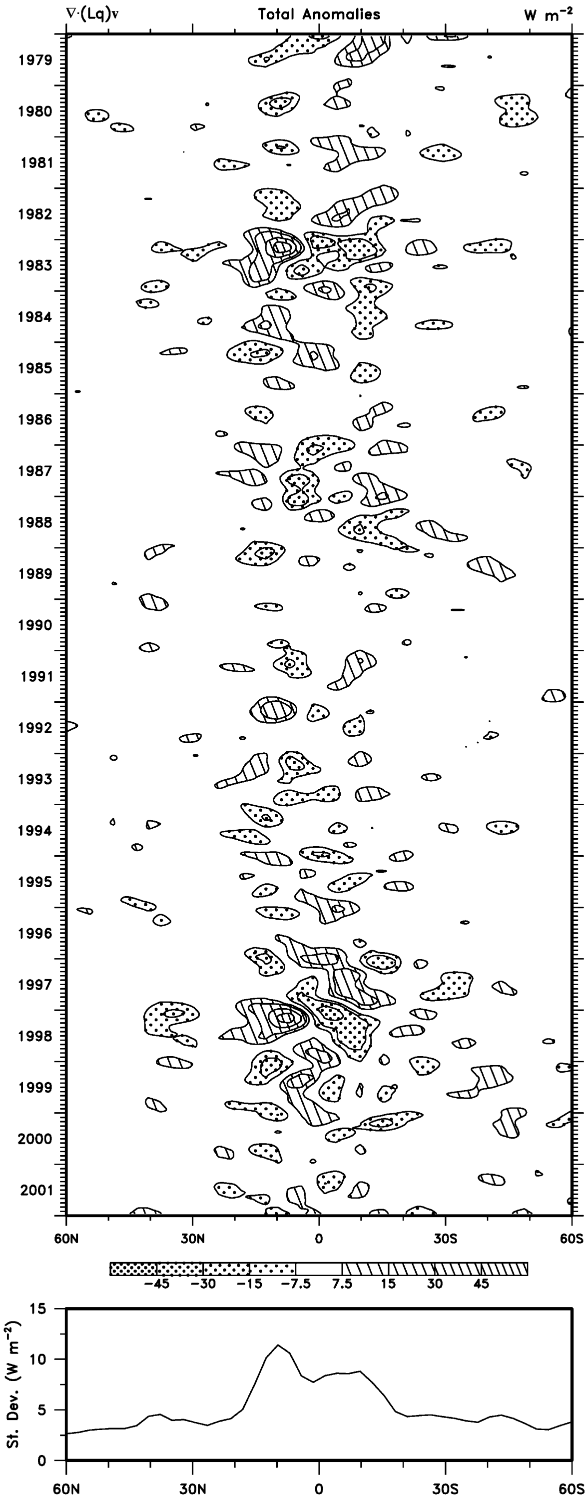

FIG. 8. (*Continued*)

60 W m^{-2} or less in the total. Even in the summer months, standard deviations of the TE divergences are almost half those of the transients. Cancellation is also evident in midlatitudes of the Southern Hemisphere.

Although all months are combined, the pattern is quite clear from the correlation matrices of the departures from the mean annual cycle (Fig. 12). A seasonal breakdown of Fig. 12 (not shown) reveals much the same relationships year round; the variances are the main parameters that vary with time of year (Figs. 10, 11), not the covariability. The DSE quasi-stationary component, when correlated with itself, shows a highly significant negative correlation with values about 20° to the north and south. Hence strong poleward DSE transports in one zone are accompanied by weak transports 20° farther north and south. Moreover, outside of the Tropics, strong quasi-stationary wave transports of DSE correspond to weak (less than normal) poleward transports of DSE by transient eddies. Correlations at the same latitude are about −0.5 in the Southern Hemisphere and exceed −0.6 in the Northern Hemisphere. The quasi-stationary components of DSE and LE are significantly negatively correlated (<-0.6) throughout the Tropics and extend into the Southern Hemisphere to 65°S with strongest negative correlations at 15°N (−0.8). However, for the quasi-stationary LE and DSE, the strongest negative correlations deviate slightly from the diagonal, for example the DSE at 35°N with LE at 25°N and DSE at 65°S with LE at 60°S. Positive correlations of the transient components with each other are evident in the extratropics of both hemispheres between the DSE and LE components, although with the LE component shifted equatorward by perhaps 5° latitude.

These figures provide quantitative evidence of the strong cancellation between LE and DSE transports in the Tropics, and also between quasi-stationary and transient transports of DSE in the extratropics seen in Figs. 8 and 9. Therefore, returning to Figs. 8 and 9, the main features that stand out are the El Niño–Southern Oscillation (ENSO) variations. Strong persistent anomalies occur in the Tropics in 1982–83, late 1986–early 1988, and 1997–98, and anomalies of opposite sign in 1988–89 exceed 20 W m^{-2} in the DSE. Divergence of DSE near or just north of the equator derives its source from increased latent heating in precipitation, as seen in the convergence of LE. Although all ENSO events are different, intense anomalies of one sign are always balanced by anomalies of the opposite sign nearby within the Tropics, characteristic of a shift in climatological features such as the ITCZ and South Pacific convergence zone (SPCZ), as is known to happen with El Niño events (e.g., Trenberth et al. 1998). The ENSO events are therefore more easily seen in the time series of LE divergence. Signatures of moderate events such as those in 1993 can also be seen. The divergence of DSE also features anomalies of perhaps half the magnitude in the extratropics that are not well linked to LE anomalies and have the same rather than opposite sign. However, they are not as persistent in time and occur mainly in winter (Figs. 10, 11).

Similar time series and statistics for the Pacific basin (not shown), where El Niño has its origin, reveal that

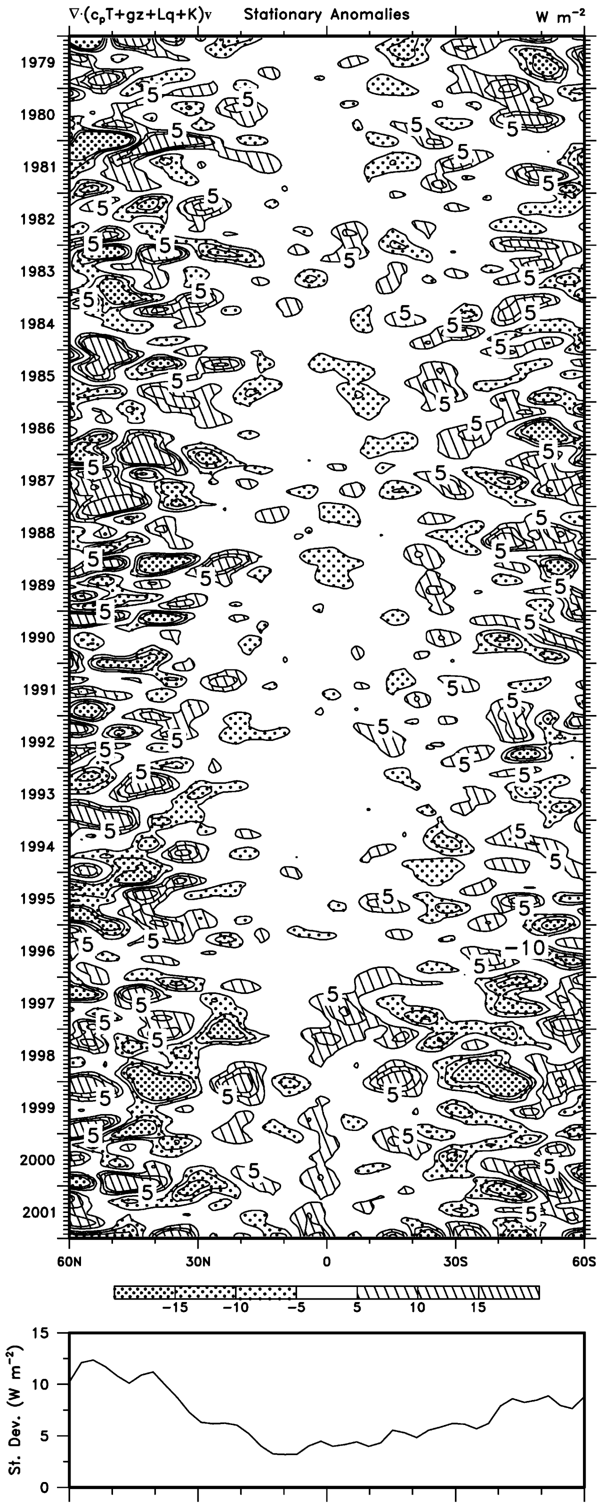

FIG. 9. Time series of zonal mean divergence of northward transport of TE for the (left) quasi-stationary and (right) transient components. The time series have been smoothed with a 1/12(1–3–4–3–1) filter that removes less than 3-month fluctuations. Units are W m^{-2} and shading as in the key.

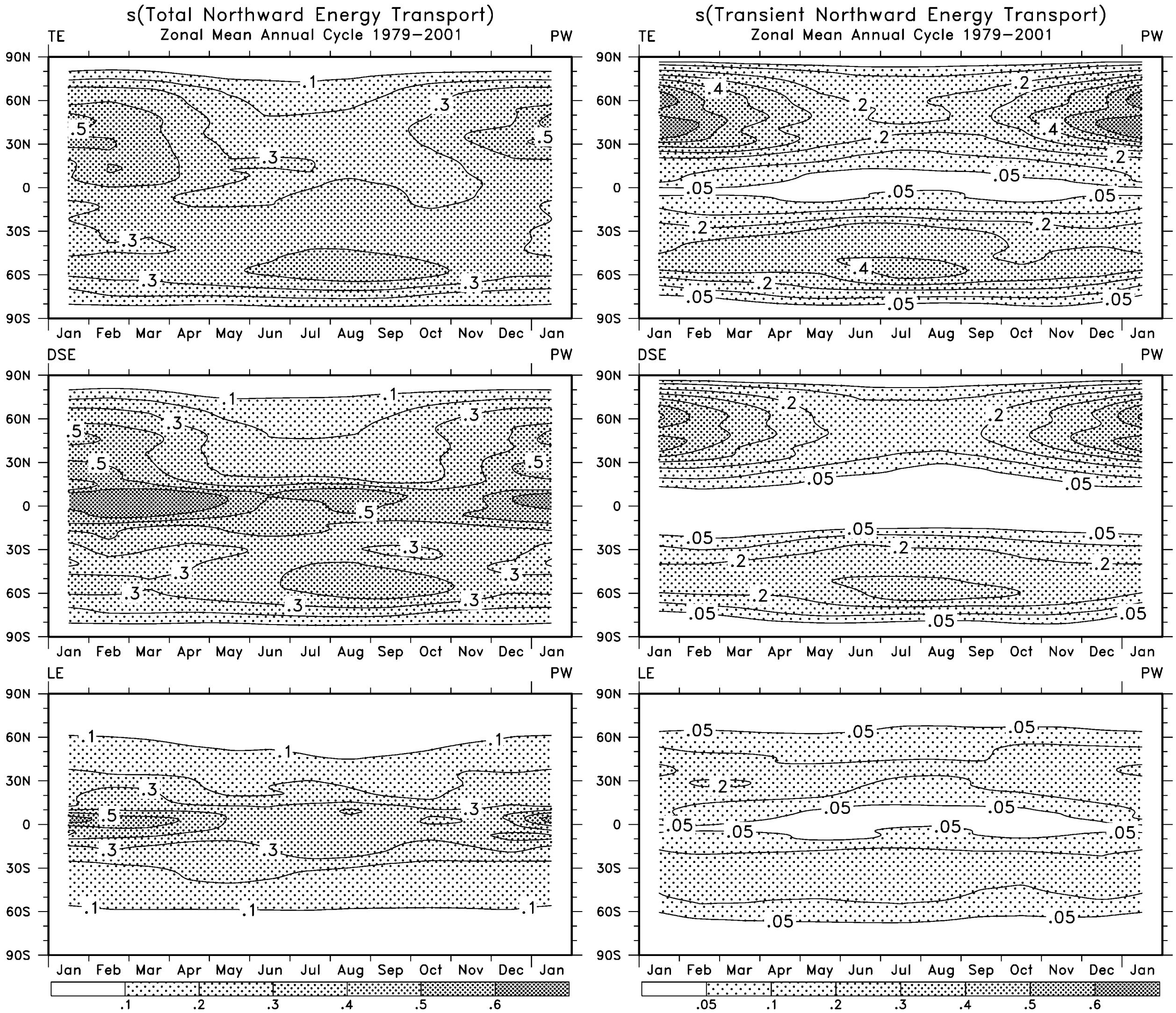

FIG. 10. Standard deviations of total zonal mean northward energy transport for 1979–2001 for the mean annual cycle from Fig. 3, for (top) TE, (middle) DSE, and (bottom) LE, for the total (left) and transients (right), with shadings given in the key. The contour interval is 0.1 PW with 0.05 PW in some panels.

ENSO events have typically double the magnitude of the zonal mean for the 150°-longitude-wide Pacific basin with anomalies in energy divergence exceeding 75 W m^{-2} for the 1982–83 and 1997–98 events, as analyzed in detail by Trenberth et al. (2002b). Hence the rest of the hemisphere is not contributing substantively to these anomalies.

5. Discussion

The presentation above has focused on the zonal means, and the spatial structures add important details but are dealt with in the companion paper (Trenberth and Stepaniak 2003). In the Southern Hemisphere, the stronger zonal symmetry allows the storm track transient statistics to emerge from the zonal mean statistics, along with their relationship to the quasi-stationary component. However, in the Northern Hemisphere, the storm tracks are distinctive only over the Pacific and Atlantic. Nevertheless, many regional relationships are also evident in the zonal means and are therefore important for the atmospheric general circulation and its variability. Several robust and highly statistically significant results of importance are clear.

Previous estimates of the meridional profiles of vertically integrated energy transports have been given by Peixoto and Oort (1992) based on radiosonde data, although their partitioning into components differs. Because they are not independent, we combine the sensible heat and potential energy transports into those of dry static energy. In addition, they break the quasi-stationary component into contributions from the zonal mean and the ''standing eddies.'' The most direct comparisons can be made with divergences (Fig. 2) owing to dif-

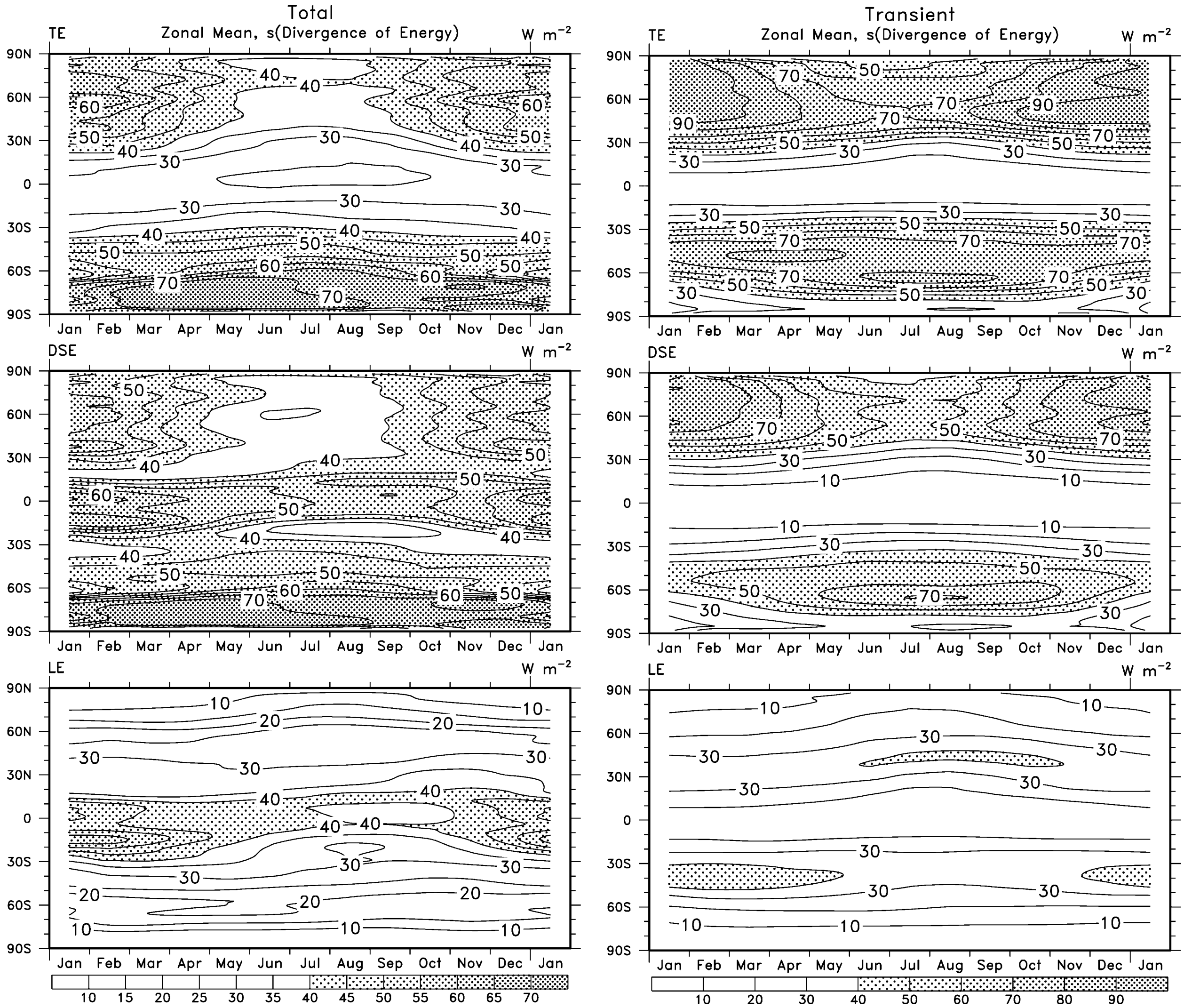

FIG. 11. Standard deviations of the total divergence of the zonal mean northward energy transport for 1979–2001 for the mean annual cycle, for the (top) TE, (middle) DSE, and (bottom) LE, for the total (left) and transients (right), with shadings given in the key. The units are W m^{-2}.

ferences in units for the transports. Differences are considerable in our results, especially in the Southern Hemisphere and throughout the Tropics. Magnitudes are somewhat greater here and the profiles differ in important ways. These differences are manifested in very different implied ocean heat transports (Trenberth and Caron 2001).

A key aspect is that the total atmospheric transport in the Tropics is a fairly small residual of the cancellation between DSE and LE, as noted by Pierrehumbert (2002). The dominant processes are those associated with large-scale overturning: the global monsoon in which the Hadley and Walker circulations are embedded. An important driving component of the Hadley circulation is the latent heating released in the upward branch associated with moisture convergence from sources in the subtropics. Cooling in the subtropics that balances the adiabatic warming from subsidence in the downward branch is a combination of radiative cooling to space and cooling by transient baroclinic waves that transport the heat to higher latitudes. These features are not only present in the climatological mean, but also in the variability on timescales longer than a month. The interannual variability reveals the negative anomalies in the Tropics covarying with positive anomalies 20° farther south or north, and vice versa. These aspects are pursued in more detail in Trenberth and Stepaniak (2003) who estimate the surface, atmospheric, and TOA heat budgets in the subtropics.

In contrast, poleward of about 20° latitude, the transient poleward energy transports have contributions from both DSE and LE. Moreover, they are positively

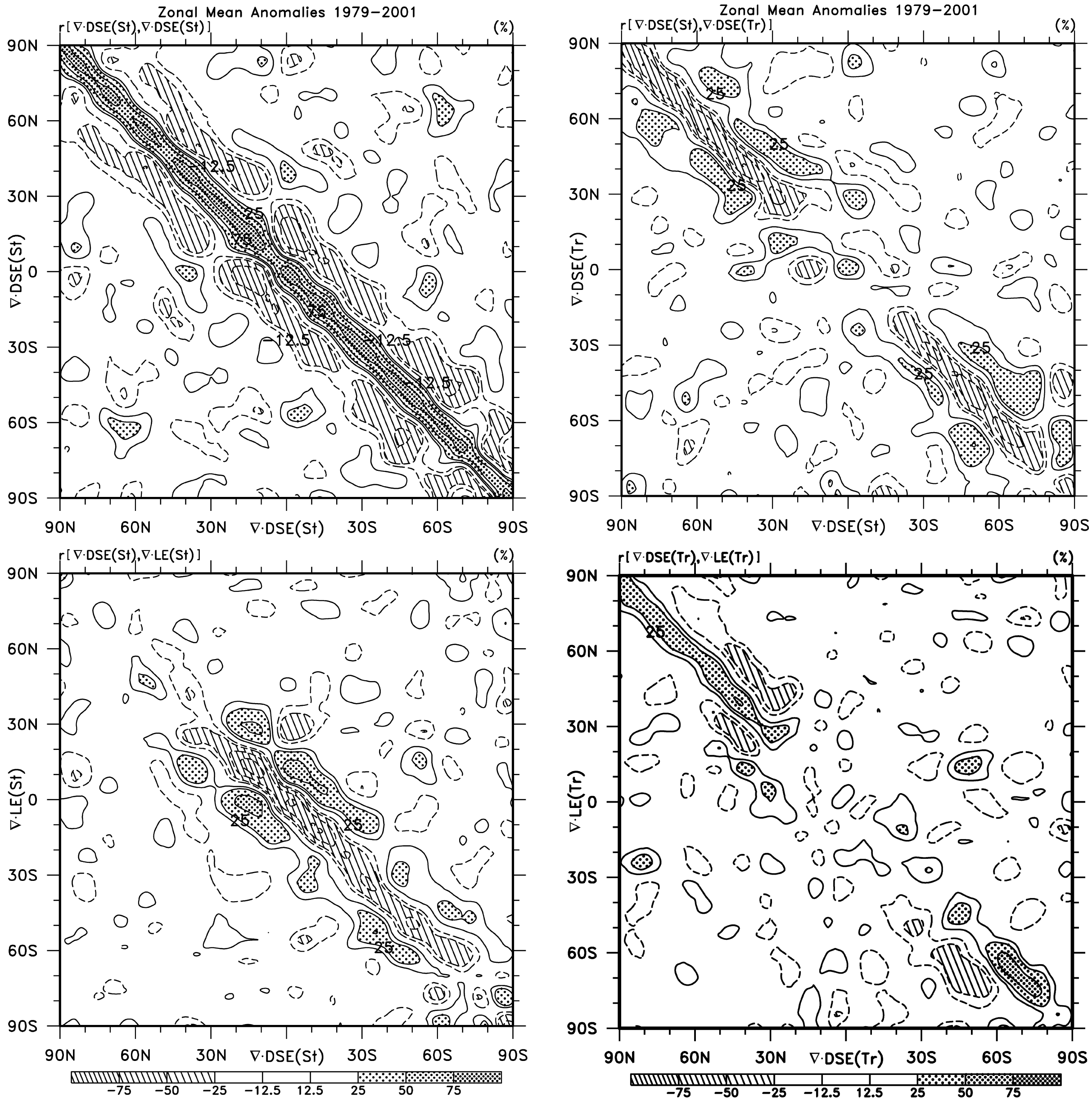

FIG. 12. Cross correlations of monthly transports of DSE (quasi-stationary) vs DSE (quasi-stationary), DSE (quasi-stationary) vs DSE (transient), DSE (quasi-stationary) vs LE (quasi-stationary), and DSE (transient) vs LE (transient). A contour of ± 0.125 is plotted and beyond that the contour interval is 0.25, which is the 5% significance level if a degree of freedom is gained every 4 months (and hence is highly conservative).

correlated for the annual cycle and interannual variability, as expected in baroclinic storms, although the LE transports are more important at somewhat lower latitudes and not a factor at high latitudes.

Of particular note are the intriguing relationships between the quasi-stationary and transient waves in the Northern Hemisphere winter, and also in the Southern Hemisphere even though the quasistationary component is not as prominent there. Remarkable cancellation exists near 50°N where convergence of energy by the transients feeds the quasi-stationary wave component and at the same time the divergence of energy by the quasi-stationary waves drives the transients to transport energy into the region and apparently determines their location. This relationship and the offset in latitudes as to where the heat transports occur in each component was documented by van Loon (1979) for sensible heat in a preliminary way, but is now more thoroughly documented for energy and moisture in a more comprehensive framework.

If the divergence of DSE by the quasi-stationary waves is strong at one latitude, then it is apt to be weak

20° latitude north and south. However, divergence of DSE by transient disturbances is weak in the same zone but stronger 20° north and south, as the storm tracks are displaced. The quasi-stationary waves are forced by the distribution of land, topography, and ocean and this creates regions favorable for baroclinic instability and storm tracks. Variability in atmospheric heating patterns, such as associated with El Niño, causes changes in atmospheric heating, quasi-stationary waves, and storm tracks (Trenberth and Hurrell 1994; Trenberth et al. 1998). There is also good evidence from diagnostic studies to suggest that the transient eddies play a vital role in the nature of the quasi-stationary waves (e.g., Held et al. 2002). However, the evidence suggests that the location and intensity of the storm tracks are mostly a consequence of the quasi-stationary waves (Branstator 1995; Branstator and Haupt 1998; Chang et al. 2002). Swanson (2002) reviews the interaction between low-frequency variability and transients and notes the importance of their two-way interaction for the time evolution to be understood. Perhaps the observed inverse and symbiotic relationship among the quasi-stationary and transient waves should be obvious given the need to satisfy the heat budget, which can be thought of as a strong constraint. Hence this interaction contributes to the seamless nature of the heat transports.

6. Summary and conclusions

In this paper we have presented results of new analyses of the atmospheric energy and heat budgets from a zonal mean perspective. The approach is to analyze the vertically integrated atmospheric energy transports and their divergences and the implied heating, focusing especially on the dry static energy, the latent energy, and their sum, the moist static energy. For meridional transports, the latter is very close to the total atmospheric energy, as the kinetic energy component is small. We have also partitioned these components into the within-month transient and quasi-stationary components and documented the mean annual cycle and interannual variability. The quasi-stationary component includes the long-term mean as well as the interannual variability and contributions beyond monthly timescales. In the Tropics it corresponds primarily to the large-scale overturning global monsoon and the embedded Hadley and Walker circulations. In the extratropics, it includes the quasi-stationary planetary waves, which are primarily a factor in the Northern Hemisphere winter. By examining all these components, we are able to document the main processes that come into play.

In the extratropics, the transports of the latent and dry static energy are both poleward, with the latent energy more important at low to midlatitudes. These transports are mostly carried out by baroclinic disturbances, often organized into storm tracks in some broad sense. Quasi-stationary waves play a substantial role in the Northern Hemisphere winter and are also present in the Southern Hemisphere although much less so in the mean. However, there is a remarkable compensation between where the divergence of energy is positive in the quasi-stationary waves and negative in the transient waves, showing the cooperative nature of these components so that they contribute to the seamless character of the overall transports. In Trenberth and Stepaniak (2003) we show that this applies not only to the zonal mean but also locally. Quasi-stationary wave transports are weaker than normal about 20° to the north and south of where they are strong, and at exactly the same locations that the transient eddy transport is stronger than normal. Hence the location and strength of the transients are largely determined by the quasi-stationary waves that in turn are altered by the resulting eddy transports.

A new result is presented concerning the possibly quite strong quasi-stationary transports over the southern oceans whereby there is a pronounced poleward heat transport south of 62°S and an equatorward transport between 60° and 40°S. The poleward transport can be thought of as being part of a general katabatic-type drainage of cold air off of Antarctica and a shallow mean overturning that is ageostrophic, and hence it is not captured by the earlier analyses based on geostrophic flow. Strong surface heat fluxes and divergence of energy out of the zone near 60°S drive the equatorward transports to the north. Nevertheless, there are major reservations about these features owing to the way the sea ice was specified and the coarse-resolution topography of the coastal Antarctic region in the reanalyses. The features are present in both the NCEP–NCAR and ERA-15 reanalyses but appear to be much too strong in the former, presented here.

This work has suggested intriguing relationships among several quantities resulting in overall energy transports and divergences that are essentially seamless. These relationships appear to also hold on a monthly mean timescale so that the variability of the total poleward energy transport has a standard deviation of only about 0.3 PW, less than 10% of the total. Therefore it is necessary to resolve daily timescales to better understand how these relationships come about and the extent of lead and lag relationships, such as those arising from cold surges. Research into these aspects will then provide a better basis for understanding how the Hadley circulation responds to transient eddy transports, and vice versa, and how transient eddies and quasi-stationary waves interact.

Finally, it is worth highlighting the importance of these results for understanding atmospheric dynamics. The global energy budget evidently provides a very strong constraint on the system. The heating of the planet is largely externally controlled by the sun–Earth geometry, and can mainly be modified by changes in albedo (Stone 1978), although Pierrehumbert (2002) discusses other possibilities. Other considerations are the changes in heat storage and the partitioning of energy among the components of the climate system, especially how much heat is taken up by the ocean (Stone and Miller 1980). But observationally the latter are of secondary importance. However, the constraint applies to the whole system and emphasizes the strong tendency for compensations to occur: among climate system components and among components within the atmosphere. Of course, changes in planetary waves and storm tracks make an enormous difference to the climate locally, so this conclusion is not intended to diminish the vital role of atmospheric dynamics. But it does mean that there are important constraints, as noted by Stone (1978), which helps provide some justification for simpler ''energy balance'' models of the climate system.

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