

Seamless Poleward Atmospheric Energy Transports and Implications for the Hadley Circulation

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ABSTRACT

A detailed vertically integrated atmospheric heat and energy budget is presented along with estimated heat budgets at the surface and top-of-atmosphere for the subtropics. It is shown that the total energy transports are remarkably seamless in spite of greatly varying mechanisms. From the Tropics to about 31° latitude, the primary transport mechanisms are the Hadley and Walker overturning circulations. In the extratropics the energy transports are carried out by baroclinic eddies broadly organized into storm tracks and quasi-stationary waves that covary in a symbiotic way as the location and activity in storm tracks are determined by, and in turn help maintain through eddy transports, the quasi-stationary flow. In the upward branch of the Hadley cell, the predominant diabatic process is latent heating that results from convergence of moisture by the circulation itself. Hence large poleward transports of dry static energy are compensated by equatorward transports of latent energy, resulting in a modest poleward transport of moist static energy. The subsidence warming in the downward branch is compensated by cooling in the subtropics that mainly arises from energy transport to higher latitudes by transient baroclinic eddies that are stronger in the winter hemisphere. Effectively, the outgoing longwave radiation to space is distributed over middle and high latitudes and is not limited to the clear dry regions in the subtropics. Further, some of the radiative cooling in the subtropics is a consequence of the circulation. Hence the cooling by transient eddies in the subtropics is a fundamental driver of the observed Hadley circulation and realizes the seamless transport from Tropics to extratropics, while tropical sea surface temperatures over the oceans determine where the upward branch is located. The relatively clear skies in the subtropics further provide for ample absorption of solar radiation at the surface where it feeds strong evaporation, which exceeds precipitation, and supplies the equatorward flow of latent energy into the upward branch of the Hadley circulation as well as the poleward transports into midlatitude storm tracks. The evaporation is sufficiently strong that it is also compensated by a subsurface ocean heat transport that in turn is driven by the Hadley circulation surface winds.

1. Introduction

A primary driver of the atmospheric circulation is the requirement to balance the global heat and energy budgets. The sun–earth orbital geometry greatly determines the distribution of incoming solar radiation, while the outgoing longwave radiation (OLR) is more or less uniformly distributed, and these fundamental factors mandate a poleward heat transport by the fluid components of the climate system: the atmosphere and ocean. Other influences, such as the surface albedo and cloud effects, are of secondary importance, and so the global heat budget provides a strong constraint on the climate system (Stone 1978; Trenberth and Stepaniak 2003). Observations show that not only is the total poleward heat

transport continuous with latitude, so too is the atmospheric transport (Trenberth and Stepaniak 2003). Yet the mechanisms for carrying out the transport vary greatly. The large-scale overturning Hadley circulation is dominant in low latitudes while the baroclinic transient eddies, assisted by the quasi-stationary planetary waves in the Northern Hemisphere winter, are dominant in midlatitudes (Trenberth and Solomon 1994). Yet most of the theories (discussed further below) of the overturning circulations have an abrupt cutoff at about 30° latitude at the poleward edge of the Hadley circulation for the heat transport. So how is it that the poleward heat transports are so seamless from the tropical to the extratropical regime?

The total poleward heat transport peaks near 35° latitude in each hemisphere, while the poleward atmospheric transport peaks near 40° latitude (Trenberth and Caron 2001). Heating occurs in the Tropics, where it is already hot, and cooling at higher latitudes where it is cold, and heat can become manifested in various forms of energy. Strictly speaking, there has to be a transport of energy by the atmosphere and ocean from source to

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sink. In the atmosphere, most of the transport occurs as moist static energy (MSE). Hence, overall, air parcels moving poleward must have a higher MSE than air parcels moving equatorward. Trenberth and Stepaniak (2003) document the global vertically integrated atmospheric heat budget as zonal means for the annual mean, mean annual cycle, and the interannual variability for 1979–2001. They further examine the transports and their divergences partitioned into contributions from within-month transients and quasi-stationary components; in the Tropics the latter correspond to the large-scale overturning global monsoon and the embedded Hadley and Walker circulations. The results highlight the 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 waves and transient components in the extratropics. Hence the total atmospheric energy transports and divergences are remarkably seamless with latitude and the total interannual variability is substantially less than that of the components.

From a diabatic heating diagnostic standpoint, the Hadley cell overturning is driven by heating in the deep Tropics and cooling in the subtropics. It is widely assumed that the primary heat balance in the subsiding branch of the Hadley circulation is between the adiabatic warming from subsidence and the diabatic effects of infrared radiative cooling to space. Yet how can this be, given the seamless poleward heat transports? Instead the continuity of the heat transports across latitude implies that other dynamical mechanisms are also playing key roles. In particular, as we show here, the cooling in the subtropics must also arise from heat transports to higher latitudes by the transient baroclinic eddies and quasi-stationary waves. Effectively, energy is transported from the subtropics to higher latitudes, and thus the radiation to space is distributed over middle and high latitudes and is not limited to the clear dry regions in the subtropics. This discussion therefore raises key questions about the role of the transients in setting up the heating gradients that drive the Hadley and monsoonal circulations.

The relatively clear skies in the subsiding air in the subtropics mean that solar radiation is abundant at the surface, and it heats the ocean. The subtropical highs are also the regions of highest evaporation on the globe (Trenberth and Guillemot 1995, 1998) not coincidentally, and some moisture is transported poleward by transient eddies and some equatorward by the lower branch of the Hadley and Walker circulations to be realized as latent heat of condensation in the intertropical convergence zone (ITCZ) and South Pacific convergence zone (SPCZ). In turn this fuels the overturning and controls the size and magnitude of the upward branch as a powerful feedback. While the low-level winds transport latent energy equatorward, thereby diminishing the total poleward energy transport, they provide the dominant fuel to drive the upward branch of

the overturning. Accordingly, the overturning transports are seen more clearly in the dry static energy (DSE) than in the MSE because of large compensation that occurs in the latter as moisture fluxes are converted into sensible heat through release of latent heat (Trenberth and Solomon 1994; Trenberth and Stepaniak 2003). However, a second powerful positive feedback also operates in the subtropics because the establishment of the subsiding air and its relative dryness enhances radiative cooling to space, which helps compensate for the adiabatic warming in the downward branch of the circulation (Hoskins 1996).

Another way of comparing the DSE and MSE is to note that the overturning is driven by the atmospheric diabatic heating, Q_1 , but that this in turn is dependent on the condensational latent heating arising from moisture convergence. It thus depends on moisture transport as well as the moisture sources. Column-integrated latent heating is often referred to as Q_2 . Under a steady state or where the tendency terms are small, the divergence of the atmospheric energy transports is $\nabla \cdot \mathbf{F}_A \approx Q_1 - Q_2$ (Trenberth and Stepaniak 2003).

The discussion has focused on the zonal mean picture of the atmospheric general circulation and the poleward energy transports across latitudinal zones and, although these are dominant, zonal asymmetries are also important (Cook 2003). The latter arise from the distribution of land and surface topography, in particular, and give rise to regional monsoons and subtropical anticyclones (Trenberth et al. 2000; Rodwell and Hoskins 2001; Chen et al. 2001). Heat transports by the quasi-stationary planetary waves are substantial in the Northern Hemisphere in winter. In the Tropics, the zonal mean Hadley circulation is but part of the deep tropospheric overturning mode, called the “global monsoon” by Trenberth et al. (2000), which also encompasses the Walker circulation. The dominant energy outflow center in the atmosphere coincides closely with the region of highest sea surface temperatures (SSTs) in the oceans and migrates back and forth across the equator following the sun (Trenberth et al. 2000). But what determines the location of the downward branch of the Hadley circulation and its change with the seasons?

A number of studies have explored the extent to which the Hadley circulation and more general thermally driven overturning circulations can be explained with fairly simple theories that exclude the role of synoptic transient eddies and other high-frequency variability; see Lorenz (1967) and Newell et al. (1974) for historical perspectives. Schneider (1977) developed a model for a zonally symmetric steady state that was subsequently expanded by Held and Hou (1980), Lindzen and Hou (1988), and Hou and Lindzen (1992) to include effects of the distribution of heating, related to latent heat feedback, and displacement of the upward branch away from the equator to be more representative of the winter/summer extremes. Schneider (1987) and Emanuel (1995) generalized the model to include non-

zonal monsoonal-type circulations. These theories are successful in accounting for certain features of the tropical tropospheric circulation, notably the width of the Hadley circulation and the position of the subtropical jet, which are controlled by geostrophy and conservation of heat and momentum. Fang and Tung (1999) introduced time-varying heating and found the mean Hadley circulation was about a factor of 2 stronger than the steady-state case. Many of these studies recognized that midlatitude eddies play an important role in enhancing the Hadley circulation (e.g., Schneider 1984). Kim and Lee (2001) investigated the effects of baroclinic eddies on the zonally symmetric Hadley cell using a simplified model symmetric about the equator and found that the eddies contribute to a greatly strengthened Hadley cell through direct effects as well as indirect effects (feedbacks) on the diabatic heating and surface friction. However, all of these theories and models use a radiative-convective equilibrium base state of some sort, perhaps generalized into some form of Newtonian heating/cooling. It is evident that latent heating arising from convergence of moisture into the upward branch of the overturning is crucial in defining the detailed structure and intensity of the circulation, but such effects are not fully accounted for in these models.

The importance of the downward branch of the Hadley circulation has also been greatly emphasized recently because of its role in drying the subtropical atmosphere above the boundary layer, and the possible role this may play in water vapor feedback (Pierrehumbert 1995, 1999; Spencer and Braswell 1997; Lindzen et al. 2001; Salathé and Hartman 1997). The latter study notes the swirling paths of motions that carry moisture from source regions into the upper-troposphere subtropics and that such tracks are not adequately reflected by a zonally averaged Hadley circulation. Yet the predominant arguments rest heavily on the idea that steady-state large-scale subsidence, driven by infrared radiative cooling to space, is the primary governing process. Zonal asymmetries and the origin of the subtropical anticyclones have been explored by Rodwell and Hoskins (1996, 2001) and Chen et al. (2001) using idealized models with specified heating and implied cooling (such as through relaxation to a specified basic state, or because the zonal mean has to be zero). Although descent occurs into the subtropical anticyclones, the associated adiabatic warming has to be balanced either by diabatic processes or horizontal atmospheric transports, and in these models it is a by-product of the way the models are forced.

In addition, the Hadley and Walker circulations are far from steady and the level of the variability in monsoon areas is quite high. Trenberth et al. (2000) show that the mean vertical motion in the peak monsoon seasons is only about 60% of the standard deviation of the daily mean values in the monsoon areas—although this is much greater than in other regions. Many transients play a role of mixing, both in the vertical and horizontal

and, as we show here, extratropical storms commonly have an influence in winter into the Tropics. Rodwell and Hoskins (1996) point out, theoretically and in agreement with observations, that the subtropics are where both vertical and horizontal advection are of comparable importance in balancing diabatic heating. Therefore key questions of interest are to determine what the dominant terms and processes are in the heat budget of the subtropics.

There are a number of interesting issues related to the vertical structure of the atmosphere and the energy transports and how the transports come about, such as through the Hadley and Walker overturning circulations, but those issues will be taken up elsewhere as results depend on the datasets used. Instead, in this work, we explore what the latest datasets can tell us about the poleward heat transports and their divergences in a vertically integrated framework. Trenberth and Stepaniak (2003) provide the background to this paper. They outline the datasets used and the theoretical framework, and document the global vertically integrated atmospheric heat budget as zonal means for the annual mean, mean annual cycle, and the interannual variability. Here, we examine in detail the full geographical structure of the heating, the atmospheric transports, and their divergences, with a special focus on the implications for the Hadley circulation dynamics.

Accordingly, the heat budget is analyzed in detail in the Tropics and subtropics and the relative roles of the overturning and transients in the heat transport from source to sink are determined. Section 2 briefly discusses the datasets used. The physical background and mathematical expressions for the transports and their components are given in Trenberth and Stepaniak (2003) and briefly outlined in section 3. The vertically integrated heat budget and its breakdown into the mean and transients, the components of dry static energy, latent energy, and kinetic energy, and the rotational and divergent circulation components are presented in section 4. Detailed estimates of heat budgets are made in the subtropics of both hemisphere, not only for the atmosphere, but also at the top-of-atmosphere (TOA) and the surface. Section 5 discusses the results.

2. Methods and data

The overall energy transports are derived from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalyses (Kalnay et al. 1996) as given in Trenberth et al. (2001) because they are most consistent with the overall heat budget based upon TOA and ocean measurements (Trenberth and Caron 2001). Hence we use those reanalyses from 1979 to 2001 to examine the components (see Trenberth and Stepaniak 2003).

The atmospheric transports vector \mathbf{F}_A can be split into rotational and divergent parts and a potential function χ can be defined such that $\nabla \cdot \mathbf{F}_A = \nabla^2 \chi$. The rotational

component is large but, as it is not linked to the diabatic forcings, we focus on the divergent component of the transports. Plots of χ depict a highly smoothed version of the divergence, which is not especially revealing. Instead we have experimented with different smoothings in order to emphasize the large-scale features of the circulation and we settled on a T31 truncation with a taper to avoid ringing effects for the figures. Experience suggests that the features of interest are well picked up although their intensity and some gradients are underestimated. While higher resolution adds greater reality, it also adds complexity and makes the figures less readable. However, all computations are performed at T63 resolution.

The transports and components are split into those associated with the time mean circulation, given by the overbar, and the transients, given by the prime, so that $h = \bar{h} + h'$, for example. The transients are defined to be the within-month variability and the quasi-stationary component includes the interannual variability.

Complementary estimates of the heat budget are obtained for the surface from the Southampton Oceanographic Centre (SOC) heat budget atlas based on surface marine data (Josey et al. 1998, 1999). Sampling uncertainties and systematic biases arising from bulk flux parameterizations are substantial in the results (Trenberth et al. 2001), but they are nevertheless the best available and can be useful if physical constraints are utilized, as is done here. At the TOA we use the Earth Radiation Budget Experiment (ERBE) measurements of radiation (Trenberth 1997). We also use the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) precipitation estimates from Xie and Arkin (1997). For temporal consistency, we use monthly values from the SOC and CMAP data for the ERBE period February 1985–April 1989.

3. Physical framework

The mathematical expressions for the vertically integrated energetics of the atmosphere are given in Trenberth and Stepaniak (2003). The total atmospheric energy A_E can be broken up into components of kinetic energy K_E , internal energy I_E , potential energy P_E , and latent energy L_E ; the total energy $A_E = P_E + I_E + K_E + L_E$ is conserved in the absence of forcings. However, when the transports of energy are considered, there is a difference between the total energy and the quantity transported that arises from the pressure–work term in the thermodynamic equation and the conversion of kinetic to internal energy. We thus need to consider the MSE transports, which in turn can be broken up into components from the DSE, and latent energy (LE):

$$\frac{\partial A_E}{\partial t} = -\nabla \cdot \mathbf{F}_A + Q_1 - Q_f - Q_2, \quad (1)$$

where the total atmospheric transport

$$\mathbf{F}_A = \mathbf{F}_{M_E} + \mathbf{F}_K$$

and \mathbf{F}_{M_E} is the MSE flux. The total energy flux includes the kinetic energy component (second term) but, as shown in Trenberth et al. (2002), this is small. Consequently the atmospheric energy transports \mathbf{F}_A predominantly correspond to the MSE transports:

$$\mathbf{F}_{M_E} = \mathbf{F}_{D_E} + \mathbf{F}_{L_E},$$

where the terms on the rhs are the DSE and LE fluxes. The atmospheric diabatic heating is

$$Q_1 - Q_f = R_T - R_s + H_s + \tilde{L}P = R_T - F_s + Q_2,$$

where $Q_2 = L(\tilde{P} - \tilde{E})$ is the column latent heating; Q_f the (small) frictional heating; R_T and R_s the net downward radiation at the TOA and the surface respectively, H_s the sensible heat flux at the surface, and $F_s = LE_s + H_s - R_s$ the net upward flux at the surface. The tilde refers to vertical integrals (see Trenberth and Stepaniak 2003).

4. Results for the energy budget

To set the stage for subsequent analysis, we first present some aspects of the divergent circulation to define the realms of interest. Trenberth et al. (2000) provide global seasonal figures of the Hadley circulation and global monsoon up to 10 mb, and here we focus on the mean divergent circulation from about 40°N to 40°S for the zonal average (left) and a Pacific sector 140°E–140°W (right) for December–February (DJF) and the annual mean below 100 mb (Fig. 1). As the zonal mean circulation is closed, streamfunctions of mass flow contours are added to show the Hadley circulations. For the Pacific sector, only the average flow can be indicated, weighted appropriately by mass (Trenberth et al. 2000). These figures reveal the extent of the Hadley circulation and where the subsidence in the subtropics transitions from that identified with the Hadley circulation to that associated with the Ferrel cell at midlatitudes. In DJF the Hadley circulation extends from 13°S to 31°N both regionally over the Pacific and for the zonal mean. For the annual mean, the subsidence extends to 31°N and 31°S, with the rising motion centered north of the equator between 10°S and 15°N and a somewhat stronger southern Hadley cell. Accordingly, we will later focus on zones on both sides of about 30° latitude.

a. Annual means

The spatial patterns of annual mean heating and energy transports and their divergences are given in this section. The annual means of the TOA radiation, based on ERBE measurements from February 1985 to April 1989, are given in Fig. 2. Although the absorbed solar radiation (ASR) and the OLR both depict distinctive signatures of clouds, the net radiative heating exhibits well-known but nevertheless remarkable cancellation

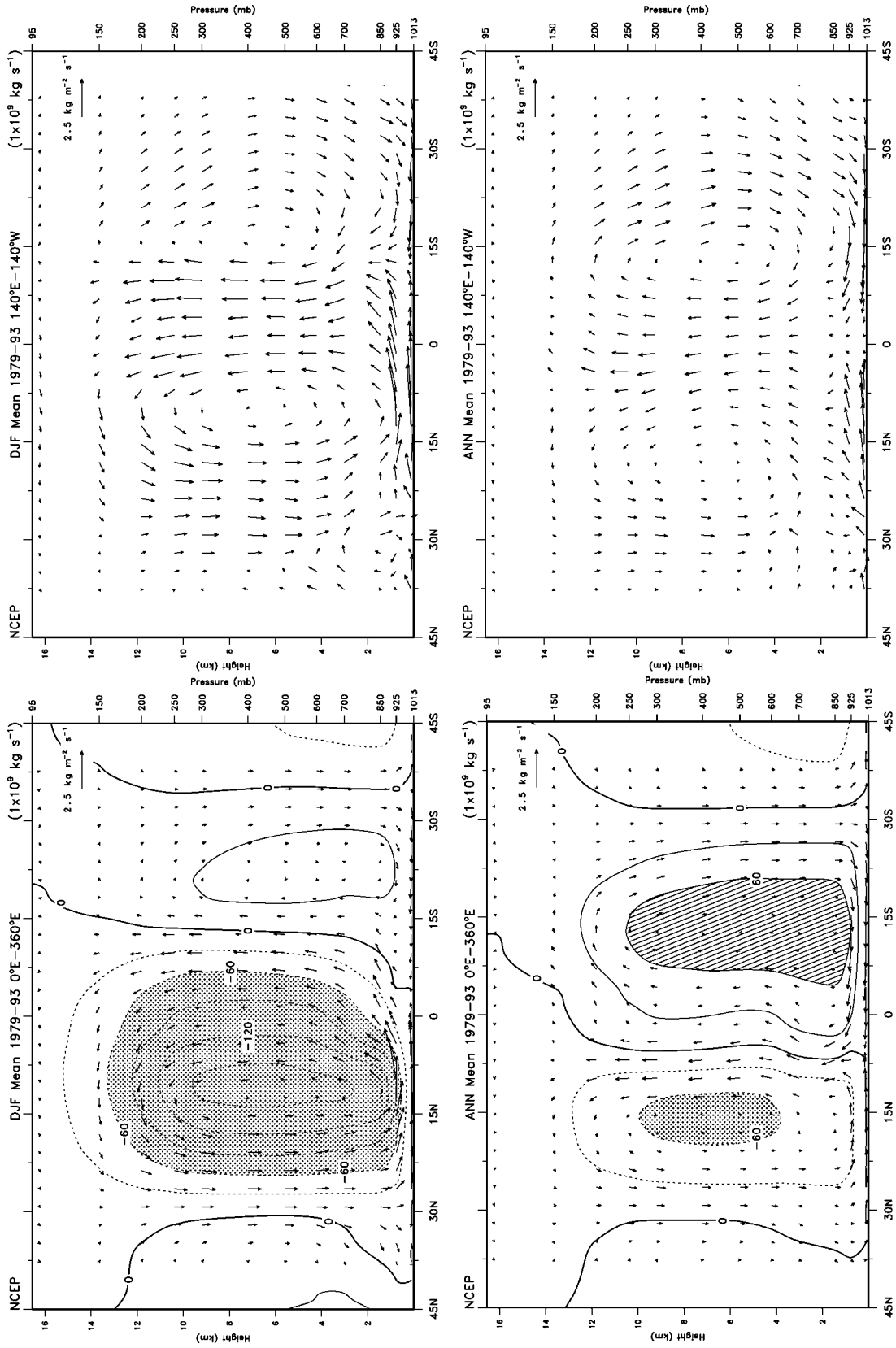


FIG. 1. The (top) DJF and (bottom) annual mean divergent circulation from about 40°N to 40°S for the (left) zonal average and (right) 140°E-140°W. Streamlines of the mass flow are shown in the left-hand panels with contour interval $30 \times 10^9 \text{ kg s}^{-1}$ and values greater than 60 units shaded. The mass scale vector is in upper-right corner of each panel.

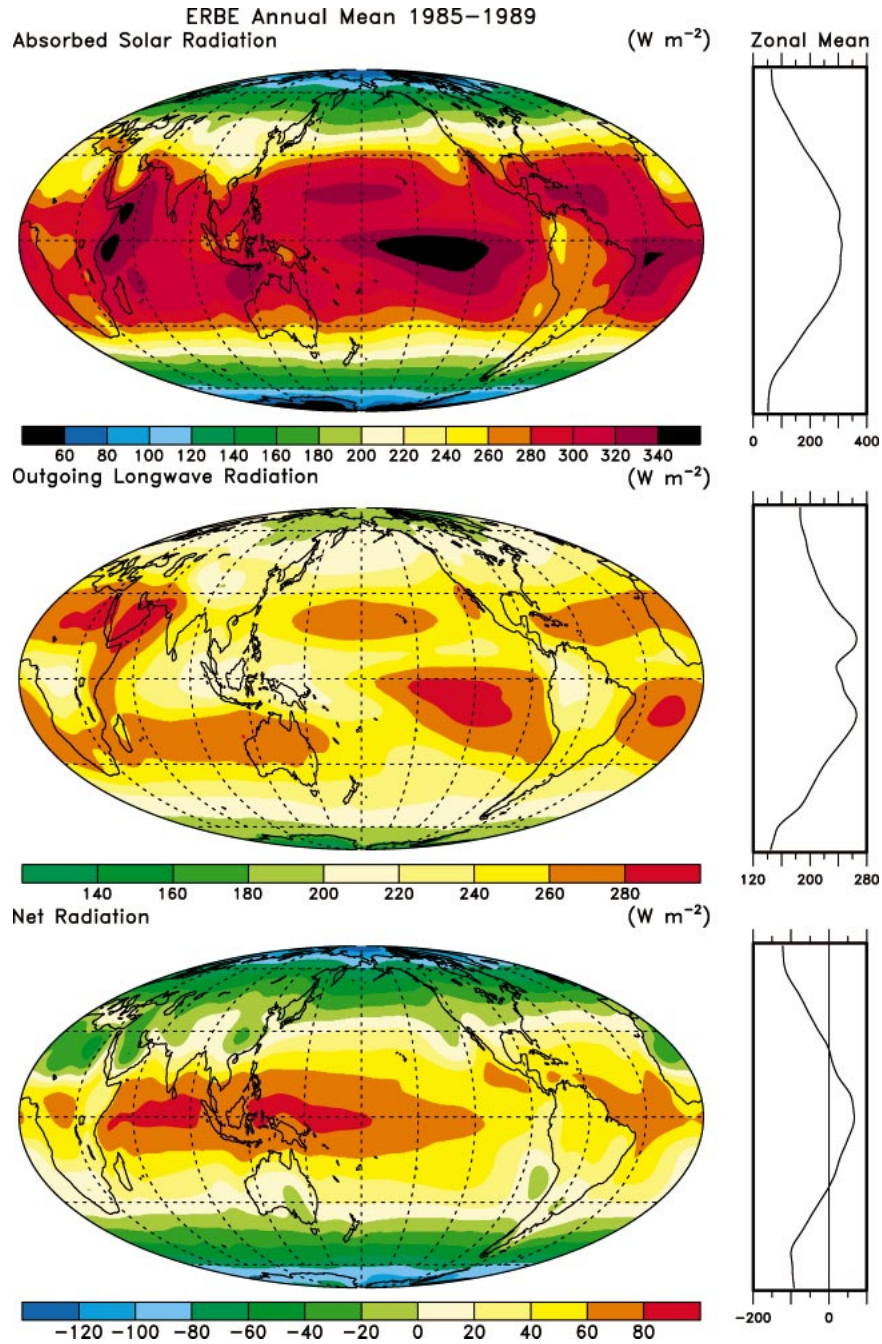


FIG. 2. Annualized mean TOA ERBE measurements for the period Feb 1985–Apr 1989 for the ASR, OLR, and net in $W m^{-2}$. The color key is under each plot and the contour interval is $20 W m^{-2}$. Zonal mean profile panels are given at right.

for most clouds; the main exception being the low stratocumulus cloud decks such as in the eastern Pacific.

Figure 3 provides the inferred annual mean diabatic heating $Q_1 - Q_f$, latent heating Q_2 , and net heating $Q_1 - Q_f - Q_2$. The latter is equal to the net downward radiation at TOA (Fig. 2) plus the net surface flux of heat into the atmosphere. Hence the difference with the net radiation in Fig. 2 over the oceans is due to ocean

heat transports. Over land, for the annual mean, differences should be small, as there is only a very small change in energy storage. These aspects are discussed in detail in Trenberth et al. (2001) and Trenberth and Caron (2001), who note problems especially in mountain areas. However, such problems are greatly reduced over the oceans. For instance, the equatorial minimum in the zonal mean in the lowest panel of Fig. 3 is seen

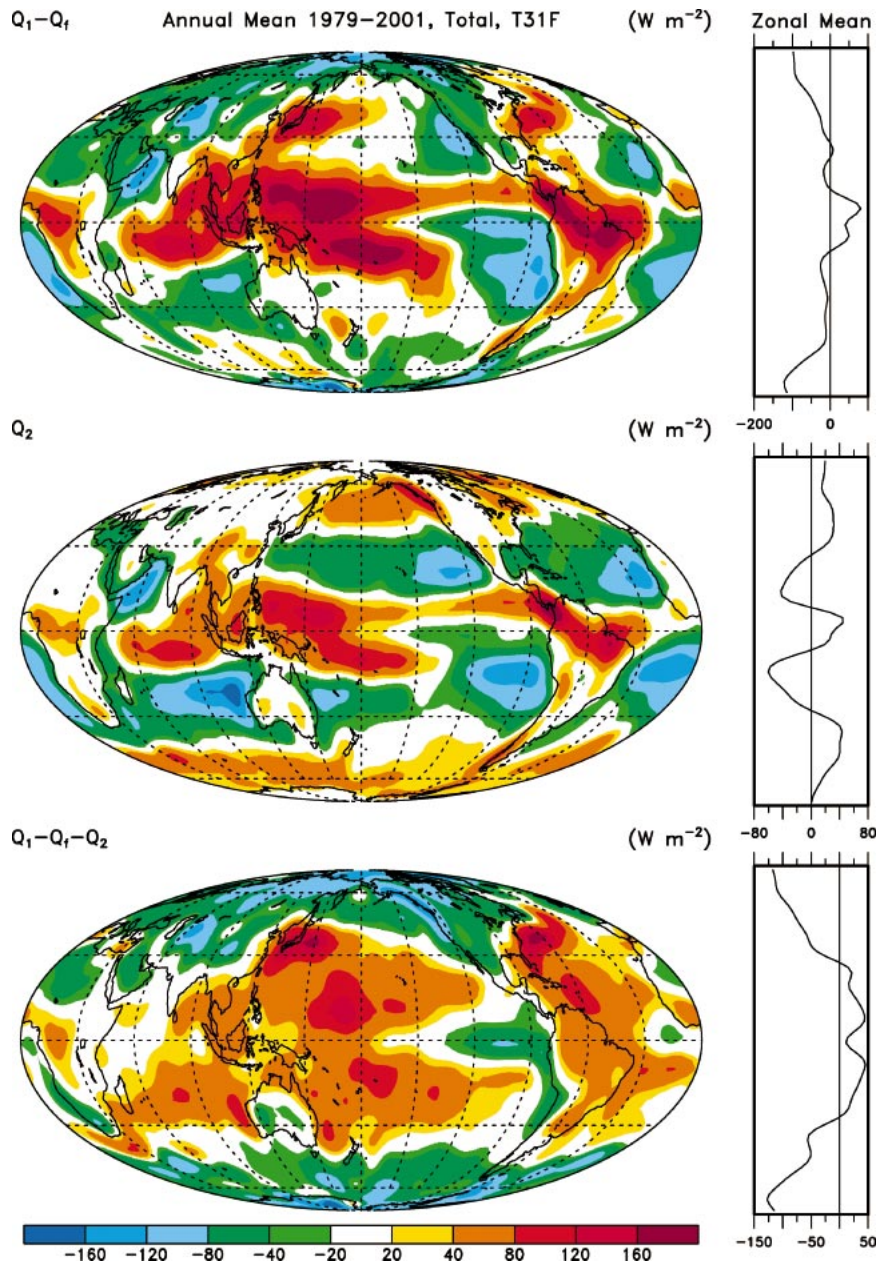


FIG. 3. Annual mean heating components for 1979–2001 in W m^{-2} . Shown are the (top) atmospheric diabatic heating $Q_1 - Q_f$ (middle) column latent heating Q_2 , and (bottom) total column atmospheric heating $Q_1 - Q_f - Q_2$. Zonal mean profile panels are given at right.

to arise mainly from cooling over the cold tongue of SSTs in the equatorial Pacific where radiation enters the ocean in relatively clear skies. Perhaps the most striking features in the lowest panel are the large positive regions off the east coasts of the northern continents, signaling the surface sensible and latent heat fluxes from the ocean into the atmosphere in these regions in the winter half year. Again, the difference with the lowest panel in Fig. 2 highlights the fact that these are compensated by ocean transports of heat.

Recall that the diabatic heating includes the latent heating from precipitation but not from evaporation at the surface. The figure reveals the strong zonal asymmetries associated with the land distribution that make the zonal means (Trenberth and Stepaniak 2003) only a part of the picture. The ITCZ and SPCZ are evident in the top two panels over the Pacific, along with the cooling and moistening in the South Pacific high. Together, the South Pacific high and the SPCZ form part of the Walker circulation. The evaporative sources of

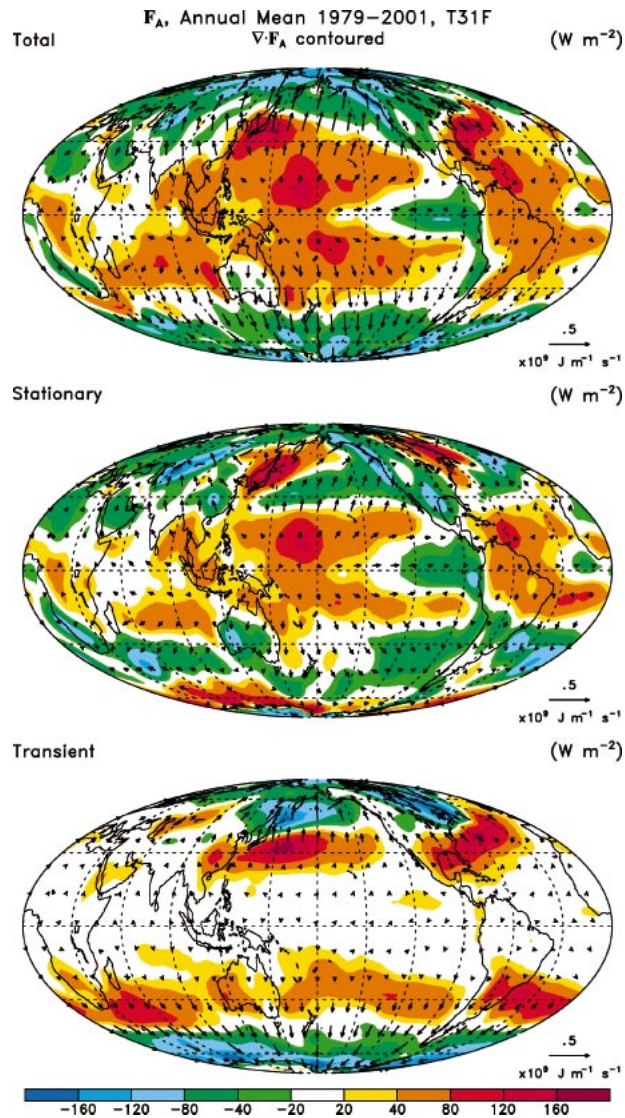


FIG. 4. Annual mean divergent energy transport for 1979–2001 as vectors and the divergence in W m⁻². Shown are the atmospheric energy transports for the (top) total, (middle) quasi-stationary, and (bottom) transient components.

moisture in the subtropical highs are strongly evident in the second panel (Fig. 3). Typical values of E throughout the tropical oceans range from 3 to 5 mm day⁻¹ (Trenberth and Guillemot 1998) and lack much spatial structure. They correspond to about -90 to -145 W m⁻² of cooling, as is seen in the subtropical anticyclones. Hence the structure in Q_2 arises primarily from the P field. Monsoon-related heating over central and northern South America and central Africa are present, and the similarity between patterns in the top two panels indicates the primary role of precipitation and thus latent heating.

The bottom panel of Fig. 3 looks almost exactly the same as the divergence of the atmospheric energy transports, given in Fig. 4 in the top panel, as it should, as

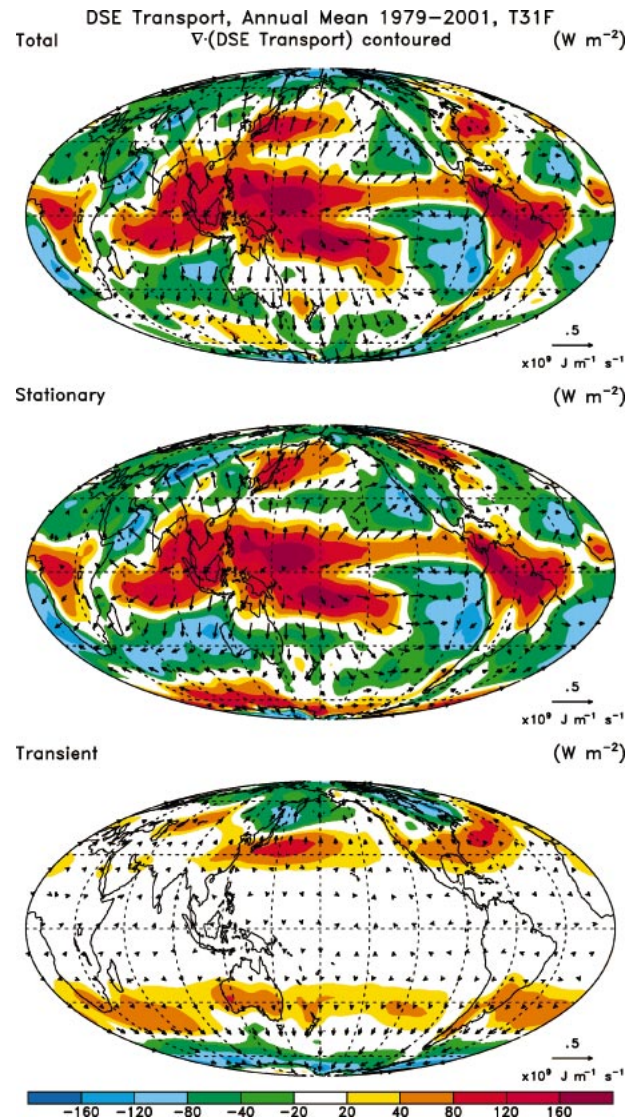


FIG. 5. Annual mean divergent northward DSE transport for 1979–2001 as vectors and the divergence in W m⁻². DSE transports for the (top) total, (middle) quasi-stationary, and (bottom) transient components.

the difference is the change in storage (tendency term), which is small for a long-term average. However, this figure also allows presentation of the actual divergent vector transports and their partitioning into components. Note the flow of atmospheric energy from the source regions to the sinks, many of which are at higher latitudes. For instance these include the source in the western tropical Pacific and the sink over the tropical eastern Pacific, where the energy flow is via the Walker circulation.

Figure 4 also provides the quasi-stationary and transient components. The latter highlights the storm tracks over the North Pacific and North Atlantic and around the Southern Hemisphere as dipole structures with divergence on the equatorward side and convergence at

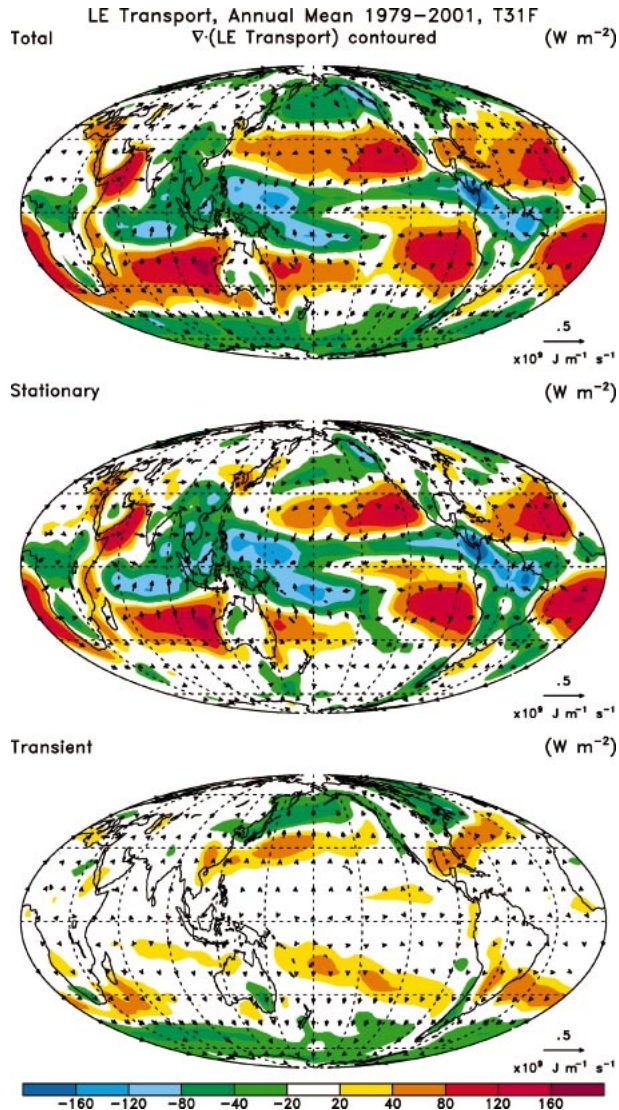


FIG. 6. Annual mean divergent northward LE transport for 1979–2001 as vectors and the divergence in W m^{-2} . LE transports for the (top) total, (middle) quasi-stationary, and (bottom) transient components.

higher latitudes, as the baroclinic storms transport heat and energy poleward. The quasi-stationary component dominates throughout the Tropics but provides a strong complement to the transient component in the extratropics. Hence the pronounced negative correlation, noted by van Loon (1979) for the geostrophic sensible heat transports and by Trenberth and Stepaniak (2003) for the zonal means, also carries over to local spatial structures.

The breakdown of these three panels into the DSE and LE components is given in Figs. 5 and 6. Once again, both of these feature the ITCZ and SPCZ structures in the total and quasi-stationary parts that are not apparent in Fig. 4 for the MSE. Of particular note is the strong region of convergence of DSE by the quasi-

stationary flow in the subtropics of the Northern Hemisphere over the Pacific and Atlantic (Fig. 5). There is a direct link from this back to the tropical source in the ITCZ and other monsoonal rainfall regions. Meanwhile, the moisture flow (Fig. 6) is from the subtropics to the rain regions.

b. Regional and seasonal relationships

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. Nevertheless, in the subtropics about 22% of the zonal mean of the Southern Hemisphere is land (Australia, South America, and southern Africa). However, in the Northern Hemisphere, the storm tracks are distinctive only over the Pacific and Atlantic. The Atlantic storm track is oriented somewhat northeast–southwest whereas the Pacific storm track is more zonal (lower panel Fig. 5). Accordingly it is relatively easy to isolate and relate features in the Pacific by simply extracting zonal means over a section such as 140°E to 140°W , which is over the ocean away from the influences of Asia and Japan although it misses the storm track entry region. As shown in Fig. 1 it is also a region where the Hadley circulation is stronger than the zonal mean by a factor of 2 or so but with the same dimensions. Note, however, that the interpretation of regional sector results is complicated by the presence of the rotational transports and the apparent overturning mass flows do not depict those of particles.

The zonal kinetic energy transport is significant in DJF (convergence $\sim 30 \text{ W m}^{-2}$ near 30°N) and for the annual mean but has been omitted from the plots in the interests of simplicity. Figure 7 shows the annual mean total energy (called TE in figures) across this section for the total, quasi-stationary, and transient components along with their breakdown into DSE and LE parts. The total, quasi-stationary and transient components are then shown together on the same plots for the four seasons DJF, etc., in Fig. 8.

The pattern for the transients in all seasons is quite similar to that of the annual mean (Fig. 7). Divergence of DSE and LE out of the subtropics and convergence at higher latitudes demonstrates the poleward transports across midlatitudes and with the LE component nearly in phase with, but shifted somewhat equatorward of, the DSE contribution. However, the transient role is much weaker in summer (JJA) and shifted farther poleward. Typically between 20° and 60°N the quasi-stationary component of DSE divergence has opposite sign to the transient component but does not completely cancel it. In particular, in DJF strong divergence of DSE from 30° to 45°N is complemented by LE divergence out of the subtropics occurring in the stationary waves, with convergence at higher latitudes.

In the Tropics, the total divergence (Fig. 8) closely

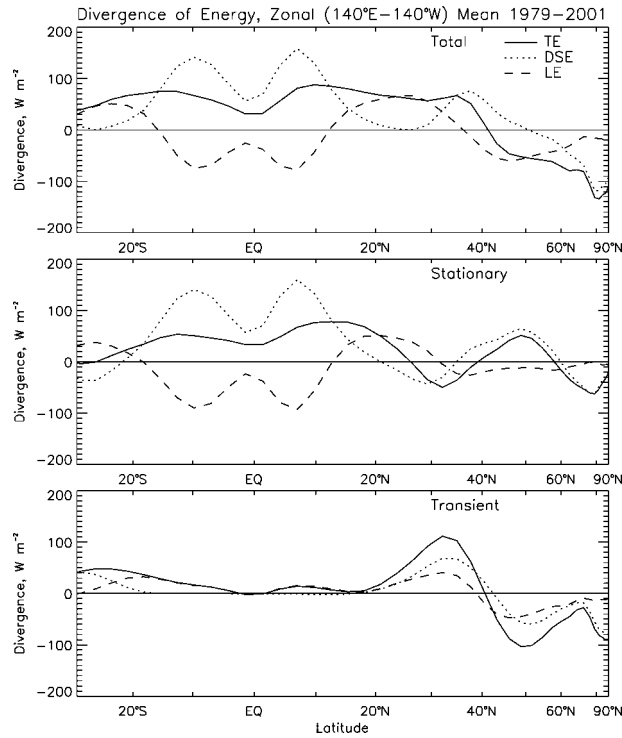


FIG. 7. The divergence of the (top) annual mean total, (middle) quasi-stationary, and (bottom) transient energy for the total energy (TE) and the components from the DSE and LE zonally averaged across the Pacific 140°E–140°W. Units are W m^{-2} .

matches that of the quasi-stationary component and features the DSE and LE with opposite signs, but with a net divergence, all of which is a characteristic signature of the Hadley circulation. Of note is the double hump related to the ITCZ in the Northern Hemisphere and the SPCZ in the Southern Hemisphere, with the latter strongest in DJF near 11°S for this zone, but with the northern maximum strong in both JJA and SON and farthest north at 10°N in SON. In this sector of the Tropics, rather than migration of the region of upward motion typical in monsoon areas, modulation of the intensity of quasi-permanent features occurs.

For DJF the picture is governed by the substantial extratropical stationary wave transports associated with the Aleutian low and Siberian high pressure systems. These transports are almost entirely of the DSE, and they set up the mean state that the baroclinic storms work on. Hence the stationary waves are responsible for the location of the storm track (Branstator 1995). The maximum divergence of total energy at 35°N (Fig. 8) arises from offset peaks in both the transient and the quasi-stationary components. The divergence out of the subtropics by the transients is partially compensated by convergence in the downward branch of the local Hadley circulation, but energy is also gained from the surface (see also section 4c), especially in the form of latent energy evaporated from the oceans.

In SON (Fig. 8) the pattern is somewhat similar ex-

cept the quasi-stationary wave DSE divergence is reduced from 190 to 120 W m^{-2} and shifted poleward from about 40° to 50°N. The transients remain very strong and, because SSTs are near their maximum in September, feed on the warm surface ocean waters for energy. In MAM (Fig. 8), the pattern is closest to the annual mean and the magnitude of the transient component is reduced from winter and autumn as the ocean is depleted of heat. In summer (JJA) the transients are weakest but still distinctive with the storm track near 48°N. Monsoonal overturning helps feed the storm track, and LE emanating from the large subtropical high is significant.

In DJF and MAM a strong symbiotic relationship is apparent between the transients and the subsidence in the subtropical highs (convergence of DSE 20°–30°N in Fig. 8) associated with the downward branch of the local Hadley circulation in which the transients feed on the warmth, while helping to drive the subsidence. Remarkable cancellation also exists near 50°N where convergence by the transients feeds the quasi-stationary wave component and, at the same time, the divergence of energy by the quasi-stationary waves is balanced by the transport of energy by the transients into the region and determines the location of the storm tracks.

c. Subtropical heat budgets

Given the new estimates of the atmospheric transports, we have also estimated the TOA, surface, and atmospheric heat budgets for the ERBE period in the subtropics to provide a more complete view of the processes involved. Based on Fig. 1, we have chosen to focus on the oceans in two zones, from 25° to 30° and 30° to 35° latitude in both hemispheres. The former is clearly part of the Hadley cell subsidence.

We have devised heat budgets of the quantities illustrated in Fig. 9. The net radiation R_7 is the sum of the ASR and OLR from ERBE with appropriate sign; ASR is directed downward and OLR is upward. The sensible heat (H_s) flux and surface shortwave radiation R_s^{sw} are computed from the SOC atlas for the same period, and the amount absorbed in the atmosphere R_a is also given. Estimates of the latent energy from evaporation are taken from the SOC atlas and the NCEP reanalyses, and for precipitation from the SOC atlas and CMAP, but these are used only as guidelines, and adjustments are imposed to fit the total Q_2 based upon $E - P$ from the reanalyses. The surface longwave radiation R_s^{lw} is then estimated as a residual from Q_1 and the total atmospheric heat budget. The net radiation at the surface R_s combined with the evaporative losses and H_s gives the net surface flux $F_s = LE_s + H_s - R_s$. The large arrows indicate divergences of heat transports by the atmosphere for the DSE (left) and the LE (right), with the component from the transient eddies (top) and quasi-stationary component (bottom). Not shown are the kinetic

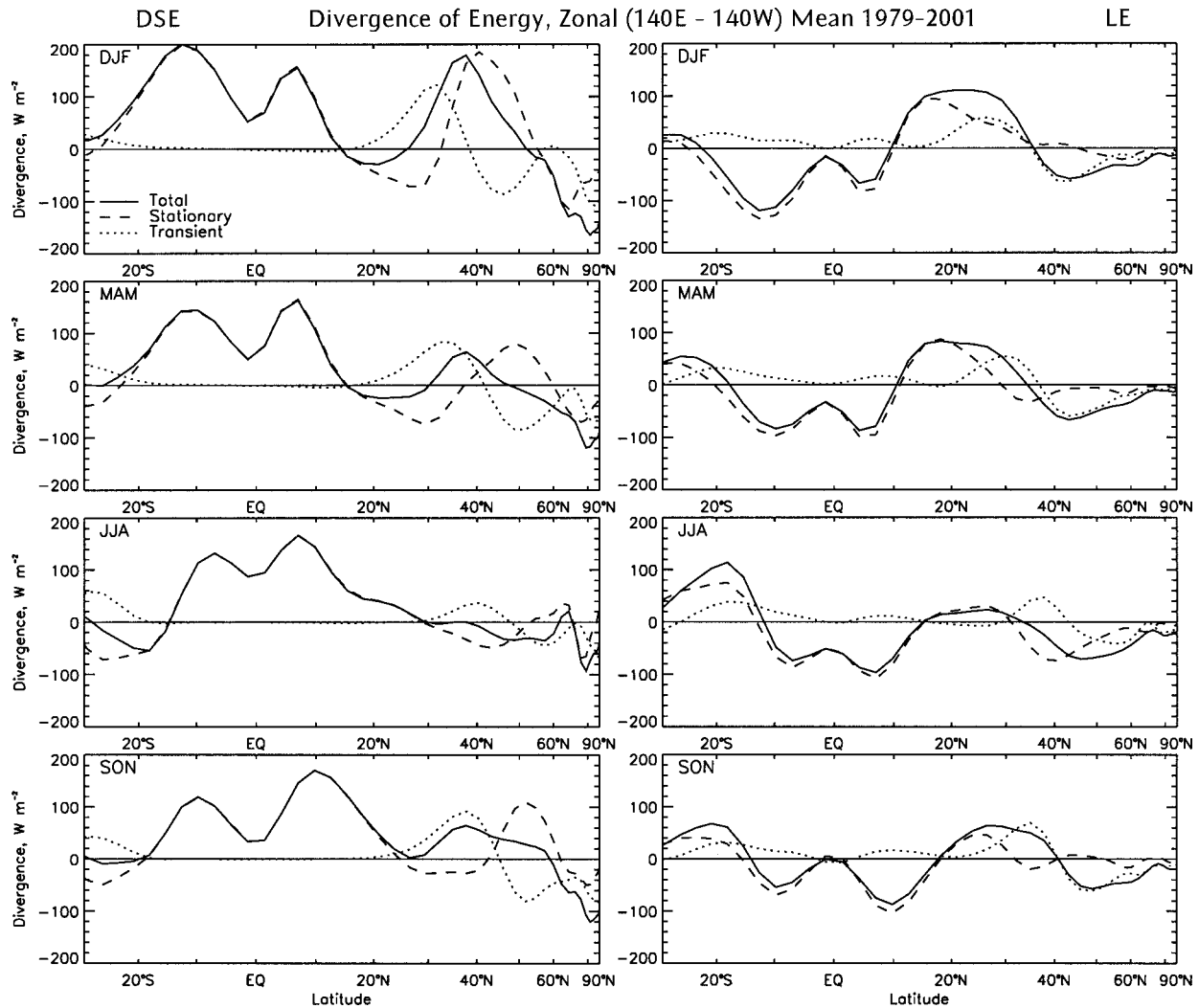


FIG. 8. The divergence of the (left) DSE and (right) LE mean total (solid), quasi-stationary (dashed), and transient (dotted) energy zonally averaged across the Pacific 140°E–140°W for the four seasons, DJF, MAM, JJA, and SON. Units are W m^{-2} .

energy divergences. Monthly means are averaged to get annualized values.

Because these values are based upon different datasets, they are not compatible, and so compromises have been made to achieve a balance. In some cases these are nontrivial although we believe the result is useful and illustrates the uncertainties. For instance, for the annual mean from 25°–30°N, 140°E–140°W, the estimates of LE_s are 111 W m^{-2} from SOC and 127 W m^{-2} from NCEP; estimates of LP are 83 W m^{-2} from SOC and 75 W m^{-2} from CMAP, yet our estimate of $L(E - P)$ of 62 W m^{-2} greatly exceeds the SOC value of 28 W m^{-2} . Our compromise values place more weight on the LP estimates and hence LE and LP are chosen as 134 and 72 W m^{-2} . In DJF our estimate of $L(E - P)$ of 102 W m^{-2} also greatly exceeds the SOC value of 44 W m^{-2} , requiring adjustments as large as 18% in LE_s . Adjustments are much smaller at other latitudes.

Figure 10 presents our estimates for the Northern

Hemisphere Pacific region for annualized means (top) and DJF (bottom) for the two zones 25°–30°N (left) and 30°–35°N (right). Similarly, in the Southern Hemisphere we present the zonal means over the oceans for the same two zones but for the annual mean and JJA (winter) (Fig. 11). In all regions and times, except for DJF 30°–35°N in the Pacific, the divergence of DSE by the quasi-stationary component is negative, suggesting domination by subsidence and hence convergence of energy by the Hadley circulation. At 30°–35°N in DJF, this subsidence contribution is overcome by the divergence in the quasi-stationary waves (Fig. 10). Both hemispheres at all times have substantial transports of DSE out of the zones by the transient waves that average about 100 W m^{-2} in the northern winter in both northern zones and, for the annual means, 30–40 W m^{-2} in the Southern Hemisphere and up to 73 W m^{-2} in the Northern Hemisphere. The annual cycle of the atmospheric transports in the Southern Hemisphere is small for 30°–35°S and

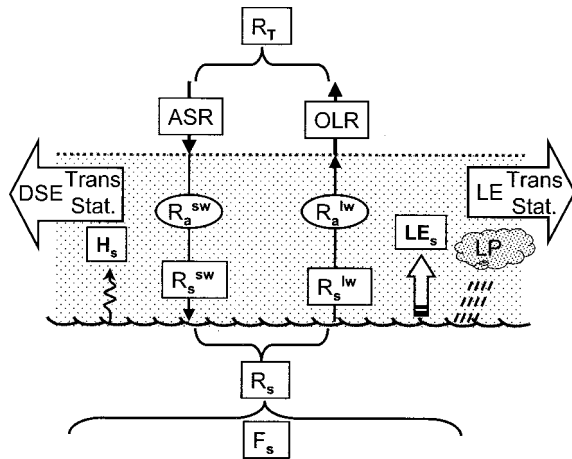


FIG. 9. Schematic layout of the energy flows in zones through the TOA (dotted line, subscript “T”), surface (scalloped line, subscript “s”), and atmosphere (stippled, subscript “a”). Arrows or brackets indicate direction of flows. Here R indicates radiation flows with amounts in square boxes and amount deposited in ovals for shortwave (superscript “sw”) or longwave (superscript “lw”). The large horizontal arrows indicate divergence of energy by the atmosphere for the (left) DSE and (right) LE broken down into transient and quasistationary components. All units are in terms of energy, hence latent heating from evaporation is given here by LE_s (to distinguish it from latent energy LE) and precipitation by LP , while the sensible heat is H_s and the net surface flux is F_s .

the main changes are in ASR and ocean heat uptake and release. At 25° – 30° S in winter, however, there is over 50% increase in DSE export by transient eddies and a substantial increase (to 83 W m^{-2}) in convergence of energy through subsidence in the Hadley circulation.

Evaporation exceeds precipitation in all zones and times (Figs. 10, 11), although more so from 25° to 30° latitude. Transient eddies carry latent energy poleward (Figs. 7 and 8) while the quasi-stationary component carries similar amounts out of the zones equatorward in the lower branch of the Hadley cell (Fig. 8). The exception is the Pacific from 30° to 35° N, where quasi-stationary waves converge moisture in the region farther north to feed the Mei Yu and Baiu convergence zones in summer (see Fig. 8).

Large seasonal variations in F_s (Figs. 10, 11) arise from the uptake of heat by the ocean in summer and its release in winter; however, the annual mean values indicate that the net transports of heat into these zones by the ocean range from 11 W m^{-2} in the Southern Hemisphere to 61 W m^{-2} for 30° – 35° N in the Pacific.

Figures 10 and 11 leave out kinetic energy transports, which are a factor in the North Pacific mainly because of zonal transports, and so there is an imbalance of as much as 33 W m^{-2} in DJF at 30° – 35° N. For the annual means the imbalance is 13 W m^{-2} in the same zone, while there is a balance in the overall budgets to within $\sim 1 \text{ W m}^{-2}$ in the Southern Hemisphere (and note some roundoff errors).

Only 30%–40% of the OLR might be considered to

come from the surface (in reality, of course, this may be absorbed and transported away and replaced by other energy), the rest arises from emission from greenhouse gases and cloud tops and originates from the absorbed solar radiation and latent heating in precipitation, plus small contributions from sensible heating. In most cases, the realized latent heating in the same zone also exceeds the net surface longwave radiation, hence the hydrological cycle provides the primary means of transferring energy away from the surface.

d. Interannual variability

Trenberth and Stepaniak (2003) explored interannual variability of the zonal means and showed that El Niño–Southern Oscillation (ENSO) provides the main signal. Moreover, the quasi-stationary wave transports are found to be 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, which in turn are altered by the resulting eddy transports. This result therefore applies not only to the mean fields but also the variability. These conclusions are also valid for the Pacific sector except that the magnitudes of the changes are enhanced by at least a factor of 2. Examination of the NCEP reanalysis monthly mean ω fields at 500 mb reveals that, for the quasi-stationary component, they are very strongly positively correlated with divergence of LE and negatively correlated with the DSE component throughout the Tropics (not shown), confirming the association of the variability in the Hadley circulation with the energy transports.

The variability on monthly and longer timescales is quite small compared with the annual mean divergences (see Fig. 6 of Trenberth and Stepaniak 2003), which are about 55 W m^{-2} at 25° – 30° S and 45 W m^{-2} at 25° – 30° N. In southern winter (JJA) the standard deviation of monthly zonal mean anomalies of divergence of DSE by transient eddies is 7 W m^{-2} at 25° – 30° S and 3 W m^{-2} at 25° – 30° N. The southern divergence is correlated 0.6 with zonal mean 500-mb ω (i.e., cooling accompanies downward motion) and corresponds to a linear regression of $4 \times 10^{-4} \text{ Pa s}^{-1}$ per W m^{-2} . It further significantly correlates with upward motion at 0° – 10° S and subsidence centered near 18° N, confirming the link between subtropical eddy cooling and the Hadley circulation.

In the northern winter (DJF), transient eddies in the subtropics of both hemispheres play a role (standard deviation of monthly zonal mean anomalies of divergence of DSE by transient eddies is 5 W m^{-2} for 25° – 30° S versus 8 W m^{-2} for 25° – 30° N). Near 30° N, divergence (cooling) is again accompanied by subsidence locally, upward motion near the equator and further subsidence near 15° S. However, cooling near 30° S is sig-

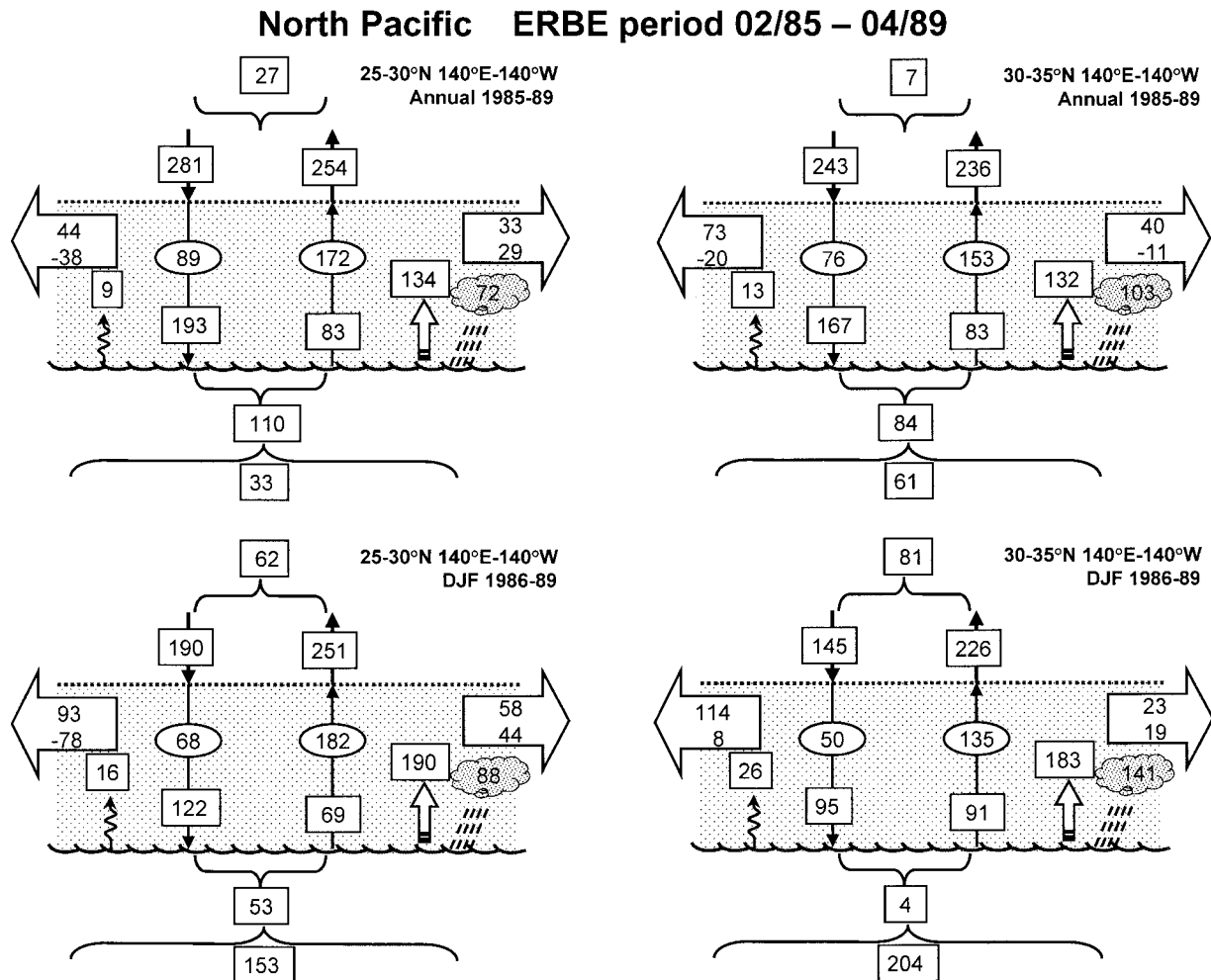


FIG. 10. Energy flow diagrams for the North Pacific sector 140°E–140°W for (left) 25°–30°N and (right) 30°–35°N, (top) annual and (bottom) DJF for the ERBE period Feb 1985–Apr 1989 in W m^{-2} .

nificantly correlated with subsidence near 30°S and 10°S, and upward motion near the equator.

5. Discussion

The development of theories of the atmospheric general circulation are very nicely summarized by Lorenz (1967) up to that time. He reviews the attempts to explain the general circulation by zonal mean overturning cells, the realization that eddies are important, and confirmation through utilization of upper-air measurements. The need for and observations of the three cells of meridional overturning in each hemisphere were established and simulated quantitatively in the famous numerical experiment of Phillips (1956). In terms of the heat budget, baroclinically unstable transient eddies provide the primary transports poleward in midlatitudes, while the Hadley cell prevails in the Tropics. It has only been since the late 1970s that several attempts, reviewed in the introduction, have been made to develop a more

complete theory of the Hadley circulation. In many ways these have been very successful, but they are also incomplete because of assumptions made about the heating.

It is well established that the Ferrel cell in middle latitudes is driven by the transient eddy transports of heat and momentum, and can be thought of as a means of quickly adjusting the atmosphere so that it remains hydrostatic and geostrophic. The transformed Eulerian framework (e.g., Andrews et al. 1987) is an alternative way to build in some of this automatic compensation. Accordingly, the poleward transient eddy heat transports are to some extent compensated by subsidence in the subtropics poleward of the Hadley circulation. However, the picture presented here is one where the average subsidence is relatively seamless, and extends equatorward of 31° into the domain of the Hadley cell. The heat divergence out of these regions by advection by the transient eddies causes dynamical cooling that compensates subsidence warming, which is linked instead to

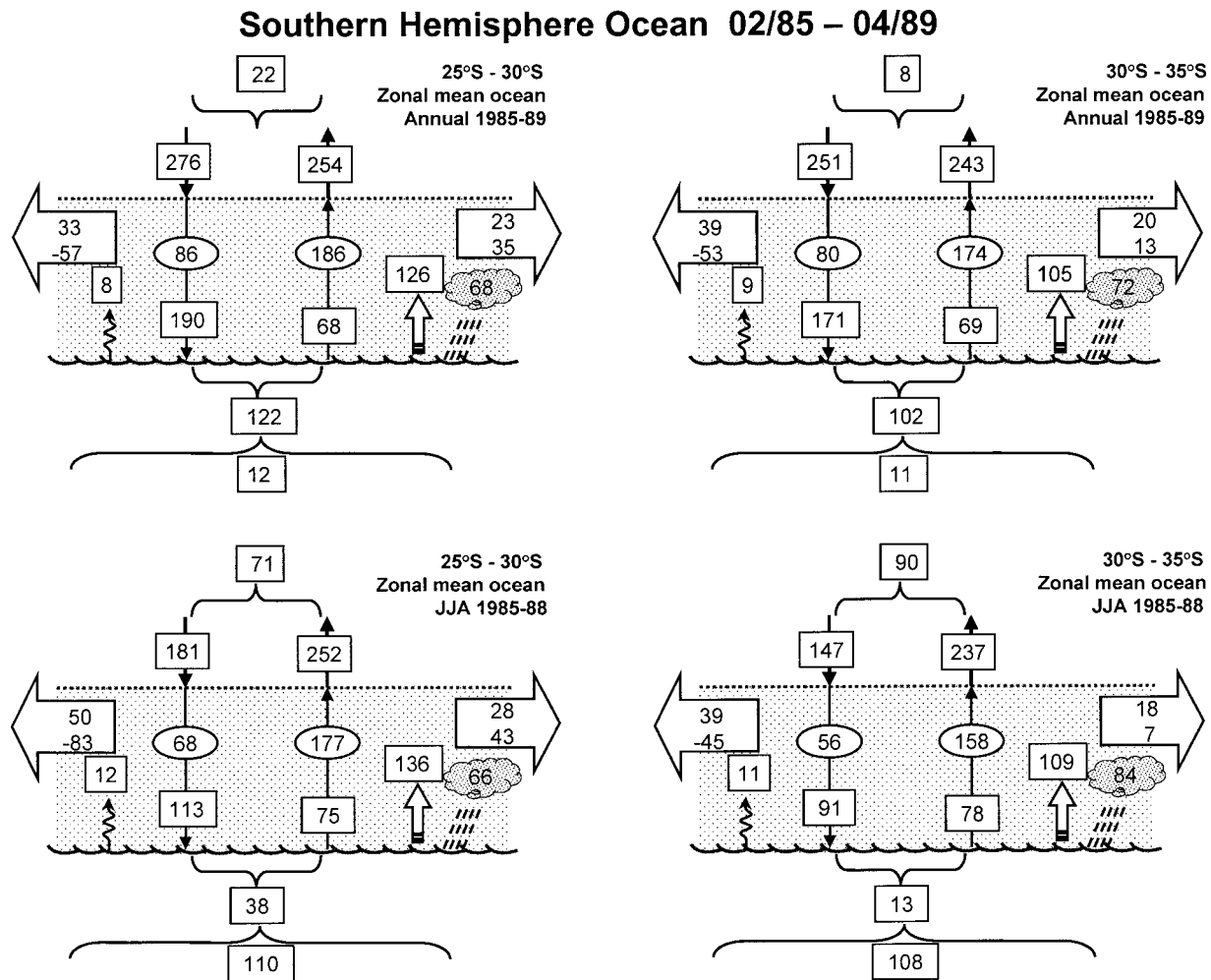


FIG. 11. Energy flow diagrams for the Southern Hemisphere zonal mean over the oceans for (left) 25°–30°S and (right) 30°–35°S, (top) annual and (bottom) JJA for the ERBE period Feb 1985–Apr 1989 in $W m^{-2}$.

the Hadley circulation. In turn, this also changes the cloudiness and water vapor distribution and makes for a relatively cloud-free and dry subtropics that is a consequence of the circulation. Despite substantial absorption of solar radiation at the surface in the relatively clear skies, large evaporative surface cooling is compensated in part by heat from ocean transports. The atmospheric moisture then helps feed the upward branch of the Hadley cell. Therefore, additional aspects of the driving of the Hadley circulation are the latent heating in the equatorial regions and the radiative cooling in the subtropics, which are feedbacks from the circulation and not fundamental drivers of it. A schematic view of the processes involved is given in Fig. 12.

The picture put forward here applies mostly to the oceans and is observationally based. Cook (2003) explores the role of continents and surface friction on the Hadley circulation. The global reanalyses have enabled us to provide new quantitative insights; however, they are diagnostic relationships, and the heat balance has to

occur by design, so it is not from these diagnostics alone that we can infer cause and effect.

For instance, one perspective is that the subsidence in the subtropics associated with the downward branch of the local Hadley circulation provides heat (energy) that the transients feed on and transport toward higher latitudes. Another, just as legitimate, viewpoint is that the transients drive the subsidence through advective cooling. The latter can be argued as the main process that is operating because both are dynamical consequences of the baroclinic instability that occur on the same timescale, whereas radiative processes have a somewhat longer timescale. What is less obvious is the link to the upward branch of the Hadley circulation until we consider the heat budget and where the heat in the subtropics comes from.

Many phenomenological studies support the second view. In particular, there is now considerable evidence that cold surges from East Asia over the South China Sea lead to an intensification of the local Hadley circu-

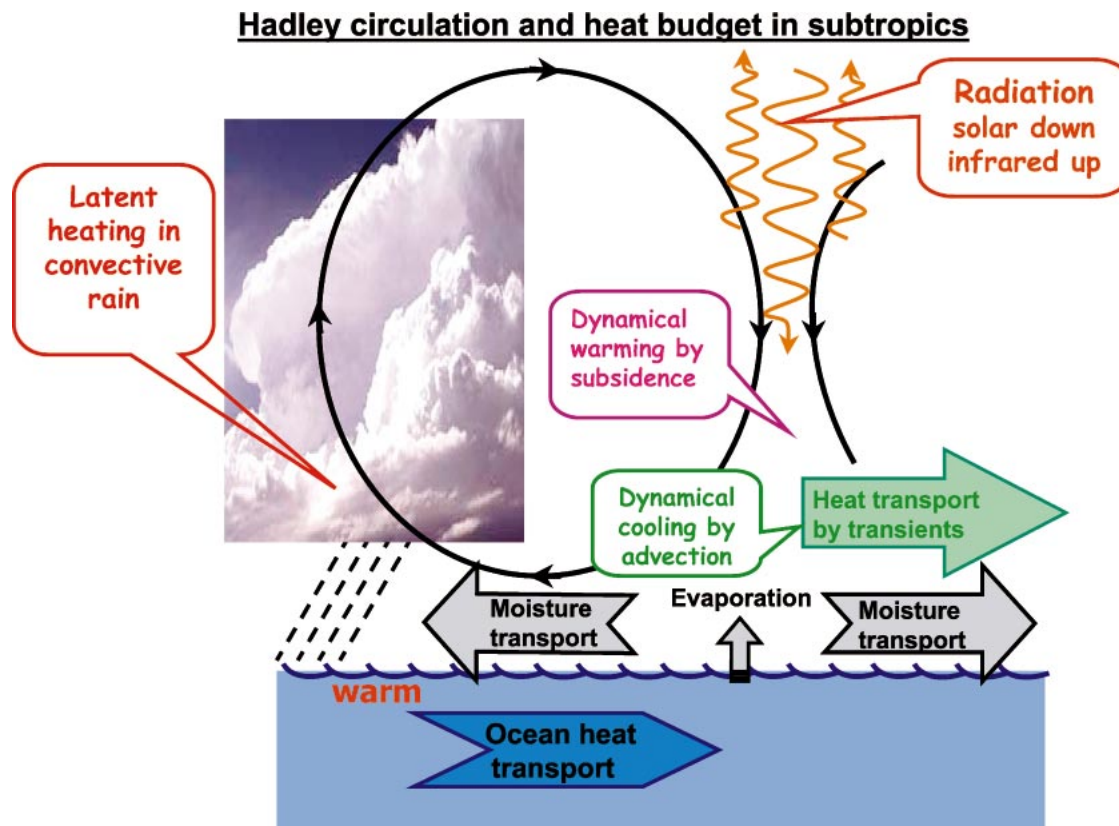


FIG. 12. Schematic of the Hadley circulation and the heat budget in the subtropics along with key processes.

lation (Ramage 1971; Chang and Lau 1980, 1982; Lau et al. 2000; Compo et al. 1999; Yang et al. 2002) and these are well simulated in models (Slingo 1998). To quote from the latter “. . . tropical east Pacific convection is initiated by the ascent and decreased static stability ahead of an upper tropospheric extratropical trough, which has penetrated the deep Tropics in the region of upper-level equatorial westerlies. Over the maritime continent, convection is enhanced by cold-surge events, in which the increased near-surface northerlies substantially enhance the air–sea interaction over the South China Sea. These cold surges are triggered by the movement of the Siberian anticyclone in association with the passage of midlatitude weather systems.” In fact such cold surges are not unique to East Asia but are also found east of the Rockies and Mexican Sierras, and east of the Andes in the Southern Hemisphere, and they move from the midlatitudes well into the Tropics to about 20°N in about 4 days (Garreaud 2001). The cold surges have a major cooling and drying effect and represent a major sink of energy for the Tropics (Garreaud 2001).

Evidence for disturbances going in the other direction are not as abundant. The main evidence is from the intraseasonal oscillation with a period of about 2 months where cloud perturbations are traceable from 10° to 35°N in the East Asian sector, mainly in the northern summer (e.g., Kang et al. 1999).

On the other hand, when the interannual variability is considered, ENSO is the predominant mode. Changes in SSTs in the tropical Pacific determine the preferred location of the moisture convergence and organized deep convection, and alter the heating patterns of the atmosphere. In turn this drives divergence that helps to set up quasi-stationary Rossby waves and teleconnections into midlatitudes, which are associated with changes in storm tracks (Trenberth et al. 1998). Nevertheless, the location of the downward branch is a key to the Hadley circulation and this is driven by the divergence of energy (cooling) by transient eddies in the subtropics, which is why the Hadley circulation is directed into the winter hemisphere. It is also why there is a very weak connection in JJA in the Northern Hemisphere but a somewhat stronger link in DJF into the Southern Hemisphere, making for a stronger southern Hadley circulation in the annual mean (Fig. 1).

6. Summary and conclusions

Results of new analyses of the atmospheric energy and heat budgets are presented. 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. These components are

also partitioned into the within-month transient and quasi-stationary components, and the annual cycle and spatial patterns are documented. The quasi-stationary component includes the long-term mean as well as the inter-annual 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 quasistationary planetary waves that are primarily a factor in the Northern Hemisphere winter. By examining all these components the main processes that come into play are documented.

There remain considerable uncertainties in the heat budgets in the subtropics, as seen in disparate estimates of evaporation and precipitation. The atmospheric moisture budget was used to constrain $E - P$ and hence to construct surface and TOA heat budgets in addition to those of the atmosphere, for the subtropical regions, with foci on the North Pacific and the zonal mean over the oceans in the Southern Hemisphere. The results are physically consistent with all the available information on the energy, mass, and moisture budgets, which is not true of the bulk fluxes computed in isolation.

There are several characteristics of the energy transports that seem quite remarkable in the way they individually feature strong signatures yet combine to give an overall seamless profile of energy transports and of energy divergences. In the Tropics, a characteristic of the Hadley circulation is the divergence of energy and poleward heat transports of the dry static energy but strong compensating equatorward moisture, or equivalently, latent energy transports. The convergence of low-level moisture, on average just north of the equator into the mean ITCZ, provides the energy that predominantly fuels the upward branch of the Hadley circulation through latent heat release in precipitation.

In the extratropics, the transports of the latent and dry static energy are both poleward although the latent energy is more important at low to midlatitudes. These transports are carried out by baroclinic disturbances, often organized into storm tracks in some broad sense. However, there is a remarkable compensation between where the divergence of the quasi-stationary energy is positive and where it is negative by the transient waves, showing the cooperative nature of these components so that they contribute to the seamless character of the overall transports. Hence the location and strength of the transients are largely determined by the stationary waves that in turn are altered by the resulting transports.

Of particular interest is the interaction between the quasi-stationary component and the transients in the subtropics. We have emphasized the importance of the reach of the energy transports by the transients well into the Tropics so that cooling results (of order 60 to over 100 W m^{-2} in winter) and this is compensated by subsidence in the downward branch of the Hadley circulation. The resulting relatively clear skies produce radiative cooling to space, which does not change much

with season and should be regarded as a modest feedback, not a fundamental forcing. It also provides for ample absorption of solar radiation at the surface where it feeds the strong evaporation that exceeds precipitation and feeds the equatorward flow of energy into the upward branch of the Hadley circulation as well as the poleward transports by storm tracks (see Fig. 12). Nevertheless, the evaporation is sufficiently strong that it also has to be compensated by a subsurface ocean heat transport. Held (2001) argues theoretically that this is because the ocean overturning and associated heat transport is driven by the Hadley circulation winds. Thus both the heating in the upward branch of the Hadley circulation and cooling in the downward branch are dependent on the circulation and should properly be regarded as feedbacks.

The seamless nature of the atmospheric poleward heat transports relates directly to how the Hadley circulation is driven and is linked with the midlatitude storms. It is a picture consistent with views of the general circulation in Lorenz (1967) but nonetheless at odds with some current perceptions about the Hadley circulation (discussed in the introduction). The latter emphasize the importance of radiative cooling in the subtropics as a driver of the Hadley cell (albeit often deliberately to explore the possible atmospheric states without eddies), whereas both the latent heating in the upward branch and the radiative cooling in the downward branch are really processes that result in large part from the circulation. Instead, as suggested by Hoskins (1996) and Rodwell and Hoskins (1996) and documented here, the cooling is more fundamentally caused by the transient baroclinic eddies advecting cooler air into the region, and these eddies play a vital role in driving the Hadley circulation. The theories of the Hadley circulation discussed in the introduction are still pertinent, although the cooling that drives the downward branch of the circulation should be properly interpreted and, like the latent heating, a portion should be part of the solution and not specified as the forcing.

This work has suggested intriguing relationships among several quantities, which combine to produce overall energy transports and divergences that are seamless. These relationships also hold on a monthly mean timescale, and therefore it is necessary to resolve daily timescales to better understand how they come about and the extent of lead and lag relationships, such as those arising from cold surges. Research into these aspects should provide a better basis for understanding how the Hadley circulation responds to transient eddy transports, and vice versa.

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