2.7 HEAT BUDGETS AND POLEWARD ATMOSPHERIC ENERGY TRANSPORTS

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1. INTRODUCTION

Observations show that not only is the total poleward heat transport continuous with latitude, so too is the atmospheric transport. 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 mid-latitudes. So how is it that the poleward heat transports are so seamless?

Most theories have an abrupt cut off at about 30° latitude at the poleward edge of the Hadley circulation for the heat transport. 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. Instead the continuity of the heat transports across latitude implies that other dynamical mechanisms are also playing key roles. We show, in a new analysis of the atmospheric heat budget, that the cooling in the subtropics also arises from heat transport to higher latitudes by quasi-horizontal air flow in the transient baroclinic eddies and quasi-stationary waves. Effectively, the radiation to space is distributed over middle and high latitudes and is not limited to the clear dry regions in the subtropics. Further we argue that some of the radiative cooling in the subtropics is a consequence of the transient baroclinic eddies.

2. THE HEAT BUDGET IN THE SUBTROPICS

Using the NCEP/NCAR reanalyses (Trenberth et al. 2001), we have computed the vertically integrated northward energy transport as the annual mean from 1979-2001 for the total and the breakdown into the contributions from transients (within-month) and the quasi-stationary component (which includes the long-term mean). The quasi-stationary component includes the contributions from the mean overturning, and the Hadley cell or monsoonal contributions are dominant in the tropics. As well as the total energy, a breakdown is made into the contributions from the dry static energy (DSE) and the latent energy (LE).

In the tropics, the cross over between the characteristic transports in each hemisphere (Fig. 1) occurs at about 7°N, the time mean location of the Intertropical Convergence Zone (ITCZ). Low level moisture transports in the Hadley circulation toward the ITCZ give rise to the LE transports in the opposite direction to those of the total and the DSE. In contrast, at higher latitudes, the transports by transient eddies for LE and DSE are both polewards. 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. Kinetic energy contributions are tiny for the northward transports and so the total energy transported meridionally is closely aligned with that of the moist static energy.

Not only are the total atmospheric transports seamless, so too is the divergence of the atmospheric transports (Fig. 2) which varies remarkably smoothly with latitude. However, the transports by the stationary component tend to reverse sign near 30-35°S and it is only the poleward transport of DSE by the stationary waves in winter the keeps the total polewards in the Northern Hemisphere. Note how the poleward transient eddy component is substantial at 25°latitude, and hence the divergence of both LE and DSE out of the subtropics is non-trivial.

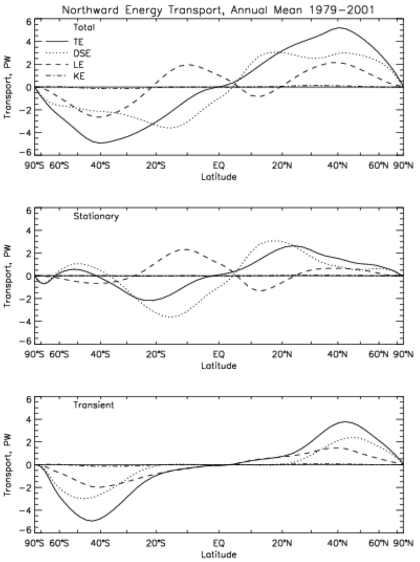

Fig. 1. Annual and zonal mean for 1979 to 2001 northward energy transport for the atmospheric energy (top), quasi-stationary component (center) and transient component (bottom), with the curves showing the total, dry static, latent and kinetic energy components; in PetaWatts. The coordinate is labeled as latitude but plotted as sinϕ so that values properly depict the area.

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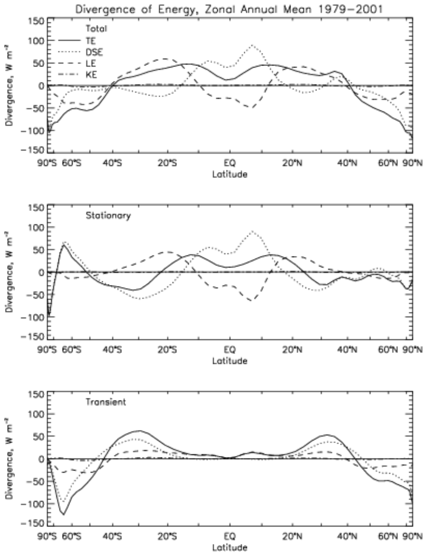

Fig. 2. Annual and zonal mean for 1979 to 2001 northward energy transport divergence for the atmospheric energy (top), quasi-stationary component (center) and transient component (bottom), with the curves showing the total, dry static, latent and kinetic energy components; in W m^{-2}. The coordinate is labeled as latitude but plotted as sinϕ so that values properly depict the area.

Given the new estimates of the atmospheric transports, we have estimated the top-of-atmosphere (TOA), surface, and atmospheric heat budgets in the subtropics to provide a more complete view of the processes involved. At the TOA we use data from the Earth Radiation Budget Experiment. The diference between the R'TOA energy divergence and the total in Fig. 2 is due to the ocean transports, and hence the minimum near the equator is related to the equatorial cold tongue in the tropical Pacific Ocean where heat enters the ocean.

At the surface the atlas from the Southampton Oceanographic Centre is used along with NCEP estimates and independent CMAP estimates of precipitation. The compromise result for the subtropics of the Southern Hemisphere zonal and annual mean from 25 to 30°N is shown in Fig. 3. 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 stationary component (bottom). The rhs shows the components for moisture: surface evaporation (latent flux), precipitation, and divergence by the atmosphere. The center shows the radiative fluxes and divergences, and the left shows the sensible heat flux at the surface.

There is a net transport of heat into the zone by the ocean of 9 W m^{-2} and at TOA of 19 W m^{-2}. Evaporation exceeds precipitation and transient eddies carry latent energy polewards (19 W m^{-2}) while the stationary component carries similar amounts equatorwards in the lower branch of the Hadley cell (27 W m^{-2}). The surface evaporative cooling in the same zone exceeds the net surface longwave radiation, hence the hydrological cycle provides the primary means of transferring energy away from the surface.

The divergence of DSE by the stationary component is negative (63 W m^{-2}), suggesting domination by subsidence and hence convergence of energy by the Hadley circulation. Baroclinic transient waves are responsible for a energy loss from the zone (63 W m^{-2}). Within the atmosphere, net radiative divergence (80 W m^{-2}) is compensated for by latent heating (64 W m^{-2}), modest sensible heating (9 W m^{-2}) and subsidence (63 W m^{-2}) but with a loss of 44 W m^{-2} in DSE divergence by the transient eddies. The small imbalance arises from kinetic energy contributions.

Only 31% of the OLR might be considered to come from the surface (90 W m^{-2}) (in reality, of course, this may be absorbed and transported away and replaced by other energy), the rest arises from emission from the greenhouse gases and cloud tops and originates from the absorbed solar radiation and latent heating in precipitation, plus small contributions from sensible heating. The warming by subsidence also contributes. The myth is that the heat balance is between subsidence from the Hadley circulation and radiative cooling to space (that is enhanced by the dry air). In winter, the subsidence contribution is greater as is the divergence of DSE by transients, and there is a strong seasonal variation in ocean heat uptake and release.

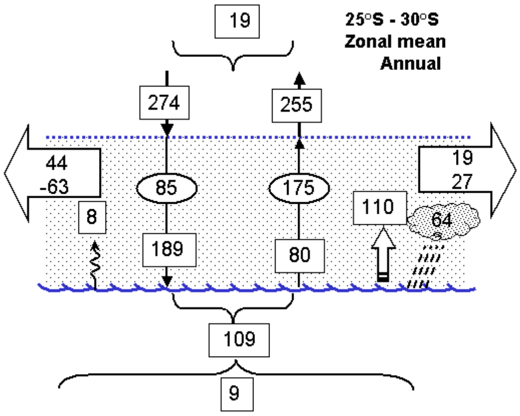

Fig. 3. Energy flow diagram for the TOA (dotted line), surface (scalloped line), and atmosphere (stippled) for the zonal mean for 25-30°S annual mean in W m^{-2}. Arrows or brackets indicate direction of flows with radiation flows in the center, with amounts in square boxes and divergence in ovals for shortwave (left) and longwave (right). The large horizontal arrows indicate divergence of energy by the atmosphere for the DSE (left) and LE (right) broken down into transient (top) and stationary (bottom) components. The surface sensible heat is at left and latent evaporative energy at right, along with that realized as precipitation. The net surface flux is given below.

The enhancement of OLR through dryness appears to be at most 20 W m^{-2} but this is only a small fraction of the loss of heat to higher latitudes by transient eddies. Exploration of interannual variability reveals strong ENSO relationships. Sea surface temperatures (SSTs) in the tropics determine the location of the upward branch of the Hadley circulation, with preferred convergence near warmest SSTs, but the organization is provided by the circulation itself. The heat divergence out of the subtropics by advection by the transient eddies (including events such as cold surges) causes dynamical cooling that drives subsidence which is linked to the Hadley circulation rather than the Ferrel cell. We argue that this process determines the downward branch of the Hadley circulation and why it switches hemispheres with the seasons.

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, and the moisture helps feed the upward branch of the Hadley cell. Therefore, key aspects of the driving of the Hadley circulation: the latent heating in the equatorial regions and the radiative cooling in the subtropics, are *feedbacks* from the circulation and not *fundamental* drivers of it.

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Reference

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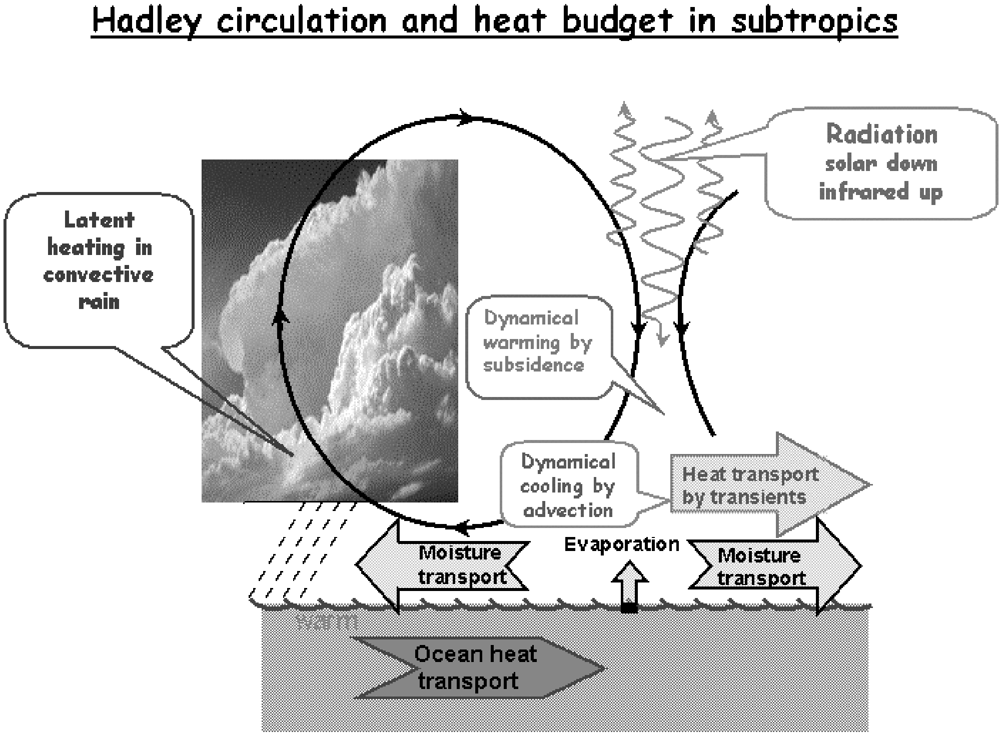

Fig. 4. Schematic of the Hadley circulation and key processes.