

Estimates of Tropical Diabatic Heating Profiles: Commonalities and Uncertainties

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ABSTRACT

This study aims to evaluate the consistency and discrepancies in estimates of diabatic heating profiles associated with precipitation based on satellite observations and microphysics and those derived from the thermodynamics of the large-scale environment. It presents a survey of diabatic heating profile estimates from four Tropical Rainfall Measuring Mission (TRMM) products, four global reanalyses, and in situ sounding measurements from eight field campaigns at various tropical locations. Common in most of the estimates are the following: (i) bottom-heavy profiles, ubiquitous over the oceans, are associated with relatively low rain rates, while top-heavy profiles are generally associated with high rain rates; (ii) temporal variability of latent heating profiles is dominated by two modes, a deep mode with a peak in the upper troposphere and a shallow mode with a low-level peak; and (iii) the structure of the deep modes is almost the same in different estimates and different regions in the tropics. The primary uncertainty is in the amount of shallow heating over the tropical oceans, which differs substantially among the estimates.

1. Introduction

To the first order, the atmospheric general circulation redistributes energy and balances the horizontal and vertical gradients of diabatic heating. Since the earth's atmosphere is primarily heated from the surface, convective processes are required to maintain the troposphere close to neutral stratification. On the large scale, the heating gradient between the tropics and extratropics is balanced by the poleward transport of the heat of the general circulation. However, the heat fluxes from

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the surface to the atmosphere are influenced by the ambient surface winds as well as temperature and moisture distributions. Hence, the three-dimensional structure of the diabatic heating is closely related to the atmospheric circulation because it not only drives the circulation, but also receives feedback from it.

This is particularly true for the diabatic heating associated with tropical precipitation, which on the one hand is a result of instability due to the accumulation of convective-scale moist static energy near the surface and, on the other, drives circulation. In fact, this heating accounts for three-fourth of the total heat energy available in the earth's atmosphere and two-thirds of this rainfall occurs in the tropics (Tao et al. 2006). The interaction of diabatic heating and the circulation is further complicated by the fact that the vertical structure of the heating is related to the microphysical processes within convective systems. As pointed out by Houze (1982) and Johnson and Young (1983), there is a remarkable difference in the heating profiles between convective and stratiform regions of mesoscale convective systems (MCSs).

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They found that in convective regions of MCSs, the heating profile has positive heating throughout the troposphere with a maximum in the midtroposphere, while, in stratiform regions, there is an upper-level heating and cooling below the melting level. Hartmann et al. (1984) showed that the pattern of the large-scale circulation is sensitive to the vertical structure of the diabatic heating. In their linear modeling study, the inclusion of the topheavy heating profile associated with mature cloud clusters elevates the circulation response, resulting in a better agreement of the simulated Walker circulation with the observations than a conventional middle-heavy profile that is often associated with young deep convection. Another modeling study by Schumacher et al. (2004) also suggests significant sensitivity of the circulation to variations in the stratiform-convective heating fraction across the tropical Pacific.

In addition to their influence on the structure of largescale circulation, diabatic heating profiles and their variability play an important role in the organization of mesoscale convective systems through the generation of vorticity. For example, the midtropospheric positive vertical gradient of heating in stratiform regions favors the generation of positive potential vorticity anomalies (Zhang and Fritsch 1987; Raymond and Jiang 1990), which are believed to contribute to a longer life span for precipitation systems and to heavy rainfall. Furthermore, the vertical structure of the heating in concert with temperature anomalies contribute to the generation of available potential energy, thereby influencing the energetics of disturbances (Wang 2006).

For the last 10 yr, global tropical precipitation has been observed at high resolution by instruments aboard the Tropical Rainfall Measuring Mission (TRMM) satellite (Kummerow et al. 2000). One of these instruments is the TRMM Precipitation Radar (PR), which resolves the vertical structure of precipitation and enables the identification of convective and stratiform precipitation based on the reflectivity and echo-top height of the precipitating clouds. The other is the TRMM Microwave Imager (TMI) that enables the measurement of rainfall characteristics over a wider areal swath. Thus, for the first time, estimation of the three-dimensional structure of diabatic heating associated with precipitation and its temporal variability over the entire tropics became possible.

Several ways of utilizing the TRMM data to calculate diabatic heating profiles have been proposed and implemented. Tao et al. (2001) presented an intercomparison of profiles from three diabatic heating algorithms, the hydrometeor heating (HH; Yang and Smith 1999a,b), convective–stratiform heating (CSH; Tao et al. 1993), and the Goddard Profiler heating (GPROF; Olson et al. 1999) for February of 1998. Based on the results of the spectral precipitation statistics of Takayabu (2002), Shige et al. (2004, 2007, 2008) also developed the spectral latent heating (SLH) algorithm and data. Grecu et al. (2009) developed a similar technique to utilize TMI data to remedy the undersampling associated with the narrow swath of the PR using a training algorithm (TRAIN). Yet another estimate from TRMM is based on the precipitation radar heating (PRH) algorithm by Kodama et al. (2009). Even though these algorithms differ in their details and they continue to be improved, the basic approach remains to involve an examination of the vertical structure of the precipitation and an assignment of the appropriate heating or vertical velocity profiles.

While the microphysical basis for the above-described heating estimates is justified, errors in the categorization of precipitation systems as well as the structure of the assigned profiles can easily introduce significant uncertainties in the final products. The accuracy and usefulness of an estimate of the heating profiles are ultimately hinged on their consistency with the circulation. Specifically, the heating estimates based on the microphysics, and those based on the large-scale circulation and thermodynamics, need to show some degree of agreement not only in terms of averages over a certain region and/or time but also in terms of their spatial and temporal variabilities. In practice, however, estimates of heating from the circulation present a different set of challenges. For example, the common approach of calculating diabatic heating using a residual diagnosis of the thermodynamic budget depends on the estimate of divergence or vertical velocity, which are prone to errors associated with low resolution. In the case of diabatic heating from reanalysis products, the estimate is further complicated by parameterization of moist processes in the assimilation schemes.

Because of the various potential sources of uncertainties, a comparison of diabatic heating estimates based on independent data sources, assumptions, and methods would enable us to test the validity of the assumptions and methods, to build confidence in the elements of the estimates that are consistent with each other, and to draw cautionary attention to those that differ substantially. With this general purpose in mind, this study aims to

- (i) present the mean and variability characteristics in estimates of heating profiles over various tropical regions based on the observations by the TRMM satellite, global reanalyses, and sounding data; and
- (ii) identify primary interproduct differences and similarities in the profiles and quantify their uncertainties.

2. Data and method

a. TRMM products

Four available heating estimates derived from TRMM (CSH, SLH, PRH, and TRAIN) are included in this study. In the CSH algorithm (Tao et al. 1993, 2000), the diabatic heating is determined by the surface rainfall rate and its stratiform fraction, which are obtained from the PR. The CSH algorithm uses a lookup table (LUT) of rain-normalized heating profiles associated with various types of cloud systems in different geographic locations (see Figs. 3 and 4 in Tao et al. 2001) that have been averaged into three convective and stratiform rain types: oceanic, continental, and shallow. The profiles are generated by cloud-resolving model (CRM) simulations that have been validated against sounding observations in limited tropical regions. The depth of the heating varies depending on the PR echo-top height and its magnitude is determined according to the PR surface precipitation amount The SLH algorithm (Shige et al. 2004, 2007, 2008) follows generally the same strategy of the CSH algorithm except a CRM was used to generate the predetermined vertical profiles of the latent heating that vary continuously with the PR echo-top height, instead of only a limited number of heating profiles in the LUT as in the CSH algorithm. The PRH algorithm (Kodama et al. 2009) estimates the latent heating from the growth-evaporation of raindrops during their vertical displacement. It utilizes the vertical gradient of precipitating water with respect to the motion of precipitating particles. An observed increase in precipitation water amount with respect to the direction of the motion of the precipitating particles is regarded as the result of the condensation and deposition. A decrease, on the other hand, is regarded as the result of the evaporation of the precipitating particles. In a manner similar to that of SLH, the TRAIN algorithm utilizes the PR data and a cloud-resolving model. However, in this algorithm heating profiles along with coincident TMI brightness temperature observations are assembled into a large database. Then, if TMI provides a set of brightness temperatures at a given location, the large database can be queried to find brightness temperatures that are consistent. The surface rain rates, stratiform rain rates, precipitation profiles, and the profiles in the database that are associated with consistent brightness temperatures are composited using a Bayesian method to find the "expected values" of these parameters, given the TMI observations. This algorithm for estimating heating is referred to as TRAIN because the TMI method is essentially trained to find a best estimate of Q1-QR, where Q1 is the total diabatic heating and QR is the radiative heating. To calculate Q1, the radiative heating

estimated from the atmospheric radiative heating climatology derived from an approach known as the Hydrologic Cycle and Earth's Radiation Budget (HERB) algorithm (L'Ecuyer and Stephens 2003, 2007) is added to the Q1–QR.

All the estimates depend on lookup tables: base heating profiles in CSH, SLH, and TRAIN, and vertical motion profiles in PRH. CSH and SLH are daily on a $0.5^{\circ} \times 0.5^{\circ}$ horizontal grid and at 19 height levels; TRAIN provides the orbital data on 29 height levels. The PRH data are in pentad format on a $2.5^{\circ} \times 2.5^{\circ}$ grid at 41 height levels. All of these data cover 1 January 1998–31 December 2007.

b. In situ soundings

The apparent heating sources (Q_1) calculated from in situ soundings from eight field campaigns at various tropical locations are included in this study. These are the Tropical Ocean Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA COARE), the Global Atmospheric Research Program Atlantic Tropical Experiment (GATE), the Kwajelin Experiment (KWAJEX), the Tropical Warm Pool International Cloud Experiment (TWP-ICE), the South China Sea Monsoon Experiment's Northern and Southern Enhanced Arrays (SCSMEX-N and SCSMEX-S), the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA), and the Mirai Indian Ocean Cruise for the Study of the MJO-Convection Onset (MISMO). The locations and durations, as well as references of these field campaigns, are listed in Table 1. In calculating Q_1 , vertical velocity is first derived from the horizontal wind and pressure by vertical integration of the divergence; then, the three-dimensional wind, pressure, and temperature are substituted into the energy conservation equation (Yanai et al. 1973). The spatial coverage areas and temporal resolutions, as well as the lengths of the datasets, vary substantially among these datasets. For all the field campaigns, the Q_1 data are available every 6 h at a fixed location, except for GATE. In GATE the average of the 3-hourly gridded data from the inner hexagon is averaged into 6-hourly data for consistency. The Q1 values estimated from sounding observations are usually taken as the ground truth for calibration and validation of satellite products. They, therefore, are included in this study in spite of their very limited coverage in time and space. A more detailed diagnostics of sounding Q1 using similar methods as in this study is given by Zhang and Hagos (2009).

c. Reanalysis products

Estimates of diabatic heating associated with precipitation from four global reanalyses are also included

Experiment	Location	Period	Reference		
TOGA COARE	Equatorial western Pacific	1 Nov 1992–28 Feb 1993	Webster and Lukas (1992)		
GATE	Tropical Atlantic	26 June-19 Sep 1974	Houze and Betts (1981)		
KWAJEX	Marshall Islands	24 Jul-15 Sep 1999	Yuter et al. (2005)		
TWP-ICE	Darwin, Australia	21 Jan-12 Feb 2006	May et al. (2008)		
SCSMEX (-N and -S)	South China Sea	5–25 May and 5–22 Jun 1998	Lau et al. (2000)		
LBA	Amazonia	1 Nov 1998–28 Feb 1999	Silva Dias et al. (2002)		
MISMO	Equatorial Indian Ocean	24 Oct-25 Nov 2006	Yoneyama et al. (2008)		

TABLE 1. Locations, durations, and references of soundings data.

in this study: the National Centers for Environmental Prediction-Department of Energy (NCEP-DOE) reanalysis (NCEPII; Kanamitsu et al. 2002), the Japanese 25-yr reanalysis (JRA25; Onogi et al. 2007), the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40; Uppala et al. 2005); and the Modern Era Retrospective Analysis for Research and Applications (MERRA) from the National Aeronautics and Space Administration (NASA) Global Modeling and Assimilation Office (Bosilovich et al. 2006). NCEP and JRA25 are 6-hourly data; ERA-40 and MERRA are daily. To overlap with the TRMM data, all of the reanalysis products used in this study start from 1 January 1998. The lengths of the time periods, however, vary depending on the data availability: 10 yr for NCEPII and JRA25, 4 yr for ERA-40, and 6 yr for MERRA.

For all of the reanalyses, the diabatic heating associated with precipitation is estimated from the threedimensional wind, temperature, and precipitation fields. This estimate of the heating from the reanalysis products involved a two-step process. First, total diabatic heating Q_1 is calculated as the residual of the thermodynamic equation on pressure surfaces [Eq. (1)] in a manner similar to that presented by Nigam et al. (2000):

$$Q_1 = \frac{C_p T}{\theta} \left(\frac{\partial \theta}{\partial t} + u \frac{\partial \theta}{\partial x} + v \frac{\partial \theta}{\partial y} + \omega \frac{\partial \theta}{\partial p} \right), \tag{1}$$

where u and v are the zonal and meridional wind components; $\theta = T(p_s/p)^{R/C_p}$ is the potential temperature, with T being the temperature; p is the pressure and p_s the surface pressure; C_p is the specific heat capacity of dry air; and R is the specific gas constant of dry air. Here, Q_1 is calculated using central finite differencing at the horizontal grids at the 17 pressure levels. To reduce error due to irregular pressure level spacing, $\partial\theta/\partial p$ is replaced by $\partial\theta/p\partial \ln(p)$ in the finite differencing.

The second step is to estimate the diabatic heating associated with precipitation. That is calculated by conditioning the total diabatic heating (Q_1) by the presence of precipitation. In other words, the diabatic heating associated with precipitation is equal to the total diabatic heating if the precipitation is greater than zero and is zero otherwise. This is because the heating profiles in the TRMM products are available only in regions with precipitation (and hence dominantly latent heating); this conditioning would eliminate the effects of diabatic heating in grid points where precipitation is absent (where sensible heat fluxes and radiative cooling dominate). One has to keep in mind that even this is not a perfect comparison, because even though the conditioning by precipitation in the TRMM products is at the satellite footprint level, those for the reanalyses are at their own resolutions. Therefore, the diabatic heating estimates from the reanalyses are likely to be contaminated by diabatic heating not necessarily associated with precipitation.

It is important to note that the vertical velocity and associated divergent circulation are influenced by the particular convection parameterization in the reanalyses. Furthermore, in the calculation of diabatic heating using the soundings, vertical velocity is calculated by the vertical integration of divergence. Because divergent wind generally composes only a small fraction of the total wind, calculation of the vertical velocity using only divergence can result in significant errors in diabatic heating. To address this problem, Sardeshmukh (1993) proposed a method of calculating the vertical velocity in which both conservations of energy and vorticity requirements are satisfied. For consistency with the sounding estimates, results with diabatic heating estimated as a residual of the energy budget in the reanalyses are presented in this study. Since the primary focus of this study is on the structure of the heating profiles over the tropics, not the actual magnitude (which depends on estimates of total rainfall, which are more sensitive to cumulus parameterizations in the reanalysis products), the profiles presented in this study are all normalized (divided by the norm, which is the square root of the sum of the squared heating at the 17 levels.) for proper comparison. However, the magnitudes of the heating from all the products are briefly discussed at the end of the next section.



FIG. 1. Comparison of diabatic heating from the standard output of the MERRA reanalysis and that estimated from the associated dynamical fields according to the method discussed in the text: (a) Q_1 and (b) normalized Q_1 .

To provide insight into the nature of the uncertainty associated with the above-discussed approach of estimating diabatic heating conditioned by precipitation using the analysis data, an estimate from the MERRA reanalysis is compared to its standard total diabatic heating output, which is also conditioned by precipitation. Figure 1a shows a comparison of the diabatic heating over the Atlantic (Q_1) from the standard model output and that calculated from the dynamical fields, both conditioned by precipitation. The estimate is quite close to the standard output not only in magnitude but also in the levels of the peaks (600 and 900 hPa). The normalized profiles of the estimated and standard output latent heating results, on the other hand, are fairly close (Fig. 1b).

For proper comparisons, the 6-hourly reanalysis heating data are averaged onto daily data and the TRMM products are regridded on to the reanalyses $(2.5^{\circ} \times 2.5^{\circ})$ horizontal grids. They are also interpolated onto 17 reanalysis pressure levels. In comparing diabatic heating profiles from the soundings with those from the TRMM and reanalysis products, one should bear in mind that the estimates from the TRMM and reanalysis products are either purely latent heating (SLH and PRH) or diabatic heating only when there is precipitation (CSH, TRAIN, NCEPII, JRA25, ERA-40, and MERRA), while those from the soundings are purely total diabatic heating. But diabatic heating profiles from the soundings include clear-sky points, which presumably do not contribute much to the total heating and hence have little impact on the normalized profiles of the total heating. For brevity, however all the variables will be referred to as diabatic heating.

3. Results

a. Mean profiles over global tropics profiles and regional variability

In this section, the global and regional mean profiles from the eight products (four reanalyses and four TRMM), as well as the soundings, are compared. The tropical domain is divided into nine regions based on TRMM (3B42) gridded 10-yr mean rainfall results (Fig. 2). They represent regions of continents (Africa and South America), monsoons (Asian monsoon), warm pools (West Pacific), the ITCZ (central, east Pacific, and Atlantic), the SPCZ (South Pacific), and the Indian Ocean. Table 2 shows their latitudes and longitudes. These regions together define the global tropics for the rest of this article.

Tropical mean profiles and spatial variability are compared first. Figure 3 shows the spatially and temporally averaged profiles (solid lines) and ± 1 standard deviation (dashed lines) calculated using the normalized profiles at every grid point in all regions. The differences among the estimates are striking. CSH is dominated by a topheavy mean profile with little low-level heating, while the SLH mean profile has two peaks: one in the upper troposphere (400 hPa) and another in the lower troposphere (850 hPa). The PRH profile shows one sharp maximum near the melting level, while TRAIN has two peaks: one at 400 hPa and another at about 750 hPa. Somewhat more subtle differences exist among the reanalyses products. ERA-40 has its peak near the 500-hPa level with a hint of a low-level peak near 850 hPa. NCEPII is bottom heavy, with a peak near 700 hPa. MERRA has a middle-level heating peak near 600 hPa and secondary low-level heating near 900 hPa. JRA25 has a peak at 400 hPa and a secondary peak at about 900 hPa. The profile from the average of all of the soundings combined end to end tends to be relatively top heavy compared to those of the reanalysis estimates. This might be due to the fact that unlike the other products, which are climatological averages, the in situ measurements are often performed over regions and periods where deep intense heating is frequent. The main point here is that a secondary lower-tropospheric heating peak exists in most estimates, even though its exact pressure level and relative magnitude in comparison to the primary upper-middle-tropospheric peak differ among the estimates.

The mean profile in each region and each estimate is shown in Fig. 4. As noted above, the nature of the



FIG. 2. The 10-yr mean precipitation from TRMM (3B42) (mm day⁻¹). The boxes indicate the domains of analysis (listed in Table 2). The locations of the soundings are marked by an X.

differences and similarities among the mean profiles shows little regional variability. The major differences among the products can be generalized to most of the regions. The primary peak of NCEPII is at relatively lower levels (600-700 hPa). In MERRA, the low-level peak is closer to the surface (900 hPa). PRH has a particularly sharp peak at 500 hPa. CSH has a peak near 400 hPa (highest of all the products) and no secondary low-level peak. SLH, in agreement with the reanalysis estimates, has more low-level heating than the other TRMM estimates. The TRAIN profile over the oceans often lies between CSH and SLH. Overall, with the exception of MERRA, which has unusually bottomheavy heating in the central Pacific, the reanalysis estimates appear to be in better agreement with each other than do the TRMM estimates. This suggests that the influences of the input observations on the data assimilation procedures dominate those from differences parameterization schemes.

Based on mesoscale cloud dynamics, it is known that there are several categories of precipitation systems, each with a characteristic heating profile (e.g., Schumacher et al. 2007). Even though identifying these profiles in the estimates based on satellites, sounding observations, and global reanalyses is impractical, given their spatial and temporal resolutions, the roots of the differences in the mean profiles can be explored by asking the following questions:

- What kind of individual instantaneous profiles constitute the regional and temporal mean profiles?
- Do interproduct differences come from the structures of these individual profiles or from their combinations (relative amounts)?

These questions are the subject of the next subsection.

b. Relationship of latent heating profiles with precipitation rate

To aid in the interpretation of the agreements and discrepancies among the mean profiles discussed pre-

viously in terms of physical processes, compositions of these mean profiles have to be analyzed. For example, an individual type of heating profiles that occurs infrequently with large amplitudes should be distinguished from those that occur frequently with small amplitudes. Both may contribute similarly to the mean but they represent different physical processes. Therefore, from a statistical point of view, a physical agreement among heating profiles requires consistency in their higher-order moments or probability distribution functions (PDFs), as well as in their mean structures. For this purpose, we examine the heating profiles as functions of precipitation rate. Since the magnitude of the precipitation spans a wide range, it is convenient to consider its probability distribution in log scale. The range of precipitation rate between 10^{-2} and 10^2 mm day⁻¹ is partitioned into 60 bins to construct the PDF. The mean heating profile within each bin is normalized and plotted in Fig. 5 for the Atlantic region.

All TRMM and reanalysis estimates, except PRH, show their heating peaks becoming elevated as the precipitation rate increases. The only estimate that produces stratiform cooling in the lower troposphere at high precipitation rate is TRMM PRH. The relationships between the profiles and the precipitation rate are consistent between CSH and SLH, with shallow heating at low precipitation rate, except at a very low precipitation rate where the CSH heating is elevated. The

TABLE 2. Definition of domains.

Region	Lat	Lon		
Africa	10°S-10°N	10°-30°E		
Indian Ocean	10°S-10°N	50°-110°E		
South Asia	10°-20°N	60°-110°E		
West Pacific	0°-22°N	110°-170°E		
South Pacific	$20^{\circ}\text{S}-0^{\circ}$	130°E-160°W		
Central Pacific	0°-15°N	170°E-130°W		
East Pacific	0°-15°N	130°-80°W		
South America	15°-5°S	80°-45°W		
Atlantic Ocean	0°-10°N	$45^{\circ}W-0^{\circ}$		



FIG. 3. (a)–(h) Normalized mean heating profiles averaged over the entire tropics (all the boxes in Fig. 2) and (i) the mean profile of the diabatic heating from all the soundings.

deep heating in CSH is deeper than in SLH and the reanalyses. The gradual transition of the SLH profile from shallow to deep as the precipitation rate increases is in better agreement with the reanalyses than other TRMM estimates. This relationship between the latent heating profile and the precipitation intensity is in agreement with the results of Short and Nakamura (2000) that show a correlation of 0.71 between PR echo-top height



FIG. 4. Normalized mean profiles of heating, averaged over the respective regions in Fig. 3.

and conditional rain rate over the Atlantic and eastern Pacific Oceans. In PRH, the relationship between the precipitation rate and the heating profiles is very different. Top-heavy profiles dominate throughout the precipitation rate range, and they are even more elevated at the low-precipitation tail. As with CSH and SLH, TRAIN has upper-level heating and low-level cooling at higher precipitation rate limits and some shallow heating at low precipitation rates, but unlike in those products, heating is essentially absent at very low precipitation rates ($<1 \text{ mm day}^{-1}$).

A similar diagnostic process is performed over Africa (Fig. 6). There is no low-level heating peak in any of the three TRMM estimates (TRAIN has no estimate of heating over land). At the low precipitation rate tails, the TRMM estimates have elevated heating and low-level



FIG. 5. (a)–(h) Normalized heating profiles as functions of (top panels of two panels) PDFs and (bottom panels) precipitation intensity of precipitation over the Atlantic.



cooling. In the reanalysis estimates, there is an abrupt transition in the profile of the diabatic heating with sensible heat fluxes and radiative cooling dominating below about 1 mm day⁻¹ and elevated latent heating at higher precipitation rates, because shallow latent heating is essentially absent there.

In summary, in the mean, these estimates differ from each other mainly in where their heating peaks are and whether they have just a single peak or double peaks. With respect to precipitation intensity, the profiles of SLH are well within the uncertainties of the reanalyses at the high precipitation limit, while CSH is more top heavy. Because observed information on precipitation depth is used in addition to precipitation type and intensity, the amount of shallow heating is greater in SLH than CSH (Shige et al. 2007). PRH has a characteristic sharp midtropospheric peak and in general TRAIN profiles lie in between CSH and SLH. The differences in the oceanic low-level heating among the TRMM products are, however, in the amount and structure of the shallow latent heating, which is most abundant in SLH, small in CSH and TRAIN, and essentially absent in PRH. On the other hand, while all the reanalyses have low-level heating peak near the surface, the magnitude and height vary.

c. Temporal variability

Because of the differences in the methodologies and the stochastic nature of precipitation and diabatic heating, one cannot expect to gain much insight from direct comparison of instantaneous heating. However, since these estimates should represent the same physical processes, they may share similar temporal characteristics, such as the primary modes of variability. One way of comparing their temporal variabilities is the use of empirical orthogonal functions (EOFs). However, the vertical structure of physically meaningful modes should not be constrained a priori. For example, there is no physical reason for stratiform and convective heating profiles to be spatially orthogonal. In this study, varimax rotated EOF (REOF) analysis (Kaiser 1958; Wilks 2006) is performed at every grid point in all eight of the TRMM and reanalysis datasets using their respective daily time series (5 times daily for PRH) as well as the soundings. This method maximizes the simplicity (the sum of the variances of squared eigenvectors) so that physical interpretation of the modes might be possible. The eigenvectors are normalized such that the REOFs are not orthogonal in space (see Mestas-Nuñez 2000). Temporally, however, the principal components are kept uncorrelated. The rotation is applied on the EOF modes that satisfy the North et al. (1982) condition for the separability of the modes, $[\lambda_i/(\lambda_i - \lambda_{i+1})] < \sqrt{2/M}$, where

 λ_i is the eigenvalue of the *i*th mode and *M* is the sample size.

Figure 7 shows the first and second REOF modes for the TRMM estimates. The dashed lines represent the range of spatial variability, that is, the tropical average ± 1 standard deviation calculated using every grid point where the REOF analysis is performed. The relatively small standard deviation, in comparison to the profile of the mode itself, shows that the structures of the two modes have little variability in space. Note also that the two modes explain much of the variance (99% for CSH, 97% for SLH, 74% for PRH, and 96% TRAIN). For all four products, the first mode peaks at about 400 hPa (deep mode hereafter) and the second mode peaks at about 700 hPa (shallow mode). There are small amounts of low-level cooling in the deep mode of CSH and PRH, suggesting contributions from stratiform precipitation. In SLH the shallow mode explains a larger fraction of the variance than the others, in agreement with its relatively strong low-level peak.

The first two modes account for much of the variance in the reanalyses as well (Fig. 8). Both deep and shallow modes maintain the same sign throughout the troposphere. In NCEPII, where the mean profile is generally bottom heavy (Fig. 3), its shallow mode is the first mode and its deep mode is the second.

Figure 9 further compares all estimates in terms of their mean profiles and respective deep and shallow modes. Note the contrast among the mean profiles on the one hand and the agreement among their respective shallow and deep modes on the other. The differences among the mean profiles (Figs. 9a and 9e) are larger than those among the deep modes (Figs. 9b and 9f) as well as the shallow modes (Figs. 9c and 9g). The agreement among the modes is also shown in Fig. 9d for the soundings. This is also true for TRMM and reanalysis products (Fig. 9h). But there are discrepancies. The deep modes of CSH and PRH are outliers in their lack of heating at low levels. The peak of the deep heating of PRH and CSH (at 300 hPa) is higher than that of the sounding average (near 400 hPa). For the shallow modes, PRH has a peak near 600 hPa and JRA25 at 850 hPa, while those of the other estimates as well as the soundings are at 700 hPa. The main point is that the bimodal variability of the latent (diabatic) heating is shared by all the estimates and the modes of variability in the estimates show better agreement than the mean profiles.

If the differences among the modes of variability of the estimates are in fact very similar, as shown in Fig. 9, then how do the regional differences among the profiles arise? To address this question, the variances explained by the deep and shallow modes are considered. Table 3 shows the variance explained by the first two modes of



FIG. 7. The mean profile, and the (left) deep and (right) shallow modes of the variability averaged throughout the tropical domain for the TRMM products. The dashed lines indicate their respective spatial variabilities $(\pm 1 \text{ std dev})$.



FIG. 8. The (left) deep and (right) shallow modes of the variability averaged throughout the tropical domain for the reanalyses. The dashed lines indicate their respective spatial variabilities (± 1 std dev).



FIG. 9. (a) Mean profile, and the (b) deep and (c) shallow modes, as well as (d) the average of the deep and shallow modes and their standard deviation from the soundings. (e)–(h) As in (a)–(d), but for the reanalyses and TRMM products.

TABLE 3. The variance explained by the deep and shallow modes for soundings.

Sounding	Var ₁	Var ₂		
TOGA COARE	84	11		
GATE	81	12		
KWAJEX	82	15		
TWP-ICE	89	6		
SCSMEX-N	88	8		
SCSMEX-S	89	10		
LBA	49	35		
MISMO	86	9		
All combined	81	12		

the variability in the soundings. The smaller the percentage of the variance explained by the shallow mode, the more top heavy a sounding is (TWP-ICE, SCSMEX-N) and vice versa (GATE). When the REOF analysis is performed on all the soundings combined, the deep mode explains about 81% of the variance and the shallow mode explains only 12% of the variance. This is consistent with the fact that most of the soundings have top-heavy profiles (Fig. 9a). Similarly, the regional differences in the variance of the TRMM and reanalyses estimates are shown in Table 4. With the exception of PRH, all estimates show that the first two modes explain more than 80% of the variance in all the tropical regions. Overall, the variance explained by the deep mode is larger over the western and southern Pacific and smaller over the eastern and central Pacific. The top-heavy profiles of TRAIN and CSH are manifested in the large variance explained by their deep mode throughout the tropics. The fractional variance explained by the deep mode of TRAIN is the largest among all the estimates.

Even though the purpose of the study is to evaluate the uncertainties and commonalities in latent heating products, one has to keep in mind that there are also significant differences in the magnitudes of the diabatic heating from these products. The total variance obtained from EOF analysis provides a convenient proxy for heating activity. Table 5 shows the total variance averaged over each region in the global tropics. Among the TRMM products, SLH has the largest heating and PRH the lowest (likely because the 5-day averaging reduces the variance, the use of variance as a proxy breaks down in this case). CSH and TRAIN have comparable magnitudes of heating.

4. Summary and discussion

The vertical structures of the diabatic heating profiles have been compared among their estimates from three sources: TRMM satellite retrievals, global reanalyses, and in situ sounding data. Similarities shared by most or all of them provide a certain confidence in our ability to estimate certain features of the heating profiles and their applications. Discrepancies among them, however, call for their further improvement and caution us to use their current versions with care.

In the TRMM products considered in this study (CSH, SLH, PRH, and TRAIN), diabatic heating is estimated from the precipitation rate and its vertical structure as observed by the TRMM Precipitation Radar. However, these products differ in their utilizations of the observed data and retrieval algorithms. While in the reanalyses (ERA-40, NCEPII, and JRA25), the total diabatic heating is calculated as a residual of the thermodynamic budget and then conditioned by the presence of precipitation. This study also includes diabatic heating estimates from eight field campaigns at various tropical locations over the last 35 yr (TOGA COARE, GATE, KWAJEX, SCSMEX-N and -S, TWP-ICE, LBA, and MISMO). In these soundings, the diabatic heating (Q_1) is also calculated as a residual of the energy budget.

The general characteristics agreed upon by most or all of the estimates include the following:

- Over the oceans, profiles have two peaks—one in the midtroposphere (500–400 hPa) and the other in the lower troposphere (900–700 hPa). The upper peak is associated with an intense precipitation rate and the lower peak with low precipitation intensity.
- The temporal variability of latent heating is dominated by the first two rotated EOF modes: a deep

Region/product	ERA-40	NCEPII	MERRA	JRA25	CSH	SLH	PRH	TRAIN
Africa	66 (23)	56 (28)	48 (28)	N/A	77 (22)	86 (12)	42 (32)	N/A
Indian Ocean	71 (16)	26 (65)	61 (19)	76 (8)	78 (22)	58 (39)	47 (25)	85 (12)
Asian monsoon	63 (21)	46 (45)	76 (9)	72 (13)	78 (22)	48 (49)	49 (27)	N/A
Western Pacific	65 (21)	86 (5)	58 (23)	83 (5)	81 (19)	63 (33)	54 (20)	86 (11)
Southern Pacific	66 (19)	50 (38)	66 (15)	79 (6)	79 (21)	67 (30)	60 (18)	84 (13)
Central Pacific	26 (54)	10 (74)	48 (24)	66 (14)	83 (17)	68 (27)	53 (23)	78 (17)
Eastern Pacific	51 (37)	18 (70)	72 (10)	65 (16)	79 (20)	76 (22)	43 (33)	82 (15)
South America	22 (60)	15 (73)	74 (12)	55 (21)	76 (23)	73 (24)	50 (21)	N/A
Atlantic	68 (24)	6 (85)	68 (19)	74 (9)	74 (25)	60 (37)	55 (25)	86 (12)

TABLE 4. Percentages of the variance explained by deep (shallow) modes.

TABLE 5. Total variance by region $(K^2 day^{-2})$.

Region/product	ERA-40	NCEPII	MERRA	JRA25	CSH	SLH	PRH	TRAIN
Africa	80.0	31.8	25.4	33.0	51.33	789	15.6	N/A
Indian Ocean	157.5	84.6	28.5	88.3	94.7	342.9	14.2	156.6
Asian monsoon	85.0	77.0	42.9	97.6	70.9	327.0	21.1	N/A
Western Pacific	143.5	70.4	28.0	128.3	122.3	345.0	22.3	201.1
Southern Pacific	149.9	62.8	20.9	108.9	96.3	289.33	12.0	157.6
Central Pacific	83.8	59.1	17.17	72.7	86.9	202.9	13.1	110.5
Eastern Pacific	158.4	72.4	40.0	84.9	91.5	294.4	7.4	175.2
South America	124.5	55.6	50.2	51.5	58.6	531.8	13.0	N/A
Atlantic	188.1	82.7	50.6	102.8	98.7	374.3	8.0	166.5

mode with a peak between 500 and 400 hPa and a shallow mode with a peak between 850 and 700 hPa. Combined, these two modes explain between 74% and 99% of the total variance, respectively.

• Differences among the estimates are significantly smaller in their respective leading modes than in their mean profiles.

The main discrepancies are as follow:

- The mean profiles differ in where their heating peaks are (mid- to upper versus lower troposphere) and whether they have a single peak or double peaks.
- Differences among the TRMM estimates are in general larger than those among the reanalysis estimates. SLH, in agreement with the reanalysis estimates, has more low-level heating than do the other TRMM estimates. There is a unique sharp midlevel peak in PRH, and CSH has a relatively top-heavy profile.
- Differences among the shallow REOF modes are larger (due mainly to the singular structures of JRA25 and PRH) than those among the deep modes.

Among others, the most intriguing finding in this study is perhaps the ubiquity of the two REOF leading modes in all of the heating estimates. Considering that all three types of estimates rely on almost independent data sources (satellite remote sensing, data assimilation of large-scale dynamical variables, and sounding observations) and different methods (cloud microphysics plus CRM versus heat budget), one cannot help but believe that the similarities in the two REOF leading modes of all the estimates carry the same physical implications. In a separate study (Zhang and Hagos 2009), we argue that the two leading modes suggest the existence of two distinct populations of precipitation systems: warm rain with latent heating peaks in the lower troposphere (below the melting level) and cold rain with latent heating peaks in the upper troposphere (above the melting level). If this is the case, then the large discrepancies among the heating estimates compared in this study at lower precipitation ranges and for the shallow modes indicate that the key to producing accurate heating structures in both models and remote sensing observations is to get the amount of warm rain right.

In this study, the regional and temporal variabilities of the heating profiles and their relationships with the precipitation rate are used to compare the different products. While the results from this study provide some guidance to applications of these products, one has to keep in mind that this evaluation is neither complete nor final. The techniques of diabatic heating retrieval from the satellite measurements as well as its estimation from large-scale dynamics, continue to be refined, and advances will be reported upon in the future. Another aspect of the evaluation of the uncertainties in the heating estimates pertains to their implications to our understanding of the large-scale circulation and climate. The relationship of these uncertainties to those of other important variables in tropical dynamics has to be quantitatively assessed. Those issues will be investigated in a separate study.

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