Heating Structures Derived from Satellite

W.-K. Tao\(^1\), R. Adler\(^1\), Z. Haddad\(^2\), A. Hou\(^1\), R. Kakar\(^3\), T. N. Krishnamurti\(^4\), C. Kummerow\(^5\), S. Lang\(^1\), R. Meneghini\(^1\), W. Olson\(^7\), S. Satoh\(^8\), S. Shige\(^8\), J. Simpson\(^1\), E. Smith\(^1\), Y. Takayabu\(^1\), and S. Yang\(^10\)

\(^1\)NASA/Goddard Space Flight Center
\(^2\)NASA/JPL
\(^3\)NASA/HQ

\(^4\)Florida State University
\(^5\)Colorado State University

\(^6\)Science Systems and Applications Inc.
\(^7\)Joint Center for Earth Systems Technology
University of Maryland, Baltimore County
Baltimore, MD

\(^8\)Japan Aerospace Exploration Agency (JAXA)

\(^9\)CCSR/UI. of Tokyo

\(^10\)George Mason University
Fairfax, VA


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Corresponding author address: Dr. Wei-Kuo Tao, Mesoscale Atmospheric Processes Branch, Code 912, NASA GSFC, Greenbelt, MD 20771
email: tao@agnes.gsfc.nasa.gov
Abstract

Rainfall is a key link in the hydrologic cycle and is a primary heat source for the atmosphere. The vertical distribution of latent-heat release, which is accompanied by rainfall, modulates the large-scale circulations of the tropics and in turn can impact midlatitude weather. This latent heat release is a consequence of phase changes between vapor, liquid, and solid water.

The Tropical Rainfall Measuring Mission (TRMM), a joint U.S./Japan space project, was launched in November 1997. It provides an accurate measurement of rainfall over the global tropics which can be used to estimate the four-dimensional structure of latent heating over the global tropics. The distributions of rainfall and inferred heating can be used to advance our understanding of the global energy and water cycle.

This paper describes several different algorithms for estimating latent heating using TRMM observations. The strengths and weaknesses of each algorithm as well as the heating products are also discussed. The validation of heating products will be exhibited. Finally, the application of this heating information to global circulation and climate models is presented.
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1. Introduction

The global hydrological cycle is central to climate system interactions and the key to understanding their behavior. Rainfall and its associated precipitation processes are a key link in the hydrologic cycle. Fresh water provided by tropical rainfall and its variability can exert a large impact upon the structure of the upper ocean layer. In addition, almost two-thirds of the global rainfall occurs in the tropics\(^1\). Precipitation from convective cloud systems comprises a large portion of tropical rainfall and associated heating. Furthermore, the vertical distribution of convective and stratiform latent-heat release modulates large-scale tropical circulations and climates (Hartmann et al. 1984; Lau and Peng 1987; Sui and Lau 1988; Schumacher et al. 2003).

The Tropical Rainfall Measuring Mission (TRMM), a joint U.S./Japan project, is a satellite mission intended to provide an adequate measurement of rainfall as well as an estimation of the four-dimensional structure of diabatic heating over the global tropics using an inclined low-altitude orbit and the combination of a precipitation radar (PR), a visible infrared scanner (VIRS) and the TRMM microwave imager (TMI) (see Simpson et al. 1988, 1996). The distributions of rainfall and inferred heating can be used to advance our understanding of the global energy and water cycle. In addition, TRMM data can be used for global circulation and climate models for testing and improving their parameterizations.

Latent heating is the heat released or absorbed by the atmosphere as a result of phase changes in water (i.e., gas to liquid, liquid to solid, gas to solid or vice versa). It is dominated by phase changes between water vapor and small, cloud-sized particles, which cannot be directly detected with TRMM sensors. Cloud-resolving models (CRMs), however, can simulate the phase changes in water and

\(^1\) The Tropics is loosely defined as the longitudinal belt from 25 N to 25 S.
the conversion of water species explicitly (i.e., Soong and Tao 1980; Tao and Soong 1986; Tao et al. 1993a, and many others). For example, (1) shows the thermodynamic (or temperature budget) that can be explicitly calculated from CRMs.

\[ Q_1 - Q_R = \overline{\pi} \left[ -\frac{1}{\overline{\rho}} \frac{\partial \overline{w'} \theta'}{\partial z} - V' \cdot \nabla \theta' \right] + \frac{L_v}{C_p} (c - e) + \frac{L_f}{C_p} (f - m) + \frac{L_s}{C_p} (d - s) \]  

(1)

The primes indicate deviations from large-scale environment (cloud or small scale). The variable \( \theta \) is the potential temperature, \( \overline{\rho} \) is the density, and \( \overline{\pi} = (\pi / \pi_{oo})^{R/CP} \) is the nondimensional pressure, where \( \pi \) is the dimensional pressure and \( \pi_{oo} \) the reference pressure taken to be 1000 mb. \( C_p \) is the specific heat of dry air at constant pressure, and \( R \) is the gas constant for dry air. The variables \( L_v, L_f \) and \( L_s \) are the latent heats of condensation, fusion and sublimation, respectively. The variables \( c, e, f, m, d \) and \( s \) stand for the rates of condensation, evaporation of cloud droplets and raindrops, freezing of raindrops, melting of snow and graupel, deposition of ice particles and sublimation of ice particles, respectively. The term \( Q_1 \) is the apparent heat source (Yanai et al. 1973) and \( Q_R \) is the cooling/heating rate associated with radiative processes. Also, the first two terms on the right-hand side of (1) is the horizontal and vertical eddy heat convergence. The horizontal eddy heat convergence can be neglected when the (1) is averaged horizontally over a large area (Yanai et al. 1973).

Figure 1 shows the instantaneous latent heating structure associated with a tropical and a midlatitude mesoscale convective system (MCS) simulated by a 2D CRM, the Goddard Cumulus Ensemble (GCE) model. Generally, there are many similarities in the latent heating structure between these two cases. These include (condensation) heating in the lower to middle troposphere in the convective leading edge of the cloud system. Deposition heating occurs in the upper part of the
convective region and in the upper part of the stratiform region. The cooling at low levels in the stratiform region is from the evaporation of rain. Cooling from melting of precipitation particles can also contribute to latent heating and mainly occurs in a narrow layer near the freezing level (Tao et al. 1993b). There is cooling from sublimation adjacent to depositional heating in the stratiform region. The heating/cooling pattern is mainly caused by gravity waves induced by the deep convection. This feature is more significant in the midlatitude case because the midlatitude convective updrafts are stronger. There are also some major differences between these cases, however. For example, the cooling from the stratiform region is larger and thicker for the midlatitude case than the tropical case. This is due to the drier, midlatitude environment. In addition, the level separating the heating and cooling in the stratiform region (indicating the freezing or melting level) is different for these two convective systems.

Latent heating profiles and the vertical eddy heat convergence can be derived indirectly by measuring the vertical profiles of temperature and the three-dimensional wind fields from extensive rawinsonde networks through a residual method as shown in (2) (called a diagnostic budget; Yanai et al. 1973; Houze 1982, 1989, 1997; and Johnson 1984). Heating profiles for the TRMM field campaign sites (i.e., SCSMEX, May - June 1998; LBA - TRMM/Brazil, January - February 1999; and KWAJEX, July - September 19992) as well as other major field campaigns such as

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South China Sea Monsoon Experiment (SCSMEX), May - June 1998; Large Scale Biosphere-Atmosphere Experiment in Amazonia, (LBA) - TRMM/Brazil, January - February 1999; and Kwajalein Experiment. (KWAJEX), July - September 1999. DOE/ARM stands for Department of Energy Atmospheric Radiation Measurement
DOE/ARM can be used for validation. \( Q_1 \) can be calculated either from grid values in a large- or regional-scale prediction model or from large-scale re-analyses (Nigam et al. 2000).

\[
Q_1 - Q_l = \pi \left( \frac{\partial \theta}{\partial t} + \mathbf{\nabla} \cdot \mathbf{\nabla} \theta + \mathbf{\bar{w}} \frac{\partial \theta}{\partial z} \right)
\]  

In section 2, the latent heating algorithms developed for TRMM will be discussed. The strengths and weaknesses of each algorithm will also be shown. Highlights from these algorithms will be presented and discussed in section 3. Validation of the heating algorithms will be presented in section 4. Future work and the application of the heating products will be discussed in section 5.

2. How can latent heating be derived?

Time series of the apparent heat source \( Q_1 \) diagnostically determined by soundings and explicitly calculated by the GCE model for the period 19-26 December 1992 are illustrated in Figs. 2(a) and (b). The pattern of temporal variability between the heating profiles derived from the soundings and estimated by the GCE model agree quite well. This is because that the large-scale advective forcing in temperature and water was superimposed into the GCE model as the main forcing (Soong and Tao 1980; Tao and Soong 1986). The latent heat release associated with all five major rainfall events are well simulated by the GCE model. Model results, however, show more temporal variability. This is perhaps caused by the fact that diagnostically determined \( Q_1 \) was calculated using 6-hourly soundings and a 1-2-1 filter was applied (Lin and Johnson 1996). The GCE model estimates are based on 2 minute statistics of cloud processes (i.e., condensation, evaporation, deposition, sublimation, freezing and melting rates) without any smoothing. This result clearly indicates that
CRMs can provide cloud data sets associated with various types of clouds and cloud systems from different geographic locations for the TRMM retrieval algorithm database [see review by Tao et al. (2000, 2001)]. The data represent instantaneous values and are selected from periods where the cloud and precipitation fields meet predetermined characteristics that are unique or complementary to the database requirements.

Five different latent heating algorithms, the Goddard Convective-Stratiform Heating (CSH), the Goddard Profiling (GPROF) heating, the Hydrometeor Heating (HH), the Spectral Latent Heating (SLH) and the Precipitation Radar Heating (PRH) algorithm have been developed to retrieve latent heating profiles using TRMM rainfall products. The HH algorithm estimates the latent heating profiles of clouds/cloud systems as a function of the vertical derivative of their retrieved hydrometeor profiles termed a hydrometeor/heating (HH) algorithm (Tao et al. 1990, 1993; Yang and Smith 1999 a,b,2000). The derivation and evaluation of the HH algorithm was based on CRM simulations, and it requires information about the vertical profiles of cloud- and precipitation-sized water and ice particles, all of which can be obtained from the TMI retrievals (Kummerow et al. 1996; Smith et al. 1992, 1994). The terminal (fall) velocities of the large cloud (precipitating) particles (rain, snow and graupel/hail) are also required for the HH algorithm. Empirical coefficients associated with the condensation of small liquid water droplets and deposition of small ice particles are needed in Tao et al. (1990). These coefficients can also be determined using the surface rain rates (Tao et al. 1993b). Cloud-scale velocity is needed in the HH algorithm developed by Yang and Smith (1999a). It is obtained by applying a regression method to a CRM-simulated data base.
The second method, the CSH algorithm, only needs information on surface precipitation rates, fraction of stratiform rain, and the type and location of observed cloud systems (Tao et al. 1993b). A lookup table however, is needed containing stored convective and stratiform latent heating profiles, normalized by total surface rain rates, for various types of cloud systems in different geographic locations. These profiles are mostly obtained from CRM (GCE model) simulations. In the third method, the GPROF, CRM-simulated hydrometeor/latent heating vertical profiles that have radiative characteristics consistent with a given set of multi-spectral, microwave, radiometric observations are composited to create (retrieve) a best estimate of the observed profiles (Olson et al. 1999).

The SLH algorithm (Shige et al. 2003) is also a table method based on GCE model results. But its uniqueness resides in the fact that it utilizes spectral latent heating tables based on precipitation top heights or melting-level rain rates, for convective rain and for stratiform rain, respectively. The PRH algorithm (Satoh and Noda 2001) also uses PR information but without using any heating profiles simulated by CRMs. However, it needs to estimate the cloud drafts and (standard) thermodynamic structures associated with cloud systems. An iteration calculation is applied to match the relationship between rainfall and latent heating. Table 1 summarizes the information required by each algorithm and lists some of the cases to which they have been applied in previous latent heating retrieval studies.

The CSH, SLH, and GPROF algorithms can estimate the latent heating [microphysics processes shown in (1)] $Q_1-Q_R$, and/or $Q_1$ because they use the cloud data generated from CRMs. The CRMs can provide cloud data bases consisting of either latent heating or $Q_1-Q_R$ explicitly. The HH and PRH algorithms can only estimate the latent heating profiles.
A quantitative comparison between three of the heating algorithms (CSH, GPROF and HH) was performed (Tao et al. 2001). The results indicated that the horizontal distribution or patterns of latent heat release retrieved by these three different methods are quite similar and highly relate to the surface rainfall. They can all identify the areas of major convective activity [i.e., a well defined Intertropical Convergence Zone (ITCZ) in the Pacific and a distinct South Pacific Convergence Zone (SPCZ)]. The magnitude of their estimated latent heat release is also in good agreement with each other and with those determined from diagnostic budget studies. The major difference between these three heating retrieval algorithms is in the altitude of the maximum heating level. The CSH algorithm-estimated heating profiles only show one maximum heating level, and the level varies between various geographic locations. These features are in good agreement with diagnostic budget studies. A broader heating maximum, often with two embedded peaks, is generally obtained by the GPROF and HH algorithms, and the response of the heating profiles to variations in convective activity is less pronounced. Also, GPROF and HH generally yield heating profiles with a maximum at somewhat lower altitudes than those from the CSH. The strengths and weakness of these heating algorithms are listed in Table 2.

3. Heating structures estimated from various heating algorithms

3.1 Instantaneous latent heating structure

Figure 3 shows the algorithm-derived surface rain rates, convective rain rates, total precipitation and Q1-QR estimated from TMI (GPROF) observations of a squall line in the tropical North Atlantic. The heaviest rains are seen along the convective
leading edge of the system, while generally lower rain intensities are observed in the trailing stratiform areas to the north and west of the leading edge. The cross section [Fig. 3(c)] is nearly perpendicular to the leading edge, crossing not only the stratiform rain behind the line but also what appears to be decaying convection further rearward. The leading-edge convection is characterized by relatively high water contents, exceeding 1 g m\(^{-3}\) near the surface. Horizontally collocated with the maximum rain water contents are the maximum estimated heating rates, which exceed 9 K h\(^{-1}\) between 5 and 8 km latitude. A secondary heating peak associated with possible decaying convection is seen near the 80 km mark. Also, the maximum cooling (3 K h\(^{-1}\)) is located beneath this secondary heating peak. The overall heating structure is similar to those shown in Fig. (1) except that very fine features simulated by the GCE model cannot be captured by TRMM due to the coarser resolution of the TMI.

Figure 4 shows surface rain rates and latent heating for hurricane Bonnie from the HH algorithm which is based on the vertical derivative of rain mass flux from the combined TMI/PR rain retrieval algorithm. The early version of this combined (TMI/PR) algorithm has been described in detail by Ziad et al. (1997). A Legendre Polynomial (LP) function is introduced to smooth unrealistic spikes or noise in the retrieved rain profiles so that HH provides the general characteristics of the latent heating structure. The structure of the hurricane eye and the convective rain spiral bands are well captured. Rain rates appear at very high altitudes where deep convection exists, such as around 200km along the track [Fig. 4(b)]. There are lots of weak raining areas located in between the convective cells. In these weak precipitation areas, rain rates are mostly concentrated in the middle to lower troposphere, where stratiform conditions likely exist. Large latent heating profiles are always associated with the strongest deep convective cells [Fig. 4(c)]. The peaks
of maximum latent heating vary with different conditions. For example, the peak is located at 3-5 km at 180 km along the track, while it is at 3-4 km at 200 km along the track. The heights of latent heating maximum seem mostly to be at and below 5 km. Cooling occurs in the lower troposphere in these stratiform regions. Overall, the general structure of latent heating based on the HH algorithm appears reasonable for the hurricane Bonnie case. However, it should be pointed out that the height of maximum latent heating is lower than that from published large-scale heating budget studies for strong storms and from previous retrieved latent heating profiles. This conclusion is expected because the current combined TMI/PR rain retrieval algorithm does not retrieve solid hydrometeor profiles. Thus, a portion of the latent heating from phase changes of these hydrometeors is missing from the current HH algorithm output. This issue will be corrected in the next version.

Figure 5 shows the latent heating profiles associated with a typhoon at its developing stage retrieved by the SLH and PRH algorithm. The PR-estimated rain rates that are used as the input for these heating algorithms are also shown in Fig. 5. Overall, there are many similarities between the SLH- and PRH-retrieved latent heating profiles. For example, strong heating is retrieved from these two algorithms on both sides of the eyewall. The strong heating is very narrow in the lower troposphere on the right side of the eyewall. Away from the eyewall, the heating pattern is quite similar to that observed and simulated by CRMs in the stratiform region of mesoscale convective systems (Houze 1982, 1997; Tao et al. 1993b, 2000; Lang et al. 2003). However, there are also some major differences between the two algorithm-retrieved heating profiles. For example, the SLH algorithm-retrieved maximum heating level is lower than for the PRH algorithm [i.e., Fig. 5(d) and (e)]. The cooling retrieved by the PRH algorithm in the lower troposphere is stronger than that for the SLH algorithm. In addition, finer and
more detailed heating structures are retrieved by the PRH algorithm. The general structure between the SLH-retrieved $Q_1 - QR$ and latent heating profile is similar except that the $Q_1 - QR$ profile has higher and stronger maximum heating level [Fig. (5(e)].

Figure 6 shows the latent heating profiles associated with a mesoscale convective system over the tropical ocean northwest of Australia retrieved by the SLH and PRH algorithm. The PR-estimated rain rates that are used as the input for the SLH algorithm are also shown in Fig. 6. Strong heating ($>10 \text{ K h}^{-1}$) is always associated with large rain rates ($> 50 \text{ mm h}^{-1}$) in the convective region of the squall system. There is weak heating aloft and cooling below in the trailing stratiform region. The SLH algorithm can estimate both latent heating and $Q_1 - QR$. Both $Q_1 - QR$ and latent heating averaged profiles peak at middle levels [about 6.0 km and see Fig. 6(d)]. This is in good agreement with having a heating maximum in the midtroposphere for Australian Monsoon Experiment (AMEX) convective systems (Frank and McBridge 1989). The estimated latent heating profile has a distinct cooling near 4.0 km, which is due to the melting processes. On the other hand, the estimated $Q_1 - QR$ profile does not have this cooling near 4.0 km. This is because the eddy heat flux convergence compensates the distinct cooling due to the melting (i.e., Tao et al. 2003). As the typhoon case, the PRH-estimated heating has very fine structure and shows stronger cooling in the lower troposphere compared to the SLH-estimated.

Latent heating profiles for a midlatitude squall line retrieved by the PRH algorithm are shown in Fig. 7. The PR-observed radar reflectivity and estimated rainrate used as inputs into the PRH algorithm are also shown in Fig. 7. The radar reflectivity is very similar to that in an observed PRESTORM squall line (Rutledge et
al. 1988). Strong heating (>10 K h⁻¹) is always associated with large rain rates (> 50 mm h⁻¹) at the leading edge of the squall system. There is weak heating aloft and cooling below in the trailing stratiform region. These features are very similar to those simulated by CRMs [i.e., Fig. 1(b), Lang et al. 2003], observed (Johnson and Hamilton 1988) and retrieved by the GPROF algorithm [Fig. 3(c)]. The total heating shown in Fig. 7(d) is also quite similar simulated by CRM and observed.

The heating profiles retrieved by these different heating algorithms qualitatively agree with each other for a squall line (PRH and GPROF), a typhoon/hurricane (SLH, PRH and HH) and a tropical oceanic MCS but not quantitatively. For example, the PRH-estimated heating has very fine structure and shows stronger cooling in the lower troposphere compared to the SLH-estimated. Some of the differences are caused by the different resolutions used in these algorithms. The assumptions used in different algorithms can also cause the difference. A thorough and detailed comparison is under way.

3.2 Temporal and spatial averages

Figures 8(a), (b) and (c) show five-yearly mean latent heating at three different altitudes (2, 5 and 8 km) over the global tropics from the CSH algorithm using PR-based rainfall products. The horizontal distribution of the CSH-estimated Q₁ structures is very similar to the pattern of surface rainfall [Fig. 8(d)], especially at middle and upper levels. For example, a well defined ITCZ in the east and central Pacific and in the Atlantic Ocean, the SPCZ, and broad areas of precipitation events spread over the continental regions are present. Also, strong latent heat release (5 K day⁻¹ or greater) in the middle and upper troposphere is always associated with heavier surface precipitation. Heating in the upper troposphere over the Pacific and
Indian Oceans covers a much broader area than the heating over Africa, S. America and the Atlantic Ocean. The differential heating distribution between land and ocean in the upper troposphere could generate strong horizontal gradients in the thermodynamic fields and interact with the global circulation.

One interesting result from Fig. 8 is the relatively weak heating and cooling (-1 to 1 C day$^{-1}$) at the 2 km level over the Pacific Ocean. This result may be due to the fact that the moisture content is high over the Pacific ocean. Cooling by evaporation of raindrops in the lower troposphere could be weak over moist areas. Another possibility is that the convective heating and the stratiform cooling in the lower troposphere cancel each other.

Figure 9 shows the vertical average $Q_1$ profiles for spring, summer, fall and winter over the global tropics, land, and oceans. Globally, the summer and fall seasons show stronger heating associated with larger and heavier rainfall. Over land, the summer season has the strongest heating. Heating during the spring and fall seasons is quite similar. A cooling at lower troposphere occurs over land but not over ocean. The heating pattern (maximum heating level and its magnitude) over oceans is very similar to the global average. This is due to the fact that 70% of the tropics is covered by ocean.

The $Q_1$ structure associated with two climate events, an El Nino (December 1997 through February 1998) and a La Nina (December 1998 through February 1999) are examined. Figures 10(a) and (b) show the retrieved heating anomalies for these two climate events. The results show the largest signal over the equatorial Pacific, west Pacific and Indian ocean. The $Q_1$ pattern over the maritime continent, America and Africa is quite similar. Time (monthly) series of latent heating profiles
over the tropics and their deviations (from the mean) are shown in Fig. 10(c). The level of maximum heating is at 7.5 km. The variation of the maximum heating level as well as the magnitude are quite small. This is caused by the fact that the global tropical rainfall for El Nino (2.35 mm day\(^{-1}\)) and La Nina (2.40 mm day\(^{-1}\)) is quite similar as observed by the PR. However, there are cold and warm anomalies during El Nino and La Nina periods. These features are due to the fact that the PR observed a higher percentage of stratiform precipitation during the El Nino which is conducive to retrieving stronger low-level cooling compared to the La Nina.

4. How can latent heating be validated?

4.1 Validation with CRMs - a consistency check

Consistency checks were performed by several CRM-generated cloud data base heating algorithms (i.e., the CSH and SLH algorithms). The procedure is to use CRM-simulated parameters [i.e., surface rain rate, stratiform percentage, rain rate at the melting level, and precipitation top height (PTH)] to re-construct (or retrieve) heating profiles and compare them to sounding estimates and/or the CRM simulation. The TOGA COARE IFA region for the 16-26 December 1992 period (shown in Figure 2) was used for a consistency check for both the CSH and SLH algorithms. Other TOGA COARE periods, GATE\(^3\) and DOE/ARM periods were also used for consistency checks (Tao et al. 2000; Shige et al. 2003).

\(^3\) GATE stands for GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment
Figure 11 shows the time series of the CSH-retrieved Q1 averaged over the TOGA COARE IFA region. The results indicate the CSH-retrieved Q1 profiles are in very good agreement with those determined diagnostically by sounding as well as simulated by the GCE model (Fig 2). It is perhaps not too surprising because the heating profiles based on the GCE model-simulated rainfall rates and stratiform amounts are in very good agreement with those diagnostically determined. The GCE model is driven by the large-scale advective forcing in temperature and water vapor, and therefore the model's simulated rainfall and stratiform amount is simply a response to the forcing (Soong and Tao 1980). But, using the output from the GCE model for the CSH heating algorithm does not assure a good Q1 retrieval. For example, errors in the estimated amount of stratiform rainfall can retrieve maximum heating at the wrong height.

Figure 12 shows the SLH algorithm-retrieved latent heating. The GCE model-simulated latent heating (not Q1) is also shown in Fig. 12. Note that the difference between GE model simulated Q1 and latent heating is quite small. This is because the latent heating term (20-40 K day\(^{-1}\)) is the dominant term in (1) compared to QR (1-2 K day\(^{-1}\)) and the vertical eddy heat convergence terms during active convective events (Soong and Tao 1980; Johnson et al. 2002). The temporal variations of the retrieved heating profiles agree well with that of the GCE-simulated heating profiles. In particular, the SLH (and CSH) algorithm-retrieved heating profiles captured the evolution of a quasi-2-day oscillation (Takayabu 2002) during the period 1800 UTC 23 - 1800 UTC 25 December 1992. The retrieved results

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4 The heating profiles selected in the CSH algorithm's look-up table for this period are the GCE-modeled (6 hourly), time-averaged heating profiles from December 19 to 27, 1992.
have much smoother features [compared to Fig. 12(a)]. This is because the lookup tables represent the averaged profiles for each index, either PTH or precipitation rate at the melting level. Shige et al. (2003) also estimated the errors in the instantaneous heating structure at a grid point (1 km) spatial scale. The results show that spatial averaging (at least 50 km) is required to derive meaningful instantaneous heating profiles using the SLH algorithm.

4.2 Validation with sounding networks

Several field campaigns (SCSMEX, LBA and KWJEX) conducted during 1998 and 1999 were aimed at the validation of TRMM products (i.e., rainfall and the vertical distribution of heating). Since latent heating profiles cannot be directly measured, CRMs are used in TRMM algorithms to provide a link between the latent heating profiles, and PR and TMI observations. Consequently, one of the key components of the TRMM field campaigns is to provide observations of the structure and evolution of MCSs, and individual convective clouds and their embedded large-scale environment. CRMs require these data sets for initial conditions as well as for the validation of their vertical latent heating structure.

Figure 13 shows a comparison between algorithm-retrieved heating and sounding estimates for SCSMEX during the most convectively active period (May 15 - June 20). Selecting the appropriate latent heating profiles from the CSH algorithm's look-up table for specific convective events is not a trivial problem. Two different approaches for selecting the latent heating profiles in the look-up table are used to obtain distinct estimates of the latent heating profiles in this comparison. In the first approach, normalized heating profiles representing oceanic conditions are obtained by averaging profiles from the look-up table based on a set of diagnostic
studies and the growing (but still limited) number of GCE model simulations (Figs. 3 and 4 in Tao et al. 2000). In the second approach, the heating profiles from look-up table profiles based on geographic locations and months of interest are utilized in the CSH algorithm (South China Sea for this comparison). In the SLH algorithm, the look-up table from the GCE SCSMEX simulation is selected.

The CSH algorithm-retrieved (Q1) heating structures are stronger than sounding-estimated using the first approach. Nevertheless, there is some good agreement in the overall distribution (i.e., the maximum heating level using the heating profiles representing oceanic regions and cooling in the boundary layer). In contrast, the CSH algorithm-retrieved heating structures is in very good agreement with sounding estimated using the heating profiles from the GCE SCSMEX simulation. The maximum retrieved heating level is about 0.5 - 1 km lower than observed. The SLH algorithm-retrieved latent heating profile is in agreement both quantitatively and qualitatively with the sounding estimates (Q1) between the 2 and 5 km levels. The SLH algorithm-retrieved latent heating profile is stronger in the middle troposphere.

5. Future work

Heating profiles for the other TRMM field campaign sites as well as other major field campaigns such as DOE/ARM will be compared to profiles determined from the different heating algorithms. Dual-Doppler radar observations could also provide validation for algorithm-retrieved instantaneous heating profiles. This future comparison can provide an assessment of the absolute and relative errors of the heating retrieval algorithms. In addition, global analyses will be used to identify/compare the large-scale circulation patterns for the retrieved periods and
for periods during previous field campaigns (i.e., TOGA COARE and GATE). It is reasonable to assume that the latent heating structures for westerly wind bursts (WWBs) and super cloud clusters (SCCs) occurring in similar large-scale circulations and with similar SSTs may not be very different. An intercomparison between different heating algorithms (latent heating, $Q_1$, and/or $Q_1-QR$) is planned in 2004.

Since several heating algorithms require CRM-simulated cloud data sets including heating profiles (i.e., the lookup tables for the CSH and SLH algorithms, and rain rates and cloud profiles for GPROF), the number of heating profiles associated with different types of clouds and convective systems from various geographic locations needs to be increased. Data from TRMM field experiments and other major field experiments (i.e., DOE/ARM) can be used to provide initial conditions for CRMs and validate the CRM-simulated latent (diabatic) heating. The heating obtained from numerical model simulations and large-scale model reanalysis (Nigam et al. 2000) can be compared with those from retrieval algorithms. This comparison could identify what are the major physical processes that cause the similarities and differences between models. In addition, data from field campaigns can be used to validate and improve CRM microphysics because they are the major processes responsible for latent heat release.

The HH, GPROF, SLH and PRH algorithms can produce instantaneous heating profiles at the satellite foot print. The assumption is that instantaneous heating profiles and cloud/rain structures are related. Shige et al. (2003) showed that spatial averaging (at least 50 km) is required to derive meaningful instantaneous heating profiles using the SLH algorithm. The key developers for the TRMM heating algorithms have agreed to examine the possibility of producing a unified
heating algorithm using microwave sensors (i.e., TMI/SSM-I\textsuperscript{5}) and radar (i.e., PR) products for TRMM. It would require comparing the various heating algorithms using the same rainfall products as in Tao et al. (2001).

Two global climate models, from the NASA Goddard Space Flight Center (GSFC) and the Florida State University, are currently using TRMM data sets to either improve their cumulus parameterization schemes and/or identify the problems in these schemes. The direct use of satellite (and or other ground-based) products on heating profiles for atmospheric models requires a physical initialization design. For example, the Florida State University global, spectral model (Krishnamurti et al. 1991) has been developing a new cumulus parameterization scheme (NCPS) to use observed and/or satellite-retrieved heating profiles through an empirical approach. Since temperature (heating) and water vapor (moistening/drying) are closely related, a moisture profile is also needed in NCPS. The initial results with the NCPS incorporated into the FSU global spectral model shows improved precipitation and circulation (Rajendran et al. 2003) forecasts on day-2 and day-3 (Fig. 14). The use of satellite-derived profiles in data assimilation appears very promising but requires much further work. Particularly, there has to be closer cooperation between latent heating algorithm developers and the data assimilation/large-scale modeling communities. Research is currently underway at NASA GSFC to develop variational techniques to assimilate TMI-derived convective and stratiform latent heating rates within the general framework of parameter estimation using disposable parameters in moist physics schemes as a control variable. The aim is to explore the feasibility of improving global analyses and forecasts through the assimilation of CRM-based latent heating profiles that are radiatively compatible with multi-channel TMI brightness temperatures. The optimization of moist physics parameterizations in the

\textsuperscript{5} SSM/I stands for Special Sensor Microwave/Imager.
context of data assimilation can provide valuable information for diagnosing model deficiencies and guiding the improvement of parameterization schemes.

There is another major application using NWP and/or global circulation models with satellite-retrieved heating profiles. As the number of such models subjected to initialization by the different observed/retrieved heating profiles increases major improvements in forecasting capabilities via ensemble or superensemble (Krishnamurti et al. 2001) techniques can be expected. This is being established as a powerful technique. The goal is to reduce overall uncertainties as well as to better estimate errors associated with models, data sets and parameterizations.

6. Acknowledgement

This study is supported by the U. S. NASA and Japan Aerospace Exploration Agency (JAXA) TRMM project.

7. References


TABLES

Table 1  Summary of previous latent heating retrieval studies.

Table 2  Strengths and weaknesses of the latent heating retrieval methods.
Figure Captions

Fig. 1: Latent heating (sum of heating by condensation, freezing and deposition, and sum of cooling by evaporation, melting, and sublimation) associated with (a) a midlatitude (PRESTORM) squall line and (b) a tropical (TOGA COARE) mesoscale convective system. These systems were simulated, and the results were presented in Tao et al. (1993a, 1995, 1996), Wang et al. (1996), and Lang et al. (2003). PRESTORM stands for Preliminary Regional Experiment for Storm Central, and TOGA COARE for Tropical Oceans Global Atmosphere (TOGA) - Coupled Ocean Atmosphere Response Experiment (COARE).

Fig. 2: Evolution of the apparent heating source ($Q_1$) averaged over the TOGA COARE (Intensive Flux Array) IFA for the 8-day period during December 19-27, 1992 (a) derived diagnostically from soundings (Lin and Johnson 1996) and (b) simulated from the GCE model.

Fig. 3: TMI-retrieved (a) surface rain rates, (b) convective rain rates, and (c) cross sections of total precipitation water content (shading) and $Q_1 - QR$ (in K h$^{-1}$, contours) from GPROF from observations of a squall line in the North Atlantic on 7 April 1998. The horizontal resolution of the cross section is about 28 km.

Fig. 4: (a) TMI/PR retrieved near surface rain rate map for hurricane Bonnie (22 August 1998). (b) Cross section of rain rates and (c) HH algorithm-estimated latent heating profiles along the track of the TRMM satellite at nadir from the precipitation radar.
Fig. 5  Cross section of (a) PR-estimated rain rate (in mm h\(^{-1}\)), (b) SLH-retrieved and (c) PRH-retrieved latent heating profiles (in K h\(^{-1}\)) associated with a tropical typhoon in the developing stage (2 August 2000). The arrow indicates the location of eye. The horizontal mean (d) SLH-retrieved Q\(_1\) - QR and latent heating profiles and (e) PRH-retrieved latent heating profiles.

Fig. 6  Cross section of (a) PR-estimated rain rate (in mm h\(^{-1}\)), (b) SLH-retrieved and (c) PRH-retrieved latent heating profiles (in K h\(^{-1}\)) associated with a MCS over Australia. (d) is the horizontal mean SLH-retrieved latent heating and Q\(_1\) - QR, and (e) the PRH-retrieved latent heating profiles.

Fig. 7  Cross section of (a) PR-observed radar reflectivity (ZE in dBZ), (b) PR estimated rain rate (in mm h\(^{-1}\)) and (c) PRH-retrieved latent heating profiles associated with a midlatitude (Oklahoma) squall line (10 May 1999). (d) is the horizontal mean PRH-retrieved latent heating profiles.

Fig. 8  Five-yearly mean Q\(_1\) profiles at (a) 8, (b) 5 and (c) 2 km (above ground level, AGL) over the global tropics. Heating profiles representing just tropical oceanic and general land regions from the CSH look-up table (LUT) are used.

Fig. 9  Vertical average heating profiles for spring, summer, fall and winter over (a) the global tropics, (b) land, and (c) oceans.

Fig. 10  Retrieved heating anomalies for El Nino during DJF 1997-8 (a) and La Nina during December, January and February (DJF) 1998-9 (b) using
TRMM PR data and the Goddard Convective and stratiform heating (CSH) algorithm at 8 km AGL. (c) shows the average heating profiles over the global tropics.

Fig. 11 Time series of CSH-retrieved $Q_1$ profiles averaged over the TOGA COARE IFA for the 8-day period during December 19-27, 1992. The GCE model-simulated rainfall rates and stratiform percentages are used. Contours are every 5 K day$^{-1}$.

Fig. 12 Time series of (a) GCE model simulated and (b) SLH algorithm-retrieved latent heating profiles averaged over the TOGA COARE IFA for the 8-day period during December 19-27, 1992. The GCE-simulated precipitation path top, convective/stratiform characteristics, precipitation rate at the melting level, and precipitation rate at the surface. These retrieved heating profiles are averaged over the GCE model domain (512 km in the horizontal). Contours are every 5 K day$^{-1}$.

Fig. 13 Heating from observations and retrieved from the CSH and SLH algorithms for SCSMEX from 15 May to 20 June 1998. Two sets of look-up-table profiles, one representing general tropical oceanic regions and another representing the South China Sea region, from the CSH algorithm were used for comparison. The observed, sounding-estimated profile comes from Johnson and Ciesielski (2002).

Fig. 14 Precipitation for 8 February 1998 from (a) the Global Precipitation Comparison Project (GPCP, observation), (b) the Florida State University
global spectral model (FSUGSM) day-2 forecast with NCPS, and (c) the FSUGSM control day-2 forecast. From Rajendran et al. (2003).
<table>
<thead>
<tr>
<th>Input</th>
<th>Cases</th>
<th>Resolution</th>
</tr>
</thead>
</table>
| **Tao et al. (1991)**  
HH Algorithm                                      | GATE (1974), PRESTORM (1985)                | 200 - 300 km daily  |
| **Tao et al. (1993)**  
| **Tao et al. (1999)**  
GPROF                                          | Hurricane Andrew (1992), TOGA COARE (1992-93) | 25 - 50 km Instantaneously |
| **Yang and Smith**  
(1999a, b, 2000)  
HH Algorithm                                      | TOGA COARE (1992-93)                        | 15 - 50 km Instantaneously |
| **Tao et al. (2000)**  
CSH Algorithm                                      | Global Tropical region (1992)               | 2.5° x 2.5° Monthly  |
| **Tao et al. (2001)**  
CSH, GPROF and HH Algorithms                        | TOGA COARE (1992-93)                        | 500 x 500 km 3-6 hourly |
| **Shapiro et al. (2003)**  
SLH Algorithm                                  | February 1998                               | 1° x 1° Daily       |
| **Tao et al. (2003)**  
SLH-PRH, HH, GPROF, CSH Algorithms                 | Major convective event (i.e., hurricane), global tropical, validation sites | Instantaneously |
|                                                                  |                                            | 2.5° x 2.5° Monthly |

Table 1
<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Strengths</th>
<th>Weakness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convective and</td>
<td>Based on (convective/stratiform) heating characteristics derived from</td>
<td>Sensitive to stratiform amount</td>
</tr>
<tr>
<td>Stratiform</td>
<td>diagnostic budget study</td>
<td>Sensitive to the heating profiles stored in the CSH look-up table</td>
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<tr>
<td>(Tao et al. 1993,</td>
<td>Validated with 1992-1993 TOGA COARE, LBA, KWAJEX, SCSMEX data</td>
<td>No rainfall -&gt; no latent heating aloft</td>
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<tr>
<td></td>
<td>with observations</td>
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<tr>
<td></td>
<td>Method is physically-based; latent heating profiles are consistent with</td>
<td>Rainfall and latent heating may have different temporal scale.</td>
</tr>
<tr>
<td></td>
<td>other retrieved parameters. Random error of retrieved parameters can be</td>
<td>Errors in cloud/radiative model simulations can lead to biases in retrieved heating profiles.</td>
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<tr>
<td></td>
<td>be estimated using Bayesian approach.</td>
<td>Under-representation of observed precipitation and latent heating structures in cloud/radiative model database can lead to errors in estimates.</td>
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<td></td>
<td>Latent heating profiles are retrieved at footprint resolution (~10 km); may</td>
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<td></td>
<td>be “verified” using coincident dual-doppler radar observations.</td>
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<tr>
<td>GPROF</td>
<td>(Olson et al. 1999)</td>
<td></td>
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<tr>
<td></td>
<td>(Yang et al. 1999a,b, 2000; Tao et al. 1990, 1993)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Physical approach — Latent heating is closely related to the reality of</td>
<td>Sensitive to accuracy of retrieved hydrometeor profiles — Any error from hydrometeor profiles will be passed to latent heating profiles</td>
</tr>
<tr>
<td></td>
<td>atmosphere if retrieved hydrometeor profiles are accurate</td>
<td>Uncertainty with cloud scale atmosphere vertical motion (assumed W=0 if W is unknown)</td>
</tr>
<tr>
<td></td>
<td>Both pixel and area mean resolutions</td>
<td>Uncertainty in identifying melting layer</td>
</tr>
<tr>
<td></td>
<td>Ready to use — Could be easily adapted to 2A-7J, 2B-31 outputs to estimate latent heating</td>
<td>Uncertainty in estimating terminal velocity of particles</td>
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<td></td>
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<tr>
<td>HH</td>
<td></td>
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<tr>
<td>(Shige et al. 2003)</td>
<td>Produces realistic heating profiles for various cloud system regimes (e.g.</td>
<td>Sensitive to the heating profiles generated from cloud-resolving model</td>
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<tr>
<td></td>
<td>shallow and deep convective regimes) - PTH</td>
<td>Low sampling rate due to the narrow swath width of PR (spatial averaging is needed)</td>
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<tr>
<td></td>
<td>Produces heating profiles for decaying MCSs even with no surface rain -</td>
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<td></td>
<td>RRmelt</td>
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<td></td>
<td>Heating profiles are retrieved at footprint resolution (4 km)</td>
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<tr>
<td>SLH</td>
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<tr>
<td>(Satoh and Noda 2001)</td>
<td>Produces realistic heating profiles for various cloud systems (e.g. squall lines, typhoons)</td>
<td>Sensitive to the estimated air velocity and hydrometeor profiles (especially in the mixed phase)</td>
</tr>
<tr>
<td></td>
<td>Does not depend on cloud-model-simulated heating profiles</td>
<td>Produces cooling near cloud top and in the upper parts of clouds sometimes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low sampling rate due to the narrow swath width of the PR</td>
</tr>
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Table 2
Orbit 2681 (16 Feb. 1998, tropical ocean northwest of Australia)

PR2A25 rain rate (angle=Nadir)

SLH (v3.5.0c) latent heating (angle=Nadir)

PRH (v1.4) latent heating (angle=Nadir)

SLH LH and Q1R (angle=Nadir)

PRH LH (angle=Nadir)

Fig. 6
Orbit 8329 (10 May 1999, Oklahoma squall line)

**Fig. 7**
Fig. 9

Diagram showing seasonal variations in average heating for land and ocean.
Fig. 10
Fig. 12

(a) GCE simulated LH (total)
(b) SLH reconstructed LH (total)
GPCI (Cbs) Rain: 12Z 8 February 1996

FSU T126 NCPS Rain: Day-2 Forecast

FSU T126 Control Rain: Day-2 Forecast

mm/day

4 10 20 30

Fig. 14