Spectral Retrieval of Latent Heating Profiles from TRMM PR Data. Part II: Algorithm Improvement and Heating Estimates over Tropical Ocean Regions

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ABSTRACT

The spectral latent heating (SLH) algorithm was developed for the Tropical Rainfall Measuring Mission (TRMM) precipitation radar (PR) in Part I of this study. The method uses PR information [precipitationtop height (PTH), precipitation rates at the surface and melting level, and rain type] to select heating profiles from lookup tables. Heating-profile lookup tables for the three rain types-convective, shallow stratiform, and anvil rain (deep stratiform with a melting level)-were derived from numerical simulations of tropical cloud systems from the Tropical Ocean and Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA COARE) utilizing a cloud-resolving model (CRM). To assess its global application to TRMM PR data, the universality of the lookup tables from the TOGA COARE simulations is examined in this paper. Heating profiles are reconstructed from CRM-simulated parameters (i.e., PTH, precipitation rates at the surface and melting level, and rain type) and are compared with the true CRMsimulated heating profiles, which are computed directly by the model thermodynamic equation. CRMsimulated data from the Global Atmospheric Research Program Atlantic Tropical Experiment (GATE), South China Sea Monsoon Experiment (SCSMEX), and Kwajalein Experiment (KWAJEX) are used as a consistency check. The consistency check reveals discrepancies between the SLH-reconstructed and Goddard Cumulus Ensemble (GCE)-simulated heating above the melting level in the convective region and at the melting level in the stratiform region that are attributable to the TOGA COARE table. Discrepancies in the convective region are due to differences in the vertical distribution of deep convective heating due to the relative importance of liquid and ice water processes, which varies from case to case. Discrepancies in the stratiform region are due to differences in the level separating upper-level heating and lower-level cooling. Based on these results, improvements were made to the SLH algorithm. Convective heating retrieval is now separated into upper-level heating due to ice processes and lower-level heating due to liquid water processes. In the stratiform region, the heating profile is shifted up or down by matching the melting level in the TOGA COARE lookup table with the observed one. Consistency checks indicate the revised SLH algorithm performs much better for both the convective and stratiform components than does the original one. The revised SLH algorithm was applied to PR data, and the results were compared with heating profiles derived diagnostically from SCSMEX sounding data. Key features of the vertical profiles agree well-in particular, the level of maximum heating. The revised SLH algorithm was also applied to PR data for February 1998 and February 1999. The results are compared with heating profiles derived by the convective-stratiform heating (CSH) algorithm. Because observed information on precipitation depth is used in addition to precipitation type and intensity, differences between shallow and deep convection are more distinct in the SLH algorithm in comparison with the CSH algorithm.

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1. Introduction

The Tropical Rainfall Measuring Mission (TRMM; Simpson et al. 1988, 1996; Kummerow et al. 2000), a joint Japanese–U.S. cooperative earth probe satellite, was successfully launched in 1997 to advance understanding of the global energy and water cycle. The TRMM satellite has been in operation for more than 9 years, providing the distribution of rainfall throughout the Tropics using microwave observations from the precipitation radar (PR) and the TRMM Microwave Imager (TMI). Estimating vertical profiles of latent heating released by precipitating cloud systems is one of the key objectives of TRMM, together with accurately measuring the horizontal distribution of tropical rainfall [see a review by Tao et al. (2006)].

The PR is the first spaceborne precipitation radar and can provide height information based upon the time delay of the precipitation-backscattered return power. This allows for vertical profiles of precipitation to be obtained directly over the global Tropics (Kozu et al. 2001; Okamoto 2003). The classification between convective and stratiform regions of mesoscale convective systems (MCS) became more straightforward utilizing observed precipitation profiles (Awaka et al. 1998). The accuracy of this classification is very important for estimating latent heating because differences in diabatic heating profiles exist between convective and stratiform regions of MCSs (Houze 1982; Johnson and Young 1983). For convective regions of MCSs, the heating profile has warming at all levels with a maximum at midlevels, whereas in stratiform regions there is a warming peak in the upper troposphere and a cooling peak at low levels. The resulting MCS heating profile is positive at all levels but with a maximum value in the upper troposphere (top-heavy profile). Hartmann et al. (1984) demonstrated with a simple linear global model that the top-heavy heat source produces a Walker circulation, which is in much better agreement with observations than those that are produced with a more conventional heat source having a maximum value in the middle troposphere. Recently, Schumacher et al. (2004) showed that the horizontal variation of the vertical distribution of heating, controlled by the horizontal variation of stratiform rain fraction [as obtained from TRMM PR data by Schumacher and Houze (2003a)], is also very important in simulating the largescale tropical circulation correctly.

Tao et al. (2001) used TRMM precipitation information to estimate the four-dimensional latent heating structure over the global Tropics for one month (February 1998). Three different latent heating algorithms, the hydrometeor heating (HH; Yang and Smith 1999a,b, 2000), the convective-stratiform heating (CSH; Tao et al. 1993, 2000), and the Goddard profiling (GPROF) heating (Olson et al. 1999) algorithms were used, and their results were intercompared. The HH and GPROF algorithms are microwave radiometer based for the TMI. Only one of the three algorithms, the CSH algorithm, can use PR products as input, as well as TMI products. This is because the CSH algorithm utilizes only the surface rain rate and an estimate of the fractions of rainfall produced by convective and stratiform processes. Recently, Magagi and Barros (2004) also proposed a simple algorithm to estimate latent heating from a combination of radiosonde and TRMM PR data.

The concept of spectral approach originates from Austin and Houze (1973) and Houze (1973) in which precipitation-top height (PTH) observed by surfacebased radar data were utilized in estimating the vertical mass transports (proportional to latent heating) by cumulus-scale convection as a function of storm-top height. This spectral approach was extended by Houze and Leary (1976), Leary and Houze (1980), Houze et al. (1980), and Cheng and Houze (1980). Takayabu (2002) used a similar concept and obtained a spectral expression of precipitation profiles to examine convective and stratiform rain characteristics as a function of PTH over the equatorial area (10°N–10°S) observed by the TRMM PR. In her study, nadir data from PR 2A25, version 5, (Iguchi et al. 2000) for the period of 1998-99 were utilized, and convective and stratiform precipitation were separated based on the TRMM PR version-5 2A23 convective-stratiform separation algorithm. Precipitation profiles with a 0.3 mm h^{-1} precipitation-top threshold were accumulated and stratified according to PTHs. The threshold of 0.3 mm h^{-1} corresponds to 17.2 dBZ (stratiform) and 15.5 dBZ (convective) above the 0° C height and 17.0 dBZ (stratiform) and 14.2 dBZ (convective) just below the 0°C height in typical initial Z_e -R relations used in the PR 2A25 version-5 algorithm (Iguchi et al. 2000), where Z_e is the effective radar reflectivity factor and R is the rainfall rate. Convective rain profiles show near monotonic change with cumulative frequency. Stratiform rain profiles consist of two groups. One group consists of shallow stratiform rain profiles, which are very weak and increase downward. The other group consists of anvil rain profiles, characterized by maximum intensity around the melting level, much less intensity above, and a downward decrease below as indicated in traditional radar observations (e.g., Leary and Houze 1979). Schumacher and Houze (2003b) recently suggested that because the shallow, isolated echoes represent warm-rain processes, they should be classified as convective. After the suggestion

of Schumacher and Houze (2003b), the spectral plots of Takayabu (2002, her Fig. 1) were revised by reclassifying shallow, isolated rain (rain type 15 in product 2A23) as convective (Shige et al. 2004, their Fig. 2).

Based on the results of the spectral precipitation statistics of Takayabu (2002), the spectral latent heating (SLH) algorithm was developed for the TRMM PR in Shige et al. 2004, hereinafter Part I). The method uses PR information (i.e., PTH, precipitation rates at the surface and melting level, and rain type) to select the heating profiles in lookup tables. Heating profile lookup tables for the three rain types—convective, shallow stratiform, and anvil rain (deep stratiform with a melting level)-were derived with numerical simulations of tropical cloud systems in TOGA COARE (Webster and Lukas 1992) utilizing a cloud-resolving model (CRM). For convective and shallow stratiform regions, the lookup table is based on the PTH. Considering the sensitivity of the PR, we used a threshold of 0.3 mm h^{-1} to determine the PTH. Properties of the convective and shallow stratiform heating profiles show near monotonic change with PTH, suggesting the distribution of latent heating is a strong function of PTH. On the other hand, the PR cannot observe the PTH accurately enough for the anvil regions because of its insensitivity to the small ice-phase hydrometeors (Heymsfield et al. 2000). Thus, for the anvil region, the lookup table refers to the precipitation rate at the melting level P_m instead of PTH. The utilization of PTH and P_m provides two distinct advantages for the SLH algorithm. First, the differences in heating profiles between the shallow convective stage and the deep convective stage can be realistically retrieved. Second, heating profiles in the decaying stage with no surface rain can also be retrieved. Preliminary applications of the SLH algorithm using TRMM PR data have been done. Tao et al. (2006) presented latent heating structure for a tropical Pacific Ocean typhoon and a tropical, oceanic MCS estimated by the SLH algorithm. Morita et al. (2006) examined latent heating structure of the Madden-Julian oscillation (MJO; Madden and Julian 1994) using the SLH estimates. On the other hand, Grecu and Olson (2006) used a procedure similar to the SLH algorithm to assign a heating profile physically consistent with each precipitation profile derived from the combined TRMM PR-TMI algorithm.

For global applications of the SLH algorithm using TRMM PR data, it is necessary to examine the universality of the lookup table. If the relationship between the precipitation profiles and associated latent heating profiles changes between regions, the lookup table would lead to large errors. In this study, lookup tables from TOGA COARE, the Global Atmospheric Research Program Atlantic Tropical Experiment (GATE; Houze and Betts 1981), the 1998 South China Sea Monsoon Experiment (SCSMEX; Lau et al. 2000), and the 1999 Kwajalein Atoll field experiment (KWAJEX; Yuter et al. 2005) simulations are compared to examine their universality. The SLH algorithm is applied to PR data, and the results are compared with heating profiles derived diagnostically from SCSMEX sounding data (Johnson and Ciesielski 2002). It is also applied to PR data for February 1998 and February 1999 and compared with heating profiles derived by the CSH algorithm (Tao et al. 1993, 2000) using PR data.

2. Approach

Figure 1 shows the procedure for refining and validating the SLH algorithm. Because of the scarcity of reliable validation data and difficulties associated with the collocation of validation data and satellite measurements, a consistency check of the SLH algorithm is performed using CRM-simulated precipitation profiles as a proxy for the PR data. Algorithm-reconstructed heating profiles are derived from CRM-simulated precipitation profiles and compared with CRM-simulated true heating profiles, which are computed directly from the model thermodynamic equation. The consistency check is a useful and necessary precondition for the application of the algorithm to actual TRMM PR data. In addition to TOGA COARE simulations, GATE, SCSMEX, and KWAJEX simulations produced with a CRM are used as part of the consistency check in this study. Locations of sounding arrays deployed during TOGA COARE, GATE, SCSMEX, and KWAJEX are shown in Fig. 2. Only precipitation over ocean is considered in the current investigation. In this paper, the SLH algorithm is applied to PR data, and the results are compared with heating profiles derived diagnostically from SCSMEX sounding data (Johnson and Ciesielski 2002).

a. CRM simulations

The CRM used in this study is the two-dimensional version of the Goddard Cumulus Ensemble (GCE) model and is primarily documented in Tao and Simpson (1993). Recent improvements were presented in Tao (2003) and Tao et al. (2003a).

The model includes solar and infrared radiative transfer processes, and explicit cloud-radiation interactive processes (Tao et al. 1996). Simulations presented in this study employ a parameterized Kessler-type two-category liquid water scheme (cloud water and rain) and a three-category ice-phase scheme (cloud ice, snow, and graupel) by Rutledge and Hobbs (1984). Subgrid-scale (turbulent) processes in the GCE model are pa-



FIG. 1. Diagram showing the procedure for refining and validating the SLH algorithm. Letters denote convective and stratiform classification (C/S), PTH, the precipitation rate at the lowest observable level P_s , and the precipitation rate at the melting level P_m . The "?" means to compare and examine the heating profiles reconstructed from the SLH algorithm with the heating profiles from model simulations. This consistency check is a necessary precondition for the application of the algorithm to actual TRMM PR data.

rameterized using a scheme based on Klemp and Wilhelmson (1978) and Soong and Ogura (1980). The effects of both dry and moist processes on the generation of subgrid scale kinetic energy have been incorporated in the model. The model domain is 1024 km in the x direction (horizontal) and 22.4 km in the z direction (vertical). The horizontal resolution is 1000 m. The vertical resolution varies from 100 m at the lower boundary to 1000 m at the top of the domain. The time step is 12 s.

In this study, tropical convective systems in TOGA COARE, GATE, SCSMEX, and KWAJEX are simulated with an approach, so-called cloud ensemble modeling. In this approach, many clouds of different sizes in various stages of their life cycles can be present at any model simulation time. Observed large-scale advective tendencies of temperature, moisture, and horizontal momentum are used as the main large-scale forcings that govern the GCE model in a semiprognostic manner (Soong and Ogura 1980). These are applied uniformly over the model domain with the assumption that the model domain is considerably smaller than the large-scale disturbance. Large-scale advective tendencies for temperature T and specific humidity q are defined as

$$\left(\frac{\partial T}{\partial t}\right)_{\rm LS} = -\mathbf{v}_{\rm obs} \cdot \boldsymbol{\nabla} T_{\rm obs} - \omega_{\rm obs} \frac{\partial T_{\rm obs}}{\partial p} + \frac{\alpha_{\rm obs}}{C_p} \,\omega_{\rm obs} \quad \text{and}$$
(1)

$$\left(\frac{\partial q}{\partial t}\right)_{\rm LS} = -\mathbf{v}_{\rm obs} \cdot \nabla q_{\rm obs} - \omega_{\rm obs} \frac{\partial q_{\rm obs}}{\partial p} \tag{2}$$

and were derived from sounding networks deployed during TOGA COARE, GATE, SCSMEX, and KWAJEX. Here, **v** is the horizontal wind vector, ω is the vertical pressure velocity, α is the specific volume, and C_p is the heat capacity at constant pressure.

Because accurate calculations of the large-scale horizontal momentum forcing terms are difficult to obtain from observations in the Tropics (Soong and Tao 1984), the terms are instead replaced by a nudging term:

$$\left(\frac{\partial \mathbf{v}}{\partial t}\right)_{\rm LS} = -\frac{\overline{\mathbf{v}} - \mathbf{v}_{\rm obs}}{\tau},\tag{3}$$

where $\overline{\mathbf{v}}$ is the model domain averaged horizontal velocity, \mathbf{v}_{obs} is the observed large-scale horizontal vector over the sounding networks, and τ is the specified adjustment time scale of 6 h. This method constrains the domain-averaged horizontal velocities to follow the ob-



FIG. 2. Locations of sounding arrays deployed during TOGA COARE, GATE, SCSMEX, and KWAJEX.

served values, and thereby provides a simple means in controlling the cloud system dynamics by the largescale momentum and shear. Cyclic lateral boundary conditions are incorporated to ensure that there is no additional heat and moisture forcing inside the domain other than the imposed large-scale forcing.

The TOGA COARE simulations in this study are not the same as in Part I. An ice-water saturation adjustment scheme following Tao et al. (1989), which is a modified version of the water-phase-only saturation adjustment that does not require iterative computations (Soong and Ogura 1973), was used in Part I. The simulations in this study were made with a new saturation technique (Tao et al. 2003a), which allows the temperature to change after the water phase before the ice phase is treated. Although the overall cloud system structure and character are not sensitive to the different saturation schemes, the biggest differences between the two methods occur at about 9 km (-25° C). The alternating heating and cooling pattern at about 9 km seen in Part I (see Fig. 3e of Part I) is removed in the simulations using the new saturation technique.

The accuracy of the convective–stratiform separation affects the inference of the vertical distribution of heating. The TRMM PR rain-type classifications, in which brightband identification is very important, cannot be directly applied to GCE outputs (Awaka et al. 1996). The microphysical schemes utilized in CRMs (e.g., Lin et al. 1983; Rutledge and Hobbs 1984) typically do not contain an explicit description of the partially melted precipitation particles that lead to a bright band of enhanced radar reflectivity. Thus, the GCE convective and stratiform separation method (Lang et al. 2003) is used with some modifications done in Part I to maintain the consistency with the TRMM PR rain-type classification.

b. Latent heating

In diagnostic studies (Yanai et al. 1973; Yanai and Johnson 1993), it is customary to define the apparent

heat source Q_1 of a large-scale system by averaging horizontally the thermodynamic equation as

$$Q_1 = \overline{\pi} \left(\frac{\partial \overline{\theta}}{\partial t} + \overline{\mathbf{v}} \cdot \nabla \overline{\theta} + \overline{w} \frac{\partial \overline{\theta}}{\partial z} \right), \tag{4}$$

where θ is the potential temperature, $\pi = (p/P_{00})^{R/C_p}$ is the nondimensional pressure, P_{00} is the reference pressure (1000 hPa), C_p is the specific heat of dry air at constant pressure, and *R* is the gas constant for dry air.

Here, Q_1 can be directly related to the contributions of cloud effects, which can be explicitly estimated by CRMs as

$$Q_1 = \overline{\pi} \left(-\frac{1}{\overline{\rho}} \frac{\partial \overline{\rho} \, \overline{w'\theta'}}{\partial z} - \overline{\mathbf{v}' \cdot \nabla \theta'} + \overline{D}_{\theta} \right) + \overline{\mathrm{LH}} + \overline{Q}_R.$$
(5)

The overbars denote horizontal averages, the primes indicate deviations from the horizontal averages, $\overline{\rho}$ is the air density, Q_R is the cooling/heating rate associated with radiative processes, and D_{θ} is the subgrid-scale (smaller than the cloud scale) diffusion that is usually small relative to other terms above the boundary layer (Soong and Tao 1980). The term LH is the net latent heating due to the phase change of water:

LH =
$$\frac{L_v}{C_p}(c-e) + \frac{L_f}{C_p}(f-m) + \frac{L_s}{C_p}(d-s).$$
 (6)

Here, L_v , L_f , and L_s are the latent heats of vaporization, fusion and sublimation, respectively. Variables c, e, f, m, d, and s stand for the rates of condensation, evaporation, freezing of raindrops, melting of snow and graupel, deposition of ice particles, and sublimation of ice particles, respectively. These processes are not directly detectable with remote sensing (or for that matter, with in situ measurements). Thus, latent heating retrieval schemes depend heavily on the use of CRM. The first term on the right-hand side of Eq. (5) is the vertical eddy heat flux convergence from upward and downward cloud motions. The second term is the hori-



FIG. 3. Eight-day average profiles of (a) the GCE-simulated LH and (b) Q_{1R} without and (c) with horizontal eddy heat flux for the total (solid), convective (dashed), and stratiform (dotted) regions for the TOGA COARE (19–26 Dec 1992) case.

zontal eddy heat flux convergence. Traditionally, the horizontal eddy heat flux convergence is neglected when Eq. (5) is spatially averaged over an area suitable for diagnostic analysis. The justification for this omission has been that the net lateral transports across the boundaries of a fixed area by cumulus convection are negligible relative to the horizontal transports by the large-scale motion (Arakawa and Schubert 1974). Figures 3a-c show GCE-simulated average profiles of LH and of $Q_1 - Q_R$ (hereinafter Q_{1R}) without and with horizontal eddy heat flux for the 19-26 December 1992 period, respectively. The vertical eddy heat flux convergence compensates for the distinct LH cooling due to the melting for the total region (Sui et al. 1994; Shie et al. 2003). Neglecting the horizontal eddy heat flux convergence is appropriate for Q_{1R} for the total region because differences between profiles of Q_{1R} without and with horizontal eddy heat flux are negligible. However, there are the differences between profiles of Q_{1R} without and with horizontal eddy heat flux in the convective and stratiform regions. Largest differences occur around the melting level (4 km). This is because both the vertical eddy heat flux convergence and the horizontal eddy heat flux convergence compensate for the distinct heating and cooling in the convective and stratiform regions.

The precipitation falling at a given time is not related to latent heating that is occurring at the same time but rather to the accumulated latent heating that led up to the precipitation over a finite time period. Therefore, LH and Q_{1R} should be basically integrated over the time periods encompassing the life cycles of cloud processes producing the precipitation. However, it is extremely difficult to tabulate, for example, the effect of individual mesoscale systems. Instead, we depend here on the statistics. In the CRM simulation, as well as in the real world, cloud systems develop and decay. Although instantaneous matching between a certain rainfall profile and a heating profile is an ill conceived concept, statistical tabulation still could be done, if the life cycle of cloud systems are realistically reproduced in the CRM. For example, a shallow convective rain profile may be at a developing stage of a mesoscale system with a certain probability A, or it may be just an isolated convection with a probability of 1 - A. The latent heating associated with the two cases should be different. However, if the CRM reproduce the statistics of rain systems well enough, CRM-based tables can statistically represent an average heating profile for a certain rain profile. Besides, we accumulate LH and Q_{1R} over a period of 5 min for each data sampling, since accumulation over long periods are inadequate for growing convective cells (Shige and Satomura 2000, their Fig. 4a) and moving convective systems. Additional sensitivity tests with periods of 1 and 2 min do not alter the overall results of our study. Hereinafter heating (LH and Q_{1R}) accumulated over a period of 5 min for each data sampling is represented as instantaneous heating.

Apparent heat source Q_1 is more important than LH as a dynamical quantity. Yanai et al. (2000) have shown that during TOGA COARE the generation of available potential energy, wherein positive Q_1 anomalies coincide with the warm amplitude, maintains the perturbation kinetic energy of the MJO (Madden and Julian 1994). On the other hand, positive (negative) isentropic potential vorticity can be generated where Q_1 increases (decreases) with height (Holton 2004, p. 110). Braun



FIG. 4. Eight-day averaged profiles of Q_{1Rp} reconstructed by the original SLH algorithm (SLH1) with the COARE lookup table (thick solid line) and Q_{1R} simulated by the GCE model (dotted line) for the (a) TOGA COARE (19–26 Dec 1992) case, (b) GATE (1–8 Sep 1974) case, (c) SCSMEX (2–9 Jun 1998), and (d) KWAJEX (6–13 Sep 1999), respectively. Left panels are for the convective regions, center panels for the stratiform regions, and the right panels are for the total regions. Thin solid lines indicate differences between the SLH1-reconstructed and the GCE-simulated profiles.

and Houze (1996) discussed the production of potential vorticity anomalies from the Q_1 associated with a midlatitude squall line. Although the PR footprint scale (4 km) estimates of Q_{1R} are less meaningful because Q_{1R} is a large-scale variable, the SLH algorithm aims to estimate Q_{1R} for each precipitation profile. Over the tropical oceans, heat released by condensation within deep cumulus convection provides the major heat source (e.g., Yanai and Tomita 1998). However, other processes can be a major source of heat over local areas. For example, in spring over the Tibetan Plateau, sensible heating from the surface is a major component

TABLE 1. Domain averaged surface rainfall amounts and stratiform percentage from the GCE model for the COARE, GATE, SCSMEX, and KWAJEX episodes used in the consistency check. Rainfall estimated by sounding network is also shown.

	GCE rainfall (mm day ⁻¹)	GCE stratiform (%)	Sounding rainfall (mm day ⁻¹)
TOGA COARE (19–26 Dec 1992)	20.26	43	19.91
GATE (1-8 Sep 1974)	11.80	35	10.97
SCSMEX (2-9 Jun 1998)	17.35	35	22.76
KWAJEX (6-13 Sep 1999)	9.17	46	8.66

of the heat source (Luo and Yanai 1984; Yanai and Tomita 1998). In such a situation, the SLH algorithm cannot estimate Q_{1R} because it estimates Q_{1R} mainly due to precipitation processes. Hereinafter, Q_{1R} estimated by the SLH algorithm is represented as Q_{1Rp} to bring attention to this point.

The SLH algorithm is severely limited by the inherent sensitivity of the PR. For latent heating, the quantity required is actually cloud top, but the PR can detect only precipitation-sized particles. For convective clouds, cloud-top and radar-echo top may often correlate well. The consistency check of the SLH algorithm showed that the transition from the shallow convective stage to the deep convective stage of a quasi-2-day oscillation (Takayabu et al. 1996) can be retrieved very well (Part I, their Fig. 15). This may be because during the growing phase of a congestus cloud, cloud-top and radar-echo top may correlate well (Kingsmill and Wakimoto 1991). On the other hand, during the decaying phase of a cumulonimbus cloud, the two tops may differ significantly, leading to storm-height underestimation. The problem of storm-height underestimation is revisited in section 4a, when we evaluate the algorithm against radiosonde. The limited PR sensitivity also results in the failure to detect very weak precipitating systems and small convective cells (Heymsfield et al. 2000). Contributions to the distribution of heating from very weak precipitating systems or small convective cells, though smaller, are not negligible. Therefore, measurements from other sensors will have to be integrated to obtain a more complete estimation of latent heating profiles. Nevertheless, the latent heating profiles in the Tropics from the SLH algorithm using the TRMM PR data is felt to make a contribution to better understand global climate.

3. Algorithm improvements

a. Consistency check of the original algorithm

In addition to an 8-day period from TOGA COARE (19–26 December 1992) as shown in Part I, three 8-day periods from GATE (1–8 September 1974), SCSMEX (2–9 June 1998), and KWAJEX (6–13 September 1999)

are used for a consistency check of the original SLH algorithm (hereinafter SLH1), as shown in Fig. 4. For each period, heating profiles were also reconstructed using the simulated parameters (i.e., PTH, convective/ stratiform characteristics, P_s , and P_m) as input. The algorithm-reconstructed heating profiles from the GCEsimulated precipitation profiles are compared with GCE-simulated true heating profiles for the convective, stratiform, and total regions. Domain-averaged surface rainfall amounts and stratiform percentage from the GCE model for the COARE, GATE, SCSMEX, and KWAJEX periods used in the consistency check are shown in Table 1. The importance of the fraction of stratiform rainfall on the total heating profile shape has been shown by Johnson (1984) and has been taken into account by the CSH algorithm. Figure 4 and Table 1, however, indicate that a higher percentage of stratiform rain does not always imply a maximum heating rate at a higher altitude. A higher-level heating maximum is found in the SCSMEX case with a stratiform percentage of 35% than in the GATE (KWAJEX) case with 35% (46%). This is because the total heating profile shape is affected not only by the fraction of stratiform rainfall but also the shape of the convective heating profile.

Observed (determined from sounding networks) rainfall is also shown in Table 1 for comparison. The rainfall amount simulated by the GCE model and estimated by sounding is in good agreement with each other for COARE and KWAJEX cases. The model overestimates the rainfall by 8% for the GATE case and underestimates 24% for the SCSMEX case, respectively, relative to that diagnosed from sounding. All of these cases are forced by a prescribed large-scale advective forcing determined from soundings. The radiation and surface fluxes can be influenced by clouds simulated by the models and may cause the rainfall differences between the model and the sounding estimates. The model physics may be another reason for this discrepancy. Accurate and consistent large-scale advective tendencies in temperature and water vapor are also needed for CRM simulations. Tao et al. (2000) found that the large-scale advective terms for temperature and water vapor are not always consistent. For example, large-scale forcing could indicate strong drying (which would produce cooling in the model through evaporation) but could not contain large-scale advective heating to compensate. This discrepancy in forcing would cause differences between the observed and modeled rainfall.

The SLH1 algorithm with the COARE lookup table produces excellent agreement between the SLHreconstructed and GCE-simulated heating profiles for TOGA COARE (Fig. 4a) as shown in Part I. However, the SLH1-reconstructed convective heating above the freezing level is slightly stronger than was simulated by the GCE. This is because the simulated data used for the construction of the lookup tables includes the two subperiods with 9-day durations (9-17 February 1993, and 18-26 February 1993) in which convective heating was stronger above the freezing level than in the 19-26 December 1992 period. This is consistent with the result of DeMott and Rutledge (1998a,b), who reported that convection in cruise 3 (29 January–25 February 1993) had greater liquid and ice water masses above the freezing level than cruise 2 (21 December 1992-19 January 1993) using radar data.

For the GATE case, the TOGA COARE lookup table results in less agreement between the SLHreconstructed and GCE-simulated heating profiles for the convective and stratiform regions (Fig. 4b). The SLH1-reconstructed heating at z = 4-6 km is stronger than the GCE-simulated for the convective heating profiles, and while the SLH1 algorithm produces cooling at z = 4-6 km, the GCE model simulates heating for the stratiform heating profiles. The reconstructed total heating is in good agreement with the simulated profile. Compensating errors at z = 4-6 km from each component (convective and stratiform) is the reason for this good agreement.

The TOGA COARE lookup table produces better agreement between reconstructed and simulated heating profiles for the SCSMEX convective region than for the GATE convective region (Fig. 4c). The SLH1reconstructed convective heating profile decreases more rapidly with height above the freezing level than the GCE-simulated one does. However, the reconstructed total heating is in poorer agreement with the model for SCSMEX than for GATE. The level of maximum heating in the reconstructed total heating profile is about 5 km, while in the simulated total heating profile it is about 7 km. This is because the SLH1 algorithm reconstructs cooling at z = 4-6 km whereas the GCE model simulates heating in the stratiform profiles and the error for each component does not compensate.

The SLH1-reconstructed total heating profile at z =

4–6 km is weaker than was simulated by the GCE model for KWAJEX (Fig. 4d). Relatively large discrepancies between the reconstructed and GCE-simulated heating profiles are found in the stratiform regions where the SLH1 algorithm reconstructs cooling at z = 4-5 km and the GCE model produces heating. Thus, the algorithm needs to be improved in the stratiform region.

In general, the disagreement between the reconstructed and GCE-simulated heating profiles is smaller for the convective region than for the stratiform region. The convective lookup table of the SLH1 algorithm prepares spectral vertical profiles of latent heating for various PTHs, leading better agreement for the convective region than for the stratiform region. However, as pointed out by Houze (1989), the heating profile shape for convection within a given PTH may vary, leading a small but nonnegligible disagreement in convective heating profiles.

b. Comparisons of lookup tables

Figures 5a–d show lookup tables for convective rain produced from TOGA COARE, GATE, SCSMEX, and KWAJEX simulations. The GCE-simulated precipitation profiles with a 0.3 mm h^{-1} precipitation-top threshold and corresponding heating profiles are accumulated and averaged for each PTH with model grid intervals. Two periods from SCSMEX (18–26 May and 2–11 June 1998), two from GATE (1–8 and 9–18 September 1974), and four from KWAJEX (7–11 August, 17–20 August, 29 August–5 September and 6–12 September 1999) are used to increase the number of sample profiles.

The similarity in the lookup tables from case to case is evident. Features of the convective heating profiles show near-monotonic changes with PTH. The shallow convective heating profiles (PTH < 6 km) are characterized by cooling aloft due to an excess of evaporation over condensation, such as in trade wind cumulus (Nitta and Esbensen 1974). Another interesting feature is that the convective heating profiles for the highest PTH are also characterized by cooling aloft. This feature is consistent with the strong cooling above mesoscale convective systems observed by Johnson and Kriete (1982) and Lin and Johnson (1996b). Because the population of deep convection is small in the GATE (KWAJEX) simulations, the confidence level in the mean heating profiles with PTH higher than 15 km (14 km) from GATE (KWAJEX) is low.

On the other hand, there exist variations in vertical structure (e.g., the level of maximum Q_{1Rp} heating) for a given PTH. These account for the differences be-



FIG. 5. Ensemble-mean GCE-simulated Q_{1Rp} profiles plotted as a function of PTH from the convective regions of the (a) COARE, (b) GATE, (c) SCSMEX, and (d) KWAJEX cases. Contours indicate confidence intervals for a mean at the 95% level using the Student's *t* test. The contour interval (CI) is 2.0 K h⁻¹.

tween the SLH1-reconstructed convective heating profiles and GCE-simulated ones seen in Fig. 4. Figure 6 shows GCE-simulated Q_{1Rp} and precipitation profiles with selected PTHs of 3.1, 5.9, 8.2, and 11 km from the convective regions of the COARE, GATE, SCSMEX, and KWAJEX cases. Note that the Q_{1Rp} profiles and precipitation profiles are normalized by the nearsurface rain rate. Heating top height is determined by the PTH, and the heating depth for a given PTH does not vary from location to location. The vertical structure (e.g., maximum heating level) of the shallow convective heating profiles (PTH = 3.1 km) does not vary from location to location. However, the differences in convective heating profile shape among the cases increase with PTH. TOGA COARE convection has stronger heating above the melting level with a higherlevel maximum than GATE convection does, but is weaker with a lower-level maximum than SCSMEX convection. Similarly, the differences in corresponding precipitation profile shape among cases also increases with PTH. TOGA COARE convection has stronger precipitation intensity above the melting level than GATE convection, but weaker intensity than SCSMEX convection. KWAJEX convection shows somewhat anomalous features. Although convection in KWAJEX has a lower maximum heating level than in COARE,

heating above the melting level in KWAJEX convection is comparable to that of COARE convection. Correspondingly, KWAJEX convection has somewhat stronger precipitation intensity above the freezing level than COARE convection does. This accounts for the small difference between the SLH1-reconstructed convective heating and that simulated by the GCE for the KWAJEX period. Though KWAJEX convection is somewhat anomalous, the same systematic variability of heating and precipitation profiles due to the relative importance of liquid water and ice processes is found above the melting level. Convective cells with enhanced liquid water processes have latent heating and precipitation concentrated below the freezing level, whereas convective cells with significant ice processes provide stronger latent heating and more precipitation above the freezing level. Thus, the precipitation profiles may be indicative of the convective heating profile shape.

Petersen and Rutledge (2001) showed a large systematic variability in precipitation vertical structure between tropical locations above the freezing level using the TRMM PR and Lightning Imaging Sensor (LIS) observations. They found slightly stronger convection over the South China Sea (i.e., SCSMEX) relative to isolated oceanic regimes (i.e., COARE, GATE, and KWAJEX) while convection over the western Pacific



FIG. 6. Ensemble-mean GCE-simulated Q_{1Rp} profiles plotted as a function of PTH from the convective regions of the (a) COARE, (b) GATE, (c) SCSMEX, and (d) KWAJEX cases. Contours indicate confidence intervals for a mean at the 95% level using Student's *t* test. The CI is 2.0 K h⁻¹.

warm pool (i.e., COARE and KWAJEX) was slightly more intense than that sampled over other oceans (i.e., GATE). Thus, the aforementioned differences between COARE, GATE, SCSMEX, and KWAJEX convection in the GCE results may be consistent with their results.

Figures 7a–d show lookup tables for anvil (deep stratiform with a melting level) rain produced from the COARE, GATE, SCSMEX, and KWAJEX simulations. The similarity in the anvil heating profiles among the various lookup tables for each case is readily apparent, although there are differences in the level separating upper-level heating and lower-level cooling, which is tied to the 0°C level. These results agree well with observations of stratiform heating profiles summarized in Houze (1989), who concluded that stratiform heating profiles are not substantially different from one location to the next.

c. Revised procedure for heating retrieval

To retrieve convective heating profiles, the SLH algorithm selects a heating profile corresponding to the PTH in the convective heating profile lookup table (Fig. 5a). In the original procedure (Fig. 8a), the entirelevel heating amplitude is determined by

$$Q(z) = \frac{Q(z)}{\tilde{P}_s} P_s,$$
(7)

where P_s is the precipitation rate at the lowest observable level and tildes denote the variables in the lookup table.

Comparisons of convective lookup tables suggested that the variability in heating profiles above the freezing level should be taken into account for convective heating retrieval. Hence, the upper-level heating amplitude due to ice processes and the lower-level heating amplitude due to liquid water processes are determined separately in the revised procedure for convective heating retrieval (Fig. 8b). Braun and Houze (1995) showed the peak heating rate by freezing within the convective region occurs immediately above the freezing level. Based on sensitivity tests, the level separating upperlevel heating from lower-level heating is determined to



GCE-simulated Q1Rp Profiles == Anvil Regions ==

FIG. 7. Lookup tables for the stratiform region produced from the (a) COARE, (b) GATE, (c) SCSMEX, and (d) KWAJEX simulations.

be 1 km above the melting level. In the revised procedure for convective heating retrieval, the upper-level heating due to ice processes is determined by

$$Q(z)_{\text{high}} = \frac{\tilde{Q}_{\text{high}}(z)}{\tilde{P}_f} P_f, \qquad (8)$$

where P_f is the precipitation rate at the level separating upper-level heating from lower-level heating. Likewise, the lower-level heating due to liquid water processes is determined by

$$Q(z)_{\rm low} = \frac{\tilde{Q}_{\rm low}(z)}{\tilde{P}_{\rm s}} P_{\rm s}.$$
 (9)

This revised procedure is only applied to convective rain with PTHs that are 3 km higher than the level separating upper-level heating from lower-level heating. The original procedure shown in Fig. 8a is applied to the remaining convective rain.

For stratiform regions, the heating profile is shifted by matching the melting level of the COARE lookup table with the observed melting level. Although, in principle one can use the melting levels grid by grid from the CRM simulations (or PR observations), consistency checks indicate the SLH algorithm performs much poorer (not shown) when the melting levels grid by grid are used. Thus, the climatological melting levels are used here.

d. Consistency check of the revised algorithm

Again, the four periods from TOGA COARE (19–26 December 1992), GATE (1–8 September 1974), SCSMEX (2–9 June 1998), and KWAJEX (6–13 September 1999) are used for the consistency check of the revised SLH algorithm (hereinafter SLH2) as shown in Fig. 9.

For the COARE period, the SLH2-reconstructed heating profiles for the convective, stratiform, and total regions are almost identical to those reconstructed by the SLH1 algorithm. Actually, the SLH2-reconstructed heating profile for the stratiform region is exactly the same as the SLH1-reconstructed one because adjustment of the melting level is not needed. The SLH2 algorithm produces slightly weaker convective heating at z = 5-6.5 km than the SLH1 algorithm does and is in better agreement with the GCE model.

Although the total heating profile reconstructed by the SLH2 algorithm is almost identical to that reconstructed by the SLH1 algorithm for GATE, the error in each component is reduced. For the convective region, the SLH2 algorithm produces weaker heating above



FIG. 8. Diagram showing the procedure for deriving latent heating profiles using the SLH algorithm.

z = 5 km than the SLH1 algorithm does and is in much better agreement with the GCE model. For the stratiform region, the discrepancy in the level separating upper-level heating from lower-level cooling as reconstructed by the SLH2 algorithm and simulated by the GCE model is reduced.

For SCSMEX, the SLH2 algorithm produces stronger convective heating above z = 5 km than the SLH1 algorithm does, different from the COARE and GATE periods, and in very good agreement with the GCE model. For the stratiform region, the discrepancy in the level separating upper-level heating from lower-level cooling as reconstructed by the SLH2 algorithm and simulated by the GCE model is reduced such that very good agreement is obtained between the two heating profiles. As a result of the improvements in the convective and stratiform estimates, the total heating profile reconstructed by the SLH2 algorithm is in very good agreement with that simulated by the GCE model. The level of maximum heating reconstructed by SLH2 agrees with the GCE-simulated one.

For KWAJEX, the better agreement between the total heating profile reconstructed by the SLH2 algorithm and that simulated by the GCE model is explained by the fact that the discrepancy between the level separating upper-level heating from lower-level cooling as reconstructed by the SLH2 algorithm and simulated by the GCE model is reduced in the stratiform region. Still, the SLH2 algorithm produces slightly weaker convective heating at z = 5-6 km than the

SLH1 algorithm does in better agreement with the GCE model.

e. Error estimation

As mentioned in Part I, lookup tables are constructed based on the assumption that heating profiles correspond statistically to precipitation profiles or precipitation parameters (i.e., PTH, P_m). However, the instantaneous grid cell relationship between precipitation profiles and heating profiles is somewhat ambiguous. Part I performed a preliminary evaluation of the horizontally averaged estimates and found that horizontal averaging over ~50 km width was required to reduce random errors in the SLH-reconstructed heating profiles to acceptable levels.

Following Part I, a preliminary evaluation of the horizontally averaged estimates for the COARE, GATE, SCSMEX, and KWAJEX periods used in the consistency check is performed. Heating profiles were reconstructed grid by grid for each 8-day period using the simulated parameters as input. Then, the differences between the reconstructed heating profiles and the simulated ones were examined statistically to see the errors in the instantaneous grid cell estimates using the table method. Larger root-mean-square (rms) errors were found for COARE and SCSMEX than with GATE and KWAJEX. This is because there were larger surface rainfall amounts and thus were larger heating associated with COARE and SCSMEX than with GATE and KWAJEX (Table 1). For COARE and



FIG. 9. Same as Fig. 4, but reconstructed with the revised SLH algorithm (SLH2) using the TOGA COARE lookup table and simulated by the GCE model. Thin solid line indicates differences between SLH2 and the GCE.

SCSMEX, horizontal averaging reduces the rms error. Averaging over ~ 30 km in width reduces the rms to about 1 K² h⁻². From these results, averaging over ~ 30 km in width is recommended so as to use the SLH algorithm estimates quantitatively. The large rms errors at about 9-km height seen in Part I (see their Fig. 12) are not found in the COARE case (Fig. 10a). This is because the alternating heating and cooling pattern at about 9 km seen in Part I (see their Fig. 3e) is gone in the new saturation technique (Tao et al. 2003a) used in this paper.

4. PR applications

In this section, the revised SLH algorithm is applied to precipitation profiles from version 6 of the TRMM PR 2A25 dataset, which is instantaneous and at footprint-scale (i.e., a level-2 product). Brightband height rms between SLH2 reconstructed Q1Rp and GCE simulated Q1R



FIG. 10. The rms error in the horizontal averaged profiles between the SLH algorithm-reconstructed Q_{1Rp} and the GCE-simulated Q_{1R} for the (a) TOGA COARE, (b) GATE, (c) SCSMEX, and (d) KWAJEX cases.

estimates from version 6 of TRMM PR 3A25, gridded 5° spatial resolution monthly composite of instantaneous and footprint-scale data (PR 2A25), are also used as the melting levels.

a. Comparison of Q_1 profiles over the SCSMEX NESA region

The accuracy of the SLH-retrieved heating can be evaluated by comparing with a rawinsonde-based analysis of diabatic heating for the SCSMEX Northern Enhanced Sounding Array (NESA) derived by Johnson and Ciesielski (2002). Magagi and Barros (2004) and Grecu and Olson (2006) also compared their results with heating estimates over the SCSMEX NESA derived by Johnson and Ciesielski (2002). Figure 11 shows a comparison between SLH-retrieved Q_{1Rp} from version 6 of the TRMM PR datasets and sounding-based Q_1 during the campaign's most convectively active period (15 May-20 June 1998). Mapes et al. (2003) suggested that averages of about 30 days reduce sampling errors in the rainfall-rate estimate (proportional to integrated Q_1 or Q_2) to 10% for the SCSMEX NESA. There is good agreement in several key features of the vertical profiles, particularly the level of maximum heating. The SLH-retrieved Q_{1Rp} heating magnitudes are somewhat greater than the sounding-derived magnitudes. This difference is mainly caused by the fact the SLH-retrieved Q_{1Rp} does not include Q_R which is included in the sounding-derived Q_1 . Tao et al. (2003b, 2004) reported that net radiation (cooling) accounts for about 20% or more of the net



FIG. 11. Heating from diagnostic calculations (Johnson and Ciesielski 2002) and the SLH2 algorithm using version 6 of the TRMM PR datasets for SCSMEX (15 May–20 Jun 1998).





FIG. 12. Contribution to total rain rate as a function of the surface rain intensity estimated by TMI 2A12, version 6, over the PR swath (\sim 215 km) and over the full TMI swath (\sim 760 km).

condensation for the SCSMEX cloud systems simulated by the GCE model. The vertical profile of Q_R simulated by the GCE model for the SCSMEX periods (18–26 May 1998 and 2–11 June 1998) is shown on the left side of the figure. This Q_R component is added to the SLHretrieved Q_{1Rp} estimates. The level of maximum heating of $Q_{1Rp} + Q_R$ and its magnitude are in very good agreement with the sounding-derived Q_1 .

Figure 11 shows that in the lower troposphere, the $Q_{1Rp} + Q_R$ heating magnitudes are somewhat greater than the sounding-derived magnitudes, because the SLH-estimated convective $Q_{1Rp} + Q_R$ heating magnitudes are larger than the SLH-estimated stratiform $Q_{1Rp} + Q_R$ cooling magnitudes. Heating estimates from PR data are subject to sampling errors attributable to the PR's narrow swath width, leading to a discrepancy with the sounding estimates. Grecu and Olson (2006) showed that the rawinsonde surface precipitation estimates are better correlated with the TMI surface precipitation estimates than with the TRMM PR surface precipitation estimates. Although all of the estimates are affected by sampling errors, the TRMM PR surface precipitation estimates are probably subject to the largest sampling errors despite being the most accurate at the footprint instantaneous level, leading to a discrepancy with the other estimates. Sampling errors affect not only the precipitation estimates but also heating estimates, and therefore it is expected that for periods when sampling errors in the precipitation estimates are large heating estimates will also be subject to large sampling errors (Grecu and Olson 2006, their Fig. 9). Figure 12 presents a histogram of surface rain rates estimated by the TMI (i.e., 2A12, version 6) over the PR

swath (~215 km) and over the full TMI swath (~760 km). The occurrence of moderate-to-heavy rain rates ($\geq 5 \text{ mm h}^{-1}$) is more for the PR swath than for the TMI swath. These moderate-to-heavy rain pixels are classified mostly as convective rain. The heating estimates are sensitive to the estimated fraction of stratiform rainfall from the PR data. Thus, sampling errors may account for the overestimation of $Q_{1Rp} + Q_R$ heating in the lower troposphere.

It is also evident from Fig. 11 that the $Q_{1Rp} + Q_R$ heating magnitudes are smaller than the soundingderived magnitudes above 9 km. Magagi and Barros (2004) also showed differences in the upper limit between their heating estimates and the sounding-derived Q_1 over the SCSMEX NESA together with in the lower limit. The radiative cooling of the upper troposphere must be balanced by deep convection. Because the saturation mixing ration is low in the upper troposphere, deep convection heats the upper troposphere largely by eddy heat-flux convergence (Mapes 2001).

As mentioned before, the SLH algorithm is severely limited by the inherent sensitivity of the PR that can detect only precipitation-sized particles. During the growing phase of a congestus cloud, cloud-top, and radar-echo top may correlate well during the growing phase of a congestus cloud (Kingsmill and Wakimoto 1991). However, during the decaying phase of a cumulonimbus cloud and in stratiform regions, the two tops may differ significantly, leading to underestimate of heating in the upper troposphere. Therefore, measurements from other sensors [e.g., Visible and Infrared Scanner (VIRS)] will have to be integrated to obtain a more complete estimation of latent heating profiles, but it is beyond the scope of this study.

b. Comparison with the CSH algorithm

Tao et al. (2001) represented the first attempt at using version-5 TRMM rainfall products to estimate the latent heating structure over the global Tropics for February 1998, corresponding to the warm phase (El Niño) of the 1997/1998 El Niño-Southern Oscillation (ENSO). Three different latent heating algorithms the HH algorithm, the convective-stratiform heating CSH algorithm, and the GPROF heating algorithm were used, and their results were compared. Only one of the three algorithms, the CSH algorithm, can use PR products as input (CSH can also use the TMI products). The CSH algorithm has been developed based on the assumption that the shape of the overall MCS heating profile is determined by the relative amounts of convective and mesoscale heating, which are proportional to the relative amounts of convective and stratiform precipitation:



FIG. 13. Monthly mean rainfall (mm day⁻¹) derived from PR 2A25, version 6, for (a) February 1998 and (b) February 1999. The heating profiles will be compared and examined for the various geographic locations identified by the boxes.

$$Q(z) = P_{\rm conv}Q(z)_{\rm conv} + P_{\rm stra}Q(z)_{\rm stra}.$$
 (10)

Here, $P_{\rm conv}$ and $P_{\rm stra}$ are observed surface precipitation rates in the convective and stratiform regions, and $Q(z)_{\rm conv}$ and $Q(z)_{\rm stra}$ are model-generated convective and stratiform heating profiles, normalized by the convective and stratiform rainfall. An appropriate selection of latent heating profiles from the lookup table is very important for the CSH algorithm (Tao et al. 2000). Schumacher et al. (2004) demonstrated the horizontal variation in the heating profile across the Tropics calculated from TRMM PR observations using a method similar to the CSH algorithm, except they used simpler, assumed profiles. In addition, they input their heating profiles into an idealized climate model to determine the response of the large-scale circulation to the heating patterns. The SLH algorithm performance is compared with the CSH algorithm using version 6 of the TRMM PR products for February 1998 and February 1999, corresponding to the warm and cold phase (La Niña), respectively.

Figures 13a,b show the monthly mean surface rainfall $(mm day^{-1})$ for February 1998 and February 1999, re-

spectively. Heating structures over the six oceanic regions (western Pacific, central Pacific, east Pacific, South Pacific, Indian Ocean, and Atlantic Ocean) shown in Fig. 13 will be examined and compared. Three regions (central Pacific, east Pacific, and South Pacific) are completely the same as those examined by Tao et al. (2001). Because only precipitation over oceans is considered in the current investigation, smaller areas over oceans are selected than those in Tao et al. (2001) for the Indian and Atlantic Oceans. On the other hand, for western Pacific, larger areas are selected than those in Tao et al. (2001) in order to improve sampling. Table 2 shows the PR-derived rainfall and its stratiform percentage for the six different geographic areas. The monthly surface rainfall and its stratiform percentage for February 1999 are larger than those for February 1998 over the western Pacific and Atlantic Oceans. On the other hand, the monthly surface rainfall and its stratiform percentage for February 1998 are larger than those for February 1999 over the central and east Pacific, and the Indian Ocean. The surface rainfall over all six geographic areas for February 1998 derived from the PR version-6 (V6) data is larger than that derived

TABLE 2. PR version-6-algorithm-derived rainfall and stratiform percentage for February 1998 and February 1999 for the various geographic areas. Figures in parentheses indicate PR version-6-algorithm-derived rainfall and stratiform percentage for the same areas examined by Tao et al. (2001) for western Pacific Ocean (TOGA COARE Intensive Flux Array), Indian Ocean, and Atlantic Ocean.

	Feb 1998		Feb 1999	
	Rainfall (mm day ⁻¹)	Stratiform (%)	Rainfall (mm day ⁻¹)	Stratiform (%)
Western Pacific	5.67 (4.68)	45 (45)	8.75	51
Central Pacific	9.78	57	3.38	38
East Pacific	5.44	47	1.16	30
South Pacific	2.16	52	4.70	55
Indian Ocean	4.99 (3.94)	46 (45)	2.51	33
Atlantic Ocean	1.29 (1.21)	25 (28)	2.02	31

from the PR version-5 (V5) data used in Tao et al. (2001; see their Table 2). Shige et al. (2006) recently investigated the consistency between TMI-observed brightness temperatures at 10 GHz and those simulated from PR 2A25 V5 and V6 rain profiles for ITCZ rain systems during the warm phase of the 1997/98 ENSO using a radiative transfer model. They showed that simulated brightness temperatures from PR 2A25 V6 are higher than those from PR 2A25 V5 and exhibit better agreement with the observed brightness temperatures, especially for higher values (associated with heavy rainfall). This is explained by the inclusion of attenuation corrections for water vapor and cloud liquid water, and more relative weight to the surface reference technique estimate of the path-integrated attenuation in V6 than in V5.

Figures 14 and 15 show the monthly mean convective, stratiform and total heating profiles derived from the SLH algorithm for six locations over the tropical oceans for February of 1998 and February of 1999, respectively. Also the CSH algorithm estimates using PR rainfall information are shown for comparison. Because the CSH algorithm estimates Q_1 due to precipitation processes, Q_1 estimated by the CSH algorithm is denoted as Q_{1p} . It should be noted that the SLHestimated heating does not include Q_R , while the CSH estimated heating does.

The SLH- and CSH-estimated mean latent heating profiles over the western Pacific for February 1998 and February 1999 are in good agreement with each other (Figs. 14a and 15a). For February 1998, however, a secondary maximum at low levels (~2 km) is found in the SLH-estimated total heating profile, while the CSH algorithm-estimated heating profiles only show one maximum heating level. This low-level maximum in the SLH-estimated total heating profile comes from the SLH-estimated convective heating profile with a low-level maximum, reflecting the abundance of shallow convection. Diagnostic budget studies over west Pacific regions (Reed and Recker 1971; Nitta 1972; Yanai et al.

1973; Lin and Johnson 1996a) indicate a single heating maximum at 7-8 km altitude. The SLH-estimated mean heating profile for February 1999 resembles those determined from the diagnostic budget studies as well as the CSH algorithm. Furthermore, the SLH-estimated convective heating profile for February 1999 indicates a single heating peak at 4.5 km, similar to the result from Johnson (1984) who partitioned the total heating profile of Yanai et al. (1973) into convective and mesoscale component. On the other hand, the SLH-estimated mean heating profile with the low-level maximum for February 1998 does not resemble those determined from the diagnostic budget studies. It should be noted that diagnostic budget studies over the western Pacific do not contain periods corresponding to the warm phases of ENSO, except for two months out of the period from March to July of 1958 in Nitta (1972). Deep convection over the western Pacific is suppressed during the warm phase of ENSO (February 1998) relative to the cold phase (February 1999) because of lower sea surface temperatures. Tradelike regimes with abundant shallow cumulus (Johnson and Lin 1997) are expected to be more frequent during the warm phase of ENSO (February 1998) than during the cold phase (February 1999). Thus, the difference in the SLH-estimated mean heating profile between February 1998 and February 1999 may be reasonable.

Total heating profiles over the central and eastern Pacific for February 1998 and over the south Pacific for February 1999 from the SLH algorithm also have secondary maxima at low-levels (~2 km), while those estimated by the CSH algorithm have a single heating maximum at 7 km altitude. Although both the SLH and CSH algorithms estimate shallow heating over the eastern Pacific for February 1999, the SLH-estimated heating peak is much sharper than the CSH-estimated one. Because it uses observed information not only on precipitation type and intensity but also on precipitation depth, the SLH algorithm estimate between shallow and deep convection are more distinct than the CSH



FIG. 14. Monthly (February 1998) mean total, convective and stratiform heating profiles derived from the SLH2 algorithm for various locations. Total Q_{1Rp} profiles derived from the SLH algorithm are also shown. The geographic areas are the (a) western Pacific, (b) central Pacific, (c) east Pacific, (d) South Pacific, (e) Indian Ocean, and (f) Atlantic Ocean. Note that the abscissa scales are the same except in (f).

algorithm (see Part I). Zhang et al. (2004) recently presented observational evidence of a shallow meridional circulation cell in the eastern tropical Pacific. The top of the shallow meridional circulation cell was found to be immediately above the atmospheric boundary layer, which may be consistent with the SLH-estimated shallow heating profile over the eastern Pacific for February 1999.

Schumacher and Houze (2003a) showed dramatic differences in PR stratiform rain fraction and precipitation between the 1998 El Niño event and the 1999 La Niña event. Based on the results of Schumacher and Houze (2003a), Schumacher et al. (2004) demonstrated that the response of the tropical circulation to latent heating during the 1998 El Niño is extremely sensitive to the magnitude and horizontal variability of the stratiform rain fraction across the Pacific. Figures 14a–c and

15a-c indicate that the 1998 El Niño event and the 1999 La Niña event exhibit dramatic differences in the shape of convective heating profile, together with those in the amplitude of stratiform heating profile. Schumacher et al. (2004) did take into account the effect of shallow as well as deep convection, but they did not fully take into account the variation of height of the profile from region to region. By utilizing the information about precipitation profiles, the SLH algorithm retrieves differences in the shape of convective heating profile between the eastern Pacific and the western Pacific during the cold phase. The differences in the shape of convective heating profiles across the Pacific could have an important effect on the tropical circulation. It is possible that the radar echoes observed by PR are shallower over the eastern Pacific in comparison with those over the western Pacific during the 1999 La Niña event,



FIG. 15. Same as Fig. 14, but for February 1999.

but the cloud top are still high. Figures 16a,b show the monthly mean outgoing longwave radiation (OLR) from National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites (Liebmann and Smith 1996) for February 1998 and February 1999, respectively. The east–west gradient in the monthly mean OLR is more pronounced during the cold phase than the warm phase. The OLR values in the eastern Pacific are much higher than those in the western Pacific, supporting the notion that the convection is shallower in the eastern Pacific relative to the western Pacific during the cold phase.

A larger difference exists between the SLH- and CSH-estimated mean heating profiles over the South Pacific for February 1998. There is a distinct double peak in the SLH-estimated heating, while the CSHestimated heating profile shows a minimum near 4 km but not very pronounced. The SLH-estimated heating profile is very similar to the vertical distribution of heating during the undisturbed Barbados Oceanographic and Meteorological Experiment (BOMEX) period in the trade wind belts (Nitta and Esbensen 1974) and that during episodic trade wind regimes over the western Pacific (Johnson and Lin 1997).

The SLH- and CSH-estimated mean latent heating profiles over the Indian Ocean for February 1998 are in good agreement with each other. On the other hand, there are differences between the two estimates over the Indian Ocean for February 1999. The SLH-estimated mean latent heating profile has a midlevel maximum, while the CSH-estimated mean latent heating profile has a lower-level maximum. Similar differences can be found over the Atlantic Ocean for February 1998 and February 1999. These SLH-estimated heating profiles resemble the mean heating profile with a midlevel maximum that was determined from a diagnostic budget study during GATE (Thompson et al. 1979) and simulated by the GCE model (see Figs. 4b or 9b).



FIG. 16. Monthly mean OLR (W m⁻²) for (a) February 1998 and (b) February 1999. The heating profiles are compared and examined for the various geographic locations identified by the boxes.

In general, the SLH-estimated heating magnitudes at 7–8 km are somewhat larger than the CSH-estimated values, even if the two estimates are qualitatively in good agreement with each other. This is caused by two reasons. First, the SLH-estimated heating does not include Q_R , while the CSH estimated heating does. Second, as shown in Part I (see their Fig. 15d), the SLH algorithm can retrieve heating profiles in the decaying stage with no surface rain from the precipitation rate at the melting level in the stratiform region, while the CSH algorithm estimates no heating profiles from the no-surface rain [see Eq. (10)].

c. Variability of heating profile

The average profiles shown in Figs. 14 and 15 may not be very representative, because there is great spatial and temporal variability in rainfall over a larger region such as those selected in Figs. 13 and 16. To provide actual variability of latent heating profile shapes, we used contoured-frequency-by-altitude diagrams (CFADs; Yuter and Houze 1995).

Many of the negative values in the low to middle troposphere in Figs. 17a–e and Figs. 18a,b,d are associated with evaporation and melting in the stratiform region, suggesting great variability in stratiform rain fraction over the regions. The distinct peak in the frequency of heating at levels below 3 km with weak (≤ 2 K day⁻¹) heating is also evident for all six geographic areas for both February 1998 and February 1999 in the CFADs (Figs. 17 and 18), corresponding to a heating peak at 2 km seen in the mean convective heating profiles (Figs. 14 and 15). It is inferred from the convective heating-profile lookup table (Fig. 5a) that shallow convection with PTHs lower than 4 km (shallow cumulus) accounts for this distinct peak. Capping of cloud growth by the trade wind stable layer (2 km), with some overshooting, leads to large populations of shallow cumulus.

Although a lower-level heating peak cannot be seen in the mean convective heating profile over the western Pacific for February 1999 (Fig. 15a), it remains true that the CFAD (Fig. 18a) indicates a distinct population of heating at levels below 2 km. Johnson and Lin (1997) showed that, in association with the MJO, the western Pacific warm pool lower troposphere periodically develops tradelike characteristics with abundant shallow cumulus. The CFAD (Fig. 18a) indicates another dis-



FIG. 17. CFADs of monthly (February 1998) total Q_{1Rp} profiles at 0.5° resolution derived from the SLH2 algorithm for various locations. The geographic areas are the (a) western Pacific, (b) central Pacific, (c) east Pacific, (d) South Pacific, (e) Indian Ocean, and (f) Atlantic Ocean. The bin size is 0.5 K. CFAD contour interval: 1% for values <4% and 4% above. Values >20% are shaded.

tinct population of lower-level heating, extending up to ~4 km with stronger heating (~3.5 K day⁻¹). It is inferred from the convective heating-profile lookup table (Fig. 5a) that convection with PTHs between 4 and 8 km (cumulus congestus) accounts for the latter one. The relative abundance of cumulus congestus can be attributed to a single heating peak at 4.5 km in the mean convective heating profile over the western Pacific for February 1999 (Fig. 15a). This is consistent with the result from Johnson et al. (1999) who indicate that cumulus congestus with tops between 4.5 and 9.5 km are the most abundant of all precipitating clouds in TOGA COARE based on cumulus echo-top statistics from 5-cm radar aboard the R/V Vickers. They showed that large populations of cumulus congestus correspond to the stable layer near the melting level (Johnson et al. 1996; Zuidema 1998).

5. Summary and future work

In this study, the universality of the lookup table produced from TOGA COARE simulations used in the SLH algorithm (Shige et al. 2004) was examined for its global application to TRMM PR data. Heating profiles were reconstructed from CRM-simulated parameters (i.e., PTH, precipitation rate at the melting level, rain rate, and type) with the TOGA COARE table and then compared with CRM-simulated true heating profiles, which were computed directly from the model thermodynamic equation. GATE, SCSMEX, and KWAJEX periods were used for the consistency check.

The consistency check indicates that the COARE table produces discrepancies between the SLH-reconstructed and GCE-simulated heating above the melting level in the convective region and at the melting level in the stratiform region. Comparisons of the TOGA COARE lookup table with those from GATE, SCSMEX, and KWAJEX simulations show that the discrepancies in the convective region are explained by differences in the vertical distribution of deeper convective heating due to the relative importance of liquid water and ice processes that varies from case to case. On the other hand, the discrepancies in the stratiform region are explained by differences in the level sepa-



FIG. 18. Same as Fig. 17, but for February 1999.

rating upper-level heating and lower-level cooling near the melting level.

Based on these results, algorithm improvements have been made to the SLH algorithm. In the revised procedure for convective heating retrieval, the upper-level heating amplitude due to ice processes and lower-level heating amplitude due to liquid water processes are determined separately. For stratiform regions, the heating profile is shifted up or down by matching the melting level of the TOGA COARE lookup table with the observed one. A consistency check indicates that the revised SLH algorithm performs better for each component (convective and stratiform) than the original one.

The revised SLH algorithm was applied to PR data and the results were compared with heating profiles derived diagnostically from SCSMEX sounding data (Johnson and Ciesielski 2002). There is a good agreement in the key features of the vertical profiles, particularly the level of maximum heating. The SLHretrieved Q_{1Rp} heating magnitudes are somewhat greater than the sounding-derived magnitudes. This is caused by the fact the SLH-retrieved Q_{1Rp} does not include the Q_R implied by the sounding-derived Q_1 . Adding GCE-simulated Q_R to Q_{1Rp} provides better agreement. It was also shown that the heating estimates from PR data are subject to sampling errors attributable to the PR's narrow swath width (~215 km), leading to a discrepancy with the sounding estimates.

The revised SLH algorithm was also applied to PR data for February 1998 and February 1999, and the results were compared with heating profiles derived by the CSH algorithm (Tao et al. 1993, 2000) using PR data. Because it uses observed information not only on precipitation type and intensity but also on precipitation depth, the SLH algorithm estimates between shallow and deep convection are more distinct than the CSH algorithm (see Part I). The SLH- and CSH-estimated mean latent heating profiles over the western Pacific for February 1998 and February 1999 are in good agreement with each other. For February 1998, however, a secondary maximum at low levels ($\sim 2 \text{ km}$) is found in the SLH-estimated total heating profile, while the CSH algorithm-estimated heating profiles only have one maximum heating level. This low-level maximum in the SLH-estimated total heating profile comes from the SLH-estimated convective heating profile with a low-level maximum, reflecting the abundance of shallow convection. Deep convection over the western Pacific is suppressed during the warm phase of ENSO (February 1998) relative to the cold phase (February 1999) because of lower sea surface temperatures. Thus, the difference in the SLH-estimated mean heating profile between February 1998 and February 1999 may be reasonable. Total heating profiles over the central and eastern Pacific for February 1998 and over the South Pacific for February 1999 from the SLH algorithm also have secondary maxima at low levels (~ 2 km), while those estimated by the CSH algorithm have a single heating maximum at 7 km altitude. Although both the SLH and CSH algorithms estimate shallow heating over the eastern Pacific for February 1999, the SLH-estimated heating peak is much sharper than the CSH-estimated one. The tops of shallow meridional circulation cells were found to be immediately above the atmospheric boundary in the eastern tropical Pacific (Zhang et al. 2004), which may be consistent with the SLH-estimated shallow heating profiles over the eastern Pacific for February 1999. The SLH- and CSHestimated mean latent heating profiles over the Indian Ocean for February 1998 are in good agreement with each other. On the other hand, there are differences between the two estimates over the Indian Ocean for February 1999. The SLH-estimated mean latent heating profile has a midlevel maximum, while the CSHestimated mean latent heating profile has a lower-level maximum. Similar differences can be found over the Atlantic Ocean for February 1998 and February 1999. These SLH-estimated heating profiles resemble the mean heating profile with a midlevel maximum that was determined from a diagnostic budget study during GATE (Thompson et al. 1979) and simulated by the GCE model.

Only precipitation over oceans was considered in the current investigation. To preserve the simplicity and transparency, we use the lookup table produced from COARE simulations as the oceanic lookup table. On the other hand, significant differences in precipitation features between ocean and land have been shown by TRMM observations (e.g., Nesbitt et al. 2000; Petersen and Rutledge 2001; Takayabu 2002; Schumacher and Houze 2003a,b). Continental locations exhibit marked variability in precipitation structure both regionally and seasonally, thus possibly we need to vary the lookup table regionally and seasonally. This study will be extended to simulations of other field experiments [e.g., Global Energy and Water Cycle Experiment Asian Monsoon Experiment (GAME) in the Indochina Peninsula (Yasunari 1994) and Atmospheric Radiation

Measurement Program (ARM) in the southern U.S. Great Plains (Ackerman and Stokes 2003)] to produce lookup tables for precipitation over land. The results will be reported in a publication in the near future.

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REFERENCES

- Ackerman, T. P., and G. M. Stokes, 2003: The atmospheric radiation measurement program. *Phys. Today*, 56, 38–44.
- Arakawa, A., and W. H. Schubert, 1974: Interaction of a cumulus cloud ensemble with the large-scale environment. Part I. J. Atmos. Sci., 31, 674–701.
- Austin, P. M., and R. A. Houze Jr., 1973: A technique for computing vertical transports by precipitating cumuli. J. Atmos. Sci., 30, 1100–1111.
- Awaka, J., H. Kumagai, T. Iguchi, and K. Okamoto, 1996: Development of an algorithm for classifying rain types (in Japanese). J. Commun. Res. Lab., 42, 325–337.
- —, T. Iguchi, and K. Okamoto, 1998: Early results on rain type classification by the Tropical Rainfall Measuring Mission (TRMM) precipitation radar. *Proc. Eighth URSI Commission F Open Symp.*, Aveiro, Portugal, Union Radio-Scientifigue Internationale, 143–146.
- Braun, S. A., and R. A. Houze Jr., 1995: Melting and freezing in a mesoscale convective system. *Quart. J. Roy. Meteor. Soc.*, 121, 55–77.
- —, and —, 1996: The heat budget of a midlatitude squall line and implications for potential vorticity production. J. Atmos. Sci., 53, 1217–1240.

- Cheng, C. P., and R. A. Houze Jr., 1980: Sensitivity of diagnosed convective fluxes to model assumptions. J. Atmos. Sci., 37, 774–783.
- DeMott, C. A., and S. A. Rutledge, 1998a: The vertical structure of TOGA COARE convection. Part I: Radar echo distribution. J. Atmos. Sci., 55, 2730–2747.
- —, and —, 1998b: The vertical structure of TOGA COARE convection. Part II: Modulating influences and implications for diabatic heating. *J. Atmos. Sci.*, **55**, 2748–2762.
- Grecu, M., and W. S. Olson, 2006: Bayesian estimation of precipitation from satellite passive microwave observations using combined radar–radiometer retrievals. J. Appl. Meteor. Climatol., 45, 416–433.
- Hartmann, D., H. H. Hendon, and R. A. Houze Jr., 1984: Some implications of the mesoscale circulations in tropical cloud clusters for large-scale dynamics and climate. J. Atmos. Sci., 41, 113–121.
- Heymsfield, G. M., B. Geerts, and L. Tian, 2000: TRMM precipitation radar reflectivity profiles as compared with high-resolution airborne and ground-based radar measurements. J. Appl. Meteor., 39, 2080–2102.
- Holton, J. R., 2004: An Introduction to Dynamic Meteorology. 4th ed. Academic Press, 529 pp.
- Houze, R. A., Jr., 1973: A climatological study of vertical transports by cumulus-scale convection. J. Atmos. Sci., 30, 1112– 1123.
- —, 1982: Cloud clusters and large-scale vertical motions in the tropics. J. Meteor. Soc. Japan, 60, 396–410.
- —, 1989: Observed structure of mesoscale convective systems and implications for large-scale heating. *Quart. J. Roy. Meteor. Soc.*, **115**, 425–461.
- —, and C. A. Leary, 1976: Comparison of convective mass and heat transports in tropical easterly waves computed by two methods. J. Atmos. Sci., 33, 424–429.
- —, and A. K. Betts, 1981: Convection in GATE. *Rev. Geophys. Space Phys.*, **19**, 541–576.
- —, C.-P. Cheng, C. A. Leary, and J. F. Gamache, 1980: Diagnosis of cloud mass and heat fluxes from radar and synoptic data. J. Atmos. Sci., 37, 754–773.
- Iguchi, T., T. Kozu, R. Meneghini, J. Awaka, and K. Okamoto, 2000: Rain-profiling algorithm for the TRMM precipitation radar. J. Appl. Meteor., 39, 2038–2052.
- Johnson, R. H., 1984: Partitioning tropical heat and moisture budgets into cumulus and mesoscale components: Implications for cumulus parameterization. *Mon. Wea. Rev.*, **112**, 1590– 1601.
- —, and D. C. Kriete, 1982: Thermodynamic and circulation characteristics of winter monsoon tropical mesoscale convection. *Mon. Wea. Rev.*, **110**, 1898–1911.
- —, and G. S. Young, 1983: Heat and moisture budgets of tropical mesoscale anvil clouds. J. Atmos. Sci., 40, 2138–2146.
- —, and X. Lin, 1997: Episodic trade wind regimes over the western Pacific warm pool. J. Atmos. Sci., 54, 2020–2034.
- —, and P. E. Ciesielski, 2002: Characteristics of the 1998 summer monsoon onset over the northern South China Sea. J. Meteor. Soc. Japan, 80, 561–578.
- —, —, and K. A. Hart, 1996: Tropical inversion near the 0°C level. J. Atmos. Sci., 53, 1838–1855.
- —, T. M. Rickenbach, S. A. Rutledge, P. E. Ciesielski, and W. H. Schubert, 1999: Trimodal characteristics of tropical convection. J. Climate, 12, 2397–2418.
- Kingsmill, D. E., and R. M. Wakimoto, 1991: Kinematic, dynamic, and thermodynamic analyses of a weakly sheared severe

thunderstorm over northern Alabama. Mon. Wea. Rev., 119, 262–297.

- Klemp, J., and R. Wilhelmson, 1978: The simulation of three-dimensional convective storm dynamics. J. Atmos. Sci., 35, 1070–1096.
- Kozu, T., and Coauthors, 2001: Development of precipitation radar onboard the Tropical Rainfall Measuring Mission (TRMM) satellite. *IEEE Trans. Geosci. Remote Sens.*, 39, 102–116.
- Kummerow, C., and Coauthors, 2000: The status of the Tropical Rainfall Measuring Mission (TRMM) after two years in orbit. J. Appl. Meteor., 39, 1965–1982.
- Lang, S., W.-K. Tao, J. Simpson, and B. Ferrier, 2003: Modeling of convective-stratiform precipitation processes: Sensitivity to partitioning methods. J. Appl. Meteor., 42, 505–527.
- Lau, K. M., and Coauthors, 2000: A report of the field operations and early results of the South China Sea Monsoon Experiment (SCSMEX). Bull. Amer. Meteor. Soc., 81, 1261–1270.
- Leary, C. A., and R. A. Houze Jr., 1979: Melting and evaporation of hydrometeors in precipitation from the anvil clouds of deep tropical convection. J. Atmos. Sci., 36, 669–679.
- —, and —, 1980: The contribution of mesoscale motions to the mass and heat fluxes of an intense tropical convective system. J. Atmos. Sci., 37, 784–796.
- Liebmann, B., and C. A. Smith, 1996: Description of a complete (interpolated) outgoing longwave radiation dataset. *Bull. Amer. Meteor. Soc.*, **77**, 1275–1277.
- Lin, X., and R. H. Johnson, 1996a: Heating, moistening and rainfall over the western Pacific warm pool during TOGA COARE. J. Atmos. Sci., 53, 3367–3383.
- —, and —, 1996b: Kinematic and thermodynamic characteristics of the flow over the western Pacific warm pool during TOGA COARE. J. Atmos. Sci., 53, 695–715.
- Lin, Y.-L., R. D. Farley, and H. D. Orville, 1983: Bulk parameterization of the snow field in a cloud model. J. Climate Appl. Meteor., 22, 1065–1092.
- Luo, H., and M. Yanai, 1984: The large-scale circulation and heat sources over the Tibetan Plateau and surrounding areas during the early summer of 1979. Part II: Heat and moisture budgets. *Mon. Wea. Rev.*, **112**, 966–989.
- Madden, R. A., and P. R. Julian, 1994: Observations of the 40–50 day tropical oscillation—A review. *Mon. Wea. Rev.*, **122**, 814– 837.
- Magagi, R., and A. P. Barros, 2004: Estimation of latent heating of rainfall during the onset of the Indian monsoon using TRMM PR and radiosonde data. J. Appl. Meteor., 43, 328–349.
- Mapes, B., 2001: Water's two height scales: The moist adiabat and the radiative troposphere. *Quart. J. Roy. Meteor. Soc.*, **127**, 2253–2266.
- —, P. E. Ciesielski, and R. H. Johnson, 2003: Sampling errors in rawinsonde-array budgets. J. Atmos. Sci., 60, 2697–2714.
- Morita, J., Y. N. Takayabu, S. Shige, and Y. Kodama, 2006: Analysis of rainfall characteristics of the Madden–Julian oscillation using TRMM satellite data. *Dyn. Atmos. Oceans*, 42, 107–126.
- Nesbitt, S. W., E. J. Zipser, and D. J. Cecil, 2000: A census of precipitation features in the tropics using TRMM: Radar, ice scattering, and lightning observations. J. Climate, 13, 4087– 4106.
- Nitta, T., 1972: Energy budget of wave disturbances over the Marshall Island during the years of 1956 and 1958. *J. Meteor. Soc. Japan*, **50**, 71–84.

—, and S. Esbensen, 1974: Heat and moisture budget analyses using BOMEX data. *Mon. Wea. Rev.*, **102**, 17–28.

- Okamoto, K., 2003: A short history of the TRMM precipitation radar. Cloud Systems, Hurricanes, and the Tropical Rainfall Measurement Mission (TRMM): A Tribute to Dr. Joanne Simpson, Meteor. Monogr., No. 51, Amer. Meteor. Soc., 187– 195.
- Olson, W. S., C. D. Kummerow, Y. Hong, and W.-K. Tao, 1999: Atmospheric latent heating distributions in the Tropics derived from satellite passive microwave radiometer measurements. J. Appl. Meteor., 38, 633–664.
- Petersen, W. A., and S. A. Rutledge, 2001: Regional variability in tropical convection: Observations from TRMM. J. Climate, 14, 3566–3586.
- Reed, R. J., and E. E. Recker, 1971: Structure and properties of synoptic-scale wave disturbances in the equatorial western Pacific. J. Atmos. Sci., 28, 1117–1133.
- Rutledge, S. A., and P. V. Hobbs, 1984: The mesoscale and microscale structure and organization of clouds and precipitation in midlatitude cyclones. XII: A diagnostic modeling study of precipitation development in narrow cold-frontal rainbands. J. Atmos. Sci., 41, 2949–2972.
- Schumacher, C., and R. A. Houze Jr., 2003a: Stratiform rain in the Tropics as seen by the TRMM precipitation radar. J. Climate, 16, 1739–1756.
- —, and —, 2003b: The TRMM precipitation radar's view of shallow, isolated rain. J. Appl. Meteor., 42, 1519–1524.
- —, —, and I. Kraucunas, 2004: The tropical dynamical response to latent heating estimates derived from the TRMM precipitation radar. J. Atmos. Sci., 61, 1341–1358.
- Shie, C.-L., W.-K. Tao, J. Simpson, and C.-H. Sui, 2003: Quasiequilibrium states in the Tropics simulated by a cloudresolving model. Part I: Specific features and budget analysis. *J. Climate*, **16**, 817–833.
- Shige, S., and T. Satomura, 2000: The gravity wave response in the troposphere around deep convection. J. Meteor. Soc. Japan, 78, 789–801.
- —, Y. N. Takayabu, W.-K. Tao, and D. E. Johnson, 2004: Spectral retrieval of latent heating profiles from TRMM PR data. Part I: Development of a model-based algorithm. *J. Appl. Meteor.*, 43, 1095–1113.
- —, H. Sasaki, K. Okamoto, and T. Iguchi, 2006: Validation of rainfall estimates from the TRMM precipitation radar and microwave imager using a radiative transfer model: 1. Comparison of the version-5 and -6 products. *Geophys. Res. Lett.*, **33**, L13803, doi:10.1029/2006GL026350.
- Simpson, J., R. F. Adler, and G. R. North, 1988: A proposed satellite Tropical Rainfall Measuring Mission (TRMM). *Bull. Amer. Meteor. Soc.*, 69, 278–295.
- —, C. Kummerow, W.-K. Tao, and R. F. Adler, 1996: On the Tropical Rainfall Measuring Mission (TRMM). *Meteor. Atmos. Phys.*, **60**, 19–36.
- Soong, S.-T., and Y. Ogura, 1973: A comparison between axisymmetric and slab-symmetric cumulus cloud models. J. Atmos. Sci., 30, 879–893.
- —, and —, 1980: Response of tradewind cumuli to large-scale processes. J. Atmos. Sci., 37, 2035–2050.
- —, and W.-K. Tao, 1980: Response of deep tropical cumulus clouds to mesoscale processes. J. Atmos. Sci., 37, 2016–2034.
- —, and —, 1984: A numerical study of the vertical transport of momentum in a tropical rainband. J. Atmos. Sci., 41, 1049– 1061.
- Sui, C.-H., K.-M. Lau, W.-K. Tao, and J. Simpson, 1994: The

tropical water and energy cycles in a cumulus ensemble model. Part I: Equilibrium climate. J. Atmos. Sci., **51**, 711–728.

- Takayabu, Y. N., 2002: Spectral representation of rain features and diurnal variations observed with TRMM PR over the equatorial area. *Geophys. Res. Lett.*, **29**, 1584, doi:10.1029/ 2001GL014113.
- —, K.-M. Lau, and C.-H. Sui, 1996: Observation of a quasi-2day wave during TOGA COARE. *Mon. Wea. Rev.*, **124**, 1892–1913.
- Tao, W.-K., 2003: Goddard Cumulus Ensemble (GCE) model: Application for understanding precipitation processes. *Cloud Systems, Hurricanes, and the Tropical Rainfall Measurement Mission (TRMM): A Tribute to Dr. Joanne Simpson, Meteor. Monogr.*, No. 51, Amer. Meteor. Soc., 107–137.
- —, and J. Simpson, 1993: Goddard cumulus ensemble model. Part I: Model description. *Terr. Atmos. Oceanic Sci.*, 4, 35–72.
- —, —, and M. McCumber, 1989: An ice-water saturation adjustment. *Mon. Wea. Rev.*, **117**, 231–235.
- —, S. Lang, J. Simpson, and R. Adler, 1993: Retrieval algorithms for estimating the vertical profiles of latent heat release: Their applications for TRMM. *J. Meteor. Soc. Japan*, **71**, 685–700.
- —, —, —, C.-H. Sui, B. Ferrier, and M.-D. Chou, 1996: Mechanisms of cloud-radiation interaction in the Tropics and midlatitudes. J. Atmos. Sci., 53, 2624–2651.
- —, —, —, W. Olson, D. Johnson, B. Ferrier, C. Kummerow, and R. Adler, 2000: Vertical profiles of latent heat release and their retrieval for TOGA COARE convective systems using a cloud resolving model, SSM/I, and ship-borne radar data. J. Meteor. Soc. Japan, **78**, 333–355.
- —, and Coauthors, 2001: Retrieved vertical profiles of latent heat release using TRMM rainfall products for February 1998. J. Appl. Meteor., 40, 957–982.
- —, and Coauthors, 2003a: Microphysics, radiation and surface processes in the Goddard Cumulus Ensemble (GCE) model. *Meteor. Atmos. Phys.*, 82, 97–137.
- —, C.-L. Shie, J. Simpson, S. Braun, R. H. Johnson, and P. E. Ciesielski, 2003b: Convective systems over the South China Sea: Cloud-resolving model simulations. J. Atmos. Sci., 60, 2929–2956.
- —, D. Johnson, C.-L. Shie, and J. Simpson, 2004: The atmospheric energy budget and large-scale precipitation efficiency of convective systems during TOGA COARE, GATE, SCSMEX, and ARM: Cloud-resolving model simulations. J. Atmos. Sci., 61, 2405–2423.
- —, and Coauthors, 2006: Retrieval of latent heating from TRMM measurements. *Bull. Amer. Meteor. Soc.*, 87, 1555– 1572.
- Thompson, R. M. J., S. W. Payne, E. E. Recker, and R. J. Reed, 1979: Structure and properties of synoptic-scale wave disturbances in the intertropical convergence zone of the eastern Atlantic. J. Atmos. Sci., 36, 53–72.
- Webster, P. J., and R. Lukas, 1992: TOGA COARE: The Coupled Ocean–Atmosphere Response Experiment. Bull. Amer. Meteor. Soc., 73, 1377–1416.
- Yanai, M., and R. H. Johnson, 1993: Impacts of cumulus convection on thermodynamic fields. *The Representation of Cumulus Convection in Numerical Models, Meteor. Monogr.*, No. 46, Amer. Meteor. Soc., 39–62.
- —, and T. Tomita, 1998: Seasonal and interannual variability of atmospheric heat sources and moisture sinks as determined from NCEP–NCAR reanalysis. J. Climate, 11, 463–482.

- —, S. Esbensen, and J.-H. Chu, 1973: Determination of bulk properties of tropical cloud clusters from large-scale heat and moisture budgets. *J. Atmos. Sci.*, **30**, 611–627.
- —, B. Chen, and W.-W. Tung, 2000: The Madden–Julian oscillation observed during the TOGA COARE IOP: Global view. J. Atmos. Sci., 57, 2374–2396.
- Yang, S., and E. A. Smith, 1999a: Four-dimensional structure of monthly latent heating derived from SSM/I satellite measurements. J. Climate, 12, 1016–1037.
 - —, and —, 1999b: Moisture budget analysis of TOGA COARE area using SSM/I-retrieved latent heating and large scale Q₂ estimates. J. Atmos. Oceanic Technol., 16, 633–655.
- —, and —, 2000: Vertical structure and transient behavior of convective-stratiform heating in TOGA COARE from combined satellite-sounding analysis. J. Appl. Meteor., 39, 1491– 1513.

- Yasunari, T., 1994: GEWEX-Related Asian Monsoon Experiment (GAME). Adv. Space Res., 14, 161–165.
- Yuter, S. E., and R. A. Houze Jr., 1995: Three-dimensional kinematic and microphysical evolution of florida cumulonimbus. Part II: Frequency distribution of vertical velocity, reflectivity, and differential reflectivity. *Mon. Wea. Rev.*, **123**, 1941– 1963.
- —, —, E. A. Smith, T. T. Wilheit, and E. Zipser, 2005: Physical characterization of tropical oceanic convection observed in KWAJEX. J. Appl. Meteor., 44, 385–415.
- Zhang, C., M. McGauley, and N. A. Bond, 2004: Shallow meridional circulation in the tropical eastern Pacific. J. Climate, 17, 133–139.
- Zuidema, P., 1998: The 600–800-mb minimum in tropical cloudiness observed during TOGA COARE. J. Atmos. Sci., 55, 2220–2228.