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

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Abstract

Latent heating profiles associated with three TOGA COARE active convective episodes (December 10–17 1992; December 19–27 1992; and February 9–13 1993) are examined using the two-dimensional version of the Goddard Cumulus Ensemble (GCE) Model, and retrieved by using the Goddard Convective and Stratiform Heating (CSH) algorithm. The following sources of rainfall information are input into the CSH algorithm: Special Sensor Microwave Imager (SSM/I), shipborne radars and the GCE model. Diagnostically determined latent heating profiles are calculated using 6 hourly soundings used for validation.

The GCE model simulated rainfall and latent heating profiles are in excellent agreement with those estimated by soundings. In addition, the typical convective and stratiform heating structures (or shapes) are well captured by the GCE model. Radar measured rainfall is smaller than that estimated by the GCE model and SSM/I in both December convective episodes. SSM/I derived rainfall is more than the GCE model simulated for the December 19–27 and February 9–13 periods, but it is in excellent agreement with the GCE model for the December 10–17 period. The GCE model estimated stratiform amount is about 50 % for December 19–27, 42 % for December 11–17 and 56 % for the February 9–13 case. These results are consistent with large-scale analyses. Accurate estimates of stratiform amount are needed for good latent heating retrieval. A higher (lower) percentage of stratiform rain can imply a maximum heating rate at a higher (lower) altitude. The GCE model always simulates more stratiform rain (10 to 20 %) than the radar for all three convective episodes. The SSM/I derived stratiform amount is about 37 % for December 19–27, 48 % for December 11–17 and 41 % for the February 9–13 case.

Temporal variability of CSH algorithm retrieved latent heating profiles using either the GCE model simulated or radar estimated rainfall and stratiform amount is in good agreement with that diagnostically determined for all three periods. However, less rainfall and a smaller stratiform percentage estimated by radar resulted in a weaker (underestimated) latent heating profile, and a lower maximum latent heating level compared to those determined diagnostically. Rainfall information from SSM/I can not retrieve individual convective events due to poor temporal sampling. Nevertheless, this study suggests that a good rainfall retrieval from SSM/I for a convective event can lead to a good latent heating retrieval.

Sensitivity testing has been performed and the results indicate that the SSM/I derived time averaged stratiform amount may be underestimated for December 19–27. Time averaged heating profiles derived from SSM/I, however, agree well with those derived by soundings for the December 10–17 convective period. The heating retrievals may be more accurate for longer time scales, provided there is no bias in the sampling.

An appropriate selection of latent heating profiles from the CSH look-up table is important. Sensitivity tests addressing this issue have been performed.

1. Introduction

The global hydrological cycle is central to climate system interactions and is the key to understanding their behavior. Rainfall and its associated precipitation processes are a key link in the hydrologic cycle. Fresh water provided by tropical rainfall and its

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variability can exert a large impact upon the structure of the upper ocean layer. In addition, two-thirds of the global rain falls in the tropics, while the associated latent heat release accounts for three-fourths of the total heat energy for the Earth's atmosphere. Precipitation from convective cloud systems comprises a large portion of tropical heating and rainfall. Furthermore, the vertical distribution of convective latent-heat release modulates large-scale tropical circulations (e.g., the 30–60-day intraseasonal oscillation—see Sui and Lau 1989), which, in turn, impact midlatitude weather through teleconnection patterns such as those associated with El Niño. Shifts in these global circulations can result in prolonged periods of droughts and floods, thereby exerting a tremendous impact upon the biosphere and human habitation. Yet, monthly rainfall over the tropical oceans is still not known within a factor of two over large (5-degrees latitude by 5-degrees longitude) areas (Simpson et al. 1988, 1996). Hence the Tropical Rainfall Measuring Mission (TRMM), —a joint U.S./Japan space project— is a critical mission that will provide an adequate measurement of rainfall, as well as estimate the four-dimensional structure of diabatic heating over the global tropics using an inclined low-altitude orbit and a combination of precipitation radar, VIS/IR and microwave radiometers (see Simpson et al. 1988). The distributions of rainfall and inferred heating can be used to advance our understanding of the global energy and water cycle. In addition, this information can be used for global circulation and climate models for testing and improving their parameterizations.

Two latent heating retrieval techniques, the hydrometeor heating (HH) and convective-stratiform heating (CSH) algorithms, have been developed by the Goddard Cumulus Ensemble (GCE) Modeling Group (see Tao et al. 1990, 1993a). The HH algorithm requires information about the vertical profiles of cloud- and precipitation-sized water and ice particles, all of which cannot be obtained from the current set of spaceborne retrievals. The CSH algorithm was therefore developed, which uses as input surface precipitation rates, amount of stratiform rain, and the type and location of observed cloud systems. It takes into account the fact that when cloud latent heating is separated into convective and stratiform regions, the profiles for each region take on a characteristic shape even for systems from different geographic locations (Johnson 1984; and a review by Houze 1997). The method works by selecting an appropriate set of heating profiles, which have been normalized with respect to surface rainfall. Then, these profiles are multiplied by either an observed or satellite-derived rainfall rate. The percentage of that rate which is stratiform is also required in order to properly weight the convective and stratiform profiles used in the retrieval.

Fig. 1. Diagram showing the procedure for deriving a latent heating profile using the Convective-Stratiform Heating (CSH) algorithm. The heating profile (Q_1) is normalized by the surface precipitation rate (P_o). The “?” means to compare and examine the latent heating profiles derived from the CSH algorithm with actual measurements (soundings). This comparison is necessary for providing some kind of “validation” of the retrieved latent heating. The CSH algorithm was mainly developed to retrieve heating profiles using satellite (i.e., TRMM, EoS) derived information (Tao et al. 1993).

Figure 1 is a flow chart that shows the procedure for deriving a latent heating profile from the CSH algorithm. There are many sets of normalized heating profiles, each set has a convective profile and a stratiform profile simulated by the cloud resolving model (or cumulus ensemble model). Each set represents different system organizations as well as various geographic locations. The sensitivity tests of choosing an appropriate set of heating profiles from the look-up table will be investigated. The CSH derived heating profile can be evaluated by comparing it with those estimated at well designed field campaigns (i.e., GATE,¹ TOGA COARE² and TRMM field programs).

1 GATE stands for GARP {Global Atmospheric Research Program} Atlantic Tropical Experiment.

2 TOGA COARE stands for Tropical Oceans Global Atmosphere (TOGA)—Coupled Ocean Atmosphere Response Experiment (COARE).

Fig. 2. Diagram showing the procedure for deriving latent heating profiles using precipitation radar, SSM/I and the GCE model generated rainfall information (rainrate and stratiform amount). The derived heating profile will be compared to the profile diagnosed from the sounding network and from GCE model simulations.

In this paper, the performance of the CSH algorithm will be evaluated for several TOGA COARE cloud systems that occurred during Westerly Wind Burst (WWB) events. Inputs for the CSH algorithm will be from shipborne radar measurements, from spaceborne (SSM/I) algorithm derivations, as well as from GCE model simulations.³ The heating profiles derived from sounding networks will be used for comparison and validation.

2. Approaches

Figure 2 shows the procedure for evaluating the performance of the CSH algorithm using data from different sources. Gridded maps of rain rates and rain classification (convective and stratiform) were estimated from two shipborne radars during TOGA COARE (Short et al. 1997). Olson et al. (1999) using a spaceborne (SSM/I) sensor were able to retrieve both surface rainfall and convective/stratiform amount during TOGA COARE. The two-dimensional GCE model is used to simulate latent heating profiles in both convective and stratiform regions. These profiles will be used in the CSH algorithm's lookup table, and for validation against profiles retrieved from the CSH algorithm and from sounding diagnostics. Additionally, the GCE simulated surface rainfall will be used as input for the CSH algorithm. During the TRMM mission, rainfall maps and stratiform amounts generated from TRMM algorithms, such as products from the TRMM Microwave Imager (TMI) and from the

Precipitation Radar (PR) (Simpson et al. 1996), can be used as input for the CSH algorithm.

2.1 TOGA COARE convective systems

TOGA COARE has provided datasets over the Intensive Flux Array (IFA) which can be used to develop and test cumulus and cloud microphysical parameterizations (Webster and Lukas 1992; Moncrieff et al. 1997). The most intense convection over the IFA occurred in middle and late December 1992, prior to the peak of westerly wind bursts around 1 January 1993. Westerlies started to appear near the surface over the IFA in early December and gradually developed and intensified, although the middle and upper troposphere were still dominated by easterlies. The moderate vertical wind shear favored organized deep convection.

Several major convective events occurred around 11–16 and 20–25 December 1992, mainly due to low-level large-scale convergence of easterlies and westerlies. However, the synoptic conditions were different for these two December events. An easterly flow prevailed at low levels from near the date line westward to the IFA, and convection over the IFA arrived from the east with an easterly surge on 11–16 December. Both cases show a similar order of magnitude of peak heating, 10 K day^{-1} between 350 and 500 mb. During 21–24 December, there was a greater contribution to heating from stratiform precipitation caused by the increased wind shear (see Lin and Johnson 1996). There was less of a stratiform contribution for the December 11–16 convective episode. In middle and late February, westerly flow, although weaker than that in early February and December, still dominated levels below 500 mb. Stratiform clouds dominated the IFA during this period although shallow cumuli were also present (Lin and Johnson 1996). Three different periods, December 10–17, 1992, December 19–27, 1992,⁴ and February 9–13, 1993 are chosen for this study.

2.2 Goddard cumulus ensemble (GCE) model

The GCE Model has been described in Tao and Simpson (1993). Recent improvements were presented in Ferrier (1994), Tao et al. (1996), Wang et al. (1996) and Lynn et al. (1998). It has been extensively applied to explicitly represent cloud-environment interactions, cloud-cloud interactions and mergers, cloud-radiation interaction, air-sea interactions, cloud draft structure and trace gas transport (see a review by Simpson and Tao 1993). The GCE model has been used to study convective systems in numerous environments and the results have generally agreed well with both remote (such as radar and passive microwave) and insitu obser-

3 The GCE model simulations will be also used to expand the set of normalized heating profiles in the CSH algorithm over a broader range of conditions, as well as provide new data sets for algorithm developers (Olson et al. 1999).

4 This period has also been used by the GCSS working group 4 (WG4) model intercomparison project for CRMs and Single Column Models (SCMs).

uations from aircraft penetrations (Simpson et al. 1988, 1996; Adler et al. 1991; Prasad et al. 1995; and Yeh et al. 1995). The model includes solar and infrared radiative transfer processes, and explicit cloud-radiation interactive processes (Tao et al. 1996). The cloud microphysics includes a parameterized Kessler type two-category liquid water scheme (cloud water and rain). It also has two parameterizations of a three-category ice phase scheme (cloud ice, snow, and hail/graupel; Lin et al. 1983; Rutledge and Hobbs 1984) and a four-class ice scheme (Ferrier 1994; Ferrier et al. 1995). Subgrid scale (turbulent) processes in the GCE model are parameterized using a scheme based on Deardorff (1975), 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.

For the present study, a 2-D version of the model which incorporates stretched vertical coordinates with 46 levels has been used. The model has finer resolution (about 70 meters) in the boundary layer, and coarser resolution (about 1000 meters) in the upper levels. The grid spacing in the horizontal plane is 1000 meters with 512 grid points. Surface fluxes from the ocean and cloud-radiation interactive processes are explicitly included in this study.

Observed large-scale advective tendencies of potential temperature, water vapor mixing ratio, and horizontal momentum were used as the main large-scale forcing in governing the GCE model in a semi-prognostic manner (Soong and Ogura 1980; Soong and Tao 1980; Tao and Soong 1986). The major characteristic of this approach is that ensembles of clouds can be generated by the “*observed-prescribed forcing*”. The large-scale advective tendencies for potential temperature and water vapor mixing ratio q ,

$$\left[\frac{\partial \bar{\theta}}{\partial t} \right]_{L.S.} = -\bar{v} \cdot \nabla \bar{\theta} - \bar{w} \frac{\partial \bar{\theta}}{\partial z}$$

and

$$\left[\frac{\partial \bar{q}}{\partial t} \right]_{L.S.} = -\bar{v} \cdot \nabla \bar{q} - \bar{w} \frac{\partial \bar{q}}{\partial z}$$

were derived every six hours over the IFA (approximately 700 by 500 km) from the TOGA COARE analyses of Lin and Johnson (1996). Observed sea surface temperature was used for latent and sensible heat flux calculations. Since accurate calculations of the large-scale horizontal momentum forcing terms are difficult to obtain from observations in the tropics, these terms were instead replaced by a nudging term:

$$\left[\frac{\partial \bar{v}}{\partial t} \right]_{L.S.} = -\frac{\bar{v} - \bar{v}_{obs}}{\tau}$$

where $\bar{v}$ is the model domain averaged horizontal velocity, $\bar{v}_{obs}$ is the observed large-scale horizontal velocity, and τ is the specified adjustment time scale (one hour). This method constrains the domain-averaged horizontal velocities to follow the observed values, and thereby provides a simple means in controlling the cloud system dynamics by the large-scale momentum and shear. The observed large-scale advective tendencies of potential temperature, water vapor mixing ratio, and horizontal momentum were averaged over the IFA and provided at 6-hour intervals. Cyclic lateral boundary conditions were incorporated to ensure that there was no additional heat, moisture or momentum forcing inside the domain apart from the large-scale forcing (Soong and Tao 1980; Tao and Soong 1986).

In the GCE model convective-stratiform partitioning method, convective, stratiform and non-surface precipitation regions are identified using the information from surface rainrates first (Churchill and Houze 1984). Two additional criteria are applied which have been included to identify regions where convection may be quite active *aloft* though there is little or no precipitation yet at the surface, such as areas associated with tilted updrafts and *new cells* initiated ahead of an organized squall line (Tao and Simpson 1989; Tao et al. 1993b). Non-surface precipitation regions are considered to be convective if cloud water exceeds a certain threshold (i.e., the minimum of either 0.5 g kg^{-1} or half of the maximum cloud water at that specific simulation time), or if the updraft exceeds a certain threshold (i.e., the minimum value between 3 m s^{-1} and half of the maximum updraft at that specific simulation time) below the melting level. The presence of this amount of cloud water is a good indication of a saturated area (100 % Relative humidity). This method has been adapted by Chin (1994), Cotton (personal communication) and Redelsperger et al. (1999).

2.3 Goddard profiler algorithm (GPROF)

The basis of the retrieval method is the estimated expected value, or “Bayesian” technique, described in Kummerow et al. (1996) and Olson et al. (1996; 1999). The retrieval method is supported by a large database of hydrometeor profiles which are generated using three-dimensional, numerical cloud-resolving models. Microwave radiances at SSM/I frequencies/polarizations are simulated from the three-dimensional model fields using an Eddington radiative transfer method. Given a set of actual SSM/I-observed radiances, the retrieved hydrometeor profile is calculated as a weighted mean of the model profiles: only those model profiles associated with radiances similar to the observed radiances are assigned significant weights. A detailed description of the retrieval method utilized in the present study may be found in Olson et al. (1999).

In principle, any geophysical parameters (including hydrometeor profiles) derived from the cloud-resolving model simulations can be retrieved, as long as there is sufficient signal in the SSM/I radiance observations to distinguish various magnitudes of the desired parameters. In current applications of the SSM/I retrieval method, surface rainfall rate is defined as the 12.5 km $\times$ 12.5 km area average rain rate at the lowest model level. The dimension of the averaging area (12.5 km) corresponds to the SSM/I sample spacing at the highest-resolution, the 85.5 GHz channel. Since the horizontal resolution of the cloud model simulations is on the order of 1 km, there are roughly 100 gridpoint rain rates which contribute to the area-average. The convective rain fraction is defined by first classifying each model gridpoint as either convective, or non-convective, using the technique described in Tao et al. (1993b). The convective fraction is then given by

$$f_R \equiv \frac{\sum_{i,j} R_{ij} \delta_{ij}}{\sum_{i,j} R_{ij}}, \quad (1)$$

where

$$\delta_{ij} \equiv \begin{cases} 0; & \text{non-convective gridpoint} \\ 1; & \text{convective gridpoint} \end{cases}. \quad (2)$$

Here, R_{ij} is the rain rate associated with gridpoint ij , and the summation is over all gridpoints within a given 12.5 km $\times$ 12.5 km area.

2.4 TOGA COARE radar measurements

Radar-derived rainfall measurements were collected by two shipboard Doppler radars (MIT and TOGA) during the TOGA COARE intensive observing period (November, 1992–February, 1993). A comprehensive dataset of gridded rainfall fields, convective and stratiform identification maps, and vertical structure products have been produced, covering an average area approximately 400 km (E–W) by 300 km (N–S) within the Intensive Flux Array (IFA), centered near 2 S, 156 E.

A convective-stratiform texture algorithm was applied to the initial Cartesian gridded rainfall rates using a conversion of $Z = 120 R^{1.43}$, resulting in a convective core classification for grid points whose value exceeded the average of the surrounding 24 grid points, centered at 5 $\times$ 5 matrix, by a factor of 2 or more (see, e.g., Churchill and Houze 1984; Steiner et al. 1995). The eight grid points surrounding each core were classified as convective. Also, all grid points with a rainfall rate exceeding 22 mm h⁻¹ (or 40 dBZ) were classified as convective, in order to avoid misclassifying large contiguous areas of high rainfall rates as stratiform. All other points were then classified as stratiform and their

rainfall rates were halved according to a Z–R relationship of $Z = 323 R^{1.43}$ (for details, see Short et al. 1997).

3. Results

3.1 Surface rainfall and its convective–stratiform components

Figure 3 shows the time series of rainfall rates averaged over the TOGA COARE IFA region that were simulated by the GCE model, estimated by shipborne radar, and derived by SSM/I for the period December 19–December 27, 1992. The GCE model simulated rainfall agrees with that estimated from soundings⁵ (Lin and Johnson 1996). This good agreement is mainly caused by the fact that the GCE model was forced by large-scale tendencies in temperature and water vapor computed from the sounding network. Rainfall estimated from the ship radars is smaller than the rainfall estimated by the GCE model and SSM/I (Table 1). SSM/I derived rainfall is more than the GCE model simulated (as well as sounding estimated). The difference between these three different estimates has been reported and discussed in Lin and Johnson (1996), Frank et al. (1996) and Johnson and Ciesielski (2000). For example, Johnson and Ciesielski (2000) found that the moisture budget (derived from soundings) estimated average rainfall for the 120 day Intensive Observing Period (IOP) is 8.2 mm day⁻¹ compared to 5.2 mm day⁻¹ averaged over 101 days by the two radars (MIT and TOGA radars). Their analysis also indicated that the ship radars were located within a relatively dry region of the IFA.

The smaller rainfall estimated from the ship radars could also be caused by the specific Z–R relationship applied in the stratiform region in Short et al. (1997). Recent rainfall statistics from the TRMM ground validation program indicate that the convective and stratiform reflectivity (Z) to rainfall (R) conversions (Z–R) are similar and can not support the dual Z–R used in Short et al. (1997). These four sites are: Kwajalein, Republic of Marshall Islands; Darwin, Australia; Houston, Texas; and Melbourne, Florida. This result is based on analyzing radar and rain gauge data from four TRMM ground validation sites for all of 1998, using a similar rain classification algorithm (Steiner et al. 1995) as was used in Short et al. (1997). The data also indicates that when the meteorological conditions more closely resemble the tropical oceanic environment of TOGA COARE, the convective Z–R from Short et al. (1997) should also be applied to stratiform precipitation. Such a modi-

5 The good agreement in rainfall amount between model and moisture budget calculations is also true in the other two cases. Most cloud resolving models that participated in the GCSS WG4 model intercomparison produced rainfall amounts that agreed quite well with the moisture budget derived from observations (soundings).

Fig. 3. Evolution of precipitation (a) simulated from the GCE model, (b) measured from radar, and (c) derived from SSM/I. The convective and stratiform components are also shown for the December 19–27, 1992 period.

fication would double the stratiform contribution to total rainfall, increase the fraction of stratiform rain, and, then increase the daily accumulated rainfall.

In spite of the difference in rainfall amount, the pattern of temporal variability between ship radars and GCE model estimated rainfall is quite good. For

Table 1. The average surface rainfall (mm/day) and stratiform amount (%) for the December 19–27, 1992 period.

	Rainfall Amount (mm/day)	Stratiform Portion (%)
GCE Model	20.2	50
SSM/I	27.8	37
Radar	10.7	40

Table 2. Same as Table 1 except for the December 10–17, 1992 period. Note that rainfall data was missing from December 11 to December 13 for the shipborne radars and was counted as zero in the calculations.

	Rainfall Amount (mm/day)	Stratiform Portion (%)
GCE Model	17.5	42
SSM/I	18.6	48
Radar	7.6	21

example, the radars and GCE model both identify five major convective events during this period. The SSM/I trace does not identify all five events due to poor temporal sampling. But, SSM/I derived rainfall matches pretty well with GCE simulated rainfall for the December 20–22 and December 24–25 convective events. The GCE model estimated stratiform amount is about 50 %, compared to 40 % by ship radars and 37 % by SSM/I over the 8 day period (Table 1). It is known that stratiform rain amounts are typically about 40–50 % in well organized convective systems in the tropics (Houze 1997). This implies that radar, SSM/I and GCE estimated stratiform amounts could all be reasonable. Note that the rainfall rates and stratiform amounts associated with each of the individual convective events show more differences than the 8-day averages between the radar, SSM/I and GCE model (Fig. 3). There is no specific pattern or bias with each method's estimate, however. The uncertainty in rainfall and stratiform amount over shorter time scales by the different methods suggests that latent heating profiles can not be reliably retrieved on shorter time scales.

For the second period (December 10–December 17, 1992), the GCE simulated and SSM/I retrieved rainfall amounts (17.5 and 18.6 mm/day, respectively), as well as stratiform percentages (42 % and 48 %, respectively) are in very good agreement (Table 2). They are, however, larger than ship radar estimates. One of the most vigorous convective events (December 11 to December 13) during this period is missing from the radar observations, and that is the reason for its underestimation of rainfall amount (Fig. 4). The radar, SSM/I and

Fig. 4. Same as Fig. 3 except for the December 10–17, 1992 period.

GCE model estimated rainfall amounts agree well for the last four days of this period except that the radar estimated stratiform percentage is 21 %, and is lower than the GCE model simulated and SSM/I retrieved. The SSM/I retrieved rainfall amount is in excellent agreement with the GCE model simulated for the convective event that occurred during the period December 11 to December 13. However, its estimated stratiform percentage is over 50 % compared to only about 35 % simulated by the GCE model.

This is the main reason for the different stratiform percentages calculated between SSM/I and the GCE model during this period.

Note that the GCE model simulated stratiform percentage during this second period is 8 % less than that of the first period. As suggested by Lin and Johnson (1996), there was a greater contribution from stratiform precipitation due to increased wind shear during December 21–24 compared to the December 11–15 period. The good agreement between Lin and Johnson (1996) and the GCE model is caused by the fact that the horizontal wind is nudged in the model, and it is well known that the vertical shear of the horizontal wind is the dominant factor for determining the organization of convective systems.

Figure 5 shows the time series of rainfall rates that were simulated by the GCE model, estimated by shipborne radar, and derived by SSM/I for the period February 9–February 13, 1993. There is good agreement in temporal variation between the GCE model simulated, and radar estimated rainfall. For example, all major convective events after February 10 appeared in both the GCE model simulations and radar observations. However, the GCE model did not simulate the rainfall that occurred on February 9 as observed by radar. The reason for the GCE model's inability to simulate this weak convective event is that the observed large-scale advective tendency for water vapor imposed upon the GCE model had $6 \text{ g kg}^{-1} \text{ day}^{-1}$ of drying in the lower troposphere. Precipitation formed aloft will evaporate in this dry layer before it reaches the ground. Another difference between the GCE model simulation and radar observations is that the GCE model simulated rainfall is larger than the radar estimated.

The GCE model simulated convective events are generally weaker and produce a lot of stratiform precipitation (56 %, see Table 3) compared to the first and second periods. These features are in good agreement with Lin and Johnson (1996).⁶ SSM/I retrieved rainfall is larger than both the GCE model simulated and radar estimated (10.1 mm day^{-1} compared to 8.8 mm day^{-1} and 6.4 mm day^{-1} , respectively). The stratiform rain percentage from both SSM/I (41 %) and radar (35 %) is smaller than the GCE model simulated. Note that the GCE model always simulates more stratiform rain (10 to 20 %) than the radar for all three TOGA COARE convective periods. These differences will be investigated in a future modeling paper with a more detailed comparison with radar observations (case

⁶ This is because of weaker large-scale forcing in temperature and water vapor in the February 1993 period than the two that occurred in December 1992. Other observations also indicated that the convection during December 1992 was stronger than that which occurred during February 1993.

Fig. 5. Same as Fig. 3 except for the February 9–13, 1993 period.

study).

3.2 Sounding determined and CSH retrieved latent heating profiles

In diagnostic studies (e.g., Yanai et al. 1973), it is customary to define the apparent heat source Q_1 of a large-scale system by averaging horizontally the thermodynamic equation (θ , potential temperature) as:

Table 3. Same as Table 1 except for the February 9–13, 1993 period.

	Rainfall Amount (mm/day)	Stratiform Portion (%)
GCE Model	8.8	56
SSM/I	10.1	41
Radar	6.4	35

$$Q_1 - Q_R = \bar{\pi} \left(\frac{\partial \bar{\theta}}{\partial t} + \bar{V} \cdot \nabla \bar{\theta} + \bar{w} \frac{\partial \bar{\theta}}{\partial z} \right) \quad (3)$$

Q_1 can be calculated either from observations or from grid values in a large- or regional-scale prediction model. Q_1 can be directly related to the contributions of cloud effects which can be explicitly estimated by the GCE model and other cloud resolving models (i.e., Soong and Tao 1980; Tao and Soong 1986; Krueger 1988; Tao and Simpson 1989):

$$Q_1 - Q_R = \bar{\pi} \left[-\frac{1}{\bar{\rho}} \frac{\partial \bar{\rho} \bar{w}' \bar{\theta}'}{\partial z} + \bar{D}_\theta \right] + \frac{L_v}{C_p} (\bar{c} - \bar{e}_c - \bar{e}_r) + \frac{L_f}{C_p} (\bar{f} - \bar{m}) + \frac{L_s}{C_p} (\bar{d} - \bar{s}) \quad (4)$$

The overbars denote horizontal averages; the primes indicate deviations from the horizontal averages. The variable $\bar{\rho}$ is the air density, and $\bar{\pi} = (p/P_{00})^{R/C_p}$ is the nondimensional pressure, where p is the dimensional pressure and P_{00} the reference pressure taken to be 1000 mb. C_p is the specific heat of dry air at constant pressure, and R is the gas constant for dry air. The variables L_v , L_f and L_s are the latent heats of condensation, fusion and sublimation, respectively. The variables c , e_c , e_r , f , m , d and s stand for the rates of condensation, evaporation of cloud droplets and raindrops, freezing of raindrops, melting of snow and graupel/hail, deposition of ice particles and sublimation of ice particles, respectively. The term Q_R is the cooling/heating rate associated with radiative processes. Also, the first term on the right-hand side of (4) is the vertical eddy heat flux convergence. The subgrid scale turbulence term is represented by D_θ and is usually small compared to other terms above the boundary layer (Soong and Tao 1980; Tao and Soong 1986; Krueger 1988).

3.2.1 Sounding determined and GCE model simulated latent heating profiles

Time series of the apparent heat source Q_1 diagnostically determined by soundings, and explicitly calculated by the GCE model for the period December 19–December 27, 1992 are illustrated in Figs. 6(a) and 6(b). The pattern of temporal variability between the heating profile derived from the soundings and estimated by the GCE model is quite

Fig. 6. Evolution of the apparent heating source (Q_1) averaged over the TOGA COARE IFA for the 8-day period during December 19–27, 1992. (a) Derived diagnostically from soundings (Lin and Johnson, 1996). (b) Simulated from the GCE model. The GCE model simulated Q_1 over (c) the convective region and (d) the stratiform region.

good. The latent heat release associated with all five major rainfall events as shown in Fig. 3 are well simulated by the GCE model. Model results, however, show more temporal variability. This is perhaps caused by the fact that diagnostically determined Q_1 was calculated using 6 hourly soundings and a 1-2-1 filter was applied (Lin and Johnson 1996). The GCE model estimates are based on 2 minute statistics of cloud processes (i.e., condensation, evaporation, deposition and sublimation rates) without any smoothing.

Figures 6c and 6d show the time series of the GCE modeled Q_1 in the convective and stratiform regions, respectively, during the period December 19–December 27, 1992. The typical convective and stratiform heating structures (or shapes) discussed in Houze (1997) are well captured by the GCE model. For example, the convective profiles show heating throughout the troposphere, which is maximized in the 600–650 mb level. In the stratiform region, heating is maximized in the upper troposphere (around 400 mb) while cooling prevails below the melting level. Another interesting feature is

that the heating structure in the stratiform region is smoother than that in the convective region. This is because convective bursts have a shorter temporal evolution than that of the stratiform region where mesoscale processes are dominant. Also, Fig. 6(d) indicates that there is stronger heating aloft and stronger cooling below in the stratiform region. The cooling in the lower troposphere is from the evaporation of rain that originates from the melting of precipitating ice particles (Tao et al. 1996). These ice particles are generated by deposition processes aloft.

Time series of the apparent heat source Q_1 diagnostically determined and explicitly calculated by the GCE model for the period December 10–December 17, 1992 are shown in Fig. 7. Very good agreement (a peak over 35 K/day) is found for the major convective event (December 11–12). The maximum heating peak in the upper troposphere (above the 400 mb level) mainly occurred in the stratiform region (Fig. 7d). Again, the results from the GCE model show more temporal structure in the convective region than diagnostically determined for

Fig. 8. Same as Fig. 6 except for the February 9–13, 1993 period.

convective region for the February event is weaker than those of the two December periods.

3.2.2 Retrieved latent heating profiles

Figure 10 shows the CSH algorithm retrieved latent heating using (1) GCE estimated rainrates and stratiform percentages, (2) radar based rainfall rates and stratiform percentage and (3) SSM/I based rainfall rates and stratiform percentage.⁷ The results clearly indicate that rainfall information based on SSM/I (or TMI) may not resolve latent heat release associated with “individual convective events” because of poor temporal sampling. However, SSM/I retrieved latent heating profiles are in very good agreement with observations during the December 24–25 period. Note that SSM/I retrieved rainfall amounts are in good agreement with budget determined, and GCE simulated amounts, during the same period. This implies that if the SSM/I can capture a representative rainfall sample for a convective system, the retrieved heating profile can be

quite accurate.

Heating profiles based on radar derived information (Fig. 10b) captured the five major observed convective events, but their magnitudes are smaller compared to the diagnostically determined (Fig. 6a) because of the under-estimate of rainfall rates (Fig. 3). Heating profiles based on the GCE model estimated information are in very good agreement with those determined diagnostically by sounding. It is perhaps not too surprising because the heating profiles based on the GCE model simulated rainfall rates and stratiform amounts are in very good agreement with those diagnostically determined (see Fig. 9c). It is true that the GCE model is driven by the large-scale advective forcing in temperature and water vapor. Therefore the model’s simulated rainfall and stratiform amount is simply a response to the forcing (Soong and Tao 1980). But, using the output from the GCE model for the CSH heating algorithm does not assure a good Q_1 retrieval. For example, errors in the estimated amount of stratiform rainfall can retrieve maximum heating at the wrong height.

Comparing Figs. 7 and 11(a) indicates that a good (bad) rainfall retrieval from SSM/I for a convective

7 The heating profiles selected in the CSH algorithm’s look-up table for this period is the GCE modeled (6 hourly) time-averaged heating profiles from December 19 to 27, 1992. Sensitivity of selecting the heating profile from the look-up table will be discussed in a later section.

Fig. 9. Evolution of the observed large-scale advective tendencies for (a) potential temperature and (b) water vapor mixing ratio (converted to K day^{-1}) during February 9–13, 1993. Negative values in potential temperature and water vapor are warming and drying, respectively. These observed-prescribed tendencies are imposed into the GCE model as the main forcing. Contours are every 2 K/day.

event always leads to a good (bad) latent heating retrieval. Note that no latent heating profile is retrieved during the period of December 11–13 using radar derived information because the radar data is missing (Fig. 11b). The level of maximum heating using radar information is at the 650 mb level and is lower than observed (Fig. 7a). This is because the radar estimated stratiform rain amount averages only 21 % (Table 2). The heating profiles based on the GCE model derived information show more temporal variation than observed during this period. Note that similar temporal variation of surface rainfall is simulated by the GCE model (Fig. 7b). Since the input of the CSH algorithm is the surface rain rates, there should be a similar temporal variation between rainrate and retrieved latent heating. There is good agreement between the observed and GCE derived heating for convective events that occurred during December 11–13 and December 14–15, except that the level of maximum heating is about 50 mb lower than observed for the convective event on December 11. The GCE simulated stratiform percentages is only 20–30 % for the two relatively weak convective events that occurred on December 13 and 16. This resulted in a lower level maximum in the latent heating profile.

Figure 12 shows the CSH algorithm retrieved latent heating profiles during the third period (February 9–13 1993). Differences in both temporal, as well as quantitative variation between the SSM/I retrieved latent heating profiles and those diagnostically determined, are present. Retrieved latent heating profiles using radar derived information are fairly good for the two major convective events (February 10 and February 11–12), except a lower

level maximum heating is retrieved. The retrieved latent heating profiles using the GCE model simulated rain rate and stratiform amount are too strong for the February 10 case, and have higher maximum latent heating levels than the February 11–12 case. In general, the performance of the CSH heating algorithm using rainfall information from SSM/I, and the GCE model, is not as good as that in the two December 1992 periods.

3.3 Time averaged latent heating profiles

Eight-day average profiles of Q_1 using information from SSM/I, radar and the GCE model for the period December 19–December 27, 1992 are shown in Fig. 13(a). These profiles are simply the time average of the profiles shown in Figs. 6(a), 10(a), 10(b) and 10(c). The CSH algorithm retrieved latent heating profile using the GCE model simulated rainfall and stratiform amount, is in excellent agreement with that diagnostically determined using sounding data (Lin and Johnson 1996). The agreement in the level of maximum heating between that determined diagnostically and that retrieved using the GCE model simulated rainfall and stratiform amount, indicates that the GCE model simulated stratiform amount is reasonable. An overestimate of latent heat release is expected when the SSM/I derived rainrate is used. Radar estimated rainfall is much less than that of the GCE model estimated, which therefore also leads to greatly underestimated latent heating over the period.

The sensitivity of derived rainfall amount upon the latent heating profile retrieval is now examined. Figure 13(b) shows the eight-day averaged profiles of Q_1 that are derived from the CSH algo-

Fig. 10. Time-height cross-sections of Convective-Stratiform Heating (CSH) algorithm derived Q_1 for the TOGA COARE IFA region for the 8-day period spanning December 19–27, 1992. (a) Estimated from the GCE model based rainfall rates and stratiform percentages and look-up table profiles stored in the look-up table. (b) Same as (a) except with radar estimated stratiform percentages and rain rates. (c) Same as (a) except with SSM/I derived rain rates and stratiform percentages. The heating profiles selected in the CSH algorithm's look-up table for this period is the GCE modeled (6 hourly) time-averaged heating profiles from December 19 to 27, 1992. Contours are every 5 K/day.

Fig. 11. Same as Fig. 10 except for the December 10–17, 1992 period. The heating profiles selected in the CSH algorithm's look-up table for this period is the GCE modeled (6 hourly) time-averaged heating profiles from December 10 to 17, 1992.

algorithm using GCE model simulated rainfall but incorporating: (1) SSM/I, and (2) radar estimated stratiform percentages. Major improvements (as expected) in the magnitude (strength) of the latent heating profiles occur when the GCE model simulated rainfall amount is used. Lower maximum heating levels, compared to the sounding observations, are still present using the SSM/I stratiform percentages. This could be a result of the SSM/I estimated

Fig. 12. Same as Fig. 10 except for the February 9–13, 1993 period. The heating profiles selected in the CSH algorithm's look-up table for this period is the GCE modeled (6 hourly) time-averaged heating profiles from February 9 to 13, 1993.

stratiform percentages being smaller (13 %) than those in the GCE model simulation (Table 1). Another sensitivity test is to increase the SSM/I derived stratiform rain percentage by 10 % (for every convective event during the 8-day period). This results in the maximum heating level being lifted from 550 mb to the 425 mb level (the diagnostically determined maximum heating level), and suggests that the SSM/I retrieved stratiform amount is underes-

timated for this period (December 19 to 27, 1992).

Averaged profiles of Q_1 , using 8-day averaged rainrate and stratiform percentages from Table 1, are shown in Fig. 13c. The retrieved latent heating profiles are almost identical to those determined by adding the latent heating profiles (shown in Fig. 13(a)). This is also true for the other two TOGA COARE periods (not shown). This result suggests that the CSH algorithm can be used to retrieve time-averaged latent heating profiles from both the time-averaged rainfall amounts, and stratiform percentages.

Figure 14(a) shows the seven-day averaged profiles of Q_1 using information from the SSM/I, radar, and GCE model for the second period (10–17 December 1992). The CSH algorithm-retrieved latent heating profiles using the GCE model simulated and SSM/I derived rainfall, and stratiform amount, are in good agreement with that diagnostically determined using sounding data (Lin and Johnson 1996)—with the exception of a slightly lower maximum heating level (25 mb) in the retrieved profile. Note that very similar rainfall amounts and stratiform percentages are estimated between the GCE model and SSM/I (Table 2). Radar estimated rainfall, as well as stratiform percentage, is 50 % less than the GCE model estimated and SSM/I derived due to several days of missing data, which therefore leads to greatly underestimated latent heating by the radar above 600 mb over the period.

If the period Dec 11–17 is instead reduced to the period when the radar data is available, Dec 14–17, then the rainfall amounts are in good agreement (see Table 4). In fact, in contrast with other periods, the radar estimates are actually larger than those from the SSM/I, and sounding network though the stratiform percentage for the radar is much lower. The corresponding average retrieved heating profiles for the abbreviated period are shown in Fig. 14(b). As expected, the model profile still shows the greatest agreement with observations. The radar profile though improved in magnitude is still in poor agreement due to a vastly underestimated stratiform percentage resulting in a maximum heating level that is at least 200 mb too low. Interestingly, the SSM/I profile does not match as well as it did for the longer Dec 11–17 period by also having a stratiform percentage that appears too low.

Time-averaged Q_1 profiles show good agreement between the retrieved values using the GCE model simulated rainrate and stratiform percentage, and that diagnostically determined using sounding data for the February 1993 period [Fig. 14(c)]. This result is not expected because of some notable differences (strength of heating and its maximum heating level) in Q_1 evolution during this period shown in Figs. 8(a) and 12(c). Note that cooling in the lower troposphere is retrieved (both averaged and tempo-

Fig. 13. Eight-day average profiles of Q_1 in K/day for the TOGA COARE IFA region during December 19–27, 1992. (a) The observed Q_1 is the black solid line (obs), the retrieved Q_1 using the CSH algorithm with both SSM/I rainrates and stratiform percentages is the short-dashed gray line (Ss), the retrieved Q_1 using both radar estimated stratiform percentages and rainrates is the dashed black and gray line (Rr), and the retrieved Q_1 using both the GCE model simulated stratiform percentages and rain rates is the short-dashed black line (Mm). (b) Same as (a) except the GCE model simulated rainfall is used in combination with SSM/I (gray solid line—Ms) and radar estimated stratiform percentages (black long-short-dashed line—Mr). Long-short-dashed gray line (Ms+) is the Q_1 profile with an increased SSM/I derived stratiform rain percentage of 10 % (for every convective event during the 8 day period). (c) Same as (a) except using 8-day averaged rainrate and stratiform percentages from Table 1.

Fig. 14. (a) Same as Fig. 13(a) except for the December 10–17, 1992 period. (b) Same as (a) except for the December 14–17, 1992 period. (c) Same as Fig. 13(a) except for the February 9–13, 1993 period.

Table 4. Same as Table 2 except for the December 14–17, 1992 period only.

	Rainfall Amount (mm/day)	Stratiform Portion (%)
GCE Model	14.7	46
SSM/I	13.8	33
Radar	16.0	22

ral) by the CSH algorithm using the GCE model results. This cooling is not retrieved when using either the SSM/I, or radar derived rainfall information. Excessive heating below 600 mb (near the melting level) is retrieved by the SSM/I and radar.

Fig. 15. Normalized apparent heating source Q_1 (K day^{-1}) in convective and stratiform regions, associated with various types of cloud systems in different geographic locations. These profiles are obtained from the GCE model simulations of GATE, PRE-STORM, EMEX, and the TOGA COARE 11 February 1993 squall cases (erect convective updraft or upshear types). Time-averaged and normalized Q_1 in the convective and stratiform regions for three TOGA COARE periods (10–17 December 1992; 19–27 December 1992; and 9–13 February 1993) are also shown.

3.4 Sensitivity of heating profiles used in the look-up table

The heating profiles for all three periods (Figs. 10–14) are retrieved from their respective time-averaged convective and stratiform profiles. Now the sensitivity of the CSH algorithm for selecting an appropriate latent heating profile (in the look-up table⁸)

8 More than 20 profiles (from cloud modeled simulations and sounding budgets) are in the current look-up table. It is still limited, and we are getting more from recently completed TRMM field campaigns.

needs to be investigated. Figure 15 shows the normalized apparent heating source, Q_1 , in the convective and stratiform regions, associated with various types of cloud systems occurring in different geographical locations. The heating profiles associated with each of the squall-line systems share major common features. These include maximum convective heating in the lower to middle troposphere, maximum stratiform (anvil) heating in the upper troposphere, and regions of stratiform cooling prevailing in the lower troposphere. The simulated

Fig. 15. (Continued)

heating profiles in the stratiform regions show very good agreement with those obtained from diagnostic studies (Houze 1982; Johnson 1984; Gallus and Johnson 1991; Chong and Hauser 1990). However, some notable differences do exist. First, large cooling in the stratiform region occurs for the squall system that developed in midlatitudes [PRE-STORM; Fig. 15(e)], due to a drier environment and as a consequence, stronger evaporative cooling. Second, large stratiform cooling occurs with the vertically erect cloud updraft case (11 February 1993, TOGA COARE)⁹ as a result of strong and high-level rear

inflow, which leads to strong melting [Halverson et al. 1996; Fig. 15(g)]. These two cases also appear to have strong heating in the stratiform regions. Stratiform cooling for the EMEX, GATE, and 11 February 1993 TOGA-COARE upshear cases are relatively small [see Figs. 15(d), 15(f) and 15(h)]. The double maximum in heating in the stratiform region for the 11 February upshear case is related to the initial temperature structure at the 6–8 km levels. The CSH algorithm look-up table includes these heating profiles.

⁹ The 11 February erect and upshear squall systems are case studies. The GCE model simulated convection is sensitive to the initial temperature, water vapor, and ver-

tical shear of the horizontal winds (i.e., Convective Available Potential Energy—CAPE). No large-scale advective tendencies of temperature and water vapor are needed. A cool pool is specified to initiate convection.

Fig. 16. Retrieved eight-day-averaged profiles of Q_1 ($K \text{ day}^{-1}$) for the TOGA-COARE IFA region during 19–27 December 1992, using the heating profiles in the CSH algorithm look-up table (depicted in Fig. 15). (a) Retrieved Q_1 using the GATE, EMEX, and PRE-STORM convective and stratiform heating profiles, depicted as solid gray, dashed black, and short-dashed gray lines, respectively. (b) Retrieved Q_1 using the erect and upshear type convective and stratiform heating profiles, shown as long-dashed gray and black-gray lines, respectively. The retrieved Q_1 using the time-averaged heating profile from the third TOGA-COARE period (9–13 February 1993) is shown by a short-dashed black line. The observed Q_1 is depicted by the black solid line in (a) and (b).

Figure 16 shows the CSH algorithm retrieved latent heating profile for the 19–27 December 1992 period, computed by using different stored convective and stratiform heating profiles from the look-up table. Clearly, the retrieved latent heating profile is sensitive to the selection of profiles stored in the look-up table. The selected profiles with strong heating aloft and cooling below (PRE-STORM and vertical erect updraft cases) produce the poorest agreement between the retrieved—and diagnostically determined heating—profiles for this period. The retrieved profile using the convective

and stratiform heating profiles associated with the vertical upshear-tilted updraft case is also not in good agreement with that observed. The upshear tilt (with respect to the vertical shear of the environmental horizontal wind) of the cloud updrafts develops during the December 19–27 period. Since the observed Q_1 is averaged over an 8-day period, it represents many cloud systems throughout their respective life cycles (developing, mature, and dissipating stages). That is the major reason for the disagreement between the observed and retrieved heating profiles. The retrieved profiles using the convective and stratiform heating profiles associated with the GATE and EMEX squall cases capture the strength of the heating and the maximum heating level well. A good agreement between the observed and retrieved Q_1 heating profile is associated with selection of the second period (10–17 December). A close resemblance between heating profiles for the first and second periods in the look-up table [Figs. 15(a) and 15(b)] is the reason for this good agreement. The retrieved profile using the convective and stratiform heating profile associated with the February convective period results in more cooling below the 750 mb level and larger heating between the 550–300 mb levels. That is because the cooling below, and heating aloft are greater in the stratiform region for February than for December.

The February 9–13 period, having more stratiform clouds, differed from the December periods in that the observed average heating profile for the period shows net cooling below 800 mb. A variety of look up table profiles were also tested for this period including profiles based on the December 19–27 and December 10–17 (not shown) simulations (Fig. 17). Despite the fact that the PRESTORM and erect updraft profiles are able to generate low-level cooling, neither set of profiles is able to provide a good overall fit to the observed Q_1 for the February 9–13 period. They both produce cooling that is too strong and too deep at lower levels and heating that is too strong at upper levels. Although the GATE, EMEX and December 19–27 (similar to December 10–17) profiles do not capture the low level cooling, they all give reasonably close estimates of the latent heating aloft, and only minimal heating where there should be cooling at low levels. In fact their minimal heating is closer to the observed Q_1 than the cooling from the PRESTORM and Erect look up table profiles.

These sensitivity tests indicate that an appropriate selection of convective and stratiform heating profiles from the look up table is crucial for retrieving latent heating profiles correctly. The stratiform amount (high or low), geographic location (midlatitude land or tropical ocean), melting level (high or low), types of convection (erect, upshear and others) and Convective Available Potential Energy (CAPE)

Fig. 17. Same as Fig. 16 except for the February 9–13, 1993 period. Also, the retrieved Q_1 using the time-averaged heating profile from the first TOGA-COARE period (19–27 December 1992) is shown by a short-dashed black line in (b).

will be incorporated into the CSH algorithm in the future.

4. Summary and future work

Latent heating profiles associated with several TOGA COARE convective systems are examined using the GCE model and retrieved using the Goddard Convective and Stratiform Heating (CSH) algorithm. The inputs for the (CSH) algorithm are surface precipitation rates, amount of stratiform rain, and information on the type and location of observed cloud systems. The CSH algorithm also needs a look-up table consisting of latent heating profiles associated with various types of cloud systems occurring in different geographic locations. In this study, the inputs for the CSH algorithm are SSM/I, Radar and GCE model derived rainfall and stratiform amount. Three periods (December 11–17 1992; December 19–27 1992; and February 9–13 1993) containing intense convection that occurred over the TOGA COARE IFA were used for this study. Diagnostically determined latent heating profiles calculated using 6 hourly soundings (Lin and Johnson 1996) are used for validation.

The GCE model simulated rainfall and latent heating profiles are in excellent agreement with

those estimated by soundings. This good agreement is mainly caused by the fact that the GCE model was forced by large-scale tendencies in temperature and water vapor computed from the sounding network. In addition, the typical convective and stratiform heating structures (or shapes) discussed in Houze (1997) are well captured by the GCE model. Another interesting feature is that the heating structure in the stratiform region is smoother than that in the convective region. This is because convective bursts have a shorter temporal evolution than that of the stratiform region. Radar measured rainfall is smaller than that both estimated by the GCE model, and SSM/I, in all three different TOGA COARE IFA periods. SSM/I derived rainfall is more than the GCE model simulated for the December 19–27 and February 9–13 periods. During the December 10–17 period, both the GCE model simulated and SSM/I derived rainfall are in excellent agreement with each other. The difference between these different estimates in rainfall has been reported and discussed in Lin and Johnson (1996), Frank et al. (1996) and Johnson and Ciesielski (2000). Johnson and Ciesielski (2000) indicated that the radars were located within a relatively dry region of the IFA, and consequently, the radar estimated rainfall is smaller than that determined from the moisture budget (derived from soundings). The Z–R relation used by Short et al. (1997) could also contribute to less stratiform rain, and consequently to less total rain.

The GCE model estimated stratiform amount is about 50 % for December 19–27, 42 % for December 11–17 and 56 % for the February 9–13 case. These results are consistent with Lin and Johnson's (1996) analyses. Their results indicated that there was a greater contribution from stratiform precipitation during December 19–27, than during December 11–17. Their results also indicated that stratiform clouds dominated during the February 9–13 period. Accurate estimates of stratiform amount (within 10 %) are needed for proper latent heating retrieval (Tao et al. 1993a). A higher (lower) percentage of stratiform rain can imply a maximum heating rate at a higher (lower) altitude, consistent with diagnostic studies (e.g., Johnson 1984). The GCE model always simulates more stratiform rain (10 to 20 %) than the radar for all three convective episodes. Again, this may be a result of the relatively dry region in which the ship radars were located [a drier environment can enhance evaporation resulting in less light precipitation (stratiform rain) reaching the ground]. The SSM/I derived stratiform amount is about 37 % for December 19–27, 48 % for December 11–17 and 41 % for the February 9–13 case. The SSM/I derived stratiform amount is larger (smaller) than the GCE model simulated for December 11–17 (December 19–27, February 9–13).

Temporal variability of the retrieved latent heating profiles using either the GCE model simulated or radar estimated rainfall and stratiform amount is in good agreement with that diagnostically determined for all three periods. However, less rainfall and a smaller stratiform percentage estimated by radar resulted in weaker (underestimated) latent heating profiles, and lower maximum latent heating levels compared to those determined diagnostically. Rainfall information from SSM/I can not retrieve individual convective events due to poor temporal sampling. Nevertheless, this study suggests that a good rainfall retrieval from SSM/I for a convective event can lead to a good latent heating retrieval.

Time averaged retrieved latent heating profiles using the GCE model simulated rainfall and stratiform amount are in excellent agreement with those diagnostically determined using sounding data for all three TOGA COARE convective periods. Less rainfall and smaller stratiform percentages estimated by radar again resulted in weaker (underestimated) time averaged heating profiles and lower maximum latent heating levels compared to those determined diagnostically. A sensitivity test was performed, and the results indicated that the SSM/I derived time averaged stratiform amount may be underestimated (by 10 %) for December 19–27. Averaged heating profiles derived from SSM/I, however, are not in bad agreement with those derived by soundings for the December 10–17 period. The heating retrievals may be more accurate for longer time scales.

Furthermore, it is necessary to make an appropriate selection from the lookup table. Lookup table profiles for a midlatitude and a vertically erect updraft convective case, for example, performed poorly for both December periods while a tropical one from a similar environment (i.e., EMEX) did quite well. The heating profiles for both December periods are quite similar and no major difference in the retrieved latent heating profile is present with selecting either set of heating profiles stored in the lookup table. Finally, the heating profiles in the lookup table are based on area and time averages. Therefore, the retrievals which are based on profiles stored in the lookup table must be utilized in a similar fashion. The retrievals are appropriate for spacial resolutions on the order of convective systems (about 200×200 km). Finding a systematic method to select an appropriate set of profiles from the lookup table is an area that requires further investigation.

TRMM was successfully launched in November 1997. Efforts are under way to use TMI and SSM/I derived rainfall and stratiform percentages (Kummerow et al. 1996; Olson et al. 1996, 1999) as input for the CSH algorithm to retrieve the four dimensional structure of monthly latent heating profiles. It is also planned to compare the CSH algorithm retrieved latent heating profiles

with those derived from other methods (Olson et al. 1999; Yang and Smith 1999). The CSH algorithm retrieved latent heating profiles can be also compared to those simulated in a General Circulation Model (GCM) (Krishnamurti 1999—personal communication). Data from TRMM field experiments (i.e., SCSMEX, May–June 1998; LBA-TRMM/Brazil, January–February 1999; and KWA-JEX, July–September 1999) will be used to compare profiles of latent heating obtained from larger-scale sounding arrays, radar estimates, GCE model simulations, and from the latent heating algorithms.¹⁰ These results can be further compared with divergence and heating derived from dual-Doppler radar analyses and airborne Doppler radar techniques (e.g., Yuter and Houze 1995; Mapes and Houze 1995).

Real clouds and cloud systems are three-dimensional. Because of the limitations of computer resources, however, most cloud ensemble models (CEMs) today are still two-dimensional (Krueger 1988; Xu 1995; Xu and Randall 1996; Tao et al. 1996; and many others, see a review, Tao et al. 1997). Few 3-D CEMs (e.g., Tao and Soong 1986; Tao et al. 1987; Lipps and Hemler 1986) have been used to study the response of clouds to large-scale forcing. Recently, we performed a 3-D GCE model simulation for the 8-day period December 19–27, 1992 using a 256 by 256 km domain (with 2 km resolution). The preliminary results indicate that cloud statistics as well as surface precipitation and latent heating profiles are very similar to the 2-D GCE model simulations. Grabowski et al. (1998 and personal communication) also found a similar conclusion for their GATE and TOGA COARE multi-day 2-D and 3-D simulations. The reason for the strong similarity between the 2-D and 3-D CEM simulations is that the same observed (time-varying), large-scale advective tendencies of potential temperature, water vapor mixing ratio, and horizontal momentum were used as the main forcing in both the 2-D and 3-D models. However, we did find that the 3-D GCE modeled water vapor (Q_2) budget is in better agreement with observations in the lower troposphere than its 2-D counterpart. This is due to the fact that turbulent processes in the PBL are 3-D in nature. We will report our results in a publication in the near future.

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10 The rainfall and stratiform percentage derived from TMI and TRMM PR will be used as inputs for the CSH algorithm. Their derived latent heating profiles can be compared to GCE model simulations and estimates from sounding networks.

large-scale forcing for the GCE model simulations and validations.

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雲解像モデル、SSM/I、観測船レーダのデータを用いて求めた TOGA COARE 対流システムの潜熱放出の鉛直分布とそのリトリーバル

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TOGA COARE 集中観測中の3つの対流活動の活発な期間(1992年12月10-17日、1992年12月19-27日、1993年2月9-13日)の潜熱加熱鉛直分布を Goddard Cumulus Ensemble (GCE) Model の2次元バージョンを用いて調査するとともに、Goddard Convective and Stratiform Heating (CHS) アルゴリズムを用いて推定した。CHS アルゴリズムに入力した降雨に関するデータソースは SSM/I、観測船レーダ、GCE モデルである。6時間ごとのゾンデデータを用いて診断的に求めた潜熱加熱鉛直分布を検証データとして用いた。GCE モデルを用いて計算した降雨強度及び潜熱加熱鉛直分布はゾンデ観測から見積もられた値と良い一致を示した。典型的な対流性及び層状性加熱構造(形態)は GCE モデルで良く再現されていた。レーダで観測した降雨強度は12月の両期間については GCE モデルや SSM/I から見積もった値よりも小さくなった。SSM/I から求めた降雨強度は12月19-27日と2月9-13日については GCE モデルより大きな値となったが、12月10-17日については GCE モデルと良い一致を示した。GCE モデルで見積もった層状性降水の割合は12月19-27日が50%、12月11-17日が42%、2月9-13日が56%であった。これらの結果は大規模場の解析と矛盾しない値であった。精度の良い潜熱加熱のリトリーバルのためには層状性降水の割合の正確な見積もりが必要である。層状性降水の割合が高く(低く)なると最大加熱率がより高(低)高度に出現する。GCE モデルは三つの期間について常にレーダよりも層状性降水の割合を10-20%高く計算した。SSM/I から求めた層状性降水の割合は12月19-27日が38%、12月11-17日が48%、2月9-13日が41%であった。GCE モデルまたはレーダから見積もった降水強度と層状性降水の割合を用いて CHS アルゴリズムで推定した潜熱加熱の鉛直分布の時間変化は、三つの期間について診断的に計算した結果と良い一致を示した。しかし、レーダから見積もられた降雨強度や層状性降水の割合が小さめであったために、診断的に計算された結果と比べると潜熱加熱量を減少評価し、最大潜熱加熱高度を低く目に推定した。SSM/I の降雨に関する情報は時間解像度が低いために、ここの対流活動を推定することはできない。しかし本研究は対流活動に関する SSM/I による良い降雨強度のリトリーバルは良い潜熱加熱のリトリーバルにつながることを示唆した。感度実験の結果は、SSM/I から求めた12月19-27日の時間平均した層状性降水の割合は過少評価されるとを示した。しかし、12月10-17日については、SSM/I から求めた時間平均した層状性降水の割合はゾンデ観測から得られた結果とそれほど矛盾しない値であった。観測結果にバイアスがなければ、長期間の加熱量を求めるリトリーバルはより精度の高いものと思われる。CHS の look-up table から適切な潜熱加熱鉛直分布を選択することが重要である。この問題を取り扱った感度実験も実施した。