The Next-Generation Goddard Convective–Stratiform Heating Algorithm: New Tropical and Warm-Season Retrievals for GPM

STEPHENV. LANG
Mesoscale Atmospheric Processes Laboratory, NASA Goddard Space Flight Center, Greenbelt, and Science Systems and Applications, Inc., Lanham, Maryland

WEI-KUO TAO
Mesoscale Atmospheric Processes Laboratory, NASA Goddard Space Flight Center, Greenbelt, Maryland

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ABSTRACT

The Goddard convective–stratiform heating (CSH) algorithm, used to estimate cloud heating in support of the Tropical Rainfall Measuring Mission (TRMM), is upgraded in support of the Global Precipitation Measurement (GPM) mission. The algorithm’s lookup tables (LUTs) are revised using new and additional cloud-resolving model (CRM) simulations from the Goddard Cumulus Ensemble (GCE) model, producing smoother heating patterns that span a wider range of intensities because of the increased sampling and finer GPM product grid. Low-level stratiform cooling rates are reduced in the land LUTs for a given rain intensity because of the rain evaporation correction in the new four-class ice (4ICE) scheme. Additional criteria, namely, echo-top heights and low-level reflectivity gradients, are tested for the selection of heating profiles. Those resulting LUTs show greater and more precise variation in their depth of heating as well as a tendency for stronger cooling and heating rates when low-level dB values decrease toward the surface. Comparisons versus TRMM for a 3-month period show much more low-level heating in the GPM retrievals because of increased detection of shallow convection, while upper-level heating patterns remain similar. The use of echo tops and low-level reflectivity gradients greatly reduces midlevel heating from; 2 to 5 km in the mean GPM heating profile, resulting in a more top-heavy profile like TRMM versus a more bottom-heavy profile with much more midlevel heating. Integrated latent heating rates are much better balanced versus surface rainfall for the GPM retrievals using the additional selection criteria with an overall bias of +4.3%.

1. Introduction

Latent heat release within the atmosphere arises from heat exchanges as water changes phase between vapor, liquid, and solid and is an important component or principal driver for many atmospheric circulations. Even at midlatitudes, latent heating (LH) can be an important part of midlatitude cyclone dynamics and the larger-scale storm track (Willison et al. 2013) and can be especially important for the rapid deepening of such storms (Whitaker and Davis 1994; Pirret et al. 2017). In the tropics, however, LH is typically the primary component for a wide range of tropical circulations beginning with the large-scale Hadley circulation where latent heat release within “hot towers” is the principal driver (Riehl and Malkus 1958; Fierro et al. 2009, 2012). LH can also lead to important feedbacks within monsoon circulations such as the East Asian summer monsoon (Jin et al. 2013), the West African monsoon (Hagos and Zhang 2010), and the South Asian monsoon (Choudhury and Krishnan 2011). The convectively coupled Madden–Julian oscillation (MJO; Madden and Julian 1971, 1972) is another frequently studied, larger-scale tropical circulation strongly influenced by LH, including its characteristic transition from low-level heating during its build-up phase (Wu 2003) to a top-heavy, stratiform-type heating profile during its mature phase (Lin et al. 2004). Its propagation also depends on the depth and shape of the vertical heating profile (Lau and Peng 1987; Kemball-Cook and Weare 2001). GCMs have traditionally struggled to properly simulate the MJO, and inaccuracies in their
simulated heating profiles are one possible factor (C. Li et al. 2009). At smaller scales, LH is a fundamental energy source for the maintenance and intensification of tropical cyclones (Schubert and Hack 1982; Nolan et al. 2007).

Because it is an integral part of the phase changes of water, LH is closely tied to cloud systems and precipitation. And despite its great importance, LH is hard to measure directly. However, the launch of the Tropical Rainfall Measuring Mission satellite (TRMM; Simpson et al. 1996; Kummerow et al. 2000) in November of 1997 made it possible to obtain quantitative precipitation measurements over the global tropics and, as a consequence of their close connection, estimates of tropical LH as well. In support of this effort, five different LH algorithms were developed to retrieve profiles of LH using TRMM rainfall products. Different approaches were adopted for each algorithm but most required the use of a cloud-resolving model (CRM) to ultimately link satellite observables with quantitative amounts of LH. Among these, the first LH algorithm to be put forth was the Goddard convective–stratiform heating (CSH) algorithm by Tao et al. (1993a). Based on the common characteristic shapes of the heating profiles within the convective and stratiform regions of convective cloud systems, rain-normalized profiles of convective and stratiform heating from sounding budgets and CRM [i.e., Goddard Cumulus Ensemble (GCE) model; Tao and Simpson 1993] simulations are scaled by observed surface rain rates and weighted by stratiform fraction to estimate cloud heating profiles. The algorithm was revised by Tao et al. (2010) to use conditional rain rates and more detailed bins in its lookup tables (LUTs) and is described in more detail in section 2a. Shige et al. (2004) built upon this approach by binning heating profiles according to precipitation top height (or rate at the melting level for deep anvil) in addition to rain type in the spectral latent heating (SLH) algorithm. They too used simulated heating profiles from the GCE to build their LUTs. The algorithm was later improved (Shige et al. 2007) and expanded to include apparent moistening (Shige et al. 2008). In the Goddard profiling (GPROF) algorithm (Olson et al. 1999, 2006), CRM-simulated hydrometeor profiles and their accompanying LH are linked by their radiative characteristics to satellite microwave radiometric observations via a Bayesian technique. This approach later evolved into the “trained radiometer” or TRAIN algorithm (Grecu and Olson 2006; Grecu et al. 2009) wherein the passive microwave algorithm is “trained” using space-borne radar profiles; those reflectivity profiles are in turn linked to heating profiles from CRM simulations in a manner similar to the SLH algorithm. The hydrometeor heating (HH) algorithm (Yang and Smith 1999a,b, 2000) uses the vertical derivative of retrieved hydrometeor profiles to estimate LH. Its derivation was also based on CRM simulations. The precipitation radar heating (PRH) algorithm (Satoh and Noda 2001; Satoh 2004; Kodama et al. 2009) does not require CRM data to estimate heating but must estimate cloud drafts and thermodynamic structures instead. Please see Tao et al. (2006) for an additional overview of these TRMM-related heating algorithms. Several studies have taken advantage of the availability of TRMM heating products to characterize and study the MJO (Lau and Wu 2010; Zhang et al. 2010; Jiang et al. 2011; Barnes et al. 2015), tropical cyclones (Zagrodnik and Jiang 2014), and the monsoon (Zuluaga et al. 2010), among others. Please also see Tao et al. (2016a).

Other approaches for estimating LH have also been developed. For example, Guimond et al. (2011) revised a technique by Roux (1985) to estimate LH within tropical cyclones from airborne Doppler radar observations and the thermal energy equation. More recently, Ahmed et al. (2016) built an algorithm to retrieve LH based on the sizes of convective and stratiform areas as well as their echo-top heights from a multiweek Weather Research and Forecasting (WRF) Model simulation using data from the Dynamics of the MJO (DYNAMO) field campaign in the Indian Ocean. In addition, the original TRMM-related algorithms have and will need to continue to evolve, especially with the expansion of TRMM’s successor, the Global Precipitation Measurement (GPM) mission (Hou et al. 2014; Skofronick-Jackson et al. 2017), to higher latitudes. However, given the continued coverage as well as the immense importance of LH over the tropics, it is essential to continue and to improve heating retrievals for this region.

As such, this study is focused on improving heating retrievals from the Goddard CSH algorithm in the tropics and for warm-season conditions using precipitation products from GPM. The paper is organized as follows. Section 2 describes the Goddard CSH algorithm and the new GCE CRM simulations used to support the algorithm as well as the algorithm’s new resulting LUTs, including an new construct method that includes echo-top heights and low-level reflectivity gradients. Retrieval results for a 3-month period when TRMM and GPM overlapped are presented and compared in section 3. An analysis of the balance between heating and surface rainfall is also given in section 3, and the summary and future work are presented in section 4.

2. The CSH algorithm

a. Description and history of the CSH algorithm

The framework for the original Goddard CSH algorithm was put forth by Tao et al. (1993a) based upon the
common characteristic shapes of observed (e.g., Johnson 1984; Houze 1982, 1997) and simulated (e.g., Chong and Hauser 1990) cloud heating profiles obtained when convective cloud systems are separated into their convective and stratiform regions. The original CSH algorithm consisted of two pairs of rain-normalized convective and stratiform diabatic heating profiles [i.e., \( Q_1 \) or the apparent heat source; Yanai et al. (1973)], one pair for land and one for ocean, obtained from composites of both GCE model (Tao and Simpson 1993) simulations and sounding budget calculations; a single additional pair was later added for shallow heating. Using surface rainfall rates and the proportion of stratiform rain, cloud heating profiles could then be retrieved remotely from satellite or other data (Tao et al. 2000), including TRMM (Tao et al. 2001).

The CSH algorithm was later redesigned and improved by Tao et al. (2010). Instead of heating profiles being composited into just a few pairs (i.e., land, ocean, and shallow), new LUTs were constructed with their heating profiles partitioned into detailed intensity and stratiform bins (i.e., 36 intensity every 20 mm day\(^{-1}\) and 20 stratiform every 5%). The rain intensities were also calculated, stored, and accessed based on the conditional rain rates for a given area (e.g., 0.5° × 0.5°, TRMM gridded product resolution), so for a given domain average intensity, heating profiles from a smaller area of more intense rain can be different from those associated with a broader area of weaker rain rates. These two new features allowed for the possibility of many more heating structures and greater variation in the depth of heating. The LUTs were still composited into land and ocean categories based upon multiweek 2D GCE (Tao et al. 2003) simulations from three oceanic field campaigns (i.e., GATE, SCSMEX, and TOGA COARE) and two continental (i.e., ARM 1997 and 2002) using an improved version of the Rutledge and Hobbs (1983, 1984) three-class ice scheme (Lang et al. 2007) wherein the unrealistic dry collection of snow and ice by graupel was turned off. Because heating components can easily be separated in the model, LUTs were constructed for each of the heating components (i.e., LH, eddy heating, and radiative) and later the two moistening components (i.e., microphysical and eddy). The LUTs were constructed by subdividing the GCE model into 64-km subdomains to approximate the 0.5° resolution of the gridded heating products. Convective–stratiform separation followed the GCE method (Tao et al. 1993b) wherein a technique similar to Churchill and Houze (1984), which uses horizontal reflectivity gradients to identify peaks above the background average, is first applied to the surface rain rates; after which, any rates over 20 mm hr\(^{-1}\) are also made convective. Nonraining and stratiform areas are then screened for updrafts over 3 m s\(^{-1}\) below and above the freezing-level height, respectively, and for cloud water over 0.5 and 1.0 g kg\(^{-1}\), respectively. If both \( w \) (the vertical velocity) and cloud water exceed their respective thresholds, the grid column is made convective as well. Finally, the LUTs were further separated into rainy areas, areas adjacent to rain, and areas far from rain (i.e., more than one model subdomain from rain).\(^1\)

One of the main goals of TRMM was to provide accurate estimates of LH over the global tropics (Simpson et al. 1988). The CSH algorithm has been one of the TRMM standard algorithms and officially uses data from the combined radar–radiometer algorithm for its input (the same is true for GPM). Table 1 lists the input data, names, and types of products produced with the CSH algorithm for TRMM. The current version 7 (V7) TRMM heating products are based on the Tao et al. (2010) version of the algorithm with the corresponding LUTs still derived from multiweek 2D GCE simulations. However, for the TRMM V7 LUTs, the GCE was run with a further improved three-class ice scheme (Lang et al. 2011), which included an allowance for ice supersaturation, corrections to the vapor growth of ice to snow, and the introduction of snow and graupel size mappings amongst others, with additional simulations for the Kwajalein Experiment (KWAJEX) and the Tropical Warm Pool–International Cloud Experiment (TWP-ICE) included in the construction of the oceanic LUTs. Figure 1 shows cross sections taken through the land and ocean CSH V7 LH LUTs for the most convective (i.e., having surface rain rates with stratiform fractions <5%) and most stratiform (i.e., having surface rain rates with stratiform fractions >95%) LUT bins, wherein the model is sampled over 64-km subdomains [please see Tao et al. (2010) for more details]. Over ocean, the depth and level of maximum convective heating quickly increase with increasing rain intensity followed then by a further increase in magnitude at higher rain rates. For land, convective heating rates are comparable but noisier, and the transition from shallow to deeper heating more abrupt. Stratiform profiles for both land and ocean have very similar structures, with heating above ~6 km and cooling below but with the cooling rates stronger over land.

With the transition from TRMM to GPM, cloud heating retrievals from the CSH algorithm will need to

\(^1\)Radiative heating/cooling rates \( (Q_a) \) are retrieved in a similar manner, but the LUT rates are mean and not conditional rates, as they do not depend on surface rain intensity. Currently, they are retrieved for all grids/pixels but are not separated into their long- and shortwave components.
be expanded to cover higher latitudes and cold-season conditions. However, given the continued satellite coverage as well as the importance of LH over the tropics, it essential to continue and to improve heating retrievals for this region.

b. New GCE simulations for the CSH algorithm

Since the CSH algorithm was last updated for TRMM, a new Goddard four-class ice (4ICE) scheme has been developed using the GCE (Lang et al. 2014).

Table 1. TRMM cloud heating and moistening products from the CSH algorithm. The three individual heating components of the total apparent heat source or $Q_1$ (i.e., LH, EHT, and $Q_R$) are retrieved separately, where LH is latent heating, EHT is the eddy heating rate, and $Q_R$ is the radiative heating/cooling rate. Likewise, the apparent moistening source or $Q_2$ is separated into its microphysical and eddy components.

<table>
<thead>
<tr>
<th>TRMM CSH product</th>
<th>Type</th>
<th>Spatial scale</th>
<th>Temporal scale</th>
<th>Retrieved products</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSH-Combined (3G31)</td>
<td>Gridded orbital</td>
<td>$0.5^\circ \times 0.5^\circ$; 19 vertical layers</td>
<td>Instantaneous</td>
<td>LH, EHT, $Q_R$, micro/eddy $Q_2$</td>
</tr>
<tr>
<td>CSH-Combined (3H31)</td>
<td>Gridded monthly</td>
<td>$0.5^\circ \times 0.5^\circ$; 19 vertical layers</td>
<td>Monthly</td>
<td>LH, EHT, $Q_R$, micro/eddy $Q_2$</td>
</tr>
<tr>
<td>CSH-Combined (2H31)</td>
<td>Orbital*</td>
<td>Pixel; 19 vertical layers</td>
<td>Instantaneous</td>
<td>LH, EHT, $Q_R$, micro/eddy $Q_2$</td>
</tr>
</tbody>
</table>

* Orbital (pixel) heating is available but is not a standard TRMM product.
with the addition of a frozen drops/hail category along with several other modifications, including the addition of a bin-based rain evaporation correction (X. Li et al. 2009). This scheme was then further modified and improved (Tao et al. 2016b) using the NASA-Unified WRF Model, as well as tested globally in the Goddard multiscale modeling framework (GMMF; Chern et al. 2016). The new scheme results in several improved radar structures, including the ability to produce narrow but intense convective cores, a semblance of a transition zone between the convective leading edge and the trailing stratiform region, and a more coherent, vertically stratified stratiform region with more realistic reflectivity values and a more realistic aggregation/sedimentation signature as well as better surface rain rate histograms (Lang et al. 2014; Tao et al. 2016b). As such, a new series of multiweek GCE simulations were conducted incorporating the new Goddard 4ICE scheme in order to upgrade the CSH algorithm’s tropical/warm-season LUTs. The simulations were still 2D with 70 stretched vertical levels and 1-km horizontal resolution, but the horizontal domains were expanded from 256 to 512 km, allowing more room for organized systems to grow. In addition, three new cases (two continental and one oceanic) from the Midlatitude Continental Convective Clouds Experiment (MC3E, conducted in late spring/early summer of 2011 over the southern Great Plains), the Green Ocean Amazon Experiment (GOAmazon, conducted in 2014 and 2015 over the Amazon basin), and DYNAMO (conducted from late 2011 to early 2012 over the equatorial Indian Ocean), respectively, were added to improve sampling. Figure 2 shows results from the new DYNAMO and GOAmazon simulations, which form the basis for the CSH algorithm’s new LUTs. On average, the model responds well to the forcing, be it fewer large events over ocean (e.g., DYNAMO) or more numerous weaker events over land (e.g., GOAmazon). Including the three new cases, a total of 10 cases (six oceanic and four continental), which are listed in Table 2, were simulated to provide data for the new LUTs. The simulations all used the same model domain.

c. New tropical and warm-season LUTs

As with building the CSH TRMM LUTs, the GCE simulations were first divided into subdomains; however, gridded GPM products are being produced at 0.25° resolution, so the new LUTs were built by subdividing the GCE into 32-km subdomains. All other procedures follow the same Tao et al. (2010) method, including the convective–stratiform separation. Figure 3 shows cross sections of LH through the new CSH rainy LUTs corresponding to those for the TRMM LUTs shown in Fig. 1. Overall, the basic heating structures are quite similar; however, there are some notable differences. First, the intensity patterns are much smoother in the new LUTs, especially over land, and they cover a greater range of intensities for both convective and stratiform bins for both ocean and land as a result of the increased sampling from both more cases and larger domains. In terms of lower-tropospheric cooling in the stratiform profiles, although maximum cooling rates now reach higher values for both land and ocean as a result of the expanded coverage to higher rain rates, cooling rates are significantly reduced over land for a given rain intensity. This is a result of the rain evaporation correction in the new 4ICE scheme. The impact over ocean is much less because of the moister environments. Worth noting is that the LUTs have inherent heating biases. Figure 4 shows the bias patterns for the new ocean and land LUTs for rainy areas. Convective portions of the LUT tend to have excess heating relative to their surface rainfall, whereas stratiform regions tend to have a deficit in heating, and the magnitudes generally increase with rain rate. The biases and their signs are perfectly reasonable. Some of the hydrometeors generated as a result of condensation/deposition in the convective region are transported and fall out in the stratiform region, resulting in such a bias pattern. However, as will be shown later, the magnitudes of the biases associated with the weak convective rain rates can lead to an overall imbalance in the heat budget.

With better sampling and based on better GCE microphysics, these new CSH LUTs should be an improvement over the previous versions. However, there are some additional factors worth considering with regards to the construction of the LUTs; the first involves the representativeness of the underlying GCE simulations upon which they are based. Figure 5 shows hit probabilities over land and over ocean with respect to the CSH algorithm’s LUT bins using GPM combined algorithm satellite rainfall estimates from Dual-Frequency Precipitation Radar and GPM Microwave Imager (DPRGMI) data (Grecu et al. 2016; https://pps.gsfc.nasa.gov/Documents/Combined_algorithm_ATBD_V04.rev.pdf) on a 0.25° × 0.25° grid over the global tropics (i.e., the TRMM domain) for the month of April 2014. Although there is evidence of enhanced convective vigor over land due to the increased probability of more intense convective rain, the land and ocean have similar overall probability structures, with higher probabilities aligned with weaker rain intensities (i.e., below 120 mm day⁻¹) that sharply tail off at higher rain rates. The absolute highest probabilities are concentrated in the weakest, most stratiform bins and the weakest, most convective bins. Though similar to the distributions for
FIG. 2. Time–height cross sections of large-scale $Q_1$ forcing imposed into the 2D GCE derived from a variational analysis approach (Zhang and Lin 1997) for the (a) DYNAMO and (b) GOAmazon cases that were added to the CSH GCE ocean and land databases, respectively. (c),(d) The matching time–height cross sections of GCE-simulated $Q_1$ for DYNAMO and GOAmazon, respectively; (e),(f) the corresponding time-average model vs forcing $Q_1$ profiles for each of the two simulation periods.
TRMM (please see Figs. 1a,b in Tao et al. 2010), there is a distinct difference: with its more sensitive radar, GPM is now detecting the large concentration of weak convective rain that TRMM could not (Hamada and Takayabu 2016). Shown immediately below the satellite sampling is the corresponding GCE surface rain rate probabilities from the six ocean and four land simulations used to build the LUTs, respectively. The overall model distribution patterns are fairly similar to the satellite, with the highest probabilities again shifted to the weakest rain rates with sharply decreasing tails of lower probabilities extending to higher rain rates. The model also captures the high concentration of weak stratiform rain, but much like TRMM, it also appears to lack the high concentration of weak convective rain, though there appears to still be a usable sample as shown next. Nonetheless, one positive result from this comparison is that the range of observed rain rate possibilities across all stratiform bins is either closely matched or slightly exceeded by the model and suggests the simulations, from which the LUTs are built, effectively encompass the range of observed rain intensities.

Another important consideration for building the LUTs is the value of incorporating, when available, other observables into the LUTs that may help to further constrain or delineate the cloud heating structures. The current TRMM V7 CSH LUTs do not directly consider the observed echo-top heights; it is only inferred indirectly by using conditional rain rates. Those LUTs do show a coherent, positive relation between rain intensity and depth of heating (e.g., Fig. 1a). However, incorporating echo-top heights directly into the LUTs could provide a stronger, more precise linkage to cloud heating depth. Despite the relative omission of weak, convective rain in the overall model hit probabilities, when stratified by echo-top height coherent patterns emerge, with higher hit probabilities steadily progressing from lower to higher rain rates as echo-top heights increase from shallow (Fig. 5) to deep (not shown), and suggest the simulations can support such a categorization. Though not in the right overall proportion, the simulations do contain shallow clouds.

Another potentially beneficial radar-derivable quantity to consider is the low-level reflectivity gradient. Hirose and Nakamura (2002, 2004) used the difference in rain rates between 3.5 and 2.0 km for their vertical gradient index. To focus on low-level evaporation, the reflectivity gradient between 0 and 2 km will be used instead where subcloud rain evaporation is more likely to occur. Figure 6 shows histograms of the low-level (0–2 km) reflectivity gradients from the 10 new GCE simulations grouped into ocean and land categories as functions of echo-top height and convective and stratiform area; corresponding observed histograms from the DPR Ku-band Precipitation Radar (KuPR) are also included for comparison. There is a general trend whether over land or ocean or for convective or stratiform regions for deeper echoes to shift toward increasing rainfall rates. Besides the relation to their environment, these tendencies can be indicative of storm characteristics and hence have implications for cloud heating and cooling. Stratiform precipitation that falls into a dry environment will experience more low-level evaporation and hence produce more low-level evaporative cooling than it would if it fell into a moister environment. Therefore, using the low-level reflectivity gradient to account for such conditions makes sense, as it can be linked to the evaporation of raindrops. Hirose and Nakamura (2002, 2004) used the difference in rain rates between 3.5 and 2.0 km for their vertical gradient index. To focus on low-level evaporation, the reflectivity gradient between 0 and 2 km will be used instead where subcloud rain evaporation is more likely to occur. Figure 6 shows histograms of the low-level (0–2 km) reflectivity gradients from the 10 new GCE simulations grouped into ocean and land categories as functions of echo-top height and convective and stratiform area; corresponding observed histograms from the DPR Ku-band Precipitation Radar (KuPR) are also included for comparison. There is a general trend whether over land or ocean or for convective or stratiform regions for deeper echoes to shift toward increasing rainfall rates. Besides the relation to their environment, these tendencies can be indicative of storm characteristics and hence have implications for cloud heating and cooling. Stratiform precipitation that falls into a dry environment will experience more low-level evaporation and hence produce more low-level evaporative cooling than it would if it fell into a moister environment. Therefore, using the low-level reflectivity gradient to account for such conditions makes sense, as it can be linked to the evaporation of raindrops. Hirose and Nakamura (2002, 2004) used the difference in rain rates between 3.5 and 2.0 km for their vertical gradient index. To focus on low-level evaporation, the reflectivity gradient between 0 and 2 km will be used instead where subcloud rain evaporation is more likely to occur. Figure 6 shows histograms of the low-level (0–2 km) reflectivity gradients from the 10 new GCE simulations grouped into ocean and land categories as functions of echo-top height and convective and stratiform area; corresponding observed histograms from the DPR Ku-band Precipitation Radar (KuPR) are also included for comparison. There is a general trend whether over land or ocean or for convective or stratiform regions for deeper echoes to shift toward more downward decreasing values, which is in agreement with Hirose and Nakamura (2004). Overall, the simulated histograms have a bias toward downward decreasing values, which is worse for shallower echoes that are not well resolved with a 1-km grid spacing; however, the
Simulated histograms do capture the observed trend for deeper echoes to shift toward downward decreasing values. Despite the biases, Fig. 6 shows that there is a fairly consistent range of gradient values that could be adopted as part of a metric for the LUTs and that the model, for the most part, at least spans the range of observed values. However, the reflectivity gradient metric is initially introduced here with just a simple positive/negative classification with zero gradient values grouped as positive. So, in addition to the convective/stratiform and land/ocean separation, whether or not low-level reflectivities increase or decrease toward the surface may help to distinguish the intensity of low-level evaporative cooling or convective heating. Examples of the new CSH LH LUTs and their associated reflectivity and vertical velocity structures are depicted in Figs. 7–9. Figures 7 and 9 show the corresponding heating structures for the most convective rainy ocean and land bins, respectively, when the new CSH LUTs in Fig. 3 are further differentiated based on the mean, conditional 13-dBZ echo-top heights using 2-km bins (i.e., 0–2, 2–4, 4–6, 6–8, and 8+ km) and whether or not the mean conditional low-level (i.e., 0–2 km) reflectivity gradient increases or decreases toward the surface.2 These new LUTs clearly show that much

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2 The low-level reflectivity gradient is computed by searching downward from 2 km. The first reflectivity of at least 13 dBZ defines the starting dBZ value; the last dBZ of at least 13 dBZ that exists below that level toward the surface is the ending value. This is done for each pixel within a 0.25° × 0.25° box for the satellite and each grid column within a model subdomain (32 km). The individual gradients are then averaged in each satellite grid box/model subdomain, where they exist to get the mean conditional low-level reflectivity gradient.
more detailed information on not only the depth of the heating structures but also the level of maximum heating can be obtained from using the echo-top height information directly, especially for weak to moderate rain rates (≤ 360 mm day$^{-1}$ for ocean and ≤ 300 mm day$^{-1}$ for land) where both the depth and level of peak heating vary substantially. For shallow convection with mean echo tops < 2.0 km, significant heating occurs below ~3.5 km over ocean and ~3 km over land and is capped by cooling for both. This differs substantially from the corresponding profiles for the composite LUTs in Fig. 3, which showed heating extending to at least 6 km over ocean and 10 km over land, even at the weakest rain rates, which contributes to the excessive LUT biases shown in Fig. 4. And even at more moderate rain intensities (~360 to 480 mm day$^{-1}$ for ocean), the level of peak heating varies by about 2 km between the two highest echo-top height bins. The correlation between the level of maximum heating, peak convective heating intensity, and especially the depth of heating with echo-top heights evident in these LUTs supports using echo-top height information directly in the CSH LUTs.

The impact of separating the LUTs by their low-level reflectivity gradient can be seen in both the convective and stratiform bins. Figure 10 shows rainy LUT profiles for the deepest, most stratiform bins over land and over ocean for gradients with both increasing and decreasing low-level reflectivity toward the surface (Fig. 11). As might be expected, profiles with decreasing dBZs (Figs. 11c,d), on average, exhibit noticeably stronger cooling signatures; this relation is more coherent over ocean in part because of better sampling. Coincident with the stronger cooling is more and stronger heating aloft. This suggests gradients with decreasing reflectivity may be associated with stronger cold pools and more organized convection. This is also somewhat supported by the differences in the convective profiles. For the deepest convective profiles, heating rates are consistently more intense across all rain rates over ocean and for rain rates up to ~360 mm day$^{-1}$ over land when dBZs decrease at low levels. For medium-shallow and medium echo tops over ocean, heating profiles for decreasing dBZs tend to be more intense but also shallower, with peak heating levels slightly lower down. These differences could also be reflecting differences in convective age, with younger convection more likely to be more compact and more intense with more active updrafts carrying hydrometeors aloft. In their study of vertical rain rate gradients, Hirose and Nakamura (2004) noted that elevated cores due to strong updrafts or initial precipitation formation could lead to downward decreasing rainfall rates (i.e., reflectivities that decrease toward the surface). Figure 8 shows the conditional in-cloud vertical velocities and conditional (>13 dBZ) simulated radar echoes corresponding to the convective LUTs for echo-top ranges 2–4 and 4–6 km over ocean (Fig. 7). Over ocean, for weaker rain rates (i.e., < ~120 mm day$^{-1}$), Fig. 8 does show stronger updrafts on average in association with elevated echoes (i.e., decreasing dBZs toward the surface). At higher rain rates, updrafts tend to be stronger and more elevated for increasing dBZs toward the surface, which
FIG. 5. Surface rain hit probabilities (integrated values for each panel = 100%) with respect to the CSH LUT bins (a),(c),(e),(g) over ocean and (b),(d),(f),(h) over land based upon (a),(b) 1 month (April 2014) of GPM-combined algorithm surface rainfall data, and upon simulated surface rainfall data from the 10 cases (four land, six ocean) simulated using the 2D GCE with 512 1-km horizontal grids for (c),(d) all echo-top ranges, (e),(f) conditional GCE (32 km) subdomain–simulated echo tops (13 dBZ) ranging from 2.0 to 4.0 km, and (g),(h) conditional GCE subdomain–simulated echo tops less than 2.0 km.
FIG. 6. Histograms of the low-level (0–2 km) reflectivity gradient in dBZ km⁻¹ for the 10 2D GCE simulations (dashed lines) used to construct the new CSH LUTs as well as observed values from the GPM DPR (solid lines). Distributions are composited into (a),(c),(e) ocean and (b),(d),(f) land cases and calculated from (a),(b) the entire CSH LUT domain space, (c),(d) the most convective LUT bins (i.e., stratiform percentages <5%), and (e),(f) the most stratiform LUT bins (i.e., stratiform percentages >95%). Each gradient represents the mean conditional value over either the GCE (32 km) model subdomains or a given 0.25° × 0.25° DPR grid. The gradients are further separated into the five storm-top-height bins shown in each panel using the mean corresponding GCE model subdomain conditional storm-top height (13 dBZ echo tops). Positive gradients represent increasing dBZ values toward the surface and negative gradients represent decreasing dBZ values toward the surface.
FIG. 7. New CSH LH LUTs constructed from GCE subdomains (32 km) having surface rain over ocean for the most convective bins (stratiform percentages <5%) and derived from the same oceanic GCE model simulations used in Fig. 3 but differentiated by both the mean low-level (0–2 km) conditional reflectivity gradient [(a),(c),(e),(g) increasing toward the surface or (b),(d),(f),(h) decreasing toward the surface] and the mean conditional echo-top (13 dBZ) heights [(g),(h) less than 2.0 km, (e),(f) 2.0 to 4.0 km, (c),(d) 4.0 to 6.0 km, and (a),(b) above 8.0 km]. Confidence intervals for a two-tailed t test between the positive and negative dBZ-gradient LH populations for each echo-top range are shown by the thick (75%) and thin (50%) dashed lines.
Fig. 8. Mean in-cloud (total hydrometeors $>0.1 \text{ g kg}^{-1}$ or dBZ $>13$) (a),(b) vertical velocities and (c),(d) conditional radar echoes (dBZ $>13$) corresponding to the new CSH LH LUTs shown in Fig. 7 for mean conditional echo-top heights ranging from 2.0 to 4.0 km. (e),(f) and (g),(h) are the same as (a),(b) and (c),(d) except for conditional echo-top heights ranging from 4 to 6 km. Left and right panels are for low-level (0–2 km) echo values increasing and decreasing toward the surface, respectively.
FIG. 9. As in Fig. 7, but over land regions using the same continental GCE simulations used in Fig. 3.
would be generally consistent with convection later in its life cycle (i.e., updrafts continuing upward while precipitation settles downward). Over land (not shown), the relationship is generally similar but not as coherent, possibly due to the smaller sample. At any rate, although these relationships require further study, separating the LUTs according to increasing or decreasing low-level reflectivities appears to provide additional information on the character of convective heating intensity, whether due perhaps to age or organization, and on stratiform cooling intensity due to dry/moist environments and consequently stratiform heating possibly by way of greater convective organization due to enhanced cold pool dynamics.

Last, when building the LUTs, a small amount of heating/moistening occurs in model subdomains that are neither raining nor adjacent to rain. This heating/moistening, though quite small (peak heating of ~0.02°C h⁻¹ at most levels), contributes significantly to the overall positive heating bias of CSH TRMM retrievals when applied over a large area (see Table 3 for specific values). So, for the GPM retrievals, this residual “far from rain” heating/moistening is only applied up to two grids away from rainy grids (i.e., next to the “near rain” grids).

### 3. Results

#### a. Large-scale features versus TRMM

Figure 12 shows the mean surface rainfall from the combined algorithm for the same 3-month period of...
1 April–30 June 2014 for TRMM (i.e., 2B31, bottom panel) and for GPM (i.e., DPRGMI, top panel) over the TRMM domain (i.e., 37°N to 37°S). The rainfall is gridded onto a 0.5° × 0.5° grid for both TRMM and GPM for ease of comparison, though the official grid resolutions for TRMM and GPM gridded products are 0.5° × 0.5° and 0.25° × 0.25°, respectively, including gridded CSH heating products (3G31). Prominent rainfall features commonly observed within the tropics in association with the ITCZ, the SPCZ, the Maritime Continent, and midlatitude storm tracks over and downwind of the continents are similar for both. Rain rates within the ITCZ appear similar but GPM has higher rates over subtropical oceans, which is consistent with its ability to detect lighter rain rates. Rain rates over land are generally more intense for GPM. The TRMM average surface rain rate over the entire domain and 3-month period is 2.8 mm day⁻¹, whereas for GPM, it is 3.3 mm day⁻¹; the increase is greater over land, but there is an increase over ocean (see Table 3). In terms of the rainfall characteristics, TRMM appears to have more moderate values (i.e., 4 to 6 mm day⁻¹, shown in green in Fig. 12), which could be due to its greater sampling in the tropics. Figure 13 shows the corresponding stratiform proportion of the surface rainfall for both TRMM and GPM as well as the GPM mean echo-top heights. Overall

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4 This period was selected because it occurs during the time when TRMM and GPM were both operating in orbit simultaneously and because this period has been used previously to make comparisons between various versions of the CSH and SLH algorithms for the PMM science team.

5 For GPM, this study uses V04 of the combined algorithm (Grecu et al. 2016); rainfall amounts over land are reduced significantly in the more recently released V05 because of changes in the nonuniform beam filling assumptions.
the stratiform patterns are rather similar, with stratiform fractions averaging around 50% within the ITCZ, with lower values outside the ITCZ and higher values farther poleward within the midlatitude storm tracks. GPM, however, shows higher convective fractions within the SPCZ east of the date line, the south Indian Ocean, and below 25°N in the northern Pacific west of the date line. These areas are associated with regions of mean echo tops that are predominantly less than 4 km, which is consistent with GPM detecting more shallow convective rain. Though the rain rates in these areas are not heavy, they do cover substantial areas. Some of the differences in the stratiform fraction could also be due to the different separation algorithms used between TRMM (Awaka et al. 1997, 2009) and GPM (Le and Chandrasekar 2013; Iguchi et al. 2015; Awaka et al. 2016).

Figures 14, 15, and 16 show the mean diabatic heating rates \( \left( Q_1 - Q_r \right) \) over the TRMM domain during this same 3-month period retrieved from the CSH algorithm at 2, 4, and 7 km, respectively. The lower panels show TRMM CSH–retrieved heating, the middle panels show GPM CSH–retrieved heating using the new LUTs, and the top panels show GPM CSH–retrieved heating using the new LUTs binned according to echo-top height and low-level reflectivity gradient. Immediately evident is the large increase in shallow heating in both GPM retrievals over TRMM at low levels. At 2 km (Fig. 14), there is both much more intense heating within the hot spots already apparent in TRMM (e.g., the ITCZ, SPCZ, and equatorial Indian Ocean) as well as an intensification and expansion of shallow heating outside of these regions into the subtropics. This is tied to the increased detection of shallow, mostly convective rain.

Both the composite and the split echo-top versions of the new LUTs show similar robust heating patterns at the 2-km level though the composite is somewhat stronger. At midlevels (e.g., 4 km, Fig. 15), heating is more intense within the ITCZ and over land in the GPM retrievals, especially for the composite LUTs. However, outside of these areas, the CSH GPM retrievals with the composite LUTs continue to show more expansive, robust areas of heating in the subtropics, though not quite to the same degree as at 2 km, whereas the GPM retrievals using the split echo-top LUTs show much less heating in these areas, even less than the TRMM retrievals. In these areas with shallower echo tops, much of the midlevel heating in the composite LUTs is either eliminated or replaced with weak cooling for rain rates less than 120 mm day\(^{-1}\) in the split echo-top LUTs. At upper levels (e.g., 7 km, Fig. 16), the heating patterns and mean intensities are fairly similar between the GPM and TRMM retrievals with strong areas of heating over equatorial Africa, northern South America, the Maritime Continent, and within a sharp, well-defined ITCZ extending across the central and east Pacific. Other areas of prominent heating in the equatorial Atlantic, the SPCZ, and the equatorial Indian Ocean are also similar in shape and magnitude when allowing for differences in sampling (i.e., TRMM appears smoother).

b. Heat balance and error estimation

Without direct measurements of cloud heating, it can be difficult to validate the heating retrievals. Retrievals can be compared against heating budgets derived from intensive sounding networks associated with field campaigns, but these tend to be sporadic and there can be issues with sufficient satellite sampling within the sounding array. In the past, self-consistency checks have also been used, but there is also another option to consider. Yanai et al. (1973) recognized that the column-integrated apparent heating over an area sufficient for a

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### Table 3. Observed (input) rain in bold vs equivalent rain (erain; integrated column heating) for the TRMM and GPM retrievals and their corresponding biases (%) over the global tropics (i.e., the TRMM domain), ocean, and land areas. 3G31mod shows TRMM CSH values when “far from rain” background heating is applied only up to two grids away from rain. LH indicates column-integrated LH only.

<table>
<thead>
<tr>
<th></th>
<th>Tropics (mm day(^{-1}))</th>
<th>Ocean (mm day(^{-1}))</th>
<th>Land (mm day(^{-1}))</th>
<th>Total bias (%)</th>
<th>Ocean bias (%)</th>
<th>Land bias (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRMM rain</td>
<td>2.81</td>
<td>2.83</td>
<td>2.76</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>3G31 LH erain</td>
<td>3.14</td>
<td>2.90</td>
<td>3.64</td>
<td>11.7%</td>
<td>2.5%</td>
<td>31.9%</td>
</tr>
<tr>
<td>3G31 erain</td>
<td>3.62</td>
<td>3.38</td>
<td>4.14</td>
<td>28.8%</td>
<td>19.4%</td>
<td>50.0%</td>
</tr>
<tr>
<td>3G31mod erain</td>
<td>3.18</td>
<td>2.88</td>
<td>3.65</td>
<td>13.2%</td>
<td>1.6%</td>
<td>32.1%</td>
</tr>
<tr>
<td>GPM rain</td>
<td><strong>3.26</strong></td>
<td><strong>3.08</strong></td>
<td><strong>3.67</strong></td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>3GCSH LH erain</td>
<td>4.11</td>
<td>3.99</td>
<td>4.39</td>
<td>26.1%</td>
<td>29.5%</td>
<td>19.6%</td>
</tr>
<tr>
<td>3GCSHeg LH erain</td>
<td>3.40</td>
<td>3.09</td>
<td>4.06</td>
<td>4.3%</td>
<td>0.3%</td>
<td>10.6%</td>
</tr>
<tr>
<td>3GCSH erain</td>
<td>4.56</td>
<td>4.52</td>
<td>4.64</td>
<td>39.9%</td>
<td>47.2%</td>
<td>26.4%</td>
</tr>
<tr>
<td>3GCSHeg erain</td>
<td>3.72</td>
<td>3.43</td>
<td>4.35</td>
<td>14.1%</td>
<td>11.4%</td>
<td>18.5%</td>
</tr>
</tbody>
</table>

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\(^{6}\)Since the GCE upon which the CSH LUTs are based does not have terrain, retrievals in areas of high or steep terrain should be neglected.
cloud ensemble minus the radiation effects is balanced by the net surface precipitation and the net surface heat fluxes as follows:

\[
\frac{1}{g} \int_{L_{x}} \int_{L_{y}} \left( (Q_{1} - Q_{R}) \Delta p \Delta x \Delta y \right) = LP_{o} + S_{o},
\]

where \( Q_{1} \) is the apparent heat source, \( Q_{R} \) is the radiative heating rate, \( P_{o} \) is the surface precipitation rate, \( S_{o} \) is the surface heat flux, \( g \) is gravity, and \( L \) is the latent heat of condensation. The retrieved heating can therefore be vertically integrated\(^7\) to produce an equivalent surface rain rate, which can then be compared against the observed (input) surface rain rate to check for biases. Furthermore, if the surface fluxes are neglected, integrated LH can be compared directly against the surface rain rate alone. Figure 17 shows the net difference in integrated LH minus the observed (input) surface rain rate from the combined algorithm over the global tropics for the TRMM and GPM retrievals over the same three-month period of 1 April to 30 June 2014. The differences are smoothed to eliminate local imbalances, which are reasonable, and allows for a better assessment of the overall heating balance regionally. A consistent pattern emerges for all of the retrievals with broad areas of surplus heating occurring over ocean in the weaker rain rate regimes poleward of the ITCZ and heating deficits occurring primarily over ocean at even higher latitudes along the edges of the midlatitude storm tracks. These areas are dominated by convective and stratiform rain, respectively (Fig. 13), which is consistent with the imbalance in heating versus rainfall for these two regions in convective systems (Fig. 4), as some of the condensate generated in the convective region, which produces heating there, falls out as precipitation in the stratiform region. All three sets of retrievals have deficit heating in the midlatitude storm tracks due to applying MCS-type stratiform heating/cooling profiles there, whereas these stratiform areas are mainly frontal and will require a new type of algorithm (see Houze et al. 2015). Despite their common large-scale patterns, the differences between the GPM and TRMM retrievals and the two GPM retrievals themselves are quite significant. For the GPM retrievals using the new composite LUTs, relative to TRMM, the excess heating over tropical oceans outside of the ITCZ over the subtropical

\(^{7}\) A density profile is required, which was taken from the KWAJEX data.

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FIG. 12. Mean surface rainfall rates over the global tropics (i.e., the TRMM domain) for the 3-month period of 1 April to 30 June 2014 from the (top) GPM combined algorithm (DPRGMI) and the (bottom) TRMM combined algorithm (2B31). Black boxes here and in Fig. 13 show the analysis regions presented in Fig. 19.
Pacific in both hemispheres, including the SPCZ, as well as the south Indian Ocean and South Atlantic, is much stronger, and areas of near balance or even deficit heating for TRMM within the ITCZ and the central and eastern Indian Ocean are now replaced with surplus heating. These differences can be attributed to a large overall increase in heating due again to the increased detection of mostly weak, shallow, convective rain by GPM (Figs. 12 and 13) and the corresponding deep but surplus heating in the new CSH composite LUTs (Figs. 3 and 4). The only areas of improvement are over land where there is some contraction of the surplus heating over equatorial Africa, northern India, and parts of South America, but these are minor relative to the worsening biases over ocean. In contrast, there is a substantial reduction in the amount of excess heating in the retrievals using the LUTs differentiated by echo-top and low-level dBZ gradient. The broad areas of excess oceanic heating outside of the ITCZ are greatly reduced even relative to TRMM. Figure 17 reveals that the TRMM retrievals are near balance on average over eastern parts of the Indian Ocean and southwestern Pacific, but that localized areas of negative heating bias are not nearly enough to balance the more substantial

![Mean DPRGMI Stratiform Percent (%)](image1)

![Mean 2B31 Stratiform Percentage (%)](image2)

![Mean DPRGMI Echo Top Heights (km)](image3)

**FIG. 13.** Mean stratiform percentage of surface rainfall over the global tropics (i.e., the TRMM domain) for the 3-month period of 1 April to 30 June 2014 from the (top) GPM combined algorithm (DPRGMI) and the (middle) TRMM combined algorithm (2B31). (bottom) Mean echo-top heights (13 dBZ) from the GPM DPR for the same period.
areas of positive heating bias over much of South America and central Africa. In sharp contrast to the composite LUTs, the biases for the GPM retrievals using the differentiated LUTs are vastly superior and markedly better than those for TRMM. While there is still surplus heating mainly over the subtropical Pacific (notably the SPCZ), the Maritime Continent, and part of equatorial Africa, the overall magnitude of the biases in these regions is greatly reduced such that outside of the SPCZ and midlatitude storm tracks, nearly the entire Pacific and Atlantic basins are close to balance. Biases over the Indian Ocean are also quite good relative to the others. These split echo-top retrievals also have the smallest biases over land; outside of Southeast Asia, part of equatorial Africa, and small, localized regions in Central and South America, they are in near balance over most land areas. In terms of LH, the split echo-top retrievals are largely in balance almost everywhere; they are far better balanced than the composite retrievals and much more so than TRMM.

Overall, all three sets of CSH retrievals result in a positive heating bias, but the bias varies considerably (Table 3). Again, neglecting surface fluxes allows for a much more direct assessment of LH versus surface rainfall. On average, the TRMM retrievals have the equivalent of 0.33 mm day$^{-1}$ of excess integrated LH over the input surface rainfall for a net bias of +11.7%. For the composite GPM retrievals, the mean excess

![Image of diabatic heating rates](image_url)

**FIG. 14.** Mean diabatic heating rates ($\bar{Q} - \bar{Q}_r$) at 2 km AGL for the 3-month period of 1 April to 30 June 2014 retrieved from the CSH algorithm using rainfall data from the (top) combined algorithm for GPM with new CSH LUTs differentiated by echo-top height and low-level (0–2 km) reflectivity gradient, (middle) GPM with new CSH LUTs, and (bottom) TRMM with the current V7 CSH LUTs.
heating is 0.85 mm day$^{-1}$ for a bias of +29.5%. This bias is reduced to less than 0.14 mm day$^{-1}$ when the split echo-top LUTs are used for an overall bias of +4.3%. If Eq. (1) is used to evaluate the retrievals, then on average, the TRMM retrievals have the equivalent of 0.8 mm day$^{-1}$ of excess integrated heating over the input surface rainfall for a net bias of +28.8%, the composite GPM retrievals have a mean excess heating of 1.3 mm day$^{-1}$ for a bias of +39.9%, and the split echo-top retrievals have a bias of 0.5 mm day$^{-1}$ for an overall bias of +14.1%. However, the surface sensible heat fluxes must be accounted for, which complicates the evaluation. Mean surface sensible heat fluxes over the tropical oceans have been estimated at roughly 10 to 15 W m$^{-2}$ (Weare et al. 1981). This is equivalent to approximately 0.5 mm day$^{-1}$ of surface rainfall. Subtracting this amount from the CSH retrievals lowers the excess equivalent rainfall to −0.3, 0.8, and 0.0 mm day$^{-1}$ for a bias of −10.7%, +24.5%, and 0.0% for the TRMM, composite GPM, and GPM retrievals using the split echo-top LUTs, respectively. In addition to having the lowest overall bias, the split echo-top retrievals also have the lowest biases over ocean and over land (Table 3). Table 3 also shows the effects of removing the background heating from the TRMM retrievals from areas farther than two grids from rain, as was adopted for the GPM retrievals. This reduces the overall TRMM bias to just 13.2%, putting it on par with the split echo-top LUT results. Allowing for surface fluxes would result in a low bias of −4.6%.

c. Zonal averages and mean profiles

In addition to the horizontal heating patterns shown by the latitude–longitude cross sections in Figs. 14–17,
Zonal-average vertical cross sections can be used to reveal details of the mean vertical heating structures in the tropics and subtropics. Figure 18 shows mean zonal diabatic heating as a function of height and latitude for the three CSH retrievals over the same 3-month period. All three retrievals have a closely matching deep heating signature with strong, elevated heating associated with the ITCZ just north of the equator with a smaller secondary elevated peak just south of the equator. In general, the upper-level patterns are quite similar for all three retrievals in the deep tropics. This is a reflection not only of TRMM’s ability to adequately detect and resolve deep convection and its coincident areas of deep stratiform rain, but also the relatively small differences in the basic heating structure of the CSH algorithm’s LUTs for deep, strong convection or deep stratiform rain. The biggest differences are at low to midlevels and in the subtropics. At lower levels, as already shown in Fig. 14, there is much more heating in the GPM retrievals than in the TRMM, the vast majority of which arises over ocean. This is consistent with GPM’s ability to detect more, shallow, mostly convective rain mainly over ocean. This results in an extension of the deep heating cell just north of the equator to lower levels, the elimination of shallow cooling below this cell near the surface, a substantial increase in low-level heating just outside of the deep tropics in the Southern Hemisphere as well as in the Northern Hemisphere for the composite LUTs, and an elimination of the TRMM zonal-average deep cooling.

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8 Below ~1 km, the TRMM retrievals have more heating, but this is due to a stronger vertical eddy component, not LH.
signatures between \( \sim 1 \) and \( 6 \) km in the subtropics nearer to midlatitudes, which are associated with the higher stratiform rain fractions in the midlatitude storm tracks and probably not realistic because of the application of classical MCS-type deep-stratiform upper-level heating/lower-level cooling profiles to frontal rain. In terms of the two GPM retrievals, there are significant differences between the composite LUTs and the LUTs partitioned by echo-top height and low-level reflectivity gradient. First, in the deep tropics, for the split echo-top LUTs, the main heating cell just north of the equator has a weaker peak intensity but at a higher level (\( \sim 7 \) vs \( \sim 6 \) km), making it slightly more top heavy and closer to the TRMM structure. Excess heating at midlevels is the most likely reason for the lower maximum in the composite LUT GPM retrievals. In the subtropics, using the split echo-top-height LUTs reduces the magnitude and height of the elevated heating maximum in the Southern Hemisphere between \( \sim 35^\circ \) and \( 25^\circ \) S, which is due predominantly to areas of deep convection over the SPCZ, the southern Atlantic, and South America (Fig. 16). By incorporating echo tops, the split echo-top retrievals should provide more precise heating depths, and with the better heat balance, more accurate magnitudes. In contrast, there is less difference in the corresponding elevated heating maximum in the Northern Hemisphere between \( \sim 25^\circ \) and \( 35^\circ \) N, which is due mainly to strong heating aloft over the Southeast Asian

**FIG. 17.** Mean retrieved heating rate bias obtained by differencing the mean surface rainfall rate from the combined algorithm from the mean column-integrated CSH latent heating rates for the 3-month period of 1 April to 30 June 2014 for (top) GPM with new CSH LUTs differentiated by echo-top height and low-level reflectivity gradient, (middle) GPM with new CSH LUTs, and (bottom) TRMM with V7 CSH LUTs. The differences have been horizontally smoothed to show region biases.
landmass (Fig. 16). However, the biggest difference by far between the two CSH GPM retrievals is at midlevels where the composite LUTs produce significantly more heating from ~3 to 5 km in the Southern Hemisphere and substantially more heating from ~2 to 6 km in the Northern Hemisphere, including within the deep ITCZ heating cell just north of the equator. This is a direct result of assigning the deeper heating profiles in the convective bins of the composite rainy LUTs to the more abundant areas of shallow convection detected by GPM over ocean versus the shallower heating profiles in the split echo-top LUTs. The bias in the convective LUTs (Fig. 4) is much larger than for the shallower convective bins for the same rain intensity in the split echo-top LUTs. The bias in the convective LUTs (Fig. 4) is much larger than for the shallower convective bins for the same rain intensity in the split echo-top LUTs (not shown) as reflected by the poor heat balance (Fig. 17) using the composite LUTs. This poorer overall heat balance combined with the more precise estimates of heating depth afforded by the split echo-top LUTs suggests that the abundant midlevel heating in the composite LUT retrievals is unrealistic.

In terms of the mean heating profiles for the entire global tropics (i.e., the TRMM domain), Fig. 19 shows a strongly top-heavy heating profile for the TRMM retrievals with peak heating located at around 8 km. The GPM profile from the composite LUTs, in contrast, has much more low- to midlevel warming (~2 to 6 km) as a result of the increased detection of weak, convective rain coupled with its deeper shallow convective heating, which broadens and shifts the peak heating toward midlevels (~5 to 6 km). Separating the new LUTs by echo-top and low-level gradient, however, greatly reduces midlevel heating from ~2 to 5 km such that the GPM profile from the split echo-top LUTs remains top heavy like TRMM but with peak heating around 6 to 7 km, and midlevel heating is much closer to the TRMM profile except for a marked increase in low-level heating near 2 km. This makes more sense as GPM detects more shallow, mostly convective, clouds, which should improve the detection of shallow heating. The excessive heating bias associated with the composite GPM retrievals suggests that the increased midlevel heating is too strong. Above ~6 km the two GPM profiles are quite similar while the TRMM profile is slightly stronger between ~8 and 9 km. Overall, the GPM profile for the
Fig. 19. Mean diabatic heating profiles \(Q_1-Q_r\) for the (a) entire global tropics (i.e., the TRMM domain), (b) tropical ocean regions, (c) tropical land regions, and (d) the South American, (e) Indian Ocean, (f) western Pacific, (g) central Pacific, and (h) central Atlantic regions for the 3-month period of 1 April to 30 June 2014 retrieved from the CSH algorithm using rainfall data from the combined algorithm for GPM with new CSH LUTs differentiated by echo-top height and low-level reflectivity gradient (GPMeg), for GPM with new CSH LUTs (GPM), and for TRMM with V7 CSH LUTs (TRMM). The column-integrated LH minus the surface rate biases are shown for each region in the lower-left part of each panel. The five regions in (d)–(h) are shown by the black boxes overlaid on the GPM rain, stratiform fraction, and mean echo-top height panels in Figs. 12 and 13.
split echo-top LUTs is closer in shape and magnitude to the TRMM profile than to the other GPM profile, except at low levels because of the increased detection of shallow convective rain. Mean tropical ocean profiles show TRMM is still top heavy, with a single elevated peak near 9 km. The two GPM profiles are more bottom heavy and have similar overall shapes, but the composite LUTs result in consistently more heating from ~2 to 10 km, which, as evidenced by the lack of heat balance, is excessive. Over land, all three CSH retrievals produce the same characteristic strong top-heavy-shaped profiles with a single dominant peak at around ~6 to 7 km. The two GPM retrievals are more consistent with each other and have more heating between ~2 and 5 km than the TRMM retrievals. Over land, even the composite LUTs have a better heat balance than TRMM, which could be due to the inclusion of the rain evaporation correction in the new Goddard 4ICE scheme.

Figure 19 also shows the mean heating profiles for five specific regions (Figs. 19d–h) similar to those shown in Tao et al. (2001). Mean profiles over South America (Fig. 19d) are very similar to those over land for the whole tropics, only somewhat stronger because of the heavier rain rates there. Over the Indian Ocean (Fig. 19e), the composite GPM retrievals have much more low- and midlevel heating than TRMM, resulting in a strong, bottom-heavy rather than top-heavy profile. The split echo-top retrievals have much less midlevel heating than the composite and are only slightly more bottom heavy than the TRMM. These results are generally consistent with the overall mean oceanic profiles (Fig. 19b). Heating profiles over the western Pacific are stronger and more top heavy because of higher rain rates and stratiform fraction (Figs. 12 and 13) but the relative trend between the three retrievals is the same. Similar relative relationships amongst the three retrievals persist over the central Pacific and central Atlantic, with the central Pacific being more bottom heavy overall because of the lower stratiform fractions and shallower echo tops (Fig. 13) that are included south of the ITCZ.

Overall, the much better heat balance coupled with the advantage of being able to estimate the depth of heating more accurately, combined with GPM’s ability to better detect shallow convective rain, suggests that the 3GCSHeg retrievals (i.e., those based on GPM that incorporate echo-top heights and low-level dBZ gradients) provide the most accurate depiction of cloud heating in the tropics and subtropics of the three and provide a much better estimate of shallow heating.

4. Summary and future work

The Goddard convective–stratiform heating (CSH) algorithm (Tao et al. 2010) has been newly updated in support of NASA’s GPM mission. Both the GCE CRM simulations from which the algorithm’s LUTs of cloud heating and moistening components are derived as well as the metrics used to categorize, index, and access the LUTs have been revised. First, the original database of multiweek GCE CRM simulations used to construct the algorithm LUTs was expanded and replaced with an improved series of new GCE simulations using additional cases and the new, improved Goddard four-class ice scheme with larger 2D horizontal domains (512 vs 256 km). New, multiweek, land simulations from the MC3E and GOAmazon field campaigns were added to increase sampling and fortify the algorithm’s land LUTs, while additional case days from TWP-ICE along with a new, multiweek DYNAMO simulation were incorporated into the algorithm’s ocean LUTs. Second, the algorithm’s LUTs, which are binned by conditional surface rain intensity, stratiform fraction, and surface type, were further differentiated according to echo-top height and low-level (0–2 km) reflectivity gradients. Starting with the same new GCE database, the original and new methods for constructing the CSH LUTs were then evaluated against each other using inputs from the GPM combined algorithm as well as against TRMM CSH V7 retrievals for the 3-month period of April through June 2014 when both TRMM and GPM overlapped.

The basic heating structures for the new CSH LUTs based on the new GCE simulation database are very similar to the previous TRMM V7 CSH LUTs using the same LUT constructs. Notable differences include more coherent, smoother features and an increased range in the LUTs’ intensities due to the increased sampling, larger GCE domains, and finer GPM grids, as well as a reduction in the low-level stratiform cooling over land due to the inclusion of a rain evaporation correction in the new Goddard 4ICE scheme. In contrast, new LUTs further differentiated by mean conditional echo-top heights, using bins of 0–2, 2–4, 4–6, 6–8, and above 8 km, and by increasing or decreasing mean conditional low-level (0–2 km) reflectivities toward the surface, elicit much more variation and detail in the heating profiles. In addition to the depth of the heating structures, the level of maximum heating might be obtained more precisely from using the echo-top height information directly. And, differences in the low-level reflectivity gradient are not only manifest in the amount of lower-level cooling in deep stratiform profiles where decreasing values have more cooling as might be expected, but also in the depth and intensity of convective heating, especially for weak to moderate rain intensity bins. Given sufficient sampling, the number of gradient bins could be expanded to perhaps better define the intensity of low-level stratiform cooling, for example. These relationships, however, require further study to
really prove and more definitively link convective morphology and organization with reflectivity and heating structures.

The enhanced detection of shallow, weak, mostly convective rain by GPM leads to the retrieval of much more low-level heating, mainly over ocean but also over land both within and outside the ITCZ, versus TRMM for both the composite and split echo-top CSH LUTs. At midlevels, heating is enhanced in both GPM retrievals within the ITCZ and over land but more so with the composite LUTs, which, based on their poor heat balance, is unrealistic. In the subtropics, the split echo-top LUTs have far less midlevel heating than the composite, and are comparable to the TRMM values despite GPM’s increased detection of shallow convective rain. At upper levels, the heating structures are rather similar for all three sets of retrievals. Zonal averages reveal significant differences in the main ITCZ heating cell north of the equator. Split echo-top LUTs yield a top-heavy cell with peak heating at ~7 km, similar in magnitude and shape to that for TRMM, whereas the composite LUTs have a more bottom-heavy cell with stronger peak heating located lower near ~6 km and is a result of the excessive midlevel heating. Both GPM retrievals extend and intensify the heating within the ITCZ cell to lower levels. At higher latitudes, net cooling below ~6 km associated with the midlatitude storm tracks is eliminated in the two GPM retrievals.

Vertically integrated latent and diabatic heating amounts are compared against the observed input surface rainfall from the combined algorithm to identify heating biases in the retrievals. All three sets of retrievals have a similar bias pattern of surplus heating over ocean in the subtropics, deficit heating within the midlatitude storm tracks, surplus heating over land, and better balance within the ITCZ, but the magnitudes of these biases vary widely. On average, the TRMM LH retrievals have a net heating bias of +11.7%, the composite GPM retrievals have a bias of +26.1%, and the GPM retrievals using LUTs differentiated by echo-top and low-level dBZ gradient have a bias of just +4.3%. Spatially, the split echo-top LUTs lead to column-integrated LH rates that are largely in balance with surface rainfall over the tropics and subtropics and in much better balance in nearly all regions with the exception of the Maritime Continent, the westernmost SPCZ, and part of equatorial Africa where surplus heating is comparable to the others. Trimming the background heating in the TRMM retrievals as adopted in the GPM retrievals reduces the overall TRMM diabatic heating bias to 13.2%, on par with the split echo-top LUT results, allowing for surface fluxes that would result in a low bias of –4.6%.

Mean heating profiles over the global tropics (i.e., TRMM domain) for GPM using the split echo-top LUTs and TRMM using the V7 LUTs are both top heavy and quite similar overall, except for enhanced low-level heating for GPM due to the better detection of shallow convection. The composite LUTs result in a more bottom-heavy profile, even relative to the other GPM profile, with much more midlevel heating, which is most certainly excessive. Over ocean, the TRMM profile is still top heavy, while the two GPM profiles are more bottom heavy, with similar overall shapes though the composite LUTs result in consistently more but excess heating from ~2 to 10 km. Over land, all three CSH retrievals produce strong top-heavy-shaped profiles with a single dominant peak at around ~6 to 7 km but with the two GPM retrievals having more heating from ~2 to 5 km than TRMM. It should be noted that in addition to the enhanced detection of lighter rain rates, some of the differences between the TRMM and GPM results could be due to differences in the separation techniques as well as differences in sampling over the tropics between the two satellites.

Overall, the results suggest eliminating the residual background heating in areas more than two grids distant from rain and adopting the LUTs based on the new 4ICE GCE database further differentiated by mean echo-top height and low-level reflectivity gradient for the CSH algorithm in support of GPM. Overall, the much better heat balance coupled with the advantage of being able to estimate the depth of heating more accurately, combined with GPM’s ability to better detect shallow convective rain, suggests that the 3GCSHeg retrievals provide the most accurate depiction of cloud heating in the tropics and subtropics of the three and provide a much better estimate of shallow heating. Despite the potential of the newly revised CSH algorithm, there are still several key issues to be addressed. First, even though the new GCE database from which the CSH LUTs are derived contains several improvements, including more cases, better sampling, larger domains, and improved microphysics having more realistic rain rate distributions, cloud structures, and a rain evaporation correction, the simulations were still 2D with a 1-km horizontal resolution. Further testing with 3D or larger domains at finer resolutions is required to allow for improved updraft dynamics and even larger cloud systems and circulations, and to better resolve smaller-scale clouds such as congestus. Inconsistencies in the convective–stratiform separation methods between TRMM, GPM, and the GCE must also be resolved. Additional validation as well as comprehensive comparisons with other cloud heating algorithms such as the spectral latent heating (SLH) algorithm is needed. Last, this study
has addressed the improvement of the CSH algorithm for tropical and warm-season conditions suitable for the TRMM domain, areas that remain a critical part of GPM. However, GPM’s expanded coverage to middle and higher latitudes requires the commensurate expansion of the CSH algorithm and its LUTs in order to address the midlatitude synoptic frontal systems and cold-season snow events common in those regions. This expansion to higher latitudes is being addressed in a separate study.

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