Building Blocks of Tropical Diabatic Heating

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ABSTRACT

Rotated EOF analyses are used to study the composition and variability of large-scale tropical diabatic heating profiles estimated from eight field campaigns. The results show that the profiles are composed of a pair of building blocks. These are the stratiform heating with peak heating near 400 hPa and a cooling peak near 700 hPa and the convective heating with a heating maximum near 700 hPa. Variations in the contributions of these building blocks account for the evolution of the large-scale heating profile. Instantaneous top-heavy (bottom-heavy) large-scale heating profiles associated with excess of stratiform (convective) heating evolve toward a stationary mean profile due to exponential decay of the excess stratiform (convective) heating.

1. Introduction

Evaporation, transport, and condensation of water are critical processes through which the general circulation redistributes energy globally. Specifically, latent heat release drives winds that affect the transport of moisture and evaporation, and it shapes stability profiles and subsequent release of latent heat. These interactions are further complicated by the fact that the vertical structure of the heating is related to various microphysical processes in the life cycle of convection. The difference in latent heating profiles associated with convective and stratiform regions of mesoscale convective systems (MSCs) are well known (Houze 1982; Johnson and Young 1983). In convective regions of MCSs, the latent heating profile has positive heating throughout the troposphere with a maximum at midtroposphere while in the stratiform regions there is an upper-level heating peak and cooling below the melting level. Furthermore, recent radar observations suggest the existence of other profiles such as shallow convection with a peak below the melting level and detraining congestus with low-level heating and upper-level cooling (Schumacher et al. 2007). Thus, large-scale latent heating averaged over a region is composed of heating from each cloud type in the domain and can be written as

\[ Q_h(t, p) = \sum_{ic=1}^{n} A_{ic}(t) P_{ic}(p), \]  

where \( A_{ic}(t) \) is the amount of heating contributed by each cloud type (stratiform, deep convective, shallow convective, congestus, etc.) and \( P_{ic}(p) \) is the associated vertical profile. In this sense of Eq. (1), \( P_{ic}(p) \) constitute the building blocks of latent heating \( Q_h(t, p) \) and they will be referred to as such. According to the analysis of mesoscale radar observations of heating from precipitation clouds by Schumacher et al. (2007), these building blocks have characteristic profiles (Fig. 1). This construction of large-scale latent heating from the various cloud types has been the basis for algorithms of latent heating retrieval from satellite observations. In those algorithms, cloud types are inferred from the vertical structure of radar reflectivity and the associated profiles are obtained from cloud-resolving model simulations (Shige et al. 2004; Tao et al. 2006).

Another method of estimating latent heating profiles has been the use of in situ measurements of wind, pressure, and temperature using an array of soundings over a region to calculate the total diabatic heating \( Q_1 \). In this approach, vertical velocity is first derived from horizontal wind on pressure surfaces by vertical integration of divergence, and then the three-dimensional wind, pressure,
and temperature are substituted into the conservation of energy equation to calculate $Q_1$ as a residual (Yanai et al. 1973).

Given the large contribution of latent heating to total diabatic heating in regions of precipitation, these two approaches are essentially measuring the same quantity. This raises the question as to whether a certain set of building blocks constitutes diabatic heating from soundings as well. If so, how many blocks? How do they compare with those derived from radar observations? What are their quantitative contributions? What roles do they play in the temporal variability of large-scale diabatic heating profiles? These questions are the subject of this study.

An important clue for understanding the composition of the diabatic heating from in situ measurements is their temporal variability. Empirical orthogonal function (EOF) analyses have shown that the variability of diabatic heating can be represented by the first two modes. The first mode, deep heating throughout the troposphere with a peak near 400 hPa, explains approximately 80% of the variance. The second mode with low-level heating (peak near 800 hPa) and upper-tropospheric cooling (peak near 400 hPa) explains approximately 15% of the variance (Tung et al. 1999; Lin and Arakawa 2000; Zhang and Hagos 2009). Those results were consistent for almost all the tropical sounding–based estimates of diabatic heating.

In this study, this two-mode variability and oblique EOF rotation techniques are used to indentify the building blocks in the diabatic heating from eight tropical sounding datasets. These building blocks are then used to gain insight into the nature of the temporal evolution of large-scale diabatic heating profiles.

2. Data

We calculate $Q_1$ from eight in situ sounding arrays. These are the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE), Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE), the Kwajalein Experiment (KWAJEX), the Tropical Warm Pool International Cloud Experiment (TWP-ICE), the South China Sea Monsoon Experiment Northern and Southern Enhanced Arrays (SCSMEX-N and SCSMEX-S), the Large-Scale Biosphere–Atmosphere Experiment in Amazonia (LBA), and the Mirai Indian Ocean Cruise for the Study of the MJO Convection Onset (MISMO). The GATE data are gridded ($1^\circ 	imes 1^\circ$). An average over a $3^\circ 	imes 3^\circ$ domain covering the B-scale ship was used in this study (interior hexagon). The temporal smoothing (from three-hourly to six-hourly) was done to keep it consistent with the other datasets. The latitudes, longitudes, and durations, as well as references to these field campaigns, are listed in Table 1 and their locations are marked in Fig. 2. The spatial coverage, temporal resolution, and length of the datasets vary substantially.

3. Basic structures in diabatic heating

a. EOF analysis on TOGA COARE heating

In this section the technique for identifying the building blocks of diabatic heating is demonstrated on TOGA COARE data. As noted in the introduction, the term “building blocks” refers to a small set of profiles into which the entire dataset can be decomposed. The problem is, given $Q_h(t, p)$, whether a set of $A_{ic}(t)$ and $P_{ic}(p)$ in Eq. (1) can be uniquely defined. It is important to note that $A_{ic}(t) \geq 0$ at any time since it represents the amount of a certain cloud type in the domain.

Diabatic heating processes over tropical oceans consists mainly of weak clear-sky radiative cooling and intense positive latent heat release from precipitating clouds. In other words, the time series of $Q_1$ (hereafter a two-dimensional matrix) can easily be separated into “clear sky” $Q_{rc}$ (“radiative cooling”) and those involving latent heating $Q_{hc}$ (“positive heating” or just “heating”). If present, the magnitude of latent heating is generally much larger than radiative cooling and it is predominantly positive. In this study, the two components of diabatic heating are separated rather crudely by assuming a point to be a clear sky profile if the vertically integrated diabatic heating is negative. One has to note that there is some radiative cooling in the heating. Figure 3a
shows the mean of the total diabatic heating, positive
heating, and radiative cooling according to this separa-
tion. The vertical structure of the total diabatic heating is
primarily determined by the positive heating. Further-
more, the regular EOF analysis of both the total diabatic
heating and positive heating time series shows that al-
most all the variability in the former is contributed by
the later (Fig. 3b). For both of them, the first two EOFs
explain approximately 90% of the variance (Table 2).
The fact that almost all the variability is associated with
positive heating is not surprising because although the
vertical structure of latent heating varies significantly
among cloudy scenes, the profile of clear-sky cooling
shows little variability.

Since the clear-sky points are replaced by zero in the
$Q_h$ data, the separation into its mean and variability

$$Q_h = \bar{Q}_h + Q'_h$$

implies, for clear-sky points cls where $Q_h = 0$, that

$$Q'_h(\text{cls}, p) = -\bar{Q}_h.$$  (3)

After EOF analysis, the whole positive heating data
can be reconstructed as

$$Q_h = \bar{Q}_h + \mathbf{PC}' \times \mathbf{EOF},$$  (4)

where $\mathbf{PC}'$ and $\mathbf{EOF}$ are the principal components and
eigenvectors, respectively. Since most of the variability
in $Q_h$ can be represented by the first two EOFs (Table 1),
only these two modes are considered for simplicity.
Therefore, $\mathbf{PC}'$ and $\mathbf{EOF}$ are matrices of $nt \times 2$ and $2 \times nl$, respectively, where $nt$ and $nl$ are respectively the length of
the time series and the number of vertical levels.

For the set of the clear-sky points (a subset of $Q_h$),

$$Q'_h(\text{cls}, p) = \mathbf{PC}'(\text{cls}, p) \times \mathbf{EOF},$$  (5)

where $\mathbf{PC}'(\text{cls}, p)$ is the value of $\mathbf{PC}'$ at clear-sky points.

Using Eqs. (3) and (5), Eq. (4) can be rewritten as

$$Q_h = \mathbf{PC} \times \mathbf{EOF},$$  (6)

where $\mathbf{PC} = \mathbf{PC}' - \mathbf{PC}'(\text{cls}, p)$.

As noted above, the first two modes explain approxi-
mately 90% of the total variance in TOGA COARE as
well as all the sounding arrays except for GATE and
LBA (Table 2) considered in this study, so only the first
two modes are retained. But in order to identify the
simple structures in the variability data, the varimax ro-
tation (Kaiser 1958; Wilks 2006) is applied. This rotation
maximizes the simplicity (the square of variance) of
the eigenvectors. In other words, it attempts to make the el-
ments of the normalized rotated eigenvector maximum

FIG. 2. 10-yr mean precipitation from TRMM3B43 (mm day$^{-1}$) for 1998–2007. The locations of
the soundings are marked by “X”.

<table>
<thead>
<tr>
<th>Expt</th>
<th>Location</th>
<th>Period</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>GATE</td>
<td>Tropical Atlantic</td>
<td>26 Jun–19 Sep 1974</td>
<td>Houze and Betts (1981)</td>
</tr>
<tr>
<td>TWP-ICE</td>
<td>Darwin</td>
<td>21 Jan–12 Feb 2006</td>
<td>May et al. (2008)</td>
</tr>
</tbody>
</table>
In this procedure, the EOF vectors are normalized such that the rotated EOFs are no more orthogonal upon rotation while the principal components remain uncorrelated. The effect of normalization on orthogonal properties of rotated EOFs is extensively discussed by Mestas-Nunez (2000).

Now Eq. (6) can be written as

\[ Q_h = \text{RPC} \times \text{REOF}, \]  

(7)

where RPC and REOF are the new varimax rotated principal components and eigenvectors, respectively.

According to Eq. (7), the set of vectors REOF is one of many possible mathematical bases of \( Q_h \). But as discussed at the beginning of this section, for a set of basis vectors to be building blocks, \( Q_h \) has to be uniquely represented by a certain (positive) amount of each of these basis vectors at any time.

Once \( Q_h \) is reconstructed using these rotated EOFs and PCs, the problem of identifying the structures that constitute the heating is reduced to finding the appropriate rotation such that all elements of the new set of principal components are either zero or have a positive value at any time. To find that rotation, one can rewrite Eq. (7) as

\[ Q_h = \text{ORPC} \times \text{OREOF}, \]  

(8)

such that the oblique rotated principal component ORPC = RPC × \( r \), the oblique rotated EOF OREOF = \( r^{-1} \times \text{REOF} \), and \( r \) is a rotation matrix defined as

\[ r = \begin{bmatrix} 1 & a \\ 0 & 1 \end{bmatrix}. \]  

(9)

Hereafter this rotation is referred to as oblique, since neither the new pair of EOFs nor the PCs is required to be orthogonal.

### Table 2. The variance explained (%) by the deep and shallow EOF modes for soundings.

<table>
<thead>
<tr>
<th>Sounding</th>
<th>var1</th>
<th>var2</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOGA</td>
<td>79</td>
<td>11</td>
</tr>
<tr>
<td>GATE</td>
<td>75</td>
<td>11</td>
</tr>
<tr>
<td>KWAJEX</td>
<td>79</td>
<td>15</td>
</tr>
<tr>
<td>TWP-ICE</td>
<td>89</td>
<td>6</td>
</tr>
<tr>
<td>SCSMEX-N</td>
<td>88</td>
<td>8</td>
</tr>
<tr>
<td>SCSMEX-S</td>
<td>89</td>
<td>10</td>
</tr>
<tr>
<td>LBA</td>
<td>49</td>
<td>35</td>
</tr>
<tr>
<td>MISMO</td>
<td>83</td>
<td>11</td>
</tr>
<tr>
<td>All combined</td>
<td>81</td>
<td>12</td>
</tr>
</tbody>
</table>
Now the problem is reduced to finding the rotation parameter \( a \) at which all elements of \( \text{ORPC} \geq 0 \) so that the two vectors (time series) that constitute \( \text{ORPC} \) (\( \text{ORPC}_1 \) and \( \text{ORPC}_2 \)) would represent \( A_{1c}(t) \) and \( A_{2c}(t) \) of Eq. (1), respectively. Then the two vectors that constitute \( \text{OREOF} \) (\( \text{OREOF}_1 \) and \( \text{OREOF}_2 \)) would represent \( P_{1c}(p) \) and \( P_{2c}(p) \) of Eq. (1). In other words, we seek to maximize the amount of heating that lies in the first quadrant (\( Q_{1p} \)) of the \( \text{ORPC}_1, \text{ORPC}_2 \) coordinate system. Figure 4 shows the percentage of the diabatic heating that lies on the first quadrant as a function of \( a \). At \( a = 0 \) approximately 70% of the diabatic heating lies in the first quadrant; as it increases, the new axes (\( \text{ORPC}_1 \) and \( \text{ORPC}_2 \)) are rotated such that the number of points lying in the first quadrant (and the heating there) rapidly increases until it reaches approximately 99% of the total heating, upon which it remains more or less constant. Increasing \( a \) further does not increase the amount positive diabatic heating represented by the two modes it only mixes them.

Figure 5 shows the diabatic heating as represented by the first two regular EOFs (Fig. 5a), varimax rotated EOFs (Fig. 5b), and oblique rotated EOFs (Fig. 5c) along with the scatterplot of their respective principal components. As discussed above, the first regular EOFs are orthogonal. Most of the scatterplot points lie along the \( \text{PC}_1 \) axis, for the first mode primarily represents the magnitude of heating, and variations in the profile are represented by the second mode. In the varimax rotated case, the orthogonality of the EOFs is relaxed, while the principal components are still orthogonal (uncorrelated). Upon varimax rotation, the first EOF remains essentially the same but the second is quite different. The reason for this behavior and the interpretation of varimax rotated and regular EOFs will become apparent after the oblique rotation and the idea of building blocks are discussed.

In the oblique rotated case, the first mode has low-level cooling, but the second mode is essentially the same as that of the varimax rotation (convective like). Note that in the respective scatterplots almost all the points (and 99% of the heating) lie in the first quadrant. This implies that almost the entire positive heating data can be represented by the two profiles in Fig. 5c. The fact that the first OREOF resembles the stratiform heating profile and the second OREOF resembles convective heating (Fig. 1) is not by accident. If indeed MCS heating is primarily composed of stratiform and convective heating, they naturally should constitute the large-scale diabatic heating as well. Therefore, the two building blocks will be referred to as stratiform and convective heating.

Before generalizing this result to the other sounding arrays, three points need particular attention. The first one is the uniqueness of this result. Theoretically, if the diabatic heating can be represented by the two profiles, the value of \( a \) should increase until all the points in the scatterplot (Fig. 5c) are in the first quadrant. However, increasing \( a \) beyond 99% has little effect on the amount of diabatic heating in the first quadrant. Instead it mixes the two EOFs. Considering the crudeness of the separation between positive and negative (radiative) heating, this limitation is not surprising.

The second point is on the completeness of the two building blocks. Given the coarse temporal and spatial resolution of the soundings, the existence of other fundamental structures is possible. But if these two building blocks are made of several other structures, then these structures must have strong temporal correlation so they do not appear in the EOF analysis independently. However, since the two building blocks do not explain 100% of the diabatic heating (or the variance), it is quite possible that there are other profiles in smaller proportion. Identifying them would involve a three-dimensional rotation, which, given their very small contribution (which is comparable to the error in the data), can be neglected in this study.

The final point pertains to the interpretation of the varimax rotated and regular EOFs. If, as the above result shows, tropical diabatic heating can be decomposed into two basic structures, then interpretation of the varimax rotated EOFs becomes straightforward. In that case, \( Q_{h} = \text{ORPC}_1 \times \text{OREOF}_1 + \text{ORPC}_2 \times \text{OREOF}_2 \).

According to Eqs. (7) and (8), the effect of varimax rotation (where the PCs are orthogonal) is then to take \( \text{ORPC}_2 \) and split it into a part that is orthogonal to \( \text{ORPC}_1 \) and a part that is not, such that \( \text{RPC}_1 = \text{ORPC}_1 \),
FIG. 5. The first two eigenvectors and the scatterplot of their respective PCs from (a) regular, (b) varimax rotated, and (c) oblique rotated EOF analyses. The solid and dashed lines correspond to first and second modes, respectively.
RPC_2 = ORPC_1 - aORPC_1, REOF_2 = OREOF_1 + aOREOF_2 (cf. Figs. 5b,c), and REOF_1 = OREOF_1 + aOREOF_2. Hence, the first mode in the varimax rotated (as well as the regular) EOF is composed of the two building blocks and their contributions depend on their temporal covariability. In other words, the first rotated EOF is composed of all of the first building block plus a part of the second building block that is temporally correlated with the first. The second rotated mode is entirely composed of the part of the second building block that is temporally orthogonal to the first building block. Thus, the first varimax rotated EOF does not have the low-level cooling because it includes the convective component that is temporally correlated with the stratiform heating. The regular EOFs analysis imposes a further constraint that the eigenvectors be orthogonal. Since the first eigenvector is monopolar, the second eigenvector has to be bipolar with a low-level heating and upper-level cooling or vice versa.

b. Generalization to the other tropical soundings

The extent to which the two TOGA COARE building blocks of heating represent diabatic heating in the tropics...
can be evaluated by comparing the time mean of the heating data to that reconstructed from the two building blocks. Figure 6 shows the two building blocks, means of the reconstructed time series using the two modes, and original means for all sounding datasets. The two modes can reproduce the mean well in all cases and the structures of the building blocks are similar in all cases. Also, for all of them (except GATE) the stratiform mode has low-level cooling and the convective mode has weak cooling above the 500-hPa level.

Figure 7 shows scatterplots of ORPC$_1$ and ORPC$_2$ from all sounding array datasets. Once again, the oblique rotation puts almost all the strong heating points in the first quadrant. The variations in the intensity of diabatic heating can be inferred from the scatterplot. For example, TWP-ICE has the most high diabatic heating (intense) events and GATE has the least (likely due to temporal smoothing). On the other hand, TOGA has the most clear-sky (near-zero heating) events.

4. Evolution of heating

The reconstruction of large-scale heating in terms of two building blocks enables its representation by the fractional contribution of the convective (second building block) or stratiform (first building block) heating and
the magnitude of the heating. In other words, a point at \((\text{ORPC}_1, \text{ORPC}_2)\) in Cartesian coordinates (Fig. 7i) can approximately be represented in polar coordinates \((R, \sigma)\), where

\[
R \approx \text{ORPC}_1 + \text{ORPC}_2 \tag{11}
\]

is the magnitude of heating and

\[
\sigma = \frac{\text{ORPC}_2}{R} \tag{12}
\]

is the fractional contribution of convective heating (and therefore the profile).

Figure 8 shows the relationship between \(R\) and \(\sigma\). Generally both stratiform (low \(\sigma\)) and convective (high \(\sigma\)) profiles are associated with weak heating. The most intense events contain both convective and stratiform profiles. This is consistent with the fact that much of the diabatic heating is released at times of intense convective activity when both convective and stratiform clouds and precipitation are present. Meanwhile, low and high \(\sigma\) (isolated shallow as well as dying stratiform clouds) are associated with low instantaneous heating.

In this section, the evolution of the observed latent heating profiles is analyzed by considering the evolution of \(\sigma\). Provided the denominator in Eq. (12) is nonzero at two consecutive points in time (neither of them is a clear-sky point), one can define the rate of change of \(\sigma\):

\[
\frac{d\sigma}{dt} = \sigma_{i+1} - \sigma_i.
\]

The unit for \(d\sigma/dt\) is \((6 \text{ h})^{-1}\), since the temporal interval for all soundings is 6 h. The evolution of diabatic heating profiles can then be inferred from the relationship between \(\sigma\) and \(d\sigma/dt\). Figure 9 shows the scatterplot \(d\sigma/dt\) versus \(\sigma\). For all soundings, the correlation is approximately \(-0.6\) at 95% confidence level. This means if the profile is top heavy (low \(\sigma\)) at a certain time \(t_i\), then it is most likely be less so at \(t_{i+1}\) (provided it does not become clear sky). Similarly, if it was bottom heavy (high \(\sigma\)), its \(\sigma\) likely decreases (becomes more top heavy) at the next point in time.

The entire analysis including the decomposition is applied on a concatenated dataset of all sounding arrays \(Q_i(p, t)\). Figure 10a shows the scatterplot \(d\sigma/dt\) versus \(\sigma\) for all the datasets combined. Note the existence of a stationary point \((d\sigma/dt = 0.0\) at approximately \(\sigma = 0.67\)). The continuous creation and decay of heating maintains a semisteady profile with approximately 67% convective heating (the second building block). The e-folding time is 6 h/0.65 \(\approx 9\) h. In other words, if at some time the convective fraction is 1 (all convective), in 9 h it is reduced to approximately 0.7.

The temporal evolution of large-scale heating becomes even more apparent if the trajectories in phase space are considered. In order calculate to the mean trajectories in phase space, the \((\sigma, d\sigma/dt)\) data is put into a regular 20 \(\times\) 20 grid and the mean vectors are calculated as transitions from one grid point to another, from which the trajectories are constructed. Figure 10b shows these trajectories. The shadings indicate \(R\) [Eq. (11)]. Once again, a point starting out as top heavy constantly loses its stratiform heating (first building block) to exponential decay. Similarly a point that starts out as bottom heavy also loses its shallow mode to decay, leading to a more or less steady heating profile (the stationary point).

5. A simple model of diabatic heating profile variability

In the last two sections, oblique rotated EOF analysis was used to show that tropical latent heating profile is effectively constructed by two building blocks and its variability can be represented as the decay of the excessive amount of one or the other building block. In this section these results are indirectly tested using a synthetic dataset. In the construction of a model to generate the synthetic heating dataset, the following assumptions are made: (i) the dataset is composed of two profiles; (ii) the generation of the two building blocks is random in time and is like observed precipitation (lognormally distributed); and (iii) once generated, the building blocks have fixed finite lifetimes. To put it in mathematical form, suppose an individual heating profile of type \(i\) is generated at time \(t_g\). If the observation time is \(t\), then the sounding time series \(q_i\) is given by

\[
q_i(p, t, t_g) = P_i(p)\left[H(t - t_g) - H(t - (t_i + t_g))\right] \times \exp[G_i(t_g)]. \tag{13}
\]
Here, $P_i(p)$ is the $i$th profile that was created at $t_g$ and has a lifetime of $\tau_i$ and magnitude of $\exp[G_i(t_g)]; G_i$ is the time series from the $i$th realization of the generation of Gaussian random numbers centered at 0 with a variance of 1; and $H$ is the Heaviside function. According to Eq. (13), the particular profile is observed only if $t - \tau_i < t_g < t$. Therefore, at any $t$ the total heating is the sum of all that is generated since $t - \tau_i$:

$$Q_j(t, p) = \sum_{i=1}^{r} \int_{t - \tau_i}^{t} q_i(p, t, t_g) dt_g.$$  \hspace{1cm} (14)

For simplicity, both instances of $\tau_i$ are set to 6 h. The integration is discretized such that profiles are generated every hour. The final synthetic data is sampled every 6 h for consistency with the sounding observations.

To test the effectiveness of the oblique method in recovering profiles embedded in an arbitrary two-dimensional dataset, the technique is applied on a synthetic dataset constructed using a pair of profiles with little resemblance to any observed structures. The technique is then applied. Figure 11a shows the prescribed (solid lines) and the recovered (dashed lines) profiles. The prescribed and

**FIG. 9.** Scatterplot of $d\sigma/dt$ vs $\sigma$ for the eight soundings.
recovered profiles are essentially the same. Once again, a rotation of the EOFs such that all points lie in the first quadrant of the coordinate system made of the two principal components (shown in the corresponding scatterplot) can effectively recover basic structures embedded in the data. Thus, this result provides further evidence that the two profiles discussed in last section are indeed the building blocks of heating data as defined by Eq. (1).

A similar analysis is performed on a synthetic data with convective and stratiform building blocks (Fig. 6i) used as the bases. Figure 11b shows the respective comparison of the prescribed and the recovered profiles and the scatterplot of the principal components. Although there are some slight differences, it is quite apparent that the technique is performing a reasonably good job of extracting the embedded structures.

Comparison between the scatterplots of the principal components from the soundings and synthetic data (Figs. 11b and 7i), on the other hand, shows striking differences. The reason lies in the nature of covariability between stratiform and convective heating in the observations. In the synthetic data, the time series of convective and stratiform heating are random. In reality, however, the convective and stratiform heating are just two development stages of convective systems and often appear next to each other or consecutively by a few hours (Houze 1989), which explains the covariability in the soundings where the spatial and temporal resolution is limited.

The temporal variability of the randomly generated synthetic data using the building blocks is now considered. Figure 12a shows the relationship between $\sigma$ and $d\sigma/dt$. The correlation between the two variables is negative, as in the case of the soundings. Comparison of the trajectories in Figs. 12b and 10b shows that an abundance of convective (or stratiform) heating is followed by its exponential decay so that the heating profile is always heading toward a stationary profile. Therefore, the observed variability of diabatic heating is most likely the result of a finite lifetime of the two basic building blocks that constitute the heating in the tropics, whether their creation is random or modulated by the large-scale environment. In other words, while the environment might determine the quantity and timing of precipitation and heating, the temporal variability of the stratiform and convective heating, and their duration [represented in the synthetic data by $G$, $\tau$, in Eq. (13)], the building blocks $[P_r(p)]$ appear to be common to tropical regions of precipitation.

6. Conclusions

In this study, the basic building blocks constituting tropical diabatic heating profiles are identified using an oblique rotated EOF analysis. It is shown that tropical diabatic heating can effectively be represented by stratiform heating with a peak near 400 hPa with a low-level cooling peak near 700 hPa and convective heating with a peak near 800 hPa. These results are consistent throughout the eight tropical sounding array time series considered in this study. Temporal variability of tropical diabatic heating is shown to be primarily the result of decay of excess stratiform or convective heating due to the finite lifetime of the cloud systems (Fig. 10a). Furthermore, the previously identified bimodal variability of diabatic heating profiles using various other EOF analyses (Tung et al. 1999; Zhang and Hagos 2009) simply follows from the fact that the heating profiles are constructed from the two basic structures as hypothesized by Lin and...
Fig. 11. Comparison of the two heating profiles imbedded in the synthetic data with those recovered using the oblique rotation and scatterplot of ORPC₁ and ORPC₂, for a synthetic data constructed using (a) an arbitrarily made pair of profiles and (b) the two building blocks (Fig. 5i).
Arakawa (2000), as well as the convective–stratiform heating paradigm presented by Houze (1989).

The implications of these results for tropical circulation are obvious. If the tropical diabatic heating is indeed composed of just two structures, what are their roles in moisture transport and surface winds? How sensitive is the general circulation to variations in the relative contributions of the two building blocks of heating profile? In other words, how important is the representation of the diabatic heating profile in circulation and precipitation feedback in global models, and to what degree can the existing uncertainties in tropical distribution of precipitation and surface winds in global models be reduced by the use of the two-building-block approach to the representation of diabatic heating profiles? These questions are the subject of an ongoing study and the results will be reported elsewhere.

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