An Observed Tropical Oceanic Radiative–Convective Cloud Feedback

MATTHEW D. LEBSOCK, CHRISTIAN KUMMEROW, AND GRAEME L. STEPHENS

Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

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ABSTRACT

Anomalies of precipitation, cloud, thermodynamic, and radiation variables are analyzed on the large spatial scale defined by the tropical oceans. In particular, relationships between the mean tropical oceanic precipitation anomaly and radiative anomalies are examined. It is found that tropical mean precipitation is well correlated with cloud properties and radiative fields. In particular, the tropical mean precipitation anomaly is positively correlated with the top of the atmosphere reflected shortwave anomaly and negatively correlated with the emitted longwave anomaly. The tropical mean relationships are found to primarily result from a coherent oscillation of precipitation and the area of high-level cloudiness. The correlations manifest themselves radiatively as a modest decrease in net downwelling radiation at the top of the atmosphere, and a redistribution of energy from the surface to the atmosphere through reduced solar radiation to the surface and decreased longwave emission to space. Integrated over the tropical oceanic domain, the anomalous atmospheric column radiative heating is found to be about 10% of the magnitude of the anomalous latent heating. The temporal signature of the radiative heating is observed in the column mean temperature that indicates a coherent phase-lagged oscillation between atmospheric stability and convection. These relationships are identified as a radiative–convective cloud feedback that is observed on intraseasonal time scales in the tropical atmosphere.

1. Introduction

The tropical atmosphere is composed of large-scale meridional and zonal overturning circulations that dynamically link regions of moist ascending motion with regions of dry descent. Understanding this dynamically connected system requires simultaneous observation of both the ascending and descending branches of the circulations. For example, Pierrehumbert (1995) emphasizes the importance of the tropical circulation, suggesting that the relative areas of moist ascending motion and dry descending motion play a key role in regulating tropical climate. Wallace (1992) also highlights the crucial role that must be played by dynamics in regulating tropical climate, arguing for the importance of the fractional area of the tropics covered by reflective high cloud. Hartmann and Michelsen (1993) further demonstrate that the strong local correlations observed between sea surface temperature (SST) and radiation parameters become extremely weak when the averaging area is extended over the entire tropical Pacific from 30°S to 30°N. Therefore, to address the problem of tropical climate, it is necessary to consider an averaging area appreciable to the spatial extent of the large-scale circulations. For the tropics this area would correspond to the meridional Hadley and zonal Walker circulations.

Many studies have examined the top of the atmosphere (TOA) Earth radiation budget (Vonder Haar and Suomi 1969; Harrison et al. 1990; Cess et al. 2001). While this approach has contributed greatly to our understanding of the climate system, examining only the TOA budget can be misleading because the near cancellation of cloud shortwave (SW) and longwave (LW) forcings at the TOA in the tropics (Kiehl and Ramanathan 1990; Kiehl 1994) obscures important differences in the manner in which the shortwave and longwave components of the radiation budget interact with the surface (SFC) and the atmospheric column (ATM). For example, in the particular case of high clouds, Stephens and Webster (1981) point out that all but the thinnest high clouds tend to cause a cooling of the earth’s surface and a warming of the atmospheric column. Also, relatively few studies have examined the radiation budget on the short time scales...
relevant to moist atmospheric processes. Notable exceptions are the studies of Collins et al. (1996), Lin and Mapes (2004), and Stephens et al. (2004). All of these studies demonstrate that the cloud fields are associated with deep convection, causing a radiative heating of the atmosphere and a cooling at the surface. The present paper expands upon those studies by examining the relationships between cloud, precipitation, and radiation averaged over the large-scale domain of the tropical oceans.

An important element of the atmospheric column radiation budget is its coupling to the global hydrologic cycle. This relationship is commonly understood through the paradigm of radiative–convective equilibrium (Manabe and Wetherald 1967), whereby atmospheric radiative cooling is balanced energetically by the transfer of latent and sensible heat from the surface to the atmosphere through the action of convection. This concept may also be understood through a statement of the atmospheric column energy balance:

$$-R_{\text{atm}} = LP + S + F,$$

where $R_{\text{atm}}$ is the atmospheric radiative heating rate, $L$ is the latent heat of vaporization, $P$ is the precipitation rate, the product $LP$ is the column latent heating, $S$ is the surface sensible heat flux, and $F$ is the horizontal transport of sensible energy. This statement of energy balance must also be true of the anomalies (represented by primes):

$$-R'_{\text{atm}} = LP' + S' + F'.$$

Over the tropical oceans, $S [\approx 10 \text{ W m}^{-2}; \text{i.e., Hartmann and Michelsen (1993)] is substantially smaller than } LP (\approx 70 \text{ W m}^{-2}; \text{present study}). Further neglecting the anomalous energy transport as well gives the approximate descriptive expression,

$$-R'_{\text{atm}} \approx LP',$$

which states that atmospheric radiative heating anomalies are approximately balanced by latent heating anomalies through a modified precipitation rate.

The theoretical formulation provided in Eq. (3) ignores sensible heating and transport effects but includes cloud feedbacks that could potentially dampen or amplify the hydrologic cycle response to a radiative perturbation. Therefore, a critical aspect of this approximation is quantifying the sign and magnitude of these potential feedbacks. To this end, this study attempts to quantify one aspect of the cloud feedback in the present climate.

Specifically, evidence is presented for a radiative–convective cloud feedback that acts to dampen the hydrological response to increased radiative cooling by 10%. Commensurate negative feedbacks are implied at the TOA and the surface. To identify this feedback, relationships are quantified between precipitation and the radiation budget over the tropical oceans. Furthermore, time-lagged relationships are analyzed that demonstrate the existence of the feedback mechanism on intraseasonal time scales in the current tropical atmosphere.

2. Data

Five years (2003–07) of tropical oceanic (30°S–30°N) 1° gridded daily daytime data from the National Aeronautics and Space Administration’s (NASA’s) Aqua satellite are analyzed. Of particular importance for the intraseasonal variability addressed in this study, all geophysical parameter estimates are temporally and spatially collocated due to the use of a common spaceborne platform. Estimates of oceanic precipitation rate are offered from the Advanced Microwave Scanning Radiometer–E (AMSR-E) using the Goddard profiling algorithm (GPROF; Kummerow et al. 2001). The analysis is limited to the global oceans due to the uncertainty in the passive microwave rainfall algorithm over land surfaces. Cloud properties from the Moderate Resolution Imaging Spectroradiometer (MODIS) level-3 1° daily average cloud products (Platnick et al. 2003) are employed from collection five. The MODIS variables used include the total cloud optical depth ($\tau$), cloud fraction (CF), cloud-top temperature (CTT), cloud-top pressure (CTP), and the $\tau$–CTP joint histograms. Additionally, Atmospheric Infrared Sounder (AIRS) temperature profiles (Aumann et al. 2003) are used to diagnose the structure of the atmospheric heating. AIRS provides infrared and microwave-based temperature and water vapor profiles that are available from the surface to 200 hPa under substantially overcast conditions (Susskind et al. 2003). In this work pressure-weighted column mean temperatures are calculated. Only pixels in which all pressure levels contain valid data values are considered so as not to bias the results in instances where lower-atmosphere data may be missing due to cloud and precipitation contamination.

The Clouds and Earth’s Radiant Energy System (CERES) instrument (Wielicki et al. 1996) offers estimates of the TOA and surface broadband longwave and shortwave fluxes. In this work the single scattering footprint (CERES-SSF FM3 editions 2B and 2C) products are aggregated to daily 1° averages. A time-dependent user-applied correction factor that has been approved by the CERES science team is applied to the CERES shortwave
data to account for spectral darkening of the shortwave channel (see the data quality summary available online at http://eosweb.larc.nasa.gov). To account for the variation of the solar flux with solar zenith angle, the daily mean (represented by an overbar) shortwave flux is approximated from the instantaneous estimate as $F_{SW} = F_{SW}(\bar{F}_{SW}/F_{0})$, where $F_{SW}$ is the observed reflected component and $F_{0}$ is the incident component of the TOA solar flux. The surface radiative fluxes are estimated using the surface SW Model B that provides estimates in both clear and cloudy conditions. The shortwave component of the surface flux is normalized to the daily mean in a manner analogous to the TOA flux. After this normalization, the atmospheric column radiative fluxes are derived as the difference of the reported TOA flux from the surface flux. The sign conventions for the fluxes are positive upward at the TOA, positive downward at the surface, and positive in for the atmospheric column. Finally, the net fluxes at the TOA, SFC, and ATM are derived as the sum of the shortwave and the longwave fluxes.

It is important to emphasize that the normalization of the shortwave fluxes is an approximation that does not take into account variations in albedo with solar zenith angle. This introduces a low bias in the estimated daily mean reflected shortwave flux. An additional bias that affects all of the observed parameters results from the sun-synchronous orbit of the A-Train that precludes sampling of the diurnal cycle of any of the satellite-based observables. Nonetheless, this study examines relationships between anomalies from the mean and time scales longer than the diurnal cycle. The results should therefore be largely insensitive to these sources of bias.

3. Methodology

a. Cluster analysis

A K-means clustering analysis (Anderberg 1973) is employed on the MODIS level 3 International Satellite Cloud Climatology Project (ISCCP; Schiffer and Rosow 1983) like $\tau$–CTP histograms following the methodology of Jakob and Tselioudis (2003). Recent research using ISCCP data demonstrates that this clustering approach is able to identify cloud clusters that are associated with unique radiative, thermodynamic, and dynamic atmospheric conditions (Jakob et al. 2005), as well as differentiable precipitation and latent heating characteristics (Jakob and Schumacher 2008). These traits make a clustering approach a useful construct within which to examine the relationships between tropical precipitation and radiation fields.

The ISCCP-like joint histograms contain counts of the co-occurrences of various combinations of cloud optical depth and cloud-top pressure within each 1° region. These histograms are normalized by the cloud fraction so that the sum of the histogram values varies between 0 (completely clear) and 1 (completely overcast). For the purposes of this study, the tropical oceanic region (30°N–30°S) is isolated for the clustering analysis. Six cloud clusters are selected that satisfy the objective criterion of Rossow et al. (2005).

Figure 1 shows the six cloud clusters identified by the algorithm while Fig. 2 provides the spatial distribution of the relative frequency of occurrence of the clusters. These six clusters largely correspond to those found by Rossow et al. (2005) using ISCCP data for a similar region. From a radiation budget point of view it is useful to further group these six clusters into three broad categories: 1) shallow overcast clouds, 2) convectively suppressed and clear, and 3) deep convection and cirrus. Three of the clusters are identified with mostly cloudy skies and a lack of penetrating deep convection. These clusters are labeled as stratus, shallow cumulus, and midlevel cumulus. Taken together these three clusters dominate the eastern tropical ocean basins with a relative frequency of occurrence of 20.3%. The overcast deep convection and cirrus clusters dominate the west Pacific warm pool as well as the intertropical convergence zone (ITCZ), together occupying 24.2% of the tropical oceanic area. Importantly, the mostly clear-sky regime dominates the majority of the tropical oceans with a frequency of occurrence of 55.5%. The spatial distribution of these regimes is broadly consistent with a tropical circulation composed of a meridional Hadley circulation and a zonal Walker circulation.

b. Constructing the tropical mean anomaly time series

In this work, averages over the entire tropical oceanic region are examined following the example of Hartmann and Michelsen (1993). This region can be said to include the ascending and descending branches of the Hadley and Walker circulations and thus provides a better indication of tropics-wide relationships than those derived locally. This approach further allows for examination of the relationships between precipitation and radiation within each cluster as well as how the clusters interplay with each other. To this end, anomaly time series of the daily tropical oceanic mean values of several parameters are examined. The anomaly time series of each parameter is constructed as follow:

1) All valid daily oceanic data from 30°S to 30°N are area weighted and averaged to construct a 5-yr (2003–07) time series. Time series of each variable are constructed within the area occupied by each of the six cloud clusters. Time series of the fractional area...
occupied by each cluster are also created. The domain mean of any variable ($x$) on any day ($i$) may then be calculated as the summation over the six clusters ($j$) of the value of that variable weighted by the fractional area of each cluster ($a_j$), giving, $\left[ \sum_j a_j x_{ij} \right] / C_j$.  

2) Missing days are linearly interpolated across the data gaps. AIRS data are unavailable from 29 October 2003 to 14 November 2003. In this case we use a simple linear regression incorporating the available data from the 21 days surrounding the midpoint of the event to fill missing values.  

3) The seasonal cycle is removed from the data. First, a smoothed mean annual cycle is calculated from the time series subsequent to the application of a 30-day running mean. An anomaly time series is then calculated by differencing the raw data from the cyclically continuous smoothed annual cycle. The constant annual mean is added back into the time series to

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**FIG. 1.** The six tropical oceanic cloud clusters. The CF and the relative frequency of occurrence (RFO) are provided (%).
perform a perturbation budget analysis described below.

4) The effects of El Niño–Southern Oscillation (ENSO) are removed by regressing the time series against the multivariate ENSO index (MEI; Wolter and Timlin 1993) and then subtracting the linear regression from the time series. It is noted that the use of one index is unlikely to remove all of the variability associated with ENSO through regression.

5) The daily time series (of length \( n = 1826 \) days) are then aggregated into 3-day means to reduce the sampling noise in the daily time-scale data, producing time series of length \( n = 608 \). It is noted that the conclusions drawn are insensitive to the use of the daily or the 3-day mean time series.

For each variable, the residual time series resulting from this process has a Nyquist frequency with a period of 6 days. Such a time series is useful for examining relationships on intraseasonal time scales.

4. Results and discussion

a. Relationship of the tropical mean TOA radiation budget to precipitation

The sensitivities of the radiative fluxes to changes in precipitation for each of the six cloud clusters are examined. To establish causal links between precipitation and radiation, cloud macrophysical properties are examined as well. These relationships are highlighted in Table 1, which shows the linear fit of the radiation and cloud property anomalies with the precipitation anomaly. It may generally be stated for the convective clusters that an increase in precipitation rate is associated with increased cloudiness as shown through increased cloud fractions, larger cloud optical depths, and colder cloud-top temperatures and a dominance of the shortwave effect over the longwave effect, consistent with the recent results of Kubar and Hartmann (2007). In contrast, the longwave effect dominates for the stratocumulus, shallow

<table>
<thead>
<tr>
<th>Cloud Type</th>
<th>( \text{SW}_{\text{TOA}} ) (W m(^{-2})/mm day(^{-1}))</th>
<th>( \text{LW}_{\text{TOA}} ) (W m(^{-2})/mm day(^{-1}))</th>
<th>CF 1/(mm day(^{-1}))</th>
<th>CTT K/(mm day(^{-1}))</th>
<th>( \tau_{\text{cloud}} ) 1/(mm day(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stratocumulus</td>
<td>-1.4 ± 3.0</td>
<td>-1.6 ± 2.0</td>
<td>-0.8 ± 1.3</td>
<td>-0.6 ± 0.7</td>
<td>1.0 ± 0.4</td>
</tr>
<tr>
<td>Shallow cumulus</td>
<td>1.6 ± 1.8</td>
<td>-3.9 ± 1.3</td>
<td>-0.3 ± 1.2</td>
<td>-1.1 ± 0.6</td>
<td>0.8 ± 0.2</td>
</tr>
<tr>
<td>Midlevel cumulus</td>
<td>2.4 ± 2.9</td>
<td>-1.4 ± 2.3</td>
<td>0.7 ± 1.5</td>
<td>-0.5 ± 1.1</td>
<td>0.6 ± 0.4</td>
</tr>
<tr>
<td>Mostly clear</td>
<td>3.4 ± 0.6</td>
<td>-4.3 ± 1.1</td>
<td>1.2 ± 0.5</td>
<td>-1.1 ± 0.8</td>
<td>1.2 ± 0.2</td>
</tr>
<tr>
<td>Deep convective</td>
<td>2.2 ± 3.4</td>
<td>-1.2 ± 2.4</td>
<td>0.3 ± 0.7</td>
<td>-0.6 ± 1.3</td>
<td>0.5 ± 0.5</td>
</tr>
<tr>
<td>Cirrus</td>
<td>4.5 ± 2.2</td>
<td>-3.8 ± 2.8</td>
<td>0.6 ± 1.7</td>
<td>-1.4 ± 2.3</td>
<td>0.6 ± 0.1</td>
</tr>
<tr>
<td>Total tropics</td>
<td>6.0 ± 1.5</td>
<td>-3.9 ± 1.5</td>
<td>4.0 ± 1.6</td>
<td>-2.6 ± 1.1</td>
<td>0.6 ± 0.2</td>
</tr>
</tbody>
</table>
cumulus, and clear sky with cloud fraction decreasing in the shallow cloud clusters consistent with the idea of a transition to a more open cellular structure (Wood et al. 2008). In the tropical average the shortwave effect wins over the longwave effect providing a modest cooling effect on the earth–atmosphere system.

An important result demonstrated in Table 1 is that the sensitivity of the tropical mean radiation anomalies tends to be stronger (higher correlation) and larger in magnitude than those derived within any of the individual clusters. One may infer from this result that the tropical average relationships are derived in part from the variability in the relative frequency of occurrence of the various cloud clusters. Furthermore, the implied variability in the cluster frequency of occurrence manifests itself in an evident manner as the sensitivity of the tropics-wide bulk cloud macrophysical properties, defined by the cloud fraction, cloud optical depth, and cloud-top temperature. In particular, it will be shown that the tropical mean radiation anomalies are associated with the relative areas of deep convective activity and clear sky.

Table 1 summarizes the relationships between the radiative and precipitation anomalies over the entire domain as well as the relationships within each cluster. To this point, it is unclear how the cluster sensitivities relate to the tropical mean sensitivities. For example, do the mean relationships result from the variability within each of the cloud clusters, the variability in the relative area of each of the cloud clusters, or some combination of the two. To address this issue, a perturbation budget analysis is introduced that allows for a quantification of each effect. The tropical mean precipitation rate on a given day \( i \) may be calculated as a summation of the precipitation within each cluster \( j \) weighted by the relative area \( a \) occupied by that cluster:

\[
P_i = \sum_j a_i,j P_{i,j}.
\]  

By expanding both terms on the right-hand side into a mean and an anomaly component, the precipitation anomaly may be constructed as

\[
P'_i = P_i - \sum_j \pi_j P'_j = \sum_j \pi_j P'_i + \sum_j a_i,j P_j + \sum_j a_i,j P'_j.
\]

The final term represents the covariability of the anomalies and may generally be neglected, assuming that the anomalies are small relative to the means. In the specific case of the precipitation anomaly this term explains only 0.3% of the variance in the precipitation time series. Neglecting this term gives the following approximate expression:

\[
P'_i = \sum_j \pi_j P'_i + \sum_j a_i,j P_j.
\]

where the precipitation anomaly may be described by two terms. The first term represents the component of the precipitation anomaly associated with variability in precipitation within the various clusters whereas the second term describes the component of the anomaly resulting from the variability in the relative frequency of occurrence of the various clusters. Each of these two terms may further be broken down into six terms associated with each of the individual clusters. Analogous expressions may be composed for any variable \( x \):

\[
x'_i = \sum_j \pi_j x'_j + \sum_j a_i,j x_j.
\]

Assuming a linear relationship between \( x \) and \( P \), one may write

\[
x'_i = \beta_1 \sum_j \pi_j P'_j + \beta_2 \sum_j a_i,j P_j.
\]

The \( \beta \)'s represent the sensitivity of variable \( x \) to intrACLuster variability in precipitation and the cluster frequency of occurrence, respectively. Further, the squared correlation coefficient between the time series of any variable \( x' \) and the two time series on the right-hand side of Eq. (8) gives the fractional variance in \( x' \) explained by a linear fit with each component of the precipitation anomaly. This framework facilitates a quantification of the importance of each term in Eq. (8) in explaining the variability in any other variable.

Following the framework outlined above, the precipitation anomaly, the TOA flux anomalies, and the cloud property (CF, CTT, \( \tau_{\text{cloud}} \)) anomalies are correlated with the two components of the precipitation anomaly. Table 2 outlines the variance explained by each of these linear relationships. It is immediately evident that variability in the precipitation anomaly results in large measure from variability within the clusters (explaining 62.9% of the variance), compared with precipitation variability resulting from cluster frequency of occurrence (explaining 34.4% of the variance). It is further noted that these two modes of variability are nearly linearly independent \( (r = -0.003) \). Despite the dominance of the intrACLuster variability in explaining the domain mean precipitation anomaly, the radiative anomalies are reasonably well described by the fractional occurrence of each cloud cluster and relatively independent of the intrACLuster precipitation variability. This behavior is particularly strong in the case of the longwave anomaly and less so for the shortwave
component. It is further observed that these results are consistent with those of the cloud properties as given by the cloud fraction and cloud-top temperature. The cloud optical depth anomaly is nearly equally well described by each component of the precipitation variability. This feature of the optical depth sensitivity explains the nonnegligible relationship between the shortwave flux anomaly and the cluster precipitation variability as the longwave sensitivity to $\tau_{\text{cloud}}$ is saturated long before the shortwave sensitivity. The specific results shown in Table 2 strongly suggest that the tropical oceanic mean relationships between precipitation and radiation are derived largely from the variability in the fractional occurrence of the various clusters as opposed to the variability within each cluster.

To further highlight the importance of each cluster in explaining the domain mean relationships between precipitation and radiation anomalies, Table 3 shows the variance explained by linear regression of the shortwave and longwave anomalies with the six $a_{ij}'P_j$ terms. Of particular note are the strong relationships between the mostly clear-sky cluster and the shortwave anomaly as well as the deep convective cluster and the longwave anomaly. These results are consistent with a physical system in which the shortwave anomaly is largely driven by the cloud fraction and the longwave anomaly is largely driven by cloud-top temperature. Together with the previous results, these results describe a system where variability in the precipitation variability is associated with the fractional area of deep convective cloud relative to clear sky drives the domain mean radiation anomalies.

### b. The atmospheric column and surface relationships

To examine the responses of the atmospheric column and surface radiation, Fig. 3 shows the mean tropical oceanic radiative anomalies (W m$^{-2}$) plotted as a function of the mean tropical oceanic precipitation anomaly (mm day$^{-1}$). A precipitation anomaly of 1 mm day$^{-1}$ is equivalent to a latent heating anomaly of 26.16 W m$^{-2}$. As has already been shown, a modest net radiative cooling effect is observed at the TOA due to the tendency of the shortwave and longwave effects to cancel. A stronger net cooling dominated by the shortwave effect is seen at the surface and a net warming dominated by the longwave effect is seen within the atmospheric column.

Most importantly, because these results apply to the entire tropical oceanic region including the ascending and descending branches of the large-scale circulations, they demonstrate a radiative–convective cloud feedback that applies tropics wide. An increasing tropical oceanic mean precipitation rate results in increasing tropical cloudiness that acts to decrease shortwave heating at the earth’s surface and decrease longwave cooling of the atmospheric column. In conjunction, these two effects act to stabilize the atmosphere against further precipitation and provide a modest cooling of the combined earth–atmosphere system.

It is well known that precipitation acts to stabilize the tropical atmosphere through the transfer of latent energy from the surface to the atmosphere in a manner associated with radiative–convective equilibrium. Here, it has further been demonstrated that in addition to the latent heating effect, increases in tropical precipitation rate act to establish cloud fields that result in a redistribution of radiative energy from the surface to the atmosphere causing a cooling at the surface and warming in the atmospheric column. This radiative heating is roughly 10% of the magnitude of the latent heating. Although small relative to the latent heating of precipitation, this effect is not insignificant as it demonstrates that precipitation acts to establish a radiation field that damps the need for further precipitation to balance the atmospheric column energy budget. Tropical precipitation therefore has a negative feedback against itself that we call the radiative–convective cloud feedback.

### Table 2

The percent variance explained (100$r^2$) in the anomaly time series [P$'$, SW$'_{\text{TOA}}$, LW$'_{\text{TOA}}$, CTT$'$, $\tau_{\text{cloud}}$] by linear regression with $\sum a_{ij}'P_j$ and $\sum a_{ij}'P_j$.

<table>
<thead>
<tr>
<th></th>
<th>P$'$ (%)</th>
<th>SW$'_{\text{TOA}}$ (%)</th>
<th>LW$'_{\text{TOA}}$ (%)</th>
<th>CTT$'$ (%)</th>
<th>$\tau_{\text{cloud}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sum a_{ij}'P_j$</td>
<td>62.9</td>
<td>9.2</td>
<td>0.6</td>
<td>2.3</td>
<td>1.1</td>
</tr>
<tr>
<td>$\sum a_{ij}'P_j$</td>
<td>36.4</td>
<td>59.3</td>
<td>70.5</td>
<td>53.1</td>
<td>55.3</td>
</tr>
</tbody>
</table>

### Table 3

The percent variance explained (100$r^2$) in the anomaly time series [SW$'_{\text{TOA}}$, LW$'_{\text{TOA}}$] by linear regression with the various $a_{ij}'P_j$ terms.

<table>
<thead>
<tr>
<th></th>
<th>SW$'_{\text{TOA}}$ (%)</th>
<th>LW$'_{\text{TOA}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stratocumulus</td>
<td>10.1</td>
<td>1.8</td>
</tr>
<tr>
<td>Shallow cumulus</td>
<td>2.1</td>
<td>4.0</td>
</tr>
<tr>
<td>Midlevel cumulus</td>
<td>15.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Mostly clear</td>
<td>78.5</td>
<td>27.3</td>
</tr>
<tr>
<td>Deep convective</td>
<td>18.4</td>
<td>30.1</td>
</tr>
<tr>
<td>Cirrus</td>
<td>46.6</td>
<td>71.2</td>
</tr>
</tbody>
</table>
Figure 4 offers a graphical depiction of this feedback. In a climate change scenario, cloud feedbacks are typically quantified in terms of the TOA radiation budget (Stephens 2005; Bony et al. 2006). It is emphasized that the mechanisms of this radiative feedback are different in that they act through the atmospheric column radiative heating. Observations (Stephens et al. 2004) and cloud-resolving model experiments (Fu et al. 1995; Stephens et al. 2008) have demonstrated that the mechanisms hypothesized here act on local scales through the radiative effects of high-level cirrus clouds. This work indicates that the feedback is relevant to the large-scale tropical mean as well.

c. Time-dependent behavior (a demonstration of the feedback)

The results to this point have established a precipitating-cloud radiative feedback that acts in the large-scale tropical mean sense on the 3-day mean time scale. In what follows, the time evolution patterns of these relationships are explored in an effort to demonstrate the existence of this feedback on intra-seasonal time scales. Figure 5 shows the lag sensitivities of anomalous radiative, cloud, and thermodynamic parameters with the precipitation anomaly (see also Figs. 7–11). For reference, the autocorrelation of the
The lag sensitivities of the shortwave and longwave TOA radiative anomalies with respect to the precipitation anomaly are shown in Fig. 5. Interestingly, the statistically significant \((p, 0.01)\) negative autocorrelations in precipitation seen at lags of 10–25 days show an indication of an oscillatory behavior in mean tropical precipitation on a 30–50-day time scale. This oscillation is more clearly demonstrated in the power spectrum \((\Phi)\) of the precipitation anomaly time series shown in Fig. 6. Significant spectral peaks are seen for periods between 30 and 50 days.

As has been shown in the previous section, the lag sensitivities of the radiative anomalies demonstrate that the TOA shortwave anomaly is strongly correlated with the precipitation anomaly and the TOA longwave anomaly is negatively correlated with the precipitation anomaly. The lag sensitivities further bring to light subtle yet important differences in the time evolution of these quantities. The shortwave anomaly demonstrates a high degree of symmetry about the precipitation anomaly whereas the longwave anomaly shows some degree of asymmetry. These subtle differences are amplified in the net radiative anomalies, which are provided in Fig. 7. The net TOA radiative anomaly, which depends on both the short- and longwave effects, lags the precipitation anomaly by roughly 3 days. Furthermore, the net atmospheric radiative cooling anomaly, which results primarily from the longwave effect, does not demonstrate a lag on the time scales considered here.

The above lag sensitivities of radiation may be understood through the corresponding lag sensitivities of the relative frequency of occurrence of the various cloud clusters shown in Fig. 8. Tropical mean precipitation anomalies are associated with a pulsing of the deep convective and cirrus modes compensated primarily with the expansion and contraction of the clear-sky mode with an amplitude near 7%. Statistically significant \((p, 0.01)\) lag sensitivities are also observed between precipitation and the three low cloud clusters that are roughly 90\(^\circ\) out of phase. Recalling that the shortwave anomaly is primarily associated with cloud fraction, whereas the longwave anomaly is associated with cloud temperature, the lag sensitivities of the cloud clusters are generally consistent with those of radiation. To highlight this point, Fig. 9 shows lag sensitivities of CF, \(r_{\text{cloud}}\), and CTT. Owing to the lagged response of shallow cloud, the total CF is in phase with precipitation whereas the build up of high cold clouds commensurate with the build up of precipitation results in the asymmetrical longwave sensitivity. It is interesting to note that the asymmetry observed in the cloud radiative effects on the time and space scales considered in this work are opposite those observed on shorter temporal and spatial scales of individual convective
Differences in the manner in which the large-scale circulation and storm-scale circulations interact with the radiation budget (Yuan and Hartmann 2008) pointing to differences in the manner in which the large-scale circulation and storm-scale circulations interact with the radiation budget. A Parzen estimator with a cutoff point of 107 has been applied to the power spectrum to increase the number of degrees of freedom for significance testing, giving approximately 21 effective degrees of freedom (von Storch and Zwiers 2001). The solid gray line is the theoretical infinite red-noise spectrum computed from the estimated e-folding autocorrelation time scale ($\tau_e$) of the time series as $\Phi_{105} = 2\tau_e/(1 + \tau_e^2\omega^2)$. Statistical significance of spectral peaks was determined using the $F$ statistic as $F_{105} = F_{105,c}$, where in this particular case $F = 1.57$ at the 95% significance level. The dashed gray line represents the level of spectral power that is needed to reach the 95% confidence level for significance. The vertical dashed lines show specific periods from 10 to 50 days. Note the statistically significant spectral peaks between the 30- and 50-day periods.

The net atmospheric column radiative heating shown in Fig. 3 is relevant to the tropical climate. If the net atmospheric column radiative heating shown in Fig. 3 is relevant to the tropical climate, its effects on the column mean temperature should be evident. To test this relationship, the AIRS temperature retrievals are employed. Temperature profiles are not available from AIRS at all locations; however, the data coverage is remarkably complete. Furthermore, because temperature gradients above the boundary layer are weak in the tropics, the available samples should provide a reasonable estimate of the atmospheric column mean temperature. From the time series of daily column mean temperature, an observed temperature tendency time series is derived. The importance of the radiative heating anomaly to the temperature tendency anomaly is illustrated in Fig. 10, which shows the lag sensitivities of the derived atmospheric column temperature tendency as observed by the AIRS algorithm. The temperature tendency lag sensitivities show a similar temporal evolution to that of the atmospheric radiative heating anomalies shown in Fig. 7b. The pattern of lag sensitivities of the AIRS temperature tendency (Fig. 10) and CERES atmospheric radiative heating (Fig. 7b) anomalies correlate at $r = 0.85$. Therefore, radiative heating anomalies well describe the time lag of the temperature tendency time series relative to the latent heating time series. It is also noted that the magnitude of the estimated radiative heating anomaly is twice the magnitude of the temperature tendency anomaly, implying a net transfer of energy out of the region either to adjacent land areas or the extratropics.

Figure 11 demonstrates that the observed temperature anomalies occur primarily in the middle and upper levels. The temperatures in the low levels of the atmosphere that are largely determined by surface fluxes, on the other hand, do not demonstrate significant lag correlations with precipitation. Additionally, Fig. 11 demonstrates that upper-level temperatures are approximately 90° out of phase with precipitation, which is consistent with anomalously unstable atmospheres leading precipitation with anomalously stable atmospheres lagging precipitation.

Taken together, Figs. 5–11 paint a picture of an oscillating system in which anomalies in tropical mean precipitation are dominated by oscillations in the frequency of occurrence of deep convection that in turn are associated with variability in tropical mean cloudiness, radiation, and stability. Positive precipitation anomalies appear to be preceded by colder than normal middle- and upper-level
temperatures and followed by anomalously warm temperatures consistent with the observed radiative and latent heating. Moreover, the coherent relationships between precipitation, cloud, radiation, and temperature fields on intraseasonal time scales demonstrate the action of the radiative–convective cloud feedback implied in the previous section on these time scales within the tropical oceanic atmosphere. The feedback acts through a coupling of tropical mean precipitation with the column radiative heating that is primarily associated with an expansion and contraction of the relative areas of deep convection and clear sky.

5. Summary

Five years of remote observations from several sensors on board NASA’s A-Train constellation of satellites are examined to identify the relationships between the tropical oceanic mean precipitation anomaly and radiation anomalies. Tropics-wide averages are employed to examine these relationships on a spatial scale including both the ascending and descending branches of the Hadley and Walker circulations. The tropical oceanic precipitation anomaly is well correlated with the radiative
anomaly at the top of the atmosphere, the surface, and
within the atmospheric column. At the top of the atmo-
sphere the short- and longwave components tend to
cancel each other, leaving a modest cooling effect. At the
surface a stronger shortwave cooling effect is observed
and in the atmosphere a longwave heating effect is evi-
dent. It is identified that these relationships are derived
from an increase in the relative area of tropical high cold
clouds with increasing precipitation. Commensurate with
the expansion of the deep-convective area is a contrac-
tion of the clear-sky area. These mechanisms are iden-
tified as a radiative–convective cloud feedback wherein
tropical convection tends to produce cloud fields that
cause a reduction of the atmospheric cooling rate and
a commensurate warming of the atmospheric column.
The radiative warming anomaly is roughly 10% of the
latent heating anomaly.

The shortwave component of the feedback is sug-
gestive of the thermostat hypothesis (Ramanathan
and Collins 1991) that is associated with changes in the
cloud macrophysical properties. Within the atmospheric
column the feedback is reminiscent of the global radiative–
convective feedback described by Fowler and Randall
(1994) that acts to stabilize the atmosphere thorough
increased high cloudiness associated with convection,
resulting in decreased atmospheric cooling rates. Thus,
it is shown that the weak relationships between precipi-
tation and net radiation at the TOA due to the near
cancellation of the short- and longwave effects is mani-
fest as a radiative redistribution of energy from the sur-
face to the atmosphere, which would act to stabilize the
tropical atmosphere against further precipitation. This
mechanism is supportive of the radiative–convective
elements of the humidistat feedback hypothesized by
Stephens et al. (2004), which was demonstrated to act on
local spatial scales relevant to the Madden–Julian oscil-
ation (Madden and Julian 1971, 1972). Importantly, the
present study demonstrates that these mechanisms are
applicable on the tropical mean spatial scale through a
modulation of the area of tropical high cloudiness, dem-
onstrating that the feedback is evident on a tropics-wide
scale more directly relevant to global climate.

The feedback presented here may potentially have
important ramifications on predictions of the global
hydrologic cycle in a global warming scenario. However,
it is cautioned that extension of simple correlative re-
sults found on intraseasonal time scales to the time
scales relevant to climate change may not be appropri-
ate. For example, if this analysis were repeated using
monthly averaged data, one would average over the fre-
quencies explored in this work and may well find sensi-
tivities much smaller than those derived in the present
study.

Despite the aforementioned cautionary note, it is of
some interest to briefly discuss these results within the
context of climate change because evidence exists that
aspects of the cloud feedback discussed in this work
have been identified in climate simulations (Fowler
and Randall 1994; Stephens and Ellis 2008). Global climate
models predict an enhancement of the radiative cooling
rate of the atmosphere that is largely balanced by an
increase in the global precipitation rate, resulting in an
enhancement of the global water cycle on the order of
2%–3% K⁻¹ (Allen and Ingram 2002; Held and Soden
2006; Stephens and Ellis 2008). The results presented
here suggest that the tropical atmosphere tends to
respond to increased precipitation by establishing cloud fields that act to reduce the rate of atmospheric radiative cooling. Assuming that the linear relationships derived in this study (Fig. 3) for the present climate are applicable to a perturbed climate, this negative cloud feedback could act to counter an enhancement of the global hydrologic cycle by approximately 10%. In addition, a modest negative feedback at the TOA and a stronger surface feedback would be observed. These estimates are premised on the assumption that the linearity of the relationships derived for the current climate are applicable to a future perturbed climate and therefore must be considered somewhat speculative in nature. Furthermore, the mechanisms presented here represent only one potential cloud feedback and ignore sensible heating feedbacks that tend to be nonzero in climate models (Stephens and Ellis 2008).

Finally, the feedback presented here may be understood through an expansion and contraction of the cloudy area associated with convection. Recent analysis (Viju et al. 2009) of both observations and model simulations of precipitation over a similar area over a multidecadal time scale are consistent with the idea of wet areas becoming wetter and dry areas becoming drier. This result implies fixed areas of convection and subsidence on decadal time scales. It is relevant to ask to what extent this observation implies fixed areas of tropical high cloud cover as well? This question and the previously stated concerns regarding the relevance of these results across various time scales motivate future research into the applicability of the relationships derived in this work over a broad range of time scales.

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