Seasonal and Interannual Variations in Stratiform and Convective Clouds over the Tropical Pacific and Indian Oceans from Ship Observations

LOUIS J. BAJUK* AND CONWAY B. LEOVY

Department of Atmospheric Sciences, University of Washington, Seattle, Washington

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ABSTRACT

Anomalies in frequency of occurrence of stratiform and convective cloud types identified by volunteer observing ships are related to anomalies in SST and surface wind divergence for the tropical Pacific and Indian Oceans for the period December 1952–December 1992. Cloud type frequency anomalies have also been related to outgoing longwave radiation (OLR) anomalies for the period 1979–91. The strongest cloud frequency signals are associated with the seasonal shift in the ITCZ and with the first empirical orthogonal function of SST after removal of the annual cycle. The latter corresponds to the annually averaged SST signature of ENSO. Data are separated into two seasons to display these signatures: January–May corresponding to warm eastern Pacific equatorial SST and July–November corresponding to cool eastern Pacific equatorial SST. Relationships between cloud type frequencies, SST, and divergence are generally similar for spatial variations within each season, and for seasonal and ENSO-related differences. The major cloud frequency shifts are between stratiform clouds and large cumulus east of 130°W and between small cumulus and deep convective clouds west of 130°W. East of 160°E, frequency of deep convective cloud increases rapidly above a knee in the curve of frequency versus SST located near 25.5°C in July–November and near 27°C January–May. Since this temperature difference is similar to the difference in midtropospheric mean temperature between the same seasons in the same region, this relationship suggests strong control of deep convection by mean static stability in this region. As expected, a strong and linear relationship exists between anomalies in OLR and in the frequency of deep convective clouds observed at the surface.

1. Introduction

Clouds over tropical oceans are important components of the climate system with profound feedback influences on the distributions of radiative, latent, and sensible heating. The variability of tropical convective clouds in relation to the factors controlling their distributions have been the subject of extensive study (e.g., Bjerknes 1969; Gadgil et al. 1984; Graham and Barnett 1987; Waliser and Graham 1993; Fu et al. 1990, 1994). The frequency of deep convection (FDC) at a single point is an important variable connecting convection to net incoming solar flux, outgoing longwave radiation (OLR), upper-tropospheric relative humidity, and clear-sky greenhouse effect (Ramanathan and Collins 1991; Hartmann and Michelson 1993; Soden and Fu 1995). As measures of FDC, these studies have used satellite radiance variables such as the frequency of highly reflective cloud (HRC), OLR, and indices based on cloud-top temperature and visible cloud opacity from International Satellite Cloud Climatology (ISCCP) data, with OLR the most widely used of these. Cloud observations by surface-based observers have not previously been used to infer seasonal or interannual variations of FDC or to validate FDC inferences derived from OLR.

Stratified boundary layer clouds also occur over tropical oceans and their variations have been investigated using surface as well as satellite data. Deser and Wallace (1990) compared total cloud cover with seasonal and El Niño–Southern Oscillation (ENSO) variations in SST, surface wind patterns, and other meteorological variables. Weare (1994) used satellite data and Norris and Leovy (1994) used surface data to show that coverage of boundary layer clouds over oceans is inversely correlated with SST. Klein and Hartmann (1993) and Klein et al. (1995) used surface data to show that stratiform cloud cover over subtropical oceans correlates more closely with an index of lower-tropospheric static stability than with other variables tested, including SST. Climatology, data from special observational campaigns, and modeling studies all show that the predominant low cloud type undergoes a transition from stratiform to shallow convective cloud as the subtropical inversion weakens and dissipates along boundary layer


Corresponding author address: Conway B. Leovy, Department of Atmospheric Sciences, University of Washington, Box 351640, Seattle, WA 98195-1640.

E-mail: conway@atmos.washington.edu

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wind trajectories from cool subtropical to warm tropical waters (e.g., Bretherton 1992; Bretherton and Wyant 1997; Wyant et al. 1997). The further transition from shallow to deep convective clouds occurs over the warmest waters of the tropical Pacific and Indian Oceans.

Observations of cloud type made by surface observers have both advantages and disadvantages compared to satellite observations. The latter give a global view of the climate system and reduce or eliminate errors resulting from subjective cloud identifications and sampling variability, both of which are problems of surface data. Surface observations are available over a longer time period, in this case approximately 41 yr, provide the “bottom up” view that is complementary to the satellite “top down” view, and allow identification of particular cloud types that may be associated with particular boundary layer structures. For example, surface observations can be useful for distinguishing cloud types characteristic of fully coupled (stratocumulus), partially decoupled (cumulus with stratocumulus), and fully decoupled (cumulus) boundary layers that are difficult to distinguish in satellite data (Norris 1998a).

It is now practical to use surface observations to study climatological variations of low cloud types because of the availability of a large set of marine surface cloud observations derived from the Comprehensive Ocean Atmosphere Data Set (COADS; Woodruff et al. 1987). Screening procedures have been developed and applied for cloud observations by Warren et al. (1998) and Hahn et al. (1994) and their algorithm has been applied to COADS data from December 1951 through December 1992 by Norris (1998b). The resulting dataset is used here to investigate relationships between variations of the frequencies of low cloud types as observed at the surface, SST, and surface wind divergence. Relationships between cloud observations and OLR are also investigated, but OLR data are available only for 12 out of the 41 yr for which cloud data are available.

We have divided the data into two seasons following the study of ENSO variability of Mitchell and Wallace (1996): January–May, the eastern equatorial Pacific warm SST season, and July–November, the eastern equatorial Pacific cool SST season. This seasonal division is useful for characterizing different phases of El Niño, and also distinguishes the seasonal north–south shift of the ITCZ. Because large samples are needed to yield reliable results from surface observations of clouds, we have not attempted to break the cloud frequency data down into other seasonal groups or shorter seasonal intervals that might better characterize the seasonality of the south Asian monsoon, for example. Moreover, we have limited our analysis to the tropical Indian and Pacific Oceans because of the strong ENSO signals that are found there. For the tropical Indian and Pacific Oceans, we ask: what are the seasonal and ENSO-related variations in the frequencies of low cloud types? How are these variations related to the corresponding variations in SST and surface wind divergence? How are variations in OLR related to the frequency of deep convective clouds directly observed by volunteer ships?

2. Data and analysis

a. Cloud data

Surface observers normally report total cloud cover, lower cloud cover fraction, and low, middle, and high cloud types. Cloud type identification is made according to a strict system of classification from the World Me-
teorological Organization code (WMO 1975). A brief summary of the low cloud types is given in Table 1. The choice of which low cloud type to report if multiple types are present is made according to a strict hierarchy. If any cumulonimbus (Cb) with anvil (CL9), Cb without anvil (CL3), stratocumulus (Sc) formed from the spreading of cumulus (CL4), cumulus (Cu) and Sc mixed at different levels (CL8, generally stratocumulus overlying cumulus), or Cu (CL2, cumulus of moderate or strong vertical extent) are present, in that order of preference, it is reported as the low cloud type. Otherwise, the low cloud type is reported as whichever of the following covers the largest area of sky: small Cu (CL1, cumulus of little vertical extent), Sc not formed from Cu (CL5), stratus (St) other than stratus of bad weather (CL6), or ragged St or Cu of bad weather (CL7, distinguished by the association with nimbostratus or altostratus, often with precipitation).

Cloud observations were averaged into a 10° lat × 20° long grid of monthly mean frequency of observation (the fraction of observations reporting a given cloud type) and monthly mean amount when present (the average sky cover by low clouds when the given cloud type is reported). Average low cloud amount, the overall average sky cover associated with that cloud type, is the product of these two factors. Only cloud type frequency is analyzed here in relation to the analyzed SST, divergence, and OLR variables; long-term variations of both cloud type frequency and amount when present are examined in a companion paper (Bajuk and Leovy 1998). The large grid box size (as shown in Fig. 1) was used because of the relative scarcity of low cloud observations over the Southern Hemisphere oceans during the early part of the record. Figure 1 also shows the number of observations per month averaged over the full 41-yr period.

b. Other meteorological variables

Surface wind observations were taken from COADS, averaged onto a 5° × 5° monthly grid, and then used to calculate a monthly gridded dataset of surface wind divergence, which was then averaged to the 10° × 20° grid. SST data were obtained from the Global Ocean Surface Temperature Analysis (GOSTA; see Bottomley et al. 1990) and averaged to the 10° × 20° grid of monthly means. OLR data for the period 1979–91 were obtained from the Climate Analysis Center as monthly means on a 2.5° × 2.5° grid, and were averaged into the 10° × 20° grid to match the cloud observations.

c. Analysis

As described above, the data were divided into warm (January–May) and cool (July–November) seasons of eastern equatorial Pacific SST. The transitional months (June and December) were excluded to sharpen the seasonal focus. To form the climatologies, all the months in the 41-yr period were averaged separately for the two seasons. The anomalies associated with ENSO were calculated by first removing the average annual march, and then performing a linear regression in each grid box onto an ENSO index, as in Deser and Wallace (1990). The index we used is described in the appendix and displayed in Fig. A1. The linear regression results were scaled by the standard deviation of the SST time series, so that maps displaying composite ENSO anomalies represent a “typical” variation (i.e., the amplitude associated with one standard deviation above the mean in the SST time series used for the regression). Following Mitchell and Wallace (1996), we call this derived quantity the “standard anomaly.” The linear regression ensures symmetry of the relationships for positive and negative anomalies.

Observations of St (CL6), no low cloud, or obscured
sky conditions are all quite rare in the Tropics and are not considered here. All other low cloud types are grouped into five categories intended to correspond to a sequence of boundary layer structures ranging from moderately shallow and inversion capped through transitions to shallow convection and deep convection. 1) Stratocumulus (CL5) generally corresponds to a fairly well mixed boundary layer capped by a distinct inversion. 2) Mixed stratocumulus–cumulus includes both CL8 and CL4. CL8 corresponds to an inversion capped boundary layer, but the inversion is generally higher and weaker than that associated with stratocumulus, and there is substantial decoupling between a well-mixed surface layer and the upper portion of the planetary boundary layer (Bretherton and Wyant 1997; Norris 1998a). Systematic relationships, if any, between CL4 and boundary layer structure have not been documented, but both CL4 and CL8 are assumed here to correspond to a state intermediate between stratified and convective boundary layer conditions. 3) Small cumulus clouds (CL1) are indicative of shallow convection, but they may occur with a low inversion base that is near or only slightly above the lifting condensation level (Norris 1998a). 4) Large cumulus clouds (CL2) are assumed to indicate boundary layer conditions intermediate between those of shallow and deep convection, but CL2 is sometimes reported with a high and weak trade wind inversion over subtropical oceans (Norris 1998a). 5) Deep convective clouds include Cb (CL3 and CL9) and ragged St or Cu of bad weather (CL7), which is assumed to correspond to deep convection near the observation site when it is reported in the Tropics. This separation between low cloud groups is different from, and should be considered complementary to, the separation employed in the ISSCP dataset (Rossow and Schiffer 1991). We display geographical distributions of seasonal variations and variations related to ENSO index and also translate cloud frequency distributions into a phase space projection by displaying two-dimensional scat-
Fig. 3. Same as in Fig. 2 but for the cool season. In each panel, the horizontal axis is SST in °C and the vertical axis is divergence ($s^{-1} \times 10^4$). The lettered points identify particular grid boxes whose locations are shown in Fig. 1 and Table 2.

Cloud frequency data is subject to both random and systematic errors due to incorrectly identified or ambiguous cloud types. In Bajuk and Leovy (1998), we show that there are significant global long-term drifts in frequencies of all cloud types used in this study. For purposes of the present analysis, the most significant long-term drifts include a trend toward increased frequency of large Cu at the expense of small Cu early in the record and a general decline in frequency of identification of CL4 and increases in frequency of identification of CL3, 5, and 9 between 1951 and 1980, with opposite trends thereafter. These slow global drifts are interpreted as artifacts of observational bias.

Random errors in observer identifications reduce the apparent signal of any real cloud variations. Based on comparisons between observations from volunteer observing ships and fixed weather ships in the same regions and times described in Bajuk and Leovy (1998), we estimate that random observer error diminishes cloud frequency signal amplitudes by less than 30%.
scales longer than those examined here. To the extent that these pollute our results, they will reduce the strengths of relationships between cloud type frequency variations and variations in related quantities. The analysis was done with and without an attempt to remove apparently spurious long-term Cb trends with little difference in results. Because there is inevitably a certain degree of arbitrariness in such a bias removal procedure, we have chosen to present the data without attempting to remove these trends. Based on the internal consistency of the results, we do not believe that these noise sources significantly affect our conclusions.

3. Results

a. Relationships between cloud type frequencies, SST, and divergence in warm and cool seasons

In Figs. 2 and 3, each of the cloud type frequencies and OLR are plotted as phase space projections in the plane of SST and surface wind divergence. Since SST and divergence are negatively correlated, the occupied portion of the SST-divergence domain is narrow and elongated from low SST-high divergence (upper left) to high SST-low divergence (lower right) in these figures. As expected, there is a progression across this space from stable boundary layer clouds (Sc and mixed Sc–Cu), through small and large Cu to deep convective clouds corresponding to the progression from lowest SST and highest divergence values to highest SST and highest convergence values.

This general pattern applies, with some exceptions, to both seasons. Seasonal changes at the selected points indicated by letters in Figs. 1, 2, and 3 are given in Table 2. As the season shifts, points corresponding to grid boxes in Fig. 1 shift across the SST-divergence plane while the pattern through which they shift remains quite stable. For example, point G, near northern Madagascar, shifts from a region in the plane dominated by deep convective cloud to a region dominated by small Cu as it moves from SST and divergence values characteristic of the warm season to values characteristic of the cool season. Point D, off the Central American coast, shifts from the region in the plane dominated by small Cu during the warm season to a region dominated by deep convective clouds during the cool season. As expected, the distribution of points with high frequency of deep convective cloud is very similar to the distribution of points with low OLR in Figs. 2 and 3.

Because of the correlation between SST and divergence, it is difficult to distinguish independent relationships between cloud type frequencies or OLR and SST or divergence. However, close inspection of Figs. 2 and 3 suggests that there is a tendency to shift from small Cu to large Cu to deep convective cloud as divergence increases at fixed SST, especially in the SST range 25°–28°C. This tendency is consistent with the result of Fu et al. (1994), and will be discussed further below.

b. Seasonal shifts

Figure 4 shows the seasonal (warm minus cool season) shifts in cloud type frequency, SST, and OLR. Between 10°N and 25°S and east of 130°E, where mean

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Table 2. Cold season climatological mean and warm–cool season (Δ) shift for SST, divergence, and cloud FQ by cloud type group, for points labeled in Figs. 1–3.

<table>
<thead>
<tr>
<th>Box</th>
<th>Location</th>
<th>Cold SST</th>
<th>ΔSST</th>
<th>CL1 FQ</th>
<th>ΔFQ</th>
<th>CL2 FQ</th>
<th>ΔFQ</th>
<th>CL3 FQ</th>
<th>ΔFQ</th>
<th>CL4 FQ</th>
<th>ΔFQ</th>
<th>CL5 FQ</th>
<th>ΔFQ</th>
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<th>CL7 FQ</th>
<th>ΔFQ</th>
<th>CL8 FQ</th>
<th>ΔFQ</th>
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<td>A</td>
<td>20°–30°N, 140°–160°E</td>
<td>28.06</td>
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<td>0.22</td>
<td>0.02</td>
<td>0.29</td>
<td>−0.1</td>
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<td>−0.08</td>
<td>0.05</td>
<td>0.04</td>
<td>0.02</td>
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<td>0.02</td>
<td>0.01</td>
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<tr>
<td>B</td>
<td>10°–20°N, 100°–120°E</td>
<td>28.3</td>
<td>−1.63</td>
<td>0.24</td>
<td>0.02</td>
<td>0.31</td>
<td>−0.02</td>
<td>0.29</td>
<td>−0.12</td>
<td>0.16</td>
<td>0.16</td>
<td>0.14</td>
<td>0.12</td>
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<td>C</td>
<td>10°–20°N, 140°–160°E</td>
<td>29.08</td>
<td>−1.65</td>
<td>0.24</td>
<td>0.02</td>
<td>0.31</td>
<td>−0.02</td>
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<td>−0.12</td>
<td>0.16</td>
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<td>D</td>
<td>10°–20°N, 120°–100°W</td>
<td>28.14</td>
<td>−1.51</td>
<td>0.24</td>
<td>0.02</td>
<td>0.31</td>
<td>−0.02</td>
<td>0.29</td>
<td>−0.12</td>
<td>0.16</td>
<td>0.16</td>
<td>0.14</td>
<td>0.12</td>
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<td>0.14</td>
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<td>E</td>
<td>0°–10°S, 160°–140°W</td>
<td>27.37</td>
<td>0.4</td>
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<td>0.31</td>
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<td>F</td>
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<td>23.57</td>
<td>2.33</td>
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<td>0.16</td>
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<td>0.12</td>
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<td>3.71</td>
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<td>0.31</td>
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<td>3.7</td>
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Fig. 4. Lat–long plot of warm season minus cool season climatology of monthly mean cloud frequencies and OLR (W m$^{-2}$), and surface wind divergence ($s^{-1} \times 10^6$) for the tropical Indian and Pacific Oceans. Contour intervals are 2% for cloud frequencies (a)–(e), 0.5°C for SST (f), 5 W m$^{-2}$ for OLR (g), and $1 s^{-1} \times 10^6$ for divergence (h). Zero contours are shown by heavier lines.
FIG. 4. (Continued)
Fig. 5. Lat–long plot of warm season ENSO anomalies calculated from linear regression onto an ENSO index, scaled to correspond to one standard deviation in the index time series for the warm season. Contour intervals are 0.5% for cloud frequencies (a)–(e), 0.1°C for SST (f), W m⁻² for OLR (g), and 0.25 s⁻¹ × 10⁶ for divergence (h).
Fig. 5. (Continued)
Fig. 6. Lat–long plot of cool season ENSO anomalies calculated from linear regression onto an ENSO index, scaled to correspond to one standard deviation in the index time series for the warm season. Contour intervals are 0.5% for cloud frequencies (a)–(e), 0.1°C for SST (f), W m$^{-2}$ for OLR (g), and 0.25 s$^{-1} \times 10^6$ for divergence (h).
SST is below about 25°C, Sc and mixed Sc–Cu shift to small and large Cu. South of 10°S and from 130° to 150°E, Sc and mixed Sc–Cu shift to large Cu and deep convective cloud. Over the remainder of the region, the predominant shift is from small Cu to deep convective cloud over warming waters south of the equator and from deep convective cloud to small Cu over cooling waters north of the equator. The negative correlation between small Cu and deep convective cloud is remarkably strong. Deep convective cloud frequency shifts correspond closely to shifts of opposite sign in surface divergence and OLR, and they are less closely related to shifts of the same sign in SST.

c. ENSO-related shifts, warm season

Figure 5 maps warm season standard anomalies in cloud type frequency, OLR, SST, and divergence. The most striking feature is the shift to deep convective cloud with increasingly positive ENSO index over the central and eastern Pacific in a narrow band centered at 5°S, 170°W. Although deep convective cloud increases mainly at the expense of small Cu, some increase is also at the expense of large Cu that is the most common warm season low cloud type in the equatorial region between longitudes 160°E and 180°. This narrow band centered near 5°S is bounded on its northern and southern sides and to the west by shifts in the opposite sense, with the largest located in the region 0°–15°N, 120°–140°E.

Over the Indian Ocean, shifts in cloud type frequency are small for our choice of seasons. The most striking shift as ENSO index rises is from small Cu to deep convective cloud in a narrow band centered near 5°S, 90°E with shifts of opposite sign to the north and south.

Just as for the seasonal mean shifts, the pattern of ENSO shifts in deep convective cloud frequency from the cold to the warm season are very consistent with the pattern of shifts in surface wind divergence. It is less consistent with the pattern of OLR shifts: the max-
**Fig. 8.** Scatterplot of cloud frequencies and OLR vs SST for the cool season. Each arrow represents an individual grid box. The horizontal axis in each panel is SST in °C; the vertical axis is frequency of occurrence of the cloud type in %, or of OLR in W m⁻². The tail of the arrow is the climatological value, the head of the arrow is the total field (climatological + ENSO anomaly) for one standard deviation positive phase ENSO anomaly. The dotted line is a heavily smoothed average of the climatological values.

**d. ENSO-related shifts, cool season**

During the cool season, the standard anomaly patterns are more complex (Fig. 6). East of 130°W, there is a striking shift from Sc and mixed Sc–Cu to large Cu and, less prominently, to small Cu. In the region of the intertropical convergence zone near 5°N from 130° to 110°W, deep convective cloud also increases significantly at the expense of Sc and mixed Sc–Cu.

Farther west, between 20°N and 20°S, the dominant shift is from small Cu to deep convective cloud over the Indian Ocean and the central and eastern Pacific and from deep convective cloud to small Cu over the western Pacific between about 100° and 150°E. The pattern of large Cu change tends to follow that of deep convective cloud, but it is weaker and less well organized.

Shifts in deep convective cloud frequency are closely related to shifts in both OLR and surface wind diver-
Fig. 9. (a) ENSO standard anomalies plotted as in Fig. 7 for deep convective clouds for the tropical Indian Ocean during the warm season. (b) Same as (a) but for OLR. (c) Same as (a) but for the eastern and central Pacific during the cool season. (d) Same as (c) but for OLR. Dotted lines represent the smoothed oceanwide means for the corresponding seasons. For each panel, the horizontal axis is SST in °C; the vertical axis is frequency of occurrence in % for the two left panels and W m⁻² for the two right panels. Dashed circles correspond to data points for grid boxes over the South Pacific in latitudes 20°–30°S where OLR does not represent deep convection well.

gence. The key role of SST is also indicated by these data. Where seasonal mean SST is below about 25°C, the dominant shift is from Sc and mixed Sc to large Cu. Where it is higher, the dominant shift is from small Cu to deep convective cloud and, to a lesser extent, to large Cu.

e. How consistent are seasonal mean and ENSO variations of cloud type frequency, SST, and divergence?

Standard anomalies of cloud type frequency in the five cloud type categories are plotted as arrows against SST in Figs. 7 and 8. In each panel, the tail of each arrow corresponds to the climatological mean and the head corresponds to the climatological mean plus the standard anomaly for one positive standard deviation of the ENSO index. The dashed curve in each panel represents an estimate of the dependence of the climatological mean value on SST based on a weighted running mean estimator (Chambers et al. 1979).

The standard anomaly vectors tend to follow the climatological mean trends in most, but not all, of the grid boxes. As expected, the frequencies of both Sc and mixed Sc–Cu decline with increasing SST, especially at lower values of SST. Frequency of large Cu increases with SST at all values of SST, whereas frequency of small Cu and deep convective cloud and OLR show closely coupled variations: deep convective cloud frequency increases with increasing SST at all values of SST, but there is a threshold of rapid frequency increase at about 26°C, corresponding closely to the maxima in small Cu frequency and OLR. This threshold occurs at the same temperature for three related independent variables (deep convective cloud, small Cu, and OLR) in both warm and cool seasons, but it shifts from about 25.5°C in the cool season to about 27°C in the warm season. A similar rapid increase onset, appearing as a knee in the relationship between FDC and SST, has been shown in the analysis of OLR and other satellite measures in several previous studies. For example, Walsh and Graham (1993) show a similar knee for frequencies of HRC at 26°C. Our data are consistent with this result and, in addition, the surface deep convective and small Cu cloud frequencies and OLR together suggest that there is a seasonal shift in the knee.

The pattern of standard anomaly variations shown by the arrows in Figs. 7 and 8 is dominated by large changes in the tropical Pacific east of 160°W. Standard anomaly arrows in the western Pacific and Indian Oceans are generally much smaller and do not parallel seasonal mean variations. This geographical dependence is illustrated in Fig. 9 for deep convective cloud and OLR. Warm season Indian Ocean standard anomaly arrows are very small (Figs. 9a,b) and at temperatures above about 28.5°C, several grid boxes show slight declines in deep convective cloud frequencies and corresponding slight rises in OLR with increasing
SST. The contrasting high degree of consistency between standard anomalies and seasonal mean dependencies of deep convective cloud frequency and OLR on SST for the cool season Pacific east of 160°E is shown in Figs. 9c,d.

On the other hand, standard anomalies of deep convective cloud frequency tend to follow seasonal mean variations in surface wind divergence across the entire tropical Pacific and Indian Ocean region, as illustrated in Fig. 10 for the warm season (left three panels) and the cool season (right three panels). The upper panels show the tropical Indian Ocean (west of 100°E), middle panels show the western Pacific (100°–160°E), and the lower panels show the central and eastern Pacific (east of 160°E). Although the standard anomalies are generally small west of 160°E (with the exception of two grid boxes near Australia in the warm season), there is a distinct tendency for the standard anomaly arrows to parallel the seasonal mean curve in all three regions and in both seasons.

f. What is the relationship between FDC and OLR?

OLR is a well-known and widely used measure of FDC in low latitudes, but it is not clear that it is a linear measure. Frequency of deep convective cloud gives an alternative measure of FDC, the directly observed frequency of these clouds within view of ship observers. In Fig. 11, we test the linearity of the relationship between OLR and the latter measure of FDC, including only data in the tropical band 20°S–20°N. Figures 11a–c compare cloud frequency anomalies from 1952–92 with OLR anomalies for 1979–92. Figure 11a demonstrates that this OLR–FDC relationship is strong, linear, and symmetric with respect to positive and negative variations on the seasonal timescale. A cluster of three points falling far below the linear relationship corresponds to points over strong upwelling regions off of the North and South American coasts and in the Arabian Sea where SST and low cloud properties have more influence on OLR variations than deep convective

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cloud. The correlation would be stronger if these points were removed.

The OLR–FDC relationships for the ENSO standard anomalies, shown in Figs. 11c,d, are also linear and symmetric with respect to positive and negative deviations. Not surprisingly, given the smaller range of variation and correspondingly greater role of noise, the standard anomaly data are more scattered and the correlations lower than in the seasonal case. The slopes of the regression lines are also smaller, and quite significantly so in the warm season (Fig. 11b), which compares the entire 41-yr cloud record with the 1979–91 OLR period. When the OLR-deep convective cloud regression is recalculated using cloud frequency data from only the 1979–91 period, this relationship closely resembles that for the cool season (Fig. 11d). Consistent with the results of Mitchell and Wallace (1996), differences in ENSO warm season behavior between the years 1952–78 and 1979–91 are responsible for the weaker apparent relationship shown in Fig. 11b (see the discussion of ENSO-related shifts in the warm season in section 3c above). Regression line slopes for the seasonal differences and for the two ENSO seasons (using data for 1979–92 only for the warm season) are approximately $-0.3$ (percent change in deep convective cloud) per W m$^{-2}$ change in OLR. The true slope of the best linear relationship between deep convective clouds and OLR could be slightly larger than this value because of reduction of signal of any deep convective cloud FQ variations due to random observing errors and because of the implicit assumption of the simple linear regression model that errors in the independent variable (OLR) are negligible.

4. Discussion

Surface cloud type observations support previous inferences of tropical cloud variations based on satellite data or surface cloud cover observations. Consistent with Klein and Hartmann (1993), Weare (1994), and Norris and Leovy (1994), frequencies of tropical stratiform and transitional boundary layer cloud types both decline with increasing SST. The suggestion of Deser and Wallace (1990) that boundary layer stratiform cloud types tend to shift to convective cloud types as SST rises in the eastern equatorial Pacific is confirmed. This pattern is especially prominently seen in ENSO variations during the July–November cool season east of 130°W where the shift in cloud type is mainly from Sc and mixed Sc–Cu to large Cu.

Over the central and eastern Pacific west of about 130°W, increase in frequency of deep convective cloud coincides with decrease in small Cu, but the frequency of large Cu also rises over the entire range of SST change so that the apparent trade-off between members at the large and small ends of the convective cloud size spectrum is due to an overall shift toward greater frequency of larger cloud sizes. As in previous studies, a knee in the curve of some measure of FDC (in our case, frequency of deep convective cloud observed from the surface) versus SST occurs near 26°C, with the FDC measure rising much more rapidly with SST above that.
point. However the surface observations also indicate that the position of the knee varies from about 25.5°C in the cool season to 27°C in the warm season. This variation is consistent with seasonal shifts in midtropospheric tropical mean temperatures and static stability or convective available potential energy (CAPE; Oort and Rasmussen 1971; Hoskins et al. 1989; Khalsa 1989), and it reinforces the hypothesis that CAPE changes play a dominant role in controlling deep convection in the central and eastern Pacific.

The frequency of deep convective cloud observed at the surface may be a more direct measure of FDC than satellite measures such as OLR. Our analysis shows that frequency of deep convective cloud exhibits a close linear relationship to OLR on both seasonal and ENSO timescales. Soden and Fu (1995) found little indication of a general relationship between FDC inferred from satellite data and SST. Our analysis suggests two factors that contribute to this result. In the Pacific east of 140°E, the frequency of deep convective cloud increases consistently but nonlinearly with SST, rising slowly below about 26°C and rapidly above. More important is the absence of a consistent deep convective cloud–SST relationship west of 140°W, as also shown by the satellite data analyses of Gadgil et al. (1984), Graham and Barnett (1987), Waliser and Graham (1993), and Fu et al. (1994) as well as by the present analysis. In this region, deep convective cloud frequency increases consistently with increasing convergence, however.

While the good relationship between FDC and SST in the central and eastern tropical Pacific can be understood as a response to CAPE changes, the poor relationship and clearer FDC-divergence relationship over the warmer waters of the west Pacific and Indian Ocean is harder to interpret. As SST rises above 28°C, SST and satellite measures of FDC become anticorrelated but FDC and convergence are well correlated (Gadgil et al. 1984; Waliser and Graham 1993; Graham and Barnett 1987). Figures 9a and 9b hint at a similar anticorrelation between FDC and SST in our composite data for the Indian Ocean for SST > 28.5°C. In the
western tropical Pacific, both ENSO-related surface wind divergence and deep convective cloud frequency anomalies are much stronger during the January–May warm season than during the July–November cool season. Both of these observations suggest that large-scale surface convergence is not merely a passive response to local deep convective heating, responding in turn only to local CAPE, but that it also has a component that is forced by large-scale dynamical factors, such as a compensating response to distant latent heat release and convergence.

The effect of divergence as the dynamical response to remote heating is evident in the soundings examined by Fu et al. (1994) and in a recently published 20-yr series of soundings from Pohnpei, Truk (Chuuk), Majuro, and Koror island stations near 7°N between 134.5° and 158.3°E (Gutzler 1996). Specific humidity at the 1000- and 700-hPa levels reaches distinctive minima early in the warm season when seasonal divergence is strongest at this latitude. It also reaches distinctive minima during the cool season phase of strong ENSO events. Fu et al. (1994) and Gutzler (1996) show that CAPE minima also occur at these times, and that the CAPE minima are primarily due to specific humidity minima in the boundary layer. Our results support the view that suppression of FDC in regions of prevailing high SST is primarily due to drying of the planetary boundary layer and/or lower troposphere above the boundary layer in response to divergence driven by distant heat sources.

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APPENDIX

ENSO Index for Linear Regression

The index used for the linear regression was the time series associated with the first EOF (after removal of the annual cycle) of SST in the tropical (±20°) Pacific and Indian Ocean (as shown in Fig. A1). This has a high degree of correlation (r > 0.8) with SST in the cold tongue region, which is more typically used and is a natural, objective choice for the study of large-scale processes. Figure A1a is the EOF pattern calculated from the correlation matrix, and contains 31% of the nonannual variance. The figure is equivalent to a correlation between the principal component (PC) time series and each SST grid point, and is scaled accordingly. Figure A1b is the PC time series, scaled in units of its standard deviation. ENSO anomalies of cloud frequency, SST, and surface wind divergence, which are calculated in this study from the linear regression analysis are scaled to correspond to one (positive) standard deviation in this time series to give the standard anomalies.

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Khalsa, S. J. S., 1989: Atmospheric Stability over the tropical oceans and contains 31% of the nonannual variance. The figure is equivalent to a correlation between the principal component (PC) time series and each SST grid point, and is scaled accordingly. Figure A1b is the PC time series, scaled in units of its standard deviation. ENSO anomalies of cloud frequency, SST, and surface wind divergence, which are calculated in this study from the linear regression analysis are scaled to correspond to one (positive) standard deviation in this time series to give the standard anomalies.