Reply

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We agree that the specific meteorological origin of the cloud anomalies is less relevant than the peculiarities of the cloud-weighted SST statistic (CWT) and its relationship with average cloud fraction in the western Pacific. We will begin our reply to the comment by Lindzen et al. (2002; hereafter LCH2) by considering a simple model of CWT. The model is an illustration of our contention that negative correlation between CWT and average cloud fraction is a consequence of the definition of CWT, and not indicative of a negative climate feedback process as Lindzen et al. (2001, hereafter LCH) hypothesize.

Figure 2 of Hartmann and Michelsen (2002, hereafter HM02) shows the pattern of cloud fraction variation that is associated with high CWT in the dataset used by LCH. The dominant features are a positive cloud anomaly in the warm Tropics centered around 5°S and a negative anomaly centered around 25°S. The cloud anomaly patterns are large scale, and suggest modeling the problem with a cold region and a warm region of equal areas. Suppose that the regions have SSTs of T_c and T_w and cloud area fractions of C_c and C_w. In this case the CWT and average cloud cover A are given by

$$\mathrm{CWT} = \frac{C_w T_w + C_c T_c}{2A} \quad \text{and} \quad A = \frac{1}{2}(C_w + C_c). \tag{1}$$

We will assume that the SST remains fixed with time, so the variations in CWT arise solely from variations in cloud coverage. This is very nearly true for the observations, and LCH state that the CWT varies mostly because of cloud variations and not because of temporal variations of SST. Defining $\Delta T = T_w - T_c$, and noting that $C_w = 2A - C_c$, we can write

$$\mathrm{CWT} = T_w - \frac{C_c}{C_c + C_w}\Delta T = T_c + \frac{C_w}{C_c + C_w}\Delta T. \tag{2}$$

The covariance between CWT and A depends on the statistics of the cloud cover variations in the two regions. If we begin with (2), assume that the SST is fixed, suppose that the cloud cover in the two regions are random variables with means $\bar{C}_c$, and $\bar{C}_w$, and standard deviations σ_c and σ_w, and make the approximation that the standard deviations are much less than the means, then it can be shown that the covariance between CWT and A will be negative under the condition that[1]

$$\frac{\sigma_c^2}{\sigma_w^2} > \frac{\bar{C}_c}{\bar{C}_w}. \tag{3}$$

Thus, if the cloud cover is more variable in the cold region than in the warm region, then the correlation between CWT and A will be negative. The main point that we make in HM02, that almost "any" variation in cloud cover over the cold region will result in a negative correlation between mean cloud cover and cloud-weighted SST, is clarified by (3). It is required that the lower SST area has a higher ratio of cloudiness variance to mean cloudiness than the warm area. One might expect that the cooler regions of the Tropics and subtropics would be less connectively unstable, so that cloudiness is more dependent on large-scale forcing, and that averages over large areas with lower SSTs are therefore more variable on a day-to-day basis. Below we will show that the inequality of (3) and the conditions for its derivation are satisfied by the LCH dataset.

To see how the two-region model plays against the LCH data, we define the warm region to be that part of the LCH domain within 14.5° of the equator and the cold area to be the part of the LCH region in both hemispheres between 14.5° and 30° latitude. These

[1] The derivation of this condition is available online (DOI: 10.1175/BAMS-83-9-Hartmann). See http://dx.doi.org/10.1175/BAMS-83-9-Hartmann.

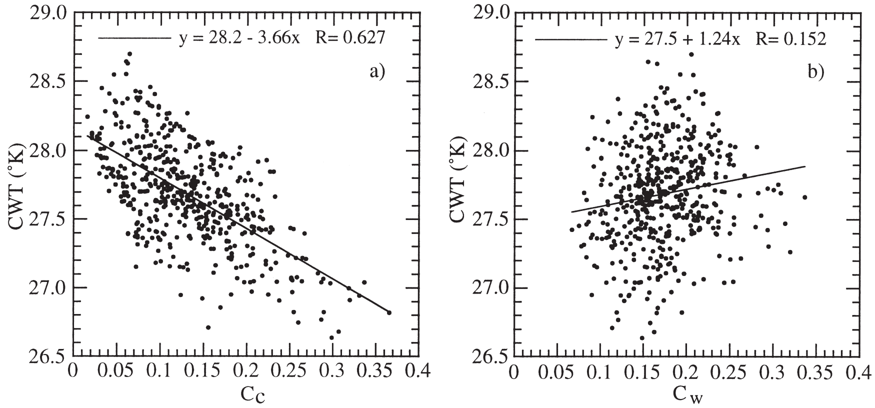

Fig. 1. Scatter diagram of CWT computed from (1) vs average cloud coverage in (a) the cool region C_c and (b) the warm region C_w.

areas are approximately equal. We then use the data from LCH to compute the mean cloud fraction for $T_{IR} < 260$ K and CWT using (1). The mean cloud areas in the cold and warm regions are 13.1% and 17.3%, and the standard deviations are 6.3% and 4.5%, respectively. So in the cold area the mean cloudiness is less and the variance of cloudiness is more than in the warm area, and condition (3) is satisfied. If the data are high-pass-filtered as in HM02, the standard deviations are 5.3% and 3.2% for the cold and warm regions, respectively, and the correlation between the cloudiness fractions in the two domains is 0.02, so that the two time series are statistically independent. The ratio of cold area cloudiness variance to the warm area variance is 1.94 for the unfiltered data and 2.75 for the filtered data. The ratio of the areas is 0.76, so the condition (3) is amply satisfied and we should expect a negative correlation between CWT and A from these facts alone.

The dependence of CWT on the cloud fraction in the cold region is shown clearly in Fig. 1, where CWT calculated from (1) is plotted versus the mean cloud fraction in the cold domain between 14.5° and 30° latitude. CWT is correlated with C_c at a level of −0.63 for the unfiltered data, and at −0.79 for the high-pass-filtered data. Also shown is CWT plotted versus the cloud fraction in the warm domain between 14.5°S and 14.5°N. CWT is not strongly related to the cloud fraction in the warm region. Figure 1 and the analysis above bear out our contention that the negative correlation between CWT and mean cloud coverage is an artifact of the definition of CWT and would be expected even if the cloud coverage was merely a random variable changing above the existing meridional SST gradient, so

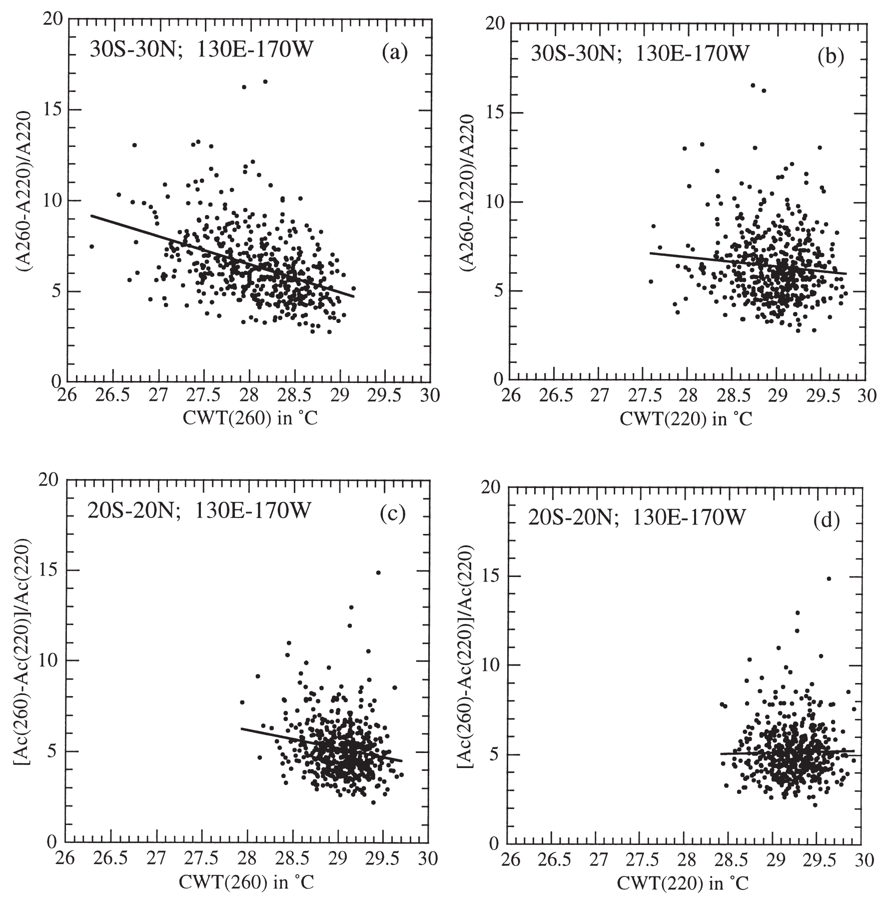

Fig. 2. Scatter diagrams of cloud area fraction against cloud-weighted SST for the regions (a), (b) 30°S–30°N, and (c), (d) 20°S–20°N, and for cloud-weighted SST based on clouds with (a), (c) $T_{IR} < 260$ K and (b), (d) $T_{IR} < 220$ K.

long as (3) is satisfied. This correlation has no significant implications for climate sensitivity analysis.

In their response to HM02, LCH2 make two arguments. First, they attempt to show that deep convective core clouds (T_{IR} < 220 K) do exist outside the near equatorial region and over cooler water. They show an example for 10 August 1998 when a small area of T_{IR} < 220 K cloud occurs near 11°N where the SST is about 28°C. The single snapshot shown in Figs. 1 and 2 of LCH2 is consistent with the long-term statistics shown in Fig. 4 of HM02, which suggest that T_{IR} < 220 K cloud covers about 1.5% of the area at 11°N and about 1% poleward of 20°N in the annual mean. The maximum coverage of convective core cloud is about 5% at 10°S.

The second point of LCH2 is to show that the correlation does not disappear when the area of interest is limited to 25°S–25°N, instead of 30°S–30°N (Fig. 4 of LCH2). In Table 1 of HM02 we have already shown the correlations for not only 25°N–25°S, but also 20°N–20°S and 15°N–15°S. A large decrease in correlation occurs when the domain is constrained to the more tropical latitudes (< 20°), but the belt from 20° to 25° is still in the subtropics where the SST is low and deep convective cores defined by T_{IR}<220 K are relatively rare.

In their Fig. 3, LCH2 show a scatter diagram of the cloud area ratio, $[A_c(260) - A_c(220)]/A_c(220)$. This statistic is thus the ratio of less deep upper-level cloud area $A_c(260)–A_c(220)$ to a measure of the deep convective core area $A_c(220)$ within the area of interest for each day of data from 1 January 1998 to 31 August 1999. LCH2 plot this statistic versus the SST weighted by the area of upper-level clouds CWT(260), averaged for the region (30°N–30°S, 130°E–170°W). Our reproduction of their Fig. 3a in our Fig. 2a shows an increase of the cloud area ratio with decreasing cloud-weighted SST. The dependence of this result on the latitudinal gradients of SST and convective core area can be illustrated in two ways.

First we may ask how this result would be different if, instead of regressing the area ratio against CWT(260), we regress against the cloud-weighted SST based on the T_{IR} < 220 K cloud fraction CWT(220). If the deep convective cores and the warmer upper-level clouds are attached, as LCH assume (LCH, their Figs. 2 and 3), then the choice of which cloud type to use to define the cloud-weighted SST should not change the result. But Fig. 2b shows that the result is very different if the colder cloud tops are used to define the cloud-weighted SST. CWT(220) is higher and less variable than CWT(260). This is because the deep convective core clouds with T_{IR} < 220 K

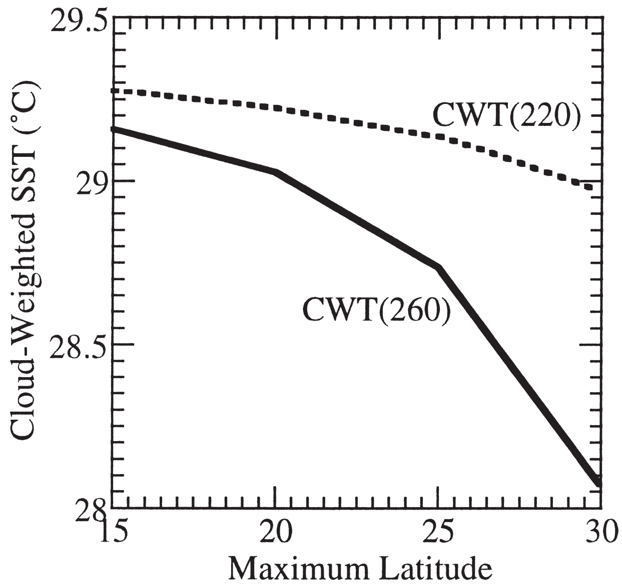

FIG. 3. Cloud-weighted SST as a function of the maximum latitudinal extent of regions centered on the equator and within the longitude range 130°E–170°W, based on the area of clouds with T_{IR} < 260 K [CWT(260)] and with T_{IR} < 220 K [CWT(220)].

are more common over the warmer waters of the Tropics and become rare in the subtropics where the SST is lower.

Another way to see this is to consider the dependence of the cloud-weighted SST on the meridional extent of the area considered. Figure 3 shows CWT(260) and CWT(220), averaged over all the days in the sample, plotted as a function of the maximum meridional extent of the averaging area. If the area 30°S–30°N is considered, CWT(220) is nearly a degree warmer than CWT(260). The deep convective cores occur preferentially over the warmest water, while the less deep upper-level clouds do not have such a strong preference. As the domain is restricted to lower latitudes, CWT(220) and CWT(260) become more similar.

In Table 1 we show regressions of the cloud area ratio calculated for different latitude belts centered on the equator and regressed against CWT(260) and CWT(220). The cloud fractions $A_c(260)$ and $A_c(220)$ are autocorrelated from one day to the next at a level of 0.88. The cloud area ratio is less autocorrelated, at about 0.7, because of the division by the relative small fraction of cold cloud. If we use the smaller number, giving the correlation the best chance to pass a significance test, then the dataset has approximately 90 independent degrees of freedom (Bretherton et al. 1999). The correlation coefficient required to reject a null hypothesis of zero correlation at the 95% level is then 0.21. This level of correlation is achieved only

Table 1. Results of linear regression of cloud area ratio $[A_c(260) - A_c(220)]/A(220)$ on cloud-weighted SST for ocean areas within the longitudinal domain 130°E–170°W and for various maximum latitudes of the domain. Regressions are shown for cloud-weighted SST based on cloud areas defined with $T_{IR} < 260$ K and $T_{IR} < 220$ K [CWT(260) and CWT(220), respectively]. Slope is the regression coefficient between cloud area ratio and cloud-weighted SST. The correlation coefficient is R and the fraction of variance explained by the regression is R^2. Regressions significant at the 95% level are indicated in blue.

	CWT(260) $T_{IR} < 260$ K		CWT(220) $T_{IR} < 220$ K	
Latitude	Slope	$R(R^2)$	Slope	$R(R^2)$
30°S–30°N	–1.54	**–0.43 (0.17)**	–0.52	–0.10 (0.01)
25°S–25°N	–1.32	**–0.30 (0.09)**	+0.05	+0.01 (0.00)
20°S–20°N	–1.00	–0.18 (0.03)	+0.12	+0.02 (0.00)
15°S–15°N	–0.82	–0.15 (0.02)	–0.18	–0.03 (0.00)

when the area of interest extends poleward of 20° and the cloud-weighted SST is defined using all upper-level cloud, $T_{IR} < 260$ K. If the cloud area ratio is regressed against cloud-weighted SST for regions restricted to latitudes less than 20°, then the correlation between cloud fraction and SST becomes statistically insignificant and the amount of variance explained is less than 4%. Furthermore, if CWT(220) is used, then the explained variance of the regression is essentially zero for any latitude belt chosen.

In HM02, we did not say that convection only occurs near the equator, or that clouds with $T_{IR} < 260$ K in the subtropics are not associated with convection. We did not assert that tropical (20°S–20°N) clouds remain fixed. We only pointed out that if they did, *any* variation in subtropical (30°–20°S to 20°–30°N) clouds would produce the negative correlation of cloud-weighted SST with cloud area, simply because when cloud fraction increases over the colder water, the cloud-weighted SST must decrease. We suggest that most of the negative correlation arises from this simple fact.

In summary, we believe that the negative correlation between cloud-weighted SST and upper-level cloud area derived by LCH arises from the tendency of cloudiness to be more variable over the lower SST areas relative to the mean cloudiness. In contrast, deep convective cores with $T_{IR} < 220$ K become increasingly rare with increasing latitude and decreasing SST. If cloud-weighted SST is defined using the convective core clouds, or the domain is restricted to the Tropics (20°S–20°N), but otherwise within the longitude range specified by LCH, then the correlation disappears. The data thus provide no evidence that the ratio of upper-level cloud area to convective core area within the Tropics is sensitive to SST.

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