

Reply to Lindzen, Chou and Hou comment on “No Evidence for Iris”

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23 April 2002

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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.

Fig. 2 of Hartmann and Michelsen (2002) (hereafter HM) shows the pattern of cloud fraction variation that is associated with high *CWT* in the data set used by LCH. The dominant features are a positive cloud anomaly in the warm tropics centered at about 5°S and a negative anomaly centered at about 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:

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

We will assume that the SST remains fixed with time, so that 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:

$$CWT = T_w - \frac{C_c}{C_c + C_w} \Delta T = T_c + \frac{C_w}{C_c + C_w} \Delta T \quad (2)$$

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 uncorrelated random variables with means  $\overline{C_c}$  and  $\overline{C_w}$ , and standard deviations  $\sigma_c$  and  $\sigma_w$ , 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<sup>1</sup>

$$\frac{\sigma_c^2}{\sigma_w^2} > \frac{\overline{C_c}}{\overline{C_w}} \quad (3)$$

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 HM, 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 convectively unstable, so that cloudiness is more

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<sup>1</sup> The derivation of this condition is available on the online resources section of BAMS or from the authors.

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 (3) and the conditions for its derivation are satisfied by the LCH data set.

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 degrees of the equator and the cold area to be the part of the LCH region in both hemispheres between 14.5 and 30 degrees latitude. These areas are approximately equal. We then use the data from LCH to compute the mean cloud fraction for  $T_{IR} < 260\text{K}$  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 HM, 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 timeseries 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 degrees and 30 degrees 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 14.5S and 14.5N.  $CWT$  is not strongly related to the cloud fraction in the warm region. Fig. 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 long as (3) is satisfied. This correlation has no significant implications for climate sensitivity analysis.

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

about 1% poleward of 20N in the annual mean. The maximum coverage of convective core cloud is about 5% at 10S.

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

In their Fig. 3 LCH2 show a scatter diagram of the cloud area ratio,  $(Ac(260) - Ac(220)) / Ac(220)$ . This statistic is thus the ratio of less deep upper-level cloud area  $Ac(260)-Ac(220)$  to a measure of the deep convective core area  $Ac(220)$  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 (30N-30S; 130E-170W). 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  $T_{IR}<220K$  cloud fraction,  $CWT(220)$ . If the deep convective cores and the warmer upper-level clouds are attached, as LCH assume (LCH 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  $T_{IR}<220K$  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. Fig. 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 30S-30N 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  $Ac(260)$  and  $Ac(220)$  are auto-correlated from one day to the next at a level of 0.88. The cloud area ratio is less auto-correlated, 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 data set 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 when the area of interest extends poleward of 20 degrees and the cloud-weighted SST is defined using all upper-level cloud,  $T_{IR} < 260K$ . If the cloud area ratio is regressed against cloud-weighted SST for regions restricted to latitudes less than 20 degrees, 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 HM we did not say that convection only occurs near the equator, or that clouds with  $T_{IR} < 260K$  in the subtropics are not associated with convection. We did not assert



that tropical (20S-20N) clouds remain fixed. We only pointed out that if they did, *any* variation in subtropical (30S-20S + 20N-30N) 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  $T_{IR} < 220\text{K}$  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 (20S-20N), 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.

*Acknowledgments.* We are grateful to Christopher S. Bretherton for providing the derivation of (3). We thank Marcia B. Baker and Robert Wood for reading this letter prior to submission. This work was supported by the NASA Office of Earth Science under the Earth Observing System Program and Grant NAGS5-10624.

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**Figure Captions:**

Figure 1. Scatter diagram of  $CWT$  computed from (1) versus average cloud coverage in;  
a) the cool region,  $C_c$  and b) the warm region,  $C_w$ .

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

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

**Table Caption:**

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

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

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

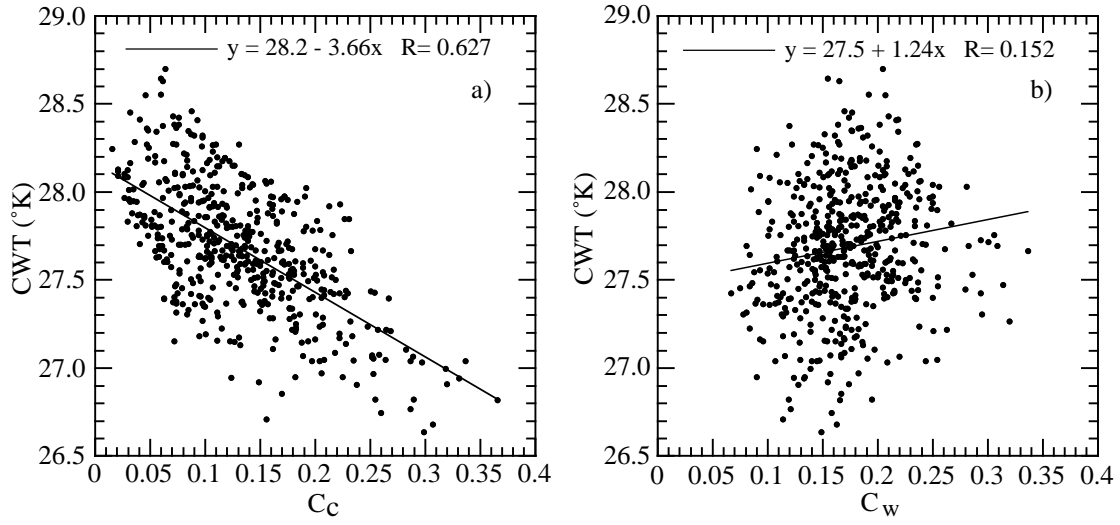


Figure 1. Scatter diagram of  $CWT$  versus average cloud coverage in; a) the cool region,  $C_c$  and b) the warm region,  $C_w$ .

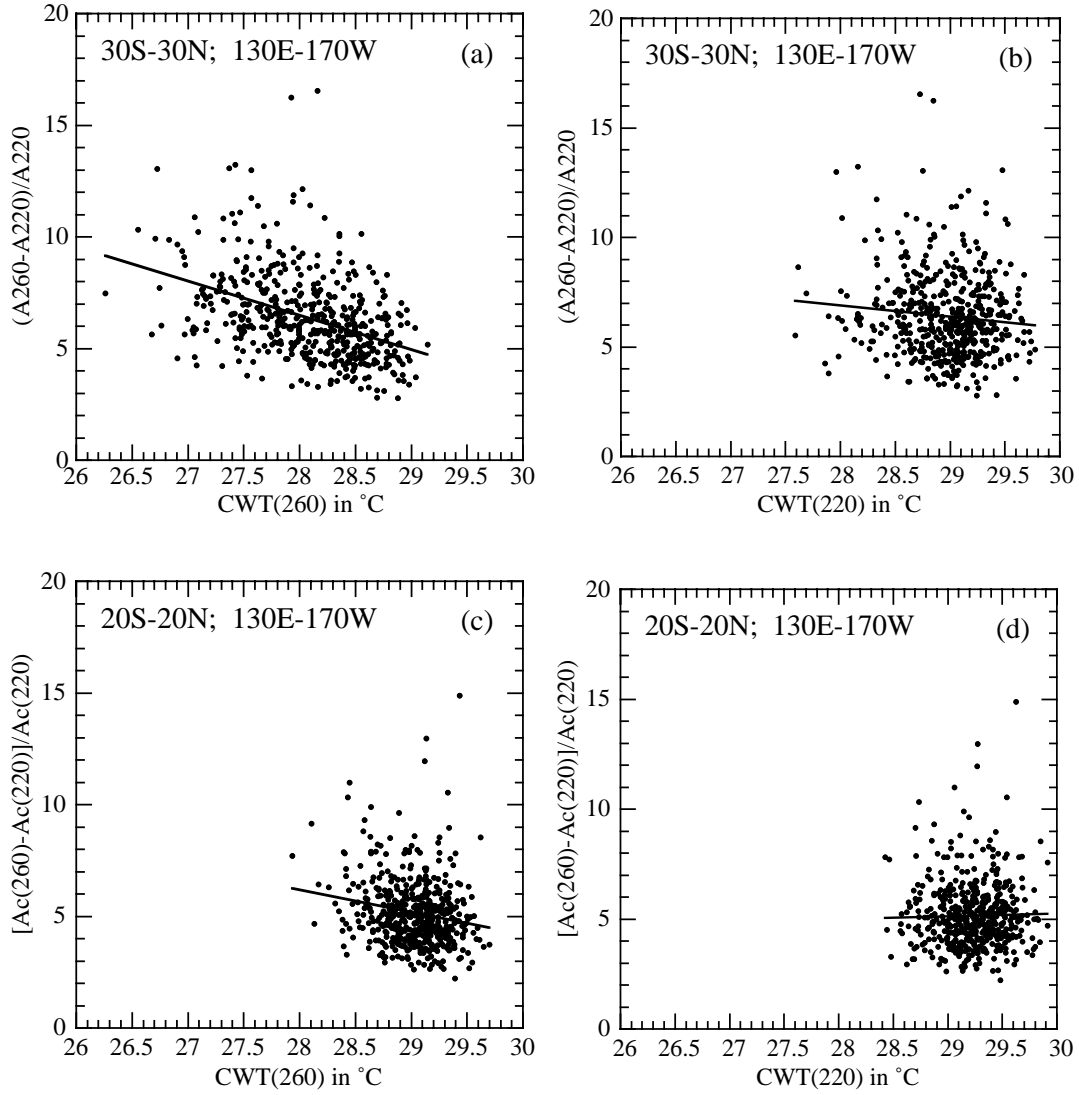


Fig. 2 Scatter diagrams of cloud area fraction against cloud-weighted SST for; the regions (30S-30N) (a) and (b) and (20S-20N) (c) and (d); and for cloud-weighted SST based on clouds with  $T_{IR}<260\text{K}$  (a) and (c), and with  $T_{IR}<220\text{K}$  (b) and (d).

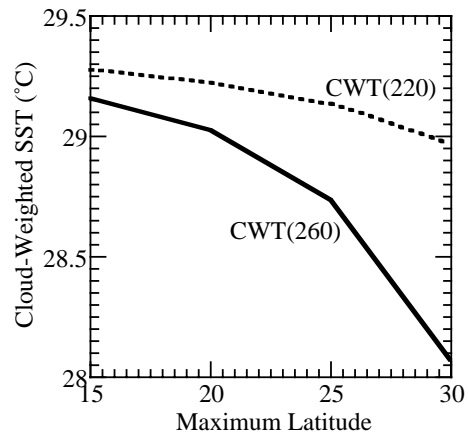


Fig. 3 Cloud-weighted SST as a function of the maximum latitudinal extent of regions centered on the equator and within the longitude range 130E-170W, based on the area of clouds with  $T_{IR} < 260K$  ( $CWT(260)$ ) and with  $T_{IR} < 220K$  ( $CWT(220)$ ).