Reply

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Lindzen et al. [2001] reported that cirrus anvil cloud fraction normalized by deep convective core cloud fraction decreases with cloud-weighted sea surface temperature (SST) by about −20%/K, while *Su et al.* [2008] showed tropical-mean upper tropospheric (UT) cloud fraction normalized by precipitation decreases with cloud-weighted SST more slowly at around −2%/K. Throughout the text, we use "%/K" to indicate the relative change of normalized cloud fraction per degree change of SST. In their comments to *Su et al.* [2008], *Rondanelli and Lindzen* [2009, hereafter *RL09*] examined several methodological choices that may contribute to the reported fractional decreases. First, they presented a regression analysis of normalized anvil cloud fraction onto SST using binned cloud fraction data within 0.5ºC of SST and 1º×1º gridded data. Both binned and gridded regressions show that anvil cloud fraction normalized by convective core cloud fraction decreases with SST at a rate of approximately −20%. In their analysis, cirrus anvil fraction is based on brightness temperature (BT) from the Tropical Rainfall Measuring Mission (TRMM) Visible and Infrared Scanner (VIRS) with values between 220 K and 260 K. Their convective core cloud fraction, which served as a measure of convective mass flux, is based on lower brightness temperature (BT<220K). The normalization focuses on the relative change of anvil cloud fraction with respect to unit convective mass flux, i.e., the efficiency of anvil formation due to convective detrainment. *Su et al.* [2008] used precipitation to normalize high-altitude cloud fraction to account for the competition between precipitation and anvil formation for a given moisture supply. When *Rondanelli and Lindzen* applied to their data the same methodology as in *Su et al.* [2008] which regressed the daily tropical-averaged cloud fraction onto the cloud-weighted SST, a decrease of −6%/K was obtained, which was rather close in magnitude to the finding of *Su et al*. [2008]. This suggests that different methodologies contribute to the differences in the rates of relative changes.

Here, we further test if different datasets could cause the differences in the regression slopes by replicating the analysis in *RL09* Figure 1 with the 1º×1º gridded cloud fraction data from the Aqua Atmospheric Infrared Sounder (AIRS) normalized by the TRMM precipitation. The daily AIRS UT (pressure < 300 hPa) cloud fraction normalized by precipitation shows a relative change of −18%/K based on the decaying exponential fit to all daily data from January to March (the same months as in *RL09*) 2006, while the binned cloud fraction shows a relative change of −25%/K (Figure 1). The correlation between the precipitation-normalized cloud fraction and SST is only −0.05. The rates of change are rather sensitive to analysis periods and data uncertainties, but the sign is always negative. Therefore, a decrease of *normalized* cirrus fraction with increasing SST appears to be robust, but different analysis methodologies and different data can give different magnitude of relative change.

However, we note that the UT cloud fraction is not simply proportional to precipitation. This has significant implications for the rate of change of precipitation-normalized cloud fraction with SST. Figure 2 illustrates the relationships among tropical UT cloud fraction, precipitation and SST using the 1ºx1º gridded data from Figure 1. Similar relations for tropical-mean values have been shown in *Su et al.* [2008]. Precipitation, binned in 0.5ºC SST intervals, increases approximately linearly with SST (Figure 2a). Cloud fraction increases with SST>27ºC, but decreases with SST<27ºC (Figure 2b), as the two regimes are associated with different large-scale circulation patterns. Cloud fraction increases with precipitation (Figure 2c) – rather rapidly for small values of precipitation and less so when precipitation > ~20 mm/day. This “saturation” behavior of cloud fraction with precipitation may contribute partly to the negative slope of precipitation-normalized cloud fraction versus SST. On the other hand, we notice that there is a high occurrence of large cloud fraction when precipitation is zero or very small. Thus, if one performs a linear least-squares

fit to the full range of cloud fraction versus precipitation, one obtains a non-zero intercept, corresponding to the fact that some high clouds are present regardless of precipitation. These high clouds may not be of convective origin and complicate the relation between the precipitation-normalized cloud fraction and SST.

Using the linear fit between cloud fraction (CFR) and precipitation (P) (which rather poorly captures their relationship) to illustrate the importance of the non-zero intercept, we can write $CFR(SST) = \alpha(SST)P(SST) + \beta(SST)$, where $\alpha(SST)$ represents the anvil-formation efficiency and $\beta(SST)$ denotes the non-zero intercept, both of which may vary with SST. Hence, the rate of change for precipitation-normalized cloud fraction with SST can be expressed as $\frac{d(CFR/P)}{dSST} = \frac{d\alpha}{dSST} + \frac{1}{P}\frac{d\beta}{dSST} - \frac{\beta}{P^2}\frac{dP}{dSST}$. The term $\frac{d\alpha}{dSST}$ is of interest for cloud-climate feedback. However, only when β is zero can we reliably obtain $\frac{d\alpha}{dSST}$ directly from $\frac{d(CFR/P)}{dSST}$. When β is not zero and $\frac{dP}{dSST}$ is positive, the $-\frac{\beta}{P^2}\frac{dP}{dSST}$ term will make a significant contribution to the rate of relative change of precipitation-normalized cloud fraction versus SST. In the data we used, the term $-\frac{\beta}{P^2}\frac{dP}{dSST}$ would make a rate of relative change about –14%/K for P = 10 mm/day and –6%/K for P = 20 mm/day, a significant contribution to the rates depicted in Figure 1. Thus, it is not clear whether the anvil-formation efficiency α increases or decreases with SST, given unknown $\frac{d\beta}{dSST}$ and other uncertainties associated with the data. Hence, while normalization by some measure of the convective source is desirable, the non-proportionality between cloud fraction and precipitation appears to compromise the usefulness of a normalization procedure that assumes proportionality (such as dividing the anvil cloud fraction by

precipitation). We expect that similar non-proportionality applies to the anvil cloud fraction and convective core fractions as defined by BT used in *RL09 (Rondanelli, personal communication)*. Thus similar uncertainty exists when interpreting the rates of relative change from their analysis.

Cloud fraction, of course, is only one cloud property that is relevant to the radiative effects of clouds. Other cloud properties, such as cloud water content (as shown in *Su et al.,* [2008]), cloud optical depth, cloud particle size and habits, are all important to the net cloud radiative forcing. The magnitude and sign of cloud climate feedback requires further study, with sustained (decadal or longer) simultaneous observations of multiple cloud parameters.

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References

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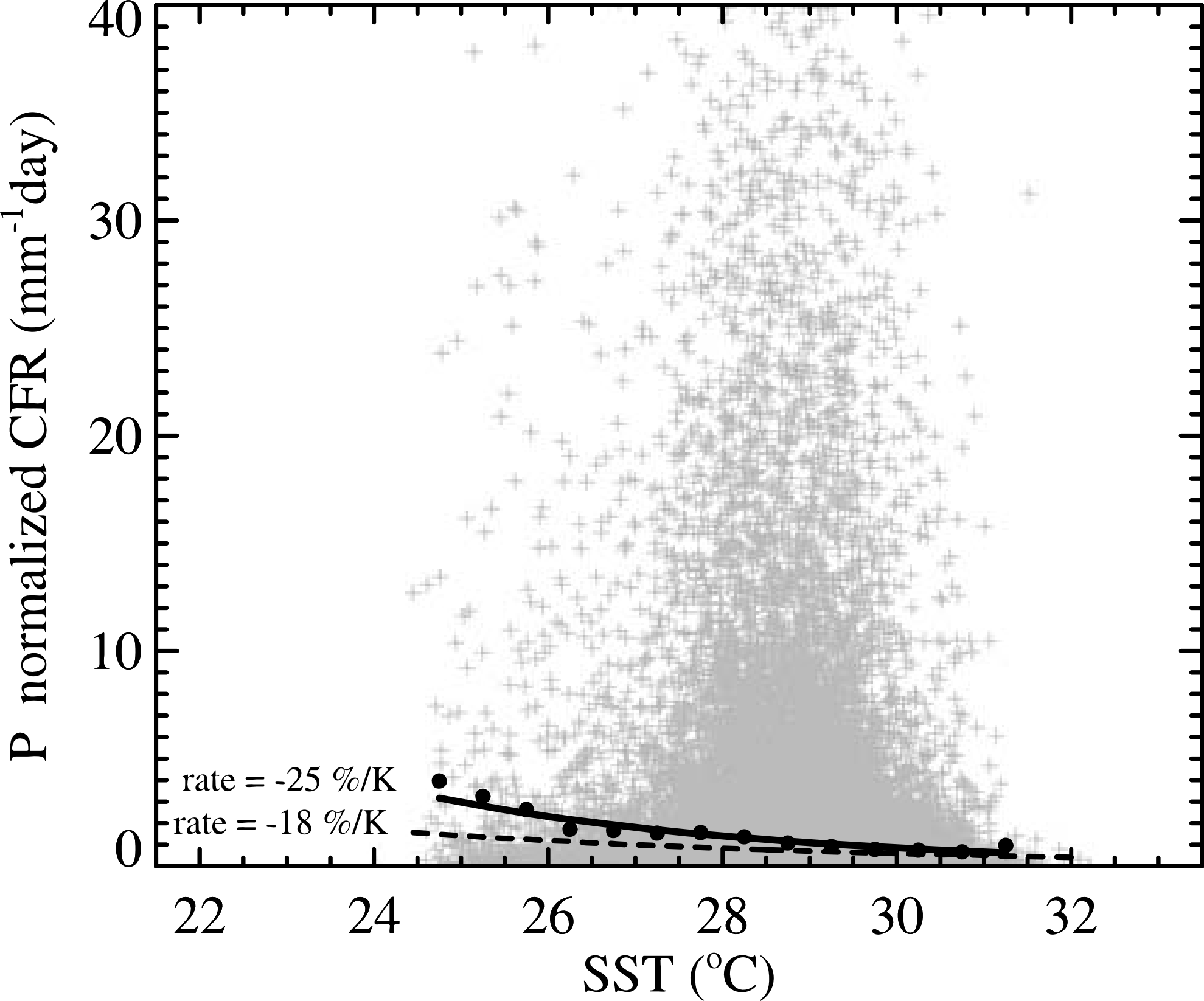
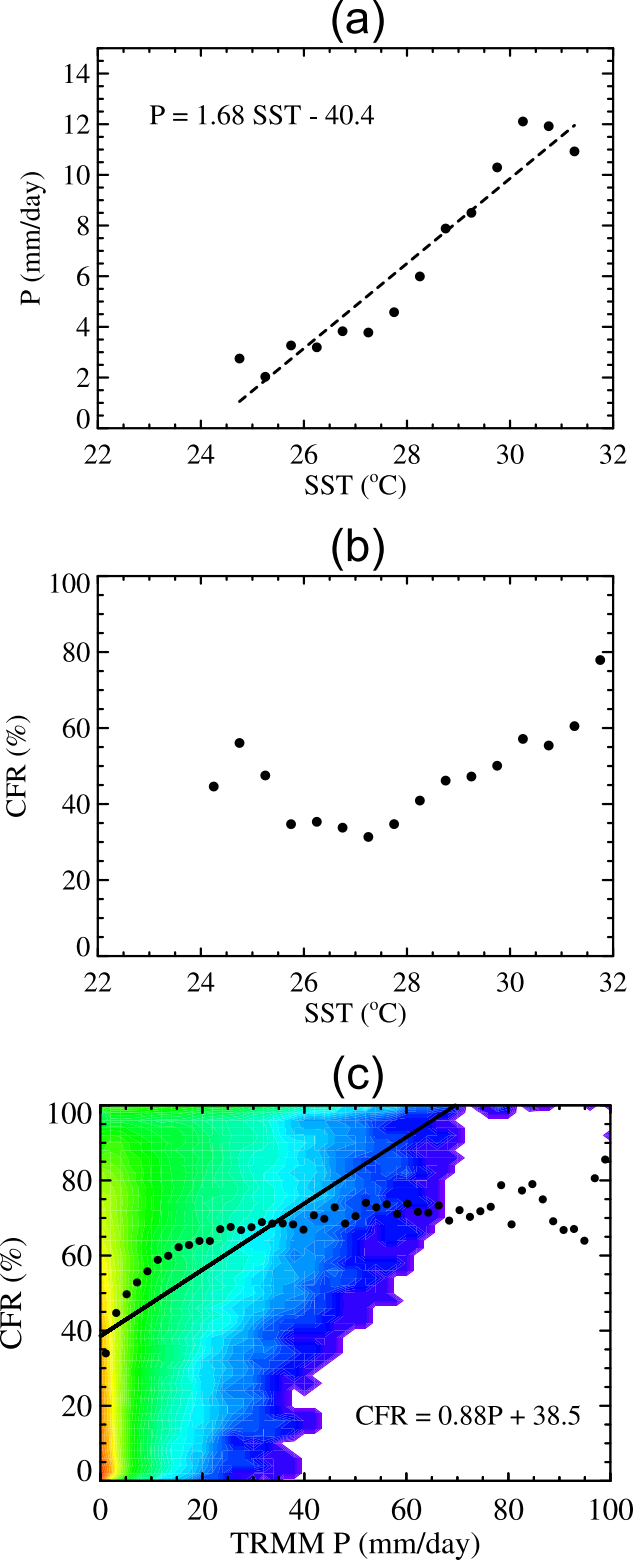
Figure Captions

Figure 1. Scatter plots of the upper tropospheric cloud fraction (with cloud top pressure less than 300 hPa) normalized by precipitation versus sea surface temperature (Similar to Figure 1 in *Rondanelli and Lindzen* [2009] but with the data used in *Su et al.* [2008]). The data are from January to March 2006 for oceanic regions within 15ºS-15ºN. The grey crosses represent individual 1º×1º gridded daily AIRS UT cloud fraction normalized by TRMM precipitation (greater than 0.02 mm/day). The black dots are the binned normalized cloud fraction for 0.5ºC SST bins. The solid black curve is the decaying exponential fit to the binned data and the dashed black curve is the decaying exponential fit to all individual gridded data. "Rate" refers to the relative change of precipitation-normalized cloud fraction versus SST based on the decaying exponential fit.

Figure 2. (a) The 1º×1º gridded precipitation (15°S-15°N) binned on 0.5°C SST bins. The dashed line is the least-squares linear fit to the binned data, with the regression equation shown. (b) The 1º×1º gridded UT cloud fraction binned in 0.5ºC SST intervals. (c) The gridded UT cloud fraction as a function of gridded precipitation. The color shading is the joint density with high density in red and low density in blue. The black dots are cloud fraction binned in 2 mm/day precipitation intervals and the solid line is the least-squares linear fit to the full range of data.


40
30
20
10
0
P normalized CFR (mm-1day)
rate = -25 %/K
rate = -18 %/K
22
24
26
28
30
32
SST (°C)


(a)
P = 1.68 SST - 40.4
P (mm/day)
SST (°C)
(b)
CFR (%)
SST (°C)
(c)
CFR = 0.88P + 38.5
CFR (%)
TRMM P (mm/day)