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# Comment on the paper "An inquiry into the cirrus-cloud thermostat effect for tropical sea surface temperature" by K. M. Lau, C. H. Sui, M. D. Chou and W. K. Tau

V. Ramanathan, W. D. Collins and B. Subasilar

Center for Clouds, Chemistry and Climate, Scripps Institution of Oceanography, University of California at San Diego

Why are the highly reflective cirrus cloud systems so extensive over the western Pacific warm pool? The fundamental reasons, suggested by Ramanathan & Collins (1991; hereafter referred as RC), are that deep convective clouds form mainly over warm oceans and that the associated cirrus-anvil cloud cover increases with sea surface temperature (SST). The physical basis for RC's reasoning is that SST has to exceed about 300°K for the boundary layer equilibrium thermodynamic energy to become large enough to induce deep convective instability (Betts and Ridgeway, 1989).

The dependence of warm pool cloudiness on SST has been shown by Waliser and Graham (1993) and Zhang (1993) using long-term (15 to 17 years) satellite data. These findings extend and clarify the results of several earlier studies (e.g. Gadgil et al, 1984), which suggested that SST is only a necessary but not sufficient condition for deep convection. Waliser and Graham (1993) and Zhang (1993) demonstrate that the frequency and intensity of deep convective clouds increase with SST for SSTs between 299° and about 302.5°-303°K. Zhang concludes that "this increase in deep convection with SST is found to be smooth and continuous . . . ".

These observational findings are at variance with Lau et al's model result, which suggests that the convective-cirrus cloud systems are insensitive to local SST. Their cloud model includes the effect of large scale circulation through a prescribed climatological vertical velocity field, W, which is assumed to be independent of the model SST, dynamics and thermodynamics. While Lau et al state that only a part of the prescribed large scale circulation is due to non-local influences, in their experiment they set W=0 entirely. The model cloud radiative forcing is governed primarily by the prescribed W field instead of SST. This result, even if it is valid, does not prove or disprove RC's thermostat hypothesis by itself. It simply identifies a mechanism for producing the extensive clouds, i.e., mean rising motion (W>0) is critical for producing deep convective clouds.

The fundamental problem with their model is that it assumes W to be independent of local SST. The observed dependence of deep convective cloudiness on SST must come from interactions between local SST and dynamical processes ranging from the convective scales to the much larger tropical scales (Zhang, 1993). RC explicitly note the importance of these coupled interactions, including the following: Latent heat released by deep convection provides the diabatic forcing for W; the mean upward motion (W>0) over the warm oceans locally enhances deep convective-cirrus anvil cloudiness; and in turn, the atmospheric radiative heating by the cirrus anvils reinforces the diabatic forcing for W. Lau et al's model omits this coupling between the warm pool atmospheric diabatic heating and the large scale circulation (W). The importance of this coupling can also be inferred from Neelin and Held (1987), who find that the observed low level convergence (or the diabatic forcing) can be parameterized in terms of surface-air moist static energy, which is determined by the absolute value of local SST.

Lau et al argue that the SST gradient is more important than local SST in determining W. Since the low level circulation driven by the SST gradient leads to convergence of air in the boundary layer over the warmer oceans (Lindzen and Nigam, 1987) accompanied by positive W aloft, this mechanism will also enhance cloudiness over the warmer oceans. In addition, SST gradient is not entirely independent of local SST, since a local increase in warm ocean SST will enhance the SST gradient.

The key element of RC's thermostat model is the observed correlation between the central equatorial Pacific SST anomalies and shortwave cloud forcing ($C_S$) anomalies during the 1986-87 El Niño. Lau et al argue that the anomalies in $C_S$ are due to the eastward migration of deep convection and not due to SST increase. The problem with this argument is that SST-$C_S$ correlation is not restricted to only El Niño anomalies; it also applies to climatological spatial variations in SST and $C_S$ (Fig. 1). All of the 5 years shown in Fig. 1 reveal negative correlation between SST and $C_S$. Note that $C_S < 0$, with larger $|C_S|$ indicating greater cooling of the ocean-atmosphere system.

The origin of the SST-$C_S$ spatial correlation is related to the increase of deep convection frequency and intensity with SST (Zhang, 1993). Associated with the increase in convection, mid and upper troposphere clouds (called cirrus by RC) increase systematically with SST toward the warm pool (Kiehl, 1994). The spatial as well as the El Niño induced variation in $C_S$ have been shown to result from corresponding variations in upper troposphere clouds (Kiehl, 1994). The net effect is an increase in planetary albedo, or a decrease in $C_S$, with SST (Fig. 1). Large scale dynamics plays an important role in two ways: first, the previously mentioned interaction between SST, deep convection, W and cirrus cloudiness will contribute to the mean trend in Fig. 1 (as described in RC); second, variations in W that are unrelated to local SST cause a large variability around the mean trends shown in Fig. 1.

Lau et al deduce that evaporative cooling, rather than cloud radiative forcing, is the primary thermostat. Two independent observational studies do not support this deduction.

1) Young et al (1992) have analyzed boundary layer radiation and turbulent flux data collected by R/V Wecoma at 10Hz resolution during a 22-day cruise in the equatorial warm pool near 147°E longitude. The data were binned according to three convective regimes: convectively disturbed (10 days); convectively suppressed, clear-sky conditions (8 days); and the transition between the first 2 regimes (4 days). The net heat flux into the ocean decreased from +95.7 $W.m^{-2}$ (surface heating) under suppressed conditions to -34.9 $W.m^{-2}$ (surface cooling) under disturbed conditions. The increase in evaporative flux contributed 21 $W.m^{-2}$, and sensible heat loss increased by 6.7 $W.m^{-2}$; the decrease in insolation due to clouds contributed the balance of 104 $W.m^{-2}$ to the total convectively induced cooling of 131 $W.m^{-2}$. The deductions from this seminal analyses are as follows: In the absence of deep convection, the warm pool sea surface is subject to a large net heating of about 100 $W.m^{-2}$. The net effect of deep convection is to arrest this intense surface warming. The reduction of insolation by clouds plays a dominant role in this thermostat action of deep convection (also see Waliser & Graham, 1993).

2) Most recent climatological estimates of evaporation from the tropical Pacific (e.g. Oberhuber, 1988) show that while evaporation increases with SST in the eastern Pacific (120°W to 150°W), it does not follow the SST variation in the central and western Pacific (Fig. 2). Analysis of an independent daily data set from buoys in the equatorial

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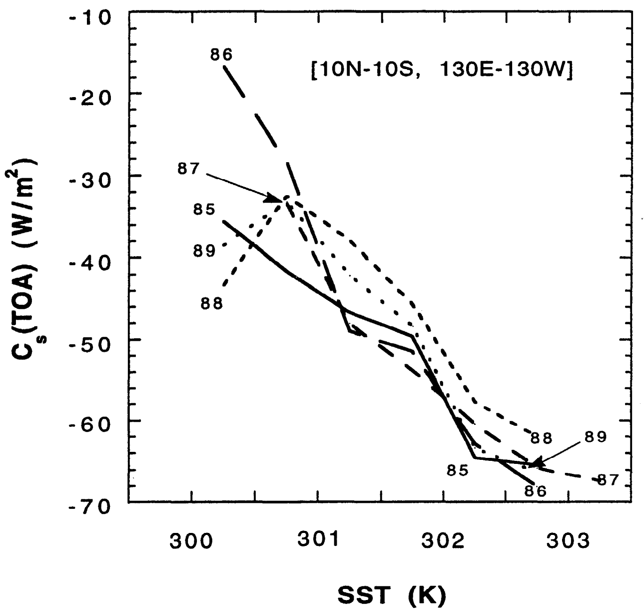

Fig 1: SST versus annually averaged top of the atmosphere short wave cloud forcing [$C_S$(TOA)] from Earth Radiation Budget Experiment data set for the years 1985 through 1989. The region is from 20°N to 20°S and 130°E to 130°W. The resolution of the data is 2.5°x 2.5°. The SSTs are interpolated from the Reynolds (1988) analysis.

Pacific reveals patterns similar to those shown in Fig. 2, with annual mean evaporation (obtained by averaging daily values) of about 100 W.m$^{-2}$ in the warm pool (Zhang et al, 1993). Lau et al's model, on the other hand, predicts that evaporation should increase from 120 W.m$^{-2}$ to 137 W.m$^{-2}$ when SST increases from 301 to 303 K.

If the annual mean evaporation from the warm pool is about 100 W.m$^{-2}$ (Fig. 2), and if the annual mean net oceanic heat export from the warm pool by lateral advection and downward entrainment is as low as 0 to 20 W.m$^{-2}$ (e.g. Godfrey and Lindstrom, 1989 and several others), then the cloud-free warm pool would be subject to an annual mean net heating of 100 W.m$^{-2}$ (Young et al, 1992). Under such conditions, the convective-cirrus thermostat effect will be required to offset the surface heating and maintain the observed annual mean SST. RC formulated the thermostat model to explain how maximum SSTs are regulated in those parts of the world oceans where there is a positive interaction between SSTs and deep convection, such as the western Pacific warm pool. It was not intended to address the zonal average SST of the entire tropics. As clearly noted in RC, it is the SST-deep convection positive feedback which gives rise to the potentially unstable super greenhouse effect and a thermostat is therefore required to limit the SSTs. It is also premature to extrapolate this to the sensitivity of warm ocean SSTs to external changes such as increase in $CO_2$ and other greenhouse gases.

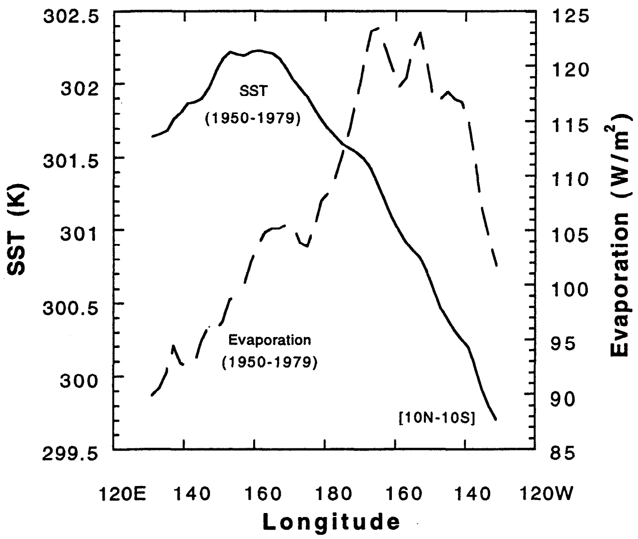

Fig. 2: Longitude versus climatological SST and climatological evaporation. SST is a 5-year (1985 to 1989) average data set from Reynolds (1988). Evaporation data are obtained from the Oberhuber atlas (1988). The region covers 10°N to 10°S and 130°E to 130°W. The resolution of the data is 2°x 2°.

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