The Role of Water Vapor, Clouds, and the Large-Scale Circulation in Regulating Sea Surface Temperatures in the Tropical Pacific

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Introduction

The western tropical Pacific is characterized by unusually warm sea surface temperatures—the so-called "warm pool"—with an asymmetric temperature distribution, as shown in Figure 1. The role of clouds and water vapor in determining the region's unique character has been the subject of a number of recent papers. They have fueled a debate on what maintains the warm pool, on the relative role of radiation and dynamics in determining sea surface temperatures, and on possible feedback mechanisms involving clouds and water vapor.

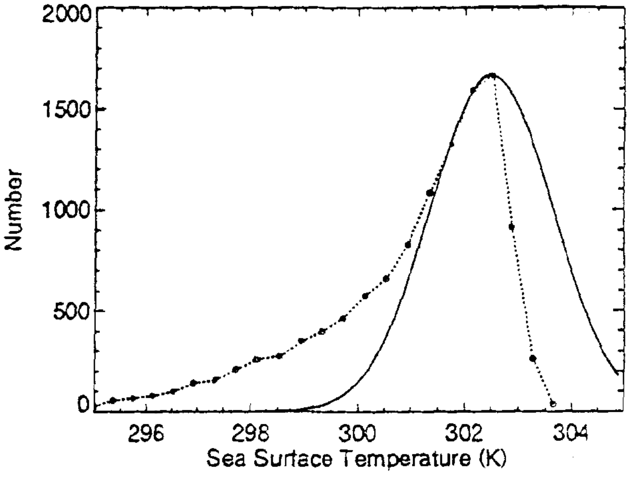

Figure 1. The frequency distribution of observed monthly mean sea surface temperatures (circles connected with a dotted line) compared with a normal distribution (solid line).

A statistical analysis of four years of observations over the tropical Pacific has provided some insight and suggests an explanation based on a greenhouse instability that is quenched when high-level clouds develop in response to increasing sea surface temperatures.

The data used in this study include earth radiation budget parameters from the Earth Radiation Budget Experiment (ERBE), cloud parameters from the International Satellite Cloud Climatology Project (ISCCP), total column water vapor from the National Oceanic and Atmospheric Administration's (NOAA) TIROS operational vertical sounder (TOVS), and sea surface temperatures from NOAA based on a blend of AVHRR (advanced very high resolution radiometer) and in situ measurements. The data consist of monthly averages on a 2.5° latitude by 2.5° longitude grid, extending from 150E to 180E and 25S to 25N, for the period February 1985 through January 1989.

Ramanathan-Collins Hypothesis

Ramanathan and Collins (1991) have advanced the hypothesis that solar radiation causes T_s to rise; the rise in T_s produces an increase in high-level clouds; and the clouds, in turn, reduce the solar radiation at the surface and arrest further warming. If this hypothesis were correct, one would expect 1) a positive correlation between clouds and T_s when high T_s causes a growth in high-level clouds, and 2) a negative correlation when the clouds reduce available solar radiation. An expected time lag between cloud development and a reduction in T_s, because of the ocean's heat capacity, would allow one to distinguish between the two correlations.

The correlation between four cloud variables (cloud fraction, cloud temperature, and the longwave and shortwave cloud radiative effects) versus T_s, as a function of the lag of T_s, is plotted in Figure 2. They show that the correlation is positive at all lags, with a peak at -1 month. (There is an indication of a small negative correlation superimposed on the distribution of the broad positive correlation, with a negative peak at a lag of 2 to 3 months, accounting for the skewness in the distribution; but it is small.) We conclude, therefore, that clouds do *not* have a significant radiative influence on sea surface temperatures. (Details appear in Arking and Ziskin 1994.)

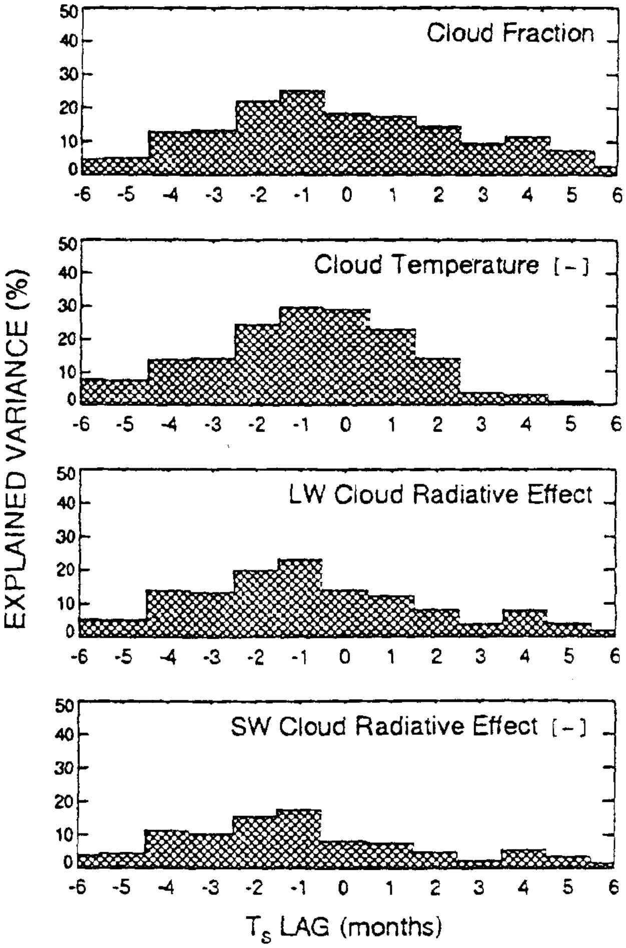

Figure 2. The explained variance (%) obtained by linear regression of four cloud parameters against sea surface temperature (T_s), as a function of the lag of T_s, for the region 10S-10N, 150E-180E. The minus sign [-] indicates a negative correlation (from Arking and Ziskin 1994).

To explain why the cloud radiative effects do not affect sea surface temperatures, it is necessary to re-examine the basis of the Ramanathan-Collins hypothesis.

Ramanathan and Collins find that for the total column—surface plus atmosphere—the cloud shortwave radiative effect, which cools the column, is nearly balanced by the longwave radiative effect, which heats the column. But when one examines the vertical distribution of the shortwave and longwave effects, one finds that the shortwave effect occurs primarily at the surface, while the longwave effect occurs primarily at cloud level in the upper troposphere. The Ramanathan-Collins hypothesis is based on an assumption that the longwave heating associated with the increase in cloud cover invigorates the large-scale circulation, so that the energy is carried away by upper level divergence, leaving a net cooling effect at the surface.

We offer an alternate hypothesis: the longwave heating serves to *weaken* the large-scale circulation, so that the upward latent and sensible heat transport diminishes by approximately the amount of the longwave heating at the upper levels. In effect, the longwave heating at cloud level is transferred to the surface through a diminished upward flux of latent and sensible heat. Further analysis of the data in the next section suggests that our hypothesis is correct and lends evidence to the idea that the high-level clouds, which develop rapidly when sea surface temperatures exceed 300K, do indeed exercise thermostatic control over sea surface temperatures—indirectly, through their effect on the large-scale circulation.

Greenhouse Instability and the Stabilizing Effect of High-Level Clouds

Comparing cloud radiative effects (*aka* cloud forcing) determined from ERBE of El Niño-Southern oscillation (ENSO) with non-ENSO conditions, Ramanathan and Collins (1991) show that when sea surface temperatures exceed ~300K, sea surface temperature is positively correlated with both longwave and shortwave cloud effects. This finding is confirmed by the analysis of Arking and

Ziskin (1994), who show that this relationship is quite general and that high-level clouds become more extensive and thicker as sea surface temperatures increase, up to the maximum observed temperatures. Lag correlations indicate that this represents the situation where clouds respond to sea surface temperature changes (see Figure 2 and related discussion).

Total column water vapor is also highly correlated with sea surface temperature. This correlation is revealed in Figure 3, where total column water vapor within equal intervals of sea surface temperature (open circles) is binned against sea surface temperature. To see how this relationship is affected by the high-level clouds that develop when sea surface temperatures exceed ~300K, we segment the data into two subsets: a "high cloud" regime, which represents the cloud conditions that obtain after clouds induced by the sea surface temperature are near maximum development (defined to be grid points where the mean cloud fraction is $\geq$0.72 and the mean cloud temperature is $\leq$256K), and a "normal cloud" regime, which represents all other cloud conditions. For each regime, the equatorial region (12.5S-12.5N) and the sub-tropics (25S-12.5S and 12.5N-25N) are plotted separately.

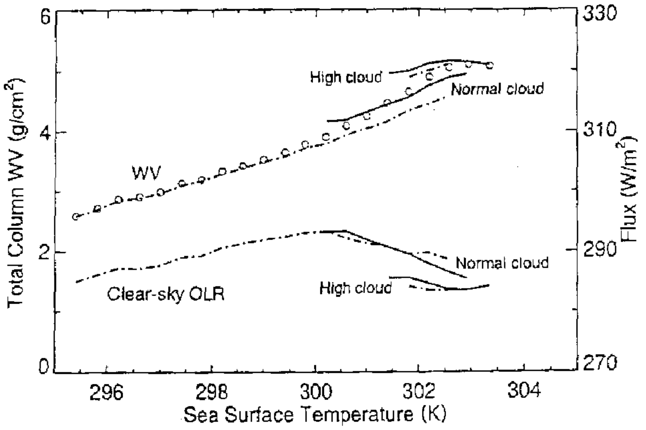

Figure 3. Total column water vapor (WV) and clear-sky outgoing longwave radiation (OLR) averaged within equal intervals of sea surface temperature, versus sea surface temperature. Open circles show mean values for WV for the entire domain. Curves labeled "High cloud" are restricted to grid points where the mean fraction is $\geq$0.72 and the mean cloud temperature is $\leq$256K; "Normal cloud" refers to all other grid points. Solid lines are for the equatorial region (12.5S-12.5N) and dash-dot lines are for the sub-tropics (25S-12.5S and 12.5N-25N).

The water vapor curves in Figure 3 reveal that for the "normal cloud" regime, the slope is nearly constant, with $d\ln W/dT_s = 0.05\ K^{-1}$, about the value that maintains constant relative humidity in a tropical atmosphere. For the "high cloud," regime the slope is less, by a factor of two, indicating that relative humidity decreases with increasing temperature. Our interpretation of this result is that low-level convergence, which supplies most of the moisture in the upward branch of the Hadley/Walker circulations, is weakened when the high-level clouds reach maximum development.

Figure 3 also shows the clear-sky outgoing longwave flux. Here we have the unusual situation that in the "normal cloud" regime the slope is *negative* at sea surface temperatures above ~300K. It is unusual because in a clear atmosphere, rising temperatures will cause the outgoing radiation to *increase*, if relative humidity remains constant.

The most likely explanation for the downturn in the slope is the greenhouse effect of a large increase in upper tropospheric moisture that occurs when sea surface temperatures increase beyond ~300K. In fact, numerical experiments with a radiation model show that the relative increase in moisture near the top of the troposphere would have to be as much as 10 times larger than near the surface to account for the observed downward slope. Such a large increase in upper tropospheric moisture is made possible by a strong circulation, including strong low-level convergence, which brings moisture into the region, and strong convection, which carries the moisture to the upper troposphere; this is the situation in the "normal cloud" regime. In the "high cloud" regime, however, the slope is flatter, indicating a weakening of the large-scale circulation, associated low-level convergence, and convection.

The negative slope is indicative of an unstable situation, where rising sea surface temperatures bring more heat into the vertical column, which could contribute to further heating of the surface and a continuing rise in sea surface temperatures. This instability, associated with the greenhouse effect of increasing water vapor, is not unlike the runaway greenhouse effect that occurs on a planetary scale on Venus, which accounts for its very high surface temperatures. In the present case it is a regional effect, and stability is restored by the high-level clouds that develop in response to the high sea surface temperatures.

An Explanation of the "Warm Pool"

If, indeed, stability is restored in this way, then there is a simple explanation for the "warm pool" characteristic of the western tropical Pacific: low-level convergence, coupled to increasing upper tropospheric moisture and a water vapor greenhouse effect, leads to an uncontrolled rise in sea surface temperature; this rise leads to a growth in high-level clouds, bringing stability and halting the rise in sea surface temperature. In this picture, the western tropical Pacific is self-regulating, with the key process being a coupling between the radiative effects of clouds and atmospheric dynamics. This mechanism behaves like the "thermostat" of Ramanathan and Collins (1991), in that it stops the rise of sea surface temperatures beyond a certain point but does not require that clouds exercise radiative control over sea surface temperatures, a mechanism that is not supported by the observations.

This explanation for the "warm pool" is consistent with published comments and investigations that followed the Ramanathan-Collins paper, that draw attention to the large-scale circulation and evaporative cooling as being potentially more important than radiation in determining sea surface temperatures (Wallace 1992; Fu et al. 1992; Stephens and Slingo 1992). The explanation is also consistent with the analysis of Waliser and Graham (1993), who find that the highest observed tropical sea surface temperatures are generally associated with diminished convection, and with the results of recent numerical experiment with a general circulation model by Fowler and Randall (1994), which finds that persistent high-level clouds increase static stability and suppress convection.

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