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Regime Behavior in the Sea Surface Temperature-Cloud Radiative Forcing Relationships over the Pacific Cold Tongue Region

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Abstract Previous analyses on the estimates of water vapor and cloud-related feedbacks in the tropics usually use observations over the Earth Radiation Budget Experiment (ERBE) period (1985–89). To examine the sample dependence of previous estimates, the authors extend the analysis to two additional periods: 1990–94 and 1995–99. The results confirm our hypothesis, i.e., the values of the feedbacks depend on the period of data coverage. The differences in the feedbacks from cloud radiative forcings (CRFs) estimated from the three periods are particularly significant. Two possible causes for these differences are proposed. First, a regime behavior in the CRFs-Sea Surface Temperature Anomaly (SSTA) relationship over the cold tongue region is revealed: when SSTA is below –0.5°C, the CRF anomalies are insensitive to the SSTA; when the SSTA is between –0.5°C and 2.0°C, the CRF anomalies are positively correlated with the SSTA; however, when the SSTA exceeds 2.0°C, the CRF anomalies decrease with the SSTA. This regime behavior is due to the regime behavior of cirrostratus and deep convective clouds. Second, the CRFs-SSTA relationship is regulated by remote forcings. Warming of the far eastern equatorial Pacific would reduce the water vapor convergence over the central Pacific by weakening the trade wind over the southeastern Pacific, thereby reducing the feeding of moisture to the convective flow. The results suggest that CRFs-SSTA relationships during ENSO events are nonlinear and strongly depend on the magnitude and the spatial distribution of the SSTA.

Keywords: cloud radiative feedback, cloud-SST regime, ENSO, nonlinearity


1 Introduction

Water vapor and clouds play a vital role in the radiation process and in the heat budgets of the earth-atmosphere system. They are two major contributors to the greenhouse effect of the earth’s atmosphere. In addition, the cloud is a major contributor to the earth’s albedo (Ramanathan and Collins, 1991). The sensitivity of the climate to anthropogenic forcings depends critically on the feedbacks from water vapor and clouds in the climate system (Manabe and Wetherald, 1967; Randall et al., 2007). According to simulations of global warming produced by general circulation models (GCMs), the water vapor feedback provides the strongest positive feedback and differs little from one model to another, even though different parameterization schemes are used, whereas the feedback from clouds varies greatly among models and is largely responsible for the large spread (approximately 3°C) in model sensitivities (Randall et al., 2007). Thus, understanding the nature of water vapor and cloud-related feedbacks remains a critical issue in the study of global climate change.

Many studies have taken advantage of a natural signal—the El Niño-Southern Oscillation (ENSO)—to gain a quantitative understanding of the nature of water vapor and cloud feedbacks (Ramanathan and Collins, 1991; Sun et al., 2003, 2006). These studies have fully exploited the satellite observations of radiative fluxes using the Earth Radiation Budget Experiment (ERBE) retrievals (Barkstrom et al., 1989). However, the ERBE data only covers the period from 1985 to 1989. Thus, questions about possible nonlinear behavior cannot be addressed because the length of the data is limited. Sun et al. (2009) found that feedbacks from water vapor and clouds estimated from the Atmospheric Model Intercomparison Project (AMIP) simulations and the corresponding coupled simulations differ significantly because of their different background states. Here, we focus on the analysis of observations but use extended data that covers two additional periods that include El Niño events: 1990–94 and 1995–99. Our purpose is to examine whether feedbacks are different during different El Niño events and to identify any nonlinear or regime behavior that the clouds- or water vapor-sea surface temperature (SST) relationship may exhibit.

The rest of this paper is organized as follows. Descriptions of the observational data and the methods are presented in Section 2. In Section 3, we show the results from three periods based on a long data set. Finally, a brief summary is given in Section 4.

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2 Data and method

2.1 Observational data

In our analysis, the observational radiative fluxes at the top of the atmosphere (TOA) were calculated from the monthly ISCCP FD (International Satellite Cloud Climatology Project Flux Dataset) data (here after ISCCP) (Zhang et al., 2004). TOA fluxes from the ERBE (Barkstrom et al., 1989) were used for comparison. Clouds properties were taken from the ISCCP data (Rossow and Duenas, 2004). The specific humidity and velocity fields were derived from the NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) Reanalysis (Kistler et al., 2001). The SST used was the Extended Reconstructed Sea Surface Temperature (ERSST) v2 (Smith and Reynolds, 2004).

2.1 Analysis method

In our analysis, the water vapor greenhouse effect (Ga) at the TOA is quantified as in Raval and Ramanathan (1989):

\[ Ga = \sigma T_s^4 - LW_{\text{clear}}. \]  

Following Charlock and Ramanathan (1985), the longwave (Cl) and shortwave (Cs) cloud radiative forcings (CRFs) at the TOA are defined as

\[ Cl = LW_{\text{clear}} - LW, \]

\[ Cs = SW - SW_{\text{clear}}. \]

In the above equations, \( \sigma \) is the Stefan-Boltzmann constant. \( T_s \) denotes the SST because only ocean regions are concerned. LW\(_{\text{clear}}\) and LW represent the upward clear-sky and full-sky longwave fluxes at the TOA, respectively. SW\(_{\text{clear}}\) and SW, respectively, are the clear-sky and full-sky net downward solar radiation fluxes at the TOA.

The responses of the Ga and CRFs to El Niño warming are examined using the regression analysis as in Sun et al. (2006). The observed variations of the Sea Surface Temperature (ERSST) v2 (Smith and Reynolds, 2004).

The feedbacks estimated from the ISCCP data averaged over the Pacific cold tongue region during the three periods are quantified in Table 1. The feedbacks from the ERBE are also listed for comparison. The feedbacks estimated from these two data sets matched reasonably well.

The feedbacks over the Pacific cold tongue region estimated from the other two periods differ from those of 1985–89 (Table 1). The feedbacks from the Ga and the CRFs in the period of 1990–94 are all approximately 5 W m\(^{-2}\) K\(^{-1}\) larger than those of 1985–89; all exceed the scope of estimate uncertainty. The estimates from 1995–99 differ from those of 1985–89, but the differences are much smaller than those between 1990–94 and 1985–89. The spatial patterns of Cs feedback are presented in Fig. 1. Compared with those of 1985–89, the feedbacks during El Niño are more vigorous in 1990–94, especially in the central tropical Pacific. For example, the Cs feedback during 1990–94 is two times larger than that of 1985–89, both in the central and western Pacific. The Cs feedback during 1995–99 is comparable to that of 1985–89, even though the negative maxima center shifts eastward.

To reveal the differences between these periods, we show the relationship between radiative forcing (RF) anomalies and the SST by grouping the data from all three periods. The resulting scatter diagrams are shown in Fig. 2. The interannual anomalies in the RFs and the SSTA at each grid point (2.5\(^\circ\) × 2.5\(^\circ\)) are plotted over the entire equatorial cold tongue region. The anomalous Ga is observed variations of the Sea Surface Temperature (ERSST) v2 (Smith and Reynolds, 2004). The observed variations of the SST and the corresponding fluxes over the domain.

Table 1 Estimations of feedbacks over the equatorial cold tongue region (5°S–5°N, 150°E–110°W) from Ga, Cl, and Cs cloud radiative forcing for three periods, i.e., 1985–89, 1990–94, and 1995–99. The values of these feedbacks are obtained through a linear regression using the interannual variations of the SST and the corresponding fluxes over the domain.

<table>
<thead>
<tr>
<th>Feedbacks (W m(^{-2}) K(^{-1}))</th>
<th>1985–89</th>
<th>1990–94</th>
<th>1995–99</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{\Delta Ga}{\Delta T} )</td>
<td>6.75 ± 0.27</td>
<td>7.50 ± 0.29</td>
<td>12.03 ± 0.93</td>
</tr>
<tr>
<td>( \frac{\Delta Cl}{\Delta T} )</td>
<td>11.82 ± 0.97</td>
<td>10.97 ± 0.81</td>
<td>15.85 ± 2.05</td>
</tr>
<tr>
<td>( \frac{\Delta Cs}{\Delta T} )</td>
<td>-10.57 ± 1.21</td>
<td>-10.40 ± 0.92</td>
<td>-16.89 ± 2.67</td>
</tr>
</tbody>
</table>
more tightly controlled by the SSTA than the anomalous CRFs. Within the entire range of the SSTA, the Ga increases with the SSTA. In contrast, the responses of the CRF anomalies to the SSTA can be divided into three regimes: 1) Regime I: when the SSTA is below \(-0.5^\circ\text{C}\), the CRF anomalies are not sensitive to the SSTA; 2) Regime II: when the SSTA is within \(-0.5^\circ\text{C}\) to \(2.0^\circ\text{C}\), both anomalous CRFs increase dramatically with the SSTA; 3) Regime III: when the SSTA exceeds \(2.0^\circ\text{C}\), CRFs anomalies decrease with the SSTA.

Based on Fig. 2, we can understand why the feedbacks from the Cl and the Cs over the period of 1990–94 are much stronger than those over the other two periods. During 1990–94, the SSTA is within the range from \(-0.5^\circ\text{C}\) to \(2.0^\circ\text{C}\), a range in which CRFs are highly sensitive to the SSTA. However, the SSTA is below \(-0.5^\circ\text{C}\) during 1985–89, while during 1995–99, the SSTA covers the whole range.

![Figure 1](image1.png)

**Figure 1** The spatial patterns of responses of Cs to El Niño warming (surrogated by the SSTA averaged over the Pacific cold tongue region (5°S–5°N, 150°E–110°W)) for the periods of (a) 1985–89 from ERBE and (b) 1985–89, (c) 1990–94, and (d) 1995–99 from ISCCP, respectively. Only regression coefficients that are significant at the 5% level are shaded. The contour interval is 4 W m\(^{-2}\) K\(^{-1}\).

![Figure 2](image2.png)

**Figure 2** Scatter diagrams showing the relationship between (a) Ga, (b) Cl, (c) Cs, and (d) the net cloud radiative forcing (Net) anomalies and the SSTA on the interannual time scale for three periods: the period of 1985–89 (blue dots), the period of 1990–94 (red dots), and the period of 1995–99 (green dots). Each dot corresponds to one grid within the Pacific cold tongue region (5°S–5°N, 150°E–110°W) at a resolution of 2.5°×2.5°.
We analyzed the corresponding total SST in the central equatorial Pacific during the three regimes. The results suggest that the lack of sensitivity in regime I is linked to the fact that the equatorial central Pacific needs to be warm enough to support deep convection. Regime I corresponds to a La Niña condition. Regime II corresponds to an equatorial central Pacific that supports deep convection. The remarkable increase in the sensitivity in regime II reflects the sensitivity of deep convection to changes in the SST in that region. Regime III corresponds to an exceptionally strong warm event that caused a maximum SST warming in the far eastern Pacific. Composite analysis shows that large positive SSTAs (>0.5°C) during 1985–89 and 1990–94 are located in the central-eastern Pacific. However, the positive SSTA is located in the eastern Pacific during the period of 1995–99, and the occurrence of large positive SSTAs (>0.5°C) is more frequent during 1990–94 than during the other two periods over the central Pacific domain (data not shown). During 1995–99, because of the low base SST over the far eastern Pacific, the total SST was still below the convective threshold temperature (~27°C), therefore the deep convection over the Pacific cold tongue region was suppressed. In the central Pacific, when the SST is higher than 0.5°C, the total SST would exceed the convective threshold temperature. In summary, the location of the SSTA has a significant influence on the convection and the convection-related radiative forcings.

How are the responses of the CRFs to the SSTA linked to the response of vertical cloud structures to the SSTA over the Pacific cold tongue region? To answer this question, the climatology of cloud properties and their responses to the SSTA were examined. Climatologically, low-level clouds are dominant, with a value approximately 26.1%. The high-level clouds represent approximately 23.4%, and they can be broken down into cirrus (17.8%) and cirrostratus together with deep convective clouds (8.1%). The middle-level clouds represent 11.53%. Cloud radiative forcing is a function of cloud type. To understand the regime behavior shown in Fig. 2, scatter diagrams of anomalous cloud properties, such as cloud optical thickness and clouds amounts of different types, are plotted versus SST in Fig. 3. Both optical thickness and cloud top temperature have two significant changes in their slopes with respect to the SSTA (Figs. 3a–b), which is similar to that of CRFs. These changes in the slope are also evident in cirrostratus and deep convective clouds (Figs. 3c–d). The total middle-level cloud amount increases with the SSTA (Fig. 3e), while low-level clouds remains unchanged until the SSTA exceeds 2.0°C (Fig. 3f). The features shown in Fig. 3 suggest the dominant contributions of deep convection and cirrostratus clouds.

![Figure 3](image-url)
to the regime behavior of CRFs and the SSTA and confirm the role of convection in radiative feedback in the Pacific cold tongue region.

The large-scale circulation also plays an important role in determining the cloud radiative response (Bony et al., 1997). The warming in the coastal region may reduce the moisture convergence to the equatorial central Pacific where deep convection takes place. The responses of water vapor transport and its divergence in three El Niño events are presented in Fig. 4. In climate mean states, the water vapor converges over the western warm pool region and along the Inter Tropical Convergence Zone (ITCZ) and the Southern Pacific Convergence Zone (SPCZ), and the subtropical oceans are the source of water vapor (Fig. 4a). Under the El Niño condition, the anomalous water vapor transport divergence is located over the central equatorial Pacific in all three periods (Figs. 4b–d). The centers of the negative response for the three periods are slightly different in location, i.e., the center of the 1990–94 period shifts eastward compared with those of the other two periods. In addition, the change of water vapor transport between the periods of 1985–89 and 1990–94 is small over the southeastern Pacific region. However, an anomalous northwesterly to the South American coast over the southeastern Pacific is evident during the period of 1995–99, corresponding to a weakening of the southeast trade wind (Fig. 4d), which is related to the warming over the far eastern equatorial Pacific. The magnitude of SST anomalies determines the change of zonal SST gradients and therefore the large-scale circulation and the responses of CRFs to El Niño warming.

4 Summary

With the motivation of examining the potential sample dependence of radiative feedbacks on the ENSO time scale, the feedbacks from Ga and CRFs over the periods of 1990–94 and 1995–99 were estimated using ISCCP. The results were compared with those derived from the period covering 1985–89, which is a period that has been widely used in previous studies. The hypothesis of sample dependence is confirmed by our analysis. The results show significant differences in cloud feedbacks associated with different events, and a regime behavior of the CRFs-SSTA relationship is revealed. The major results are summarized below:

1) Quantitative estimates of radiative feedbacks are sample dependent and those from three periods are significantly different in both magnitude and spatial pattern. In particular, the estimates for the 1990–94 period differ considerably from those from the other two periods.

2) The differences in CRFs can be explained by the regime behavior of the CRFs-SSTA relationship, which depends on the magnitude of the SSTA. Over the entire Pacific cold tongue region (5°S–5°N, 150°E–110°W), the CRF and SSTA relationship exhibits a regime behavior. When the SSTA is below –0.5°C, the CRF is insensitive to SSTA change; when the SSTA is between –0.5°C and 2.0°C, the CRF increases with the SSTA; however, when

![Figure 4](image-url)
the SSTA exceeds 2.0°C, an increase of the SSTA is followed by a decrease of CRFs. The regime behavior of the CRFs-SSTA relationship is dominated by deep convective and cirrostratus clouds.

3) The remote forcing of large-scale circulation also partly accounts for the differences in CRF changes during the three periods. For the ENSO events during 1995–99, the weakening of water vapor transport from the southeastern Pacific reduces the moisture convergence over the equatorial central Pacific, reducing the water vapor feeding to convection. This situation differs from those during the periods of 1985–89 and 1990–94. The water vapor transport is related to the spatial pattern of the SSTA during the three periods.

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