# Interactions of Clouds, Water Vapor and Radiation Budgets in the Tropical Pacific During Climate Variations

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## 1. Introduction

From a global, long-term perspective, the Earth's climate is determined by the way that temperature, water vapor and clouds respond to solar heating of the earth, which requires the balance between the absorption of solar radiation by the earth-atmosphere system and the emission of thermal infrared (IR) radiation to space. The steady increases in the atmospheric concentration of the greenhouse gases, such as $CO_2$, $N_2O$, $CH_4$, and CFC's, due to fossil fuel combustion and biomass burning cause the Earth to trap more IR radiation from emitting to space. Although this radiative forcing has an effect of warming the Earth, its magnitude is highly uncertain and is a major issue of climate research (IPCC, 1995). This uncertainty in the potential climate greenhouse warming is primarily due to our lack of knowledge on the feedback mechanisms among water vapor, cloud, temperature, and radiative energy budgets. Improving our understanding of the feedback mechanisms is critical in climate research.

The climate of the tropical Pacific undergoes significant oscillations with a period of 3-5 years. During these El Nino/Southern Oscillation (ENSO) episodes, trade winds slacken, the temperature of the central and eastern equatorial Pacific ocean increases, the Hadley and Walker circulations weaken, and the convection center shifts from the western equatorial Pacific to the central equatorial Pacific. Corresponding to these changes, the energetics in the Pacific also changes significantly. Lindzen (1990) suggested that observation of these changes during an ENSO episode could be used to study the interactions between water vapor, clouds, and radiation, thereby providing information on climate sensitivity to external radiative forcing.

The importance of large-scale atmospheric circulation and temperature distributions in affecting the cloud radiative forcing and water vapor greenhouse warming was studied by Hartmann and Michelsen (1993). Based on the Earth Radiation Budget Experiment (ERBE) (Barkstrom, 1984) and sea surface temperature (SST) data, they found that averaged over both the ascending and descending branches of large-scale circulations, the cloud forcing is not sensitive to the mean SST. Fu et al. (1992) analyzed the International Satellite Cloud Climate Project (ISCCP) B3 radiance data and concluded that large-scale cirrus clouds in the tropics is sensitive to the circulation pattern but not the SST. The relationship between SST and those parameters that are highly correlated with the incident solar flux in the western tropical Pacific was further analyzed by Arking and Ziskin (1994) using lag-correlations. Lau et al. (1994) studied the relative importance of the large scale circulation and SST on clouds using the Goddard Cumulus Ensemble Model (Tao and Simpson, 1993). Chou (1994a, 1994b, 1997) studied the cloud radiative forcing in the TOGA COARE (Tropical Ocean and Global Atmosphere / Coupled Ocean Atmosphere Research Experiment) and the changes in clouds and radiation budgets in an El Nino episode. The results of these studies have shed light on the physical processes relating cloud, radiation, and climate.

## 2. Data Sources

Monthly mean SST, high-level clouds, and the outgoing longwave radiation (OLR) and the solar radiation at the top of the atmosphere (TOA) averaged over 2.5°x2.5° latitude-longitude regions are analyzed for the equatorial and tropical Pacific (30°S -30°N, 100°E -100°W). Analyses are performed for April 1985 and April 1987. The former is a non-El Nino year and the latter is an El Nino year. The SST data are obtained from the U.S. National Center for Environmental Prediction (NCEP) analyses. The fractional cloud covers are obtained from the ISCCP (International Satellite Cloud Climatology Project) C1 data set. The OLR and the TOA solar radiation are obtained from the ERBE S-4 data archive. In addition to the satellite and surface radiation measurements, radiation budgets in the atmosphere and at the earth surface are computed for the western tropical Pacific using radiative transfer models (Chou, 1992, Chou and Suarez, 1994). Fluxes are computed eight times a day with a time interval of 3 hrs for each 2.5° x 2.5° latitude-longitude region.

Satellite and surface observations during the TOGA COARE Intensive Observation Period (IOP) from 1 November 1992 to 28 February 1993, are used to study the effect of clouds on the radiation budgets of the western Pacific warm pool. Integrated Sounding System (ISS) was installed at two island stations (Kavieng, Kapingmarangi) and two ships (Kexue#1, Shiyan#3) in the Intensive Flux Area (IFA) and two island stations (Manus, and Nauru) in the outer sounding array (OSA). Four radiosondes at six-hour intervals were launched each day to measure atmospheric temperature and humidity profiles. Surface radiation measurements were conducted at these ISS stations, as well as a buoy (IMET) station near the center of IFA. High resolution one-minute data are available from all stations, except the IMET buoy station which has a 7.5-minute resolution.

3. Clouds, radiation budgets and SST in an El Nino Episode

The relationships among clouds, water vapor, and radiation budgets in the tropical Pacific are studied for April 1987 and April 1985. The former is an El Nino year, and the latter is a non-El Nino year. Compared to April 1985, the SST in the equatorial and the Northern Hemisphere tropical Pacific is higher in April 1987. The convection center shifts from the western equatorial Pacific to the central equatorial Pacific, with corresponding changes in cloudiness and radiation budgets. Figure 1 shows changes in the total (solar+IR) flux convergence in the atmosphere and the total net downward flux at the surface west of the dateline between April 1985 and April 1987. The difference between the two years in the atmospheric and surface heating is large. In the El Nino year, the atmospheric cooling enhances in most of the western tropical Pacific, except in the equatorial region east of 150°E where the atmospheric cooling decreases by ≈30 W $m^{-2}$ in response to an increase in cloudiness. The change in the total surface flux is reversed from the change in the atmosphere. The surface heating increases in most of the western tropical Pacific. The surface heating in the equatorial region east of 150°E decreases by a maximum of ≈50 $Wm^{-2}$ due to a decrease in solar radiation associated with an increase in cloudiness in the El Nino year.

The effect of clouds on the atmospheric radiation is primarily in the thermal IR. Except in the 10-μm IR window region, clouds are rather opaque, and the radiative cooling is large at the cloud-top levels but small in and below clouds. Because of the shift in cloudiness from a non-El Nino year to an El Nino year, the vertical profile of the atmospheric cooling rate changes differently in the eastern and western sections of the western equatorial Pacific. It is found that the mean IR cooling rate profiles in the western section (100°E-150°E, 10°S-10°N) and eastern section (150°E-180°E, 10°S-10°N) of the western equatorial Pacific are very different for April 1985 and April 1987. In the eastern section, the cooling increases by ≈ 2.5 °C/day at ≈200 mb in the El Nino year but decreases by ≈ 1.0 °C/day below. In the western section, the change in the cooling profile is reversed but with a smaller magnitude.

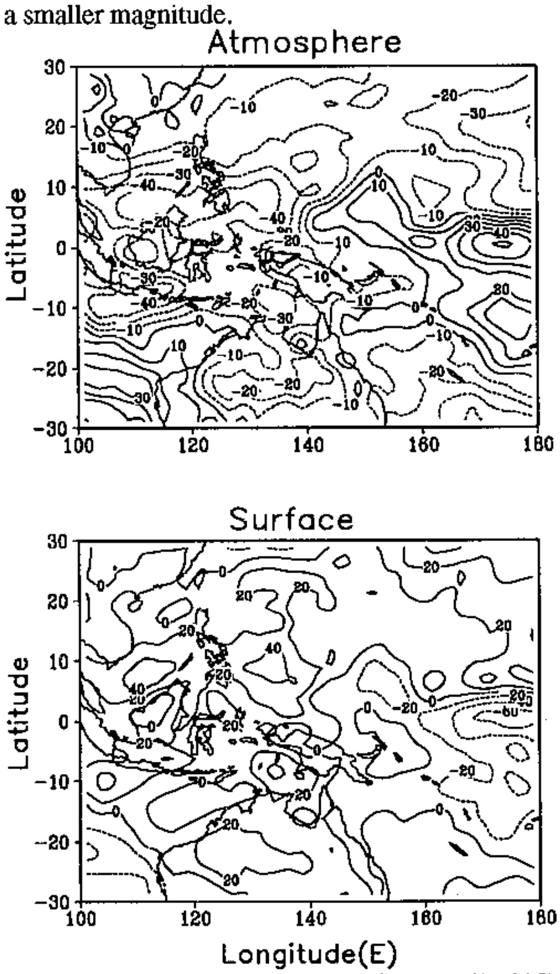

Figure 1. Changes (April 1987 minus April 1985) in the total radiative heating of the atmosphere (upper panel) and the surface (lower panel). Dashed contours are negative value. Units are W $m^{-2}$.

It can be expected that the surface latent heat flux in the Northern Hemispheric tropical Pacific is larger in April 1987 due to an enhanced Hadley circulation. The trade winds carry this heat and converge in the equatorial region, causing a stronger convection in the ITCZ in April 1987 than in April 1985. Associated with this stronger convection, temperature, humidity, and cloudiness (both cloud height and amount) increase in the central and eastern equatorial Pacific, which have a significant effect on water vapor and cloud radiative forcing of the earth-atmosphere system. The change in the water vapor greenhouse effect between April 1987 and April 1985 is shown in upper panel of Figure 2. An organized positive change with a magnitude exceeding 20 W m$^{-2}$ is found in the central and eastern equatorial Pacific. In the tropical and the western equatorial Pacific the change in water vapor greenhouse effect is mostly negative, also with a magnitude exceeding 20 W m$^{-2}$. These changes are ≈10% of the total greenhouse effect, which is in the range 130-190 W m$^{-2}$. Clouds have a large effect on both solar and IR radiation budgets at the top of the atmosphere. Due to a large degree of compensation in the solar and IR cloud radiative forcing, the net effect is small. The lower panel of Figure 2 shows the net impact of clouds on the radiation budget at the top of the atmosphere. It is about half of the impact due to water vapor as shown in the upper panel of Figure 2

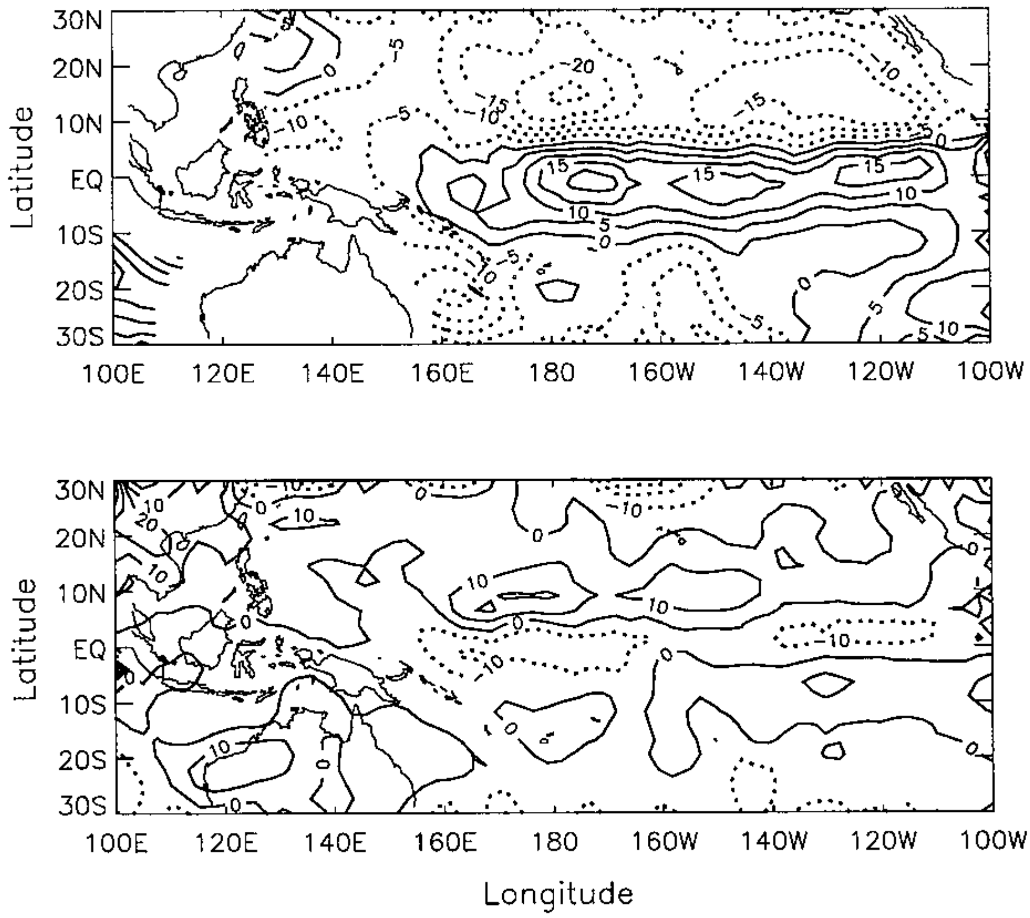


Figure 2. Changes (April 1987 minus April 1985) in the water vapor greenhouse effect (upper panel) and the cloud albedo effect (lower panel) on the radiation budget at the top of the atmosphere.

Table 1 shows changes in the energy budgets at the top of the atmosphere due to water vapor effect, cloud radiative forcing and surface IR emission. Compared to April 1985, the earth-atmosphere system of the equatorial and tropical Pacific region as a whole gains less radiative energy by 4.0 Wm$^{-2}$ in April 1987. Due to the decrease in water vapor in the off-equatorial regions and the increase in upper-level temperature, the emission of IR radiation to space increases by 1.3 W m$^{-2}$, and the absorption of solar radiation decreases by 1.2

W m$^{-2}$. Thus, the warming of the earth-atmosphere system due to water vapor is 2.5 W m$^{-2}$ smaller in April 1987 than in April 1985. The change in cloud radiative forcing is large in both the IR and solar radiation, but the net is only 0.4 W m$^{-2}$. It indicates that changes in cloudiness have a negligible effect on the net radiation budget in April 1987. The change of 1.9 W m$^{-2}$ in the surface IR emission is equivalent to an increase of surface temperature by 0.3 °C at 28 °C, which is the same as the change in SST from April 1985 to April 1987.

Table 1. Changes in the radiation budgets, water vapor effect, and cloud forcing between April 1987 and April 1985 (1987 minus 1985) averaged over the equatorial and tropical Pacific (100°E-100°W, 30°S-30°N). Units are Wm$^{-2}$.

| | IR | Solar | Total |
|---|---|---|---|
| Water vapor effect | -1.3 | -1.2 | -2.5 |
| Cloud forcing | -3.6 | 4.0 | 0.4 |
| Surface IR emission | -1.9 | | -1.9 |
| Total radiation budget | 6.8 | 2.8 | -4.0 |

Note: A positive value indicates warming, and a negative value indicates cooling.

The results shown above are consistent with Lindzen's (1990) hypothesis that reduced water vapor in the vicinity of the enhanced convection region produces cooling which counteracts warming in the tropics. Clouds are shown to have a strong effect on both the IR and solar radiation, but the effect on the net radiation budget at the top of the atmosphere is found to be small. The results are based only on two months of SST, cloud, and radiation data. Further studies are needed to provide more general conclusions on the climate feedback mechanisms involving water vapor, clouds, and SST distributions

4. Cloud radiative forcing during TOGA COARE

The TOGA COARE radiation measurements during the Intensive Observation Period (1 November 1992 - 28 February 1993) provide very useful data for studying the surface radiation budget in the western tropical Pacific warm pool and for validating radiation model calculations. Cloudiness in the warm pool is large. Even in relatively calm periods, low clouds are ubiquitous. Measurements of total surface solar radiation alone do not provide adequate information for identifying clear-sky solar radiation. The ARM (Atmospheric Radiation Measurements) site at Kavieng measured both direct and diffuse downward surface solar fluxes at high temporal resolution (1 minute). These data are used to identify clear-sky solar radiation by simultaneously imposing the following conditions:

(1) The direct downward flux is a maximum for a given solar zenith angle;
(2) The diffuse downward flux is a minimum;
(3) The total solar radiation varies smoothly with time, in concert with the insolation at the top of the atmosphere.

Of more than 20,000 measurements (one-minute resolution) per month, only a few hundreds are identified as clear-sky measurements without cloud interference. Averaged over the four TOGA COARE months, the clear-sky downward solar flux is 308 W m$^{-2}$, with a range of 301-317 W m$^{-2}$.

The estimated clear-sky solar fluxes together with the temperature and humidity radiosonding at Kavieng are used to validate radiation model calculations. Aerosols have a significant effect on the surface solar radiation. The model-calculated direct and diffuse solar fluxes are made to agree with that of measurements by setting the aerosol optical thickness to 0.12, asymmetry factor to 0.5, and the single-scattering albedo to 0.995. Without introducing aerosols, the model-calculated downward flux is significantly larger than that estimated from measurements. Averaged over a day, the difference is 13 W m$^{-2}$. Based on the SAGE (Strtatospheric Aerosol and Gas Experiment) II measurements, the stratospheric aerosols optical thickness is inferred to be ≈ 0.05 in the tropics, which is the residue of the June 1991 Pinatubo volcanic eruptions. The tropospheric aerosol optical thickness is then ≈0.07, which is a reasonable number in remote oceanic regions. Therefore, we can conclude that clear-sky surface solar fluxes can be reliably computed using a radiation model.

The cloud effect on the surface solar radiation is estimated by taking the difference between the measured all-sky radiation and the model-calculated clear-sky radiation at the surface for all the TOGA COARE radiation stations. The aerosol optical properties inferred from the radiation measurement at Kavieng is applied to all other stations in computing clear-sky fluxes. Variation in the net clear-sky surface fluxes among the seven radiation stations is small (3 W m$^{-2}$) with a mean of 299 W m$^{-2}$ over the four TOGA COARE months. The range of the cloud radiative forcing among stations is large, from 79 W $m^{-2}$ to 112 W $m^{-2}$, which is a result of a large variation in all-sky fluxes. Averaged all these stations, the cloud radiative forcing is 99 W $m^{-2}$, which is in agreement with the results of a recent study by Waliser et al. (1996).

## 5 Conclusions

Clouds have a large impact on the surface solar radiation in the western tropical Pacific warm pool, which reduce the solar heating of the ocean by 100 W $m^{-2}$ during the TOGA COARE period. Due to the eastward shift in clouds from the western equatorial Pacific to the central equatorial Pacific in an El Nino event, the radiation budgets undergo significant changes. The change in the atmosphere is primarily due to thermal IR radiation, whereas the change at the surface is primarily due to solar radiation. The magnitude of the change is ≈40 W $m^{-2}$ in both the atmosphere and at the surface but with opposite signs, which has a significant impact on the stability of the atmosphere and, hence, the large-scale circulation. Averaged over the entire tropical Pacific, the earth-atmosphere system receives less radiative energy during an El Nino year than a non-El Nino year, which is consistent with Lindzen's hypothesis that reduced upper-tropospheric water vapor in the vicinity of the enhanced convection regions produces cooling that counteracts warming in the Tropics.

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