Radiation Budgets and Cloud Radiative Forcing in the Pacific Warm Pool Derived from GMS Measurements during TOGA COARE

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1. INTRODUCTION

Energy budgets at the western tropical Pacific warm pool is particularly important because this is one of the most energetic convective regions on the Earth. Nearly half of the solar radiation incident at the top of the atmosphere (TOA) is absorbed at the surface. A large portion of the excess heat is transferred to the lower troposphere through evaporation that drives the Hadley circulation. Radiation budgets in the western tropical Pacific is complicated by the nature of strong convection and associated mesoscale subsidence, which have large variations in both cloud height and amount. Kiehl (1994) studied the Earth Radiation Budget Experiment (ERBE) fluxes and found that clouds nearly have no impact on the radiative budget of the earth-atmosphere system in the tropics. On the other hand, Chou (1994) compared the change in radiation budgets between an El Nino year and a La Nina year and found that two thirds of the change in the absorbed solar (shortwave, or SW) radiation occurred at the surface and only one third is in the atmosphere. The reverse is true for the thermal infrared (longwave, or LW) radiation. These changes are caused by the shift in cloud distributions between an El Nino year and a La Nina year. The uneven partitioning of energy between the atmosphere and the surface in both the SW and LW radiation will certainly have a significant impact on oceanic and atmospheric circulations.

The Tropical Ocean and Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA COARE) conducted during the Intensive Observation Period (IOP), 1 November 1992-28 February 1993, measured SW and LW surface radiation at a number of surface stations, on board research ships, and at a research buoy. During this period, we also have Japan's Geostationary Meteorological Satellite-4 (GMS-4) radiance measurements. In addition, the TOA fluxes during 1985-1989 are available from the ERBE data archive. These data are used in this study to derive the SW and LW radiation budgets, cloud radiative effect, and the role of large-scale atmospheric dynamics on the convection within the Pacific warm pool

2. DATA SOURCE

During the COARE IOP, from 1 November 1992 to 28 February 1993, integrated sounding systems (ISS) (Parsons et al, 1994) were installed at two island stations (Kappingamarangi, Kavieng) and two research ships (Kexue #1, Shiyan #3) in the Intensive Flux Array (IFA), and two island stations (Manus, Nauru) in the Outer Sounding Array. Besides the six ISS sites, a research buoy, IMET, was located in the middle of IFA. At each of these sites, the downward surface SW flux was measured by an Eppley PSP pyranometer, and the downward surface LW flux was measured by an Eppley PSP pyrgeometer. The ISS installed at the six sites also included a balloon-borne sounding system for measuring atmospheric temperature and humidity profiles.

The GMS-4 was located at 140° E above the equator and measured albedo in the visible, a_v, (0.5-0.75 μm) and the brightness temperature in the thermal infrared, T_b, (10.5-12.5 μm). It scanned the Earth's disk once every hour. The spatial resolution of each pixel is 1 km for the visible channel and 5 km for the thermal IR channel. The daily total precipitable water derived from the Special Sensor Microwave/Imager (SSM/I) radiance measurements (Wentz, 1994) are used in this study in the calculations of clear-sky surface SW fluxes in the region 10°S - 10°N and 135°E - 175°E (narrowly defined as warm pool). The TOA clear-sky and all-sky SW fluxes from the ERBE archive are used to approximate that in the warm pool during

COARE IOP. Finally, the sea surface temperature (SST) is taken from the National Centers for Environmental Prediction (NCEP) reanalysis (Kalnay, et al., 1996).

3. SATELLITE RETRIEVAL OF SURFACE RADIATION

In this study, empirical relationships between α_v and T_b and the surface radiative fluxes are derived using the GMS-4 data and the radiation measured at the surface network during the COARE IOP.

a. *SW radiation*

Although radiative transfer calculations show that the TOA SW flux is nearly linearly correlated with the surface SW flux (Chou, 1991), we do not expect the relationship to be strictly linear because of the highly non-linear nature of radiative transfer, especially with complicated cloud situations. Nevertheless, we can expect that the atmospheric transmittance, τ, decreases smoothly with increasing a_v for a given μ_o and with increasing μ_o for a given α_v, where μ_o is the cosine of the solar zenith angle. The latter is a result of an increased atmospheric pathlength and absorption for a larger solar zenith angle. In this study, we empirically derive τ as a function of α_v and μ_o.

During the COARE IOP, there are a total of 877 GMS-4 visible images available (Flament and Bernstein, 1993). Therefore, the maximum number of albedo-transmittance pairs at each surface radiation site is 877. The transmittance, τ, in all available data pairs at the seven surface sites are combined and binned into equal intervals in both μ_o, and α_v. The interval is 0.05 for μ_o and 0.02 for α_v. A mean transmittance, $\bar{\tau}$, is then computed for each of the μ_o-α_v bins. The computed $\bar{\tau}$ is found to vary rather irregularly with μ_o and α_v, as can be expected from complicated cloud situations and the incomplete match in time and space between the satellite and surface measurements. We therefore apply smoothing to $\bar{\tau}$ in both μ_o and α_v directions, and the results are saved in tables.

Applying the transmittance tables together with the information on the extraterrestrial SW radiation and μ_o, hourly downward surface SW fluxes are computed from α_v, and daily mean downward surface SW fluxes are computed from hourly values. Figure 1a shows the scatter plot of the daily-mean satellite-inferred vs surface-measured downward SW fluxes at the seven surface sites. The mean error (satellite retrieval minus surface measurement) is +5.4 W m^{-2} and the rms error is 25 W m^{-2}.

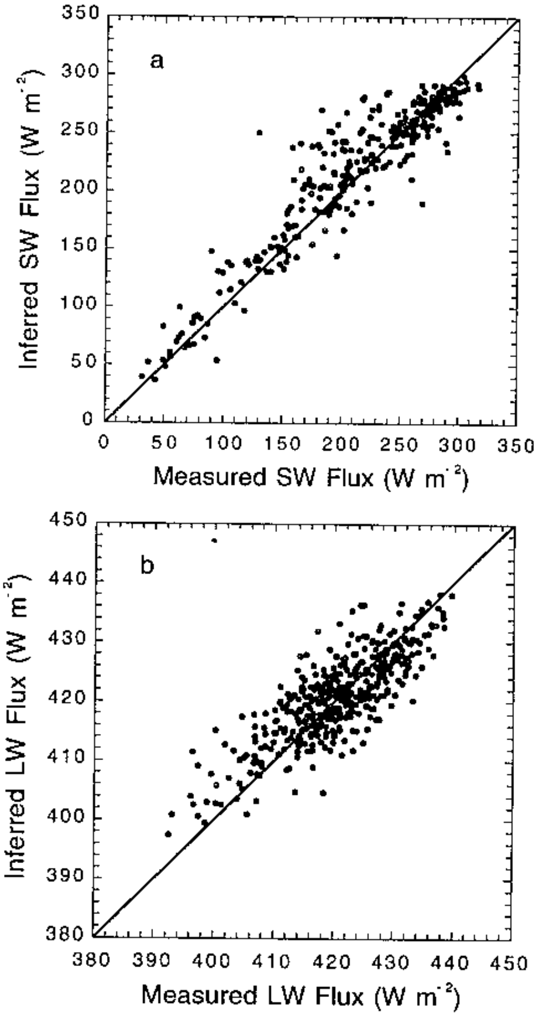

Figure 1. Scatter plots of the daily satellite-inferred vs. surface-measured downward SW flux (a) and LW flux (b) at the seven surface sites.

b. *LW radiation*

Radiative transfer calculations show that over 90 % of the downward LW flux at the surface, F, comes from the lowest 1 km during COARE IOP. Thus, the downward

LW flux is not only related to T_b but also to the temperature and humidity in the atmospheric boundary layer. The near-surface temperature is closely tied to the sea surface temperature, T_s, while the near-surface humidity is closely tied to the total precipitable water, w. To derive an empirical function for F, we first separate the effect of T_s from that of w and T_b by the following normalization,

$$F = F_0 (T_s/T_0)^4 \quad (1)$$

and fit F_0 by

$$F_0 = 502-0.464T_b-6.75w+0.0565wT_b \quad (2)$$

so that the rms difference between F and the downward LW flux measured at the surface sites are minimized, where T_0 = 302.1 K is the mean T_s in the warm pool during COARE IOP. The units are K for T_b and cm for w.

We have applied Eqs. (1) and (2) to compute F using T_b from GMS-4 measurements, w from SMM/I retrievals, and T_s from the NCEP reanalysis. Figure 1b shows the scatter plot of the daily-mean values of the computed and measured downward LW fluxes. The mean error in the computed LW flux is 0.4 W m^{-2} and the rms error is 5.2 W m^{-2}.

4. Spatial and temporal distributions

The methods mentioned in the previous section are used to compute the net downward SW and LW fluxes for 1° x 1° latitude-longitude regions in the warm pool. Figure 2a shows the net downward SW radiation (solar heating) at the sea surface averaged over the COARE IOP. The solar heating varies significantly between the eastern and western sections of the region. The minimum heating of 170 W m^{-2} is located near 170°E longitude and north of the equator, while the maximum of 220 W m^{-2} located near the equator extends from 150°E westward to 135°E. The spatial distribution of the solar heating is dominated by that of clouds. The GMS-4 images show a region with a maximum albedo covering the entire island of New Guinea during the COARE IOP. The maximum SW heating and, hence, minimum cloudiness just north of New Guinea is influenced by the strong convection over New Guinea, which is induced by strong solar heating of the land surface.

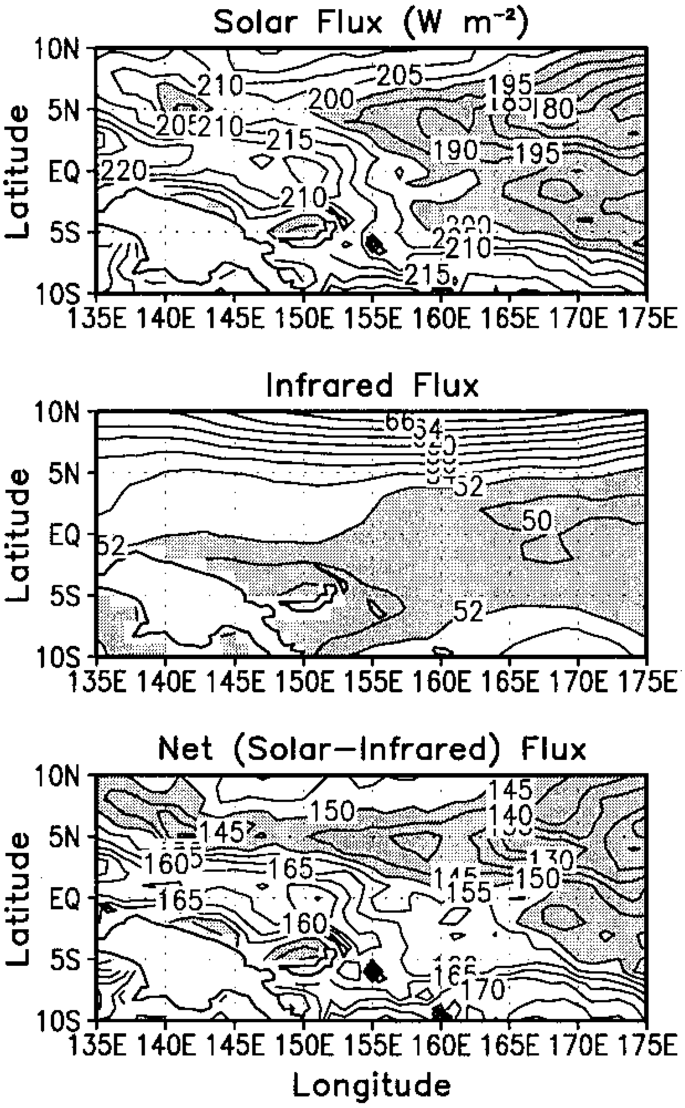

Figure 2. The net downward SW flux, the net upward LW flux, and the total surface radiative heating (SW flux - LW flux) at the sea surface averaged over the COARE IOP. Units are W m^{-2}.

The net upward LW radiation (IR cooling) at the sea surface averaged over the COARE IOP is shown in Figure 2b. The downward LW flux is computed from Eqs. (1) and (2), and the upward LW flux is computed from σT_s^4 As can be seen in the figure, both the magnitude and spatial variation of the IR cooling are small. As judged from the solar heating shown in Figure 2a which indicates a much larger cloud amount in the eastern section than the western section, the effect of clouds on the surface IR cooling is secondary. This can be expected from the high humidity in the warm pool.

The spatial distribution of the total surface radiative heating (solar heating minus IR cooling) averaged over the COARE IOP is shown in Figure 2c. It follows closely that of SW flux but with reduced magnitude. The range of spatial variation is 50 W m^{-2}. This differential heating is equivalent to a change in the temperature of a 60-meter ocean mixed layer by 2° C over a period of four months, if other factors are not considered. We can expect this surface heating variation to have significant impact on air-sea interaction and atmospheric convection.

The daily variation of area-averaged solar heating of the ocean is shown in Figure 3. The prominent feature is a large range of the area-averaged solar heating, reaching 90 W m^{-2}. The minimum on 22 December 1992 coincides with the strong westerly wind-burst episode during 22 December 1992-5 January 1993 (Sui et al., 1997). The westerly wind-burst episode during 22 January-2 February 1993 does not appear to have any significant effect on the area-mean solar heating.

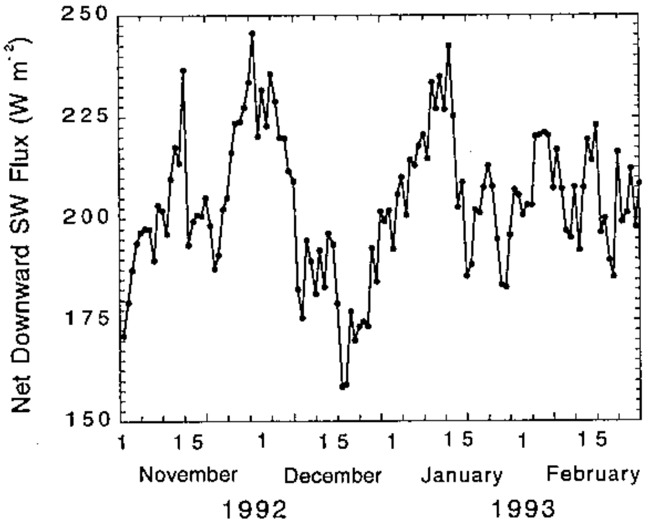

Figure 3. The daily variation of solar heating of the ocean averaged over the warm pool (10°S-10°N and 135°E-175°E).

5. Partitioning of radiative heating and cloud forcing

The partitioning of solar radiative heating between the atmosphere and the ocean is important as it affects the transfer of latent heat from the ocean to the atmosphere and, hence, convection. We have derived the surface radiative heating over the warm pool during COARE IOP based on the relationship between the surface flux measurements and the GMS radiance measurements. Because there were no measurements of the TOA flux during COARE, we cannot directly derive the absorption of SW radiation in the atmosphere. However, there are ERBE flux measurements during 1985-1989, which can be used to indirectly estimate the partitioning of solar heating between the atmosphere and the ocean.

The Northern Hemispheric winter of 1986-1987 is an El Nino. Spatial distributions of the ERBE-derived planetary albedo show that there is more clouds in the warm pool in this season than the other season, and the convection center is moved eastward closer to the dateline. The planetary albedo of the warm pool is 0.301 in this season, which is larger than the mean planetary albedo of 0.281 of the four northern winters. The effect of cloud (or cloud forcing) on the TOA flux reaches 81 W m^{-2}.

A convenient parameter for assessing the effect of clouds on the atmospheric solar heating is the ratio of the cloud forcing at the surface to that at the TOA,

$$R = CRF_{sfc} \, / \, CRF_{toa} \tag{3}$$

where CRF_{sfc} and CRF_{toa} are the cloud SW forcing at the surface and the TOA defined by

$$CRF_{sfc} = (F_{sfc,a} - F_{sfc,c}) \tag{4}$$

$$CRF_{toa} = (F_{toa,a} - F_{toa,c}) \tag{5}$$

F_{sfc} and F_{toa} are the net downward fluxes at the surface and the TOA, and the subscripts a and c denote all-sky and clear-sky, respectively.

The COARE IOP is characterized by a rather warm central equatorial Pacific. We have found that the longitudinal distributions of SST, clouds, and radiation budgets of the COARE IOP are close to that of the NDJF (November, December, January, February) in 1986-1987. If we assume that the TOA net downward SW fluxes during the COARE IOP is the same as that during the NDJF of 1986-1987, then the solar heating of the atmosphere during COARE IOP is 94.9 W m^{-2} for all-sky and 80.1 W m^{-2} for clear-sky, and CRF_{toa} = -80.7 Wm^{-2}. Clouds enhances the atmospheric solar heating by 14.8 W m^{-2}. Since the estimated CRF_{sfc} during COARE IOP is -95.5 W m^{-2}, we have R = 1.18, which is only slightly larger than 1.1 as suggested by radiative transfer model calculations. Considering all the uncertainties involved in the flux measurements and estimations at both the TOA and the surface, the difference is trivial.

6. Conclusions

Empirical relationships between the surface radiation and satellite-measured radiances derived for the seven Tropical Ocean and Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA COARE) radiation sites are applied to compute the shortwave (SW) and longwave (LW) fluxes over the Pacific warm pool (narrowly defined as the region 10°S-10°N and 135°E-175°E). Even averaged over the entire COARE Intensive Observation Period (IOP), November 1992-February 1993, the surface radiation has a large spatial variation. Regions of minimum SW heating do not coincide with regions of maximum sea surface temperature (SST). It indicates that the large-scale atmospheric dynamics and the land-sea distribution are more important than SST in forcing convection within the warm pool. The total radiative heating (SW heating minus LW cooling) ranges from 125 to 175 W m^{-2}. This large spatial variation of surface radiative heating could have a significant impact on SST and atmospheric circulation.

Partitioning of the SW heating between the surface and the atmosphere has been estimated. For the entire warm pool and the COARE IOP, two-thirds (198.5 W m^{-2}) of the total heating of the earth-atmosphere system is absorbed at the surface, and one-third (95 W m^{-2}) is absorbed in the atmosphere. The effect of clouds on the SW heating of the atmosphere is +13 W m^{-2}, which is not much different from radiation model calculations. The ERBE fluxes at the top of the atmosphere for the Northern Hemispheric winter of 1986-1987 are used as proxy for the solar heating of the earth-atmosphere system.

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