Clouds, Radiation, and the Diurnal Cycle of Sea Surface Temperature in the Tropical Western Pacific

P. J. Webster, C. A. Clayson, and J. A. Curry
Program in Atmospheric and Oceanic Sciences
University of Colorado
Boulder, Colorado

Introduction

In the tropical Western Pacific (TWP) Ocean, the clouds and the cloud-radiation feedback can only be understood in the context of air/sea interactions and the ocean mixed layer.

Considerable interest has been shown in attempting to explain why sea surface temperature (SST) rarely rises above 30°C, and gradients of the SST. For the most part, observational studies that address this issue have been conducted using monthly cloud and SST data, and the focus has been on intraseasonal and interannual time scales. For the unstable tropical atmosphere, using monthly averaged data misses a key feedback between clouds and SST that occurs on the cloud-SST coupling time scale, which was estimated to be 3-6 days for the unstable tropical atmosphere (Chu et al. 1990). This time scale is the time needed for a change in cloud properties, due to the change of ocean surface evaporation caused by SST variation, to feed back to the SST through its effect on the surface heat flux.

To clarify the SST, we must distinguish between the "skin" SST, which is the radiometric temperature of the sea surface, and the "bulk" SST. The true bulk SST is defined to be the temperature within the upper few centimeters of the ocean surface. The bulk SST determined from buoy measurements is typically obtained at a depth of 0.5 m, while the bulk SST determined from ship measurements may be obtained from depths as large as 5 m. The radiative, latent, and sensible heat exchanges between the atmospheric and oceanic boundary layers depend on the actual skin temperature of the ocean, making the skin temperature the critical SST for examining air/sea interactions. The skin temperature can differ from the bulk water temperature in the tropics by values as large as 1-3 K (e.g., Cechet 1993), although the magnitude of the bulk-skin temperature difference is usually < 1 K (e.g., Wick et al. 1992).

Table 1. Changes in surface heat flux components associated with a 1°C change in SST for average conditions during the TOGA COARE IOP.

	Flux Change	
Component	**(Wm^{-2})**	**(%)**
Upwelling Longwave	6.3	1.3
Sensible Heat	2.4	23.3
Latent Heat	18.7	16.2

Table 1 shows the changes in surface heat flux components associated with a 1°C change in SST for average conditions during the Tropical Ocean Global Atmosphere (TOGA) Coupled Ocean Atmospheric Response Experiment (COARE) Intensive Observation Period (IOP). Substantial changes are seen particularly in the surface latent heat flux. All of the changes are of the same sign (i.e., none of the changes cancel if the net surface heat flux is being evaluated). Therefore, a 1°C change (or error) in sea surface skin temperature would result in a change (or error) of 27 W m^{-2} in the net surface heat flux. In many instances, an error of this magnitude would be large enough to change even the sign of the net surface heat flux and could significantly modulate atmospheric boundary layer and convective processes. Therefore, care must be taken in using the correct skin SST to evaluate the surface fluxes and in determining the diurnal variation of SST in the TWP.

In this paper, we use data obtained from the TOGA COARE IOP along with an ocean mixed layer model to address the relationship between clouds, surface radiation flux, and SST of the TWP Ocean over the diurnal cycle. A blending of the model and observations are used for this investigation as this analysis would not be possible using only the observational data. By examining the relationship between clouds, surface fluxes, and SST over the diurnal cycle, we can interpret the details of the direct influence of clouds on SST. We examine the effects not only of the surface heat fluxes, but the fresh water and momentum fluxes as well. We also interpret these relationships in the context of the temperature variations at various depths in the ocean that are commonly used to describe “surface” temperature. Sensitivity studies are conducted with the model to investigate the roles of surface wind speed, precipitation, ocean turbidity, and ocean initial state in modulating the radiation-induced diurnal cycle in SST.

TOGA COARE Data

The TOGA COARE IOP occurred from November 1992 through February 1993 in the Western Pacific region bordered by 10°N, 10°S, 140°E, and 180°W. Oceanographic and meteorological data were gathered from ships, buoys, aircraft, and satellites.

In this study, we use the measurements obtained from the Research Vessel *Moana Wave*, which provided a co-located dataset of surface fluxes and ocean microstructure measurements. Further details of these observations are described by Webster et al. (1995).

A summary of the surface meteorology, surface fluxes, and ocean mixed layer depth from the Research Vessel *Moana Wave* is given in Table 2, with the maximum and minimum values presented for hourly averages.

Model Description

The 1-D ocean mixed layer model that we use here used a second-order turbulence closure scheme described by Kantha and Clayson (1994). Penetration of shortwave radiation into the upper ocean is modelled following Morel and Antoine (1994). A parameterization for skin SST has been added to the Kantha-Clayson model, following Wick (1995).

Table 2. Average values of surface parameters and fluxes measured by the R/V *Moana Wave* during the TOGA COARE IOP (surface flux is positive into the ocean).

Parameter	Average	Min	Max
SST, 1 cm (°C)	29.1	25.7	31.5
Wind speed, surface ($m\,s^{-1}$)	4.9	0.1	15.9
Peak insolation (Wm^{-2})	732.9	180.0	958.0
Longwave , down (Wm^{-2})	413.0	370.0	441.0
Latent heat flux (Wm^{-2})	-115.6	-7.0	-347.0
Sensible heat flux (Wm^{-2})	-10.3	8.0	-69.0
Precipitation (mm hr^{-1})	0.45	0	37.1

The surface fluxes of radiation, sensible and latent heat, fresh water, and momentum are specified using hourly values measured on the *Moana Wave*. Also included are additional surface fluxes associated with precipitation. The surface momentum flux associated with rain is included following Kantha and Clayson (1994). The surface sensible heat flux associated with rain is parameterized following Gosnell et al. (1995).

The performance of the model during TOGA COARE is discussed in Webster et al. (1995). After an initial spin up period of 3 days, the modeled 1-cm temperature is within 0.1°C of the observed value, the model reproducing much of the fine structure in the thermal and salinity profiles of the upper ocean.

Diurnal Cycle

The joint time series of SST, ocean mixed-layer characteristics, surface heat flux components, surface wind speed, and rainfall rate are now examined using a blend of observations and model calculations. In this analysis, we consider data and model calculations for the fourth day of a four-day model integration.

Table 3 presents a summary of seven cases representing a range of conditions encountered, for which we could obtain a reasonably homogeneous four-day time series (as determined by the surface fluxes) and good comparison of the model with observations by the third or fourth day of model integration. The ocean mixed layer depth was determined from the modeled density field. The difference between the skin and true bulk SST is seen to range between 0.3 and 0.43°C, with the skin always cooler than the true bulk SST. Differences between the daily average skin SST and the buoy (0.5 m) and ship (4.5 m) bulk SST range from 0.3 to 0.6°C. Nearly clear-sky conditions were present for cases 1, 4, 5; isolated clouds were present for cases 3 and 6; and cases 2 and 7 represent disturbed conditions. Table 3 shows that there is no strong correlation between the daily peak insolation and average skin SST. The diurnal temperature range was determined by the skin SST difference between the predawn minimum and the maximum value that occurs shortly after the peak insolation. The negative values of diurnal temperature range shown in Table 3 for cases 2 and 7 reflect the general absence of a diurnal cycle and an overall cooling of the SST. The highest values of skin SST and greatest diurnal range in skin SST occur for cases 1 and 5. These two cases have the lowest windspeeds and the shallowest mixed layer depths.

Table 3. Summary of case study statistics.

Case	Date	Peak Insolation (Wm^{-2})	Wind Speed (Ms^{-1})	Total Precip (mm)	Average Skin SST (°C)	Diurnal SST Range (°C)	Average 1cm SST (°C)	Average 0.5m SST (°C)	Average 4.5m SST (°C)	OML Depth (m)
1	11/16-11/17	929	2.7	3.3	29.2	1.31	29.6	29.8	29.6	3.8
2	12/23-12/24	368	6.0	6.9	28.7	-0.14	29/1	29.1	29.1	24.3
3	12/26-12/27	629	5.5	70.5	28.5	0.30	28.8	28.8	28.9	41.5
4	12/31-1/1	857	9.5	2.2	28.3	0.10	28.6	28.6	28.6	35.2
5	1/9-1/10	910	1.8	0.2	28.8	1.50	29.2	29.3	20.1	4.7
6	2/3-2/4	852	5.3	10.3	28.7	0.48	29.1	29.1	29.1	28.4
7	2/9-2/10	557	4.9	51.4	28.7	-0.09	29.0	29.0	29.0	23.9

The shallow mixed layer depth increases the response of the mixed-layer temperature to surface heating. Cases 3 and 4 occur just after a westerly wind burst and are accompanied by high wind speeds and a deepened ocean mixed layer, resulting in a very low diurnal range in skin SST, even though the peak insolation for case 4 is fairly high. Although there is only a few tenths of a degree difference between the different determinations of the daily mean "surface" temperature, there are large differences in the amplitude of the diurnal surface temperature range, from 0.36°C at a depth of 4.5 m to 1.22°C at a depth of 1 cm. The peak heating at a depth of 4.5 m occurs approximately 8 hours after the maximum value of skin SST. At the time of peak insolation, the mixed layer is above 4.5 m. The daytime heating is only reflected at depths greater than 4 m following the nocturnal deepening of the mixed layer.

A comparison of this case with case 1 illustrates the importance of wind speed and ocean mixed layer depth on sea surface temperature under clear sky conditions. The deeper ocean mixed layer and increased evaporative cooling result in lower surface temperatures, a reduced diurnal amplitude in SST, and a reduced phase lag of temperature with depth.

Sensitivity Studies

Simple correlation between variables is not sufficient to reveal causality. This is especially true for a complicated, nonlinear system such as the upper ocean. Therefore, diagnostic studies cannot unambiguously identify feedbacks. However, carefully designed model experiments can be used to quantify the relative importance of different physical processes and to isolate causal mechanisms, provided that the models accurately simulate the relevant climate processes and sensitivities. The Kantha and Clayson (1994) ocean mixed layer (OML) model is now used to explore some of the characteristics of the relationships between solar radiation, wind speed, precipitation, and oceanic state in influencing the diurnal SST variability. The model is initialized with average ocean conditions for the TOGA COARE period as listed in Table 2. The model is integrated for periods of four days. The results presented in Figure 1 are for the diurnal cycle at 1 cm of the last day of the integration.

Solar radiation is responsible for the diurnal cycle in SST and surface solar radiation flux is primarily modulated by cloud characteristics. The amplitude of the diurnal cycle is largest for the largest insolation, the amplitude of the diurnal cycle being virtually zero for peak insolation values less than 300 Wm^{-2} (Figure 1). A phase lag exists between the time of the peak insolation and the SST maximum.

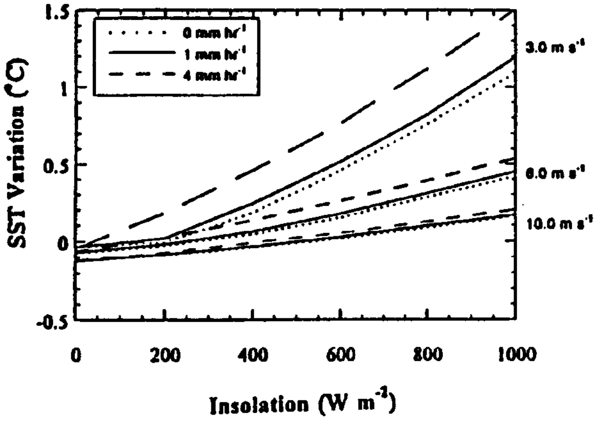

Figure 1. The amplitude of the diurnal variation of the SST as a function of peak insolation for different values of wind speed and rainfall following the rainfall. The coldest SST is for the night rain and the warmest SST is for the a.m. rain.

Surface wind speed modulates the amplitude of the diurnal cycle by influencing the surface heat flux (through the sensible and latent heat flux) and by determining the momentum flux. In general, wind speed is negatively correlated with SST, with increased wind speeds decreasing the net surface heat flux and by increasing the upper ocean mixing, thus distributing the surface heating throughout a greater depth of the ocean and diminishing the surface warming. Figure 1 shows that the diurnal amplitude of the surface temperature decreases nonlinearly with increasing wind speed. This nonlinearity is explained by the work being done on the mixed layer, is proportional to the cube of the surface wind speed (Webster and Lukas 1992), and depends on whether the presence of buoyancy barriers at different depths are overcome by the mixing.

The effects of precipitation on SST are very complex, since precipitation influences the surface fluxes of heat, freshwater, and momentum. Precipitation results in a decrease in surface salinity, cooling of the surface, and increased mixing. Figure 1 shows that the magnitude of the diurnal SST amplitude is not influenced by rainfall rates less than 0.5 mm hr^{-1}; small amounts of fresh water are rapidly mixed downward. At larger rainfall rates, the diurnal amplitude of SST increases as the formation of a fresh and stable layer at the surface allows greater surface heating. For higher wind speeds, the diurnal amplitudes are much smaller and much less influenced by precipitation. Furthermore, the impact of precipitation may depend on when the precipitation occurs in the diurnal cycle. At 5 a.m. of the day following the rainfall, the coldest SST is for the night rain, and the warmest SST is for the a.m. rain.

A number of experiments were run to assess the sensitivity of the diurnal amplitude in SST to the initial profile of temperature, salinity and chlorophyll in the ocean, and the depth of the mixed layer. An evolving ocean mixed layer will certainly have an influence on the SST, and a deepening OML will have a cooling effect on SST as cold water from below is entrained into the mixed layer. However, whereas the effect of the ocean initial conditions on the absolute SST is important, the effect on the diurnal amplitude of the skin SST is relatively small. Over the range observed during the TOGA COARE IOP (Siegel et al. 1995), increased chlorophyll concentrations increase the diurnal amplitude of SST only slightly. Absorption by chlorophyll occurs only in the visible part of the spectrum, and the visible radiation penetrates into the ocean, thus influencing surface temperature relatively little.

To summarize the results shown in Figure 1, we find that the magnitude of the diurnal variation of the SST increases with increasing insolation, decreases with increasing wind speed, and increases with increasing precipitation. For peak insolation values of less than 200 Wm^{-2}, the diurnal amplitude is near zero or slightly less than zero for all values of wind speed and precipitation that were considered. Increasing wind speed diminishes the impact of precipitation on the diurnal SST amplitude.

Discussion

The discussion presented here has focused on sea surface temperatures over a range of 3°C, with a diurnal amplitude of 1.5°C or less. Are variations of SST on the order of 1°C important in the TWP? To put these temperature variations into context, the difference in the TWP SST from El Niño to La Niña is only about 1°C. The importance of surface temperature variations (or errors) of 1°C at these high surface temperatures arises from the exponential relationship between saturation vapor pressure and temperature. As pointed out in Table 1, a 1°C error in SST in the TWP will result, on average, in an error of 27 Wm^{-2} to the surface energy balance. The effect of such an error on the ocean surface buoyancy flux is further enhanced by the associated error to the evaporation component to the fresh water flux, which acts in the same direction as the errors to the surface heat balance.

Correct observation and simulation of the diurnal cycle of SST is undoubtedly essential to understanding and modelling the correct feedback between clouds and the SST. Because of the nonlinear relationships between clouds and the surface fluxes, incorrect simulation of the interactions between clouds and the surface on the diurnal cycle may result in errors to the simulation of larger-scale cloud systems and feedback to the large-scale atmospheric dynamics.

Current SST climatologies are effectively climatologies of the upper ocean at a depth of 5 m (corresponding to the level at which ships routinely measure “surface” temperature). Temperatures at 5 m have been shown to differ substantially from the skin SST, particularly under conditions of low winds and strong insolation. The data on the diurnal amplitude of skin SST presented here can provide the foundation for adding a diurnal cycle to satellite-derived skin SST values, by including ancillary information regarding surface insolation, wind speed, and precipitation that is also available from satellite (e.g., Curry et al. 1993).

References

Cechet, R. P. 1993. Diurnal SST cycle in the western equatorial Pacific: Measurements made aboard the R.V. Franklin during the TOGA-COARE and pre-COARE cruises, *Atmos. Bull*, **6**, 26-32.

Chu , P. C., and R. W. Garwood. 1990. On the two-phase thermodynamics of the coupled cloud-ocean mixed layer, *J. Geophys. Res.*, **96**, 3425-3436.

Curry, J. A., C. A. Clayson, W. B. Rossow, Y. Zhang, and P. J. Webster. 1993. Determination of the tropical sea surface energy balance from satellite. In *20th AMS Conference on Hurricanes and Tropical Meteorology, 10-14 May, San Antonio, Texas*, pp. 591-594. American Meteorological Society, Boston, Massachusetts.

Gosnell, R., C. W. Fairall, and P. J. Webster. 1995. The surface sensible heat flux due to rain in the tropical Pacific Ocean, *J. Geophys. Res.*, in press.

Kantha, L. H., and C. A. Clayson. 1994. An improved mixed layer model for geophysical applications, *J. Geophys. Res.*, **99**, 25235-25266.

Morel, A., and D. Antoine. 1994. Heating rate within the upper ocean in relation to its bio-optical state, *J. Phys. Oceanogr.*, **24**, 1652-1665.

Siegel, D. A., J. C. Ohlmann, L. Washburn, R. R. Bidigare, C. Nosse, E. Fields and Y. Zhou. 1995. Solar radiation, phytoplankton pigments and the radiant heating of the equatorial Pacific warm pool, *J. Geophys. Res.*, in press.

Webster, P. J., and R. Lukas. 1992. TOGA COARE - The coupled ocean and atmosphere response experiment, *Bull. Am. Met. Soc.*, **73**, 1377-1416.

Webster, P. J., C. A. Clayson, and J. A. Curry. 1996. Clouds, radiation, and the diurnal cycle of sea surface temperature in the tropical western Pacific, *J. Clim.*, accepted.

Wick, G. A., W. J. Emery, and P. Schluessel. 1992. A comprehensive comparison between satellite-measured skin and multichannel sea surface temperature, *J. Geophys. Res.*, **97**, 5569-5595.

Wick, G. 1995. Evaluation of the variability and predictability of the bulk-skin SST difference with application to satellite-measured SST. PhD thesis, University of Colorado, Boulder, Colorado.