JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 101, NO. C12, PAGES 28,515–28,528, DECEMBER 15, 1996

Determination of surface turbulent fluxes for the Tropical Ocean-Global Atmosphere Coupled Ocean-Atmosphere Response Experiment: Comparison of satellite retrievals and in situ measurements

C.A. Clayson

Department of Earth and Atmospheric Sciences Purdue University, West Lafayette, Indiana

J.A. Curry

Program in Atmospheric and Oceanic Sciences, University of Colorado, Boulder

Abstract. A new approach is introduced for determining from satellite the turbulent fluxes of heat, moisture, and momentum at higher frequencies and spatial resolution than have been reported previously. Values of "skin" sea surface temperature, surface wind speed, surface air temperature, and surface water vapor mixing ratio are required inputs for a bulk turbulence flux model based on surface renewal theory. Each of these input variables is determined from satellite. Multiple satellite sensors, model results, and diagnostic studies of in situ and satellite observations are used to determine the optimal manner in which to determine the input parameters. The diurnal cycle of SST is determined to vary with peak solar insolation, daily-average precipitation, and daily-average wind speed. The static stability of the atmospheric surface layer is hypothesized to be reflected in the cloud characteristics and thus is determined to depend on cloud top temperature and whether or not it is raining. The validity of the satellite-derived surface fluxes and input parameters are examined using in situ measurements in the western equatorial Pacific Ocean made during the Tropical Ocean--Global Atmosphere Coupled Ocean--Atmosphere Response Experiment. Pixel-scale comparisons of the satellite fluxes with the ship fluxes show biases that are within the accuracy of the ship measurements. An attempt is made to determine daily-averaged fluxes from satellite, which is complicated by the fact that some of the satellite-derived input variables are obtained from polar-orbiting satellites with at best twice daily coverage in the tropics. Judicious interpolation allows reasonable daily-averaged fluxes to be obtained from satellite on a spatial scale of 50 km.

1. Introduction

Determination of the tropical sea surface fluxes of energy, fresh water, and momentum is central to understanding and modeling air-sea interactions [e.g., *Webster and Lukas,* 1992]. The Tropical Ocean-Global Atmosphere (TOGA) Coupled Ocean-Atmosphere Response Experiment (COARE) is an observation and modeling program that aims specifically at the elucidation of the physical processes that determine the mean and transient state of the warm pool region and the manner in which the warm pool region interacts with the global ocean and atmosphere. This program recently culminated in a major field experiment in the tropical western Pacific Ocean, with an intensive observing period (IOP) from November 1992 through March 1993. Central to the scientific objectives of TOGA COARE is the determination and interpretation of the surface fluxes of heat, moisture, and momentum at the air-sea interface.

The coupling of the atmosphere and ocean occurs on spatial scales ranging from less than 1 km to over 10,000 km and on timescales from minutes to years. It is commonly stated that the surface energy balance of the tropical oceans must be known to 10 W m^{-2} [e.g., *Webster and Lukas*, 1992], implying that the individual component fluxes must be known to accuracy greater than 5 W m^{-2}. This is a difficult goal to achieve even using in situ measurements of surface fluxes because of instrumentation errors and/or ancillary techniques that are used to derive the fluxes from the surface measurements. Additionally, in situ measurements of surface fluxes are sparse, infrequent, and costly. Therefore it is desirable to determine all of the components of the surface energy, water, and momentum balance from satellite measurements. Satellite observations cover a large range of scales, but we do not know whether all of the relevant quantities can be inferred from satellite observations on the required timescales. Detailed comparisons between in situ measurements and satellite inferences are necessary to establish this capability.

Previous satellite determinations of some components of the sea surface heat fluxes have been made for weekly [e.g., *Michael and Nunez*, 1991] or monthly timescales [e.g., *Gautier et al.*, 1988; *Liu and Gautier*, 1990; *Liu et al.*, 1994]. *Gautier et al.* [1988] found discrepancies (when compared with climatological values) of 50-90 W m^{-2} in the Arabian Sea and discrepancies as high as 190 W m^{-2} south of India. *Michael and Nunez* [1991] estimated rms differences of 50 W m^{-2} in the

Paper number 96JC02022.
0148-0227/96/96JC-02022 $09.00

weekly-average total heat flux into the tropical ocean when compared with in situ measurements. *Jourdan and Gautier* [1995] found differences between mean monthly values of latent heat fluxes determined from Defense Meteorological Satellite Program (DMSP), special sensor microwave images (SSM/I) and Comprehensive Ocean-Atmosphere Data Set (COADS) to differ in the Arabian Sea by as much as 200 W m^{-2} for certain months.

Use of monthly- or weekly-averaged flux values misses key feedbacks between the tropical atmosphere and ocean. *Chu and Garwood* [1991] estimate atmosphere-ocean coupling timescales in the unstable tropical atmopshere of approximately 0.6 days (the cloudiness damping timescale), 3-6 days (the cloud-SST coupling timescale), and 20-30 days (the fractional cloudiness-damping timescale). Cross-timescale air-sea interaction scenarios are described by *Webster et al.* [1996] and *Zhang* [1996]. Smaller clouds and cloud clusters appear to undergo a distinct diurnal cycle. Larger mesoscale clusters are also tied to the diurnal cycle with a predawn maximum in convective activity, vertical extension, and precipitation. During the morning the convective activity of these mesoscale clusters diminishes, but cloudiness persists as extended stratus decks [*Mapes and Houze*, 1995]. Organized convection may last for days. The larger-scale convection, in turn, appears to modulated by a long period (30-60 days) dynamical pulse that is probably associated with large-scale ocean-atmospere interaction [e.g., *Lukas et al.*, 1995], which may in turn be modulated by the diurnal cycle in a cross-scale air-sea interaction scenario [*Zhang*, 1996].

In this paper we introduce a new approach for determining from satellite the turbulent fluxes of heat, moisture, and momentum at higher frequencies and spatial resolution than has been reported previously. Values of "skin" sea surface temperature, surface wind speed, surface air temperature, and surface water vapor mixing ratio are required inputs for a bulk turbulence flux model based on surface renewal theory. Each of these input variables is determined from satellite. Multiple satellite sensors, model results, and diagnostic studies of in situ observations are used to determine the optimal manner in which to determine the input parameters. The validity of the satellite-derived surface fluxes and input parameters is examined using in situ measurements in the western equatorial Pacific Ocean obtained during TOGA COARE.

2. Data Sets

The period and location that were chosen for this study are coincident with the TOGA COARE intensive observing period during the period November 1992 through February 1993. The availability of in situ data obtained from ships with which to compare the satellite-derived fluxes allows careful determination of errors associated with the satellite fluxes. The validation data set used in this study is obtained from the R/V *Moana Wave*. The R/V *Moana Wave* obtained measurements during three separate cruises: leg 1, from November 11 through December 17, 1992, in the vicinity of 1.7°S, 156°E; leg 2, from December 17, 1992, to January 12, 1993, in the vicinity of 1.7°S, 156°E; and leg 3, from January 28, to February 16, 1993, initially near 1.7°S, 156°E, and moving to 0.0°N, 156°E on February 5 (other days also contained some ship motion). The location and period of the measurements obtained from the R/V *Moana Wave* define the specific times and location used in this study for the determination of the turbulent fluxes from satellite.

2.1. Satellite

The satellite data sets used in this analysis are the DMSP SSM/I brightness temperatures, the NOAA advanced very high resolution radiometer (AVHRR) radiances, and the International Satellite Cloud Climatology Project (ISCCP) cloud analysis results.

The SSM/I [*Hollinger et al.*, 1990] has seven separate total-power radiometers at frequencies of 19.35, 22.235, 37, and 85.5 GHz [hereinafter referred to as 19, 22, 37, and 85 GHz]. Dual-polarization measurements are taken at 19, 37, and 85 GHz, and only vertical polarization is observed at 22 GHz. The spatial resolution ranges from 69 x 43 km at 19 GHz to 15 x 13 km at 85 GHz. The swath width is 1394 km on the Earth's surface and the antenna beams intersects the Earth's surface at an angle of 53°. In the tropics the narrow swath results in reduced local coverage. During the period under consideration, data from both the F 10 and F 11 satellites were used, resulting in local coverage in the equatorial oceans of approximately twice per day. SSM/I brightness temperatures were obtained from the SSM/I antenna temperature data set distributed by Remote Sensing Systems [*Wentz*, 1988].

AVHRR data for the TOGA COARE period from two satellites were used in this study. The early morning pass (~0330 local time) of the NOAA 11 satellite was used, as were data from the morning pass of NOAA 12 (~0730 local time).

A special high ISCCP analysis [DX] has been prepared for the TOGA COARE IOP (W. Rossow, personal communication, 1995). The temporal interval of the DX data set is 3 hours, and the spatial resolution is 30 km. This spatial resolution is achieved by randomly selecting one pixel from among approximately 15 pixels that is then used to represent a 30 km "pixel." The analysis procedures for all the parameters are similar to those used for the former ISCCP CX data [*Rossow and Schiffer*, 1991], but the present analysis includes an ice cloud model which improves the determination of cirrus cloud optical depth and cloud top temperature. The specific parameters employed in this study from the ISCCP DX data set are cloud top temperature and cloud optical depth.

2.2. In Situ Validation Data

Surface fluxes and meteorological measurements used for validation of the satellite-derived input parameters and fluxes were obtained from the R/V *Moana Wave* during the TOGA COARE IOP [*Bradley et al.*, 1996; *Young et al.*, 1995; *Fairall et al.*, 1996a]. A complete description of the observing system employed during these cruises and their accuracy is given by *Fairall et al.* [1996c]. For some input parameters, new satellite algorithms are developed that make use of the ship data. To ensure that an independent data set was used in developing the satellite algorithms, data from the R/V *Franklin* were employed for algorithm development.

Mean and perturbation wind and temperature measurements were made using a sonic anemometer. A dual-wavelength infrared hygrometer was used to measure both mean and perturbation humidity. Sea surface temperature (SST) was measured at a depth of approximately 5 cm using a thermistor sealed in the top of a floating hose. Surface radiation fluxes were measured using an Eppley pyranometer and pyrgeometer. Precipitation was measured using an optical rain gauge. Data collected from the sonic anemometer, infrared hygrometer, and sea surface thermistor were used to calculate the surface sensible and latent heat fluxes.

In this study we use the values of turbulent fluxes determined by using the eddy correlation method for comparison with the satellite-derived values. To reduce the possibility for errors in the eddy correlation observations, we have eliminated observations obtained under precipitating conditions, ship maneuvers, and unfavorable wind direction relative to the ship orientation. All of the in situ data haVE averaged over 50-min periods for use in this study.

3. Turbulence Flux Model

The turbulence flux model used in this study is described by *Clayson et al.* [this issue]. This model utilizes both Monin-Obukhov similarity theory and the surface renewal theory as described by *Brutsaert* [1975]. *Liu et al.* [1979] (hereinafter referred to as LKB) made partial use of surface renewal theory, and further improvements to the LKB parameterization have been made by *Fairall et al.* [1996a]. The model used here includes the following improvements relative to the LKB and Fairall et al. models: incorporation of a new timescale parameterization for surface renewal, inclusion of capillary waves in the surface roughness model; and derivation of the surface roughness scales of water vapor and heat based solely upon surface renewal theory.

Using Monin-Obukhov similarity theory, the turbulent fluxes of momentum (τ), sensible heat (H), and moisture (E) are defined as

$$\begin{aligned} \tau &= \rho_a u_*^2 \\ H &= -\rho_a c_p u_* T_* \\ E &= -\rho_a u_* q_* \end{aligned} \qquad (1)$$

where T_*, q_*, and u_* are the Monin-Obukhov similarity scaling parameters for temperature, water vapor mixing ratio, and horizontal wind. In order to determine T_*, q_*, and u_* the model requires the following inputs: 10-m air temperature, specific humidity, and wind speed, and the sea surface temperature and humidity. These are the variables that will be determined from satellite data in this paper.

The turbulence flux model has been validated using shipborne observations of surface fluxes and surface meteorology that were obtained in the central Pacific Ocean, the western tropical Pacific, the subtropical Pacific, and the midlatitude North Atlantic. In a comparison of this bulk model with eddy correlation measurements obtained from the R/V *Moana Wave* during TOGA COARE (hourly-averaged measurements), it was found that the mean differences between the measured (eddy covariance) and bulk-derived fluxes of latent heat, sensible heat, and momentum were 3.7 W m^{-2}, 0.3 W m^{-2}, and 0.004 N m^{-2}, respectively, with rms errors of 20.5 W m^{-2}, 4.2 W m^{-2}, and 0.028 N m^{-2} and correlation coefficients of 0.90, 0.76, and 0.72.

4. Determination of Input Parameters From Satellite

To use the *Clayson et al.* [this issue] model to determine the surface fluxes of sensible and latent heat and momentum from satellite, the following input parameters are required: surface wind speed, skin SST, sea surface specific humidity, and surface atmospheric temperature and humidity. Additionally, the values of the peak solar insolation and daily-averaged precipitation are used in determining the diurnal amplitude of the skin SST (section 4.2). This section describes the method used to determine these parameters from satellite and the comparison of the satellite-derived values with the in situ measurements from the R/V *Moana Wave*.

4.1. Surface Wind Speed

Surface wind speed is utilized directly in determination of the surface latent and sensible heat fluxes and also the momentum flux. In this study, surface wind speed is determined from SSM/I data. Several algorithms are available for determining wind speed from the SSM/I brightness temperatures. These include the *Bates* [1991] algorithm derived for tropical regions, as well as global algorithms by *Goodberlet et al.* [1989], *Schluessel and Luthardt* [1991], and *Wentz et al.* [1986]. All of these algorithms were developed using data from the F 8 DMSP satellite, which had a significantly different scan angle than the F 10 and F 11 satellites (used in the present study). As was shown by *Wentz* [1992] and *Halpern and Wentz* [1994], different scan angles can significantly influence determination of wind speed, and algorithms developed for F 8 may not be appropriate for F 10 and F 11.

Therefore we have developed a new wind speed for the tropical oceans using the F 10 and F 11 satellites. We follow the procedure adopted by *Bates* [1991], whereby we regress the SSM/I brightness temperatures against 69 ship observations of surface wind speed measured by the R/V *Franklin*. The following regression equation is used here to determine wind speed using the SSM/I brightness temperatures:

$$\begin{aligned} u_a &= 223.3 + 0.206\, T_{B19V} - 0.246\, T_{B22V} - 0.693\, T_{B37V} \\ &\quad - 0.189\, (T_{B19V} - T_{B19H}) - 0.625\, (T_{B37V} - T_{B37H}) \end{aligned} \qquad (2)$$

where the subscripts V and H denote vertical and horizontal polarizations, respectively, and 19, 22, and 37 refer to the SSM/I frequencies. Because of the large influence of precipitation on the SSM/I brightness temperatures and the sea state, only nonprecipitating cases are used here (the satellite-derived threshold for precipitation is discussed in section 4.2). Therefore surface wind speeds cannot be derived directly under precipitating conditions from SSM/I brightness temperatures using (2).

Figure 1 shows the time series of SSM/I-derived wind speeds compared with observations obtained from the R/V *Moana Wave*. The bias of the satellite-derived values is very small, the satellite-derived value of the mean surface wind speed being 0.07 m s^{-1} greater than the ship values. The rms error is 1.55 m s^{-1}, and the correlation between the two data sets is 0.79. As can be seen in Figure 1, there are three satellite observations of surface wind speed per day during some periods, but there are gaps as large as 2 days during rainy periods.

4.2. Sea Surface Temperature

The radiative, latent, and sensible heat exchanges between the atmospheric and oceanic boundary layers depend on the actual "skin" temperature of the ocean. The skin temperature needs to be distinguished from the true bulk SST (measured

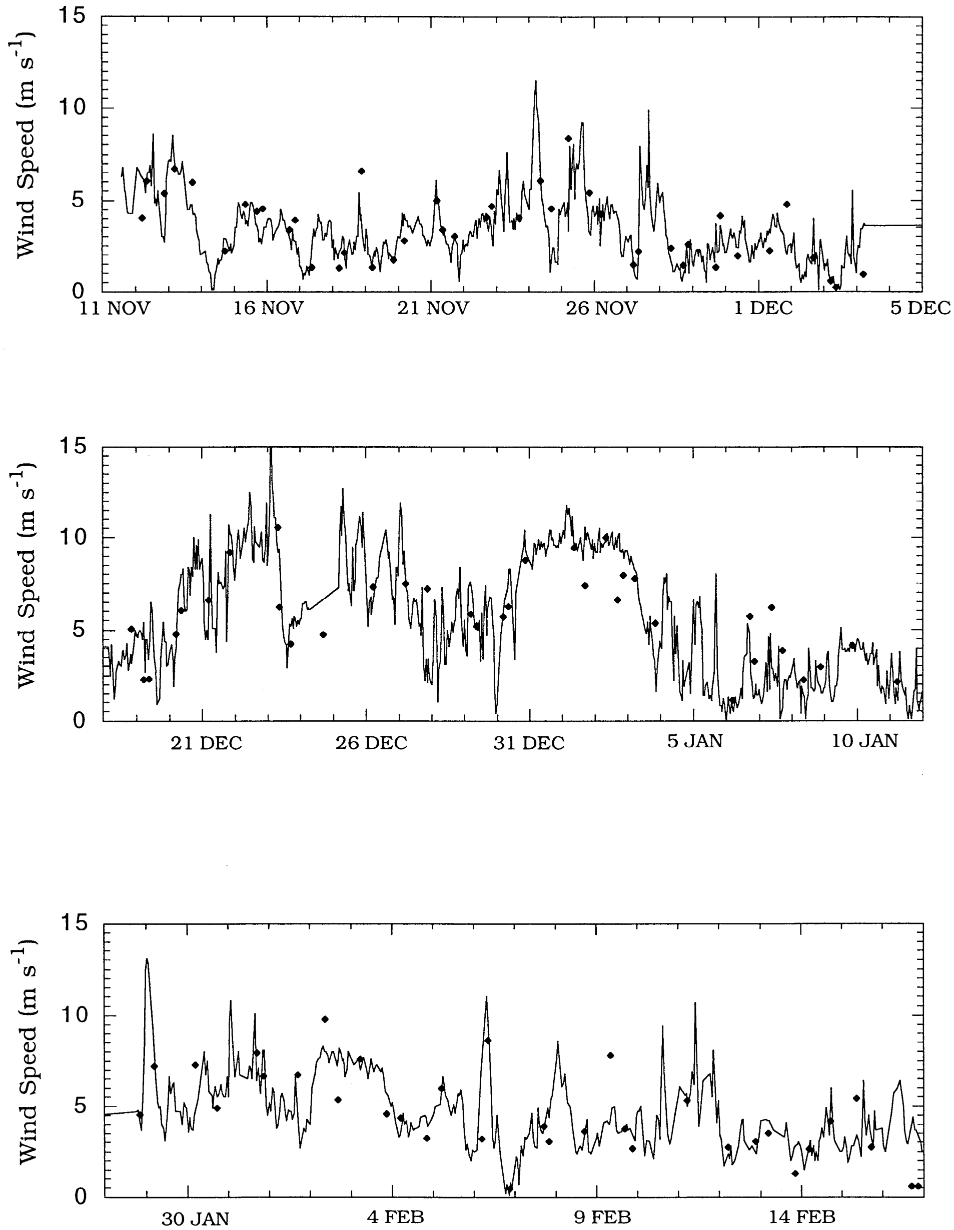

Figure 1. Time series of wind speed for all three legs of the R/V *Moana Wave*: solid line, ship measurements; diamonds, values determined from SSM/I.

within 1 cm of the surface) and the bulk temperature measured by buoys or ships, which may be at depths from 0.5 to 10 m below the surface. The skin temperature can differ from the true bulk water temperature by values that are typically in the range -0° to 0.6°C (bulk temperature is generally warmer) [e.g. *Schluessel et al.*, 1987, 1990; *Wick et al.*, 1992; *Webster et al.,* 1996]. Sea surface temperature determination from infrared satellite measurement can be interpreted directly in terms of this skin temperature, although most methods of satellite SST retrieval have been regressed to reproduce bulk temperatures for comparison with in situ bulk temperature measurements made by ships and buoys [e.g., *Reynolds and Marsico* 1993].

Infrared methods of satellite SST determination are limited to clear-sky conditions. A comparison of SST from AVHRR data using several algorithms with coincident in situ skin measurements was conducted by *Emery et al.* [1994]. The quality of the satellite-derived SST values depends on the accuracy of the cloud detection method and the accuracy with which water vapor and aerosol effects are removed. Persistently cloudy conditions and very large water vapor abundances make SST retrievals in the tropical western Pacific particularly challenging.

The approach used here to determine the skin SST is described as follows. First, a value of the predawn skin SST under clear-sky conditions is obtained from the AVHRR data. These values are linearly interpolated to obtain daily values of predawn skin SST. A parameterization for the diurnal amplitude of the skin SST that is determined from an ocean mixed layer model is then applied to the daily predawn values of SST, yielding values of skin SST over the diurnal cycle.

To determine the values of predawn skin SST from AVHRR data, we use the satellite-measured SMSST algorithm described by *Mislinski et al.* [1996] which was developed specifically for the TOGA COARE region. In a 30-km radius surrounding the

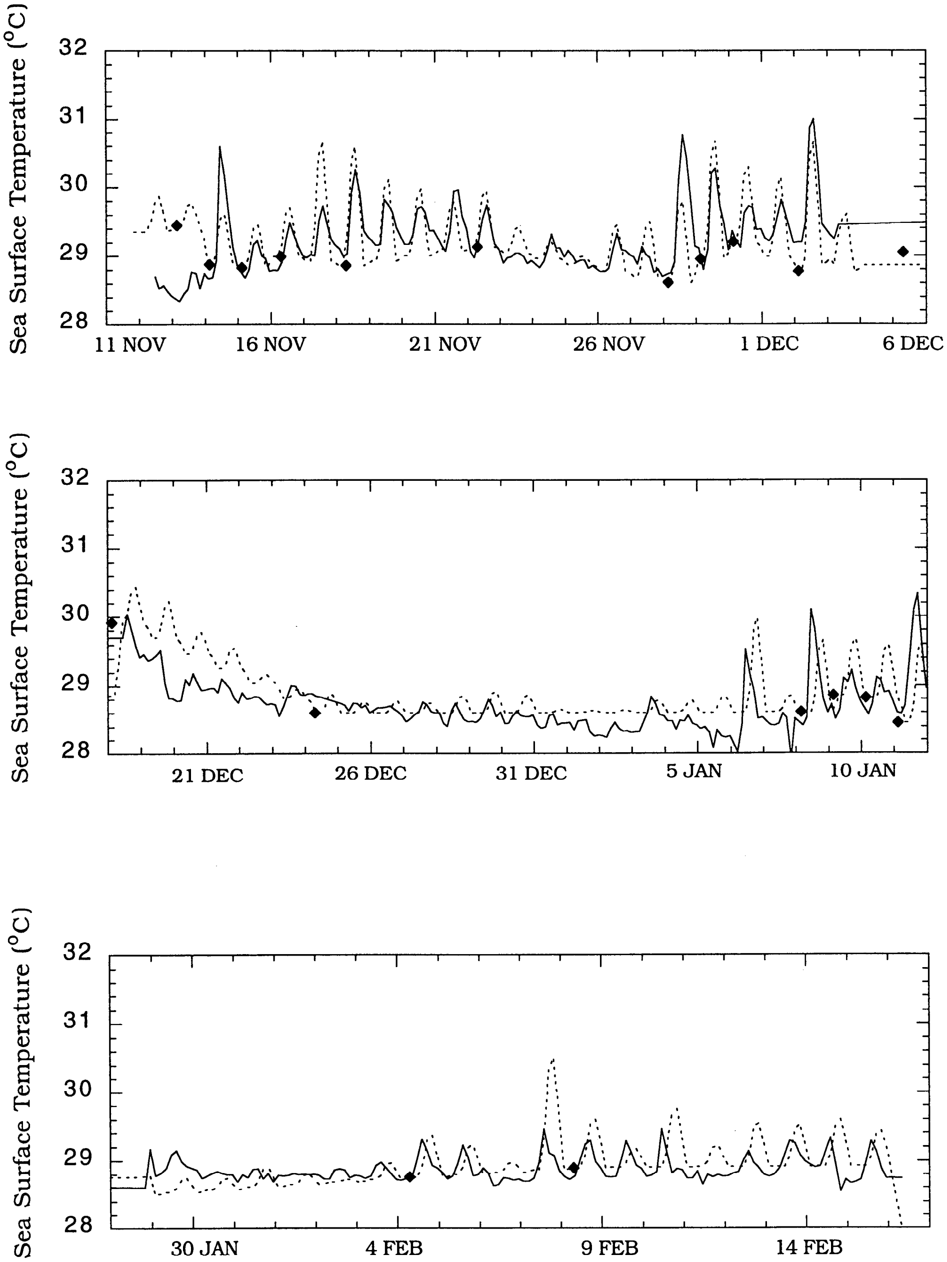

Figure 2. Time series of sea surface temperature for all three legs of the R/V *Moana Wave*: solid line, ship-derived measurements of skin temperature; diamonds, values of skin SST determined from AVHRR data using the SMSST algorithm; dashed line, satellite derived values of skin SST using the parameterization for diurnal amplitude.

location of the R/V *Moana Wave*, on average four retrievals of clear-sky skin SST are obtained per week, although the retrievals are not uniformly distributed in time. Figure 2 compares the skin temperature derived from the bulk 1 cm ocean temperature measured by the R/V *Moana Wave* using the *Soloviev and Schluessel* [1996] algorithm with the satellite-derived skin SST using the SMSST algorithm. Several very low values of SMSST were discarded because of inferred cloud contamination. Note that the bulk SST measured by the *Moana Wave* at 1 cm is expected to be approximately 0.2 to 0.4°C warmer than the skin SST [e.g., *Wick*, 1995; *Fairall et al.*, 1996b]. It is seen that the values of skin SST derived from the SMSST algorithm (indicated in Figure 1 by diamonds) show SMSST skin values that are on average 0.16°C less than the 5 cm values measured from the ship. The stated accuracy of the SMSST algorithm is 0.5°C [*Emery et al.*, 1994].

We then use these relatively infrequent observations to determine daily predawn SST values by linear interpolation. The amplitude of the diurnal cycle (referred to hereinafter as dSST) is determined using the model results described by *Webster et al.* [1996], who used the ocean mixed layer model of *Kantha and Clayson* [1994] with a skin SST parameterization [*Soloviev and Schluessel*, 1996] to examine the diurnal cycle of sea surface temperature during TOGA COARE. Figure 12 of *Webster et al.* [1996] is used here to develop a parameterization of dSST that depends on the magnitude of the peak solar

Table 1. Coefficients for Determination of Diurnal Sea Surface Temperature Amplitude (dSST) From (8)

Coefficient	Value
a_0	0.328
b_0	0.002
c_0	0.041
d_0	0.212
e_0	-1.85×10^{-4}
f_0	-0.329
a_1	0.262
b_1	2.65×10^{-3}
c_1	0.028
d_1	-0.838
e_1	-1.05×10^{-3}
f_1	0.158

Coefficients with subscripts of 0 refer to coefficients for cases where $U < 2.0$ m s^{-1}, and the subscript 1 refers to coefficients for cases where $U \geq 2.0$ m s^{-1}.

insolation, the cumulative amount of daily precipitation, and the average daily wind speed. Using these results, regression equations relating diurnal SST variability to peak solar insolation, daily average precipitation, and daily average wind speed are developed, which have the following form:

$$dSST = a + b\,(PS) + c\,(P) + d\ln(U) + e\,(PS)\ln(U) + f\,(U) \tag{3}$$

where the peak solar insolation *PS* is in watts per square meter, the daily-averaged precipitation *P* is in millimeters per hour, and the wind speed *U* is in meters per second. The coefficients are presented in Table 1.

Using ship-measured values of *PS*, *P*, and *U* in (3), a comparison of measured dSST variability with the derived dSST shows a bias of 0.13°C (derived dSST lower) with a standard deviation of 0.31°C and a correlation of 0.85. The maximum deviation between the measured and modeled dSST is 0.6°C, which occurred when highly variable morning wind speeds caused changes in the measured SST which were not accounted for by using the daily averaged wind speed.

The required input variables to determine dSST from satellite using (3) are daily-averaged wind speed, peak solar insolation, and daily-averaged precipitation. Determination of the daily-averaged wind speed is described in section 4.1. Values of the peak insolation are determined following *Zhang et al.* [1995], whereby the ISCCP-derived cloud properties are used as input parameters into a spectral radiative transfer model. W.B. Rossow and C. Zhang (personal communication, 1995) have provided us with surface radiation fluxes determined from the special ISCCP DX data set prepared for TOGA COARE. The method used to determine these fluxes differs from that described by *Zhang et al.* [1995] in the following ways: (1) improved models of surface emissivity and albedo are used, (2) rawinsonde data are used in place of TOVS, and (3) new features in the ISCCP cloud data sets are exploited (e.g., inclusion of ice microphysics). Comparisons of the ISCCP and *Moana Wave* peak solar insolation show a correlation coefficient of 0.95 and a high bias in the ISCCP peak solar radiation values of 44.6 W m^{-2}. This bias is caused mainly by overestimation of the ISCCP peak solar radiation on clear days (believed to be associated with an underestimate of aerosol optical depth). Accuracy of the shortwave fluxes measured by the R/V *Moana Wave* is of the order of 15 W m^{-2} under clear sky conditions [*Bradley et al.*, 1996]. Values of daily-averaged precipitation are determined following *Sheu et al.* [1996]. This algorithm uses both SSM/I and the ISCCP-derived values of cloud top temperature and cloud optical depth. Details of the algorithm and validation are described by *Sheu et al.* [1996]. It is noted here that when it is raining, the satellite-derived rainfall values are lower than those measured on the *Moana Wave* using an optical rain gauge; it is believed that ship motion caused this rain gauge to observe rainfall rates that were too large (F. Bradley, personal communication, 1995). Because the peak solar insolation and precipitation are determined using the ISCCP data set, values are determined every 3 hours.

A comparison of the satellite-derived time series of skin SST and the ship observations of skin temperature is shown in Figure 2. The ship skin temperatures are computed using the *Soloviev and Schluessel* [1996] skin model and the observed 1-cm temperature. The bias of the satellite-derived values is 0.08 °C relative to the ship values, with an rms error of 0.34 °C and a correlation coefficient of 0.75. The accuracy of the 1-cm temperature measurement is 0.2°-0.3°C [*Bradley et al.*, 1996].

4.3. Surface Air Temperature

One approach to determining T_a from satellite is to use the satellite-derived values of q_a with an assumed relative humidity in order to determine T_a [e.g., *Liu*, 1988]. The use of relative humidity requires an accurate value of q_a and a good assumption of the relative humidity. *Jourdan and Gautier* [1995] determined T_a from a relationship between T_a and precipitable water *W*.

Our parameterization of T_a-T_s is based on the hypothesis that atmospheric static stability will be reflected by the type of clouds present. A new classification scheme for tropical clouds has been developed by *Liu et al.* [1995] that combines infrared and microwave satellite data. Eight cloud categories are determined that are a function of cloud top temperature and the water characteristics of the cloud (small ice crystals, graupel, liquid water, and precipitation). A simplified version of the cloud classification scheme is used here, which includes the cloud top temperature determined from the ISCCP DX data set, whether or not it is precipitating, and whether it is day or night. To determine T_a-T_s, we use the values of T_a-T_s measured from the ship (R/V *Moana Wave*), and determine an average value for each cloud class (note that the ship measures bulk SST; these values are used to determine the skin value of T_s using the model of *Soloviev and Schluessel* [1996]). The differences between the classes were compared to determine those differences which were statistically significant at the 99% level. Seven different categories could be distinguished, which are shown in Table 2. The average surface relative humidity (RH) for each category is also shown in Table 2.

Table 2. Categories for Determination of T_a

	T_a-T_s, °C	RH, %
Daytime clear	-0.25	71.15
Nightime clear	-0.90	75.12
Daytime low, non precipitating clouds	-0.57	73.86
Nightime low, non precipitating clouds	-0.83	75.90
Cirrus clouds	-1.00	76.70
Low level precipitation clouds	-2.62	83.04
Precipitating convective systems	-2.13	81.20

Table 3. Comparisons of Different Methods for Determining T_a

Method	Bias,* °C	SD, °C	Correlation
Class (T_a-T_s)	-0.034	0.603	0.70
Class RH	0.778	0.963	0.53
RH=80%	1.586	1.128	0.20

* Satellite minus ship.

As can be seen in Table 2, day-night discrimination is not useful under precipitating conditions and for cirrus clouds that are not associated with precipitation. During nonprecipitation conditions, nighttime values of T_a-T_s are greater than daytime values because of the different rates at which the ocean and atmosphere gain and lose heat. The larger negative values of T_a-T_s under precipitating conditions reflect the cooling of the atmospheric boundary layer associated with convective downdrafts and cooling due to evaporation of rain. The increased values of relative humidity under precipitating conditions also reflect the evaporation of rain.

Table 3 compares the statistics of T_a values determined three different ways: using the cloud classification scheme of T_a-T_s (Class (T_a-T_s)), using the relative humidity for each class (Table 2) along with the value of q_a observed from ship (Class RH), and using the ship-measured q_a and an assumption of constant (80%) relative humidity (RH=80). The T_s and q_a values used in Table 3 are derived from ship measurements, and thus the numbers in Table 3 represent the maximum amount of information about T_a contained in the different approximation methods. Particularly for RH=80, there is little correlation between the observed and parameterized values of T_a. Use of the cloud classification scheme to determine T_a-T_s yields very favorable results, provided that there is an accurate input value of T_s.

A time series of T_a is shown in Figure 3, comparing ship observations with satellite observations determined using the Class (T_a-T_s) procedure and the values of T_s shown in Figure 2. The mean bias in the satellite-retrieved T_a relative to the ship-measured T_a is 0.12°C the rms error is 0.77°C, and the correlation is 0.67.

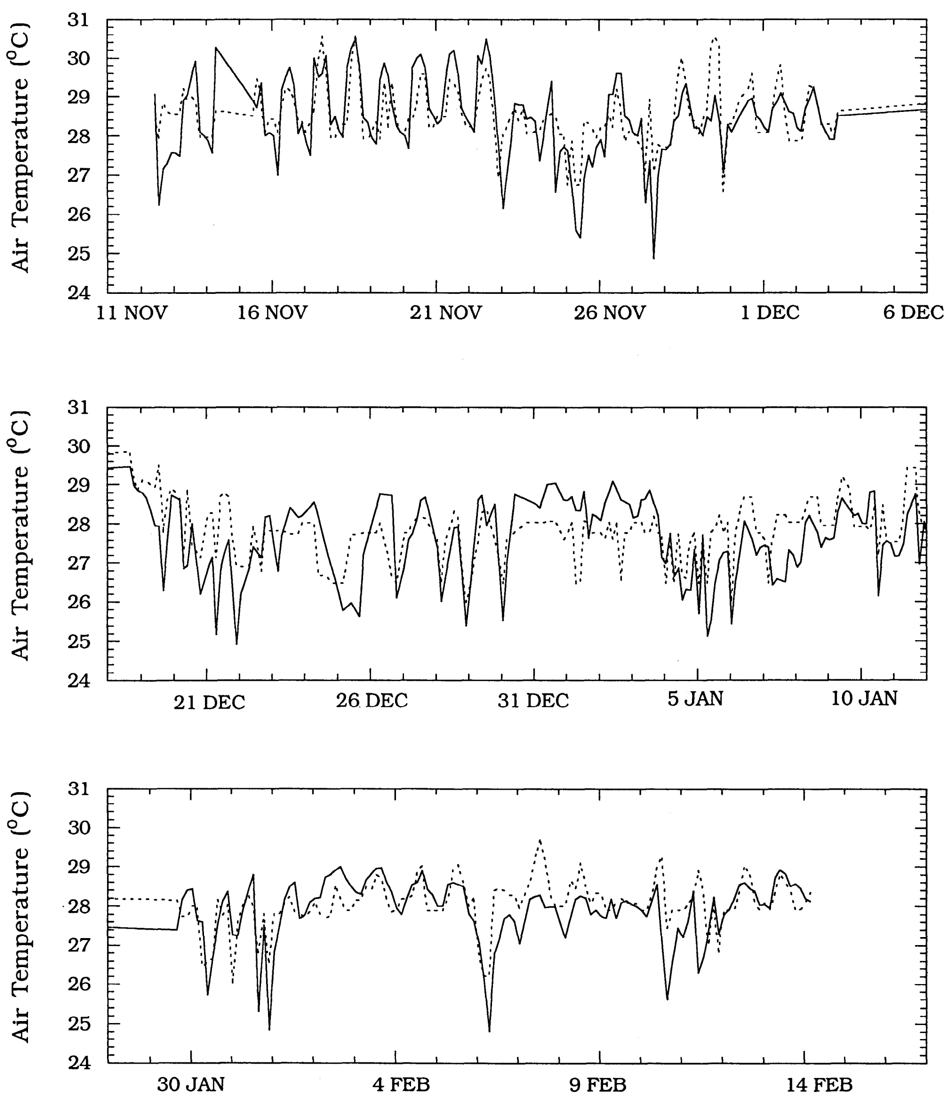

Figure 3. Time series of temperature of the atmospheric surface layer (T_a) for all three legs of the R/V *Moana Wave*: solid line, ship measurements; dashed line, satellite-derived values using the cloud classification scheme to determine T_a-T_s.

4.4. Surface Water Vapor Mixing Ratio

Values of the saturation mixing ratio at the surface (q_s) are easily determined once a value of surface temperature is known. Once T_s has been determined, a value of q_s is determined following *Fairall et al.* [1996a]

$$q_s = 0.98\, q_{sat}(T_s) \tag{4}$$

where q_{sat} is the saturation vapor pressure. This expression accounts for the reduction in vapor pressure associated with a salinity of 34‰ .

Values of the water vapor mixing ratio in the atmospheric surface layer (q_a) are not available directly from satellite analyses (the retrievals from TOVS and other satellite sounders that are currently available do not have sufficient vertical resolution). Additionally, the cloud classification scheme described in section 4.3 showed little skill in determining qa. *Liu and Niiler* [1984] have proposed a global relationship between monthly mean q_a and the precipitable water W, which can be determined from SSM/I. As a result, remote sensing of the surface latent heat flux from satellite has focused on the monthly-averaged values. *Hsu and Blanchard* [1989] compared instantaneous values of q_a derived from the Liu and Niiler algorithm with radiosonde data. They found that the mean root-mean-square error (rmse) in instantaneous q_a was approximately 1 g kg^{-1} when data from all the stations were compared. However, it appeared that the algorithm did not work as well in the tropical western Pacific.

Another algorithm was developed by *Miller and Katsaros* [1992], who have proposed a technique to use SSM/I-derived values of W with independent values of SST to determine the difference (q_s-q_a). They found that this algorithm was less sensitive to rain than the traditional methods of using W to determine q_a but that it is best applied to locations in which no large horizontal W gradient exists.

For the algorithm used here, we follow the general approach described by *Miller and Katsaros* [1992]. We note here that the cloud classification provided little skill in determining q_a-q_s. A regression of the ship values of q_a -q_s versus satellite-derived values of T_s, W, and wind speed U yields an expression of the form

$$q_a - q_s = 3.572\, W + 6.315\, T_s - 0.017\, U - 0.298\, W - 0.129\, T_s \tag{5}$$

Satellite-derived values of W are determined using SSM/I data and the algorithm of *Schluessel and Emery* [1990], which was shown by *Sheu and Liu* [1995] to have the highest correlation with values of W derived from radiosonde data during the TOGA COARE IOP. The input data for (5) depend on the SSM/I data, so direct retrievals are available only approximately twice per day. The satellite-derived values of T_s are used to calculated q_s from (4), yielding values of q_a from (5). Comparison of the satellite-derived value of q_a with the ship values is shown in Figure 4. The satellite-derived q_a had a mean bias of -0.08 g kg^{-1} (satellite high), a standard deviation of 0.6 g kg^{-1}, and a correlation of 0.53 when compared with the ship-measured values.

5. Comparison of Satellite and in Situ Fluxes

Using the input values derived from satellite, evaluation of the surface fluxes of latent and sensible heat and momentum can be made using the surface turbulent flux model outlined in section 3.

5.1. Instantaneous Fluxes

A comparison of the surface turbulent fluxes determined from satellite with those determined from ship measurements is shown in Table 4. In Table 4, values of the fluxes determined from hourly-averaged values of eddy correlation. The comparison statistics are almost as good as those determined between eddy-correlation fluxes and bulk fluxes determined using input data derived from ship (see statistics described in section 3). We note here that the biases of the satellite-determined fluxes are within the accuracy of the ship-measured fluxes. Table 4 illustrates that useful retrievals of the surface turbulent fluxes can be obtained on the scale of an individual satellite pixel.

5.2. Averaged Fluxes

Since the SSM/I passes over locally only twice per day, direct determination of the surface turbulent fluxes of sensible and latent heat and momentum can be made only at the time of an SSM/I overpass. The temporal coverage is further restricted, since SSM/I-derived wind speeds are unavailable when it is raining (section 4.1). Correct determination of the diurnal cycle and the daily (and longer) average turbulent fluxes from satellite requires some assumption about what occurs when the SSM/I is not overhead. Without accounting for the diurnal cycle, biases may be introduced into daily and longer averages because of the infrequent but regular sampling by the SSM/I. Additionally, the diurnal cycle is of interest to air-sea interaction in its own right, as was described in the introduction.

Here we investigate the possibility of determining surface fluxes from satellite every 3 hours. To accomplish this using only the SSM/I, AVHRR, and ISCCP satellite data sets, some interpolation must be done. Our investigations indicate that better surface flux values are obtained by judicious interpolation/estimation of the inputs to the parameterizations than by interpolating the fluxes themselves. Therefore we investigate the possibility of interpolating values of wind speed and q_a onto a time series with 3 hour increments, corresponding to the time periods when T_s and T_a are available.

We examine two different possibilities for interpolation: linear interpolation between values determined using SSM/I, and interpolation that includes incorporation of a diurnal cycle. Using the ship-measured wind speeds, the diurnal variability of the wind during TOGA COARE was not strong; the average amplitude of the diurnal variability was 0.8 m s^{-1}, and the diurnal variability of q_a is 0.4 g kg^{-1}. Therefore we use a simple linear interpolation between SSM/I wind speeds and the values of q_a to determine the time series of wind speeds and q_a at every 3 hours. A comparison of the 3-hour satellite time series with the corresponding ship observations of winds shows a bias of 0.01 m s^{-1}, an rms of 1.73 m s^{-1} and a correlation of 0.75. The satellite-derived q_a had a mean bias of -0.01 g kg^{-1}, a standard deviation of 0.63 g kg^{-1}, and a correlation of 0.49 when compared with the ship-measured values. Comparing these numbers with the numbers cited in section 4.1 for SSM/I wind speeds and those in section 4.4 for q_a shows that the bias is slightly reduced, the rms is increased, and the correlation is slightly reduced.

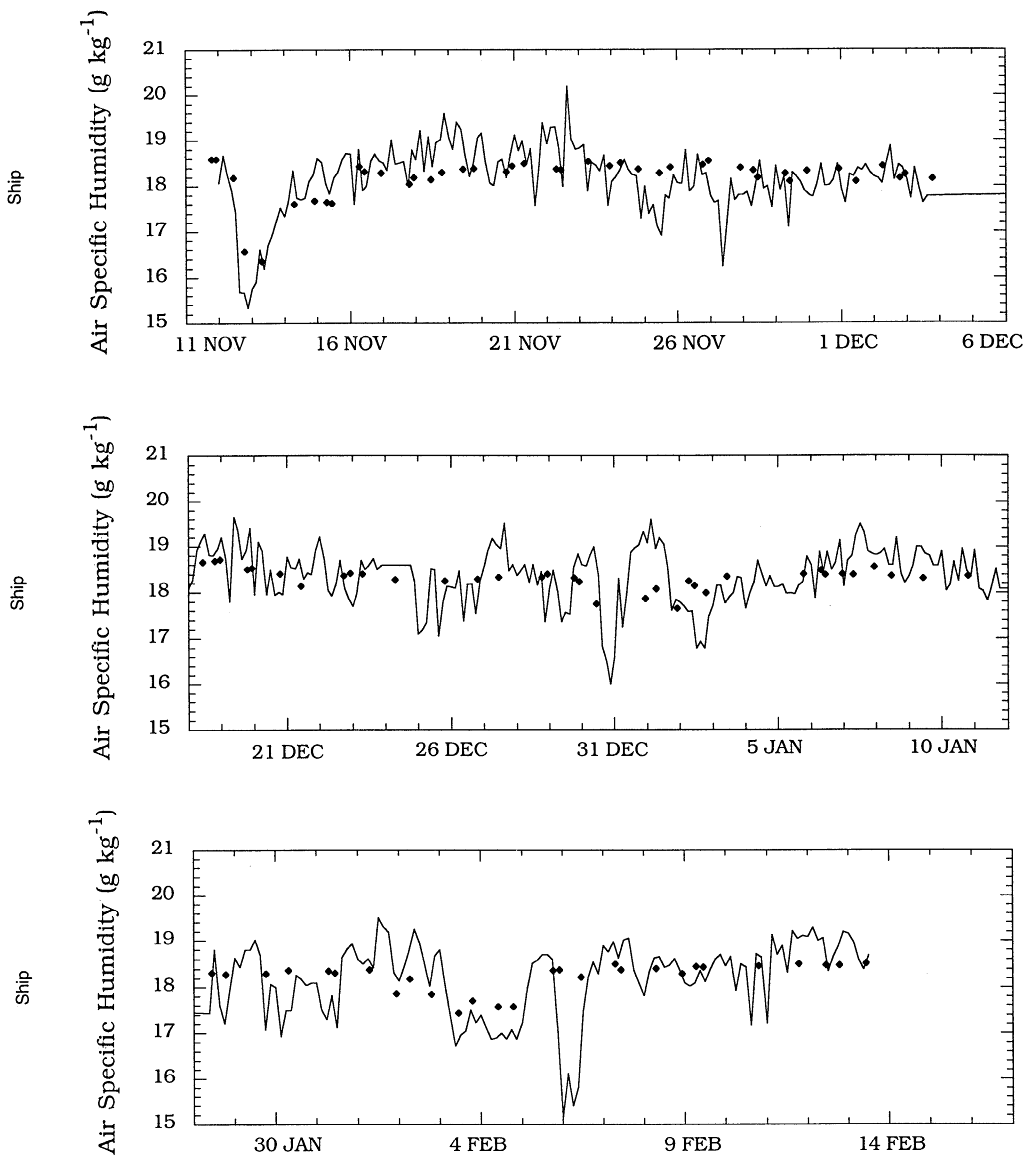

Figure 4. Time series of water vapor mixing ratio of the atmospheric surface layer (q_a) for all three legs of the R/V *Moana Wave*: solid line, ship measurements; diamonds, values determined from satellite when SSM/I observations are available.

Whether the interpolated values of wind speed and q_a can be used to determine reasonable values of the surface fluxes on a 3-hour and daily timescale is investigated using the 3-hour time series of input variables derived from the satellite fluxes. Figures 5, 6, and 7 compare the satellite time series with the ship measurements of the latent heat, sensible heat, and momentum fluxes. Also indicated in Figures 5-7 are the flux values that were derived directly from the SSM/I measurements. Largely because of the high temporal variability of wind speed (Figure 1), a comparison of the 3-hour satellite values with the ship-measured fluxes shows large rms errors and relatively low correlation. Table 5 compares the daily-averaged fluxes determined from the 3-hour satellite time series, the fluxes determined directly using the SSM/I measurements (one or two values per day are averaged), and the average daily fluxes determined from the 50-minute ship measurements. From this

Table 4. Comparison of Surface Turbulent Fluxes Derived From Satellite With Those Determined From Ship Measurements

	Latent Heat Flux, W m^{-2}	Sensible Heat Flux, W m^{-2}	Momentum Flux, N m^{-2}
Mean (satellite)	105.1	6.4	0.04
Mean (ship)	106.4	6.8	0.04
rms error	35.6	7.0	0.04
Correlation	0.69	0.42	0.58

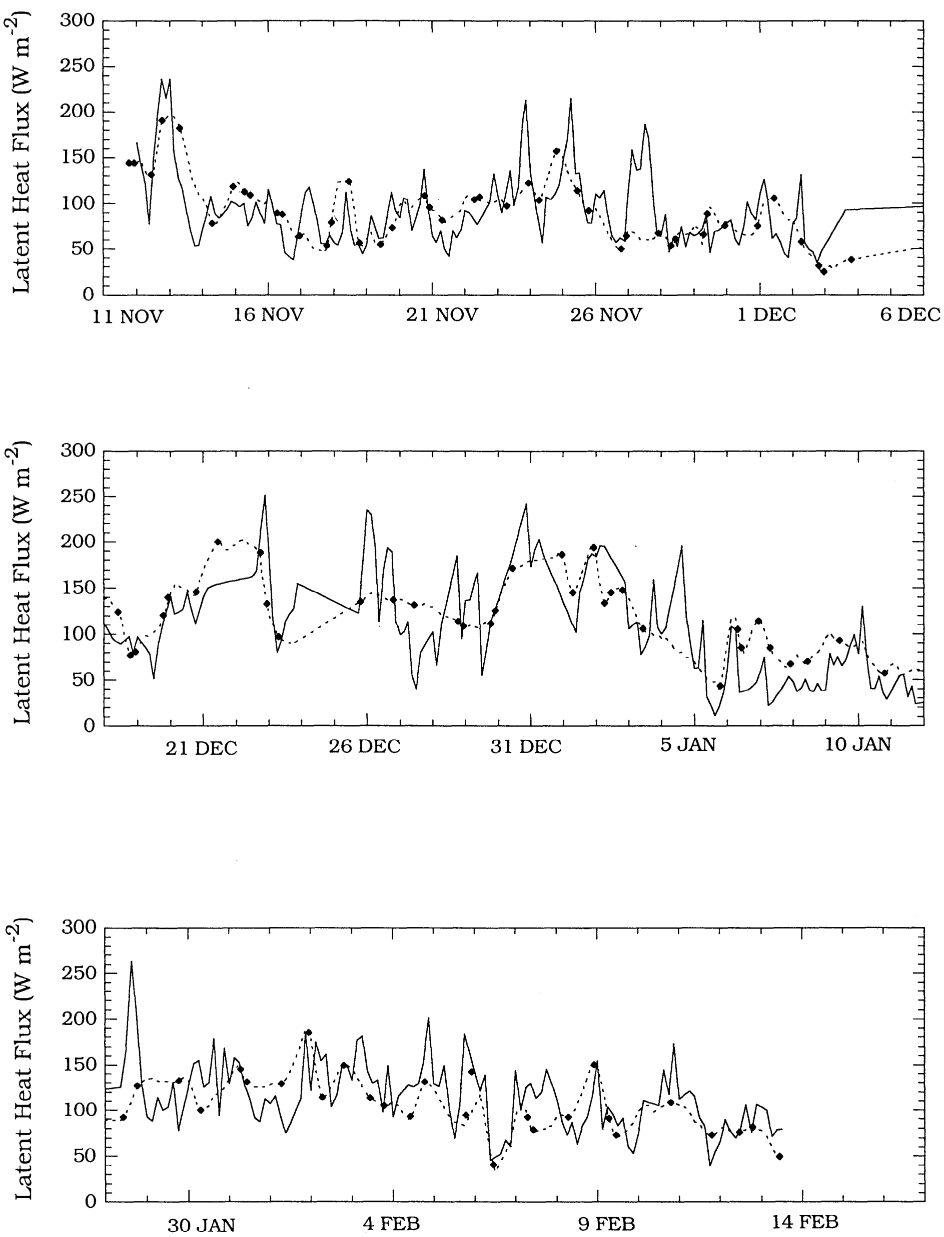

Figure 5. Time series of surface latent heat flux for all three legs of the R/V *Moana Wave*: solid line, determination from ship measurements; diamonds, values determined from satellite when SSM/I observations are available; dashed line, values determined from satellite using interpolated input variables.

comparison it is seen that determining the fluxes every 3 hours from interpolated input variables significantly improves the estimate of daily-averaged surface fluxes, the daily-averaged correlations, and rmse being nearly as good as for the instantaneous fluxes.

Shown in Table 6 are statistics for 5-day averages determined using the 3-hour interpolated values and compared with the 5-day averages using the ship-based observations every 50 min and the 5-day averages determined directly using the SSM/I measurements. Such an averaging period is useful for investigating intraseasonal oscillations. It is seen using the 3-hour interpolated values improves the results of the 5-day averages as compared with the averages using the once- or twice-per day values using the SSM/I measurements. The major improvement is in the heat fluxes, as new information is included in the 3-hour values that is not available in the other data set. The momentum flux is not much improved, as this relies heavily on the wind speed measurements, which are merely interpolated in the 3-hour values. When compared with the daily-average values in Table 5, substantially smaller root-mean-square errors are seen in the latent and sensible heat fluxes for the 5-day averages shown in Table 6.

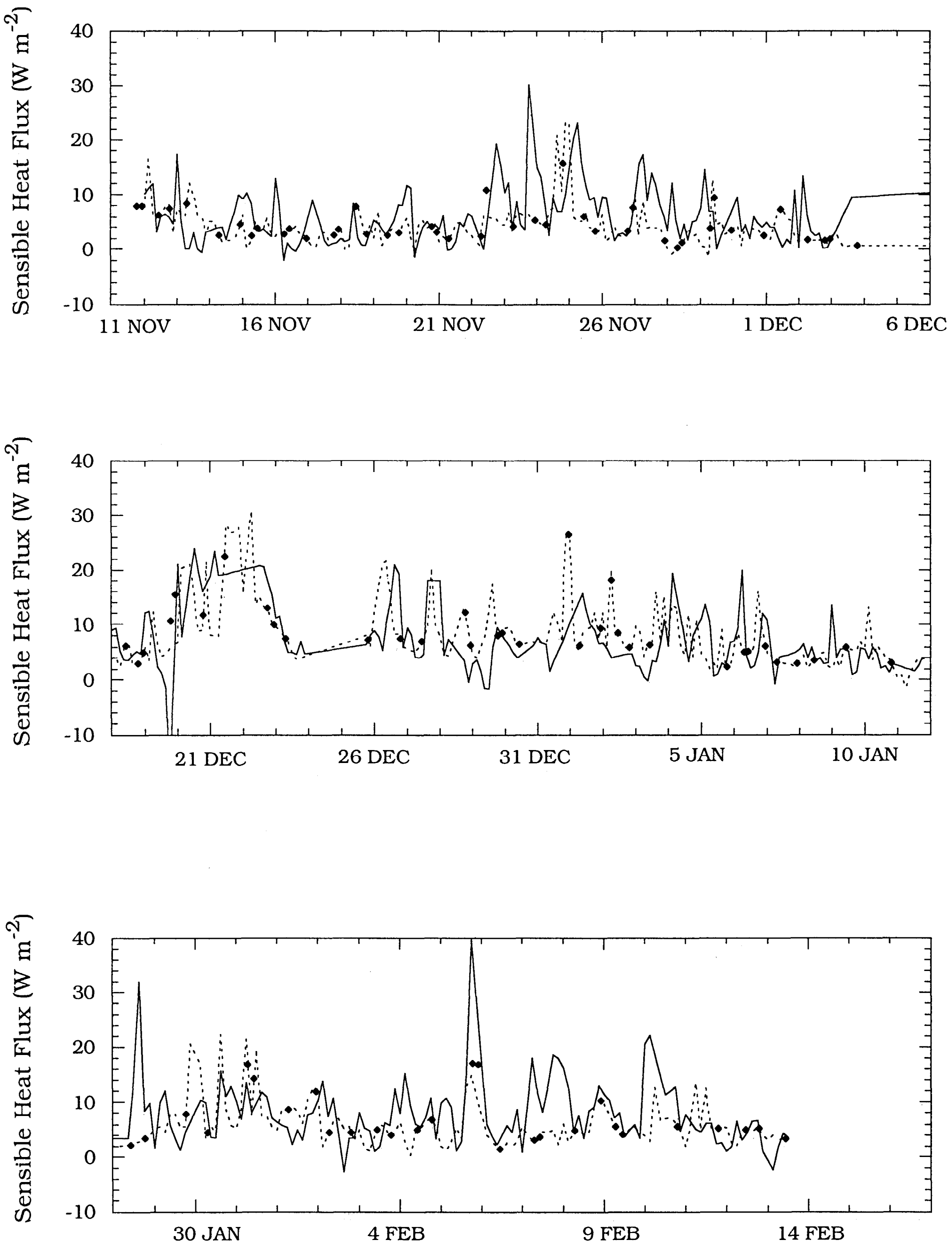

Figure 6. Time series of surface sensible heat flux for all three legs of the R/V *Moana Wave*: solid line, determination from ship measurements; diamonds, values determined from satellite when SSM/I observations are available; dashed line, values determined from satellite using interpolated input variables.

6. Conclusions

We have introduced a new approach for determining from satellite the turbulent fluxes of heat, moisture, and momentum at higher frequencies and spatial resolution than have been reported previously. Values of "skin" sea surface temperature, surface wind speed, surface air temperature, and surface water vapor mixing ratio are required inputs for a bulk turbulence flux model based on surface renewal theory. Multiple satellite sensors, model results, and diagnostic studies of in situ observations are used to determine the optimal manner in which to determine the input parameters.

A new method has been presented for determining from satellite the skin SST on a timescale that resolves the diurnal cycle. Based on results from an ocean model, the diurnal cycle of SST is determined to vary with peak solar insolation, daily-average precipitation, and daily-average wind speed. Previous methods to determine skin SST using satellite infrared observations provide values only during clear-sky periods, which seriously restricts the time-space resolution of the retrievals in the cloud tropical western Pacific. New algorithms have been presented for determining wind speed and atmospheric humidity from satellite observations. A novel approach has been presented for determining the temperature in the atmospheric surface layer. This approach is based on the hypothesis that the static stability of the atmospheric surface layer is reflected in the cloud characteristics and thus is determined to depend on cloud top temperature and whether or

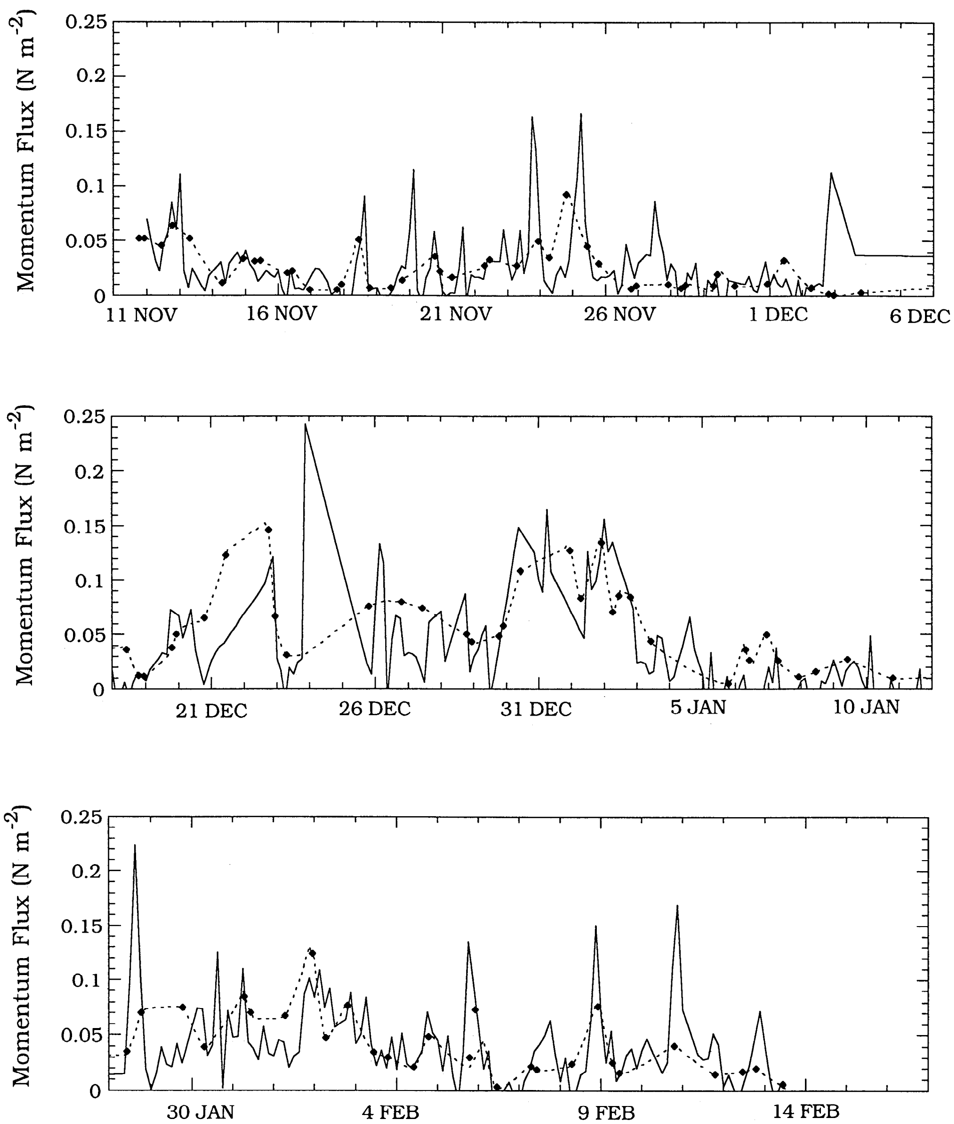

Figure 7. Time series of surface momentum flux for all three legs of the R/V *Moana Wave*: solid line, determination from ship measurements; diamonds, values determined from satellite when SSM/I observations are available; dashed line, values determined from satellite using interpolated input variables (dash).

Table 5. Comparison of Daily-Mean Surface Fluxes Derived From Ship Measurements and Satellite Observations

	Latent Heat Flux, W m^{-2}	Sensible Heat Flux, W m^{-2}	Momentum Flux, N m^{-2}
Mean (satellite-SSM/I)	106.0	6.4	0.042
Mean (satellite-3 hour)	109.1	6.8	0.043
Mean (ship)	108.1	7.4	0.049
rmse (satellite-SSM/I - ship)	53.0	4.4	0.084
rmse (satellite-3 hour - ship)	28.2	4.2	0.070
corr (satellite-SSM/I - ship)	0.21	0.57	0.42
corr (satellite-3 hour - ship)	0.78	0.60	0.55

Mean indicates a mean value for the indicated measurements, rmse stands for rms error, and corr indicates correlation. Satellite-SSM/I indicates satellite-derived values at times when SSM/I winds are available; satellite-3 hour indicates values dervied from satellite every 3 hours.

Table 6. Comparison of Mean Surface Fluxes Derived From Ship Measurements and Satellite Observations Averaged Over 5-Day Periods

	Latent Heat Flux, W m^{-2}	Sensible Heat Flux, W m^{-2}	Momentum Flux, N m^{-2}
Mean (satellite-SSM/I)	105.4	6.83	0.042
Mean (satellite-3 hour)	109.1	9.77	0.047
Mean (ship)	108.8	10.2	0.051
rmse (satellite-SSM/I - ship)	13.32	4.16	0.064
rmse (satellite-3 hour - ship)	8.22	2.25	0.060
corr (satellite-SSM/I - ship)	0.89	0.70	0.68
corr (satellite-3 hour - ship)	0.95	0.82	0.74

Mean indicates a mean value for the indicated measurements, rmse stands for rms error, and corr indicates correlation. Satellite-SSM/I indicates satellite-derived values at times when SSM/I winds are available; satellite-3 hour indicates values dervied from satellite every 3 hours.

not it is raining. This method of determining temperature in the atmospheric surface layer is a substantial improvement over the oft-used assumption that the relative humidity in the atmospheric surface layer is constant.

The validity of the satellite-derived surface fluxes and input parameters are examined using in situ measurements made from ships in the western equatorial Pacific Ocean made during TOGA COARE. Pixel-scale comparisons of the satellite fluxes with the ship fluxes show biases that are within the accuracy of the ship measurements. In comparing the satellite retrievals with single-point in situ measurements, several problems arise. Significant errors are generally associated with in situ and surface-based measurements against which the satellite retrievals are being validated. The mismatch between scales of surface observations and satellite retrievals complicates the interpretation of any comparison, since the ship measurements are representative of a much smaller area than is covered by the satellite pixel, which is approximately 50 km. Evaluation of statistics related to correlation and root-mean-square error are particularly affected by this mismatch in spatial scales.

Accurate input values of SST and atmospheric temperature were obtained with a time resolution of 3 hours. Because of the limited sampling of the SSM/I, the surface wind speed and atmospheric specific humidity could be determined only approximately twice per day. Thus the diurnal cycle of the turbulent fluxes could not be determined. To reproduce accurately the variation over the diurnal cycle requires in particular a greater frequency of satellite-derived wind observations. Combination of the surface winds derived from the ERS-1 scatterometer [*Offiler*, 1994] with the winds derived from SSM/I would provide substantially improved temporal resolution of satellite-derived winds. An attempt has been made to determine daily-averaged fluxes from satellite, which is complicated by the fact that some of the satellite-derived input variables are obtained from polar-orbiting satellites with at best twice daily coverage in the tropics. Judicious interpolation allows reasonable daily-averaged fluxes to be obtained from satellite. When compared with the daily-average values in Table 5, substantially smaller root-mean-square errors are seen in the latent and sensible heat fluxes for the 5-day averages.

Fields of surface fluxes derived from satellite fluxes on the time-space scales addressed in this paper will have application to atmospheric heat and moisture budget studies, forcing for three-dimensional (3-D) ocean models, validation of 3-D atmospheric and coupled atmosphere-ocean models, and diagnostic studies related to sea surface temperature and feedbacks between the atmosphere and ocean. Satellite remote sensing techniques that have been validated by the TOGA COARE IOP data can then be used to determine surface fluxes over extended periods and over the global tropical oceans.

Acknowledgments. This research was supported by NSF ATM-9110536. We gratefully acknowledge the helpful discussions with C. Fairall, W. Rossow, and G. Wick.

References

Bates, J.J., High-frequency variability of special sensor microwave/imager derived wind speed and moisture during an intraseasonal oscillation, *J. Geophys. Res.*, *96*, 3411-3423, 1991.

Bradley, E.F., P.A. Coppin, C.W. Fairall, J.B. Edson, and G. S. Young, Ship-based air-sea flux measurements during TOGA/COARE, *J. Atmos. Oceanic Technol.*, in press, 1996.

Brutsaert, W., A theory for local evaporation (or heat transfer) from rough and smooth surfaces at ground level, *Water Resource Res.*, *11*, 543-550, 1975.

Chu, P.C., and R.W. Garwood, On the two-phase thermodynamics of the coupled cloud-ocean mixed layer, *J. Geophys. Res.*, *96*, 3425-3436, 1991.

Clayson, C.A., C. W. Fairall, and J. A. Curry, Evaluation of turbulent fluxes at the ocean surface using surface renewal theory, *J. Geophys. Res.*, this issue.

Emery, W. J., Y. Yu, and G. A. Wick, Correcting infrared satellite estimates of sea surface temperature for atmospheric water vapor attenuation, *J. Geophys. Res.*, *99*, 5219-5236, 1994.

Fairall, C.W., E.F. Bradley, D.P. Rogers, J.B. Edson, and G.S. Young, Bulk parameterization of air-sea fluxes for the Tropical Ocean--Global Atmosphere Coupled Ocean-Atmosphere Response Experiment, *J. Geophys. Res.*, *101*, 3747-3764, 1996a.

Fairall, C.W., E.F. Bradley, J.S. Godfrey, G.A. Wick, J.B. Edson, and G.S. Young, Cool-skin and warm-layer effects on sea surface temperature, *J. Geophys. Res.*, *101*, 1295-1308, 1996b.

Fairall, C. W., A. B. White, J. B. Edson, and J. E. Hare, Integrated shipboard measurements of the marine boundary layer, *J. Atmos. Oceanic Technol.*, in press, 1996c.

Gautier, C., R. Frouin, and J.-Y. Simonot, An attempt to remotely sense from space the surface heat budget over the Indian Ocean during the 1979 monsoon, *Geophys. Res. Lett.*, *15*, 1121-1124, 1988.

Goodberlet, M.A., C.T. Swift, and J.C. Wilkerson, Remote sensing of ocean surface winds with the special sensor microwave/imager, *J. Geophys. Res.*, *94*, 14,547-14,555, 1989.

Halpern, D., and F. Wentz, On the problem of measuring interannual wind speed variations using SSMI data, *Geophys. Res. Lett.*, *21*, 193-196, 1994.

Hollinger, J., J. Peirce, and G. Poe, Validation for the special sensor microwave/imager (SSM/I), *IEEE Trans. Geosci. Remote Sens.*, *28*, 781-790, 1990.

Hsu, S.A., and B.W. Blanchard, The relationship between total precipitable water and surface-level humidity over the sea surface: A further evaluation, *J. Geophys. Res., 94*, 14,539-14,545, 1989.

Jourdan, D., and C. Gautier, Comparison between global latent heat flux computed from multisensor (SSM/I and AVHRR) and from in situ data, *J. Atmos. Oceanic. Technol., 12*, 46-72, 1995.

Kantha, L. and C.A. Clayson, An improved mixed-layer model for geophysical applications, *J. Geophys. Res., 99*, 25,235-25,266, 1994.

Liu, G., J.A. Curry, and R.S. Sheu, Classification of clouds over the western equatorial Pacific Ocean using combined infrared and microwave satellite data, *J. Geophys. Res., 100*, 13,811-13,824, 1995.

Liu, W.T., Moisture and latent heat flux variabilities in the tropical Pacific derived from satellite data, *J. Geophys. Res., 93*, 6749-6760, 1988.

Liu, W.T., and C. Gautier, Thermal forcing on the tropical Pacific from satellite data, *J. Geophys. Res., 95*, 13,209-13,217, 13,579-13,580, 1990.

Liu, W. T., and P.P. Niiler, Determination of monthly mean humidity in the atmospheric surface layer over oceans from satellite data, *J. Phys. Oceanogr., 14*, 1451-1457, 1984.

Liu, W.T., K.B. Katsaros, and J.A. Businger, Bulk parameterization of air-sea exchanges of heat and water vapor including the molecular constraints at the interface, *J. Atmos. Sci., 36*, 1722-1735, 1979.

Liu, W.T., A. Zhang, and J.K.B. Bishop, Evaporation and solar irradiance as regulators of sea surface temperature in annual and interannual changes, *J.Geophys. Res., 99*, 12,623-16,637, 1994.

Lukas, R., P. J. Webster, and M. Ji, The large-scale context for the TOGA Coupled Ocean-Atmosphere Response Experiment, *Meteorol. Atmos. Phys., 56*, 3-25, 1995.

Mapes, B.E., and R.A. Houze, Diabatic divergence profiles in western Pacific mesoscale convective system, *J. Atmos. Sci., 52*, 1807, 1995.

Michael, K.J., and M. Nunez, Derivation of ocean-atmosphere heat fluxes in a tropical environment using satellite and surface data, *Int. J. Climatol., 11*, 559-575, 1991.

Miller, D.K., and K.B. Katsaros, Satellite-derived surface latent heat fluxes in a rapidly intensifying marine cyclone, *Mon. Weather Rev., 120*, 1093-1107, 1992.

Mislinski, P., W.J. Emery, and J. Westphal, TOGA COARE satellite measured sea surface temperature maps, *Int. J. Remote Sens.*, in press, 1996.

Offiler, D., The calibration of ERS-1 satellite scatterometer winds, *J. Atmos. Oceanic. Technol., 11*, 1002, 1994.

Reynolds, R.W., and D.C. Marsico, An improved real-time global SST analysis, *J. Clim., 6*, 114-119, 1993.

Rossow, W.B., and R.A. Schiffer, ISCCP cloud data products. *Bull. Am. Meteorol. Soc., 72*, 2-20, 1991.

Schluessel, P., and W. J. Emery, Atmospheric water vapour over oceans from SSM/I measurements, *Int. J. Remote Sens, 11*, 753-766, 1990.

Schluessel, P., and H. Luthardt, Surface wind speeds over the North Sea from special sensor microwave/imager Observations, *J. Geophys. Res., 96*, 4845-4853, 1991.

Schluessel, P., H.-Y. Shin, W. J. Emery, and H. Grassl, Comparison of satellite-derived sea surface temperatures with in-situ skin measurements, *J. Geophys. Res., 92*, 2859-2874, 1987.

Schluessel, P., W. J. Emery, H. Grassl, and T. Mammen, On the bulk-skin temperature difference and its impact on satellite remote sensing of sea surface temperature, *J. Geophys. Res., 95*, 13,341-13,356, 1990.

Sheu, R.-S., and G. Liu, Atmospheric humidity variations associated with westerly wind bursts during Tropical Ocean--Global Atmosphere Coupled Ocean-Atmosphere Response Experiment, *J. Geophys. Res., 100*, 25,759-25,768, 1995.

Sheu, R.-S., J. A. Curry, and G. Liu, : Satellite retrieval of tropical precipitation using combined International Satellite Cloud Climatology Project DX and SSM/I data. *J. Geophys. Res.,* in press, 1996.

Soloviev, A.V., and P. Schluessel, Evolution of cool skin and direct air-sea gas transfer coefficient during daytime, *Boundary Layer Meteorol., 77*, 45-68, 1996.

Webster, P.J. and R. Lukas, TOGA COARE: The Coupled Ocean-Atmosphere Response Experiment, *Bull. Am. Meteorol. Soc., 73,* 1377-1416, 1992.

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

Wentz, F.J., User's manual SSM/I antenna temperature tapes, Technical Report, 36 pp., Remote Sensing Systems, Santa Rosa, Calif. March 1988.

Wentz, F., Measurement of oceanic wind vector using satellite microwave radiometers, *IEEE Trans. Geosci. Remote Sens., 30*, 960-972, 1992.

Wentz, F.J., L.A. Mattox, and S. Peteherych, New algorithms for microwave measurements of ocean winds: Applications to Seasat and the special sensor microwave imager, *J. Geophys. Res., 91*, 2289-2307, 1986.

Wick, G., Evaluation of the variability and predictability of the bulk-skin SST difference with application to satellite-measured SST, Ph.D. thesis, Univ. of Colo., Boulder, 1995.

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

Young, G.S., S.M. Perugini, and C.W. Fairall, Convective wakes in the equatorial western Pacific during TOGA, *Mon. Weather Rev., 123*, 110-123, 1995.

Zhang, C., Coherence between SST and atmospheric variability in the western Pacific warm pool, paper presented at 8th Conference on Air-Sea Interaction and Conference on the Global Ocean-Atmosphere-Land System (GOALS), Jan. 28 - Feb. 2, Atlanta, Ga, 1996.

Zhang, Y.-C., W.B. Rossow, and A.A. Lacis, Calculation of surface and top of atmosphere radiative fluxes from physical quantities based on ISCCP data sets, 1, Method and sensitivity to input data uncertainties, *J. Geophys. Res., 100*, 1149-1165, 1995.

C. A. Clayson, Department of Earth and Atmospheric Science, 1397 Civil Building, Purdue University, West Lafayette, IN 47907-1397. (e-mail: clayson@thunder.atms.purdue.edu)

J.A. Curry, Program in Atmospheric and Oceanic Sciences, University of Colorado, Boulder, CO 80302. (curryja@cloud.colorado.edu)

(Received July 28, 1995; revised May 20, 1996; accepted June 20, 1996.)