Diurnal cycle of tropical precipitation
in Tropical Rainfall Measuring Mission (TRMM)
satellite and ocean buoy rain gauge data

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[1] The climatological diurnal cycle of precipitation in the tropics is analyzed using data
from rain gauges on ocean buoys and satellite measurements by the Tropical Rainfall
Measuring Mission (TRMM) satellite. The ocean buoy data are from the NOAA/Pacific
Marine Environmental Laboratory Tropical Atmosphere-Ocean/Triangle Trans-Ocean
buoy Network in the tropical Pacific Ocean. TRMM data are from the precipitation radar
(PR) and the TRMM microwave imager (TMI). Climatological hourly mean precipitation
rates are analyzed in terms of the diurnal and semidiurnal harmonics. Both data sets
confirm an early morning peak in precipitation over ocean regions. The amplitude of the
diurnal harmonic over the oceans is typically less than 25% of the mean precipitation rate.
Over tropical land masses the rainfall peaks in the afternoon and evening hours. The
relative amplitude of the diurnal harmonic over land is larger than over the ocean, often
exceeding 50% of the mean rain rate. Previously noted differences between the TMI and
PR rainfall retrievals persist in the diurnal cycle. On average the TMI measures more
rainfall than the PR and has a larger diurnal variation. Phase differences between the two
instruments do not show a consistent bias.

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1. Introduction

[2] Simulation of clouds and precipitation has proven to be one of the most difficult problems in modeling the
Earth’s climate system. Dynamics, thermodynamics, and
radiation all play important roles in cloud and precipitation
systems. Such systems are highly nonlinear and span a huge
range of scales from the synoptic to the microphysical.
Incomplete understanding of the processes that control
clouds and precipitation, and of the climate feedbacks
involving clouds, is one of the largest sources of uncertainty
in predictions of possible future anthropogenic climate
change.

[3] The Earth’s weather and climate vary both regularly
and irregularly. Regular variations are due, for example, to
periodic external forcing by the annual and diurnal cycles of
solar radiation. The characteristics of the forcing at diurnal
and annual frequencies in terms of top-of-the-atmosphere
insolation are well known, so simulations of the climate at
those frequencies provide a valuable means of testing our
understanding of the response of the climate to direct
forcing. In addition, the periodic forcing by solar radiation
is known to produce different diurnal responses over the
continents and oceans. The two environments thus provide,
in effect, two different planets that can be used to validate
models.

[4] Evaluation of model simulations of the annual and
diurnal cycles requires observational data for comparison.
Here we use remotely sensed data from the Tropical
Rainfall Measuring Mission (TRMM) satellite and in situ
data from rain gauges on the National Oceanic and
Atmospheric Administration/Pacific Marine Environment
Laboratory (NOAA/PMEL) Tropical Atmosphere Ocean/
Triangle Trans-Ocean buoy Network (TAO/TRITON) buoy
array in the tropical Pacific Ocean to develop statistical
estimates of the diurnal cycle in tropical precipitation.
The buoy data have the important characteristic that they are
not influenced by the local thermodynamic or orographic
effects to which rain gauges located on islands are sub-
jected [Reed, 1980].

[5] There is an extensive history of observational and
model studies of the diurnal cycle of precipitation. Convec-
tive precipitation over land during the warm season tends to
peak in the late afternoon to early evening hours and is
thought to be a direct response to daytime heating of the
surface and the planetary boundary layer: Heating of the
lower atmosphere produces available potential energy that
can be released by convective overturning. Wallace [1975]
reviewed some earlier studies of the diurnal cycle and
analyzed the diurnal cycle of precipitation and thunder-
storm activity over the United States using rain gauge data.
He concluded that daytime surface heating provides the
large-scale thermodynamic control of convection and pre-
cipitation but that dynamical effects in some regions can
substantially change the phase of convection from late
afternoon to midnight or even early morning hours.
Wallace [1975] was apparently thinking of large-scale
boundary layer processes as the predominant dynamical
influence, but the growth and propagation of mesoscale
systems initially triggered by diurnal heating also affect
the timing of the peak precipitation [Carbone et al., 2002;
Rickenbach, 2004; Nesbitt and Zipser, 2003].

[6] The diurnal cycle of precipitation is typically different
over the oceans than over land. At most oceanic locations
the maximum precipitation tends to occur in the early
morning hours (typically between 0300 and 0600 LT).
Kraus [1963] analyzed midlatitude weather ship data and
found more frequent precipitation at night. He argued that
this counterintuitive diurnal cycle is due to the stabilizing
effects of solar heating of cloud tops during the day or,
equivalently, the destabilizing effects of nighttime radiative
cooling at cloud tops. Gray and Jacobson [1977] studied
precipitation in the tropics, primarily using rain gauge data
from a small set of islands, and found an early morning
maximum in deep convection and precipitation. They
argued that the early morning maximum was the result of
heating differences between organized cloud systems and
surrounding clear regions. They also noted that while larger
islands have an early morning precipitation maximum, they
also have an even larger afternoon maximum, which they
attributed to daytime heating of the land surface.

(GCM) to simulate the diurnal cycle of precipitation. They
found that a diurnal cycle exists over the oceans even on an
all-water planet. From controlled experiments with the
GCM they concluded that stabilization of the atmosphere
through absorption of solar radiation by clouds is the
dominant process responsible for the diurnal cycle, as
suggested by Kraus [1963]. They also found that a radiat-
ively forced diurnal cycle exists in a one-dimensional
column model even when there is no diurnal forcing of
the large-scale vertical motion field, which argues against
the hypothesis of Gray and Jacobson [1977].

[8] The Global Atmospheric Research Program (GARP)
Atlantic Tropical Experiment (GATE) in 1974 provided one
of the first extensive data sets of tropical oceanic precipi-
tation not based on island rain gauge data. A number of
studies examined the diurnal cycle in the GATE data and
found an afternoon maximum in precipitation, which con-
tradicted studies at other locations [Gray and Jacobson,
1977; McGarry and Reed, 1978; Albright et al., 1981]. The
precipitation during GATE phase III was dominated by a
small number of squall lines propagating through the
observing area. Because the GATE observing period was
relatively short, it is difficult to say whether the diurnal
phase of the squall lines was influenced by the small sample
size. It is interesting to note that an afternoon peak was
found during phases I and III but a morning peak occurred
during phase II. A later study by Reed and Jaffe [1981],
using Meteosat IR imagery, found that an afternoon peak in
cold clouds also occurred over the GATE area in 1978, so it
is possible that the eastern tropical Atlantic is affected by
the proximity to the African coast. That is, squall lines were
triggered by the coastal sea breeze circulation or deep
convection over West Africa.

[9] Over the years a number of authors have used tropical
cold cloud occurrence from IR satellite data or precipitation
amounts inferred from the IR data to study the diurnal cycle
[Reed and Jaffe, 1981; Albright et al., 1985; Hendon and
Woodberry, 1993; Janowiak et al., 1994; Yang and Slingo,
2001]. The advantages of geostationary IR data are high
horizontal and temporal resolutions; the principal disadvan-
tages are the indirect relationship of the measurement to
precipitation rates and the lack of a signal in areas that have
little deep convection. Albright et al. [1985] found that in
January and February of 1979 in the tropical Pacific, most
locations had an early morning peak in convective cloud-
iness. The exception was the South Pacific Convergence
Zone (SPCZ), which also exhibited an afternoon peak.
Hendon and Woodberry [1993] generally found an after-
noon or early evening peak in deep convective activity over
the continents and a morning peak over the oceans, includ-
ing the SPCZ. Janowiak et al. [1994] found similar results.
Yang and Slingo [2001] compared the observed diurnal
cycle with simulations by the UK Met Office Unified Model
and noted a number of problems with simulating the phase
of the diurnal cycle.

[10] Several authors have used data from passive micro-
wave satellite instruments such as the Special Sensor
Microwave/Imager (SSM/I) to study the diurnal cycle over
the tropical oceans. Microwave emission is more directly
related to precipitation rate than is cloud top temperature
[Wilheit et al., 1977]. Because the SSM/I instruments have
flown on Sun-synchronous satellites, it is not possible to
estimate the diurnal cycle reliably from a single satellite.
Chang et al. [1995] used SSM/I data from multiple satellites
with different equator crossing times to estimate the diurnal
cycle of oceanic precipitation. They found an early morning
peak in precipitation at most locations, although the uncer-
vainty in their estimates was large. The TRMM satellite is in
a non-Sun-synchronous orbit. During its precession period
it samples rainfall at different times throughout the diurnal
cycle. Nesbitt and Zipser [2003] identified individual storms
and mesoscale systems in the TRMM data and analyzed
rain rate versus time of day, stratified by the type of
precipitation feature. Over tropical land they found an
afternoon peak, while ocean locations showed an early
morning peak and a weaker diurnal cycle. They also found
that the early morning peak is due to increased numbers of
precipitating features rather than increased rain intensity.
Collier and Bowman [2004] compared the diurnal cycle
inferred from 4 years of TRMM data with simulations by
the National Center for Atmospheric Research (NCAR)
Community Climate Model version 3. They noted a number
of problems with the model’s simulation of the diurnal
cycle, including both amplitude and phase errors. Dai and
Trenberth [2004] analyzed the diurnal cycle in the NCAR
Community Climate System Model and compared precipitation frequencies with surface observations [Dai, 2001]. They also found significant differences between observations and simulations.

Serra and McPhaden [2004] examined the diurnal cycle of various precipitation parameters using the TAO/TRITON ocean buoy rain gauge data. They found an early morning maximum in precipitation amount, intensity, and frequency. In this study, we use the buoy data, along with more than 6 years of TRMM rainfall data, to study the diurnal cycle in rainfall rates. The goals of this research are to establish confidence limits on the amplitude and phase of the diurnal cycle for both buoy and satellite data, to compare the diurnal cycles observed by the two systems, and to analyze differences between the diurnal cycle measured by the two primary TRMM precipitation instruments, the precipitation radar (PR) and the TRMM microwave imager (TMI).

2. Data

2.1. TRMM Data

2.1.1. Satellite and Instruments

The TRMM satellite is a joint U.S.-Japan mission that was launched in November 1997. Designed to observe precipitation in the tropics, it operates in a low-inclination (35°), low-altitude orbit. During the first 3 or more years of operation, TRMM flew at an altitude of ~350 km. In August 2001 the orbit was boosted to ~400 km to reduce drag, and thus fuel use, and to increase the lifetime of the mission. TRMM has significantly outlasted its nominal 3-year design lifetime. Details of the TRMM mission and instruments are given by Simpson et al. [1988] and Kummerow et al. [1998, 2000].

The TRMM satellite measures precipitation with both the precipitation radar and the TRMM microwave imager. The PR and the launch vehicle were provided by Japan. The other instruments and the spacecraft were provided by the United States. The PR is a phased-array radar operating at 13.8 GHz (~2.1 cm wavelength). The observing footprint is ~4 × 4 km at nadir, and the vertical resolution is 250 m. The radar scans perpendicular to the satellite motion with a swath width of 220 km. Because of the comparatively narrow swath the mean sampling interval for PR measurements at the equator is roughly 2 to 3 days.

The TMI is a multichannel, dual-polarization, passive microwave radiometer based on the SSM/I instruments used on the operational Defense Meteorological Satellite Program polar orbiters. The TMI uses an offset antenna to scan the Earth's surface in a conical pattern across the satellite's flight track. This scanning pattern is designed to maintain a constant viewing angle at the Earth's surface. This design eliminates variations in emitted radiation due to viewing angle dependence of the surface microwave emissivity. The size of the instrument's field of view depends on the frequency, ranging from 63 × 37 km at 10.65 GHz to 7 × 5 km at 85.5 GHz. The TMI swath width is ~780 km, which means that the mean sampling interval at the equator is about 1 day. Precipitation retrieval algorithms over the ocean rely primarily on emission of microwave radiation from hydrometeors observed against the relatively cold background provided by the low-emissivity ocean surface.

Because of variations in the surface emissivity, rainfall retrievals over land are based on the ice scattering signals in the high-frequency (85 GHz) channel, while the ocean retrieval algorithm uses the ice scattering information in the 85 GHz channels to select rain profiles [Kummerow et al., 2001]. As a result, the retrieval algorithms over land and ocean are substantially different, with greater uncertainty in the retrievals over land.

The TRMM orbital configuration and the instrument swath widths determine the sampling frequency of the instruments. As noted above, the PR and TMI view a given location at intervals of a few days. Because of the large variability of precipitation in space and time this relatively infrequent sampling leads to constraints on estimates of space and time averages. Unlike the operational polar orbiting meteorological satellites, the TRMM orbit is not Sun-synchronous. It precesses with respect to the Sun (that is, through the diurnal cycle) with a period of about 6 weeks. Counting both ascending and descending segments of the orbit, TRMM observes a complete diurnal cycle in about 3 weeks. At higher latitudes, sequential observations are closer together in local time, and at the highest latitudes viewed by the satellite, 6 weeks are required to sample a complete diurnal cycle; however, swath overlap means that more samples are collected at higher latitudes than near the equator. Negri et al. [2002] evaluated the geographic inhomogeneity of the diurnal sampling of the TRMM orbit and its dependence on orbital characteristics such as altitude. In this study, with 6 years of TRMM data, the sampling is smoother than in the 3-year examples given by Negri et al. At the equator, for example, in 6 years, TRMM samples a 0.5° × 0.5° grid box approximately 110 times during each hour of the day (~2600 samples total). The number of samples in a given hourly bin varies from box to box by about 15%. Area averaging further reduces the inhomogeneity.

2.1.2. Data

This study uses version 5 of the TRMM 3G68 data product, which is composed of instantaneous precipitation retrievals from the PR, TMI, and a combined algorithm (referred to as COMB) that have been area averaged onto a 0.5° × 0.5° grid. Data are available from roughly 35°S to 35°N. The time period covered by the version 5 data is 7 December 1997 to 31 March 2004 (just over 6 years). Because of the changeover to the TRMM version 6 algorithms, version 5 processing stopped on 31 March 2004. Additional data will be available when the version 6 reproprocessing is complete, but they are not used here. There are very few gaps in the version 5 TRMM data record. The version 6 retrievals differ for both the the TMI and PR. It will be possible to evaluate the magnitude of the changes in the rainfall estimates when the version 6 reproprocessing is complete.

2.2. TAO/TRITON Buoy Rain Gauge Data

The NOAA/PMEL maintains an array of ocean buoys moored across the tropical Pacific Ocean [Hayes et al., 1991; McPhaden et al., 1998; Serra et al., 2001; Serra and McPhaden, 2003]. The buoys are equipped with ocean-observing instruments on the mooring cables and atmospheric instruments on the buoys themselves. Data are telemetered in real time via satellite. A subset of the buoys
is equipped with rain gauges. The locations of buoys with rain gauge data are shown in Figure 1. The gauges are numbered for reference. Two buoys with very short records (~2 months) have been omitted from this study.

[18] The buoys measure rain accumulations using capacitance-type rain gauges. Rain rates are calculated at 1-min intervals by differencing the instantaneous accumulations. The 1-min values are filtered and converted to 10-min rain rates. Instrument noise in the accumulation amounts can lead to small positive and negative rain rates. To avoid potential bias, all rain rate values are included when computing time averages. The buoy data used here have not been corrected for undercatch, which could be substantial during windy periods [Serra et al., 2001; Serra and McPhaden, 2003, 2004].

[19] The availability of data from the buoy rain gauges is shown in Figure 2. The gauge numbers are listed along the left edge of Figure 2, followed by the longitude and latitude of the gauge. Periods with valid gauge data are indicated by the black horizontal bars. The numbers along the right-hand side of Figure 2 give the total number of days of data available for each gauge. These range from a minimum of 179 days to 1967 days. As can be seen, the gauge data are intermittent, with all gauges having relatively long gaps. There are also some small gaps within the black bars that are not visible at this scale, but they are infrequent. The two

Figure 1. Locations of Tropical Atmosphere Ocean/Triangle Trans-Ocean buoy Network (TAO/TRITON) buoys with rain gauges used in this study.

Figure 2. Availability of rain gauge data from the ocean buoys. Periods with data are black; periods without are white. The two vertical dashed curves indicate the beginning and end of the Tropical Rainfall Measuring Mission (TRMM) version 5 data set. The values on the left side are the buoy reference numbers (Figure 1) and the longitudes and latitudes of the buoys. The numbers on the right side depict the number of days with valid data for each gauge.
A reasonable starting point for statistical models of the diurnal cycle is to assume that diurnal variations are composed of two parts: a regular (deterministic) component forced by the diurnal cycle of solar radiation and an irregular (random) component due to internal nonlinearity. Similar procedures are used for both the TRMM and the gauge data. For each gauge and for each TRMM $0.5^\circ \times 0.5^\circ$ grid box, all of the available observations are binned into hourly bins (UTC) and averaged to produce a 24-point representation of the diurnal cycle. Because of the limitations of the TRMM sampling, it is beneficial to area average the TRMM hourly binned data before analyzing the diurnal cycle. Area and time averages are weighted by the number of TRMM instrument pixels in each $0.5^\circ \times 0.5^\circ$ grid box that are observed during each overpass. Different TRMM area-averaging grids are used here. Most results shown here use either $5^\circ \times 5^\circ$ or $10^\circ \times 5^\circ$ longitude-latitude boxes. For the comparisons between TRMM and gauge data the TRMM area averages are computed for grid boxes centered on the gauge locations.

For each location, that is, for each gauge or TRMM averaging box, the 24 hourly values are fitted with diurnal and semidiurnal harmonics of the form

$$r(t_i) = a_0 + \sum_{k=1}^{2} \left[ c_k \cos \left( \frac{2\pi k t_i}{24} \right) + s_k \sin \left( \frac{2\pi k t_i}{24} \right) \right] + \epsilon_i, \quad (1)$$

where $t_i = (0.5, 1.5, 2.5, \ldots, 23.5)$ is the time in hours, $a_0$ is the long-term time mean, $k$ is the harmonic index, $c_k$ and $s_k$ are the coefficients of the cosine and sine components of the Fourier representation of the climatological hourly rain rates, and the residual $\epsilon_i$ is assumed to be a normally distributed random variable with zero mean. The coefficients $a_0$, $c_k$, and $s_k$ are estimated via linear regression minimizing $\sum \epsilon_i^2$, where $\epsilon_i$ are the estimated residuals from the fit of the model. Previous studies indicate that the diurnal harmonic usually dominates the diurnal cycle of precipitation. In some locations the semidiurnal harmonic is also significant, but higher harmonics can generally be ignored.

The characteristics of the harmonics can be represented in terms of the amplitude $A_k = \sqrt{c_k^2 + s_k^2}$ and phase $\phi_k = \tan^{-1} (s_k/c_k)$ of each harmonic. The statistical significance of the five estimated coefficients is evaluated by using the $F$ statistic with numerator and denominator degrees of freedom 2 and 19 = 24 − 5, respectively [Anderson, 1971].

4. Results

4.1. Diurnal Sampling

Because the satellite precesses with respect to the Sun with a period of about 6 weeks, over the $6^\circ$ year period used here the satellite has undergone roughly 50 complete precessional cycles. As a result, the number of TRMM observations in each hourly bin at all locations is uniform within a few percent. For $10^\circ \times 5^\circ$ TRMM grid boxes each hourly mean is the average of $\sim 1.2 \times 10^6$ TMI observations (pixels). Therefore there is no reason to expect biases in the observed diurnal cycles of precipitation due to a diurnal bias in the sampling. This does not eliminate the possibility that

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Figure 3. Climatological hourly mean precipitation values as a function of time of day for different area averaging sizes (black curve) and fits to the data using (1) (gray and red curves). Increasing the averaging area reduces the variability because of sampling and produces a smoother diurnal harmonic. The data are for a rainy location in the western Pacific Ocean with a mean rain rate of $\sim 9$ mm d$^{-1}$. In this and following figures colors are used to indicate the statistical significance of the diurnal and semidiurnal harmonics. Black, both harmonics are statistically significant; gray, neither harmonic is significant; red, only the diurnal harmonic is significant; blue, only the semidiurnal harmonic is significant.
there might be systematic errors in the TRMM measurements that have a diurnal component. Similarly, because the gauge data have long periods of contiguous data, the hourly sampling by the gauges is also nearly uniform with time of day, although the total number of 10-min observations at the different gauges varies from a low of $\sim 1 \times 10^3$ to a high of $\sim 1.2 \times 10^4$ per hourly bin.

4.2. Effects of Area Averaging

[25] Sampling errors in satellite rainfall estimation and the effects of space and time averaging have been considered in a series of papers by Bell and coauthors [Bell, 1987; Bell et al., 1990; Bell and Kundu, 1996, 2000, 2003; Bell et al., 2001] and by Bowman [2005]. To illustrate the magnitude of the sampling error and effects of area averaging on the TRMM data, Figure 3 shows the calculated climatological hourly mean values for one of the gauge locations ($5^\circ \text{N}, 165^\circ \text{E}$). This is a rainy location in the western Pacific Ocean with a mean rain rate of $\sim 9 \text{ mm d}^{-1}$. The diurnal cycle is shown for four different averaging areas: $1^\circ \times 1^\circ$, $2^\circ \times 2^\circ$, $5^\circ \times 5^\circ$, and $10^\circ \times 5^\circ$. The climatological mean hourly data are indicated by the black curve. The fits to the data are indicated by the smooth gray or red curves. The color code used in Figures 3, 5, 6, 7, and 8 to indicate statistical significance is explained in the Figure 3 caption. As the sampling area and number of samples increase, the variability of the hourly values decreases.

4.3. Satellite-Gauge Comparisons

4.3.1. Distribution of Residuals

[26] The significance tests assume that the residuals are normally distributed random variables with zero mean. Probability distribution functions (PDFs) of high-frequency rain gauge data are known to be nonnormal, however, and lognormal or gamma distributions are often used to represent gauge data. In this study, the climatological hourly precipitation rates are averages of many values. Following the central limit theorem, this averaging should tend to lead to PDFs that approach normal. To check this assumption, histograms of the pooled residuals for all of the buoy locations are plotted in Figure 4 (solid curves). Normal distributions computed from the sample mean and variance of each data set are also plotted (dashed curves). Figure 4 shows that the large amount of averaging that has gone into computing the climatological hourly means has led to residuals that are close to normal. There is evidence that the PDF of the gauge data has longer tails than would be the case if the data were normally distributed. The residuals are not obviously skewed, however, and the deviations from normality should not invalidate the significance tests.

[27] The residuals of the TMI, on the other hand, appear to be nearly normal, although there is some hint here as well that the tails of the distribution might be slightly larger than is the case for a normal distribution. This is not surprising, as the number of individual measurements in the TMI averages is much larger than for the gauges, and each individual TRMM observation (pixel) is already an area average over many square kilometers.

4.3.2. Diurnal cycles

[28] To illustrate the diurnal fits to the data and the differences between the TRMM and buoy data, Figure 5 shows the diurnal cycle and calculated fits for four selected locations. The top three locations are rainy (6 to 9 mm d$^{-1}$) on average, while the bottom location is relatively dry ($\sim 0.6$ to 1.5 mm d$^{-1}$). All four locations have relatively long gauge records ($\sim 1300$ or more days). Note that all available
data are used in each case, so the periods of record do not match for the gauges and the satellite. Random variability appears larger in the buoy data, which can be attributed to the smaller sample sizes. For the TMI, either the diurnal harmonic is statistically significant at the 95% level (red), or both harmonics are significant at that level (black). For the buoys (Figure 5, left), there are no significant diurnal or semidiurnal signals at (8°S, 165°E) (gray curve, first panel), and only the semidiurnal cycle is significant at (9°N, 140°W) (blue curve, second panel). It is clear from these examples that there can be substantial differences between the gauge and satellite estimates of the diurnal cycle at the gauge locations.

Figures 3 and 5 illustrate that with the available record lengths the sampling errors are substantial, even for relatively large area averages of the satellite data. These errors introduce uncertainty into the statistical estimates of the diurnal and semidiurnal harmonics. Stratifying the data further, by month or season, for example, would substantially reduce the sample sizes, increase the variability due to sampling errors, and reduce the statistical significance of the harmonic estimates. Therefore all analyses in this paper use all of the available data from both the gauges and the satellite.

### 4.3.3. Diurnal Harmonic

Figure 6 shows the estimated amplitude and phase of the diurnal harmonic at each gauge location from the gauge data and from the 10° × 5° area-averaged TMI data. Phases are represented using a 24-hour clock. Midnight is north, 0600 is east, etc. The amplitudes of the largest diurnal harmonics are ~2 mm d⁻¹. The circles centered on the tip of each vector represent 95% confidence regions for the diurnal harmonic. That is, under the assumptions of the F test, there is a 95% probability that the true amplitude and phase lie within the circle. If the confidence circle is large enough to contain the origin of its vector, the amplitude of that diurnal harmonic cannot be distinguished from zero at the 95% confidence level, and the phase cannot be reliably estimated.

Several features are immediately apparent in Figure 6. First, the maximum rainfall due to the diurnal harmonic generally occurs in the early morning hours between approximately 0300 and 0600 LT. Second, the confidence circles for the TMI data are smaller than for the

![Figure 5.](image)
gauge data, and the amplitudes and phases of the satellite estimates of the diurnal harmonic exhibit less geographic variability. This can be attributed to better sampling by the TMI compared to the gauges. Third, the amplitude of the diurnal harmonic appears to be larger in areas with larger rainfall, that is, in the western Pacific and north of the equator in the Intertropical Convergence Zone (ITCZ). Along the equator (that is, outside the ITCZ) and in the eastern Pacific south of the equator, which are both relatively dry areas, the diurnal harmonic is small.

The variability within the two data sets can be better seen in Figure 7, which superimposes all of the diurnal harmonic vectors from each data set for the buoy locations. The phase estimates are noticeably more variable in the gauge data. The diurnal harmonics estimated from the gauge data peak between 0000 and 0900 LT, with most peaking between 0200 and 0700 LT.

4.3.4. Semidiurnal Harmonic

Figure 8 shows the estimated amplitude and phase of the semidiurnal harmonic at each gauge location from the gauge data and from the area-averaged TMI data. Because the semidiurnal harmonic has two peaks per day, vectors with phases separated by 12 hours have the same diurnal cycles. For example, semidiurnal harmonics peaking
near 1800 LT have an equal peak near 0600 LT. It is difficult to see any consistent phase in the gauge data, although the handful of gauge sites at which both harmonics are statistically significant (black arrows) tend to have peaks between about 0400 and 0600 LT, which is in phase with the diurnal harmonic. In the TMI data, there is a clear tendency for one of the two daily peaks of the semidiurnal component to occur between 0200 and 0600 LT. As discussed above, the single buoy with a peak near 1800 also has a peak near 0600 LT so it falls into this category. This phase puts one of the maxima of the semidiurnal harmonic at roughly the same time as the maximum of the diurnal harmonic. In

![Figure 8](image1.png)

**Figure 8.** Semidiurnal harmonic vectors for the gauge and $10^\circ \times 5^\circ$ TMI data sets plotted using a 24-hour clock. Local midnight is up. Because there are two peaks in the diurnal cycle per day, rotating a vector by 12 hours ($180^\circ$) does not change the amplitude or phase of the semidiurnal harmonic. Significant results are blue and black (red, diurnal only; blue, semidiurnal only; black, both; gray, neither).

![Figure 9](image2.png)

**Figure 9.** (a) Amplitude and (b) phase of the diurnal harmonic throughout the tropics estimated from TMI $5^\circ \times 5^\circ$ averages.
combination with the diurnal harmonic the net effect is to increase the magnitude of the early morning diurnal maximum and to decrease the depth of the afternoon minimum. This tendency to have a localized peak in the early morning hours and a flat diurnal cycle during the rest of the day can be seen in Figure 5 for the sites with two significant harmonics (black curves). Although the semidiurnal harmonic in the TMI data is statistically significant at 13 out of the 27 gauge locations, the amplitude of the semidiurnal harmonic is typically less than half of the amplitude of the diurnal harmonic.

4.4. Diurnal Harmonic Throughout the Tropics

[34] The phase of the diurnal harmonic shown in Figures 6 and 7 generally agrees with previous studies that found an early morning peak in oceanic rainfall. The amplitude and phase of the diurnal harmonic for 5° x 5° area-averaged TMI data are shown in Figure 9 for all

Figure 10. Amplitude of the diurnal harmonic as a function of time mean rain rate for 5° x 5° (a) TMI and (b) precipitation radar (PR) grid boxes. Blue points represent ocean boxes (>80% ocean), while red points represent land boxes (>80% land). Intermediate boxes are omitted.

Figure 11. Map of the difference between the long-term mean rain rates retrieved by the TMI and PR instruments.
locations in the tropics. The amplitude (Figure 9a) resembles the time mean precipitation rate, with larger diurnal cycles in regions with larger mean rain rates (e.g., ITCZ, western Pacific, and tropical continents).

[35] The phase has a distinct land-sea difference (Figure 9b). Morning and afternoon peaks in rainfall are indicated by red and blue, respectively. Some localized anomalies appear that can be attributed to sampling fluctuations (e.g., just southeast of Hawaii). The large-scale pattern is very consistent, however. Over the tropical oceans the diurnal cycle of precipitation generally peaks in the morning hours. Over tropical land masses the peak is in the afternoon. Coastal areas may have intermediate times, but the resolution of the data is too coarse to draw firm conclusions.

In the TRMM data the GATE observing area, which is centered at about 9°N, has a morning peak of the diurnal cycle. This is not consistent with GATE analyses that found an afternoon precipitation maximum in this part of the eastern Atlantic [Gray and Jacobson, 1977; McGarry and Reed, 1978; Albright et al., 1981]. There is an area off the northwest coast of Africa (north of the GATE region) that exhibits an afternoon peak. This could be due to interactions with the diurnal cycle over the African continent.

[36] Figure 10 compares the amplitude of the diurnal cycle with the mean rain rate for 5° × 5° boxes. Blue points represent ocean grid boxes, subjectively defined as >80% ocean, and red points represent land grid boxes, similarly defined as >80% land. The gray curves in the background can be used to estimate the magnitude of the diurnal cycle relative to the daily mean rain rate. The results show that at most ocean locations the amplitude of the diurnal cycle is 25% of the mean rain rate or less, although at a few locations the amplitude ranges up to about 50% of the mean. The diurnal cycle at land locations is generally larger than over the ocean, with relative amplitudes generally above 25% and often greater than 50%. For the TMI some of the differences between land and ocean may be due to differences in the retrieval algorithms. Because the land retrieval algorithm is based on ice scattering, it may be more sensitive to deep than shallow convection and thus biased toward a larger diurnal amplitude [Nesbitt et al., 2004; Furuzawa and Nakamura, 2005]. Despite this, the amplitude of the diurnal harmonic relative to the mean rain rate appears to be similar in the two data sets. The differences between the TMI and PR retrievals are discussed further in section 4.5.

4.5. TMI-PR Comparisons

[37] Biases are known to exist between the retrieved TMI and PR rain rates [Kummerow et al., 2000; Masunaga et al., 2002; Bowman et al., 2003; Serra and McPhaden, 2003; Nesbitt et al., 2004; Furuzawa and Nakamura, 2005]. Figure 11 shows the differences in the long-term mean rain rates between the two instruments, expressed as TMI-PR. The difference pattern looks very much like the mean rain rate. That is, differences are largest where the rain rates are largest. In wetter areas, such as the ITCZ, the western Pacific, and the tropical continents, the TMI values are consistently larger than the PR values. In dry areas, such as Australia, or in the subtropics off the west coasts of the other continents, the PR sees more rain than the TMI. In wetter areas the differences can be several millimeters per day.

[38] Figure 12a is a scatterplot of the long-term mean rain rates from the two instruments in each 5° × 5° longitude-latitude box. Blue points represent ocean boxes (>80%
ocean), red points represent land boxes (>80% land), and black points are all other boxes. The gray curve represents a 1:1 relationship. The black curve is a least squares fit with a quadratic polynomial. (The differences between a linear fit and a quadratic fit are small, but the relative bias between the two instruments does appear to increase somewhat with an increasing rain rate.) The biases in wetter areas are substantial, reaching \( \gamma \times 50\% \) at the wettest locations. There is not a strong difference in the instrument biases between land and ocean, except perhaps at dry locations (mean rain rates <2 mm d\(^{-1}\)). At land locations the TMI measures less rain than the PR.

Figure 12b is a scatterplot of the amplitudes of the diurnal harmonic as estimated by the two instruments for 5° \times 5° boxes. As with the means, there is a bias in the diurnal harmonics, with the TMI seeing a larger diurnal harmonic than the PR. The differences between the means and diurnal harmonics for the two instruments can also be seen in Figure 10. Figures 12a and 12b are plotted with the same scale, and the smaller range of the PR measurements is apparent.

Figure 13a shows that the bias of the diurnal cycle amplitude is larger in wetter areas, particularly in the western Pacific and over tropical Africa and South America. The phase of the diurnal harmonic, on the other hand, does not appear to have any consistent pattern of bias (Figure 13b). In Figure 13b the phase difference never exceeds about 6 hours in either direction.

5. Discussion

Diurnal variability is an important aspect of the Earth’s weather and climate as many environmental parameters vary on diurnal timescales. The ability to simulate the response to diurnal insolation variations is an important test of climate model performance. In this study, we have analyzed the climatological diurnal cycle of precipitation in the tropics in terms of diurnal and semidiurnal harmonics, using data from rain gauges on ocean buoys and TRMM satellite data. Over the 6+ year period analyzed here, the TRMM satellite orbit has precessed with respect to the diurnal cycle of solar radiation about 50 times, providing good sampling at all local times. An important aspect of the TRMM data is that area averaging can be used to reduce the sampling errors. This does not diminish the importance of the buoy rain gauges for ground truth studies. Longer buoy and satellite records will allow improved estimates of a number of important precipitation parameters. Because both the buoy and satellite records are still relatively short, we have not attempted to stratify the data by month or season. Therefore these results are representative of the annual mean climatological diurnal cycle.
The analysis shows that at the buoy locations the peak in the diurnal cycle in the TRMM data consistently lies between 0300 and 0600 LT, in agreement with most earlier studies. The amplitude of the diurnal harmonic over the oceans is relatively weak: typically about 25% of the mean rainfall rate or less. Variability in the gauge data is larger than for the TRMM area averages, presumably due to smaller effective sample sizes. The limitations of the small sample sizes can be mitigated by pooling the data from nearby buoys, as was done by Serra and McPhaden [2004]. The semidiurnal harmonic is generally in phase with the diurnal harmonic, such that the early morning peak is enhanced, while the depth of the afternoon minimum is reduced. The combined effect is a roughly constant mean precipitation rate from noon to midnight, with a peak centered near sunrise.

The TRMM data confirm earlier results that show an early morning precipitation peak over the oceans and an afternoon to evening peak over land. Coastal ocean areas often have peak precipitation at intermediate times, suggesting interactions between the ocean and nearby land masses. Throughout the tropics the geographical variation of the amplitude of the diurnal harmonic is similar to the geographical variation of the mean rainfall rate. That is, the diurnal cycle tends to be larger where there is more rain. Over land the relative amplitude of the diurnal harmonic is generally larger than over the oceans, often exceeding 25 or even 50% of the mean rain rate.

Previously noted differences between the TMI and PR mean rain rate retrievals also appear in the diurnal cycle. On average, the TMI measures more rain than the PR, and the diurnal harmonic estimated from TMI data is larger than that estimated from PR data. In wetter locations the differences are substantial, approaching 50% in the wettest regions. Phase differences between the two instruments, on the other hand, do not show consistent geographic biases. Some of the possible physical mechanisms for interinstrument bias have been discussed by Nesbitt et al. [2004] and Furuzawa and Nakamura [2005]. The TMI and PR use fundamentally different remote sensing techniques. The rainfall retrieval algorithms for both instruments contain assumptions and uncertainties that will require continued research in a number of areas, while the continuing operation of the TRMM satellite will steadily reduce the sampling errors.

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