DIURNAL VARIATION OF TROPICAL PRECIPITATION USING FIVE YEARS TRMM DATA

A Thesis

by

QIAOYAN WU

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2004

Major Subject: Atmospheric Sciences

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Approved as to style and content by:

Gerald R. North (Chair of Committee)	Kenneth P. Bowman (Member)
H. Joseph Newton (Member)	Richard Orville (Head of Department)

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ABSTRACT

Diurnal Variation of Tropical Precipitation Using Five Years

TRMM Data. (August 2004)

Qiaoyan Wu, B.S., Nanjing University, China

Chair of Advisory Committee: Dr. Gerald R. North

The tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) and Precipitation Radar (PR) data are used in this study to reveal diurnal variations of precipitation over the Tropics $(30°S - 30°N)$ from January, 1998, to December 2002. The TMI data were used for the regions over oceans and islands and the PR data was used over continents. The observations are sorted regionally to examine the difference in diurnal cycle of rainfall over ocean, island, and continental regions. The rain rate is averaged over individual two hour intervals of local time in each region to include more observations in order to reduce the sampling error. F-test is used to determine those regions whose diurnal cycle is detected at the 95% confidence level.

In most oceanic regions there is a maximum at 0400 LST - 0700 LST. The amplitude of diurnal variation over ocean regions with small total rain is a little higher than that of the ocean regions with heavy total rain. The diurnal cycle peaks at 0700 LST - 0800 LST over islands with rainfall variation similar to surrounding oceanic regions. A maximum at 1400 LST - 1500 LST was found in areas over continents with heavy total rain, while the maximum occured at 1900 LST - 2100 LST over continents with lesser total rain. The amplitudes of variation over continents with heavy total rain and with small total rain do not show significant differences. The diurnal cycle in in JJA (June, July, August) and DJF (December, January, February) varies with latitude over continents. A seasonal cycle of diurnal cycle can also be found in some oceanic regions. The diurnal cycle annual change is not evident over continents, while the diurnal cycle annual change over oceans exists in some regions. Island regions in this paper exhibit no evident seasonal and annual diurnal change.

ACKNOWLEDGMENTS

I am most grateful to my advisor and committee chair Dr. Gerald R. North for his guidance, patience, and extraordinary support during this research. I would also like to express my gratitude to my committee members Dr. Kenneth P. Bowman and H. Joseph Newton for their generous help and advice. Thanks to Dr. Ha for the suggestions on the statistic problem encountered . Other CSRP members: Neil Smith, J. Craig Collier and Stephanie Tice also have been an incredible help to me. And last I want to thank my parents for their love and support in my whole life.

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CHAPTER I

INTRODUCTION

The atmosphere gets three fourths of its heat energy from the latent heat released by precipitation and two thirds of this precipitation falls in the Tropics. In turn the differences in large-scale rainfall patterns and their associated energy releases affect the global circulation. In many parts of the tropics the diurnal cycle and the annual cycle account for most of the variation in weather, including precipitation. The ability to successfully explain the variability of rainfall over short time scales, such as the diurnal cycle, serves as a useful measure of understanding of the physics of the atmosphere. Knowledge of variation in rainfall statistics with the time of day is also essential in interpreting non-geosynchronous satellite estimates of rainfall, since these satellites view a given spot only intermittently, and interpolating between the measurements should be adjusted according to the time of day. An accurate representation of the diurnal cycle of precipitation also provides a key test of many aspects of the physical parameterizations in a climate model, from radiative transfer and surface exchanges through to boundary layer, convective, and cloud processes. One of the priority science questions in the design of the Tropical Rainfall Measuring Mission (TRMM) was "what is the diurnal cycle of tropical rainfall and how does it vary in space?" Simpson et al. (1988).

In the most basic sense, the diurnal cycle over land and large islands can be viewed as a response to radiational forcing. As surface temperatures rise, instability and the resulting convection increase, reaching a maximum in the late afternoon or early evening. With radiational cooling of the land at night, convection decreases, reaching a minimum in the early morning. The nocturnal cooling of existing cloud tops may result in destabilization and a

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secondary convection maximum during the night. Such nocturnal cooling might also result in increased convection over water, reaching a maximum in early morning, then decreasing throughout the day. The amplitude of the diurnal variation over water is generally believed to be less than that over land, due to the smaller response of the water surface temperature to radiational heating and cooling. This simple picture is complicated in most locations by local forcing and prevailing wind patterns, which cause a complex pattern of diurnal variations that are particularly noticeable when one examines data from individual stations Meisner and Arkin (1987).

The diurnal cycle in tropical precipitation has been extensively studied using different methods for a number of years. Weather ships data, surface rain accumulation, rain gauge data, satellite infrared data, outgoing longwave radiation data, passive microwave, radar data collected during GATE [GARP(Global Atmospheric Research Program) Atlantic Tropical Experiment], and most recently TRMM data were used for the diurnal study. Most of these works agree that the amplitude of the diurnal cycle of rainfall over continents is larger than that over the open oceans. But regional differences in the rainfall diurnal cycle exist over both ocean and land, leading to different explanations of the causal mechanisms.

With progress in satellite remote-sensing techniques of precipitation estimation, large-scale patterns of rainfall can be monitored using rainfall estimates with improved accuracy and spatial/temporal resolutions. The infrared observations from geostationary satellites have high temporal sampling frequency, thus making it easier to study diurnal variations on short timescales. But the infrared techniques, which use only information on cloud-top temperature to determine surface rainfall, provide only "indirect" information about rainfall. Passive microwave techniques, which obtain measurements that reflect the distribution of hydrometeors within the cloud, are known to offer a more direct signal from the rain layer. However, almost all the space platforms that carry such instruments were put in sun-synchronous orbit, which allow just two samples of rainfall per day over a given location. Recently some studies (Adler et al. (1993), Negri et al. (2002), Xu et al. (1999), etc.) have suggested a combination of multiple sources of satellite data to improve the accuracy and resolution of rain estimates.

The tropical Rainfall Measuring Mission (TRMM, Simpson et al., 1988) satellite launched in 1997 has provided five years (January 1998 to December 2002) of precipitation rates distributed over regions between $(38°S$ and $38°N)$ for our tropical precipitation variation study. The non-sun-synchronous TRMM produces data from the first quantitative spaceborne rain radar, the precipitation radar (PR), combined with data from the passive TRMM microwave imager (TMI). TMI is the first passive microwave radiometer put into a non-sun-synchronous orbit, allowing us the first opportunity to investigate complete diurnal variation of precipitation with more direct information on the rain layer than previous infrared observations. The objective of this study is, by utilizing the advantages mentioned above, to provide a 5-year diurnal variation of precipitation with local time of day on its latitudinal/regional characteristics over the tropical oceans using the TMI. Since the "absorption-emission" passive microwave frequencies (less than 20GHz) do not work well for precipitation measurements over land, we use the PR data of TRMM, instead of the TMI data, to study the diurnal variation of precipitation over continents.

This study used five years of TRMM data, which is a longer record of data than the data used by Nesbitt and Zipser (2003). TRMM measures rain rate by looking at the distribution of hydrometeors within the cloud, offering a more direct measurement of the rain rate than the infrared observations. And this study covers the global Tropics.

The region of the earth between $30°S$ and $30°N$ is defined as the Tropics. According to the five year TRMM climatology from January 1998 to December 2002 (Fig. 1, $http://trmm.gsfc.nasa.gov/images/5-year\_TRMM\_climo.gif$), the observations over tropical regions are sorted regionally (Fig. 2) to study the diurnal cycle of rainfall over oceans, islands and continents with heavy total rain and light total rain. The diurnal variation of rainfall rates is computed by classifying the TRMM observations into bins based upon local hour and then performing an area average. To include more observations, in order to reduce the sampling error, the rain rate was binned in two hour spans in each region. The possibility of detecting the diurnal cycle in each region is studied by regression on diurnal sinusoids and tested by an F-test method. The regions with 95% or more confidence of detecting the diurnal cycle are determined and mapped for future studies.

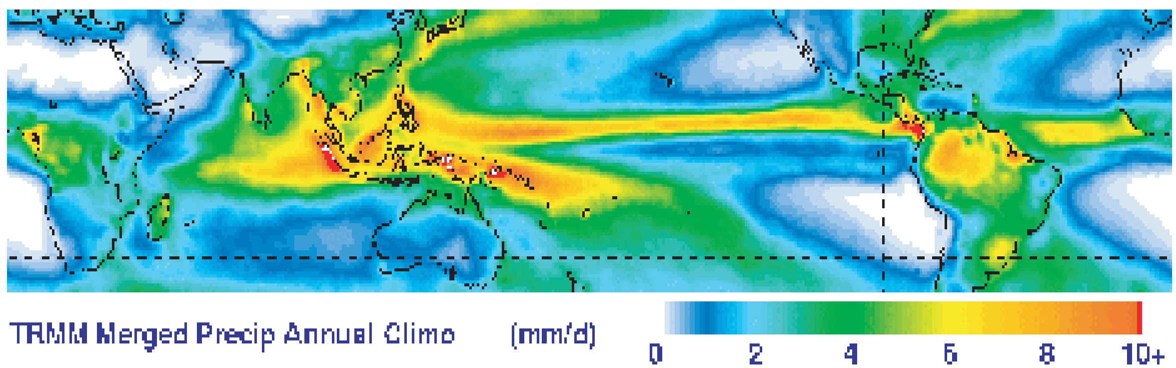

Fig. 1. The five year TRMM precipitation climatology from January, 1998 to December, 2002.

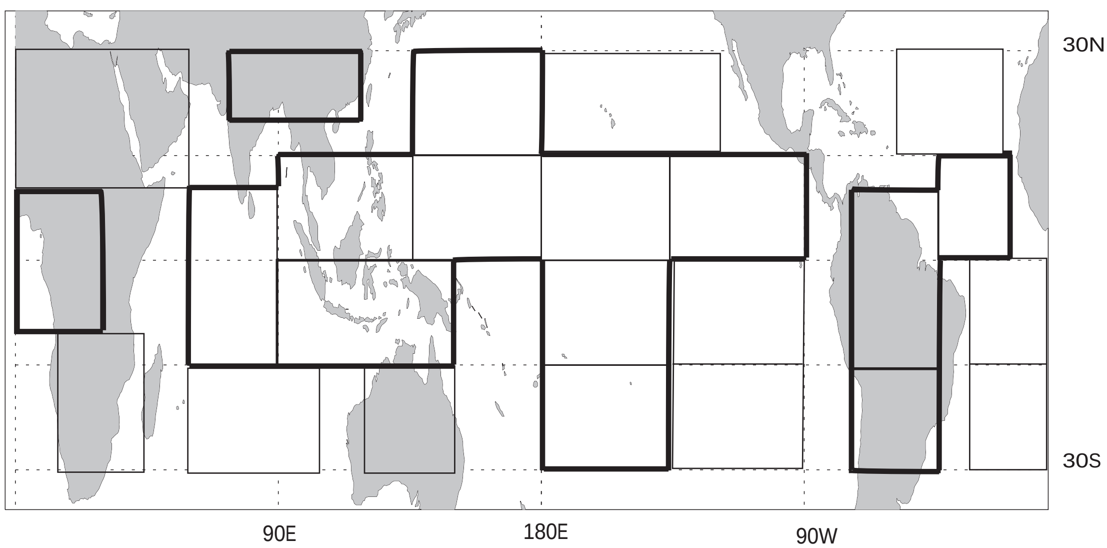

Fig. 2. Regions chosen for the study with heavy rain and with light rain. The regions enclosed with the heavy lines are the regions with heavy rain.

CHAPTER II

PREVIOUS STUDIES

The diurnal cycle of tropical rainfall and its variation in different regions remains an important question regarding global precipitation. A number of studies have focused on the diurnal variation of precipitation over Tropics in the past few years. Over land, many studies used surface rain accumulation (Dai et al. (1999); Gray and Jacobson (1977); Oki and Musiake (1994)) and surface weather reports (Dai (2001)). Because of the scarcity of rainfall data over the oceans, different parameters have been used as rainfall proxies to study the diurnal cycle. Surface weather reports (Dai (2001)), rain gauge data (Gray and Jacobson (1977)), satellite infrared data (Albright et al. (1985); Meisner and Arkin (1987)), outgoing longwave radiation data (Hartmann and Recker (1986)), passive microwave (Sharma et al. (1991)), radar data collected during GATE (McGarry and Reed (1978)), TRMM data (Nesbitt and Zipser (2003)), and various combined data (Imaoka and Spencer (2000); Sorooshian et al. (2002)) were used for the study. Most of these previous works agreed that the amplitude of the diurnal cycle of rainfall over the ocean is less than that over the continents. And most of the studies found a rainfall maximum over the oceans in the morning and a maximum in the afternoon over the continents. But regional differences in the rainfall diurnal cycle remain to be examined over both the ocean and the continent.

Gray and Jacobson (1977) found strong early morning maxima in deep convection in the Tropics using gauge data collected at small, isolated tropical islands. In many places, heavy rainfall was two or three times greater in the morning than in the late afternoon to evening. The more intense the convection and the stronger the association with organized weather systems, the more intense is the diurnal cycle. They attributed the difference to the day versus night variations in the tropospheric radiative cooling between convective weather systems and the surrounding cloud-free regions.

Dai (2001) used three-hourly present reports from about 15000 stations around the globe and from the Comprehensive Ocean-Atmosphere Data Set from 1975 to 1997 to analyze diurnal variations in the frequency of occurrence for various types of precipitation and thunderstorm. Significant diurnal variations with amplitudes exceeding 20% of the daily mean are found over much of the globe, especially over land areas and during summer.

Oki and Musiake (1994) used ground-based observations for more than 10 years both in Japan and Malaysia to investigate the diurnal cycle. They found the diurnal cycle of precipitation in Japan can be classified into three groups. The coastal regions have a precipitation peak in the morning. In the inland region both morning and afternoon peaks were found in June during the rainy season related to the southwest Asian monsoon. In the third group, no morning peak was observed in the stations but a comparatively strong evening peak occured. In the Malay Peninsula, the inland region has a pronounced peak of rainfall at 1600 LST. The morning peak of precipitation is observed during the southwest monsoon on the west coast and during the northeast monsoon season on the east coast.

Meisner and Arkin (1987) used three years of three-hourly infrared satellite data from the American geostationary satellites to determine the large-scale spatial and temporal variations in the diurnal cycle of tropical convective precipitation. They reported that the summertime diurnal cycle over tropical continents is much stronger than that over tropical oceans. They also found that diurnal cycle over ocean was evident only in the intertropical convergence zone (ITCZ) and South Pacific convergence zone (SPCZ) with near-noontime maximum.

Albright et al. (1985) used the fractional cold cloud coverage determined from the GEOS-West geostationary satellite to study diurnal cycle over the central tropical Pacific. In the ITCZ the cycle was found to have a distinct morning maximum and evening minimum. In other areas, such as the SPCZ, an afternoon maximum was observed.

Hartmann and Recker (1986) estimated the diurnal harmonic in longwave emission in the tropical belt relying on nine years of NOAA polar-orbiting satellite data. They found a consistent diurnal variation in longwave emission over the regions of intense oceanic convection as the ITCZ and SPCZ regions with a maximum in the morning (0600-1200 LST).

Sharma et al. (1991) examined the diurnal cycle using the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager derived data from July 1987 to June 1988. By averaging over a large area to reduce the random errors in the estimates, the average ratio of morning to afternoon rainfall was about 1.2.

McGarry and Reed (1978) used harmonic analysis to examine phase and normalized amplitude of the diurnal variation in the convective activity and precipitation with radar data collected during GATE. Afternoon maxima over the western Atlantic Ocean near African coast was found in their work.

Nesbitt and Zipser (2003) combined TRMM satellite measurements from the PR and TMI to yield a comprehensive 3-yr database of precipitation features throughout the global Tropics. They found rainfall over the oceans has a significant diurnal cycle (varying by 30%) that peaks in the early morning to predawn hours, with a minimum in the late afternoon and a sharp early afternoon peak in overland rainfall at 1500 local time.

Imaoka and Spencer (2000) used the TRMM TMI and SSM/I combined data to reveal diurnal variations of precipitations over the tropical oceans. In their study the diurnal variation over all the tropical oceans exhibits an amplitude of about $\pm 14\%$ of the mean, and it peaks approximately at 0400-0700 LST and has its minimum at 1900-2100 LST. Observed features of precipitation diurnal cycles have been used to examine physical processes in atmospheric models and to diagnose model deficiencies.

Sorooshian et al. (2002) used rainfall data retrieved from combined GOES and TRMM satellite to investigate the regional patterns of tropical rainfall diurnal cycles. Their result shows that only the far eastern Pacific Ocean region of ITCZ displays a strong diurnal signal in the boreal summer season. During DJF, Brazil, the northern two-thirds of South America, northern Australia, southwest of Borneo, New Guinea, and the Gulf of Carpentaria exhibit strong day-time convective rainfall over land. and then new convection develops strongly offshore.

Hendon and Woodberry (1993) used an index of deep convective activity and a global cloud index to analyze the diurnal cycle of tropical convection. They conclude that over the tropical oceans the diurnal cycle is weak. Nonetheless, oceanic convection exhibits a detectable systematic diurnal fluctuation with maximum intensity in the early morning.

Numerical model studies using cloud resolving models and general circulation models have also been useful attempting to detect the diurnal cycle and diagnose the causes of the diurnal cycle of convection over the Tropics. Liu and Moncrieff (1998) used idealized two-dimensional cloud-resolving numerical models to investigate the diurnal variability of deep tropical oceanic convection. A pronounced diurnal cycle was simulated for the highly organized convection in strong ambient shear with a maximum around predawn and a minimum in the late afternoon. A similar diurnal variability was obtained for the less organized non-squall cloud clusters without ambient shear characterized by more precipitation during the night and early morning and less precipitation in the afternoon and evening. Randall et al. (1991) used the University of California at Los Angeles/Colorado State University general circulation model (GCM) for their simulation study. They showed a maximum of precipitation in early morning over the ocean far from land.

While the models provide an attractive method for examining the physics of the diurnal cycle of precipitation, errors in model physics may lead to inappropriate conclusions (Randall et al. (1991), Young and Slingo (2001)). Observed features of precipitation diurnal cycles then were used to examine physical processes in atmospheric models and to diagnose model deficiencies. Randall et al. (1991) indicated that using diurnal features to test a GCM has the advantage of obtaining meaningful results with relatively short simulations. Dai et al. (1999) analyzed the diurnal patterns of precipitation simulated from the National Center for Atmospheric Research (NCAR) regional climate model (RegCM) and found substantial weaknesses in modeling diurnal patterns of precipitation using all three available cumulus convection schemes (Grell, Kuo, CCM3). They recommended that more attention be devoted to the simulation of the diurnal cycle of precipitation in model evaluation. Young and Slingo (2001) showed that analysis of diurnal cycle represents a powerful tool for identifying and correcting model deficiencies. In the recent work, Collier and Bowman (2004) compared hourly-averaged precipitation rates from an ensemble of CCM3 simulation with observations from the TRMM satellite from January, 1998 to August, 2001. In the work they found the model's diurnal cycle is too strong over major land massed and is too weak over many oceans. They also found the model-satellite phase differences tend to be homogenous. The peak in the model's diurnal harmonic consistently precedes that of the observations nearlyererywhere. Since the model's precipitation diurnal cycle phase and amplitude biases likely have effects on its hydrologic cycle and its surface and atmospheric energy budgets, they suggested that the causes for the model's biases need to be investigated.

CHAPTER III

DATA AND INSTRUMENT

A. A Brief Mission Overview of TRMM

TRMM is a joint mission between the National Aeronautical and Space Administration (NASA) of the United States and the National Space Development Agency of Japan. The satellite was launched on November 27th 1997 from Japan's Tanegashima Space Center aboard a Model H-II launch vehicle. The primary rainfall instruments on TRMM are the TRMM Microwave Imager (TMI), the precipitation radar (PR), and the Visible and Infrared Scanner (VIRS). In addition, the TRMM satellite carries two related Earth Observing System instruments: the Cloud and the Earth's Radiant Energy System and the Lightning Imaging Sensor. The TRMM satellite has been put in a non-sun-synchronous orbit with a low inclination angle of $35°$ to the equatorial plane and at a low altitude of 350 km. The low altitude ensures that the TRMM instruments are able to resolve the upwelling radiation over small areas. This resolution also permits a more accurate retrieval of the precipitation over an area while additionally allowing more spatial resolution of the field. Finally, the low altitude helps to increase the return signal from the PR. These features ensure that within a given period of time, a given area over the Tropics is observed by TRMM during different local hours. The frequency and coverage of observations over an area depends upon the latitude and size of averaging area. These orbital characteristics of TRMM observations may prove to be valuable for the study of the diurnal variation of rainfall over the global Tropics.

For this study, five years' observations from TMI have been used for study of the diurnal variation over ocean and islands. TMI is a nine-channel passive microwave sensor designed to provide quantitative rainfall information over a wide swath (≈ 780 km) under the TRMM satellite. It measures radiances that are the end product of the integrated effect of electromagnetic absorption-emission and scattering through the precipitating cloud along the sensor view path. The TMI is based on the design of the highly successful SSM/I, which has been flying continuously on Defense Meteorological Satellites since 1987. TMI measures the intensity of upwelling radiation at five separate frequencies: 10.7, 19.4, 21.3, 37, and 85.5 GHz. These frequencies are similar to those of SSM/I, except that TMI has the additional 10.7 GHz channel, which improved the sensitivity of the TMI algorithm to heavier rain rates. TMI also has a higher spatial resolution than the SSM/I due to its lower orbit (Kummerow et al. (1998)).

Since the absorption-emission passive microwave frequencies (less than 20GHz) do not work well for precipitation measurements over land, we use the PR observation of TRMM, instead of the TMI observation, to study the diurnal variation or precipitation over land. Unlike the TMI, the PR is an active microwave sensor. The PR is the first rain radar in space. It is a system that operates at 13.8 GHz (2.17 cm wavelength) as a 128 element active phased antenna. When the PR is in observation mode it scans in the cross-track direction over $\pm 17^{\circ}$, which is equivalent to a 215 km swath width array at the ground. The PR also provides the three-dimensional structure of rainfall, particularly of the vertical distribution and improves the overall TRMM precipitation retrieval accuracy by combined use of active PR and passive TMI and VIRS sensor data (Kummerow et al. (1998)).

The real-time processing and postprocessing of the TRMM science data are performed by the TRMM Science Data and Information System (TSDIS). It produces a number of rainfall products depending upon the combination of instruments and spatial and temporal scales. For this study, we have the 3G68 products. It contains gridded values of the total pixels (footprints), rainy pixels, mean rain rate, and percentage of convective rain from the TMI algorithm 3G68 and the PR algorithm 3G68.

Satellite rainfall estimates have substantial random and possibly systematic errors. It is important to validate satellite retrievals against other types of precipitation measurements, including ground-based radars and traditional rain gauges. The validation dataset was principally based on radar measurements but also included some rain gauge measurements. Bias accuracy refers to the difference between sample mean satellite measurements and sample mean validation measurements.

B. TRMM Data

The rainfall data used in this study is from the TRMM 3G68 combined rain rate product, which was obtained from the TRMM Science Data and Information System (TSDIS). Data are provided in $0.5° \times 0.5°$ latitude-longitude grid boxes. The observation time for each grid box is recorded to the nearest minute. The data include retrievals from three different algorithms: the TMI, the PR, and the COMB (the combination of TMI and PR instruments). In addition to the mean rain rate for the three algorithms, the 3G68 data set includes the numbers of pixels observed by TMI, PR and COMB, the number of rainy pixels TMI, PR and COMB observed, and the percentage of convective rain. For The 3G68 data is an hourly gridded product, which includes 24 hourly grids in a single daily file, it can be used for diurnal study. Fig. 3 shows the the total number of pixels observed in each two hour bin in the selected regions. The flat histogram shows that the number of pixels observed in each two hour interval are approximately the same. This indicates that there is no diurnal bias in the sampling. Generally, the TRMM satellite is able to observe a given location in the Tropics about once per day, at different times each day, with a cycle of 42 days, the cycle of its orbital precession. Therefore, for the five-year period considered in this study (January, 1998-December 2002), there are about 150 observations in each of the regions we choose to study in every two hour span.

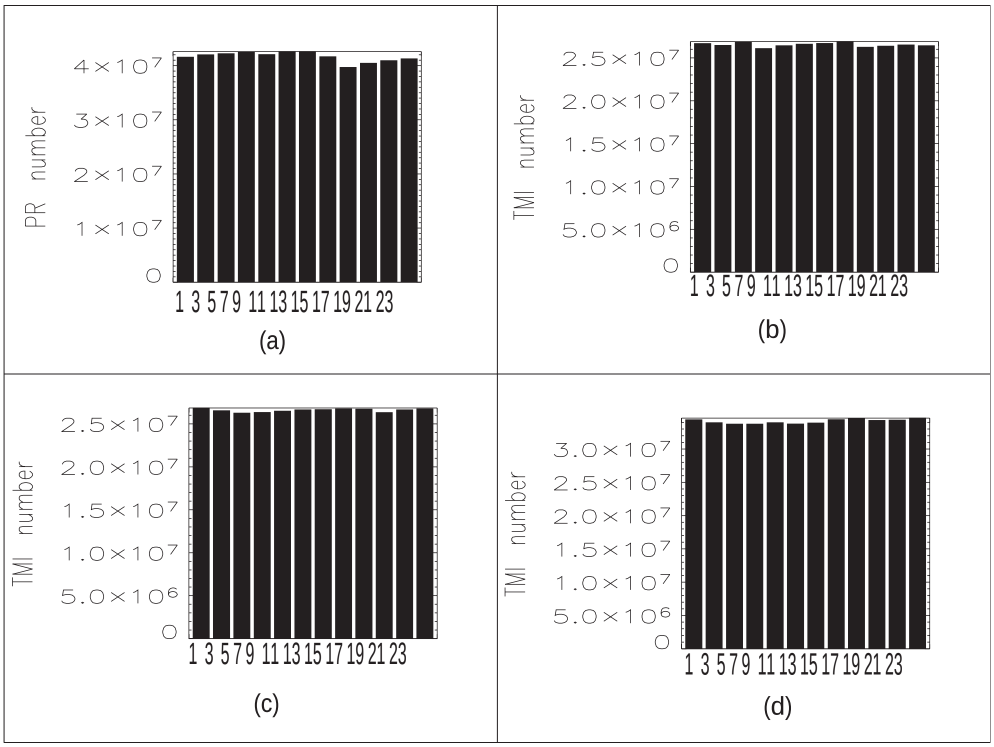

Fig. 3. The total pixel number observed in selected regions with the local time of the day in TRMM data. The histogram in each box represents the exact observation in that region. The times in each histogram represent the mid-point time of each time interval.(a) represents the of 0-60E,10-30N; (b) represents the region of 135-180E,0-15N; (c) represents the region of 135-180W,0-15S; (d) represents the region of 135-180W,15-30S.

CHAPTER IV

METHODS

A. Method to Detect Diurnal Cycle

Measurements from low-earth orbiting satellites produce different types of problems due to the discontinuous nature of the sampling process from such observing systems. Several studies have addressed the question of whether TRMM can provide enough observations at different local times to delineate the changes in average rainfall with time of day. Salby and Callaghan (1997), in a study of how different satellite orbits interact with diurnal sampling, emphasized that climatological studies using satellite data must be done with appropriate averaging of the data in order to minimize biases in the average due to varying sample sizes at different times of the day. Bell and Reid (1993) concluded before the launch of TRMM satellite that the TMI would be able to determine the first harmonic of the diurnal cycle in a $5^\circ \times 5^\circ$ grid box from 1 month of data to an accuracy of about 25 percent of the mean rain rate. This assumed rain with statistics like those of the rain data taken in the tropical Atlantic during GATE.

A diurnal cycle, if it exists, would be represented by a change in the probability distribution of rain with the time of day. This study will concentrate on determining a single aspect of this change: the variation of mean rain rate averaged in a certain area with the local time of day. The method we used here to study the diurnal cycle and the sampling error was discussed by Bell and Reid (1993).

The estimates for the area-averaged rainfall were defined as

$$R_A(t_m) = \frac{1}{|A|}\int_A R(X, t_m)dX, \tag{4.1}$$

within a given area A provided at observation times $t_m (m = 0, 1, \ldots)$. These observation times t_m will be separated by intervals ranging from roughly 2 to 24 hours, depending on the physical location of the area observed.

To see if the mean rain rate changes with the time of day the averages of the observations are found for the different intervals over the course of the day. We break the day up into time intervals of equal duration (each of 2 hours length in this study), using t to denote the time interval whose midpoint is at time t_m. In our work, local time $1, 3, 5, 7, 9, 11, 13, 15, 17, 19, 21, 23$ represent the local time intervals $0-2, 2-4, 4-6, 6-8, 8-10, 10-12, 12-14, 14-16, 16-18, 18-20, 20-22, 22-24$ respectively. Then the interval averages can be written formally as

$$\overline{R}(t) = \frac{1}{n_t} \sum_{t_m \in t} R_A(t_m), \tag{4.2}$$

where the notation $t_m \in t$ denotes observations that fall within the interval t and n_t is their number,

$$n_t = \sum_{t_m \in t} 1. \tag{4.3}$$

If there is a diurnal cycle, the climatic mean rainfall $E\overline{R}(t)$ will vary periodically during the course of the day. The expectation here is a hypothetical average over a large number of days but taken at the same time of day, with all other “climatologically influences” held fixed. The diurnal cycle in $r(t) = E\overline{R}(t)$ can be expressed by a Fourier series,

$$r(t) = r_0 + r_1 \cos(\omega t - \phi_1) + r_2 \cos(2\omega t - \phi_2) + \dots, \tag{4.4}$$

where the first term r_0 represents the daily mean rainfall.

$$\omega = 2\pi(24h)^{-1} \tag{4.5}$$

is the diurnal frequency, r_1 and ϕ_1 are amplitude and phase for simple sinusoidal variation of the mean. The number of harmonics needed to describe the variation of $r(t)$ is limited by the number of intervals into which the day has been broken up. Harmonics higher than the first few will be neglected in what follows.

We use the least-squares fit of $r(t)$ to $R_A(t_m)$ to determine the parameters of the expansion of Fourier expression (2.4). That is, the parameters can be obtained by minimizing

$$D^2 = \sum_{m=0}^{N} [R_A(t_m) - r(t_m)]^2, \tag{4.6}$$

where $N+1$ is the number of satellite observations. This approximation becomes exact as the number of observations increases.

Since we are trying here to obtain an idea of the order of magnitude of the statistical problem posed by the intermittent sampling of the satellite, we shall simplify it by making that the satellite samples are at equally spaced intervals

$$t_m = m\triangle t, \quad m = 0, \ldots, 11. \tag{4.7}$$

Here $\triangle t = 2$.

The harmonic analysis of the diurnal cycle is cast in a form amenable to least squares with linear coefficients by writing it as

$$r(t) \approx r_0 + c\cos\omega t + s\sin\omega t, \tag{4.8}$$

with $c = r_1\cos\omega\phi_1$ and $s = r_1\sin\omega\phi_1$. The higher harmonics in (4.4) are neglected, but they can be treated as a straightforward generalization of the approach followed. It can also be shown that if all hours of the day are equally sampled, estimates of the amplitudes of the diurnal harmonics can be made independently of each other because the Fourier modes are orthogonal. In our study the rain rates are sampled equally every 2 hours, so the mean r_0 can be estimated independently of the first harmonic from a simple average of the data as

$$\hat{r_0} = \frac{1}{N+1}\sum_{m=0}^{N} R_A(t_m). \tag{4.9}$$

The least-squares estimates: $\hat{s}$ and $\hat{c}$ are

$$\hat{s} = D^{-1}(A_{cc}S - A_{sc}C), \tag{4.10}$$

$$\hat{c} = D^{-1}(-A_{sc}S + A_{ss}C), \tag{4.11}$$

where

$$D = A_{cc}A_{ss} - A_{sc}^2, \tag{4.12}$$

and

$$A_{ss} = \sum \sin^2 \omega t_m, \tag{4.13}$$

$$A_{cc} = \sum \cos^2 \omega t_m, \tag{4.14}$$

$$A_{sc} = \sum \sin \omega t_m \cos \omega t_m. \tag{4.15}$$

S and C are the sine and cosine components of the rainfall data,

$$S = \sum \sin(\omega t_m)[R_m(t_m) - \hat{r}_0], \tag{4.16}$$

$$C = \sum \cos(\omega t_m)[R_m(t_m) - \hat{r}_0], \tag{4.17}$$

The estimated amplitude is $\hat{r_1}^2 = \hat{s}^2 + \hat{c}^2$ and the estimated phase is $\hat{\phi}_1 = \tan^{-1}(\hat{s}/\hat{c})$. The usual distribution theory for least-squares does not apply here because the observations $R_A(t_m)$ are correlated. Here S and C are sums of data extending over times much longer than the correlation time of rain, and it is assumed that they contain enough effectively independent observations to be approximately normally distributed, which was satisfied in our study. It is also assumed that the time series of rain rates is sufficiently long that the variances of $\hat{s}^2$ and $\hat{c}^2$ are approximately the same and that the correlation of $\hat{s}^2$ and $\hat{c}^2$ may be neglected.

The climatic mean rainfall $E\overline{R}(t)$ will vary periodically during the course of the day if there is a diurnal cycle. Whether the diurnal cycle can be detected or not can be verified by whether the rain rate with the time of the day can be expressed as (4.8). We use the F-test to show the confidence level the rain rate with the time of day can be expressed as (4.8). The locations with diurnal cycle detected with 95% confidence were then mapped.

B. F-test

The periodic expression of precipitation rates $r(t)$ in (4.8) is a multiple linear regression fit to the climatological-mean and regional-mean hourly precipitation rates $R(t)$. The precipitation rates here can be expressed with the regression expression $r(t)$ as:

$$R(t) = r(t) + \epsilon(t), \tag{4.18}$$

$\epsilon(t)$ is a residual such that $E[\epsilon(t)] = 0$, $E[\epsilon(t)^2] = \sigma_0^2$, and $E[\epsilon(t)\epsilon(t^{'})] = 0, t \neq t^{'}$.

If there is no diurnal cycle, then under these simplifying assumptions, $\hat{s}$ and $\hat{c}$ are approximately independent variables with zero mean. That's there is no linear relationship between the harmonic term and the mean precipitation rates when there is no diurnal cycle. F static test is used for the test for significance of regression. The procedure is often thought of as an overall test of regression model adequacy. The appropriate hypotheses are
H_0: $s = 0, c = 0,$
H_1: at least s or $c \neq 0,$
Rejection of this null hypothesis implies that at least one of the regressors contributes significantly to the regression model.

The test to verify the least-squares estimates of s and c satisfying the following condition:

$$(\hat{s} - s)^2 + (\hat{c} - c)^2 \leq \frac{4\sigma^2}{N} F_{2,N-3}(\alpha), \tag{4.19}$$

Where σ^2 is the least-squares estimate of σ_0^2 and the sample number N is equal 12 in this study. $F_{2,N-3}$ is the $(1-\alpha)$ cutoff value of the F distribution function with 2 (two parameters, s and c, to be estimated) and 9 (12(samples)-3(coefficients)) degrees of freedom. Then $(1-\alpha)\%$ represents the confidence level the null hypothesis can be rejected. It should be noted here that F test assumes that the mean rain rates we fit to the linear regression are independent and that the resulting residuals of the fit are normally distributed.

Fig. 4 shows the confidence level in each region the null hypothesis can be rejected, that's, the confidence level to detect the diurnal cycle in each region. The regions with more than 95% or more confidence level are shown and numbered in Fig. 5.

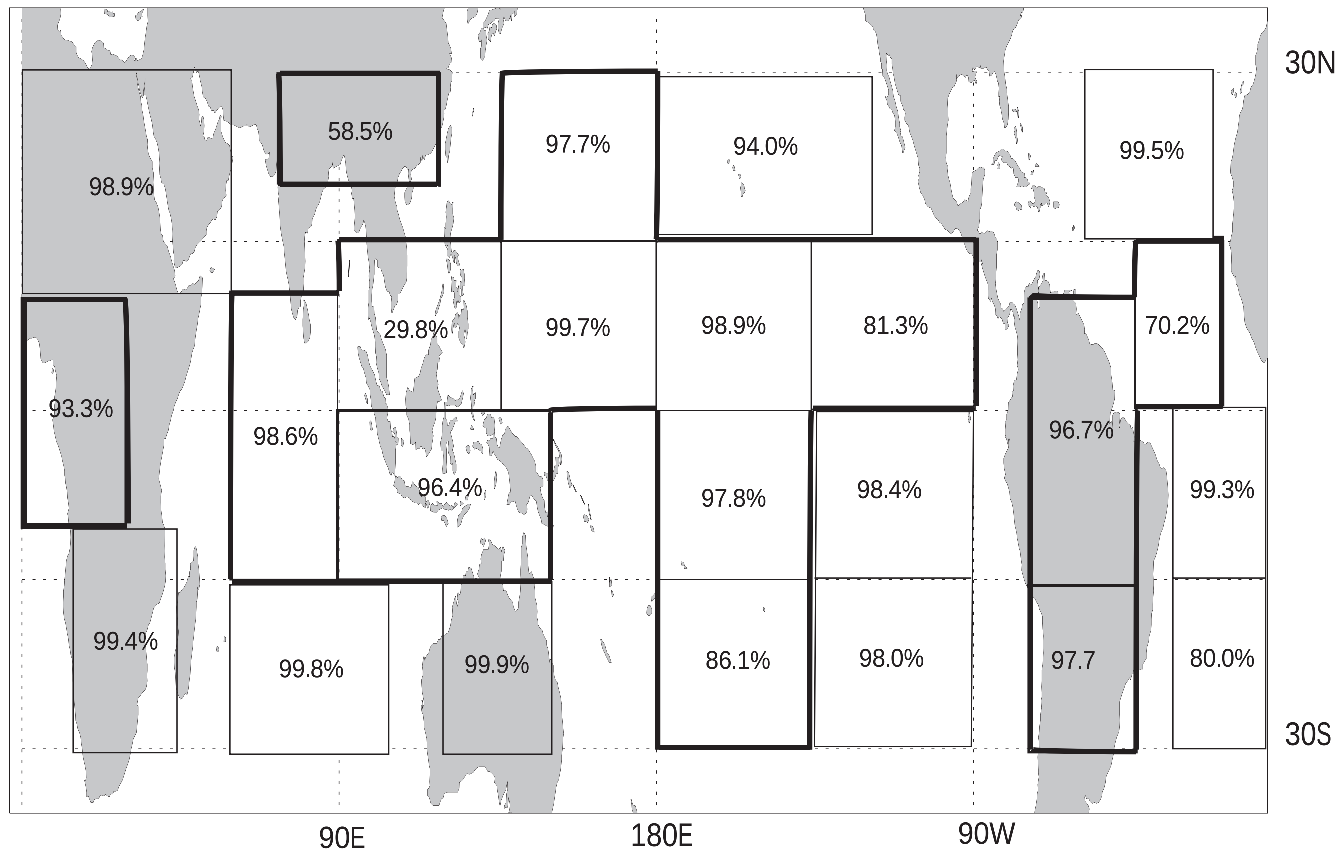

Fig. 4. The confidence to detect the diurnal cycle using F-test in each region. The confidence in each box represents the confidence in the specific region. The regions enclosed with the heavy lines are the regions with heavy rain.

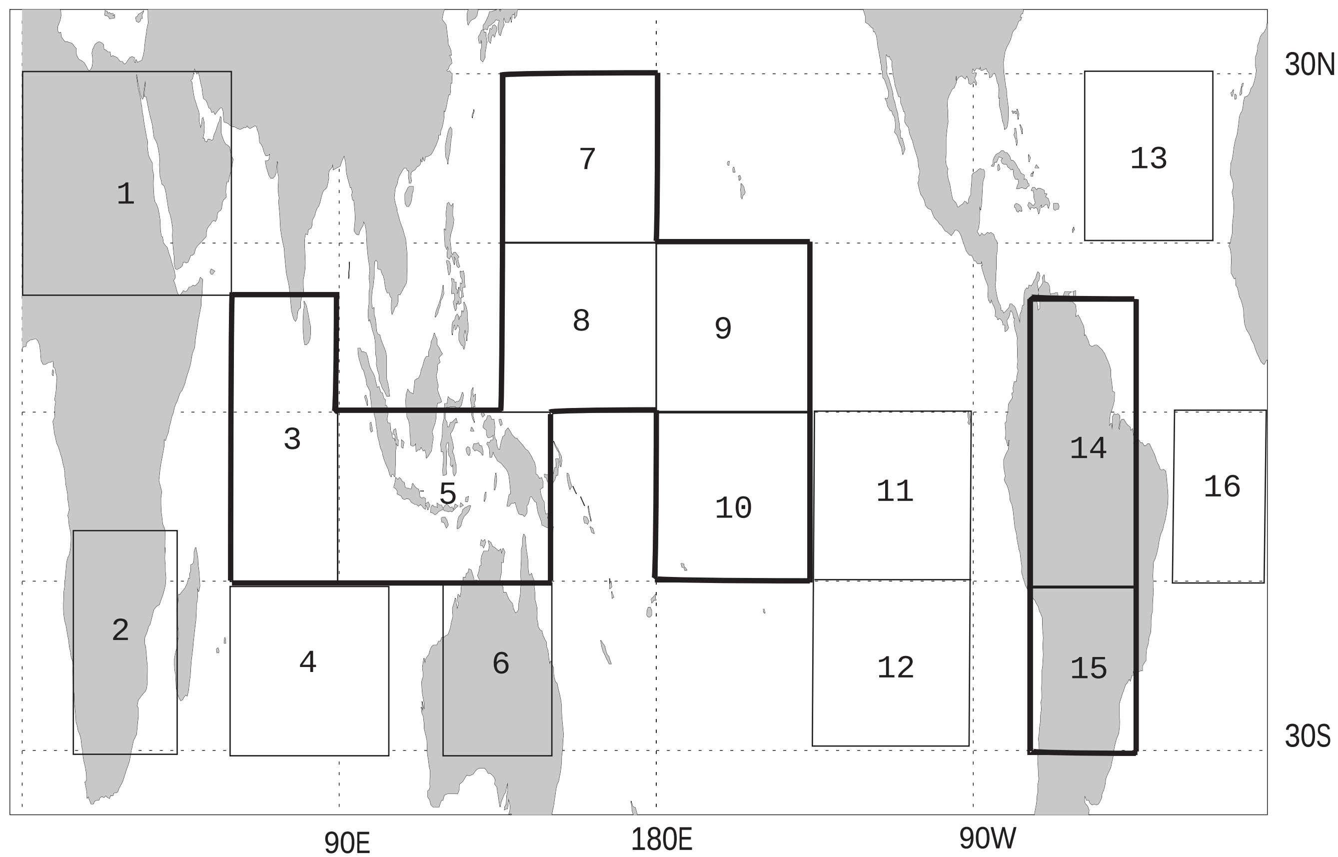

Fig. 5. The regions with more than 95% confidence to detect diurnal cycle in Fig. 4 kept for further statistical study.

CHAPTER V

RESULT

Chang et al. (1995) showed that the areas where the total rain is small, such as the Southern Pacific and the Atlantic Ocean dry zone are the areas, in which the evening rain rate is heavier than the morning rain rate. In order to study the influence of rain rate on the rainfall diurnal cycle, the diurnal variation was studied in different regions with heavy total rain and light total rain respectively. Based on the five year rainfall climatology, various regions were selected whose characteristics were nearly homogenous and that represent different climatic regimes.

Aware of the sampling constraint, in this paper the diurnal cycle was examined from relatively large area composites of the 5-year record of TRMM data with 2-hour temporal resolution and no less than $30^\circ \times 15^\circ$ spatial resolution. Investigation of the diurnal cycle on smaller spatial and temporal scales awaits the collection of more data. According to the result of the F-test in the previous section (Fig. 4 and Fig. 5), this study focuses on the areas, where the diurnal cycle can be detected with 95% or more confidence.

Variability of rainfall also occurs on longer timescales other than diurnally. Nondiurnal rainfall enhancements from passing easterly wave disturbances, midlatitude shortwave troughs, and other phenomena like the Madden-Julian oscillation are aliased in our long-term averages (Nesbitt and Zipser (2003)). As Nesbitt and Zipser did, no attempts to remove these variations caused by these phenomena are made in our results, nor are the phenomena believed to significantly alter our conclusions.

A. Oceanic Regions

Fig. 6 and Fig. 7 show the histogram of hourly rain rates in each region. In the figure the time represents the local time in each region. The rain rate is larger in the morning than in

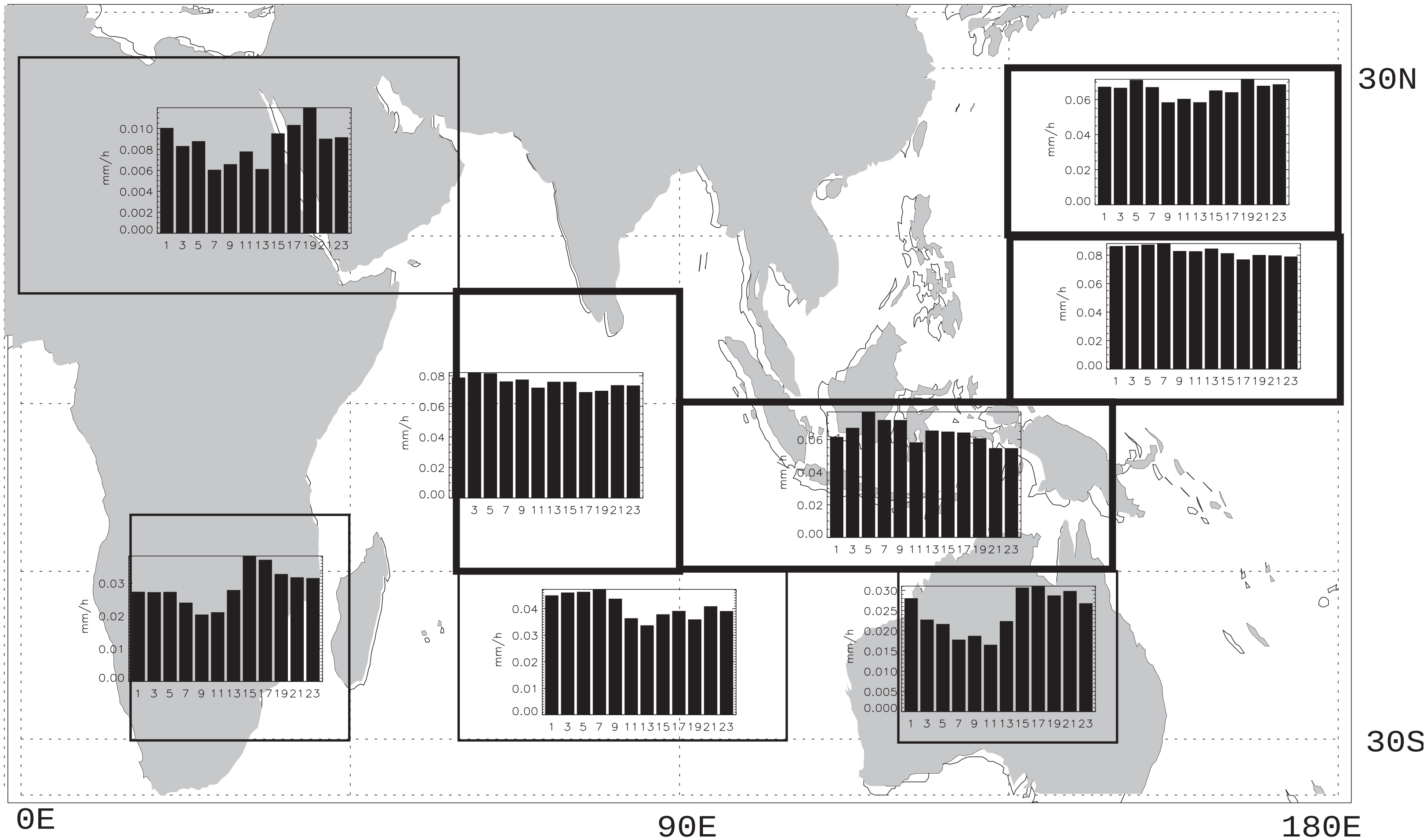

Fig. 6. The rain rate with the local time of the day in East Tropics. The regions over oceans and islands use TMI data and the region over continents use PR data.The times in the figure represent the mid-point in each time interval. The regions inside enclosed with heavy lines are regions with heavy rain.

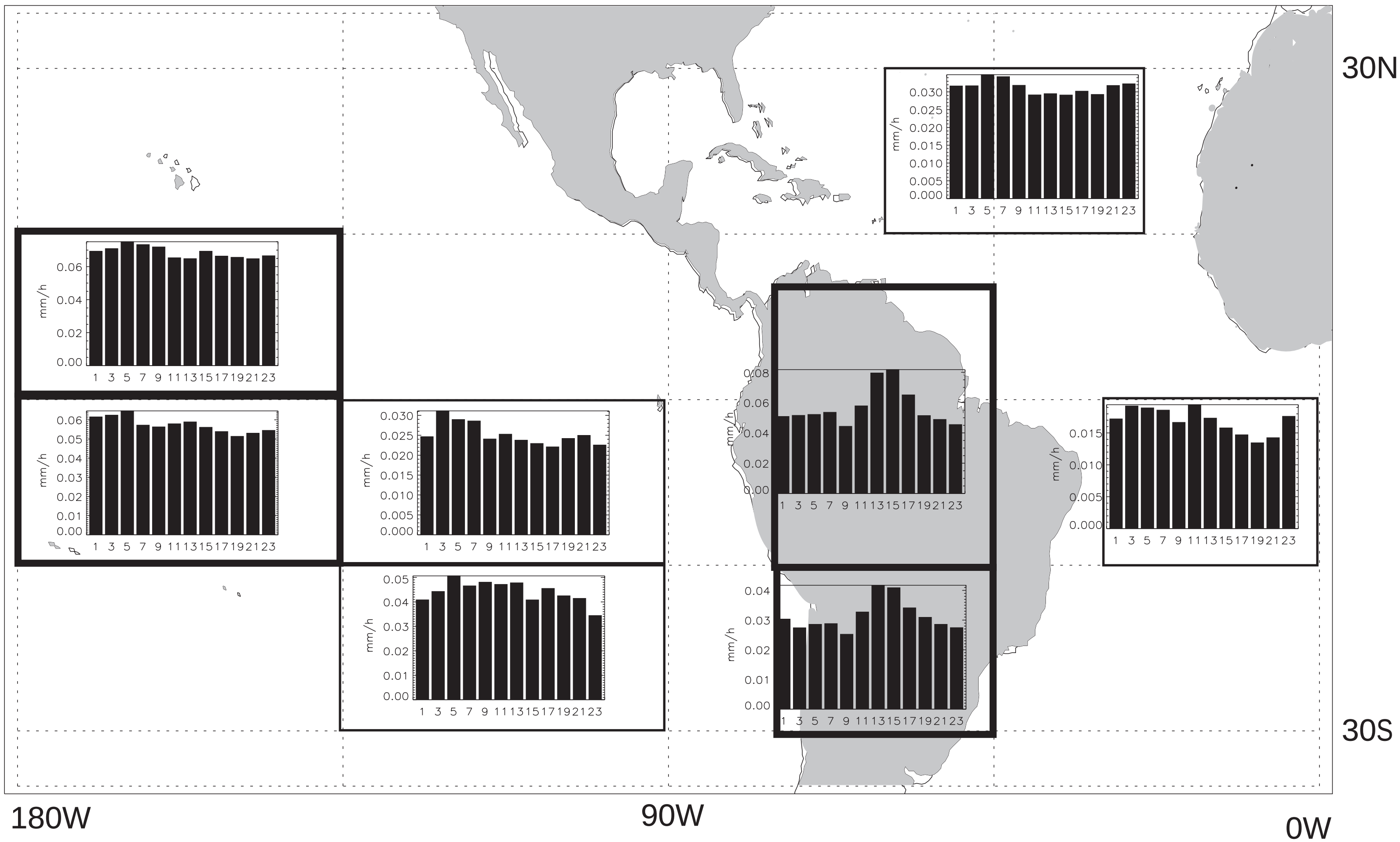

Fig. 7. The same as Fig.6, but the rain rate with the local time of the day in West Tropics

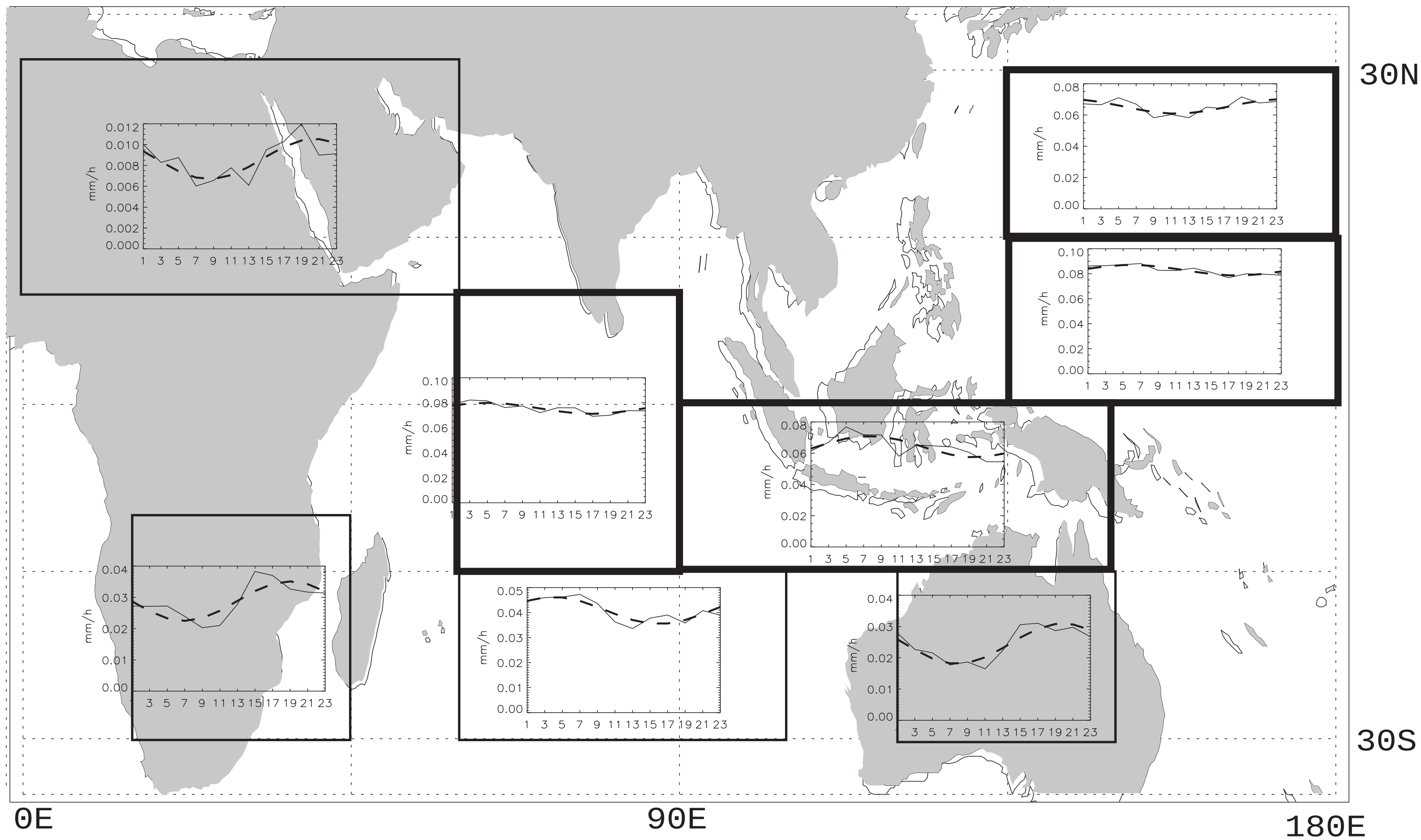

Fig. 8. The same as Fig.6, but the linear regression fit of the rain rates also plotted over the rain rate. The solid line presents the real rain rate. The dash line represents the linear regression.

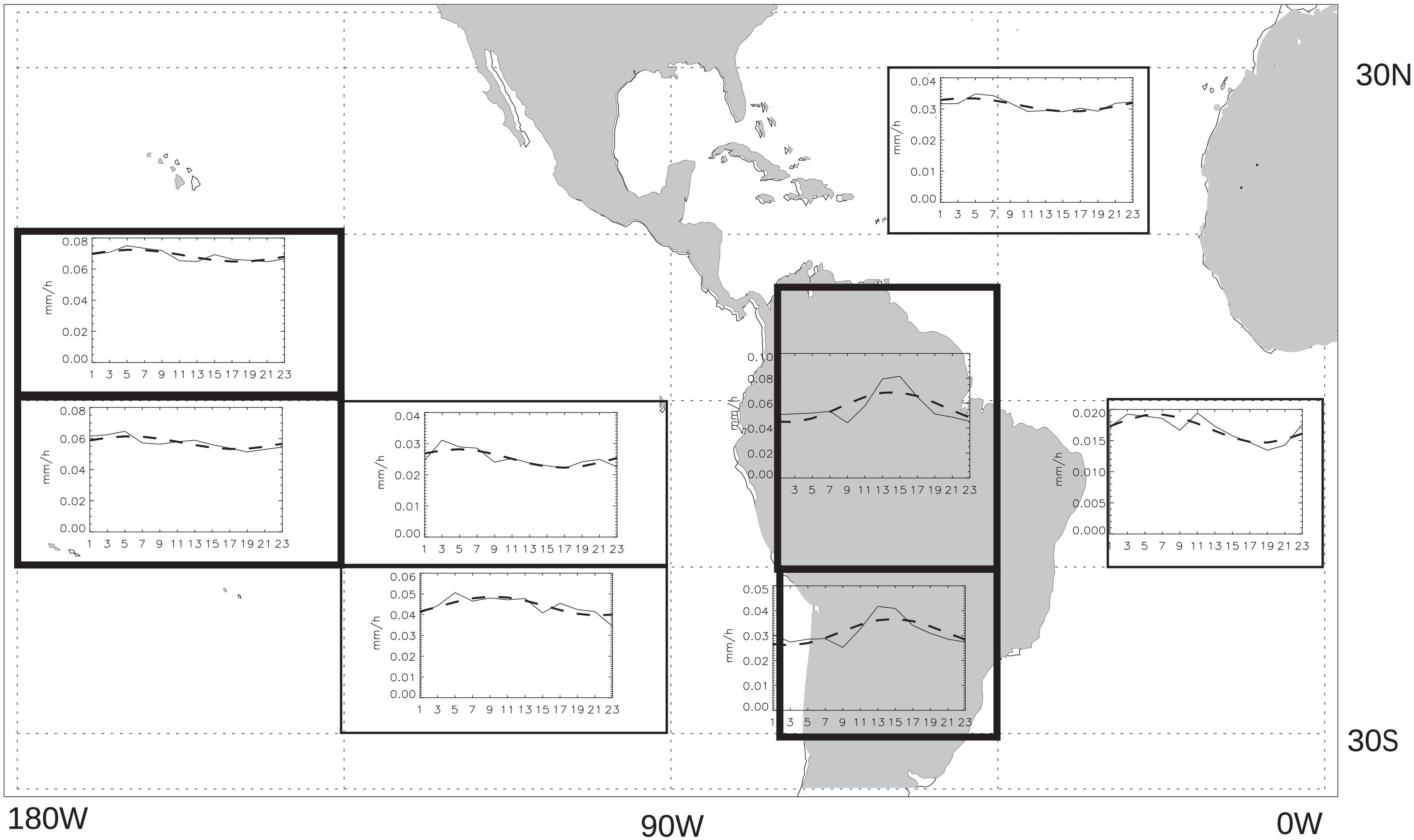

Fig. 9. The same as Fig.7, but the linear regression fit of the rain rates also plotted over the rain rate. The solid line presents the real rain rate. The dash line represents the linear regression.

the afternoon in most of the ocean regions. Except in the high latitudes of South Pacific Ocean, the diurnal cycle peaks at about 0930 LST was found and in the high latitudes of East Pacific Ocean, the diurnal cycle was found to peak at about 2330 LST. The sinusoidal plot of the rain rate in Fig. 8 and Fig. 9 also clearly shows the diurnal with a maximum in the early morning and a minimum in the later afternoon, as shown in the histogram figure, except for the high latitudes of the South Pacific Ocean and the high latitudes of East Pacific Ocean. This result does not indicate a relation between the diurnal cycle and the rain rate in the ocean region as suggested in Chang et al. (1995). Studying the peak of precipitation features with and without Mesoscale Convective Systems (MCS) over the ocean, Nesbitt and Zipser (2003) concluded the diurnal cycle of rainfall over the ocean is almost completely due to an increase of the number of systems, not the rain rates contained in them. Dai (2001) obtained similar patterns derived from global surface weather reports. The results in the present study confirm this conclusion.

Fig. 10 shows the exact time when the maximum rain rate occurred as indicated on a 24-hour clock in each region. This result agrees with most previous work, except in some regions. In previous works, besides Chang et al. (1995) found afternoon maxima in the dry ocean zone, afternoon maxima (Albright et al. (1985)) or near noontime maxima (Meisner and Arkin (1987)) in the SPCZ region were also found. McGarry and Reed (1978)) showed afternoon maxima over the western Atlantic Ocean near the African coast. Meisner and Arkin (1987) showed that the diurnal cycle over ocean was evident only in the ITCZ, which does not agree with this paper either.

Fig. 11 shows the ratio of diurnal variation to the mean rain rate. This ratio is much lower for the ocean regions than those of the land. In general, the ratio of variation is a little higher in the dry regions than in the regions with heavy rain. Our observed amplitude variation is not as large as in the results of Gray and Jacobson (1977) who showed that heavy rainfall was two or three times greater in the morning than in the late afternoon

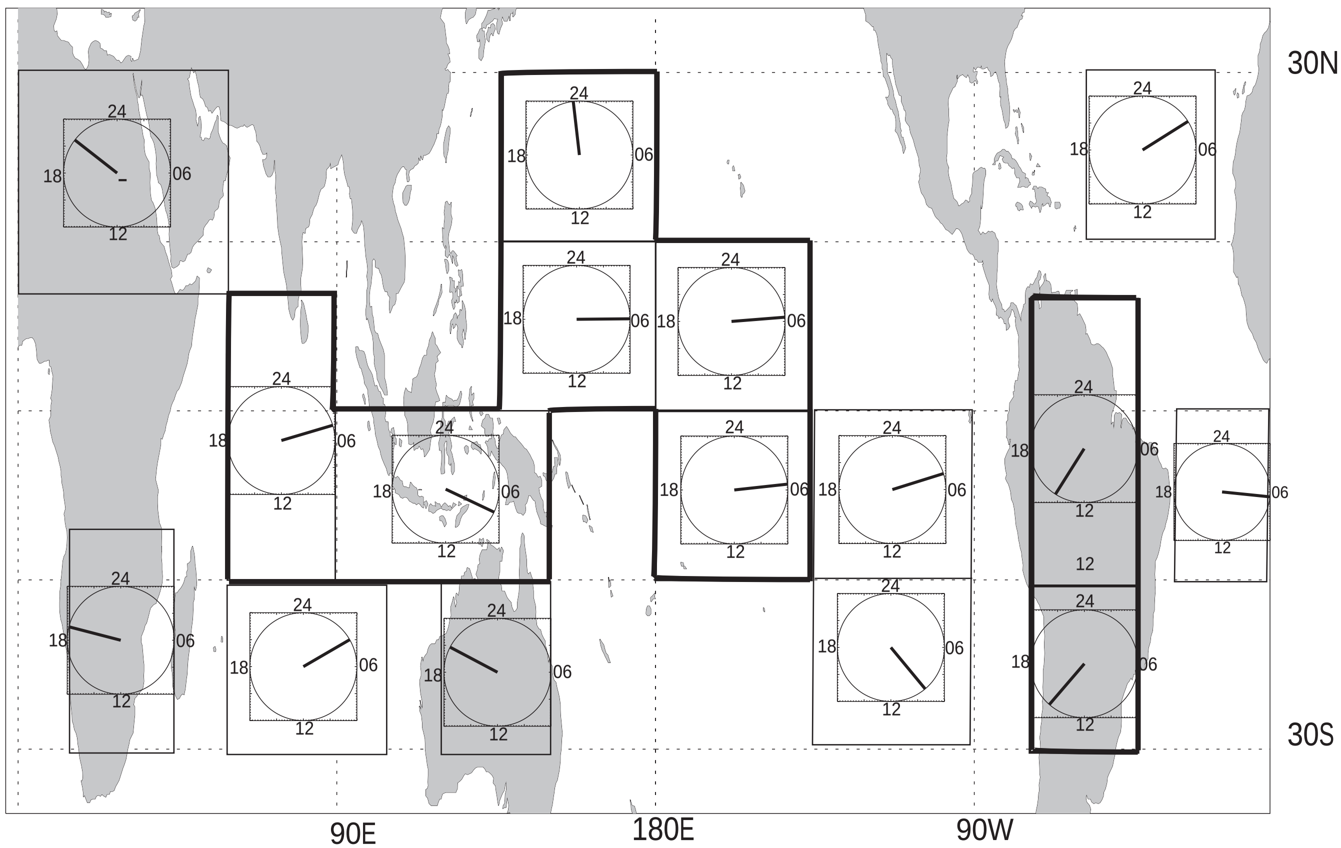

Fig. 10. The local time when the maximum rain rate happens in each region. The regions enclosed with heavy lines are regions with heavy rain.

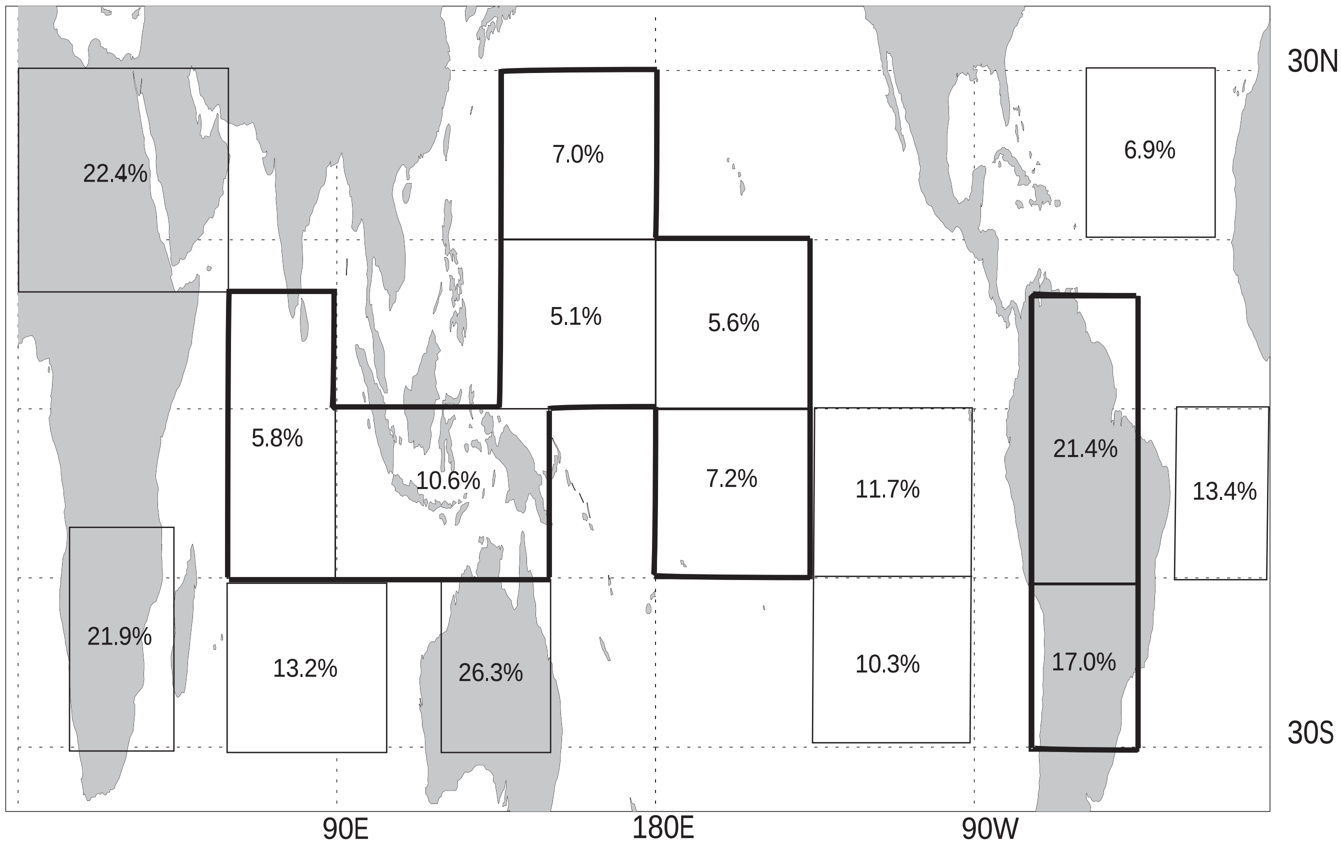

Fig. 11. The ratio of precipitation variation to the mean rain rate in each region. The regions enclosed with heavy lines are the regions with heavy rain.

to evening in many places. But our results agree with many other studies. Sharma et al. (1991) showed the average ratio of morning to afternoon rainfall was about 1.2 by averaging over a large area to reduce the random errors. Chang et al. (1995) showed the ratio of morning to evening rain estimates is about 1.22 between $50°S$ and $50°N$. Imaoka and Spencer (2000) found that the diurnal variation over all the tropical oceans exhibits an amplitude of about 14% of the mean between $30°S$ and $30°N$. In the work of Nesbitt and Zipser (2003), the diurnal cycle of rainfall has a variation of 30%, and diurnal variations with amplitudes exceeding 20% of the daily mean over much of the globe ocean in Dai (2001). Both of these last results are a little higher than this paper's result.

In our study, both of the two locations, where the diurnal maximum does not happen in the early morning, are in high latitudes. Imaoka and Spencer (2000) also showed that the ratio of, as well as the difference between morning and evening rainfall tends to decrease as latitude increases, as is seen in the combined result of TMI and SSM/I. Because of the limitation of the regions chosen for our study, we can not conclude that there is a strong relation relation between the diurnal cycle, as well as the amplitude of diurnal cycle, and latitude. But since the daily passage of the sun controls the diurnal variation of rainfall, and the solar radiation reaching earth varies with latitude, it is reasonable to expect a relation between diurnal cycle and latitude.

B. Continental Regions

Over continents, a significant afternoon maximum in precipitation was seen from Fig. 6 to Fig. 9. The amplitude of diurnal variation over continents is larger than over the oceans. Unlike over the oceans, the diurnal cycle over continents with heavy total rain and with small total rain shows an evident difference. A maximum at 1400 LST - 1500 LST was found over land with heavy total rain, while the maximum happens at 1900 LST - 2100

LST over land with small total rain. This result agrees with the work of Nesbitt and Zipser (2003) as well. Studying the number of variations of precipitation features with and without ice scattering over land and mean conditional rain rate, they observed that increased numbers of systems containing higher rain rates control the diurnal rainfall cycle for over-land precipitation features with and without ice scattering. In their work, they found that there is a sharp early afternoon peak at 1500 LST in over-land rainfall within a given latitude band. Dai (2001) obtained a similar global result. A relative minimum of precipitation of total rain in the morning around 0900 LST was found in Nesbitt and Zipser (2003). In this paper a relative minimum of precipitation was also found in the bin of 0800 LST - 1000 LST in the heavy rain region in Fig. 6. It also agrees with their work. Sorooshian et al. (2002) found the convection over the Amazon maximizing from 1600 to 1800 linked to afternoon heating, leading to a precipitation maximum is a little later compared with our work.

Unlike the ocean, the ratio of variation to the mean rain rate over continents with heavy total rain and with small total rain does not show much difference in Fig. 11. In Nesbitt and Zipser (2003), the precipitation over land has a magnitude variation of 125%, which is larger than our result.

C. Island Regions

The Maritime Continent region in Southeast Asia represents a unique geographic region that contains large islands, narrow peninsulas, and complex terrain surrounded by large oceanic and continental areas. In our data, only the south part of the Maritime Continent showed a statistically significant feature. In this work, the peak rainfall over islands is at about 0800 LST, which is a little later than the time the ocean maximum happens and is much earlier than that time for land. The ratio of diurnal variation over islands is also more similar to that of ocean than that of continents. Since the region chosen to study island diurnal cycle is with heavy rain, then the ratio of variation of islands is larger than that of ocean with heavy and less than that of land with heavy of rain.

Gray and Jacobson (1977) found that some tropical islands exhibit both morning and afternoon maxima, and attributed this to the combination of maritime and continental forcings. Sorooshian et al. (2002) found the occurrence of convection strongly centered on 1500 during the midafternoon over Malaysia. Oki and Musiake (1994) found the diurnal cycle of precipitation in Japan can be classified into three groups. The coastal regions have precipitation peak in the morning. In the inland region both morning and afternoon peaks were found in June, when it is a rainy season related to the southwest Asian monsoon. In the third group, no morning peak was observed in the stations but a comparatively strong evening peak. In the Malay Peninsula, the inland region has a pronounced peak of rainfall at 1600 LST. The morning peak of precipitation is observed during the southwest monsoon on the west coast and during the northeast monsoon season on the east coast. Combined these works with the result in this paper, it suggests that in an extension of island alone the precipitation shows a afternoon diurnal peak as continents. But this will be influenced by monsoon and land-sea breezes, that’s morning precipitation peak can be observed in the coastal regions and morning-afternoon double peaks in inland regions. When we study the Maritime continent region as a whole, which includes oceans, islands and continents, it represents a precipitation diurnal feature similar to that of ocean.

After checking all the rain rate in each region in each time interval, we found the diurnal cycle discussed previously was not caused simply by the passing of some storms.

D. Seasonal and Annual Change

Since the daily passage of the sun controls the diurnal variation of rainfall, it is reasonable to expect a weaker diurnal signal during the winter season, regardless of its precise mechanism. Fig. 12 and Fig. 13 show the rain rate diurnal cycle in each season. Over continents, the rain rate diurnal cycle in JJA is weaker than the other seasons in the Southern Hemisphere. While in North Africa the diurnal cycle in JJA is evident. This shows that the diurnal cycle over continents in JJA is stronger with latitude as we move northward. The same feature can be seen from DJF season. The diurnal cycle over continents in DJF weakens with latitude moving northward. Over the islands, the variation is almost the same in each of the four seasons. Over the ocean, in some regions, the variation is almost the same over different seasons. In some regions, the variation is different in some seasons from the others. The diurnal cycle in the spring season shows a midnight maximum over the Northeast Pacific ocean region. The diurnal cycle in the winter season exhibits the morning maximum over the Indian ocean region and the south Atlantic Ocean region. Due to the smaller response of water surface temperature to radiational heating and cooling, the seasonal change over oceans with latitude is not so evident as that over continents. There is no clear conclusion to be drawn here. But we can conclude that there is a diurnal cycle seasonal change in some ocean regions. Some data sets used in previous studies only include part of the year, such as GATE, which only has summer observations, the diurnal cycle detected in these works may not represent the diurnal cycle over the whole year.

Fig. 14 and Fig. 15 show the rain rate in each year from 1998 to 2002. There is no evident diurnal cycle that can be detected in some years in the ocean regions. But in most continental regions the diurnal detected in an individual year agrees with the diurnal cycle in the five-year averages. In the island region in this study the diurnal cycle detected in a single year also agrees the diurnal cycle in five-year averages.

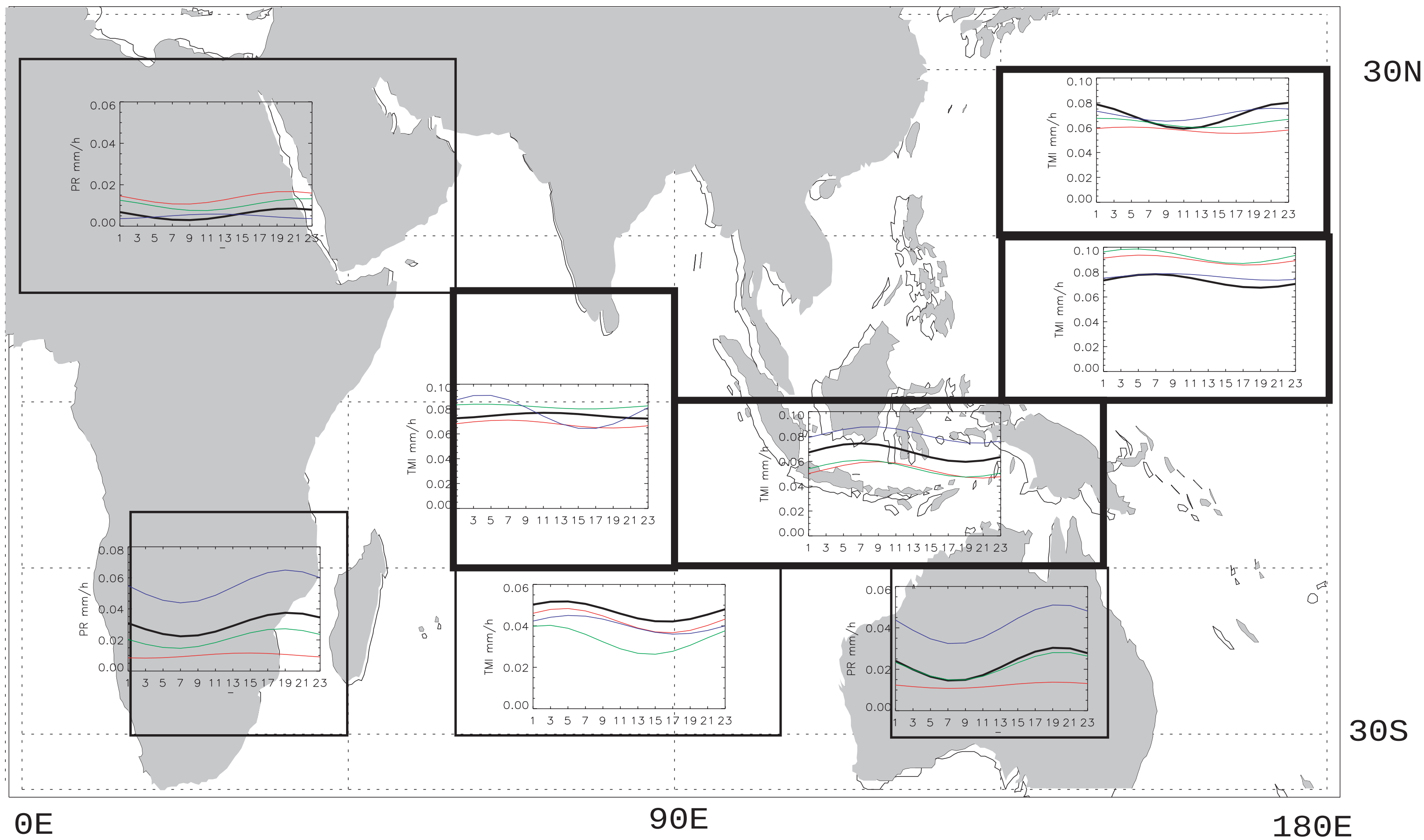

Fig. 12. The rain rate with the time of the day in each season in East Tropics. The black line represents the rain rate in MAM; The red line for JJA; The green line for SON; The blue line for DJF. The regions enclosed with heavy lines are the regions with heavy rain.

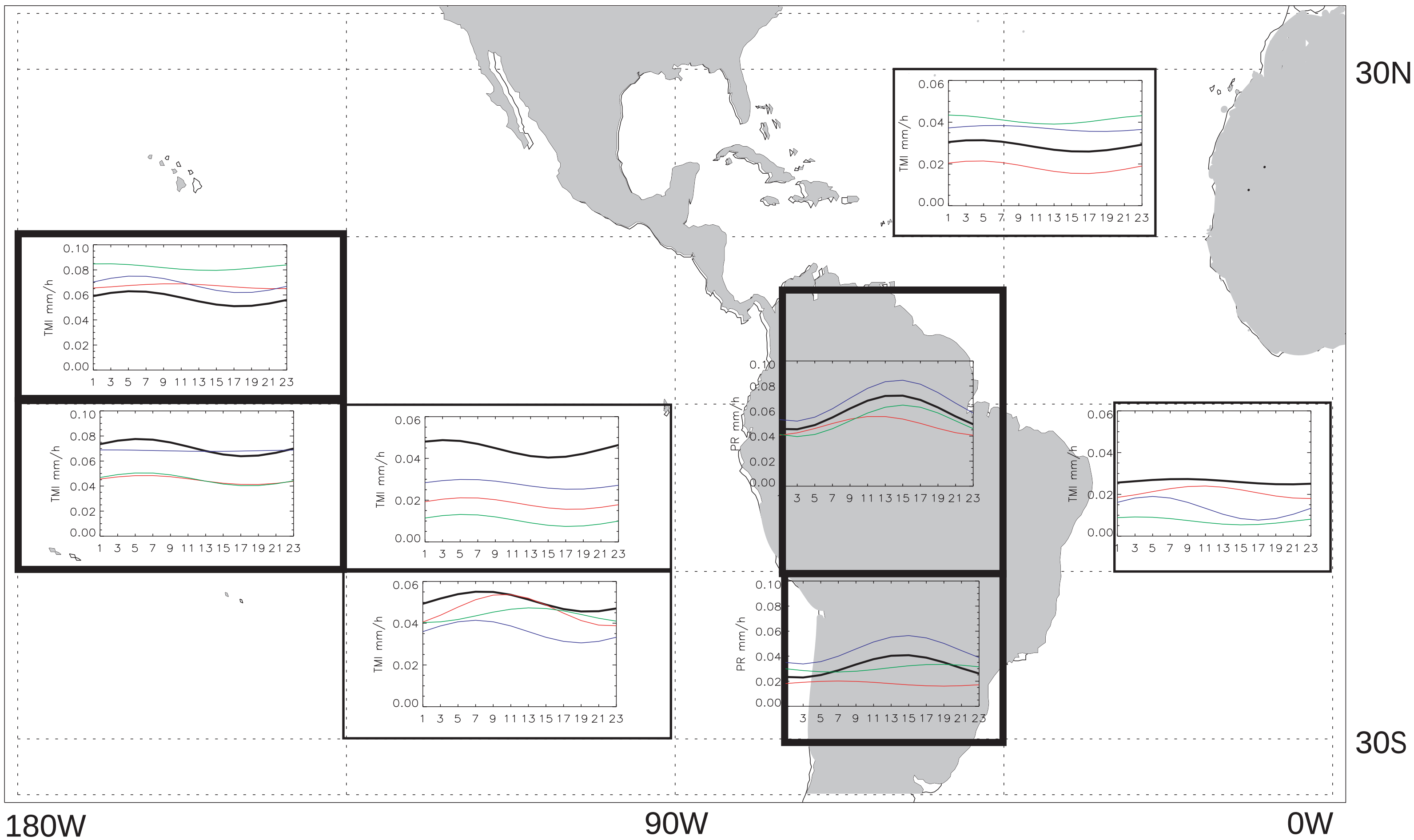

Fig. 13. The same as Fig. 12, but the rain rate with the time of the day in each season in West Tropics.

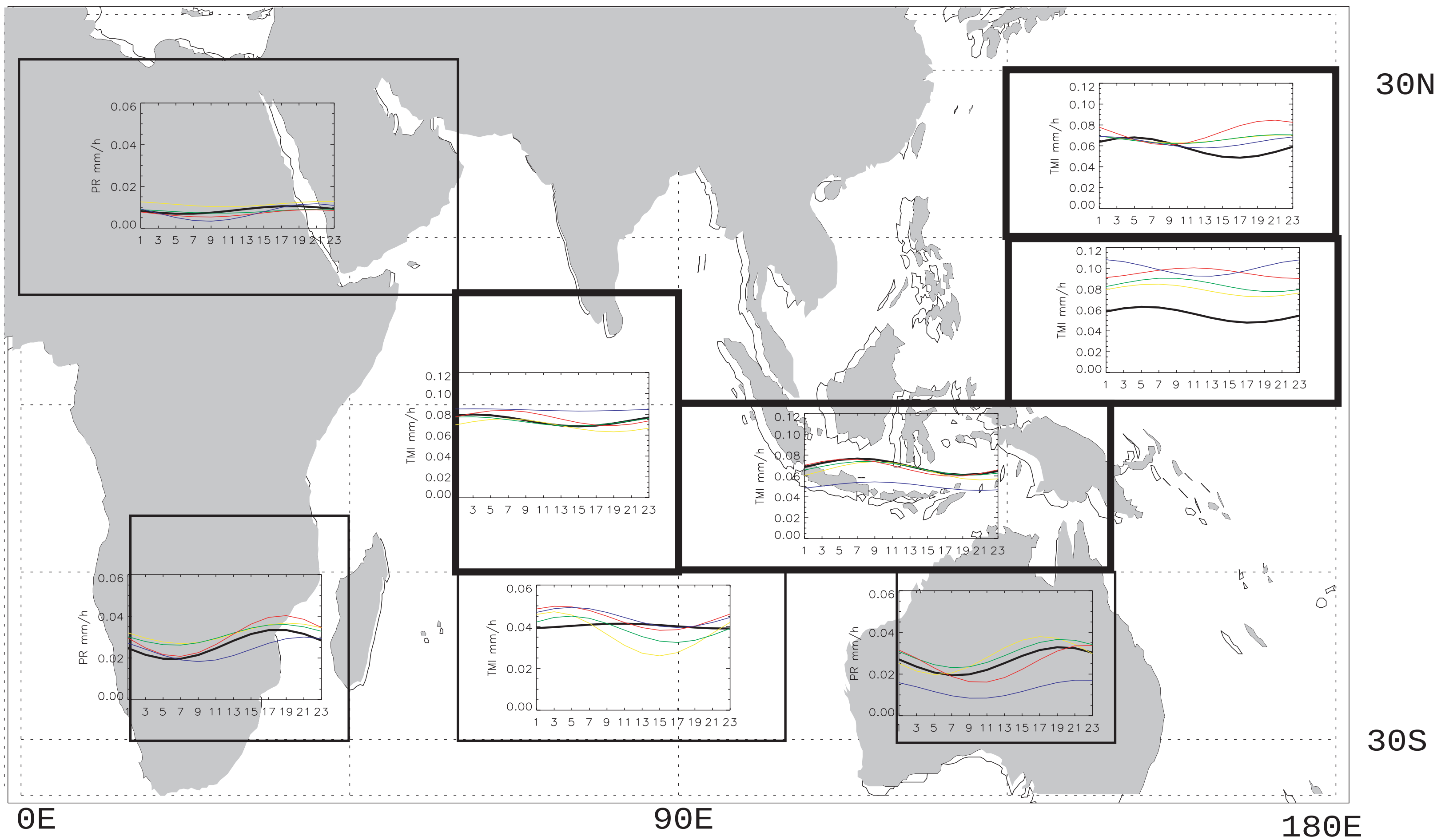

Fig. 14. The rain rate with the time of the day in each year in East. The black line represents the rain rate in year 1998; The yellow line for year 1999; The green line for the year 2000; The red line for the year 2001; The blue for the year 2002. The regions enclosed with heavy lines are the regions with heavy rain.

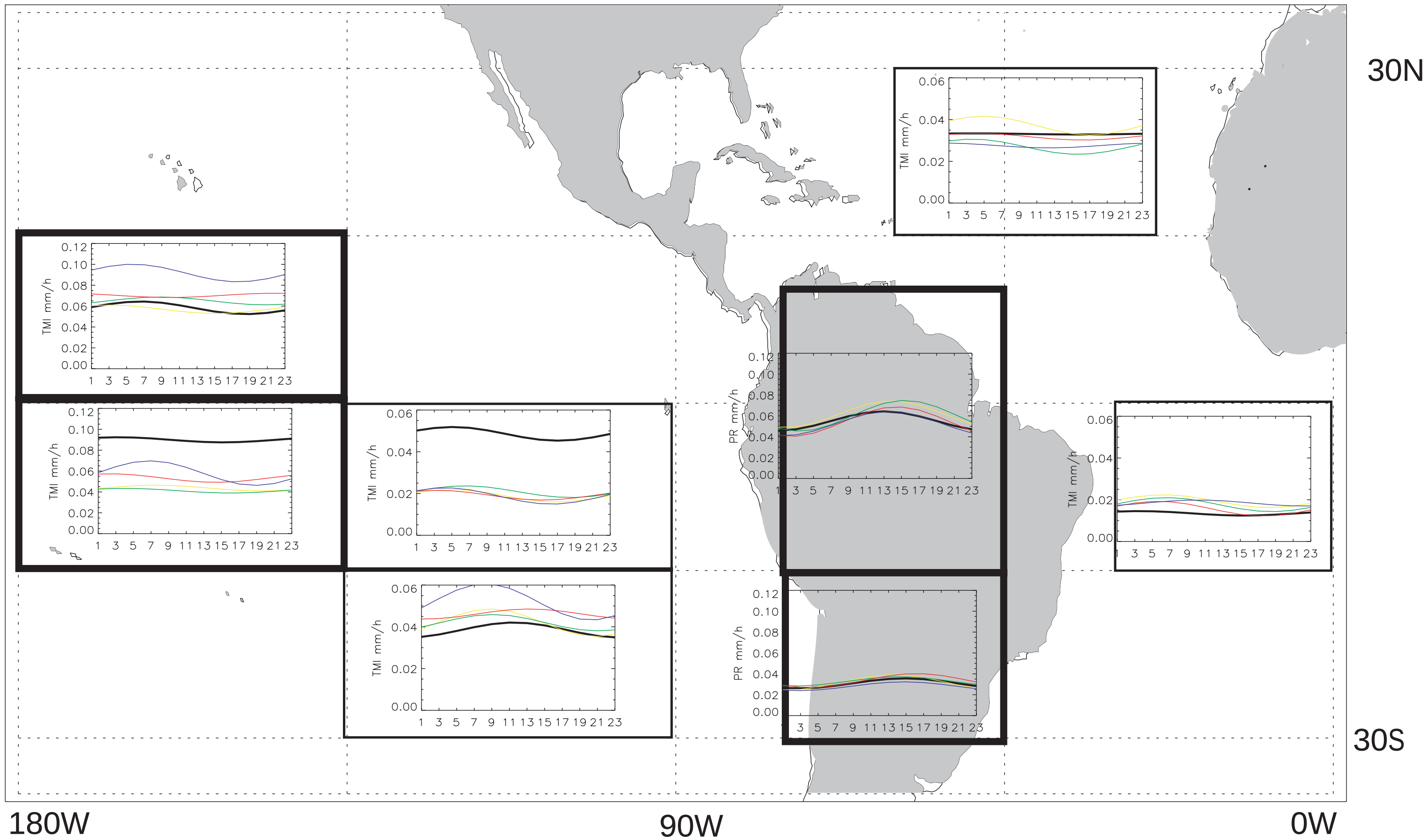

Fig. 15. The same as Fig. 14, but the rain rate with the time of the day in each year in West Tropics.

CHAPTER VI

CONCLUSIONS

Data from the TMI and PR sensors of TRMM have been analyzed for the period from Jan 1998 to Dec 2002 over the tropical region between $30°S$ and $30°N$ to study the diurnal variability of rainfall. The observations are sorted according to ocean, island and continental surfaces. Considering the sampling characteristics of TRMM, the rain rate is binned in two-hour intervals of local time in each specific area. A maximum in precipitation at 0400 LST - 0700 LST was found in most ocean regions. The amplitude of variation over the dry ocean zones is a little higher than that over the oceanic regions with heavy total rain. The diurnal cycle peaks at 0700 LST - 0800 LST in regions including islands with rainfall variation similar to oceanic regions. A maximum at 1400 LST - 1500 LST was found over continents with heavy total rain, while the maximum occurred at 1900 LST - 2100 LST in the dry continental regions. The amplitude of variation over continents with heavy total rain and with light total rain do not show distinguishable differences. The diurnal cycle in in JJA and DJF varies with latitude over continents. The diurnal cycle seasonal change can also be found in some ocean regions. A diurnal cycle annual change is not evident over continents, while the diurnal cycle annual change over oceans exists in some regions. Island regions in this study show no evident seasonal or annual diurnal change.

Even though the sampling considerations suggest that the TRMM satellite can detect the diurnal cycle of rainfall using five years of data in the regions chosen for the study, in some cases the inferred diurnal variations may be erroneous. As the averaging area becomes smaller or the averaging period becomes shorter, the error may increase and therefore the combination becomes more important. The TRMM observations should be used in addition to the data from other satellites to minimize the effect of discrepancies between satellite sampling and rainfall activity in the later work. This particular case demands that a suitable approach must be adopted to determine the diurnal variations of rainfall robustly and with certainty. One possible approach may be the use of TRMM data in combination with data from other satellites with similar sensors, such as SSM/I.

The regions chosen in the study are limited. With more data accumulated or with data combined TRMM data with other satellite data to reduce the sampling error, more regions can be used for study and more diurnal features can be concluded. With more regions for the study in the further work, the relation between diurnal cycle and latitude can be confirmed.

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