Convective–Stratiform Precipitation Variability at Seasonal Scale from 8 Yr of TRMM Observations: Implications for Multiple Modes of Diurnal Variability

SONG YANG*
Center for Earth Observing and Space Research, College of Science, George Mason University, Fairfax, Virginia, and Laboratory for Atmospheres, NASA GSFC, Greenbelt, Maryland

ERIC A. SMITH
Laboratory for Atmospheres, NASA GSFC, Greenbelt, Maryland

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ABSTRACT
This study investigates the variability of convective and stratiform rainfall from 8 yr (1998–2005) of Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) and TRMM Microwave Imager (TMI) measurements, focusing on seasonal diurnal variability. The main scientific goals are 1) to understand the climatological variability of these two dominant forms of precipitation across the four cardinal seasons and over continents and oceans separately and 2) to understand how differences in convective and stratiform rainfall variations ultimately determine how the diurnal variability of the total rainfall is modulated into multiple modes.

There are distinct day–night differences for both convective and stratiform rainfall. Oceanic (continental) convective rainfall is up to 25% (50%) greater during nighttime (daytime) than daytime (nighttime). The seasonal variability of convective rainfall’s day–night difference is relatively small, while stratiform rainfall exhibits very apparent day–night variations with seasonal variability. There are consistent late evening diurnal peaks without obvious seasonal variations over ocean for convective, stratiform, and total rainfall. Over continents, convective and total rainfall exhibit consistent dominant afternoon peaks with little seasonal variations—but with late evening secondary peaks exhibiting seasonal variations. Stratiform rainfall over continents exhibits a consistent strong late evening peak and a weak afternoon peak, with the afternoon mode undergoing seasonal variability. Thus, the diurnal characteristics of stratiform rainfall appear to control the afternoon secondary maximum of oceanic rainfall and the late evening secondary peak of continental rainfall. Even at the seasonal–regional scale spatially or the interannual global scale temporally, the secondary mode can become very pronounced, but only on an intermittent basis. Overall, the results presented here demonstrate the importance of partitioning the total rainfall into convective and stratiform components and suggest that diurnal modes largely arise from distinct diurnal stratiform variations modulating convective variations.

1. Introduction
Understanding space–time variations of precipitation is an important topic in climate research, in which modern, high quality, global-scale precipitation observations are essential. Detailed analyses of such datasets reveal the evolution and lifetime of precipitating clouds, including the embedded convection and stratiform forms of precipitation, all of which help improve rainfall climate predictions. High quality, global-scale coverage of precipitation first became available with satellite-derived passive microwave (PMW) measurements obtained from Defense Meteorological Satellite Program (DMSP) satellites flying the Special Sensor Microwave Imager (SSM/I), first flown in July 1987. These were important new measurements because they were acquired consistently for both continental and oceanic environments (Smith et al. 1998). One of the first satellite rainfall programs to produce a long-term
global record of rainfall from satellite measurements was the Global Precipitation Climate Project (GPCP), whose principal objective has been to support climate research and hydrological applications (Huffman et al. 1997).

Notably, newer satellite measurements from instruments flown on the Tropical Rainfall Measuring Mission (TRMM) satellite, that is, the nine-channel TRMM Microwave Imager (TMI) PMW radiometer and the Ku-band (13.8 GHz) Precipitation Radar (PR) developed by the U.S. and Japanese space agencies [National Aeronautics and Space Administration (NASA) and Japan Aerospace Exploration Agency (JAXA)] (Simpson et al. 1996), the JAXA Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) flown on NASA’s Aqua satellite, and the NASA–Canadian Space Agency (CSA) W-band (94 GHz) Cloud Profiling Radar (CPR) flown on the NASA CloudSat satellite (L’Ecuyer and Stephens 2002; Stephens et al. 2002), have enabled much more advanced global-scale precipitation analysis. Motivated by these advances, the goal of this study is to extend our understanding of global precipitation characteristics through analysis of the seasonal variability of convective and stratiform rainfall based on the use of long-term records of TRMM rainfall (8 yr over the 1998–2005 period) obtained from PR and TMI measurements—over the tropical global province.

Overall, the principal scientific objectives of this study are 1) to understand the climatological variability of convective and stratiform precipitation on a seasonal basis, classified by continental and oceanic environments, and 2) to understand how differences in convective and stratiform rainfall variations modulate the diurnal variability of total rainfall into multiple modes. Our most important findings are that 1) there is a dominant diurnal mode resulting from either a pure or partial convective primary harmonic, which differentiates between continents and ocean, and 2) there is a secondary mode representing either a weak or strong stratiform harmonic, which serves to modulate the convective mode but with a strong dependence on the environmental background, season, region, and the specific annual period.

The most physical approaches for retrieving rainfall and its associated latent heating impacts, particularly over oceans, are associated with microwave algorithms, either passive or active or both (Meneghini and Kozu 1990; Iguchi and Meneghini 1994; Wilheit et al. 1994; Haddad et al. 1997, 2004; Smith et al. 1997, 1998; Ebert and Manton 1998; Yang and Smith 1999a,b, 2000; Iguchi et al. 2000; Kummerow et al. 2000, 2001; Meneghini et al. 2000, Tao et al. 2006). The TRMM satellite was the first dedicated to retrieval of rainfall measurements and thus was able to justify the use of the purely physical methodologies (Simpson et al. 1988, 1996). The TRMM project produces accurate precipitation estimates from two instruments designed specifically for the measurement of rain rate according to Ku-band radar reflectivity and multifrequency passive microwave attenuation and scattering (Kummerow et al. 1998). To date, TRMM has provided reliable, continuous, and accurate rain-rate estimates based on various physical algorithms over the global tropics and subtropics that have led to a greater understanding of precipitation processes and variability (Kummerow et al. 2000; Wolff et al. 2005; Yang and Smith 2006; Yang et al. 2006a,b; E. A. Smith et al. 2008, unpublished manuscript; Yang et al. 2008).

Classifying precipitation into convective and stratiform categories is an important scientific distinction, recognizing that this capability has only been made possible by the availability of PR space radar measurements whose detailed vertical reflectivity structures reveal distinct profile slope properties that are closely associated with either convective or stratiform environments (Haddad et al. 1997; Iguchi et al. 2000). Another important phenomenon vis-à-vis precipitation processes is diurnal variability (Yang and Smith 2006). With the availability of high quality, global-scale, and long-term rainfall datasets from satellite observations, the study of the diurnal cycle of rainfall has been renewed. This topic was first examined as a scientific phenomenon over 100 yr ago (Hann 1901) and has been studied extensively since that time in intermittent periods. Yang and Smith’s (2006) study of diurnal mechanisms based on TRMM data includes a detailed review of the twentieth-century literature.

In the last decade, there have been a few studies focused on understanding the relative amounts of convective and stratiform rainfall at lower latitudes. Required reading is the paper of Houze (1997) who drew attention to the somewhat paradoxical idea of even referring to stratiform rainfall in the tropics, given that, for so many decades, meteorologists had restricted their physical definition of this rainfall category such that stratiform precipitation was taken as a strictly mid-latitude, cold rain phenomenon occurring only in baroclinic cyclones. It was the Houze (1997) paper that emphasized the fact that in the tropics there is no separating convective and stratiform rainfall, because, in essence, stratiform rainfall at lower latitudes represents convection at the end of its precipitating life cycle—or more prosaically, “old convection.” Moreover, stratiform rainfall also occurs in the tropics as a warm rain process. This can be troublesome when trying to clas-
sify precipitation based on the occurrence of a sharp radar “brightband” feature in the reflectivity profile that generally denotes the stratiform phase of a cold rain precipitation life cycle in which large frozen hydrometeors (e.g., snowflakes, aggregates, graupel, and/or hail) fall through the melting level and begin taking on the characteristics of excessively large liquid raindrops, insofar as a radar is concerned.

The study by Steiner et al. (1995) demonstrated how a combination of rain gauge and Doppler ground radar data could be used to classify precipitation into convective and stratiform categories. A partly similar study was conducted by Geerts and Dawei (2004) based on vertically pointing airborne radar measurements of reflectivity and line-of-sight Doppler velocity. There has even been an attempt by Tremblay (2005) to classify precipitation into its convective and stratiform components based on fitting exponential functions to only surface rain gauge measurements. In a much more robust study involving the use of TRMM’s PR space radar, Schumacher and Houze (2003) reported that over the tropics, stratiform rainfall accounts for ~73% of the area covered by rain while yielding some 40% of the total rainfall accumulation. In addition, they noted that convective rain rates were, on average, some 4 times stronger than stratiform rain rates; all of which indicates that stratiform rainfall is a very important tropical precipitation mode with rather complex physical properties.

Although there are many proposed mechanisms for explaining the diurnal cycle of precipitation (Yang and Smith 2006), it is generally accepted that a widespread afternoon rainfall peak over continents is due to a postnoon maximum in surface heating and the resultant static instability. However, over oceans, there are a number of mechanisms that have been proposed to explain the endemic late evening–early morning rainfall maximum. In our view, three of these have obtained conspicuous traction. The first can be called the static radiation–convection (SRC) interaction. This is a synoptic-scale mechanism that presumes that enhanced cloud-top IR cooling at night, stemming from the lack of cloud-top solar absorption, and a consequent increase in the thermal lapse rate (Kraus 1963; Lavoie 1963; Ramage 1971), leads to stronger convection and nighttime rainfall. The SRC mechanism enables radiative forcing to favor more intense rainfall during the late night period, provided a there is a preexistence of cloudiness.

The problems with this mechanism in explaining diurnal variability in deep convective environments stems from the fact that significant differences between daytime–nighttime oceanic lapse rates are not observed (Betts 1982; Emanuel 1986, 1994; Xu and Emanuel 1989). Moreover, the troposphere may actually become stabilized from deep cumulus-layer overturning (Ruprecht and Gray 1976; Gray and Jacobson 1977). However, SRC is the favored mechanism found in a study by Randall et al. (1991) based on a general circulation model (GCM). Lin et al. (2000) reported that diurnal phasing in the Randall GCM is very sensitive to a specified parameter that links cumulus kinetic energy to cloud mass flux, thus rendering the initial study open to question concerning model validity.

The second oceanic mechanism of interest can be called the dynamic radiation–convection (DRC) interaction, based on the persistent day–night differences in radiative cooling over deep convection in contrast with the surrounding clear-air areas. This feature effectively suppresses daytime convection, leading to more nighttime rainfall. Daytime suppression results from clear regions experiencing less subsidence warming in response to ongoing radiative cooling because of enhanced daytime radiative heating due to water vapor insolation absorption, thus reducing the convergence into the convection zone and inhibiting daytime convective growth. Ruprecht and Gray (1976) and Gray and Jacobson (1977) first proposed this mechanism, later supported by Foltz and Gray (1979), McBride and Gray (1980), and Ackerman and Cox (1981). However, it is only applicable to extended organized convection (e.g., meso-α-scale mesoscale convective systems, tropical cyclones, and synoptic-scale convergence zones) where background subsidence can be altered at regional scales.

Notably, regardless that both SRC and DRC diurnal interactions are rooted in daytime–nighttime radiative cooling differences, the two mechanisms are diametrically opposed in explaining which portion of the diurnal cycle is actually perturbed by the underlying forcing mechanism. The SRC interaction favors nighttime enhancement through increased thermodynamic instability, while the DRC interaction favors daytime suppression through decreased daytime convergence into the convection zone.

The third oceanic mechanism of note draws attention to two control factors that can effect the timing of the diurnal precipitation variability, specifically, the ambient precipitable water (PW) and the cloud–storm life cycle that microphysically evolves over time to produce precipitation. Based on Tropical Ocean Global Atmosphere Couple Ocean–Atmosphere Response Experiment (TOGA COARE) data and numerical modeling experiments, Sui et al. (1997, 1998) found that the nocturnal precipitation mode can be explained by an increase in relative humidity at night due to diurnally...
varying radiative cooling that is mostly controlled by surface temperature, with the resultant change in tropospheric humidity stimulating condensation and precipitation. This mechanism, referred to as SRCM (the M referring to moisture) and also addressed in the modeling studies of Tao et al. (1993, 1996), is in contrast with the Randall et al. (1991) SRC explanation that the key diurnal control is simply the nighttime thermodynamic destabilization of lapse rates.

Yang and Smith’s (2006) recent review and TRMM data analysis concerning mechanisms of diurnal rainfall variability found that the earlier published mechanisms were mostly based on limited regional datasets that lacked context and duration and, thus, could not reveal all of the key processes that produce the endemich complexity inherent to the diurnal cycle of precipitation when examined in detail and over extended space and time scales. Using 1-yr of high-resolution, level 2 TRMM rainfall retrieval products, they found that diurnal rainfall variability is a richly textured global phenomenon with embedded diurnal harmonics that produce complexities that generally cannot be explained by individual causal factors. For example, on a seasonal–regional basis, the primary late evening/early morning oceanic rainfall maximum is often accompanied by a secondary afternoon peak. Conversely, the dominant mid- to late afternoon continental rainfall maximum is often replaced or accompanied by a secondary morning peak. In fact, the main underlying lesson from their TRMM analysis is that there are a host of mechanisms at work producing diurnal rainfall variability, no single one of which can explain the entire process or, in general, an entire process. Instead, a mixture of two or more mechanisms (modes) are generally at work over regional and smaller scales, combining together to produce the averaged process at larger scales. Thus, the trick in understanding diurnal rainfall variability is to understand the contexts and modal components producing the averaged effects (that quite often become blurred through the imposed averaging), and then diagnosing the appropriate physical mechanism(s) underlying the processes being averaged.

This is why we are investigating the diurnal variability of the separate convective and stratiform components contributing to the overall diurnal variability of the total rainfall. We will show that this is very important in interpreting the multimodal nature of diurnal rainfall behavior. Although there is a history in the literature that has investigated the spatial structures and temporal variations of convective and stratiform precipitating cloud systems (Houze 1989; Short et al. 1997; Schumacher et al. 2004), almost no research has explored differences in their individual diurnal properties. Since the tropics experience the greatest precipitation loading, the long-term, global-scale, diurnally sampled TRMM rainfall products are ideal for studying spatiotemporal variations of partitioned convective and stratiform precipitation.

Results from this study are intended to improve our understanding of the mean and variable horizontal distributions of convective and stratiform rainfall, with the more important goal of explaining how distinct convective–stratiform precipitation properties determine the diurnal behavior of the total rainfall in a multimodal framework. Finally, the similarities and differences in the retrieved convective and stratiform rainfall from different TRMM algorithms will help guide the improvement of these and other algorithms for the next-generation Global Precipitation Measurement (GPM) mission (Smith et al. 2007).

2. Methodology and datasets

Due to the nature of the TRMM satellite’s design, sampling error is always an issue when a small time scale is considered for studying rainfall diurnal variations (Negri et al. 2002; Hirose and Nakamura 2005). Yang and Smith (2006) and Yang et al. (2006b) have shown that for the mean rainfall diurnal cycle the sampling issue is abated when a seasonal scale is considered.

2a. Methodology

Convective and stratiform separation is obtained from TRMM PR rain classification algorithm 2a23. Raining pixels are categorized into three different rain types: 1) convective, 2) stratiform, and 3) “other.” The classifications are based on the combination of a vertical profile method (the V method) and a horizontal profile method (the H method) described by Awaka et al. (1997, 2007). The V method can be summarized in three steps: 1) a raining pixel is classified as stratiform when a bright band (BB) exists, 2) a raining pixel is classified as convective when the maximum reflectivity (Z) is greater than 39 dBZ without the existence of the BB, and 3) all other raining pixels are defined as “other.” The H method is based on a convective–stratiform separation scheme in which the horizontal pattern of Z at a given height is examined (Steiner et al. 1995). Here, the horizontal pattern of $Z_{\text{max}}$ is examined. A raining pixel is convective when $Z_{\text{max}}$ exceeds a threshold of 39 dBZ or $Z_{\text{max}}$ stands out against the background area. The $Z_{\text{max}}$ is defined as the maximum Z for each PR profile below the frozen height (with −1 km margin). For this situation, the nearest four pixels to the
assigned convective pixel are also defined as convective. Then, a raining pixel is not defined as convective, but with certain rain echo is defined as stratiform. Any pixels that are not convective or stratiform are classified as the other type of rainfall. The V and H methods are first applied separately; then, their unified result is used to classify the raining pixel into one of the three categories. The use of these definitions ensures that the rainfall amount derived from the other-type rain pixels is very small. A detailed description of this rain-type classification procedure can be found in the TRMM Science Data and Information System (TSDIS) file specifications under dataset 2a23 (see NASA Goddard Space Flight Center 2006).

The categorized rainfall totals over a 0.5° × 0.5° latitude–longitude grid from different TRMM rain algorithms for a season are initially accumulated. Three-hour rainfall compositing is also applied in analyzing the rainfall diurnal variations. These averages are then further regrouped depending on different temporal–spatial scales used for a specific analysis. Also, five oceanic and one continental region, all with climatologically active rainfall regimes, are selected to illustrate the regional variations of convective and stratiform rainfall.

b. Description of datasets

Eight years (1998–2005) of version 6 (v6) TRMM rain products are taken from three standard level 2 algorithms: 2a12, 2a25, and 2b31. The 2a25 and 2b31 surface rain rates are the estimated rain rates near surface. The 2a12 algorithm consists of a TMI-only microphysical profile scheme cast in Bayesian form, which uses a cloud resolving model (CRM) to generate numerous microphysical profiles of liquid and frozen hydrometeors for rainfall (R) conditions as a solution basis, in which solutions arise by combining microphysical profiles into weighted averages determined from the proximity of precalculated forward radiative transfer calculations associated with the individual microphysical profiles to the TMI’s channel-specific measurement values (Kummerow et al. 1998; Olson et al. 2006). The 2a12 convective rainfall classification is not applied in this study because its convective definition cannot be directly compared to those used for the 2a25 and 2b31 algorithms (see Hong et al. 1999; Olson et al. 2006). The 2a25 algorithm consists of the PR-only rain-rate profile scheme, akin to the top-down Hitschfeld–Bordan recursive scheme, that normally uses a cloud-free surface radar cross section (\(\sigma_v\)), which PR observed over a few swaths prior to the current observation, to reassign the total path attenuation (\(A\)) and a prespecified Z–R relationship for defining the allowable rain microphysics.

The coefficients of the initial unified Z–R/Z–A relationships, designed to yield a top-down attenuation path during a first pass, are adjusted in a second pass so that the final R profile gives rise to the A estimated from the surface reflectance method (Iguchi and Meneghini 1994; Meneghini et al. 2000). The 2b31 algorithm consists of a combined PR–TMI rain-rate profile scheme, based on what has been referred to as a combined “tall vector” solution. The tall-vector solution is also cast in Bayesian form, with all Zs from the PR-measured rain gate vectors and radiometer-measured brightness temperatures (TBs) from the TMI-measured channel vectors used in an “instrument balanced” concatenated inversion scheme. The microphysical database is drawn from both disdrometer observations (from Darwin, Australia, and the TOGA COARE field experiment) and CRM-generated microphysics (Haddad et al. 1997; Smith et al. 1997). This process is guided by three Bayesian sweeps for calculating the total path attenuation, that is, 1) an initial top-down Hitschfeld–Bordan pass, 2) a second climatologically derived \(\sigma_v\)-based pass, and 3) a final 10.7-/19-/37-GHz TMI measurement–based pass. The beam discrepancy between the PR and TMI instruments is resolved through a deconvolution procedure with retrieved rain-rate values taken at native PR spatial resolution.

3. Characteristics of seasonal convective and stratiform rainfall

The 8-yr (1998–2005) mean monthly surface rainfall fields from the 2a12, 2a25, and 2b31 algorithms are illustrated in Fig. 1. The horizontal distributions are highly consistent with each other, exhibiting well-known climatological precipitation characteristics such as heavy rainfall within the intertropical convergence zone (ITCZ), the southern Pacific convergence zone (SPCZ), the Asian monsoon region, the African and South American tropical rain forests, and the subtropical storm tracks, including the feature over and off of southern Brazil’s east coast.

Since different physical assumptions are used in the three retrieval algorithms, differences among them should be expected. Compared with the composite of all TRMM rain products, the slightly larger rainfall of 2a12 and slightly smaller rainfall of 2a25 are apparent in Fig. 1. These small discrepancies in the global mean magnitudes are consistent with comparison results found at different space–time scales by Wolff et al. (2005), Yang and Smith (2006), and Yang et al. (2006a,b). However, the most salient feature of the three rainfall distributions is their overall similarity in terms of the pattern of the distributions. The near agreement in the means and the almost exact pattern
agreement affirm that the three level-2-based v6 TRMM rainfall time series reveal a highly consistent near-decadal climatology of precipitation over the global tropics and subtropics.

Using 3-month compositing, Fig. 2 shows the horizontal distributions of 8-yr mean rainfall from the 2b31 combined algorithm for the four cardinal seasons [i.e., December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON)]. (Very similar patterns of seasonal rainfall are found in the 2a12 and 2a25 rainfall products; not shown.) It is evident that the spring precipitation distribution has a dominant maximum over the equatorial area of the western Pacific Ocean and eastern Indian Ocean, but relatively weak ITCZ rainfall. In summer, the maximum rainfall is found over the Bay of Bengal, with rainfall over the Indian and Indonesian regions acting as an integral part of the Asia summer mon-
soon’s major convection sources. The large amplitude of the rainfall over the tropical eastern Pacific Ocean and across the northwest South American coastal zone is also associated with storm-generated convection. The local maxima of rainfall over the tropical eastern Atlantic Ocean and over Africa are likely due to convection produced within tropical easterly waves. Also, there is an obvious intensification of the ITCZ rainfall during summer relative to the ITCZ intensity during spring. The autumn rainfall distribution exhibits a maximum over the equatorial areas of the eastern Indian Ocean and western Pacific Ocean warm pool regions. In winter, the rainfall pattern is highly contrasted relative to summer. The dominant feature is the large belt of activity along the equatorial zone with maxima over the western Pacific and eastern Indian Oceans and the ITCZ–SPCZ intersection in the western Pacific referred to as the “V” sector. Weak rainfall over the Asian monsoon region is evident. The relative increase of rainfall over the North Pacific is linked to winter midlatitude frontal systems.

Figure 3 presents the 8-yr mean seasonal zonal rainfall from the three algorithms over oceans and continents. It is apparent that the zonal distributions with respect to the algorithms exhibit similar features, in which the oceanic profiles are nearly identical—perhaps with the exception of winter in which there are slight discrepancies within a few confined latitude bands. The discrepancies are larger over the continents in which 2a12 exhibits consistently larger tropical and Northern Hemisphere subtropical (20°–35°N belts) amplitudes. For oceanic rainfall, the zonal profiles for summer and autumn are similar, with a dominant peak near 7.5°N caused by the seasonal northward migration of the ITCZ. The winter and spring oceanic profiles also exhibit similar features with a main peak near 5°N and a secondary peak near 7.5°S. The southward ITCZ movement along with the intensification of the SPCZ during the austral summer and autumn periods lead to this double-peak structure. In the case of continental rainfall, the maximum amplitudes are located in the Northern Hemisphere (NH) during spring and summer (mainly due to the Asian monsoon), shifting to the Southern Hemisphere (SH) during autumn and winter partly due to the onsets of the rainy seasons in South Africa and South America. The unrealistically large rainfall features exhibited by 2a12 north of 20°N during winter and spring draw attention to the fact that rainfall
retrieval over cold land surfaces remains an unresolved problem for radiometer-only algorithms. However, the v6 TRMM rain products exhibit significant improvement compared to the earlier v4 and v5 releases; see Kummerow et al. (2001), Olson et al. (2006), and Yang et al. (2006a).

A similar analysis is then conducted for algorithms 2a25 and 2b31, but now including partitioning into convective and stratiform rainfall categories, with results shown in Fig. 4. (It can be seen that, in general, the two algorithms exhibit nearly identical results.) More importantly, the distribution patterns of zonal mean convective and stratiform rainfall are similar, including similar magnitudes. The fact that these distribution patterns are close to the total rainfall pattern, shown in Fig. 3 over the higher-amplitude latitude bands, simply denotes that convective and stratiform rainfall are nearly equal in importance in contributing to the total precipitation over the global tropics. For the oceanic regime, there is relatively more stratiform than convective rainfall over the heavy rainfall latitudes including those of the ITCZ, SPCZ, Asia summer monsoon, and African wet season. In contrast, there is much more stratiform rainfall over the subtropics (20°–35° latitude zones), where the total rainfall is smaller due to the greater role of frontal rainfall arising from tropical–midlatitudinal interactions. As with continental rainfall, there are relatively greater convective amounts over the continental heavy rainfall latitude zones, but in contrast to the oceanic regime, seemingly nearly equal contributions in the subtropics, except for the Southern Hemisphere in boreal winter and the Northern Hemisphere in summer.

To emphasize the contrasts, relative contributions (given in percent) to the total seasonal rainfall from the convective and stratiform categories are shown in Fig. 5. (As in Fig. 4, the results are nearly identical with respect to the two algorithms.) Now, the actual differences, in terms of the contributions between the tropics and subtropics and between the oceanic and continental regimes, are obvious. For oceans, the contributions by the two categories in the tropics are nearly equal (~50% each), whereas there is a much greater contribution by stratiform rainfall in the subtropics (~20°–35° latitude belts; ranging up to 80%). Over continents, in summer and autumn, some 60% of the rainfall is due to convective rainfall over the heavy rainfall latitudes, while there are much greater stratiform contributions in the subtropics during SH summer and NH autumn, where precipitation is relatively weak as noted in the results shown in Fig. 4. The cross-seasonal dissimilarities over the continents are found in the heavy rainfall portions of the SH winter and spring tropics where convective–stratiform contributions are nearly equal (~50%), with contributions by convective rainfall ranging up to 70% over the equatorial zone and into the NH northern edge of the high-amplitude rainfall zone. In both winter and spring in the NH subtropics, contributions due to stratiform rainfall significantly exceed those due to convective rainfall, but, conversely, the contribution due to convective rainfall in the SH subtropics during winter dominates (this same feature appears in the NH summer subtropics to a lesser degree). This feature of the continental convective and stratiform rainfall partition in the subtropics during summer and winter is similar to the convective and stratiform

![Fig. 3. Zonal mean seasonal rainfall (mm day⁻¹) over (a) oceans and (b) continents for 8 yr of rain-rate measurements from algorithms 2a12, 2a25, and 2b31.]
separation based on the 2001 surface rain gauge measurements (Tremblay 2005). This feature is possibly associated with the interannually progression of the ITCZ and more frontal rainfall contributions in the subtropics of the winter hemisphere.

The small compensating differences between algorithms 2a25 and 2b31 in Fig. 5, insofar as convective and stratiform precipitation, are due to 2b31’s greater sensitivity in detecting raining pixels (i.e., very light rain rates), which are then assigned to the stratiform category by 2b31. Note that algorithm 2a25 cannot partition these very light rain pixels into convective and stratiform categories since they have not been detected a priori as raining pixels.

Figure 6 presents horizontal distributions of the seasonal convective and stratiform rainfall contributions to the total rainfall from the 8-yr 2a25 dataset. (Similar patterns are found in the 2b31 dataset.) These results show that, in general, the percentage of convective rainfall over continents exceeds 50%, except over most of East Asia and Australia where convective rainfall contributions drop to 20%. Also, the contribution due to...
convective rainfall over North America is less than 50% during autumn and winter, also falling below 50% in South America during the boreal winter and spring because of the tendency for cold season frontal band stratiform rainfall. Over the maritime domain, the contributions of convective rainfall over the Atlantic and Indian Oceans generally exceed 50%. These contributions can range up to 70% over the western tropical area of the South Pacific Ocean and the entire tropical area of the South Atlantic Ocean where rainfall is mostly weak, emanating often from shallow cumulus convection (Short and Nakamura 2000). Over portions of the SPCZ, the convective rainfall contribution is actually less than 50%, especially over its southern seg-

Fig. 6. Horizontal distributions of mean seasonal convective and stratiform rainfall contributions (%) to the total rainfall for 8 yr of rain-rate measurements from algorithm 2a25 for (left) convective and (right) stratiform rainfall. Areas with values greater than 50%, 60%, and 80% are denoted with increasingly darker gray shades.

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ment. Alternatively, convective rainfall within the Pacific Ocean’s ITCZ generally exceeds 50% of the total—except over the western Pacific equatorial band during spring and summer, the eastern Pacific ITCZ during autumn, and the central Pacific during winter.

The results in Fig. 6 draw attention to the obvious seasonal and regional variabilities found in the relative contributions of the convective and stratiform rainfall. Summary results of the horizontal distribution analysis from both the 2a25 and 2b31 datasets are given in Table 1. (Here, it is evident that the rainfall contributions from the “other” rainfall category are very small.) Over oceans, seasonal variations of the convective or stratiform rainfall contributions are small (~2%) for both algorithms. The overall percentages of oceanic convective (stratiform) rainfall are ~45% (~55%) for 2a25 and ~42% (~58%) for 2b31, which is within the expected range of uncertainties between algorithms (Haddad et al. 1997; Iguchi et al. 2000; Olson et al. 2006). The continental convective and stratiform rainfall contributions exhibit large seasonal variations of up to 8% for 2a25 and 11% for 2b31. The overall percentages of the continental convective (stratiform) rainfall are ~52% (~48%) for both 2a25 and 2b31.

Our results are comparable with earlier results reported by Tao et al. (2000) over selected regions based on their use of a limited 2a12 dataset. Rutledge and Houze (1987), Johnson and Hamilton (1988), and Houze (1997) have found that stratiform rainfall is typically about 40%–50% for oceanic convective systems in the tropics, but smaller (about 30%–40%) for continental convective systems. Note, these values of stratiform rainfall contribution are less than our long-term mean values over the global tropics, but in line with our findings over selected regions.

4. Seasonal variability of convective and stratiform rainfall

Yang and Smith (2006) have described day and night differences in precipitation based on a 1-yr TRMM dataset. On average, they found that there is relatively more nighttime rainfall than daytime rainfall over oceans, and more daytime rainfall than nighttime rainfall over continents. In this study, the 8-yr TRMM dataset has been analyzed to remove any possible biases due to interannual variability that may have affected the Yang and Smith (2006) study. Mean solar time (MST) is used in the following discussions.

a. Day–night variations

Figure 7 shows seasonal variations of the spatial ratio distributions of daytime (0600–1800 MST) to nighttime (1800–0600 MST) rainfall from the 8-yr 2a25 and 2b31 datasets. The highly coherent ratio distributions demonstrate that the underlying rainfall features are robust. The overall contribution due to daytime oceanic rainfall is generally as much as 25% lower than the contribution due to nighttime rainfall, while continental daytime rainfall is generally up to 25% greater than nighttime rainfall. The overall seasonal variation of daytime to nighttime rainfall ratio is not very significant. However, seasonal variations of the day to night rainfall ratio are obvious at regional scales, such as over eastern China, the United States and the Gulf of Mexico area, the west coast area of Australia, the Arabian Peninsula region, and the North Pacific Ocean.

Notably, the marine stratocumulus (MSC) areas show more detailed day to night rainfall variations than were discussed by Yang and Smith (2006). The background information on MSC can be found in Houze (1993). Daytime rainfall exceeds nighttime rainfall over the North–Central American MSC region in spring, summer, and winter, with opposite behavior in autumn. However, there is generally more nighttime rainfall over the South American MSC region. The West African MSC region exhibits more daytime rainfall in winter and spring, with opposite behavior in summer and autumn. More rainfall during daytime is also found in the South Africa MSC area in spring and autumn, with opposite behavior in summer and winter. The eastern
Arabian Sea MSC area clearly exhibits more daytime rainfall, except during winter. The general propensity of MSC rainfall to exhibit a daytime maximum is important because it suggests that a controversial daytime convective overturning mode dominates over a generally accepted nighttime stratiform drizzle mode.

The greatest differences between the 2a25 and 2b31 algorithm results in Fig. 7 are in regions where the total rainfall is small, leading to small denominators in the ratios of either algorithm. Since algorithm 2b31 is more sensitive to very light rainfall and thus detects more very light rainfall pixels than algorithm 2a25 (as dis-

Fig. 7. Horizontal distributions of the ratio (%) between averaged daytime (numerator) and nighttime (denominator) seasonal rainfall for 8 yr of rain-rate measurements from algorithms (left) 2a25 and (right) 2b31, respectively. Areas with values greater than 100%, 125%, and 150% are denoted with increasingly darker gray shades.
cussed previously), ratio differences are expected in regions of weak total rainfall. Also, mostly invariant uncertainty properties in the two algorithms exacerbate differences in their day–night ratios within the weak rainfall areas, whereas the two algorithms produce very similar results for larger rain rates.

Figure 8 presents the spatial ratio distributions of the daytime to nighttime convective and stratiform rainfall. The distribution patterns for convective rainfall are somewhat similar to those of total rainfall, except the continental convective rainfall contributes as much as 50% more rainfall in daytime than in nighttime over...
some regions, while oceanic convective rainfall contributes ~25% more rainfall during nighttime than during daytime. These results elucidate how, in the mean, convective rainfall dominates during daytime over continental regions and surrounding areas, while over oceans, it dominates during nighttime, helping corroborate, by the use of a lengthy TRMM dataset, earlier reported results (e.g., Hann 1901; Gray and Jacobson 1977; Dai 2001; Yang and Smith 2006; Yang et al. 2006b). However, stratiform rainfall also exhibits very different day-to-night rainfall variations. For example, daytime stratiform rainfall nearly equals or exceeds nighttime rainfall over most areas of the oceans, especially over the winter Pacific Ocean. Alternatively, stratiform rainfall over Africa and North America indicates generally lower contributions during daytime. The greater daytime stratiform contributions over the MSC regions, excepting North Africa, are also a salient feature. In addition, the seasonal variations of the spatial ratio patterns of daytime to nighttime stratiform rainfall denote that the mechanisms of this rainfall mode are more variable in time relative to their convective counterparts, depending on the precipitating system. In other words, convective rainfall does not exhibit as much seasonal dependence in its diurnal mechanisms. The day to night changes in stratiform rainfall can also explain the total rainfall late evening secondary peak over continents and the afternoon secondary maximum over oceans, features originally discussed by Yang and Smith (2006) and Yang et al. (2006b) but only in terms of total rainfall.

The observed rainfall characteristics over the MSC areas are not in correspondence with a number of modeling studies. In fact, they are mostly contradictory from the modeling perspective in which a MSC drizzle minimum is supposed to occur during daytime along with a minimum in cloud cover (Turton and Nicholls 1987; Duynkerke 1989; Duynkerke and Hignett 1993; Smith and Kao 1996; Duynkerke and Teixeria 2001). This contradiction includes the case of the seasonal variability of MSC rainfall. Since precipitation over the major MSC domains is presumed to be mostly drizzle and warm rain, a spectral rain-rate portion of which is not detectable by the TRMM PR (its inherent 17-dBZ sensitivity cuts off rain rates below the 0.25–0.3 mm h\(^{-1}\) threshold), the observed precipitation features discussed above over the MSC regions should be treated with some caution. In the meantime, we are currently analyzing a newer CloudSat 94-GHz Cloud Profiling Radar (CPR) dataset over the MCS regions, to confirm whether our TRMM results remain valid vis-à-vis the total rainfall.

Figure 9 shows mean seasonal zonal profiles of the convective and stratiform rainfall contributions during daytime and nighttime over oceans and continents for the 8-yr 2a25 dataset (similar diagrams from the 2b31 algorithm are not shown). Over oceans (left-hand panels in Fig. 9), whereas there is considerable meridional variability in the relative daytime–nighttime contributions due to the two categories of rainfall, there is also considerable similarity in their respective zonal profiles from season to season, particularly in the high-amplitude rainfall zone. This indicates that the diurnally changing convective and stratiform rainfall mechanisms are consistently regulated, undergoing little modulation over time, that is, stationarity. However, the situation...
for the continental regime is quite different (right-hand panels in Fig. 9). The contribution of continental convective rainfall is much greater during daytime because the diurnal cycle of the continental surface heating is so strong. In addition, the zonal profiles exhibit strong season-to-season variability—even within the high-amplitude rainfall zone.

Tables 2a and 2b summarize the overall seasonal changes of the oceanic and continental convective and stratiform rainfall contributions during daytime and nighttime. The consistent agreement between algorithms 2a25 and 2b31 for both convective and stratiform categories is apparent. During daytime, the seasonal changes of the convective and stratiform rainfall contributions are small over oceans, but clearly much greater over continents, especially during the autumn to winter transition. Overall, convective and stratiform contributions are small over oceans, but considerably over continents for both convective and stratiform categories. During nighttime, the seasonal variations are small over oceans, but considerably over continents for both convective and stratiform rainfall. The nighttime convective and stratiform rainfall contributions are about 42%–46% and 54%–58% over ocean and about 45%–51% and 49%–55% over land, respectively. There are relatively more (less) convective rain contributions during autumn (winter) for both daytime and nighttime.

### b. Diurnal variations

Published studies on rainfall’s diurnal cycle have almost exclusively focused on total rainfall. Studies of diurnal variability over the global tropics with categorized rainfall were effectively impossible prior to the TRMM era due to the lack of partitioned datasets. Yang and Smith (2006) and Yang et al. (2006b) analyzed the horizontal distributions and variations of precipitation’s diurnal cycle at the global scale based on TRMM data; however, these studies did not consider convective and stratiform partitioning. Using 8 yr of partitioned TRMM data has helped us to shed light on various aspects of the root cause of the diurnal variability of precipitation.

The diurnal variation of convective, stratiform, and total rainfall from algorithm 2a25 is illustrated in Fig. 10. (Algorithms 2b31 and 2a12 exhibit similar distributions.) Differences are prominent between the oceanic and continental rainfall regimes. Over oceans, although subtle, convective rainfall exhibits a diurnal cycle that is similar to that of the total rainfall with the exception of summer, while stratiform rainfall barely exhibits a secondary peak in the early afternoon, and only in spring and winter—in addition to its primary morning maximum. The afternoon secondary peak of the oceanic total rainfall is small within a globally averaged framework. Over continents, the afternoon primary peak of the convective rainfall mimics the diurnal behavior of

### Table 2a. Mean contributions (%) of seasonal-annual convective, stratiform, and other-type daytime rainfall from 8 yr of 2a25 and 2b31 algorithm retrievals over oceans and continents, with daytime covering the period from 0600 to 1800 MST. (C, S, and O are defined in Table 1 legend.)

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<tr>
<td></td>
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<td>Spring</td>
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<tr>
<td>2a25</td>
<td>C</td>
<td>44.1</td>
<td>43.9</td>
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<tr>
<td></td>
<td>S</td>
<td>55.8</td>
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</tr>
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<td></td>
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<td>0.1</td>
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<td>2b31</td>
<td>C</td>
<td>41.0</td>
<td>40.9</td>
</tr>
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<td></td>
<td>S</td>
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</tr>
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<td></td>
<td>O</td>
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</tbody>
</table>

### Table 2b. Same as in Table 2a but for nighttime rainfall, with nighttime covering the period from 1800 to 0600 MST.

<table>
<thead>
<tr>
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<td>2a25</td>
<td>C</td>
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<td>0.1</td>
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<tr>
<td>2b31</td>
<td>C</td>
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<td>S</td>
<td>57.4</td>
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</tbody>
</table>
Fig. 10. Diurnal cycle of mean seasonal rainfall (mm day$^{-1}$) partitioned into total (T), convective (C), and stratiform (S) categories over (left) oceans and (right) continents for 8 yr of rain-rate measurements from algorithm 2a25.
the total rainfall, while stratiform rainfall clearly exhibits a significant late night maximum between 0300 and 0600 MST along with the associated primary convective maximum between 1500 and 1800 MST.

Figure 10 also shows the seasonal variations of the rainfall diurnal cycle, especially for oceanic precipitation. For example, the diurnal variation of the total rainfall indicates a dominant peak during 0300–0600 MST in spring, and a broad late evening maximum in summer, autumn, and winter. Convective and stratiform rainfall indicate in-phase diurnal cycles during spring, but not for the other seasons. Convective rainfall indicates relatively weak variations in the diurnal cycle from season to season, whereas stratiform rainfall indicates somewhat stronger seasonal variations. For continental rainfall, the seasonal variation in the diurnal cycle is more stationary for the primary afternoon peak, with the late evening secondary peak stronger in summer and winter for both total rainfall and convective rainfall. This means there are changes from season to season in the overall continental diurnal cycle, but with peak amplitudes for the secondary mode remaining fairly stationary between 0300 and 0600 MST for all seasons.

Comparisons of the overall seasonally diurnal variability for categorized rainfall over oceans and continents demonstrate that the dominant peak for the total rainfall is mainly produced by the convective mode, especially for the continental case. Since the mid- to late afternoon peak of the continental convective rainfall is mostly forced by the diurnal cycle of the solar radiation, the stationary afternoon primary peak of the convective rainfall is expected. However, the late evening secondary peak of the continental rainfall is influenced by both convective and stratiform rainfall processes, especially the later. Moreover, over oceans, the dominant peak of the rainfall’s diurnal cycle is also mainly controlled by convective rainfall, but modulated by stratiform rainfall in a somewhat subtle fashion. These results suggest that the mechanisms behind the rainfall’s multimode diurnal cycle, at least in terms of the amplitudes and phases of the primary and secondary modes, are more complex over oceans than over continents. In any circumstance, the secondary maximum in the rainfall’s diurnal cycle at the global scale appears to be mostly impacted and modulated by stratiform rainfall.

Figure 11 presents the mean seasonal relative contributions of convective and stratiform rainfall over the diurnal cycle from the 8-yr 2a25 and 2b31 datasets. (The systematic agreements for convective and stratiform rainfall diurnal variations between the two algorithms are evident.) Overall, the consistency of greater stratiform oceanic rainfall is the prominent diurnal feature in this diagram. An afternoon peak in the stratiform rainfall contribution and a late evening peak in the convective rainfall contribution are apparent over oceans. Over continents, the prominent diurnal phenomena are an afternoon peak in the convective rainfall contribution and a 0600–0900 MST peak in the stratiform rainfall. Similar analysis is conducted for three different zonal belts: zonal 1 (10°S–10°N), zonal 2 (10°S–20°N and 10°–20°N), and zonal 3 (20°–30°S and 20°–30°N). Figures 12a and 12b as an example present (a) summer and (b) winter diurnal cycles of the relative contributions of the convective and stratiform rainfall over oceans and continents, respectively. The dominant characteristics of the convective and stratiform rainfall diurnal cycles are consistent for each zone and season, especially for phases of the diurnal peaks. They are also similar to the diurnal cycles of the overall oceanic and continental convective and stratiform rain contributions, although their diurnal amplitudes vary with each zone and season.

Figure 13 shows the relative contributions (as a percentage) of rainfall in each 3-hourly diurnal time interval with respect to total daily rainfall, for the 8-yr 2a25 dataset, divided into mean seasonal total, convective, stratiform, and “other” rainfall categories. The relative changes of the percentages every 3 h depict the diurnal loading of the categorized rainfall. The seasonal diurnal patterns are relatively stationary but with distinct characteristics associated with oceans and continents. Over oceans, the diurnal patterns are very similar for the different rain categories. This property is likely due to the fact that stratiform oceanic rainfall always accompanies convective rainfall (Houze 1997). Thus, all categories are nearly equally important from a loading perspective, but obviously not from a relative contribution perspective, as the prior results confirm. This type of diagram is just as effective as a rain-rate diagram in emphasizing the modal maxima, which is why the primary oceanic mode is evident in both convective and stratiform categories (as well as in the other category), while only the stratiform rain loading exhibits the secondary mode in the early afternoon. Over continents, there are exceedingly variable but stationary diurnal loading patterns for the four different rainfall categories. An afternoon primary peak and a late evening secondary peak of convective rainfall are stationary throughout the four seasons (the secondary autumn peak is very weak), as are these same peaks in total rainfall. By the same token, the stratiform rainfall exhibits a late evening primary peak for all seasons but
only an afternoon secondary peak during spring and summer. It is worthwhile to point out that the other rainfall category exhibits a diurnal loading pattern similar to that for convective rainfall over continents regardless of the fact that this category’s rain amounts are very small, but with only one obvious delayed afternoon peak.

A synthesis of the diurnal behavior across the four
rainfall categories indicates that the primary late evening peak of oceanic rainfall is due to organized convective systems, with stratiform rainfall inevitably associated with the convective component (as described by Houze 1997). In contrast, the afternoon primary peak in continental rainfall is mostly due to the convective mode alone. In addition, the stationary late evening secondary peak of stratiform rainfall over continents indicates that the diurnal cycle of the total rainfall is strongly influenced and ultimately modulated by stratiform processes. In the case of oceans, the weak afternoon secondary peak is also due to modulation by diurnal stratiform processes, but is not exclusive of accompanying convective processes. Thus, it would be more accurate to conclude that the dual-mode behavior over oceans is a cooperative relationship between convective and stratiform processes, in which both modulate a primary mode with a nascent secondary mode, but one that never achieves prominence at the global scale within a multiyear framework.

5. Regional and interannual variability

The results discussed previously point out that oceanic rainfall at the global scale in a multiyear framework exhibits an afternoon secondary peak, but one that is much weaker than its continental counterpart and one that virtually disappears during the autumn and winter seasons. However, results from our previous study (Yang and Smith 2006) indicate that a well-defined secondary peak in oceanic total rainfall is apparent at the seasonal–regional scale for an individual year (1998). Thus, we analyze two 8-yr TRMM datasets (i.e., from algorithms 2a25 and 2b31) at the regional scale followed by an analysis within an interannual framework, both analyses designed to question if the secondary oceanic feature is consistently weak or is simply being smeared out by too much extended averaging.

To carry out the first analysis, six regional domains have been selected. Five of these are oceanic while one is continental. They are as follows: 1) west Pacific (WP; 5°S–5°N, 150°–165°E), 2) east Pacific (EP; 10°–20°N, 125°–110°W), 3) Atlantic Ocean (AO; equator–10°N, 40°–25°W), 4) Indian Ocean (IO; 5°S–5°N, 75°–90°E), 5) South China Sea (SCS; 10°–20°N, 110°–120°E), and 6) Brazil rain forest (BRF; 15°S–equator, 65°–45°W). These domains are characterized by either climatologically heavy rainfall or have been given special attention in recent field campaigns focused on major precipitation processes. For example, the west Pacific region is associated with the TRMM Kwajalein Experiment (KWAJEX; Yuter et al. 2005), the South China Sea

(a) Summer

(b) Winter

FIG. 12. Same as in Fig. 11 but for three latitude belts: zonal 1 (10°S–10°N), zonal 2 (10°–20°S and 10°–20°N), and zonal 3 (20°–30°S and 20°–30°N) during (a) summer and (b) winter.
FIG. 13. Diurnal cycle of the relative contributions of rainfall in each 3-hourly diurnal time interval to
total daily rainfall (%) for mean seasonal total (T), convective (C), stratiform (S), and “other” (O)
rainfall over (left) ocean and (right) continents for 8 yr of rain-rate measurements from algorithm 2a25.
Table 3. Mean contributions (%) of seasonal–annual convective, stratiform, and other, type rainfall from 8 yr of 2a25 and 2b31 algorithm retrievals over six selected regions: WP (5°S–5°N, 150°–165°E), EP (10°–20°N, 125°–110°W), AO (equator–10°N, 40°–25°W), IO (5°S–5°N, 75°–90°E), SCS (10°–20°N, 110°–120°E), and BRF (15°S–equator, 65°–45°W). (C, S, and O are defined in Table 1 legend.)

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<tr>
<td></td>
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<td>S</td>
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</tr>
<tr>
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<td>50.2</td>
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<td>52.4</td>
<td>50.2</td>
<td>0.1</td>
<td>52.4</td>
<td>50.2</td>
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<tr>
<td>Autumn</td>
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<td>52.4</td>
<td>0.2</td>
<td>47.5</td>
<td>52.4</td>
<td>0.2</td>
<td>47.5</td>
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<td>Winter</td>
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<td>0.1</td>
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<tr>
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<td>51.6</td>
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<td>0.1</td>
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<td>51.6</td>
<td>0.1</td>
<td>51.6</td>
<td>51.6</td>
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The diurnal cycles of the mean seasonal contributions for convective and stratiform rainfall from the 8-yr 2b31 dataset are shown in Fig. 15. This diagram is complex but helps reveal a few basic issues concerning the regional variations. Two cases are examined in de-
We first consider the continental BRF case, in which convective rainfall indicates a stationary afternoon primary peak, whereas stratiform rainfall indicates moderate to strong early morning primary peaks and moderate late evening peaks. The convective component heavily dominates the early afternoon precipitation producing $\sim 75\%$ of the total rainfall during the dry season and $\sim 60\%$ during the wet season. Alternatively, stratiform rainfall contributes $\sim 50\%$ to $60\%$ to the late evening–early morning total rainfall during the wet season and $\sim 45\%$ during the dry season. Seasonal changes in diurnal variability are consistent with the results of Machado et al. (2002, 2004) over the Amazonian rain forest domain based on LBA surface radar and satellite measurements.

An interesting maritime case is SCS. As shown in Table 4, rainfall in the SCS domain exhibits delayed primary and secondary peaks in spring and summer. Moreover, the delays are evident in both spring and summer for the primary convective mode (in which the secondary mode is not present), and in the primary stratiform mode (in which the secondary mode is present but weak). The autumn and winter seasons exhibit relatively moderate to strong primary and secondary peaks in convective rainfall but with delayed phases, unlike stratiform rainfall, which exhibits phases at the regular times. This emphasizes that the answer to the question given at the beginning of the section is that the secondary oceanic mode can be strong on a seasonal–regional basis.

Figure 16 presents the results from the interannual analysis to demonstrate that just as the secondary oceanic peak can be a major feature at regional scales, when the averaging is taken within an annual time frame even at the global scale, the oceanic secondary peak can be just as prominent. This is seen by noting that the abscissas of the two diagrams in Fig. 16 represent repeated diurnal cycles for the sequential annual intervals. Thus, for oceans there are very pronounced secondary peaks for the years 2002, 2003, and 2005; less pronounced secondary peaks for the years 1999 and 2000; and no secondary peaks for the years 1998, 2001, and 2004. It is also quite evident that whereas stratiform rainfall dominates the secondary peak structure, both convective and stratiform rainfall contribute to the primary mode. For continents, stratiform rainfall modulates the behavior of the diurnal modes, especially the secondary late evening mode, while the primary diurnal peak is completely dominated by the convective com-

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**Fig. 14.** Diurnal variations of mean seasonal surface rainfall (mm day$^{-1}$) for 8 yr of rain-rate measurements from algorithm 2b31 over six regional domains: WP, EP, AO, IO, SCS, and BRF.
known major climatic rainfall processes in the ITCZ, precipitation (e.g., see Song et al. 2004). To produce errors in the very basic properties of stratiform rainfall and stratiform variability at global and regional scales. The highly consistent behavior among these three algorithms for mean horizontal rainfall distributions, and for the underlying seasonal variations, confirms the intrinsic reliability of the TRMM rainfall products. Perhaps then our results may serve as a metric for validating climate models, which generally produce errors in the very basic properties of stratiform precipitation (e.g., see Song et al. 2004).

Seasonal rainfall variations correspond to well-known major climatic rainfall processes in the ITCZ, SPCZ, Asian monsoon, tropical African–South American rain forests, subtropical maritime storm tracks, and subtropical South African–South American wet–dry regimes, with accuracy and horizontal detail. As expected, the zonal mean rainfall patterns from 2a12, 2a25, and 2b31 exhibit small differences over both oceans and continents. The seasonal changes in zonal mean oceanic rainfall account for the seasonal movement of the ITCZ. The secondary peak in zonal mean rainfall during winter is in response to SPCZ intensification, with the major peak corresponding to movement of the ITCZ into the SH. Seasonal changes in the zonal mean continental rainfall maxima are well correlated with Asian monsoon activity and variations arising due to the wet–dry season cycles in South Africa and South America.

The overall contributions of oceanic convective and stratiform rainfall to total rainfall are ~42%–45% and ~55%–58%, respectively, while the contributions of the continental convective and stratiform rainfall are ~52% and ~48%, respectively. The seasonal variations in oceanic convective and stratiform rainfall contributions are small, ~2% for both, but up to ~11% for continents. Along with selected seasonal variations, there are significant variations in convective and stratiform rainfall contributions for both oceans and continents when the data are analyzed at the seasonal–regional and interannual global scales. In general, there is relatively more oceanic convective rainfall in areas of heavy rainfall and even over certain areas of weak rainfall, such as in the southeast Pacific Ocean, as well as over almost all tropical and subtropical continental areas. Conversely, stratiform rainfall is most dominant over subtropical ocean areas.

### 6. Discussion and conclusions

Eight years (1998–2005) of rainfall retrievals from three standard TRMM level 2 rain-rate algorithms (TMI-only 2a12, PR-only 2a25, and combined PR–TMI 2b31) have been used to analyze seasonal convective and stratiform rainfall variability at global and regional scales. The highly consistent behavior among these three algorithms for mean horizontal rainfall distributions, and for the underlying seasonal variations, confirms the intrinsic reliability of the TRMM rainfall products. Perhaps then our results may serve as a metric for validating climate models, which generally produce errors in the very basic properties of stratiform precipitation (e.g., see Song et al. 2004).

Seasional rainfall exhibits significant diurnal variations within both the day–night framework and within the continuous diurnal cycle framework. Consistently greater daytime rainfall over continental and coastal areas and greater nighttime rainfall over open oceans are the principal features. The distributions of zonal mean oceanic convective and stratiform rainfall contributions during daytime and nighttime are almost stationary over the four seasons. In addition, daytime continental convective rainfall consistently exceeds nighttime rainfall over continents, whereas for oceans the reverse is true. On the other hand, seasonal stratiform rainfall exhibits a complex horizontal ratio distribution of its daytime to nighttime rainfall. Also, there is no consistent behavior of the daytime to nighttime ratio for seasonal stratiform rainfall over either oceans or land. More daytime stratiform rainfall is found over some oceanic and continental regions, with the opposite true elsewhere, with seasonal changes apparent.

| Table 4. Summary of presence (yes, Y; no, N) and relative amplitude (strong, S; moderate, M; weak, W) of primary and secondary peaks in six regional domains (WP, EP, AO, IO, SCS, BRF) for four cardinal seasons. If “(d)” is indicated in either of the “presence” columns, this denotes a major delay in the onset of the maximum relative to typical phase times for either the primary or secondary modes. |
|---|---|---|---|---|---|---|
| Season | Region | Primary peak | Secondary peak |
| | | Presence | Relative amplitude | Presence | Relative amplitude |
| Spring | WP | Y | S | Y | M |
| | EP | N | — | Y | W |
| | AO | Y | W | N | — |
| | IO | Y | M | Y | M |
| | SCS | Y (d) | M | N | — |
| | BRF | Y | S | Y | W |
| Summer | WP | Y | S | Y | M |
| | EP | Y (d) | M | Y (d) | M |
| | AO | Y | M | N | — |
| | IO | Y | W | Y | W |
| | SCS | Y (d) | S | Y (d) | W |
| | BRF | Y | S | N | — |
| Autumn | WP | Y | M | Y (d) | M |
| | EP | Y | M | Y | M |
| | AO | Y | M | Y | W |
| | IO | Y | M | Y | S |
| | SCS | Y | S | Y | S |
| | BRF | Y | S | N | — |
| Winter | WP | Y | M | Y | M |
| | EP | Y | W | Y | W |
| | AO | Y | M | Y | M |
| | IO | Y | M | Y (d) | M |
| | SCS | Y | S | Y | S |
| | BRF | Y | S | Y | M |
These results suggest that the seasonal variation of stratiform rainfall is the important modulator of the afternoon secondary peak of oceanic rainfall and the late evening secondary peak of continental rainfall.

The generally greater daytime to nighttime rainfall over the MSC regions is in contradiction to many modeling results. It may seem odd that we find the apparent cause of the daytime MSC maximum to be due to strati-
form rainfall when the pending controversy concerns a daytime convective overturning mode. This is simply due to the fact that the 2a23 convective–stratiform categorization algorithm might not validly identify shallow warm rain as a convective process. Instead, it is assigned to the stratiform category in keeping with the generally accepted definitions of the properties of stratiform rainfall. In any circumstance, these results indicate that modelers will have to pay greater attention to the mechanisms of both convective and stratiform precipitation within MSC environments.

Overall, seasonal oceanic rainfall exhibits a dominant late evening peak, while continental rainfall exhibits a dominant afternoon peak and a late evening secondary peak.
The in-phase relationship between the dominant convective rainfall peak and the dominant peak of the total rainfall indicates that convective rainfall activities produce the overall primary diurnal mode of the surface rainfall over both oceans and continents. Stratiform rainfall exhibits a small afternoon peak over oceans and a clearly evident late evening peak over continents. Thus, we conclude that stratiform rainfall is always modulating the rainfall diurnal cycle, in terms of the presence, amplitude, and phase of the secondary mode. Seasonal stationarity is a main feature of the primary peak of rainfall’s diurnal cycle, but this is not the case for the secondary peak, particularly in terms of the stratiform component. It is also noted that the small amounts of “other” oceanic rainfall exhibit a similar diurnal pattern to its stratiform counterpart, while its delayed afternoon peak over continents mimics the diurnal cycle of cloudiness over continents (Wylie and Woollf 2002).

The diurnal cycles of rainfall over six selected regions exhibit distinct features as initially discussed in Yang and Smith (2006) and distinct seasonal variability. These results demonstrate that the seasonal–regional diurnal cycles of rainfall are strongly associated with the varying physics of precipitating cloud systems and storms, and to the atmospheric environments in which they develop. In fact, the relatively weak afternoon secondary peak of oceanic rainfall found at the global scale within the multiyear framework becomes very strong selectively at the seasonal–regional scale. Moreover, it is found that the amplitude of the secondary peak of the oceanic rainfall on a global scale varies between strong and weak (even nonexistent) depending on the year, that is, its interannually varying behavior; all of which suggests that the secondary peak is an important property of the global precipitation and one that global modelers need to address as modeling faces up to the task of replicating all but the simplest properties of global precipitation.

The underlying significance of the results is that they force a break with the past in the analysis of diurnal precipitation variability. Typically, and for over a century, studies of rainfall’s diurnal variability have considered total rainfall almost exclusively. The appearances of secondary, tertiary, and even quaternary modes have never been explained theoretically (or even heuristically) with any consensus concerning cause [see Yang et al. (2008, in this issue) for detailed discussion on the secondary diurnal modes]. The results presented here demonstrate the importance of partitioning total rainfall into separate convective and stratiform components, and then recognizing that the behavior patterns of separate diurnal modes largely arise from distinct diurnal stratiform variations modulating convective variations. This suggests, in essence, that stratiform variations are the underlying control on the amplitude and phase of the primary and secondary modes, and perhaps additional higher-frequency modes. In our view, these properties of precipitation’s diurnal variability will have to be considered in any future investigations concerning rainfall’s diurnal cycle.

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REFERENCES

Geerts, B., and Y. Dawei, 2004: Classification and characteriza-


