Persistent Nature of Secondary Diurnal Modes of Precipitation over Oceanic and Continental Regimes

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ABSTRACT

This investigation seeks a better understanding of the assorted mechanisms controlling the global distribution of diurnal precipitation variability based on the use of the Tropical Rainfall Measuring Mission (TRMM) microwave radiometer and radar data. The horizontal distributions of precipitation’s diurnal cycle are derived from 8 yr of TRMM Microwave Imager (TMI) and Precipitation Radar (PR) measurements involving three TRMM standard rain retrieval algorithms; the resultant distributions are analyzed at various spatiotemporal scales. The results reveal both the prominent and expected late-evening (LE) to early-morning (EM) precipitation maxima over oceans and the counterpart prominent and expected mid- to late-afternoon (MLA) maxima over continents. Moreover, and not generally recognized, the results reveal a widespread distribution of secondary maxima, which generally mirror their counterpart regime’s behavior, occurring over both oceans and continents. That is, many ocean regions exhibit clear-cut secondary MLA precipitation maxima, while many continental regions exhibit just as evident secondary LE–EM maxima.

This investigation is the first comprehensive study of these globally prevalent secondary maxima and their widespread nature, a type of study only made possible when the analysis procedure is applied to a high-quality global-scale precipitation dataset.

The characteristics of the secondary maxima are mapped and described on global grids using an innovative clock-face format, while a current study that is to be published at a later date provides physically based explanations of the seasonal regional distributions of the secondary maxima. In addition to a primary “explicit” maxima identification scheme, a secondary “Fourier decomposition” maxima identification scheme is used as a cross-check to examine the amplitude and phase properties of the multimodal maxima. Accordingly, the advantages and ambiguities resulting from the use of a Fourier harmonic analysis are investigated.

1. Introduction

Studies of atmospheric diurnal processes that are influenced by the regulated daily cycle of incoming solar radiation at the top of the atmosphere (TOA) have been taking place for over 100 yr. The seminal study of Hann (1901) was the first to address precipitation’s diurnal cycle. Observational and modeling analyses have demonstrated that diurnal processes are evident in many atmospheric quantities. These include precipitation (e.g., Hong et al. 2005; Yang and Smith 2006), surface temperature (e.g., Smith 1986), surface winds (e.g., Deser and Smith 1998), surface pressure (e.g., Petenko and Argentini 2002), vertical motion (e.g., Krishnamurti and Kishawal 2000), cloudiness (e.g., Wylie and Woolf 2002), and surface and TOA radiation fluxes.

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(e.g., Smith et al. 1986; Smith and Shi 1992; Smith and Rutan 2003) as some of the foremost variables. Notably, lengthy time series derived from satellite measurements of various atmospheric variables have motivated new types of research concerning diurnal variability.

This has been particularly true for precipitation since the advent of the Tropical Rainfall Measuring Mission (TRMM) and its associated TRMM Microwave Imager (TMI) radiometer and Precipitation Radar (PR) rain-rate retrievals dating back to November 1997. Many mechanisms have been proposed to explain diurnal precipitation behavior (see Table 1 for definitions of acronyms used in explaining dynamically, thermodynamically, and radiatively forced mechanisms involved in regulating the diurnal variability of precipitation). The “static radiation–convection” (SRC) mechanism (e.g., Randall et al. 1991), “dynamic radiation–convection” (DRC) mechanism (e.g., Gray and Jacobson 1977), “nighttime radiative cooling” (NRC)–“elevated relative humidity” (ERH) mechanism (e.g., Tao et al. 1996; Sui et al. 1997, 1998), or the slowly evolving, diurnally varying “large-scale vertical motion” (LSVM) mechanism (e.g., McBride and Gray 1980) represent various possible explanations for the well-established “late-evening” (LE)–“early-morning” (EM) oceanic surface precipitation maximum, while the diurnally regulated surface “solar radiative heating” (SRH) mechanism, which can manifest itself in either the form of a “static destabilization” (SD) mechanism or a “differential heating” (DH) mechanism, are the foremost explanations for the often-observed “mid- to late-afternoon” (MLA) continental surface precipitation maximum (e.g., Ramage 1971; Pielke 2002). A number of studies using regional observations (e.g., Schwartz and Bosart 1979; Oki and Musiake 1994; Anderson et al. 1996; Sui et al. 1998; Chen et al. 1999; Dai 2001) have reported a secondary LE–EM peak in the continental diurnal precipitation cycle. The main possible explanations for this mode, which have been reviewed by Yang and Smith (2006), consist of the “mobile terrain-forced precipitating system” (MTFPS) mechanism and a continentally based NRC–ERH mechanism. There is also a counter-part MLA secondary peak in the oceanic diurnal precipitation cycle (e.g., McGarry and Reed 1978; Reed and Jaffe 1981; Augustine 1984; Fu et al. 1990; Serra and McPhaden 2004), for which the only plausible explanation that can be put forward is an “ocean surface heating” (OSH) mechanism, which involves near-surface ocean, sea, and inland lake layers and moist boundary layers over water.

However, there is yet to be an investigation of the secondary diurnal mode of precipitation as a global phenomenon. Yang and Smith (2006) provide a detailed review and analysis of the variety of mechanisms controlling the diurnal cycle of precipitation. Based on the use of TRMM precipitation data, their analysis demonstrated that diurnal precipitation variability is a global phenomenon with embedded diurnal forcing factors, which are far more complex than can be explained with a few general causes (i.e., the approach followed by nearly all past literature concerning this topic). The primary and dominant LE–EM oceanic precipitation maximum is often accompanied by a secondary MLA maximum, while the primary and dominant MLA continental precipitation maximum is often accompanied or even replaced by a secondary LE–EM maximum.

As Yang and Smith (2006) emphasize, there are a host of mechanisms at work that produce the diurnal precipitation process, not one of which solely explains the entire process. Instead, a mixture of mechanisms, whose individual components control regional- and smaller-scale diurnal modes, work together to produce the averaged global process. Notably, most modeling studies investigating diurnal variability, particularly studies based on the atmospheric general circulation model (GCM), have focused on stand-alone singular mechanisms (e.g., Randall et al. 1991; Dai and Trenberth 2004). The recent study of Dai (2006), reviewing results from 18 coupled atmosphere–ocean GCMs (AOGCMs), indicates large discrepancies involving the diurnal variability of precipitation among the different models. Therefore, given these findings and our experience with analyzing TRMM data, it appears that modellers should improve the “diurnal processes” capabilities of their models, including precipitation, to ensure that they reliably simulate atmospheric circulations that themselves are diurnally modulated.

Furthermore, more detailed observational analyses

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<tr>
<th>Acronym</th>
<th>Definition of acronym</th>
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<tr>
<td>DH</td>
<td>Differential heating mechanism</td>
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<td>DRC</td>
<td>Dynamic radiation-convection mechanism</td>
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<td>LE-EM</td>
<td>Late-evening-early-morning diurnal maximum</td>
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<td>LSVM</td>
<td>Large-scale vertical motion mechanism</td>
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<td>MLA</td>
<td>Mid- to late-afternoon maximum</td>
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<td>MTFPS</td>
<td>Mobile terrain-forced precipitating system mechanism</td>
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<td>NRC-ERH</td>
<td>Nighttime radiative cooling-elevated relative humidity mechanism</td>
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<td>OSH</td>
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<td>SRH</td>
<td>Solar radiative heating mechanism</td>
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of the spatiotemporal characteristics of diurnal cycle variations are needed to reveal their unique properties so that the mechanisms of the diurnal cycle can be better explained physically. Modelers would then have a better quantitative basis from which to refine model processes that control the diurnal variability of precipitation. Yang and Smith (2008) describe the seasonal climatology of the diurnal cycle at global scales, its seasonal variability, and the contrasting behaviors of convective and stratiform components, and demonstrate that the secondary diurnal mode is largely modulated by the diurnal cycle of stratiform precipitation. In addition, Yang et al. (2006) found the consistent appearance of global-scale secondary precipitation maxima from 8 yr of TRMM data.

As a follow-up, this study demonstrates the widespread consistency in the occurrence of a secondary diurnal mode in precipitation globally, and at seasonal and regional scales. To obtain the detailed view, an innovative clock-face graphic display scheme is used to aid the analysis. Eight-year TRMM precipitation datasets derived from three level-2 TRMM standard rain-rate algorithms are used to conduct the analysis using an “explicit” scheme to identify the key diurnal modes. As a cross-check, as well as to investigate the reliability of another popular scheme, the Fourier harmonic analysis technique is also applied to identify the dominant diurnal modes of precipitation variability while suppressing the unimportant diurnal harmonics. The advantages and ambiguities related to the use of Fourier analysis are then discussed to draw attention to what can and cannot be achieved by using this technique in studying precipitation’s diurnal cycle.

2. Methodology and dataset

An explicit precipitation maxima selection scheme is first used to identify the primary and secondary diurnal modes at various space–time scales. A Fourier decomposition selection scheme is then applied as a cross-checking method and as a means to filter out ambiguous time series noise. Gridded properties of the diurnal cycle are illustrated using the clock-face display scheme. The different colors of the clock hands denote the different diurnal modes, while the length and position of the clock hands denote amplitude and phase characteristics of the separate diurnal modes. In addition, clock-face colors are used to express the canonical phase interval of the primary diurnal mode.

The explicit selection scheme is based on logic-based detection of local relative precipitation-rate maxima in a given diurnal time series. This scheme consistently identifies the appearance of either primary or secondary modes, as long as each of the separate amplitudes exceeds a minimum amplitude-emergence threshold (viz., 0.6 mm h$^{-1}$) and there is sufficient separation in the positions of the two detected peaks, according to a second phase-angle separation threshold given in time units (viz., 6 h). Application of the explicit scheme may result in identification of either primary and secondary modes, only a primary mode, or no modes at all. Tertiary and quaternary modes are also identified with the explicit scheme.

The second scheme is the Fourier decomposition selection scheme. This scheme, by definition, identifies amplitudes and phases of all wavenumbers. However, in the analysis procedure we apply, only the primary through quaternary modes are examined. It is noted that the assignment of phases for the secondary through quaternary modes requires an adjustment procedure to the raw phase information for wavenumbers 1–3 (i.e., Fourier harmonics 2–4). For example, in assigning the phase of a secondary mode, and defining the raw phase angles of the first and second Fourier harmonics as $\phi_1$ and $\phi_2$, existence of a peak for the secondary diurnal mode is only established when each of the following two conditions is satisfied:

$$|\phi_2 - \phi_1| < 45^\circ,$$  
$$|\pi + \phi_2 - \phi_1| < 45^\circ.$$  

Thus, the peak of the second harmonic is separated from the peak of the first harmonic by at least 6 h. Otherwise, the primary and secondary modes would merge into a different primary mode with a different phase. Likewise, the phase positions of the tertiary and quaternary modes must be established by ensuring appropriate phase-angle separations. As indicated earlier, the clock-face graphic display scheme can then be used to illustrate the various parameters associated with the diurnal analysis on a regular grid.

Eight-year (1998–2005) precipitation datasets derived from the three main level-2 TRMM standard precipitation algorithms are used for the study. These are the TMI-only (i.e., algorithm 2a12), PR-only (i.e., algorithm 2a25), and combined PR–TMI (i.e., algorithm 2b31) rain retrieval algorithms. The level-2 instantaneous rain rates at native orbit-swath pixel locations are first binned into eight 3-hourly mean solar time (MST) bins; then they are grouped at different spatial and temporal resolutions. A hierarchy of $5^\circ \times 5^\circ$, $10^\circ \times 10^\circ$, $20^\circ \times 30^\circ$, and $20^\circ \times 60^\circ$ latitude–longitude spatial grid resolutions are then used in processing the data at seasonal and 8-yr mean temporal scales.
3. Diurnal properties of precipitation at a global scale

The distribution of the 8-yr mean TRMM-based diurnal precipitation cycle over oceans and continents depicts a distinct climate feature on the global scale. Figure 1 shows the climate characteristics of diurnal variability from TMI-only, PR-only, and combined PR–TMI rain retrievals. This diagram clearly shows that the diurnal precipitation cycles from the three TRMM rain products are consistent in terms of amplitude and phase over oceans and in phase over continents, although with somewhat larger TMI precipitation amplitudes. Oceanic precipitation has a dominant late-night maximum in the 0300–0600 MST time frame, while continental precipitation has a prevailing late-afternoon peak in the 1500–1800 MST time frame.

Seasonal variability of the diurnal cycle is another important feature described in detail by Yang and Smith (2008). Figure 2 illustrates the climatology of seasonal variations of the diurnal cycle over oceans and continents using 8-yr 2a25 PR rain rates. The primary maximum at 0300–0600 MST of oceanic precipitation is prominent in spring [March–May (MAM)], autumn [September–November (SON)], and winter [December–February (DJF)], but is relatively weak in summer [June–August (JJA)]. At the global scale, the secondary maximum over oceans is not obvious for any season. The primary late-afternoon peak at 1500–1800 MST of continental precipitation is the most dominant feature. The secondary late-night maximum is most apparent in summer/winter, and is weak but detectable in spring/autumn.

The diurnal variations of convective and stratiform precipitation from 2a25 are also illustrated in Fig. 2. Over oceans, convective precipitation exhibits the same diurnal properties as total precipitation, while stratiform precipitation exhibits a secondary peak in early afternoon in the winter, in addition to its dominant late-night maximum. Over continents, the dominant late-afternoon peak in convective precipitation mimics the diurnal behavior of total precipitation, while stratiform precipitation exhibits a late-night maximum at 0300–0600 MST and a late-afternoon maximum at 1500–1800 MST. The TMI-only and combined PR–TMI rain-rate products (figures omitted) indicate mostly similar characteristics in regards to diurnal variability. The Yang and Smith (2008) study discusses the convective and stratiform properties of primary and secondary diurnal modes in detail.

4. Persistent nature of the secondary diurnal mode

a. Characteristics of the secondary mode

Horizontal distributions of the diurnal precipitation cycle based on the 8-yr TRMM rain products analyzed on a 5° × 5° grid are shown (see Fig. 4), illustrated in the format of clock-face diagrams. The schematic explanations on features of the clock-face diagram are illustrated in Fig. 3. A blue (green) color face of a given clock denotes a prenoon half-day (postnoon half-day) phase interval of the dominant maximum for each grid location, where the prenoon half-day phase interval is defined from 0000 to 1200 MST and the postnoon half-day phase interval is from 1200 to 2400 MST. The tran-
sition of clock-face color is evident along almost all coastlines. This draws attention to the dominance of the prenoon precipitation maximum over oceans (blue) and the postnoon precipitation maximum over continents (green). This behavior was reported by Yang and Smith (2006) for a 1-yr dataset (1998). Here it is graphically and robustly illustrated using 8 yr of data at high spatial resolution at specific grid regions. It is seen that
at the $5^\circ \times 5^\circ$ spatial scale, a few oceanic grid locations exhibit dominant postnoon maxima, while a few continental grid locations indicate dominant prenoon maxima. The reasons for these exceptions deserve further examination. In addition, close examination of the clock faces reveals that secondary maxima (denoted by light gray inner faces) are widespread throughout the tropics and subtropics observed by the TRMM satellite, in which secondary postnoon peaks are found over oceans and secondary prenoon peaks are found over continents. These characteristics are highly consistent between the TMI, PR, and combined PR–TMI rain products.

Similar analyses conducted at $20^\circ \times 30^\circ$ spatial resolution scale are illustrated (see Fig. 5). At this grid scale, there is no ambiguity as to the separation of the primary prenoon and postnoon modes over oceans and continents, respectively (with the proviso that the mixed land–water Maritime Continent exhibits purely oceanic diurnal precipitation properties in regards to the primary mode). Note that at this grid scale, there is perfect agreement among the three algorithms in regards to the arrangement of the blue and green clock faces. Also, as in Fig. 4, there is a widespread but incomplete distribution of the secondary mode (marked by light gray inner clock faces), noting that for this diurnal property, whereas there is general agreement among the three algorithms, there is not perfect agreement. These two aspects of the secondary mode, along with other more obscure characteristics found by close examination of the amplitudes and phases of the secondary mode (i.e., denoted by the appearances, lengths, and positions of green clock hands), indicate that it is a more complex process than that of the primary mode. It is also apparent that the secondary mode over continents is more prevalent. Quantitatively, the results show that there is 72%, 61%, and 77% consistency, respectively, in the occurrence of secondary peaks identified between the following three algorithm pairings: 2a12–2A25, 2a12–2b31, and 2a25–2b31.

Another set of similar analyses is presented (Fig. 6), but now based only on the PR algorithm and comparing the $20^\circ \times 30^\circ$ result shown in Fig. 5 with results at $10^\circ \times 10^\circ$ and $20^\circ \times 60^\circ$ spatial resolutions. Although there is general agreement between the members of this set of results, there are interesting and pertinent differences pertaining to spatial resolution. First, the secondary peak is not evident over the central Pacific Ocean at the $20^\circ \times 30^\circ$ grid scale, but appears over this region at the $10^\circ \times 10^\circ$ grid scale. This same effect is found over the Indian Ocean and the northwest Pacific Ocean subtropical regions. In addition, there are differences associated with the different horizontal scales on the occurrence of secondary maxima in the central-west Indian Ocean, the central-east Pacific Ocean, and North Africa.

In summarizing the effects of spatial resolution on the areal cover of the secondary mode (see Table 2), it is found that the percentage of low-resolution grid positions (Fig. 6, top) indicating the presence of a secondary peak is 78% (i.e., 14 of 18 grids), whereas for the medium-resolution grid array (Fig. 6, middle) the percentage falls to 69% (25 of 36), and then down to 65% (188 of 288), for the high-resolution grid array. Based on the PR result of Fig. 4 (middle) at the highest spatial resolution used in the study (i.e., $5^\circ \times 5^\circ$), the percentage rises to 68% (783 of 1152). This emphasizes the sensitivity to grid resolution in evaluating the areal coverage of the secondary peak in the framework of 8-yr
means, with the end result being a difference of some 13% between the smallest and largest areal cover values.

Notably, when these areal cover sensitivities to spatial resolution are decomposed into differences for oceanic and continental regimes, the percentage differences become larger—30% for ocean and 21% for continents, as Table 2 indicates. The much larger difference for ocean is primarily due to the mixing of continental and oceanic secondary peaks at the lowest resolution. Therefore, whereas it is evident that the secondary peak in precipitation’s diurnal cycle is a widespread phenomenon over the global tropics and subtropics, caution must be exercised when evaluating the quantitative cover factors for oceans and continents because of the sensitivities involved. (Similar analyses using TMI and combined PR–TMI precipitation datasets lead to almost identical percentage differences, emphasizing the robustness of the results.)

Based on analyzing the twenty-first-century climate simulations by the newest generation of 18 coupled climate system models, Dai (2006) indicates that most climate models can reproduce general precipitation patterns and their basic annual variability, although some of these models continue to generate unrealistic double intertropical conversion zone (ITCZ) patterns over the tropical eastern Pacific Ocean—a persisting problem in climate modeling (Mechoso et al. 1995). In addition, Dai (2006) found that most models produce too much convective precipitation and too little stratiform precipitation, resulting from the unrealistically strong coupling of tropical convection to local sea surface temperatures. Most relevant to the concerns in this study, analyses of the diurnal precipitation cycle suggest that most models start to precipitate too early and too frequently at reduced intensity, showing a single late-morning–early-afternoon peak over continents and a single LE–EM peak over oceans. Many of these features are different from the TRMM diurnal precipitation analysis presented in this study, as well as in the

Fig. 4. Horizontal distributions of diurnal precipitation cycles based on TRMM satellite data averaged over 8-yr period (1998–2005) and analyzed on 5° × 5° spatial grids using clock-face diagrams. Results for (top) TMI, (middle) PR, and (bottom) combined PR–TMI algorithms are shown.

It should come as no surprise that climate models are unable to realistically simulate the diurnal variations of precipitation. Their spatial resolutions are too low vis-à-vis precipitation physics either to properly simulate the narrowly confined mass and water vapor convergence processes leading to convection, or to meaningfully resolve the vertical overturning of cloud systems that actually produce convective and stratiform precipitation fallout. Moreover, they do not have any type of meaningful microphysical parameterizations in regards to the initiation, growth, loss, phase change, and vertical motion of either nonprecipitating or precipitating hydrometeors. Thus, it is appropriate that the type of observationally based study such as that presented here, concerning highly detailed properties of precipitation processes, should be used to guide and calibrate future improvements in the embedded water cycle formulations of AOGCMs.

b. Convective and stratiform partitioning of the secondary mode

We have demonstrated that the horizontal distribution of the primary diurnal mode of precipitation over both oceans and continents is little affected by spatial resolution. However, the spatial averaging scale imparts a significant impact on the horizontal distribution of the secondary mode. Yang and Smith (2008) show that in an 8-yr-averaged global framework, the secondary mode is strong over continents but weak over oceans. They also find that when considering regional
seasonal scales the secondary mode becomes significant over oceans, and even more so over continents, and the different modes are largely modulated by diurnal stratiform precipitation variability. To explain the possible cause of this secondary mode behavior, we analyze the diurnal cycles of precipitation’s convective and stratiform components.

Figure 7 illustrates the horizontal distributions of the primary and secondary diurnal cycles of precipitation from mean 8-yr PR retrievals at the $20^\circ \times 30^\circ$ grid scale. Through inspection it is evident that both convective and total precipitation exhibit the same oceanic-continental contrast in the phase of the primary diurnal peak. Also, the secondary mode of the convective component nearly mimics the secondary mode of total precipitation. Detailed inspection reveals that for some clock-face positions, the phases of the dominant modes of both convective and total precipitation are approximately equivalent; however, there are phase shifts between the secondary modes for convective and total precipitation. For example, this type of behavior is readily apparent for clock-face positions of 1–2, 2–3, 8–1, 10–2, and 11–2 in Fig. 7, where the clock-face position indices are given in column–row coordinates. This shift is due to the modulation effect of stratiform precipitation on the behavior of the secondary diurnal cycle, as has been emphasized in Yang and Smith (2008), and is evident by comparing similarities in the phases between secondary modes of total precipitation and primary or secondary modes of stratiform precipitation for the five clock-face positions identified above. As seen in the lower panel of Fig. 7, an important feature is that the dominant peak of stratiform precipitation’s diurnal cycle over central Africa, Asia, Australia, and central South America occurs during the LE–EM period, while its secondary peak occurs during the MLA period at the same time as that of convective and total precipitation.

Therefore, over continents a primary LE–EM diurnal peak of stratiform precipitation is in phase with the secondary LE–EM peak of total precipitation, while convective and total precipitation exhibit similar primary MLA diurnal peaks. These results indicate that afternoon convection forced by surface solar radiative

![Fig. 6. Same as in Fig. 4, but for the PR-only algorithm with separate panels illustrating results on (top) $20^\circ \times 60^\circ$, (middle) $20^\circ \times 30^\circ$, and (bottom) $10^\circ \times 10^\circ$ grids.](image-url)
heating reaching its maximum diurnal intensity is responsible for the dominant afternoon peak of the continental diurnal precipitation cycle, that is, the SRH mechanism. The development time of stratiform precipitation suggests that any one of a number of possible mechanisms, such as the MTFPS, continental NRC–ERH, or perhaps even a, SRC or LSVM mechanism operating within a continental environment, might explain the LE–EM maximum in stratiform precipitation, which contributes to the secondary LE–EM peak of total precipitation. In addition, the DRC mechanism operating within a continental environment might elevate nighttime precipitation while suppressing daytime precipitation, which is how the DRC mechanism operates. These processes of convective and stratiform systems draw attention to how multiple mechanisms might compete with one another for dominance, resulting in counterpoised LE–EM and MLA modes in the continental diurnal precipitation cycle.

Over low-latitude oceans, stratiform precipitation inevitably accompanies convective precipitation, especially for strong convective systems (Houze 1997). In fact, the contribution of stratiform precipitation to total accumulation is about the same as that of convective precipitation (Yang and Smith 2008). Figure 7 actually shows that the dominant LE–EM peaks of convective and stratiform precipitation are in excellent agreement, suggesting that whatever mechanism is producing the LE–EM mode, for example, one or more of the SRC, DRC, NRC–ERH, or LSVM mechanisms, is operating in synchronization with both convective and stratiform components. In addition, the secondary MLA mode, that is, resulting from the OSH mechanism, is effective for both convective and diurnal stratiform precipitation variability; however, close inspection of Fig. 7 suggests that the modulation of the ocean’s secondary mode amplitude stems mostly from fluctuations in the stratiform amplitude. Similar analyses conducted at higher spatial resolutions lead to similar findings for the primary peak, while the secondary peak exhibits more complex

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Fig. 7. Same as in Fig. 5, but for the PR-only algorithm with separate panels illustrating results for (top) total, (middle) convective, and (bottom) stratiform precipitation.
behavior (diagram omitted). The secondary mode intermittently spreads out over the entire tropics and subtropics at the 5° × 5° grid scale. Over oceans, this behavior suggests that the secondary MLA mode is more important at smaller horizontal scales.

5. Harmonic analysis of the diurnal cycle

a. Diurnal characteristics revealed from harmonic analysis

A Fourier harmonic decomposition scheme is applied to examine the diurnal variability of precipitation in order to elucidate the foremost amplitude and phase features while filtering high-frequency noise. Because this approach suppresses spurious variations in a diurnal time series, which might be detected as extrema in the explicit method, it is worthwhile to evaluate its worth. Figure 8 compares the horizontal distribution of the diurnal precipitation cycle, based on the explicit scheme applied to 5° × 5° gridded PR-only retrievals over the 8-yr (1998–2005) time period, to a counterpart result, based on application of the Fourier decomposition scheme. The clock-face plots provide all of the essential details concerning amplitudes and phases for not only the primary and secondary modes, but also for tertiary and quaternary modes. Colors and clock-hand
direction denote phase information, while clock-hand length denotes amplitude information.

A strong contrast between primary harmonic diurnal phases over oceans and continents is the eye-catching feature in the upper panel of Fig. 8 (explicit scheme), as in the middle panel (Fourier decomposition scheme). The clear-cut contrast between the oceanic LE–EM phase and continental-like MLA phase along coastlines is actually sharper in the middle panel than in the upper panel. In addition, there are fewer spurious regions in the middle panel where the primary precipitation peaks are misidentified. A four-color clock-face scheme showing a more detailed representation of the phase interval of the primary mode is shown in the lower panel. Over oceans, the frequent occurrence of late-night interval (0000–0600 MST) peaks is the dominant diurnal feature, with additional occurrences of morning interval (0600–1200 MST) peaks largely over coastal regions. Over continents, the occurrence of early-evening interval (1800–2400 MST) peaks is the dominant feature over Africa and Australia, while the afternoon interval (1200–1800 MST) peaks are dominant over South America, North America, and Asia. These more detailed diurnal features suggest that either different mechanisms are at work or singular mechanisms dominate but are dispersive in their timing of the maxima within different environments. Similar analyses at lower spatial resolution confirms that the underlying spatial distribution patterns of primary and secondary modes, as seen in Fig. 8, are not greatly affected by the use of a high-resolution scale.

The higher-order harmonic modes conform to semi-diurnal, tridiurnal, and quartic-diurnal variations, and require an interpretation of where to position the actual peaks in terms of their phase angles in time. Figure 9 presents a comparison of the first three principal diurnal modes based on the use of the explicit scheme in the upper panel, and the first two principal Fourier harmonics in the lower panel cast onto 20° × 30° grids. The clock-face color exhibits a prenoon half-day phase interval (blue) and postnoon half-day phase interval (green) of the primary diurnal mode. The secondary modes are shown by the use of light gray inner clock faces. It is obvious that the horizontal distribution of the primary diurnal mode based on the use of the explicit scheme is consistent with the horizontal distribution of the same mode based on the use of the Fourier decomposition scheme; although, close inspection of the two diagrams shows that small phase differences occur. More relevant are the greater and more frequent differences concerning both amplitudes and phases of the secondary mode between the two maxima identification schemes.

The secondary mode will appear almost everywhere with Fourier analysis, simply because even if there is no secondary peak in actuality, almost invariably some
power will leak into wavenumber 2. Even though it does not satisfy the definition of the secondary mode over the northern part of South America and central South Africa, the secondary mode from the Fourier decomposition scheme is still apparent over these areas in comparison with the explicit scheme. For those grid positions where only a primary mode is found from the explicit scheme (such as over the central Pacific Ocean and the west Indian Ocean), a secondary mode is often identified from the Fourier analysis. The sources of the ambiguities associated with Fourier harmonic analysis of precipitation’s diurnal cycle are discussed in the next section.

b. Ambiguities associated with harmonic analysis

The results presented in the previous section demonstrate that the Fourier decomposition approach is robust for the primary diurnal mode of precipitation, especially the phase of the dominant diurnal peak, as noted in, for example, the Collier and Bowman (2004) and Yang and Smith (2006) studies. However, the nature of Fourier harmonic analysis can lead to the misinterpretation of both amplitudes and phases of different modes as they mix together, and even the mixing of perfect sinusoidal modes. This can be especially problematic when seeking to both identify and describe a secondary diurnal mode. Thus, ambiguities are inevitable when using Fourier analysis in analyzing precipitation’s diurnal variability. These ambiguities arise from a number of sources. Of necessity, diurnal precipitation modes are (a) generally truncated semidiurnal modes, (b) represented as repeating cycles over the 24-h diurnal period for wavenumber 1 and beyond, and (c) not purely sinusoidal, and thus are dispersive in their power spectrum over a spread of frequencies when considering realistic diurnal modes in actual observations.

Figure 10a demonstrates a case of Fourier decomposition for two purely sinusoidal, but truncated, diurnal modes with equal amplitudes but shifted phases. The two peaks occur in early morning and late afternoon. The original components and combined time series for the double-peak cycle are illustrated in the left three panels. The right four panels present their successive reconstructed diurnal cycles using the mean and first three principal Fourier harmonics. Note that the primary mode is the second harmonic (wavenumber 2), which produces two diurnal peaks. Along with the mean value (wavenumber 0), the primary mode reproduces the basic diurnal properties, but with a phase shift. Inclusion of the secondary mode (i.e., first harmonic, wavenumber 1) produces a more realistic time series in which both amplitudes and phases are near their original values. However, it is evident that at least three harmonics are needed to reconstruct a sound representation of the original combined time series, based on the mixing of two perfect, but truncated, sinusoids.

A similar analysis is conducted for another case in which the amplitude of the late-afternoon peak is much smaller than that of the early-morning peak (Fig. 10b). The primary mode (first harmonic, wavenumber 1) depicts the phase of the principal diurnal peak nicely; however, its amplitude is too small compared with the original value. Furthermore, the single primary harmonic cannot reproduce the secondary late-afternoon peak. It is evident that the reconstructed diurnal cycle produced by the inclusion of the second harmonic (wavenumber 2) produces a realistic primary early-morning peak in both amplitude and phase, as well as a realistic secondary late-afternoon peak in amplitude but with a phase shift. Thus, a third harmonic is needed to bring about a reconstructed diurnal cycle that is similar to the original.

Figure 10c presents a final case, but now for a realistic observational situation, with a dominant peak at noon and a weaker secondary peak in late afternoon. Additional higher-frequency fluctuations are also evident, which can be considered either real data properties or, more often, noise resulting from retrieval error and/or undersampling. Clearly, the harmonic approach can be used to eliminate the high-frequency waves. In reconstruction, the primary mode (first harmonic, wavenumber 1) clearly reproduces the phase of the dominant peak, although the weak secondary peak is missed. Because of the small phase separation between the dominant primary peak and weak secondary peak, the third harmonic (wavenumber 3) represents the secondary mode. Using only the first two principal harmonics, the reconstructed diurnal cycle exhibits the basic features of the original cycle, however, with a discernible phase shift in the secondary mode.

There are two main points to this analysis: First, when using the Fourier decomposition scheme, the dominant harmonic (along with the mean value) is able to reproduce the main features of the primary diurnal peak, particularly its phase. Second, the mean and first two principal harmonics generally can reproduce some, but not all, of the key features of the secondary peak. For some cases, the dominant harmonic cannot adequately reproduce the amplitude and/or phase features of the primary mode, but for the TRMM data we have analyzed, these occurrences only arise ~6% of the time. Thus, because the diurnal cycle of precipitation often has a dominant primary peak and a weaker secondary peak, the principal Fourier harmonic is used to represent the main features of the strong primary mode, while the second harmonic is used to represent...
Fig. 10. (a) Fourier decomposition of two purely sinusoidal, but truncated, equal-amplitude and phase-shifted diurnal modes combined into a two-peak diurnal cycle. The three left-hand panels show two separate diurnal modes along with a combined diurnal cycle. The four right-hand panels show successive reconstructions of the combined diurnal cycle using mean value (wavenumber 0) and first three principal Fourier harmonics (wavenumbers 1–3). (b) Same as (a), except that the two diurnal modes are (b) unequal amplitude and (c) are realistic (nonsinusoidal and unequal amplitude).
the main features of the weak secondary mode. In doing so, it must be recognized that a phase shift is often associated with the representation of the secondary mode, as well as possible amplitude errors for both modes. Note that the second harmonic is often needed to contribute to the amplitude behavior of the primary mode. Finally, also note that the harmonic approach can bring about a false secondary mode when only a single primary mode is present, considering the case when a second harmonic is used to compensate for amplitude misrepresentation in the primary mode.

Therefore, caution is always required in identifying secondary modes when using the Fourier decomposition scheme. Background knowledge of regional precipitation properties is always helpful in mitigating against ambiguities caused by applying harmonic analysis. In terms of our secondary mode analyses with TRMM precipitation data, the incidences of misinterpretation associated with the Fourier decomposition scheme are relatively frequent, particularly for the higher spatial resolutions, contaminating the results about 45% of the time.

6. Discussion and conclusions

This study has examined the diurnal variability of precipitation at various spatial and temporal scales based on 8-yr TMI, PR, and combined PR–TMI precipitation datasets. We find that these three distinct rain products produce consistent behavior in regards to the diurnal cycle properties of precipitation. The 8-yr-averaged diurnal cycles of oceanic and continental precipitation consistently exhibit primary maxima mostly during the 0300–0600 and 1500–1800 MST periods, respectively. Moreover, counterpart secondary maxima are strongly evident throughout the global tropics and subtropics, with seasonal variation being a very prominent feature of the secondary mode. These outstanding features of the diurnal behavior of oceanic and continental precipitation on a global scale are presented by use of a specially designed graphic made up of gridded clock faces with clock hands, and coloring techniques to simultaneously display the various key parameters of harmonically complex precipitation variation at the diurnal time scale. The secondary precipitation maxima generally consist of afternoon peaks over oceans and morning peaks over continents. Notably, this is the first study in which the widespread secondary mode has been identified and given special attention.

It is important to recognize that based on our past and current TRMM data analyses, we find that the secondary maxima are largely produced and modulated by stratiform precipitation (see Yang and Smith 2008) because of the tendency of stratiform precipitation to ex-
tend the time scale of precipitation accumulation. Although we have shown that the underlying properties of the diurnal precipitation cycle are influenced by the spatial and temporal resolutions at which the data are analyzed, we find that there is a great deal of consistency in how oceanic and continental regions contrast with one another, regardless of the underlying resolutions. For example, the impact of spatial resolution is generally not significant concerning the primary diurnal mode, although it can be significant in identifying the areal coverage of the secondary diurnal mode. Most importantly, the global distribution of the diurnal precipitation cycle exhibits considerable seasonal variations, largely resulting from the occurrence of secondary diurnal modes.

The main analysis tool we have used to understand the secondary mode is the “explicit” technique. The Fourier decomposition technique can also do a satisfactory job in identifying the main amplitude and phase features of the primary mode with the advantage of eliminating spurious high-frequency fluctuations in the diurnal time series. Generally, this approach works best when representing the phase of the primary diurnal mode. However, there are cases when secondary, tertiary, and even quaternary modes are needed in reproducing realistic amplitudes of the primary mode. In cases where these features exhibit strong amplitudes, the Fourier scheme can produce ambiguities vis-à-vis the interpretation of the primary diurnal mode.

We stress that the explicit approach is more reliable in identifying multimodal diurnal phenomena. Its only shortcoming is that it will occasionally identify a noise peak as a relevant mode. Alternatively, we have demonstrated how and why the Fourier decomposition scheme can create ambiguities in describing amplitude–phase properties of the secondary diurnal mode because of up-frequency mixing of power from the first principal mode into the higher-order modes. As a result, we have shown that secondary diurnal modes over some regions derived from the Fourier scheme are not real. Because Fourier analysis is such a popular method for analyzing time series containing diurnal properties, these are important considerations. Therefore, caution is in order when interpreting the amplitudes and phases of the secondary, tertiary, and quaternary modes, apart from any coherency at the global scale, when using Fourier analysis; note that ambiguities in representing the secondary mode are generally unavoidable. Under any circumstances, background knowledge of the pertinent meteorological variables controlling precipitation, as well as understanding of how the precipitation variables behave in response to the relevant diurnal mechanisms at work, are always helpful in analyzing secondary diurnal modes when using Fourier decomposition. Ultimately, a well-balanced mixture of the explicit technique with the Fourier technique might produce optimal results.

There are a number of issues where modeling studies would be useful in refining an understanding of the causes and regional properties of secondary and higher-frequency diurnal modes. Observational analysis by itself is often not sufficient for developing deep-rooted physical theories that explain geophysical phenomena. The diurnal behavior of precipitation appears to be one phenomenon that could use the help of numerical modeling, assuming the underlying models are of sufficient resolution and contain sufficient cloud physics and microphysics to produce realistic diurnal precipitation behavior. This remains a challenge to the modeling community.

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