

## 15. DIURNAL CYCLE OF MONSOON CONVECTION

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The diurnal variability of monsoon precipitation and associated circulation features, e.g. land/sea breezes, mountain/valley breezes, and low-level jets, in the monsoon regions of the world are reviewed, with a particular focus on the Asian monsoon. The dominant pattern of diurnal variability is a maximum in rainfall over land during the afternoon/evening in response to solar heating of the surface and a morning maximum over the oceans; however, there are important exceptions to this pattern over both land and ocean. Nocturnal maxima in rainfall are found over land in proximity to major mountain barriers, e.g., at the foot of the Himalayas; downstream of the Tibetan Plateau, the Rocky Mountains, and the Andes; and within interior basins such as the Sichuan Basin. Daytime maxima in rainfall are observed over partially enclosed seas such as the Bay of Bengal, the South China Sea, and the Gulf of Guinea. These latter regions are characterized by seaward propagation of convection from adjacent coastlines.

The mechanisms for the diurnal cycle of convection over land, particularly the afternoon maximum in precipitation, are generally well understood, but the timing of precipitation is often not well handled in models. Several theories for the diurnal cycle over the ocean have been proposed, involving surface and free-tropospheric radiative heating or their horizontal gradients; however, the precise mechanisms remain unclear and are not well represented in global models. Mechanisms for propagation of convective systems over both land and ocean are not completely understood and require further research.

### 1. Introduction

The diurnal cycle of precipitation is a dominant feature of all global monsoon systems, ranging from the world's most energetic monsoon – the Asian Monsoon – to the monsoon systems of the Americas and Africa. On the largest scales, continental mountain ranges generate significant diurnally varying circulations, vertical motion, and diabatic heating features (e.g., the Tibetan Plateau in Asia, the Andes over South America). On the mesoscale, localized land and sea breezes, mountain/valley circulations, and surface heterogeneities influence the diurnal cycle of precipitation patterns. In general, precipitation tends to be a maximum over land during the daytime and over the adjacent ocean areas at night; however, there are significant regional variations in this behavior. The mechanisms for the diurnal cycle of precipitation are varied and complex. This paper reviews the progress in understanding the diurnal cycle of convection, with an emphasis on the most prominent monsoon system, the Asian monsoon.

## 2. Background

Owing to its pronounced impact on global and regional scales and on society at large, there have been innumerable studies of the diurnal cycle of precipitation. It is not possible in the short space available here to treat all of these studies, so the reader is referred to Wallace (1975) and Gray and Jacobson (1977) for reviews of papers prior to the mid-1970s, and to Dai (2001) for papers prior to the turn of the century.

Dai (2001) summarized several of the principal conclusions regarding convective precipitation based on surface station observations: 1) summer convective precipitation over inland regions is more frequent during the afternoon, while over open ocean and coastal areas the maximum rainfall is typically at night or during early morning hours; 2) there are important exceptions to this tendency over continental areas, such as the central United States where summer precipitation is most frequent from middle night to early morning hours; 3) precipitation intensity generally has a much smaller diurnal variation than precipitation frequency; and 4) in addition to the main diurnal peak, there is a secondary semidiurnal peak in precipitation at many tropical stations.

These conclusions are generally supportive of earlier findings by Gray and Jacobson (1977); however, the latter authors observed that with regard to the nocturnal maximum of precipitation over open oceans, the more intense and well organized the convection, the more prominent the diurnal cycle. This finding has been further supported and quantified by Mapes and Houze (1993), Chen *et al.* (1996), and Nesbitt and Zipser (2003). Gray and Jacobson (1977) also noted that the eastern tropical Atlantic displays a different behavior, where the maximum is delayed until afternoon. Subsequent studies have identified several prominent tropical oceanic regions as having an afternoon maximum of precipitation: the tropical eastern Atlantic (Reed and Jaffe 1981); the South Pacific convergence zone (SPCZ; Albright 1985; Sorooshian *et al.* 2002), and the tropical eastern Pacific (Augustine 1984). In addition, Dai and Deser (1999) have found using global surface wind data a maximum in surface convergence in the afternoon over many open ocean areas. Most studies of the diurnal cycle of maritime rainfall, including a number of those cited above, have used satellite data due to the lack of surface stations over ocean areas (see Dai 2001 for references). However, as noted by Dai *et al.* (2007), the satellite products do best at describing the diurnal cycle of precipitation from deep convection while they often incorrectly estimate the contribution from shallower convection.

As suggested by Wallace (1975), mechanisms for the diurnal cycle of convection can be broken into two categories: (i) thermodynamic processes that affect static stability, and (ii) processes that affect boundary-layer convergence. The first category includes daytime heating and destabilization of the boundary layer producing the commonly observed afternoon and early evening maximum of precipitation over land. This mechanism can also operate over the ocean, but to a lesser degree (Hendon and Woodberry 1993; Chen and Houze 1997; Johnson *et al.* 2001). It also includes cloud-radiative effects, e.g., absorption of solar radiation near cloud top stabilizing the atmosphere during the daytime and longwave cooling destabilizing the atmosphere near cloud top (Kraus 1963; Randall *et al.* 1991). It has also been proposed

that a day-night variation in humidity over the tropical oceans can affect static stability in the boundary layer (Sui *et al.* 1997; Dai 2001). Chen and Houze (1997) hypothesize that daytime heating of the ocean surface initiates convection in the afternoon, the showers grow into mesoscale convective systems at night, the associated downdrafts stabilize the boundary layer the following day, and this entire process contributes to a two-day cycle of convection over the tropical western Pacific. The above mechanisms and others have been recently reviewed by Yang and Smith (2006).

During the 1992-93 Tropical Ocean Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA COARE), a large amplitude diurnal cycle of the SST (up to 2-3°C) over the western Pacific warm pool was found during the light-wind phase of the Madden-Julian Oscillation (MJO; Madden and Julian 1971), contributing to a deepening of the boundary layer (Johnson *et al.* 2001) and the development of afternoon showers (Chen and Houze 1997; Rickenbach and Rutledge 1997; Sui *et al.* 1997). Without this diurnal enhancement, precipitation over the warm pool and its associated lower-tropospheric moistening would likely be far less during the suppressed phase of the MJO (Webster *et al.* 1996; Johnson *et al.* 2001). This preconditioning likely plays a key role in setting the time scale for the MJO (Bladé and Hartmann 1993; Hu and Randall 1994; Kemball-Cook and Weare 2001). The diurnal cycle can also enhance the intraseasonal response of the SST to the MJO (Bernie *et al.* 2007).

In the second category of mechanisms for the diurnal cycle, Wallace (1975) includes the following processes: (a) land and sea (or lake) breeze circulations in coastal areas, (b) mountain-valley flows in areas of sloping terrain, and (c) wind variations at the top of the boundary layer caused by diurnal variations in static stability and associated changes in frictional drag. Some of these processes may operate in combination, such (b) and (c) in the case of the United States Great Plains nocturnal precipitation maximum (e.g., Wallace 1975; Jiang *et al.* 2007).

The second category involving boundary-layer convergence mechanisms can also include other processes, such as the semidiurnal pressure wave (Brier and Simpson 1969) and coupling between cloudy sky and cloud-free regions, as proposed by Gray and Jacobson (1977). Gray and Jacobson (1977) hypothesized that a horizontal gradient longwave cooling from clear-sky regions to cloudy regions leads to a mass circulation characterized by low-level convergence into the cloudy area at night, resulting in a peak in rainfall in the late-night, early-morning hours. Dai and Deser's (1999) analysis of fields of global surface wind divergence broadly supports the Gray-Jacobson hypothesis, except over the South Pacific.

There have been numerous studies of the diurnal cycle of convection over Asia (e.g., Murakami 1983; Nitta and Sekine 1994; Chen and Takahashi 1995; Ohsawa *et al.* 2001; Fujinami and Yasunari 2001; Kurosaki and Kimura 2002; Yu *et al.* 2007; Zhou *et al.* 2008). Over land, many areas exhibit an afternoon maximum of convection, as expected from daytime heating; however, certain regions such as the base of the Himalayas and mountain basins (e.g., the Sichuan Basin) have a late-night, early-morning maximum (Akiyama 1989; Johnson *et al.* 1993; Ohsawa *et al.* 2001). While an early-morning maximum has been found over some ocean areas around Asia, the diurnal cycle there is rather complex. Ohsawa *et al.*

(2001) find late-night, early-morning maxima near the coastlines of south Asia, Thailand, Sumatra, Malaysia, and Borneo, which they attribute to an interaction of mountain or land breezes with the prevailing wind. Over the partially enclosed seas, such as the South China Sea and the Bay of Bengal, Ohsawa *et al.* (2001) and Yang and Slingo (2001) diagnose an afternoon maximum in precipitation.

During the 1978 Winter Monsoon Experiment (WMONEX), the diurnal cycle of convection off the north coast of Borneo was studied in detail using radar and sounding data. Houze *et al.* (1981) documented the development of nocturnal mesoscale convective systems (MCSs) off Borneo, arguing they were a result of low-level convergence of the nighttime land breeze with the northeast monsoon flow. The MCSs typically began as a group of convective cells near the coastline and later expanded to a several hundred km scale dimension with both convective and stratiform components, later dissipating after sunrise as the sea breeze developed.

While convection along coastlines is commonplace throughout the tropics and monsoon regions, and land/sea breezes are often implicated in the forcing of storm development, the mechanisms are often complex. In a study of convection over Taiwan, Johnson and Bresch (1991) suggested that the land breeze flow at night was augmented by evaporation of the previous evening's precipitation over the interior elevated terrain. Mapes *et al.* (2003) proposed that the land breeze by itself was inadequate to account for nocturnal convection that regularly occurs offshore Columbia in the Panama Bight. They argued that thermally forced gravity waves (produced by elevated terrain and propagating at about  $15 \text{ m s}^{-1}$ ) are an essential part of the process, and that they produce a warm anomaly offshore during the daytime, thereby capping convection, while a cooling is produced at night, thus allowing convection to develop. Propagation of convection away from coastlines, typically commencing in the early morning and continuing into the afternoon, has been observed in many regions of the Asian monsoon: the Bay of Bengal (Yang and Slingo 2001; Webster *et al.* 2002; Zuidema 2003), the northern South China Sea (Aves and Johnson 2008), off the coast of New Guinea (Liberti *et al.* 2001; Zhou and Wang 2006), off Borneo (Houze *et al.* 1981; Johnson and Priegnitz 1981; Ichikawa and Yasunari 2006), and off Sumatra (Mori *et al.* 2004; Sakurai *et al.* 2005). While gravity waves may play a role in the propagation of convection in these regions, details of the mechanisms are still not well understood.

### 3. Diurnal Cycle over the Global Tropics

The global distribution of annual rainfall in the tropics, derived from ten years of the Tropical Rainfall Measuring Mission (TRMM) 3B42 merged satellite product at  $0.25^\circ \times 0.25^\circ$  resolution (Huffman *et al.* 2007), is shown in Fig. 1. The regions of greatest rainfall – the intertropical convergence zone (ITCZ), the maritime continent, and the monsoon regions – are known to exhibit strong diurnal cycles (e.g., Dai 2001).

To investigate the diurnal cycle of precipitation using the TRMM 3B42 data set, a simple procedure is adopted, namely, to produce analyses of afternoon/evening (1200 to 2300 LT average) minus morning (0000 to 1100 LT average) rainfall (Fig. 2). Difference amounts

(afternoon/evening minus morning rainfall) are shown in the top panel of Fig. 2, whereas normalized differences (differences divided by the mean annual rain at each location) are shown in the bottom panel of Fig. 2. These figures are for the annual means and it is recognized that there are important seasonal differences from region to region (Dai *et al.* 2007). We will later examine seasonal behavior for the Asian monsoon region. It is clear from Fig. 2 (top panel) that the amplitude of the diurnal variability is largest over the regions of the maritime continent, the Asian monsoon, the North and South American monsoons, and portions of the African monsoon. The signal is very large near coastlines, where there is typically a maximum in precipitation over the land during the afternoon and evening, and a maximum just offshore during the morning (e.g., over South America; Garreaud and Wallace 1997). The majority of the open ocean regions exhibit a morning maximum in precipitation, consistent with the findings of Gray and Jacobson (1977), Janiowiak *et al.* (1994), Dai (2001) and many other studies.

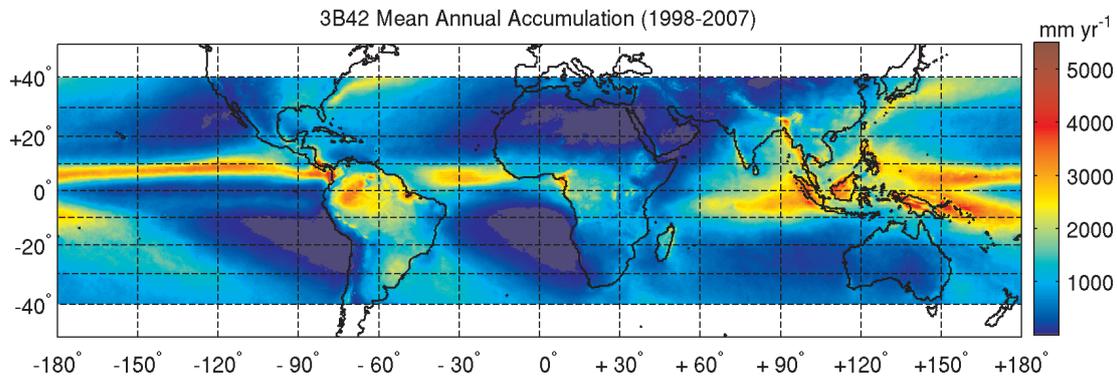


Figure 1. Ten-year (1998-2007) TRMM 3B42 annual precipitation climatology.

The normalized diurnal rainfall map (Fig. 2, bottom panel) more clearly shows the general preference for afternoon/evening rainfall over all of the land areas and morning rainfall over the ocean. However, there are important exceptions to this rule, namely, certain land areas have a morning maximum of rainfall (e.g., areas downstream of the Rocky Mountains, Andes, and Tibetan Plateau; the coastal interior of Brazil; areas south and north of the Tibetan Plateau; and the interior of Borneo), while certain ocean areas have an afternoon/evening maximum (e.g., the SPCZ, the South Atlantic Convergence Zone [SACZ], areas of the west coasts of the equatorial Americas and Africa, and enclosed ocean basins of the Americas and the Asian monsoon). Some of these exceptions are associated with propagating signals of convection. For example, eastward propagation of convection from the Rocky Mountains, Andes, and Tibetan Plateau has been reported by Carbone *et al.* (2002), Velasco and Fritsch (1987), Laing and Fritsch (1997), and Wang *et al.* (2004), whereas southward propagation of convection over the Bay of Bengal and the South China Sea has been documented by Yang and Slingo (2001), Webster *et al.* (2002), Zuidema (2003), and Aves and Johnson (2008).

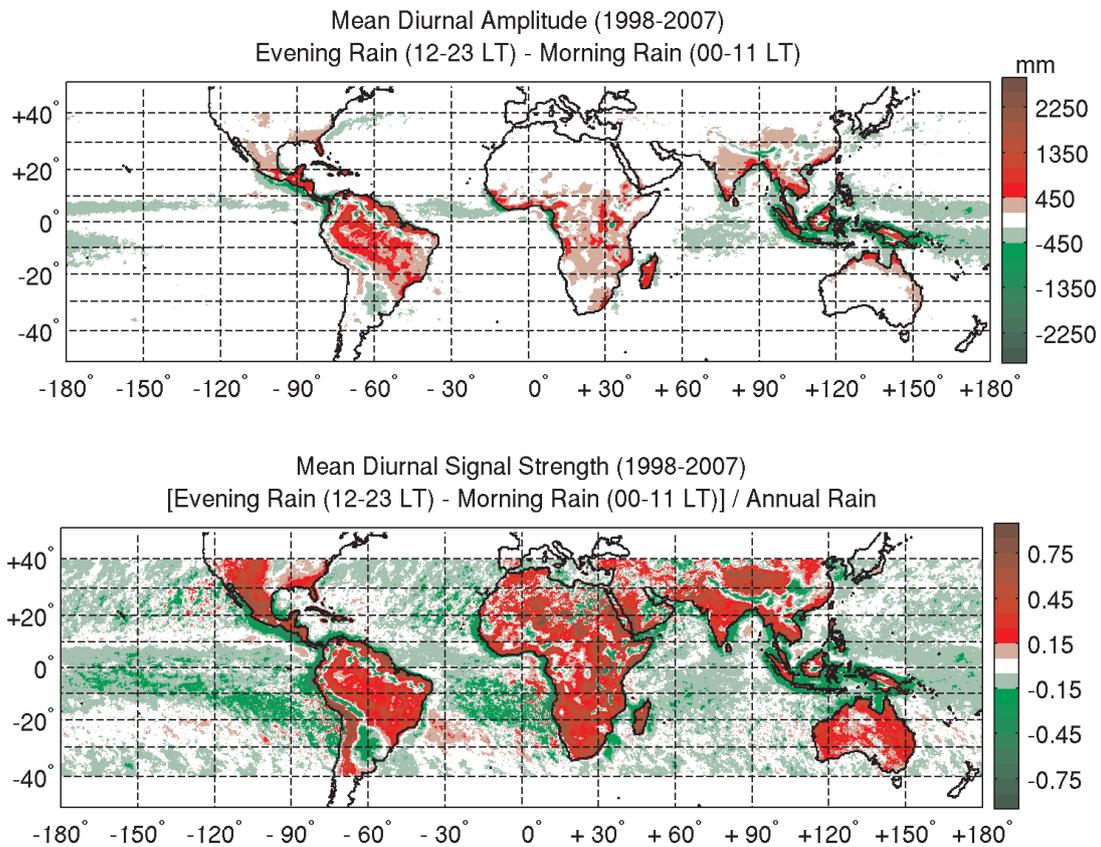


Figure 2. Evening (1200-2300 LT) minus morning (0000-1000 LT) rainfall from ten years (1998-2007) of TRMM 3B42 data. (top panel) annual average differences; (bottom panel) annual average differences normalized by annual mean rainfall.

To better view the global patterns of propagation, a plot of the time of maximum rainfall has been prepared from the TRMM 3B42 data set (Fig. 3). Once again, it can be seen that in general, rainfall maxima occur over land during the afternoon/evening and over the ocean during the morning hours. Over land, prominent signals of eastward propagation of convection can be seen downstream of the Rocky Mountains, the Andes, and the Tibetan Plateau from the afternoon and evening to the early morning hours. These propagation corridors have been studied by Laing and Fritsch (1997). Also, inland propagation of precipitation can be seen along the northeast coast of Brazil (Kousky 1980; Molion 1987). Also evident from this global map are signals of propagation westward from the coast of central America, equatorial Africa, and Sumatra; and northward from Papua New Guinea, with convection initiating near the coastline in the morning and moving seaward in the afternoon. Squall lines over West Africa propagate westward over great distances in association with African easterly waves (see review by Houze and Betts 1981); however, a persistent phasing with the diurnal cycle cannot be seen until the convective systems emerge from the west coast of Africa.

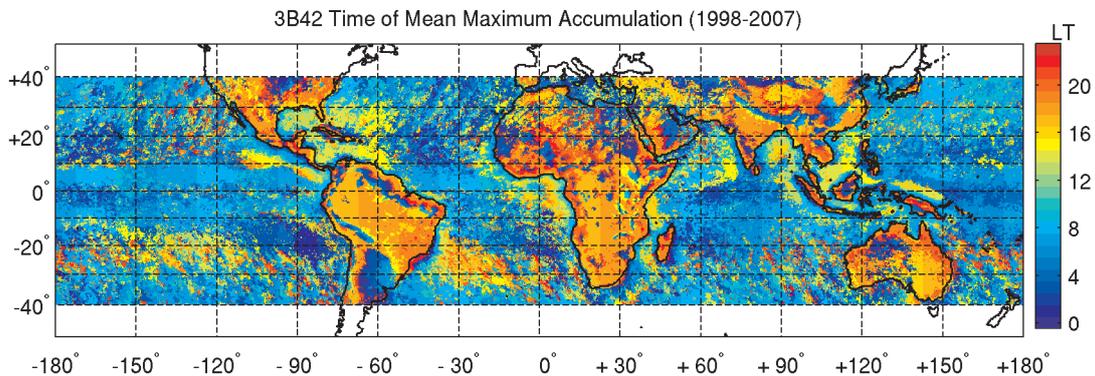


Figure 3. Time of maximum rainfall (LT) for ten years (1998-2007) using TRMM 3B42 data.

#### 4. Diurnal Cycle in the Asian Monsoon Region

We now take a closer look at the diurnal cycle in the region of the Asian summer monsoon with a particular focus on the May-June onset period. The patterns throughout the remainder of the summer (July, August) are expected to be similar; however, the precipitation shifts northward and tropical cyclones play a greater role in total precipitation at that time.

The ten-year mean May-June precipitation is shown in Fig. 4. A striking feature is the occurrence of heaviest rainfall in regions just offshore of landmasses: to the west of the Western Ghats in India (studied by Krishnamurti *et al.* 1983 and Grossman and Durran 1984), over the eastern Bay of Bengal off the coast of Myanmar (studied by Zuidema 2003), and along the western coast of the Philippines. Understanding the diurnal cycle of convection in coastal environments such as these is important because so much precipitation occurs there and global models do not properly represent the diurnal cycle of convection (Yang and Slingo 2001). There are possible global consequences of this deficiency, as demonstrated by the fact that the maritime continent heat source as represented by models is too weak in the mean (Neale and Slingo 2003).

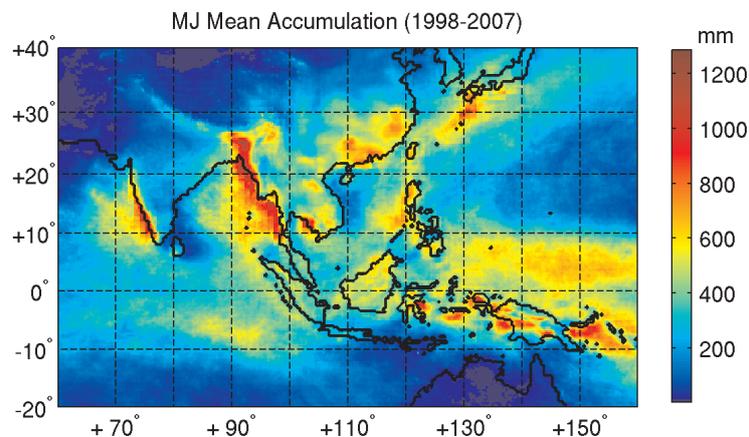


Figure 4. Average May-June rainfall for ten years (1998-2007) using TRMM 3B42 data.

These coastal rainfall maxima occur in the presence of strong southwesterly monsoon flow, as shown in Fig. 5, a plot of the 2000-2007 June-mean precipitation and surface winds from QuikSCAT. With southwesterly flow impinging on the western slopes of the coastal mountain ranges, it might be expected that the heaviest rainfall would occur over land, but it does not; it appears to occur offshore. Xie *et al.* (2006) have shown this to be the case for the area in the Bay of Bengal just off the west coast of Myanmar.

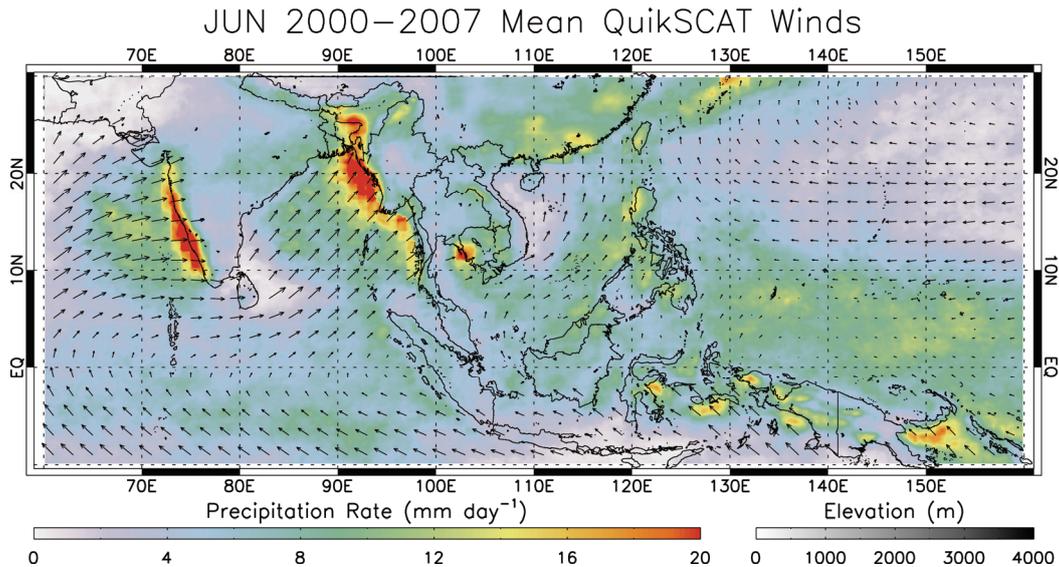


Figure 5. June TRMM 3B43 precipitation rate and QuikSCAT surface winds for eight years (2000-2007).

With respect to the rainfall near the Western Ghats, Ogura and Yoshizaki (1988) concluded that the positioning of the heaviest rainfall just offshore is dependent on the strong vertical wind shear (low-level westerlies and upper-level easterlies) and strong surface fluxes over the ocean. Upper-level easterlies advect the cirrus aloft westward over the open oceans (Krishnamurti *et al.* 1983), so there is the impression from infrared satellite imagery that the heavy rainfall is spread far offshore; however, most of it is typically confined near the coast. While there have been efforts to explain near-coastal rainfall maxima through numerical modeling of flow interacting with coastal topography, a full explanation requires consideration of the diurnal cycle.

The amplitude of the diurnal cycle of precipitation (normalized evening minus morning rainfall) for May-June over the Asian monsoon region is shown in Fig. 6. Morning rainfall maxima can be seen in many coastal regions: along the coastlines of India, in most coastal areas surrounding Indo-China, and throughout most of the maritime continent. Hence, with reference to Fig. 5, the diurnal cycle appears to play some role in the heavy rainfall off the west coasts of India and Myanmar. As noted earlier with reference to the global, annual-mean diurnal cycle, there are several prominent areas with morning rainfall maxima over land: the southern slopes of the Himalayas, the area to the lee of Tibetan Plateau, and central Borneo. Barros and Lang (2003) examined the nocturnal maximum in precipitation at the foot of the

Himalayas and found that it could be explained by convergence between the southeasterly monsoon flow and nocturnal drainage flow off the Himalayas.

Another example of the impact of mountain and valley flows on convection is provided by Fujinami *et al.* (2005). Using GMS IR satellite data, they found that over the Tibetan Plateau convection is closely tied to two major east-west mountain ranges, indicated by the topographic cross section along 90°E in the left panel of Fig. 7. A time-latitude plot of cloud-cover frequency (right panel) shows clouds developing along these ranges around 09 UTC (15 LT) and then shifting to the valley between them by 13 UTC (19 LT). This shift is presumably a consequence of the development of drainage flow convergence into the valley in the evening augmented by downdraft outflows.

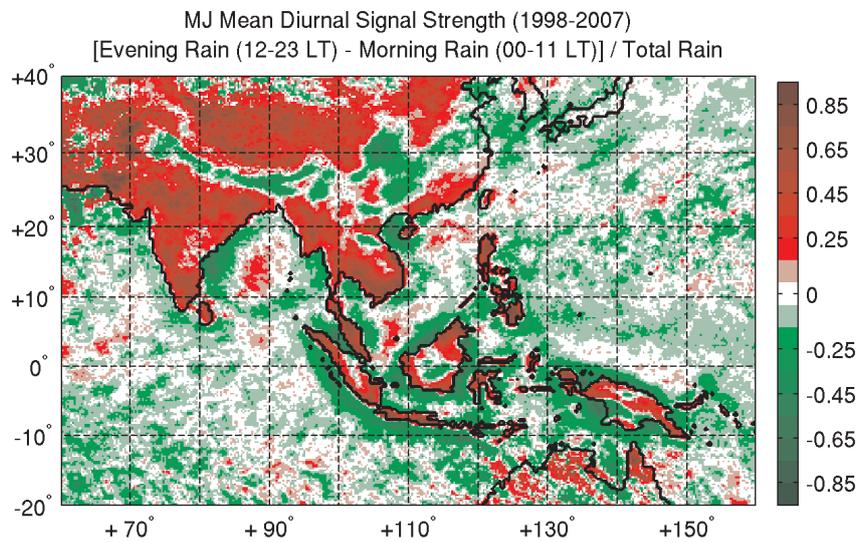


Figure 6. Average May-June evening (1200-2300 LT) minus morning (0000-1100 LT) rainfall normalized by May-June mean rainfall for ten years (1998-2007) using TRMM 3B42 data.

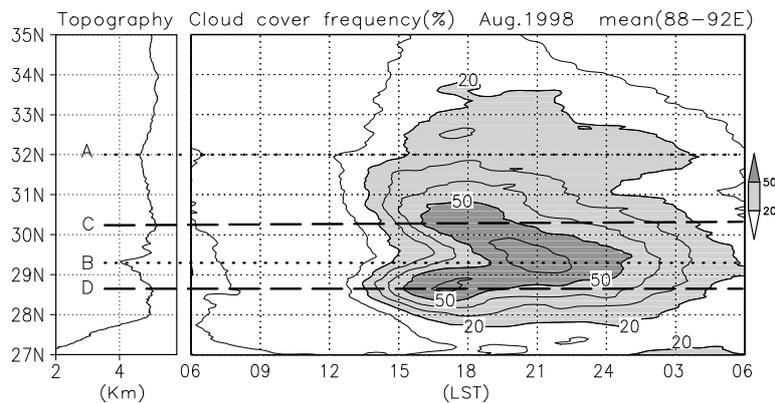


Figure 7. Latitude-time section of cloud-cover frequency along 90°E for August 1998. Left panel indicates cross section of topography along 90°E. (from Fujinami *et al.* 2005)

Most of the afternoon/evening maxima in Fig. 6 are over land, but there are several notable exceptions. Most prominent among these are the afternoon maxima in precipitation over the Bay of Bengal, and the northern and southern portions of the South China Sea. These features are associated with propagating signals of precipitation across these partially enclosed ocean basins, as shown in Fig. 8, which displays the phase of the maximum precipitation. Rainfall is seen to peak in the early morning hours in the northern Bay of Bengal along the coast of India and over the northern South China Sea along the southern China coastline. The rainfall peak occurs progressively later toward the south such that the maximum occurs in the afternoon roughly 500 km offshore. Webster *et al.* (2002) show evidence of the propagation over the Bay of Bengal in a time-latitude diagram of brightness temperatures (their Fig. 4). Precipitation systems (inferred from the cold cloud tops) were found on some occasions to propagate all the way from the India coast near 20°N to the equator over a two-day period. Radar data from the R/V *Ron Brown* in the Bay of Bengal indicate that the convection associated with the diurnal signal has characteristics of squall lines with trailing stratiform precipitation.

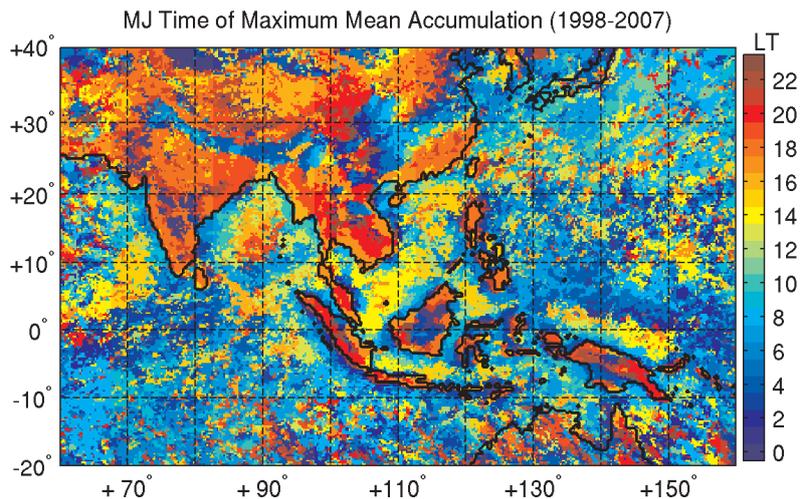


Figure 8. Average May-June time of maximum rainfall (LT) for ten years using TRMM 3B42 data.

A southward propagation of convective systems over the South China Sea was also observed during the 1998 South China Sea Monsoon Experiment (SCSMEX), similar to that over the Bay of Bengal (Aves and Johnson 2008). The monsoon onset over the northern South China Sea (near 20°N) occurred around mid-May and is characterized by a regular signal of southward propagation of convection (low values of IR brightness temperature) at an approximate speed of 15 m s<sup>-1</sup> (Fig. 9). In late-May the convection shifts southward to the central South China Sea (10°N-15°N) with a diurnal propagating signal still present, indicating that the diurnal pattern is independent of coastal effects. Then in June the convection shifts back again to China, and diurnal propagation persists.

The mechanisms responsible for the diurnally propagating signals over the Bay and

Bengal and the South China Sea are not well understood. Advective effects can be ruled out because these systems propagate approximately at right angles to the low-level southwesterly monsoon flow. Also, gravity current dynamics appear to be an unlikely explanation since the speeds of propagation ( $\sim 15 \text{ m s}^{-1}$ ) in both regions (Webster *et al.* 2002; Aves and Johnson 2008) are too fast to be accounted for by the relatively weak cold pools observed in these regions. Gravity waves, however, may play some role. One possibility is the gravity wave mechanism proposed by Mapes *et al.* (2003) for the Panama Bight, which involves the generation of thermally forced gravity waves in the deep heated boundary layer over the nearby Andes. It is possible that gravity waves to the north of the Bay of Bengal are similarly generated by heating over the Tibetan Plateau and subsequently propagate to the south over the ocean. This possibility is worthy of investigation.

However, there is another possible mechanism involving gravity waves that may be occurring leading to discrete propagation of convection. Shige and Satomura (2001) investigated the mechanism of discrete propagation during TOGA COARE and found that strong upper-level easterlies provided a critical level and ducting of waves that contributed to westward development of eastward-moving convective bands. Fovell *et al.* (2006) found that discrete propagation can occur when gravity waves generated by a squall line are ducted forward by the storm's own upper-tropospheric leading anvil outflow. For the case of the South China Sea, soundings during SCSMEX taken from R/V *Shiyan 3* near Dongsha Island shown in Johnson *et al.* (2005; their Figs. 9 and 10) indicate that in some instances there was a component of the upper-level offshore flow exceeding  $20 \text{ m s}^{-1}$ , so the existence of a critical level and wave ducting (Shige and Satomura 2001) for that region cannot be ruled out.

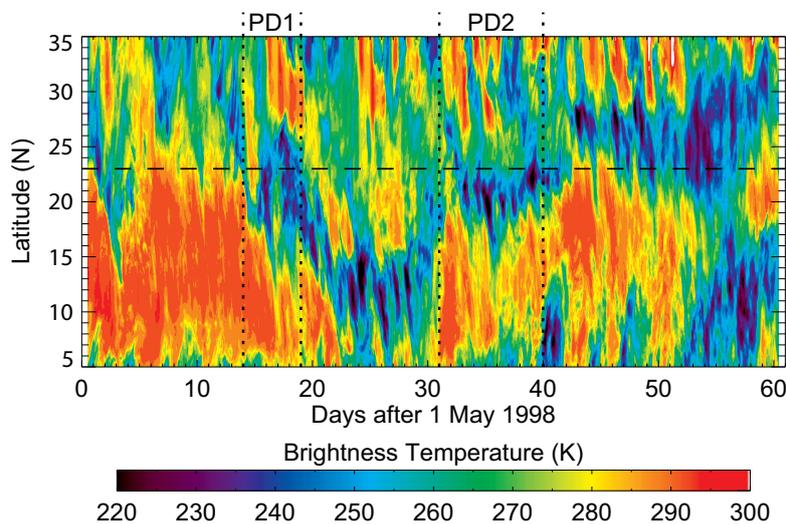


Figure 9. Latitude-time plot of IR brightness temperatures over the study region. Values along the abscissa are days after 1 May 1998, and cover the range from 1 May to 30 June. Values shown are brightness temperatures averaged over the  $116^{\circ}\text{E}$ - $117^{\circ}\text{E}$  longitude band, chosen to coincide with the location of the Dongsha Island radar during SCSMEX. The horizontal dashed line at  $23^{\circ}\text{N}$  represents the average location of the southern China coastline within this longitude band. Cool (warm) shades indicate active (suppressed) convective conditions. PD1 and PD2 refer to the first and second convectively active periods, 15-20 May and 1-10 June, respectively. (from Aves and Johnson 2008)

Afternoon/evening rainfall maxima are commonplace just inland of coastlines throughout the Asian summer monsoon region (Fig. 6). These maxima are related to low-level convergence associated with afternoon sea breezes. To illustrate the pattern of the sea/land breeze systems, evening minus morning QuikSCAT winds have been computed for June for the period 2000-2007 (Fig. 10).

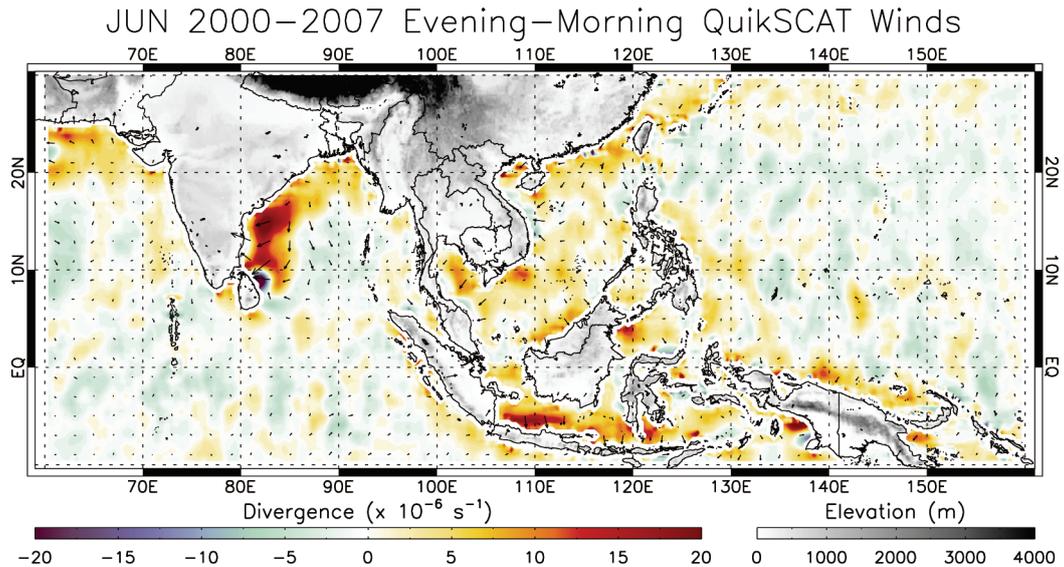


Figure 10. Average June evening minus morning QuikSCAT winds and divergence for eight years (2000-2007).

This figure shows a preponderance of divergence just off the coastlines of most of the land areas, as one might expect with local sea breeze circulations. However, since Fig. 10 is a difference map, it denotes the combined effects of afternoon/evening divergence offshore associated with the sea breeze and offshore convergence associated with the morning land breeze. The divergence maxima extend up to  $\sim 200$  km offshore over most areas and even farther (up to  $\sim 500$  km) off the east coast of India, reflecting the broad horizontal extent of these coastal circulations. The localized land breeze just offshore is likely responsible in many monsoon regions for the development of coastal convection in the early morning (e.g., Houze *et al.* 1981).

## 5. Impacts of Diurnally Varying Low-Level Jets

The topography of the monsoon regions often contributes to flow deflection or blocking and mesoscale low-level jets. The low-level jet through the Taiwan Straits is but one example. However, there are other low-level jets of mesoscale and larger dimension in the Asian monsoon. A map showing the global distribution of low-level jets is presented in Fig. 11 (Stensrud 1996). Within the tropical monsoon regions, low-level jets are observed over the

Indian Ocean/Arabian Sea (the Somali jet), the Bay of Bengal, the South China Sea, Australia, and South America. Topography plays an important role in a number of these jets, e.g., the South American low-level jet occurs downstream of the Andes, the Somali jet is influenced by the east African mountains (Krishnamurti *et al.* 1976). Many of the areas of significant mesoscale convective complex (MCC) activity are colocated with low-level jets, indicating the important role these jets play in transporting moisture into the convection thereby promoting large, long-lived systems (Maddox 1983; Laing and Fritsch 2000). Of significance to this review is the fact that many of these jets vary diurnally and hence contribute to a diurnal variation in convective activity.

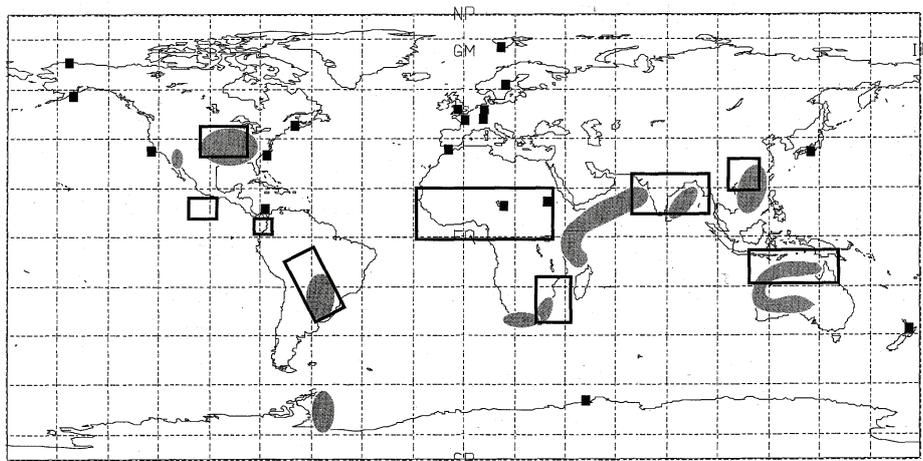


Figure 11. Regions where low-level jets are known or suspected to occur with some regularity (shaded) and where mesoscale convective complexes are known to occur frequently during the summer (open boxes). Squares denote locations where low-level jets have been occasionally observed. (from Stensrud 1996)

Low-level jets can develop in response to boundary layer nocturnal cooling and an associated inertial oscillation, as observed in the African monsoon region (Blackadar 1957) and elsewhere. Other mechanisms that can contribute to the formation of low-level jets are the diurnal heating cycle over sloping terrain (producing a diurnal oscillation in the low-level thermal wind), flow blocking by terrain, shallow baroclinic zones due to surface contrasts, and isallobaric forcing in connection with upper-level jet streaks (see Stensrud 1996 and Jiang *et al.* 2007 for detailed discussions of these mechanisms).

To illustrate the nocturnal low-level jet (LLJ) in the Asian monsoon region, consider the findings from SCSMEX shown in Fig. 12. An inertial oscillation is present as in Blackadar (1957) characterized by a clockwise turning of the wind, with maximum amplitudes at both Hong Kong and Dongsha Island at 08 LT. The amplitude of the ageostrophic wind oscillation ( $\sim 1 \text{ m s}^{-1}$ ), is considerably less than the  $\sim 5 \text{ m s}^{-1}$  found over the summertime central United States (Whiteman *et al.* 1997), but is not insignificant. Over the United States the nocturnal LLJ has been linked with a nocturnal precipitation maximum in the Great Plains associated with eastward propagation of convective systems (e.g., Wallace 1975; Carbone *et al.* 2002).

Similar low-level jets and nocturnal precipitation maxima have been found over South America by Virji (1981) and Velasco and Fritsch (1987); over southern China and Taiwan by Chen and Yu (1988) and Chen and Li (1995); and over Australia by Allen (1981).

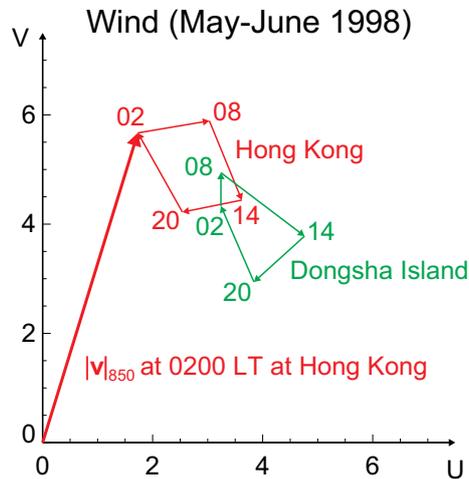


Figure 12. Diurnal wind oscillations at Hong Kong and Dongsha Island over the northern South China Sea during the 1998 SCSMEX.

## 6. Semidiurnal Variability of Precipitation

While the diurnal cycle of precipitation is the dominant mode of variability of precipitation on the daily time scale, it has been proposed that the semidiurnal pressure wave may also contribute to a semidiurnal cycle in precipitation (Brier and Simpson 1969). According to tidal theory discussed in Chapman and Lindzen (1970), the forcing of the semidiurnal pressure wave is dominated by ozone heating in the stratosphere, which contributes about 70% of the semidiurnal pressure signal. Recently, Woolnough *et al.* (2004) argued that the role of stratospheric ozone forcing of the semidiurnal tide has been overestimated and that the radiative heating profile in the troposphere, primarily associated with the water vapor distribution, is more important than previously thought.

Associated with the semidiurnal pressure wave is a global pattern of convergence and divergence (e.g., Whiteman and Bian 1996); however, Lindzen (1978) argued that convergence from the semidiurnal tide was too small and of the wrong phase to drive the semidiurnal harmonic of precipitation. Wallace (1975) notes that the interpretation of the semidiurnal cycle in regions where the diurnal cycle is large can be ambiguous since precipitation at night cannot be negative and a harmonic analysis can introduce a spurious semidiurnal cycle. However, there is evidence from some studies that a semidiurnal cycle of tropical precipitation does indeed exist (Brier and Simpson 1969; Dai 2001). Semidiurnal variability of rainfall over the oceans may in part be related the combination of the typical nocturnal precipitation maximum (Gray and Jacobson 1977) and showers that develop from afternoon heating of the ocean surface (Sui *et al.* 1997; Chen and Houze 1997; Johnson *et al.*

2001). Therefore, it can be difficult to separate this variability from that produced by the semidiurnal tide. Dai *et al.* (1999) have shown that the pressure tides can induce a diurnal cycle of convergence that helps to promote nighttime convection and suppress daytime convection over the central United States. Yasunaga *et al.* (2008), using data from the Indian Ocean, have been able to show that there is a semidiurnal variability in moisture in the boundary layer associated with the semidiurnal tide, which is independent of skin sea-surface temperature variations, and that this variability may be responsible for a semidiurnal cycle of convection and precipitation.

## 7. Summary and Outstanding Issues

This review has examined the diurnal variability of monsoon precipitation and associated circulation features – land/sea breezes, mountain/valley breezes, and low-level jets – in the monsoon regions of the world, with a particular focus on the Asian monsoon. The dominant pattern of diurnal variability is a maximum in rainfall over land during the afternoon/evening in response to solar heating of the surface and a morning maximum over the oceans. The amplitude of the diurnal variability over land generally exceeds that over the ocean. Several theories for the diurnal cycle over the ocean have been proposed, involving surface and free-tropospheric radiative heating or their horizontal gradients; however, the precise mechanisms remain unclear and are not well represented in global models.

There are many monsoon regions where there are notable exceptions to the typical diurnal pattern of precipitation over both land and ocean. For example, areas surrounding the Tibetan Plateau and downstream of major mountain ranges such as the Rocky Mountains and Andes display late-night/early morning maxima in precipitation. The latter regions typically have a characteristic pattern of eastward propagation of convection. Over the tropical oceans, there are certain regions (e.g., off the west coast of Africa, the SPCZ, the Bay of Bengal, the South China Sea) that exhibit a daytime maximum in precipitation.

In the region of the Asian summer monsoon, the daytime maximum in precipitation is associated with propagating signals of convection. During the summer monsoon, convection over the Bay of Bengal and the South China Sea typically forms along the northern coastlines of those seas in the early morning and then propagates southward over great distances (~500 km or more) before dissipating over the central or southern portions of the seas. Gravity waves are implicated in the propagation of convection in all of these regions, perhaps contributing to discrete propagation of convective cells.

Despite progress in understanding the geographical patterns of the diurnal cycle in monsoon regions, there remain a number of outstanding problems warranting further research, some of which are listed below:

- What are the mechanisms for the diurnal cycle of convection over the open oceans in the tropics and monsoon regions?
- What are the mechanisms for upstream development of convection and heavy rainfall along coastlines in monsoon regions and what role does the diurnal cycle play?

- What processes account for the diurnal evolution and propagation of convection over oceans? Over land?
- How does the nocturnal low-level jet contribute to nighttime precipitation maxima in monsoon regions?
- Does the diurnal cycle play any role in intraseasonal variability in monsoon regions?

These are just a few of many questions pertaining to the diurnal cycle of convection, which undoubtedly will motivate future observational, theoretical, and modeling studies of the Asian monsoon.

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### References

- Albright, M. D., 1985: Diurnal variation of deep convection and inferred precipitation in the central tropical Pacific during January-February 1979. *Mon. Wea. Rev.*, **113**, 1663-1680.
- Allen, S., 1981: Australian low-level jet climatology. Meteorological Note 119, Dept. of Sci. Tech., Australian Bureau of Meteorology, 23 pp. [Available from Bureau of Meteorology, G.P.O. Box 1289K, Melbourne VIC 3001, Australia].
- Akiyama, T., 1989: Large, synoptic and mesoscale variations of the Baiu front during July 1982, Part I: Cloud features. *J. Meteor. Soc. Japan*, **67**, 57-81.
- Augustine, J. A., 1984: The diurnal variation of large-scale inferred rainfall over the tropical Pacific Ocean during 1979. *Mon. Wea. Rev.*, **112**, 1745-1751.
- Aves, S. L. and R. H. Johnson, 2008: The diurnal cycle of convection over the northern South China Sea. *J. Meteor. Soc. Japan*, **86**, 919-934.
- Barros, A. P. and T. J. Lang, 2003: Monitoring the monsoon in the Himalayas: Observations in central Nepal, June 2001. *Mon. Wea. Rev.*, **131**, 1408-1427.
- Bernie, D. J., E. Guilyardi, G. Madec, J. M. Slingo, and S. J. Woolnough, 2007: Impact of resolving the diurnal cycle in an ocean-atmosphere GCM. Part 1: a diurnally forced OGCM. *Climate Dyn.*, **29**, 575-590.
- Blackadar, A. K., 1957: Boundary-layer wind maxima and their significance for the growth of the nocturnal inversion. *Bull. Amer. Meteor. Soc.*, **38**, 283-290.
- Bladé, I. and D. L. Hartmann, 1993: Tropical intraseasonal oscillations in a simple nonlinear model. *J. Atmos. Sci.*, **50**, 2922-2939.
- Brier, G. W. and J. S. Simpson, 1969: Tropical cloudiness and precipitation related to pressure and tidal variations. *Quart. J. Roy. Meteor. Soc.*, **95**, 120-147.
- Carbone, R. E., J. D. Tuttle, D. A. Ahijevych, and S. B. Trier, 2002: Inferences of predictability associated with warm-season precipitation episodes. *J. Atmos. Sci.*, **59**, 2033-2056.
- Chapman, S. and R. S. Lindzen, 1970: *Atmospheric Tides*. D. Reidel Press, 200 pp.

- Chen, G. T.-J. and C. C. Yu, 1988: Study of low-level jet and extremely heavy rainfall over northern Taiwan in the Mei-Yu season. *Mon. Wea. Rev.*, **116**, 884-891.
- Chen, S. S. and R. A. Houze, 1997: Diurnal variation and lifecycle of deep convective systems over the tropical Pacific warm pool. *Quart. J. Roy. Meteor. Soc.*, **123**, 357-388.
- Chen, S. S., R. A. Houze Jr., and B. E. Mapes, 1996: Multiscale variability of deep convection in relation to large-scale circulation in TOGA COARE. *J. Atmos. Sci.*, **53**, 1380-1409.
- Chen, T.-C. and K. Takahashi, 1995: Diurnal variation of outgoing longwave radiation in the vicinity of the South China Sea. *Mon. Wea. Rev.*, **123**, 566-577.
- Chen, Y.-L. and J. Li, 1995: Large-scale conditions favorable for the development of heavy rainfall during TAMEX IOP 3. *Mon. Wea. Rev.*, **123**, 2978-3002.
- Dai, A., 2001: Global precipitation and thunderstorm frequencies. Part II: Diurnal variations. *J. Climate*, **14**, 1112-1128.
- Dai, A. and C. Deser, 1999: Diurnal and semidiurnal variations in global surface wind and divergence fields. *J. Geophys. Res.*, **104**, 31109-31125.
- Dai, A., F. Giorgi, and K. E. Trenberth, 1999: Observed and model simulated precipitation diurnal cycle over the contiguous United States. *J. Geophys. Res.*, **104**, 6377-6402.
- Dai, A., X. Lin, and K.-L. Hsu, 2007: The frequency, intensity, and diurnal cycle of precipitation in surface and satellite observations over low- and mid-latitudes. *Climate Dyn.*, **29**, 727-744.
- Fovell, R. G., G. L. Mullendore, and S.-H. Kim, 2006: Discrete propagation in numerically simulated nocturnal squall lines. *Mon. Wea. Rev.*, **134**, 3735-3752.
- Fujinami, H. and T. Yasunari, 2001: The seasonal and intraseasonal variability of diurnal cloud activity over the Tibetan Plateau. *J. Meteor. Soc. Japan*, **79**, 1207-1227.
- Fujinami, H., S. Nomura, and T. Yasunari, 2005: Characteristics of diurnal variation in convection and precipitation over the Tibetan Plateau during the summer. *SOLA*, **1**, 49-52.
- Garreaud, R. D. and J. M. Wallace, 1997: The diurnal march of convective cloudiness over the Americas. *Mon. Wea. Rev.*, **125**, 3157-3171.
- Gray, W. M. and R. W. Jacobson Jr., 1977: Diurnal variation of deep cumulus convection. *Mon. Wea. Rev.*, **105**, 104-188.
- Grossman, R. L. and D. R. Durran, 1984: Interaction of the low-level flow with the Western Ghats Mountains and offshore convection in the summer monsoon. *Mon. Wea. Rev.*, **112**, 652-672.
- Hendon, H. H. and K. Woodberry, 1993: The diurnal cycle of tropical convection. *J. Geophys. Res.*, **98**, 16623-16637.
- Houze, R. A. Jr. and A. K. Betts, 1981: Convection in GATE. *Rev. Geophys. Space Phys.*, **19**, 541-576.
- Houze, R. A. Jr., S. G. Geotis, F. D. Marks Jr., and A. K. West, 1981: Winter monsoon convection in the vicinity of North Borneo. Part I: Structure and time variation of the clouds and precipitation. *Mon. Wea. Rev.*, **109**, 1595-1614.
- Hu, Q. and D. A. Randall, 1994: Low-frequency oscillations in radiative-convective systems. *J. Atmos. Sci.*, **51**, 1089-1099.
- Huffman, G. J., R. F. Adler, D. T. Bolvin, G. Gu, E. J. Nelkin, K. P. Bowman, Y. Hong, E. F. Stocker, and D. B. Wolff, 2007: The TRMM multi-satellite precipitation analysis: Quasi-global, multiyear, combined-sensor precipitation estimates at fine scale. *J. Hydrometeorol.*, **8**, 38-55.
- Ichikawa, H. and T. Yasunari, 2006: Time-space characteristics of diurnal rainfall over Borneo and surrounding oceans as observed by TRMM-PR. *J. Climate*, **19**, 1238-1260.
- Janowiak, J. E., P. A. Arkin, and M. Morrissey, 1994: An examination of the diurnal cycle in oceanic

- tropical rainfall using satellite and in situ data. *Mon. Wea. Rev.*, **122**, 2296-2311.
- Jiang, X., N.-C. Lau, I. M. Held, and J. J. Ploshay, 2007: Mechanisms of the Great Plains low-level jet as simulated in an AGCM. *J. Atmos. Sci.*, **64**, 532-547.
- Johnson, R. H. and D. L. Preignitz, 1981: Winter monsoon convection in the vicinity of north Borneo. Part II: Effects on large scale fields. *Mon. Wea. Rev.*, **109**, 1615-1628.
- Johnson, R. H. and J. F. Bresch, 1991: Diagnosed characteristics of precipitation systems over Taiwan during the May-June 1987 TAMEX. *Mon. Wea. Rev.*, **119**, 2540-2557.
- Johnson, R. H., Z. Wang, and J. F. Bresch, 1993: Heat and moisture budgets over China during the early summer monsoon. *J. Meteor. Soc. Japan*, **71**, 137-152.
- Johnson, R. H., P. E. Ciesielski, and J. A. Cotturone, 2001: Multiscale variability of the atmospheric mixed layer over the western Pacific warm pool. *J. Atmos. Sci.*, **58**, 2729-2750.
- Johnson, R. H., S. A. Aves, P. E. Ciesielski, and T. D. Keenan, 2005: Organization of oceanic convection during the onset of the 1998 East Asian summer monsoon. *Mon. Wea. Rev.*, **133**, 131-148.
- Kemball-Cook, S. R. and B. C. Weare, 2001: The onset of convection in the Madden-Julian oscillation. *J. Climate*, **14**, 780-793.
- Kousky, V. E., 1980: Diurnal rainfall variations in Northeast Brazil. *Mon. Wea. Rev.*, **108**, 488-498.
- Kraus, E. B., 1963: The diurnal precipitation change over the sea. *J. Atmos. Sci.*, **20**, 551-556.
- Krishnamurti, T. N., J. Molinari, and H.-L. Pan, 1976: Numerical simulation of the Somali jet. *J. Atmos. Sci.*, **33**, 2350-2362.
- Krishnamurti, T. N., S. Cocke, R. Pasch, and S. Low-Nam, 1983: Precipitation estimates from raingauge and satellite observations, Summer MONEX. FSU Rep. 83-7. Dept. of Meteorology, Florida State Univ., 373 pp.
- Kurosaki, Y. and F. Kimura, 2002: Relationship between topography and daytime cloud activity around Tibetan Plateau. *J. Meteor. Soc. Japan*, **80**, 1339-1355.
- Laing, A. G. and J. M. Fritsch, 1997: The global population of mesoscale convective complexes. *Quart. J. Roy. Meteor. Soc.*, **123**, 389-405.
- Laing, A. G. and J. M. Fritsch, 2000: The large-scale environments of the global populations of mesoscale convective complexes. *Mon. Wea. Rev.*, **128**, 2756-2776.
- Liberti, G. L., F. Chérury, and M. Desbois, 2001: Land effect on the diurnal cycle of clouds over the TOGA COARE area, as observed from GMS IR data. *Mon. Wea. Rev.*, **129**, 1500-1517.
- Lindzen, R. S., 1978: Effect of daily variations of cumulonimbus activity on the atmospheric semidiurnal tide. *Mon. Wea. Rev.*, **106**, 526-533.
- Madden, R. A. and P. R. Julian, 1971: Detection of a 40-50 day oscillation in the zonal wind in the tropical Pacific. *J. Atmos. Sci.*, **28**, 702-708.
- Maddox, R. A., 1983: Large-scale meteorological conditions associated with midlatitude, mesoscale convective complexes. *Mon. Wea. Rev.*, **111**, 1475-1493.
- Mapes, B. E. and R. A. Houze, 1993: Cloud clusters and superclusters over the oceanic warm pool. *Mon. Wea. Rev.*, **121**, 1398-1415.
- Mapes, B. E., T. T. Warner, and M. Xu, 2003: Diurnal patterns of rainfall in northwestern South America. Part III: Diurnal gravity waves and nocturnal offshore convection. *Mon. Wea. Rev.*, **131**, 830-844.
- Molion, L. C. B., 1987: On the dynamic climatology of the Amazon Basin and associated rain-producing mechanisms. *The Geophysiology of Amazonia: Vegetation and Climate Interactions*. Wiley-Interscience, (Ed.) R. Dickinson, 391-407.

- Mori, S., J.-I. Hamada, Y. I. Tauhid, M. D. Yamanaka, N. Okamoto, F. Murata, N. Sakurai, H. Hashiguchi, and T. Sribimawati, 2004: Diurnal land-sea rainfall peak migration over Sumatera Island, Indonesian maritime continent observed by TRMM satellite and intensive rawinsonde soundings. *Mon. Wea. Rev.*, **132**, 2021-2039.
- Murakami, M., 1983: Analysis of the deep convective activity over the western Pacific and Southeast Asia. Part 1: Diurnal cycle. *J. Meteor. Soc. Japan*, **61**, 60-75.
- Neale, R. and Slingo J., 2003: The Maritime Continent and its role in the global climate: A GCM study. *J. Climate.*, **16**, 834-848.
- Nesbitt, S. W. and E. J. Zipser, 2003: The diurnal cycle of rainfall and convective intensity according to three years of TRMM measurements. *J. Climate*, **16**, 1456-1475.
- Nitta, T. and S. Sekine, 1994: Diurnal variation of convective activity over the tropical western Pacific. *J. Meteor. Soc. Japan*, **72**, 627-640.
- Ogura Y. and M. Yoshizaki, 1988: Numerical study of orographic-convective precipitation over the eastern Arabian Sea and the Ghat Mountains during the summer monsoon. *J. Atmos. Sci.*, **45**, 2097-2122.
- Ohsawa, T., H. Ueda, T. Hayashi, A. Watanabe, and J. Matsumoto, 2001: Diurnal variations of convective activity and rainfall in tropical Asia. *J. Meteor. Soc. Japan*, **79**, 333-352.
- Randall, D. A., Harshvardhan, and D. A. Dazlich, 1991: Diurnal variability of the hydrological cycle in a general circulation model. *J. Atmos. Sci.*, **48**, 40-62.
- Reed, R. J. and K. D. Jaffe, 1981: Diurnal variation of summer convection over West Africa and the tropical eastern Atlantic during 1974 and 1978. *Mon. Wea. Rev.*, **109**, 2527-2534.
- Rickenbach, T. M. and S. A. Rutledge, 1998: Convection in TOGA COARE: Horizontal scale, morphology, and rainfall production. *J. Atmos. Sci.*, **55**, 2715-2729.
- Sakurai, N., F. Murata, M. D. Yamanaka, S. Mori, J.-I. Hamada, H. Hashiguchi, Y.-I. Tauhid, T. Sribimawati, and B. Suhardi, 2005: Diurnal cycle of cloud system migration over Sumatera Island. *J. Meteor. Soc. Japan*, **83**, 835-850.
- Shige, S. and T. Satomura, 2001: Westward generation of eastward-moving tropical convective bands in TOGA COARE. *J. Atmos. Sci.*, **58**, 3724-3740.
- Sorooshian, S., X. Gao, K. Hsu, R. A. Maddox, Y. Hong, H. V. Gupta, and B. Imam, 2002: Diurnal variability of tropical rainfall retrieved from combined GOES and TRMM satellite information. *J. Climate*, **15**, 983-1001.
- Stensrud, D. J., 1996: Importance of low-level jets to climate: A review. *J. Climate*, **9**, 1698-1711.
- Sui, C.-H., K.-M. Lau, Y. N. Takayabu, and D. A. Short, 1997: Diurnal variations in tropical oceanic cumulus convection during TOGA COARE. *J. Atmos. Sci.*, **54**, 639-655.
- Velasco, I. and J. M. Fritsch, 1987: Mesoscale convective complexes over the Americas. *J. Geophys. Res.*, **92**, 9591-9613.
- Virji, H., 1981: A preliminary study of summer time tropospheric circulation patterns over South America from cloud winds. *Mon. Wea. Rev.*, **109**, 599-610.
- Wallace, J. M., 1975: Diurnal variations in precipitation and thunderstorm frequency over the conterminous United States. *Mon. Wea. Rev.*, **103**, 406-419.
- Wang, C.-C., G. T.-J. Chen, and R. E. Carbone, 2004: A climatology of warm-season cloud patterns over East Asia based on GMS infrared brightness temperature observations. *Mon. Wea. Rev.*, **132**, 1606-1629.
- Webster, P. J., C. A. Clayson, and J. A. Curry, 1996: Clouds, radiation, and the diurnal cycle of sea surface temperature in the tropical western Pacific. *J. Climate.*, **9**, 1712-1730.

- Webster, P. J., E. F. Bradley, C. W. Fairall, J. S. Godfrey, P. Hacker, R. A. Houze Jr., R. Lukas, Y. Serra, J. M. Hummon, T. D. M. Lawrence, C. A. Russell, M. N. Ryan, K. Sahami, and P. Zuidema, 2002: The JASMINE pilot study. *Bull. Amer. Meteor. Soc.*, **83**, 1603-1630.
- Whiteman, C. D. and X. Bian, 1996: Solar semidiurnal tidal winds in the troposphere: Detection by radar profilers. *Bull. Amer. Meteor. Soc.*, **77**, 529-542.
- Whiteman, C. D., X. Bian, and S. Zhong, 1997: Low-level jet climatology from enhanced rawinsonde observations at a site in the southern Great Plains. *J. Appl. Meteorol.*, **36**, 1363-1376.
- Woolnough, S. J., J. M. Slingo, and B. J. Hoskins, 2004: The diurnal cycle of convection and atmospheric tides in an aquaplanet GCM. *J. Atmos. Sci.*, **61**, 2559-2573.
- Xie, S.-P., H. Xu, N. H. Saji, Y. Wang, and W. T. Liu, 2006: Role of narrow mountains in large-scale organization of Asian monsoon convection. *J. Climate*, **19**, 3420-3429.
- Yang, G. Y. and J. Slingo, 2001: The diurnal cycle in the tropics. *Mon. Wea. Rev.*, **129**, 784-801.
- Yang, S. and E. A. Smith, 2006: Mechanisms for diurnal variability of global tropical rainfall observed from TRMM. *J. Climate*, **19**, 5190-5226.
- Yasunaga, K., M. Fujita, T. Ushiyama, K. Yoneyama, Y. N. Takayabu, and M. Yoshizaki, 2008: Diurnal variations in precipitable water observed by shipborne GPS over the tropical Indian Ocean. *SOLA*, **4**, 97-100.
- Yu, R., T. Zhou, A. Xiong, Y. Zhu, and J. Li, 2007: Diurnal variations of summer precipitation over contiguous China. *Geophys. Res. Lett.*, **34**, L01704, doi:10.1029/2006GL028129.
- Zhou, L. and Y. Wang, 2006: Tropical Rainfall Measuring Mission observation and regional model study of precipitation diurnal cycle in the New Guinean region. *J. Geophys. Res.*, **111**, D17104, doi:10.1029/2006JD007243.
- Zhou, T., R. Yu, H. Chen, A. Dai, and Y. Pan, 2008: Summer precipitation frequency, intensity, and diurnal cycle over China: A comparison of satellite data with rain gauge observations. *J. Climate*, **21**, 3997-4010.
- Zuidema, P., 2003: Convective clouds over the Bay of Bengal. *Mon. Wea. Rev.*, **131**, 780-798.