13.1 THE DIURNAL CYCLE OF WARM SEASON RAINFALL FREQUENCY OVER CONTINENTS

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1. INTRODUCTION

It has become increasingly evident that a sizeable fraction of warm season continental rainfall results from long-lived “episodes” as reported by Carbone et al. 2002, 2003; Davis et al., 2003; Tuttle and Carbone, 2004. Related studies have since been conducted over portions of several other continents where there is evidence for a high frequency of organized convection (e.g. Wang et al., 2004, 2005). This paper synthesizes the diurnal cycle findings for these diverse geographical regions under environmental conditions that differ significantly in several respects. A common thread among these regions is that warm (or rainy) season conditions are often “weakly-forced” in a balanced dynamical sense and significant orography is present.

The following signals have emerged from our comparative studies over four continents:

- A disproportionately large fraction of events have their origin in the lee of major cordillera, a finding consistent with that reported by Laing and Fritsch 2000. Obvious instances are the Tibetan Plateau, the Rockies, the Ethiopian Highlands, and the eastern cordillera of Australia. While clearly insufficient in itself, a major factor in the genesis of events is thermal forcing associated with regional scale elevated heat sources.

- Many events are of long duration, sometimes spanning several diurnal cycles. In the presence of steering winds and shear, the events steadily propagate across continents, while exhibiting periods of dissipation followed by periods of phase-coherent convective regeneration.

- The combined effects of thermal excitation over mountains and steady propagation leads to sharply defined patterns in the diurnal cycle. This pattern may be characterized as “streaks” of alternately high and low frequency of occurrence in a Hovmöller diagram. We refer to this pattern as “globally phase-locked”, since the local diurnal cycle is influenced by remote forcings that project a delayed-phase diurnal signal on the region.

- One consequence of the above phenomenon is the superposition of a local maximum of “ordinary” convection with the delayed-phase arrival of remotely-forced events, both of which were forced diurnally. Nevertheless, this gives rise to semi-diurnal signals in traditional harmonic analyses. Such signals often have been mistakenly interpreted as evidence of the role of atmospheric tides in semi-diurnal convective triggering.

Herein we briefly review the observed diurnal cycles over portions of several continents mainly to convey the universality of systematic propagation and coherent regeneration in various regions worldwide.

2. Reduced Dimension Analysis

Studies currently in progress include an initial examination in reduced spatial dimension. An arithmetic average of estimated rainfall and/or the frequency of rainfall events from radar or satellite data is calculated and plotted on Hovmöller diagrams, preserving one horizontal dimension and time variation. The coherence of structures in this format reveals the mean phase and amplitude of the local diurnal cycle as well information about the relationship of these features to the triggering and systematic motion of rainfall systems.

Over the continental U.S., Carbone et al. employed the WSR-88D national composite reflectivity data, the first radar dataset to provide nearly continuous coverage of a continental region, including space and time-resolved precipitation events (2 km, 15 min.). Over Africa, Australia, East Asia, Europe and South America, geostationary and other satellite data have been employed, typically with ~4km, 30 min. resolution. Infrared blackbody brightness temperature has been the principal quantity used from the geostationary satellites. Increasingly, microwave data and TRMM radar data are being incorporated into these analyses either as merged or independent products.

Comparison of radar and satellite datasets can be problematic, in this instance owing to differences in the physical relationships to rainfall. Tuttle et al. (2005) have reported on the systematic statistical differences between radar reflectivity and satellite IR data sources. They have quantified these differences for temporal phase delay and the first three moments of the PDFs for

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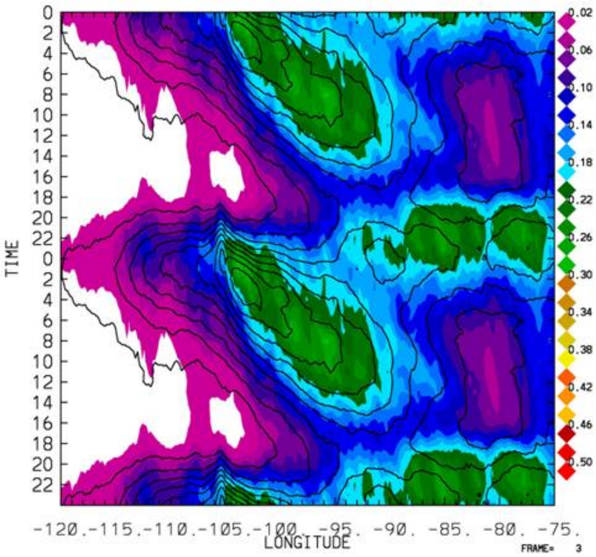

Fig. 1. Diurnal cycle of rainfall frequency, JJA, 2000-2002. Intercomparsion of radar (color) and GOES IR (contours). Mean bias of averaged fields are a satellite delay of 1.75h and an increased phase speed of 4.5 m/s. (Tuttle et al. 2005)

event span, duration and phase speed over the continental U.S. Based on environmental factors such as tropopause temperature, upper tropospheric winds, and tropospheric shear of the horizontal wind, a transfer function to correct systematic differences may then be applied to appropriate regions of other continents. Implicit in this approach is that radar reflectivity is regarded as "truth" insofar as the location and time (but not the amount) of rainfall. Figure 1 summarizes the diurnal phase delay and propagation phase speed differences between WSR-88D and GOES, as observed over the continental U.S. in mid-summer. Average differences are a 1.75 h delay and a 4.5 ms^{-1} phase speed increase in the GOES analysis. The following results are radar-based in the U.S. and Mexico and satellite-based for other continents.

3. Diurnal Cycle Examples from five continents

(a) Continental U.S.

Fig. 2 illustrates the mid-summer diurnal pattern over the U.S. from the continental divide eastward. The quantity depicted is the percentage of time rainfall is present for any UTC hour and longitude for July 1997. Among other features these results illustrate the influence of elevated terrain in triggering convection over the Rockies, which subsequently propagates and coherently regenerates eastward across the continent. The "long" events span up to three diurnal cycles before entering the Atlantic Ocean. It is evident from this pattern that the form and phase of a local diurnal cycle is in part dependent on distance from an elevated heat source and the rate of propagation. At longitudes where propagating systems are phase coincident with the local diurnal maximum, amplitude of the diurnal cycle is increased. Where these signals are completely out of phase, semi-diurnal harmonics are produced.

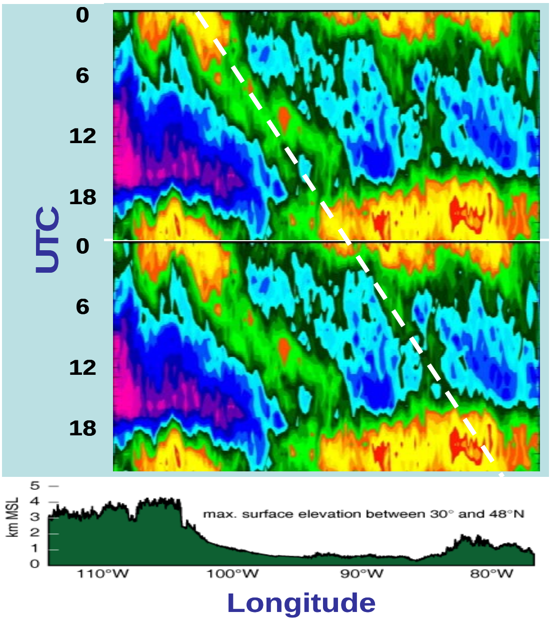

Fig. 2. % of time (purple near 0, red >70) in each UTC hour that radar echo from precipitation is present between 30-48N. This illustrates local and remote influences of thermal forcing by the Rockies on the diurnal frequency of precipitation (July 1997. as estimated from the WSR-88D network). The diurnal cycle is repeated for clarity. Individual events can span > 2 diurnal cycles (after Carbone et al. 2002).

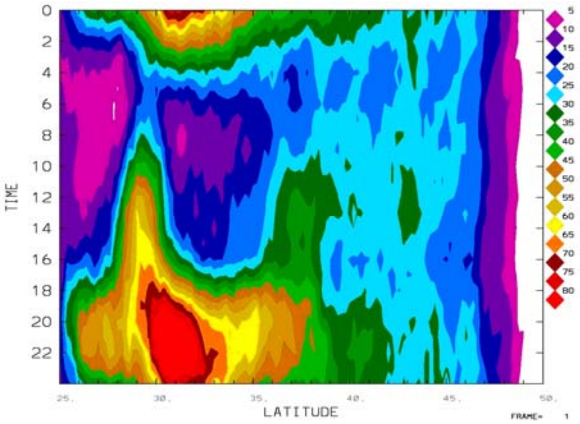

Fig 3. Semi-diurnal signals 80-95W as function of latitude. Rainfall activity circa 10-12 UTC occurs in three regions: Gulf of Mexico land breeze (28N), eastward propagating episodes (35-40N), and the Great Lakes region (43N). (Carbone et al. 2003)

Fig. 3 illustrates the semi-diurnal signals observed in the central to eastern U.S. (80-95 W) from the Gulf of Mexico to the Great Lakes region (25-48 N), for July 1996-2002. The local diurnal maxima are observed to occur near 22 UTC. However, there are three latitude bands where semidiurnal maxima occur in the middle of this diagram, circa 12 UTC. A southerly semidiurnal maximum is the result of land breeze convection south of the Gulf of Mexico coastline (~28 N). The maximum between 35-40 N marks the mean time of arrival (and dominant latitude band) of propagating systems from the west. The weak semi-diurnal signal north of 40 N is likely related to land breezes over the Great Lakes.

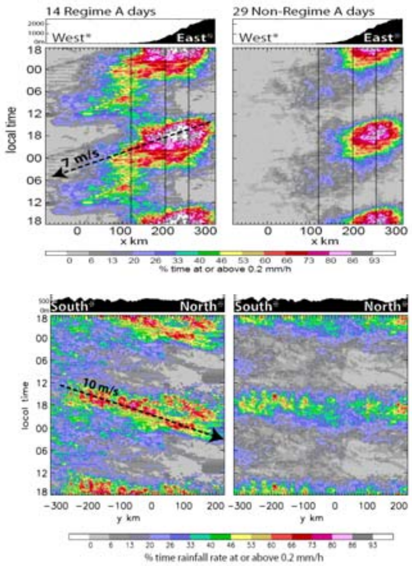

Fig. 4. Frequency of rainfall in North American monsoon region (NW Mexico, LT). Mean height of topography in black. GoC coastline at 120 km. Origin is approximate center of GoC. ***Top***: diurnal progression transverse to mean topography, July-August 2004. *Right:* Undisturbed condition - a steady progression from SMO to the coastal plain. *Left:* Regime A disturbed condition - rainfall extends well into the GoC. ***Bottom:*** diurnal progression of rainfall parallel to mean topography. Right: Undisturbed condition – non-propagating. Left: Regime B Disturbed condition – propagation "northward".

(b) North American Monsoon

July through September marks a wet season in NW Mexico that is generally regarded as a monsoon, though relatively small and weak compared to the Asian monsoon. The region is characterized by easterly and southerly flow that is periodically perturbed by the passage of easterly waves and the genesis of tropical cyclones in the eastern Pacific. The region is bounded by the Gulf of California (GoC) and the Sierra Madre Occidental (SMO) mountain range. As described by Lang et al. 2005 and illustrated in Fig. 4 (top), the diurnal cycle of rainfall is relatively simple on undisturbed days. It begins with the afternoon excitation of ordinary convection over west-facing, mid-to-upper slopes of the SMO and subsequently through sea breeze interactions at lower altitudes. These interactions lead to a modest increase in the organization of convection while moving westward, down the SMO slopes, under the dual influence of cold pool propagation and easterly momentum aloft.

Approximately 30% of days may be classified as "disturbed" wherein additional attributes to the undisturbed diurnal cycle regime are observed (Fig. 4, bottom). More rainfall is observed together with a greater dynamical organization of rainfall systems, including, for example, leading-line mesoscale convective systems. Evening activity is prominent along the coastal plain, followed by weak to moderate rainfall events near the land breeze front over the GoC coastal waters. The nocturnal phase includes rainfall well beyond the coastal waters and, on occasion, propagation across the GoC to Baja California. Furthermore, there is significant propagation of rain systems northwestward at a rate in excess of steering wind speeds. This component of propagation is approximately parallel to the SMO topography and the GoC coastline. These conditions include increased southerly and easterly wind components, moderate lower tropospheric shear and increased convective inhibition (CIN).

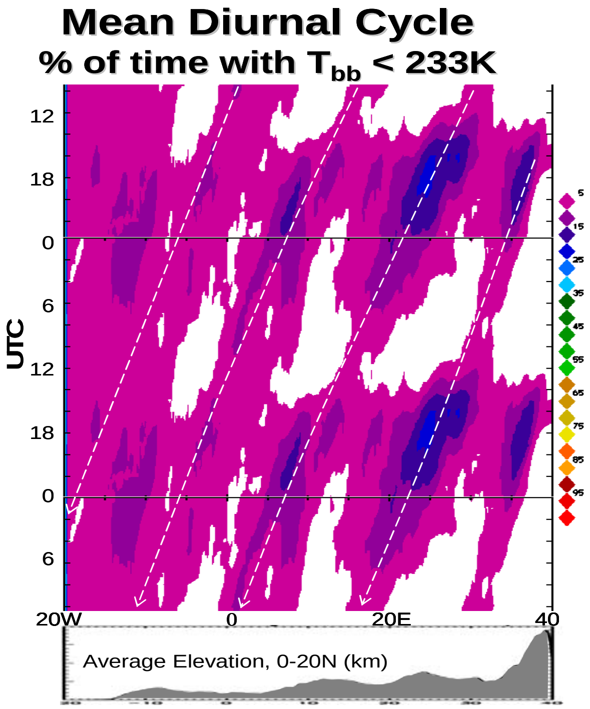

Fig. 5 Diurnal Cycle in the Sahel region of Africa. Origin of many rainfall systems over the Somalian and Ethiopean highlands of eastern Africa. Phase-locked propagation is evident across 60° longitude to the Atlantic coast.

(c) African Sahel Region

Laing et al. 2006 have examined the Sahel region, which spans 60° of longitude from Ethiopia and Somalia to the Atlantic Ocean between 20N and the equator. This is a region often frequented by an easterly jet near 600 kPa and easterly waves. Near the eastern edge of this region the Somalian and Ethiopean highlands dominate the landscape and constitute the principal source region for the excitation of propagating rainfall systems.

Fig. 5 illustrates the diurnal cycle for a two week period typical of the summer season. Laing et al.

observe a pattern similar to the U.S. in subtropical westerlies, save for the reversal of steering winds and shear. The multi-year timeseries (1998-2002) is consistent with the long term persistence of this pattern, albeit with variable rates of propagation and rainfall intensity. Individual events may span the continent and coherently propagate up to 4 diurnal cycles. For details, the reader is referred to Laing et al. (P10.13, herein).

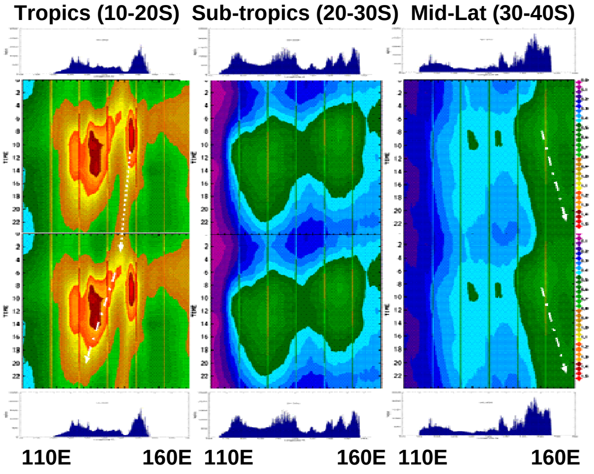

Fig. 6 Diurnal cycle of rainfall frequency in three latitude bands of Australia, DJF, 1996-2001. Propagation is absent in the sub-tropical belt (center) due to absence of steering winds and shear. Intermittent westward propagation is evident in the tropics, associated with the easterly jet regime in monsoon break periods. Eastward propagation occurs with greater regularity in the lee of the eastern cordillera at mid-latitudes.

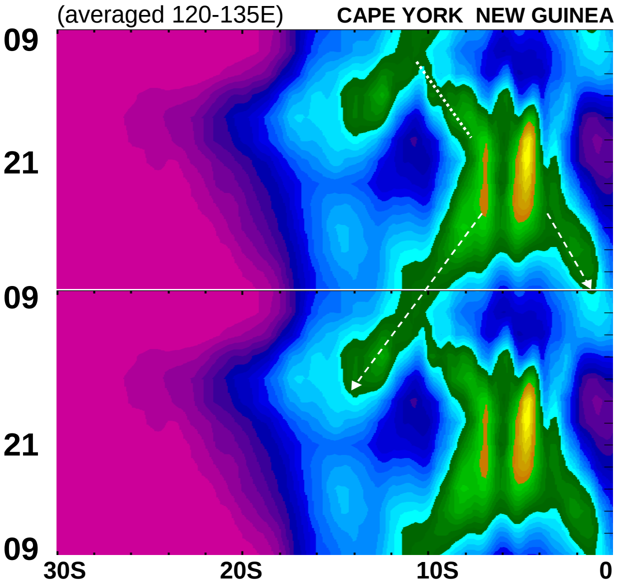

Fig. 7. Diurnal cycle (LT) over portions the equatorial Maritime Continent (New Guinea and nearby Indonesia) and tropical northern Australia, DJF 1996-2001. Meridional propagation is associated with nocturnal propagation of dissipating rainfall systems southward from New Guinea to Cape York Peninsula.

(d) Australia and the Maritime Continent

Australia and the Maritime Continent span a wide range of regimes, from equatorial to mid-latitude, including monsoonal, easterly jet, subtropical and strongly forced rainfall systems associated with cyclones and fronts. Australia is also the flattest continent, with no terrain above 2 km. This latter attribute suggests that elevated heat source excitation of convective rainfall might be less prominent there. Indeed this is the case as illustrated in Fig. 6.

While the diurnal cycle of rainfall exhibits propagation intermittently in many regions, this is a regular feature only in the lee of the eastern cordillera at mid-latitudes and in the tropical easterly jet regime. The latter conditions bear similarity to the Sahel of Africa, where a 700kPa jet combined with triggering over the Cape York peninsula gives rise to long-lived events westward to the “top end” of the Northern Territory (white dashed lines, Fig. 6, left). Propagating systems from the eastern cordillera at sub-tropical mid-latitudes are frequent, however, the duration is short and the continental impact is limited before systems exit to the Tasman Sea.

Fig. 7 illustrates more detailed findings associated with dynamical interactions between the island of New Guinea and tropical northern Australia. New Guinea is a very large island with a spine of mountains in excess of 5 km. The deepest convection on Earth develops here on the north and south flanks of this range. Down-slope propagation, both southward and northward, leads to organized maritime convection at night. The southward branch of this meridional propagation “collides” with the Cape York peninsula after sunrise. This disturbance subsequently triggers vigorous convection that is often long-lived. Owing to the easterly jet, convection at 10-15S propagates westward across the Gulf of Carpenteria and the Northern Territory.

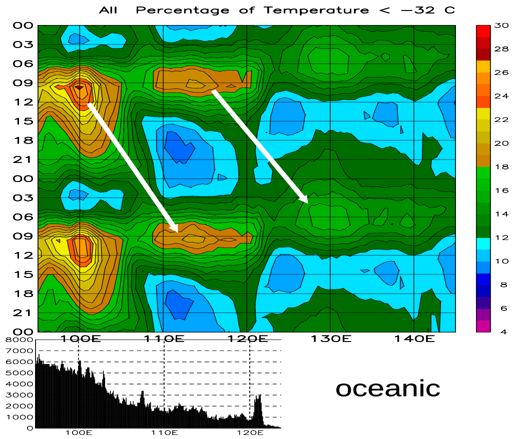

Fig. 8 Diurnal cycle in East Asia, including the Tibetan Plateau, leeward China and western N. Pacific oceanic regions. Propagation is prominent in the Mei-Yu season but ceases in mid summer when monsoon conditions prevail. (after Wang et al. 2004)

(e) East Asia

Wang et al. 2004, 2005 have published detailed findings on the diurnal cycle of the East Asian region. This region is vast and complex with several precipitation regimes having been observed. Springtime conditions include the Mei-Yu season with subtropical frontal forcing and influences from mid-latitude cyclonic systems. In mid summer the Asian monsoon is dominant, including a complete wind reversal. In the midst of this lies the Tibetan Plateau, the crown jewel of elevated heat sources. Fig 8 shows rainfall system propagation in the lee of the Tibetan plateau during Mei-Yu season (May-June), which bears a striking resemblance to North America in July. An entirely different diurnal regime prevails over the western N. Pacific, characteristic of oceanic precipitation. Following the retreat of the Mei-Yu front to northern latitudes, the Tibetean Plateau continues to excite deep convection diurnally. These conditions lack both steering winds and shear in mid-summer and propagation of rainfall systems is a rare exception.

4. Summary

There are both commonalities and quantitative differences associated with organized convective rainfall regimes among the continental regions examined so far. The most prominent commonality is associated with the elevated source for convective triggering and the subsequent dynamical organization upscale in the presence of moderate shear and adequate CAPE. What is most surprising is the statistical similarity of events in seemingly dissimilar environments (e.g. tropical easterly jet and deep westerly regimes). The full significance of this observation is not fully understood but likely central to more successful representations of convective rainfall in global climate system models. Some things that are evident in the results are:

- Some deep tropospheric shear ($\sim 10^{-3}$) is essential to the upscale organization of convection and attendant rainfall that may be diurnally forced both locally and remotely.

- Sea and land breezes play an important role in triggering convection that often constructively interacts with complex terrain and other sources of convection to produce diurnally modulated systems with both local and remote effects.

By the time of the Conference we expect to provide comparable results fromboth Europe and the Amazon region.

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