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NOCTURNAL CLOUD SYSTEMS AND THE DIURNAL CYCLE OF RAINFALL IN AMAZONIA

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1. INTRODUCTION

The diurnal variation of clouds and precipitation over tropical landmasses is the expression of a rich variety of phenomena spanning many time and space scales. Solar heating of land increases sensible heat flux and thermodynamic instability, leading to vertical mixing of water vapor in the deepening boundary layer during the morning, and favoring afternoon precipitating convection (Wallace 1975, Betts 1976). Dynamic processes are crucial to actually initiating moist convection by lifting parcels to their level of positive buoyancy, such as land/water circulations, density currents, and orographic lifting (Wallace 1975).

Over the last ten years, advances in satellite remote sensing and increased deployment of field instrumentation have led to a detailed view of diurnal changes in rainfall and cloudiness. There has been a recent focus on convective cloud systems in the Amazon Basin, in part because of field efforts to study the interaction between convection, land processes, topography, and large-scale circulations (Avissar et al. 2002, Rickenbach et al. 2002, Laurent et al. 2002). The Tropical Rainfall Measuring Mission Large-Scale Biosphere-Atmosphere (TRMM-LBA) and the coincident Wet-season Amazon Campaign (WETAMC) field programs during the 1999 wet season (Silva Dias et al. 2002) provided a detailed view of the structure and environment of convective systems in southwestern Amazonia.

Many studies of the diurnal cycle of precipitation and cloudiness over the Amazon indicated a secondary nocturnal maximum, in addition to the primary afternoon maximum. A composite of two wet seasons of TRMM rain estimates from the precipitation radar (PR) over the Amazon (Lin et a. 2000) indicated that rainfall increased at 2300 LT to a broad nocturnal maximum, weaker though than the afternoon maximum following the explosive increase between 11LT and local noon. Satellite retrievals of the diurnal cycle of precipitation and cloudiness over the Amazon Basin revealed an alternating banded structure in the diurnal phase, from the northeast coast to western Amazonia (Negri et al. 1994, Garreaud and Wallace 1997). Other investigations further suggested that the phase propagation of the diurnal rainfall maximum in Amazonia was tied to the effects of long-lived, propagating convective systems (Greco et al. 1990, Cohen et al. 1995)

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These studies highlighted several unresolved questions concerning the nocturnal maximum in clouds and precipitation over tropical South America. What accounted for the secondary nocturnal maximum in rainfall and cloud area? Was convection regenerated locally at night, or did afternoon convection evolve to produce a nocturnal maximum in rain? How important were stratiform precipitation processes in the nocturnal maximum of clouds and rainfall? Did propagating coastal squall lines influence nocturnal rainfall in southwestern Amazonia? The goal of this paper was to investigate the origin of the nocturnal precipitation maximum in Amazonia with those specific questions in mind. This study took the approach of composite and case study analysis of TRMM-LBA surface observations and geostationary satellite data for nearly two months in southwestern Amazonia during the early1999 wet season.

2. DATA

TRMM-LBA observations (49 days) of radar reflectivity from the TOGA C-band scanning radar, radiosonde thermodynamic profiles, and GOES-8 infrared (IR) cloud top imagery were the primary data sources. Radar reflectivity data were quality controlled to remove anomalous echo, and calibration biases were corrected by comparison with the TRMM precipitation radar (Rickenbach et al. 2002, Anagnostou and Morales 2002). The data were interpolated to a 1 km x 1 km x 1 km grid for analysis. Spatial gradients and local maxima provided the basis to partition the reflectivity field into regions of active convective cells, and weaker, horizontally uniform stratiform rain (see Rickenbach et al. 2002 for details).

3. DIURNAL COMPOSITES AND CASES

The radar observations showed that, following a mid-morning minimum, a sharp increase in total rain area (Figure 1a) between 1000 LT and 1400 LT was coincident with a similarly sharp increase in convective rainfall (Figure 1b), echo top height and 30 dBZ surface height (Figure 1c) over the same time period. This was the signature of rapid, widespread formation of precipitating convective cells near local noon (hereafter “noon balloon”, a term coined by Earle Williams). Convective rain area and rainfall decreased after 1600 LT, while stratiform rain area remained constant and mean echo top height (particularly stratiform) continued to increase. These observations suggest that by 1600 LT, active convection coalesced to smaller groups, stratiform anvil clouds expanded in area, and rainfall decreased, all pointing to the decay stage of the “noon balloon” convection. By about 2200 LT, the composites suggested that the afternoon convective activity had come to an end, having collapsed in vertical intensity and diminished in area, and rainfall. Animation of radar imagery for each day showed a consistency with this general scenario for most days.

a. b. c. d.

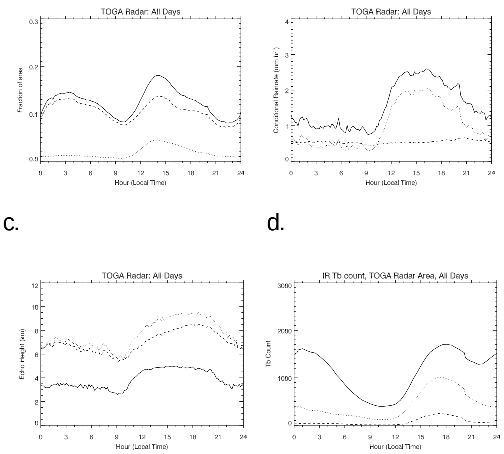


Figure 1. Diurnal composites of a) radar fractional areal coverage of rainfall (convective dotted, stratiform dashed, total solid); b) same but for conditional rainfall; c) same but for mean echo top height and 30 dBZ surface height (solid); d)IR pixel count within radar area for 250K (solid), 230K (dashed), 210K (dotted)

After 2200 LT, the radar composites indicated a resurgence of activity. Stratiform rain area increased sharply again between 2200 LT and 0300 LT, corresponding in time with increased convective intensity (mean 30 dBZ surface height) and mean echo top height. The 0300 LT stratiform rain area maximum was equal in amplitude to the afternoon maximum at 1500 LT. However the convective component of rain area showed only a weak and gradual increase, in contrast to the afternoon situation, with a 0300 LT maximum. Rainfall remained nearly constant (weak downward trend) after 2200 LT into the early morning hours, with some fluctuations in convective rain during that time. By 0600 LT, this nocturnal resurgence had diminished, ending in a general cessation of all activity by 0900 LT. The dominant nocturnal cloud maximum was in the low and mid-level clouds (250K) at 0100LT, which occurred an hour before the peak in radar echo top height and two hours before the rain area maximum. Only later, at 0300 LT, were weak maxima observed at the colder cloud area thresholds (210K and 200K, Figure 3b), which matched the mean radar echo top area maximum and was suggestive of some deep convective activity. The scenario suggested by these observations was of weak convective regeneration and a large expansion of stratiform rain area after midnight. Perusal of radar imagery revealed that nocturnal convection was indeed common, but in contrast to the afternoon convection there was no single scenario to explain what was happening at night.

The next step toward understanding the nocturnal rainfall and cloudiness maxima was to look for consistent patterns in the daily time series of radar and IR parameters and animations of radar and IR imagery. Perusal of radar and IR image animations and daily time series suggested two general scenarios qualitatively describing the nocturnal systems. On many of these nights, one or more squall line systems either formed within or propagated into the radar view. These systems typically consisted of either a large squall line system, or a series of smaller groups of active convection, with associated stratiform rain. On other nights, large regions of light stratiform precipitation formed within (and beyond) the radar area, with no clearly associated deep convection. During the TRMM-LBA campaign, many scientists in the field reported anecdotal observations of extensive nocturnal drizzle and mid-level cloudiness that at times persisted after sunrise. Such events were quite distinct from nocturnal convective systems, and of sufficient frequency and uniqueness to warrant separate investigation.

3.1 *Nocturnal convection: 18 Feb. squall line*

Afternoon "noon balloon" convection was widespread on 17 February, and had decayed to patchy stratiform remnants by 2200 LT (02Z 18 February).

a. b.

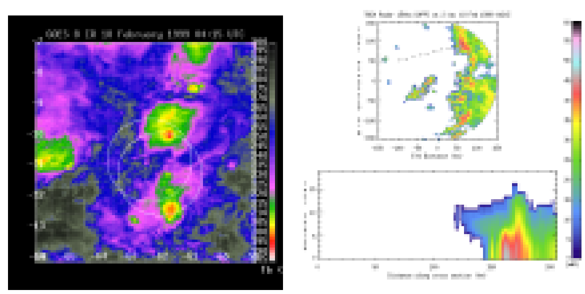


Figure 2. 18 February squall line system entering the TOGA radar view at 0015 LT (0415 Z): a) IR image; b) 2km CAPPI (top) and vertical cross section (bottom) from the radar.

Radar and IR imagery indicated that by that time, a large, pre-existing squall line began to enter the eastern edge of the radar area. Animation of IR imagery covering Amazonia strongly suggested that this squall line was a part of a large-scale, westward propagating line of cloudiness with its origin 1.5 days earlier (the afternoon of 16 February, not shown) on the northeast coast of Brazil, of the type described by Cohen et al. (1995). IR imagery at 18 February 0215Z, showed the squall line still well defined on its second night, 3000 km west of where it had formed, with new cold cloud elements on the southern end entering the TOGA radar view. The leading edge of the cloud line traveled approximately 550 km during this 12-hour period (a propagation speed of roughly 13 m s^{-1}) consistent with the speed of coastally generated lines reported in Cohen et al. (1995). Radiosonde data from 2300 LT (0300 Z, not shown) indicated an atmosphere primed for organized deep convection, with ample CAPE distributed through the column) and an easterly jet centered at 4 km height. The vertical cross section at 0015 LT (0415Z, Figure 2) showed the northern portion of the line with deep convection reaching 16 km echo top height, and both a forward-sheared anvil and trailing stratiform precipitation. By 0615 LT (1015 Z), this portion of the line decayed to extensive stratiform rain with a strong radar bright band signature. By the mid morning, all activity had ceased, and the subsequent “noon balloon” convection was completely shut down presumably from the stabilizing effect of the low-level cooling and drying induced by the system passage.

3.2 ***Nocturnal drizzle: 19 Feb. event***

This event occurred the night following the 18 February squall line discussed in the previous section. By the evening of 18 February, the GOES satellite observed a general lack of convective activity in the entire western half of Amazonia, including the TOGA radar area, as shown in 2145 LT (0145 19 February) IR image (Figure 3). An hour later, IR imagery (Figure 4a)

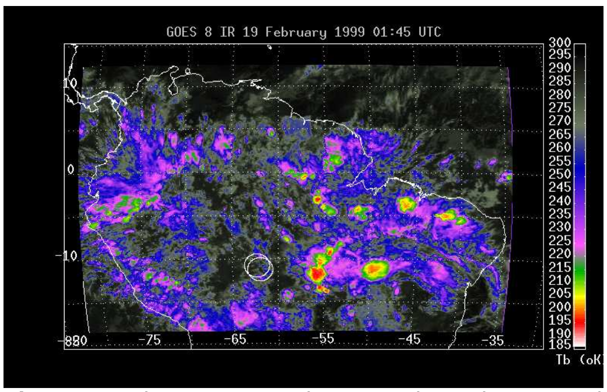


Figure 3. IR image at 19 Feb. 0145Z (18 Feb. 2145 LT) showing a large region in western Amazonia devoid of convective activity prior to the nocturnal drizzle event (from 60W – 70W longitude and 0S – 15S latitude).

revealed an expanding region of mid-level cloudiness (250K to 240K range) over the radar domain, which formed in-situ and not associated with nearby convection. At the same time the radar indicated the initial formation of weak echo above the 0^{o}C level (Figure 4), between 5 km and 8 km, within the growing mid-level cloud. In the center of the cloud mass the radar

a. b.

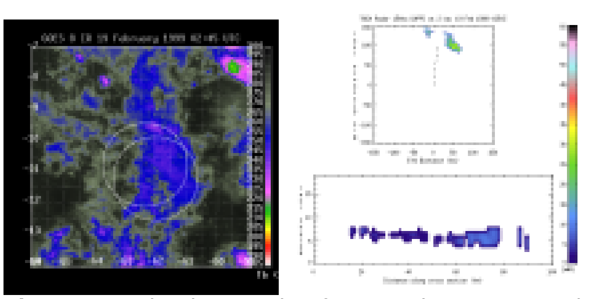


Figure 4. As in Figure 2, but for 19 February 0245Z (18 February 2245 LT).

observations suggested light rainfall at or near the surface. A sounding released from the Rancho Grande site at that time passed through the western edge of this cloud feature. The relative humidity profile indicated a 3 km thick broken cloud deck, with cloud base at 4.5 km (the 0^{o}C level) and cloud top at 7.5 km (consistent with the IR brightness temperatures), and a relatively low CAPE value of 858 J kg^{-1}. Figure 5 showed the mid-level cloud cover covered much of western Amazonia by 0145 LT (0545 Z). Note from Figure 6 the expanded area of low-level stratiform rain, and the descent of mid-level radar echo to the surface, particularly in the northern portion

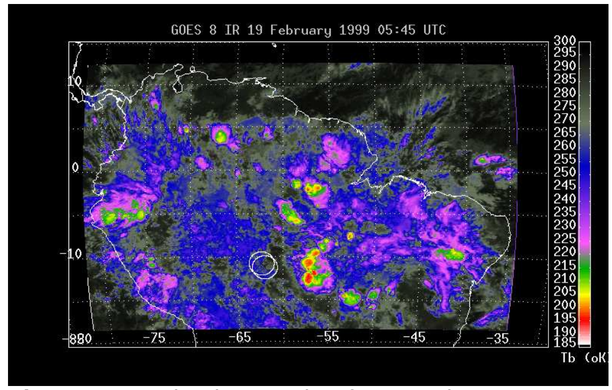


Figure 5. As in Figure 3, but for 19 February 0145 LT (0545 Z).

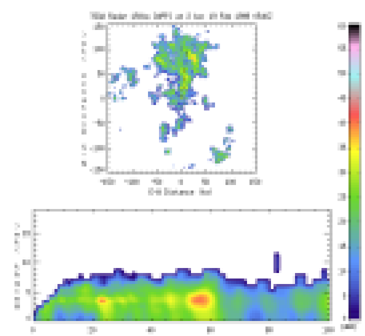


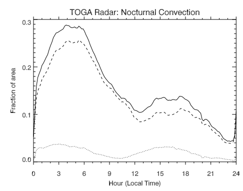
Figure 6. As in Figure 2b, but for 19 February 0145 LT (0545 Z).

of the domain. By then, the cloud deck near the radar began to gradually dissipate. At this later stage, a well-defined radar bright band had formed between 3 km and 4 km above the surface. Streamers from the more intense bright band features coincided with higher values of near-surface radar reflectivity (Figure 6), leading to increasing rainfall rate.

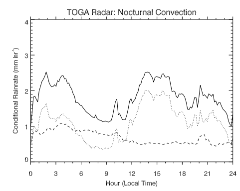
4. NOCTURNAL COMPOSITES

Composite diurnal time series for the days with “nocturnal convection” and “nocturnal drizzle” are presented in Figures 7 and 8. The nocturnal convective systems had a significant effect on the timing and intensity of the “noon balloon” convection the following afternoon. The late morning increase in convective rainfall and rain area (Figure 7) was much less rapid and was delayed by two hours (to local noon) compared to the 49-day composite (Figure 1). A greater blockage of solar insolation in the hours after sunrise, as suggested by twice as much mid-level (250K) cloud area at the 1000 LT minimum compared to the 49-day composite, likely contributed to the suppression of the “noon balloon”, in addition to the low level cooling and drying by the previous night’s convective overturning.

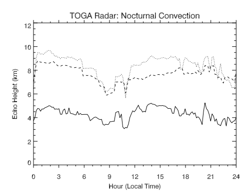
a.



b.



c.



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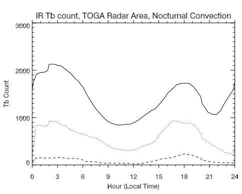
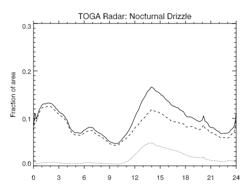


Figure 7. As in Figure 2, but composited for nocturnal convection events.

a.



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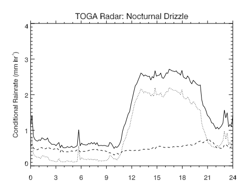

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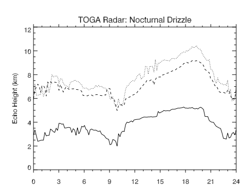

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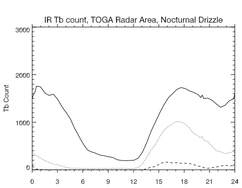

Figure 8. As in Figure 2, but composited for nocturnal drizzle events.

In contrast to the large rainrates associated with nocturnal convection, the main signature of nocturnal drizzle events (Figure 8) was a peak in the stratiform rain area near 0200 LT (with a resurgence after 0600 LT). The weak rainfall intensity associated with nocturnal drizzle events suggested that these systems played a minor role in the total nocturnal rainfall. Nevertheless, the expansive mid-level cloudiness associated with these systems were likely important, for example to the total radiation budget. The nocturnal 250K cloud area maximum was nearly as large (and two hours earlier) as the nocturnal convection cloudiness. Nocturnal drizzle systems contributed only 3% of the 48-day rainfall total, while 25% of the total was associated with nocturnal convective events. Moreover, in contrast to the nighttime convection, nocturnal drizzle events apparently had little influence on the next afternoon’s “noon balloon”, as seen by the sharp increase in convective rainrate and rain area in Figure 8.

5. CONCLUSIONS

This paper examined the origins of a secondary nocturnal maximum in cloudiness and precipitation in southwestern Amazonia during the TRMM-LBA field campaign, which had been observed previously by many investigators. The general finding was that following the collapse of the nearly ubiquitous and locally generated afternoon (“noon balloon”) convection by 2200 LT, organized deep convection contributed to a post-midnight maximum in raining area and high cloudiness, and to a lesser extent rainfall, following a nocturnal resurgence in vertical intensity of convection and subsequent expansion of stratiform rain area. For some cases, the timing of the nocturnal convective resurgence was tied to the arrival time of westward propagating of large-scale squall lines generated more than 2000 km away along the northeastern coast of Brazil. The influence of these coastally generated squall lines as far west as southwestern Amazonia had not been previously documented. Nocturnal regeneration of convection due to local triggering was also likely important. Nocturnal convective systems were found to significantly reduce and delay the onset of the “noon balloon” convection the following afternoon.

In addition, a previously undescribed nocturnal drizzle phenomenon, independent from nocturnal convective systems, was shown to contribute significantly to nocturnal mid-level cloudiness, but not to precipitation. On nearly one of every three nights in the 49 day sample, widespread cloudiness and precipitation was generated in-situ between 5 km and 8 km in height, suggesting that its origins were above the 0^oC level and were not rooted in the boundary layer. Nocturnal mid-level cloudiness was often observed to form over the entire western portion of Amazonia in regions undisturbed by deep convective systems. Possible mechanisms to drive upward motion above the melting level include weak orographic lifting, shear instability at the melting level height driven by a diurnally modulated flow feature (like a nocturnal jet), or large-scale mid-tropospheric ascent tied to radiational processes. The greatest significance of nocturnal drizzle events may be the potential effect on the diurnal radiation budget by the extensive mid-level nocturnal clouds, rather than the marginal contribution to nocturnal rainfall.

6. REFERENCES

Rickenbach, T. M., 2003: Nocturnal cloud systems in southwestern Amazonia. Submitted to *Mon. Wea. Rev.*

For the list of references and the complete paper, see *http://userpages.umbc.edu/~rickenba/main/ricken.html*