The TRMM Precipitation Radar observations of West African storms

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Abstract. The TRMM Precipitation Radar (2A25) data is used to study the nature of West African storms during the pre-monsoon (AMJ) and monsoon(JA) periods. There is remarkable contrast between the storms within the continent and those of ITCZ which are aligned along the Coast of Guinea during the pre-monsoon period. Continental pre-monsoon storms are deep, intense and scattered, while those of the ocean are relatively shallow, moderately intense and wide-spread. The onset of the monsoon involves the shift of the latter systems into the continent. After the onset, both areal mean convective and stratiform rainfall with in the continent double. Stratiform rain accounts for about 45% of the total. Both during the pre-monsoon and monsoon periods, shallow convection accounts for less than 10% of the total rainfall and is limited to the coastal regions. The rise in continental convective rainfall during the second half of May and early June suggests that the associated low-level latent heating might be responsible for the onset of the monsoon through meridional advection of moisture.

Introduction

Recent observational studies have shown that the classical vision of smooth and continuous northward migration of ITCZ during the onset of the West African monsoon is not correct. The monsoon season begins with intense rainfall near the Gulf of Guinea in April. The precipitation maximum remains there till the end of June, while a weaker precipitation field starts to develop at about 10^0N during the end of May. The former rainfall band jumps to the latitude of the latter during the last week of June and follows the approximate seasonal cycle afterwards. This 'jump' in the major rainfall system is a manifestation of the onset of intense convection and rainfall along 10^0N and its concurrent and sudden termination along the coast of Guinea. This is in sharp contrast with the fact that the ultimate cause of the seasonal migration of the ITCZ, the northward march of the sun, follows a smooth and continuous cycle.

Observational analysis of this jump in the northward migration of the ITCZ was first made by *Sultan and Janicot* [2000]. They used gridded rainfall data from West Africa compiled at IRD (Institute de Recherche pour la Developpment), ASECNA (Agence pour la Securite De La Navigation Aerienne en Afrique et a Madagascar) and CIEH (Comite Interafricain d'Etudes Hydroliques) as well as the NCEP/NCAR reanalysis data [*Kalnay et al.*, 1996] over the years from 1968 to 1999. They suggested that the abrupt shift could be the result of acceleration of the seasonal cycle by westward propagating intra-seasonal scale atmospheric circulations.

This phenomenon is also documented in a study by *Le Berbe et al.* [2002]. Using CIEH - ORSTOM daily rainfall data-set they showed that the precipitation maximum preferentially appears at these above mentioned latitudes. Similarly, using the rain-gauge data described in *Le Berbe et al.* [2002], Meteosat IR images, EPSAT-Niger network and NCEP/NCAR reanalysis, *Label et al.* [2003] further confirmed the discontinuity in the northward migration of the ITCZ over West Africa. They showed that the seasonal cycle is composed of two precipitation regimes. The first one, which they referred to as the oceanic regime, involves progressive onset of rain on the West African coast from the equatorial Atlantic. The second phase, the continental regime, involves the sudden rise in the mean daily rainfall and the mean number of rain events that occur over the Sahelian band. The continental regime starts at the end of June and accounts for the 75 to 90% of the total precipitation. They also showed that the inter-annual variability of the Sahelian rainfall is associated with the fluctuations in the number of rain efficient convective systems within the continental regime.

A detailed study of the onset process suggests that it involves complex interactions of convective processes in the ITCZ, with African Easterly Jet and circulations associated with local topography. *Sultan and Janicot* [2003] used IRD, ASECNA and CIEH rainfall data and NCEP/NCAR reanalysis to study the physical processes involved in the monsoon onset. They suggested that the Ahaggar Plateau, and the Tibesti highs could exert a significant control on the atmospheric circulation and convection in the ITCZ.

The most recent work on the problem involved rainfall and surface wind data from the Tropical Rainfall Measuring Mission (TRMM) and QuikSCAT satellites respectively, as well as the NCEP/NCAR reanalysis. In that study, *Gu and Adler* [2004] showed that the surface mean rainfall tends to be concentrated along two latitudes, 5^0N and 10^0N. They found that the precipitation field lies mainly along 5^0N during the months of April, May and June and it is mainly concentrated along 10^0N during the months of July, August and September. They suggested that the appearance of intense rainfall during the month of April may be related to the occurrence of warm SST over tropical eastern Atlantic and its disappearance might be related to the formation of an oceanic cold tongue complex over the region. Their analysis suggests that the appearance of the rainfall along the 10^0N during the end of June is independent of that of the Gulf of Guinea. They also showed that the time of the onset of rainfall events in this region coincides with the northward shift of the AEJ, the associated vertical and horizontal shear zones, low-level westerly flow and the westward propagating synoptic scale wave signals.

Documentation of the depth, intensity and composition of precipitation systems helps infer the large-scale thermodynamic conditions associated with these systems. For example the microphysical processes associated with convective and stratiform precipitation are known to be vastly different [*Houze*, 1989]. In general convective precipitation is associated with strong vertical motion ($> 1m/s$) and rain particles grow by coalescence. Their horizontal scale is 1km-10km, while stratiform systems are associated with smaller vertical velocity and tend to cover larger area (100km). Consequently, latent heating profiles associated with convective and stratiform precipitation are also quite different. Analysis of the composition of the precipitation at various stages of the monsoon onset enables identify the main sources of the continental forcing responsible for the monsoon onset. Identifying of pre-monsoon and monsoon storm characteristics also helps to clearly define the timing of the onset of the monsoon for future inter-annual variability studies.

The aim of this study is to address the following questions;

- What are the distinctive characteristics of pre-monsoon continental and oceanic storms and how do they evolve during the transition into monsoon season?
- What precipitation categories comprise the West African precipitation and how do they change from spring to summer?
- What are the implications of storm characteristics for the thermodynamics of the onset of the monsoon?

For brevity, the months of April, May and June are will collectively be referred to as pre-monsoon period. The Coast of Guinea and the continental regions will be defined as the region enclosed by box 1 and box 2 in Figure 1a respectively.

Data and Analysis

The launch of the Tropical Rainfall Measuring Mission satellite in November 1997 marked the new era of space borne precipitation research [*Kummerow et al.*, 2000]. The satellite follows a 35^0 inclination, low earth orbit. Its orbital altitude was about 350km before the 7th of August 2001, and 403km afterwards. The satellite makes about 16 orbits a day. The instrument package aboard the satellite includes a precipitation radar, which has provided novel perspectives on three dimensional structure and composition of tropical precipitation. The swath width of the PR is 215km and 247km before and after the 7th of August 2001 respectively. The horizontal resolution of the radar during these two periods are 4.3km and 5.0km respectively. The vertical resolution is 250m. The PR operates at 2.17cm wavelength and it has sensitivity of 17dBZ. The 2A25 equivalent reflectivity profiles are corrected for attenuation by heavy rain using surface reference technique [*Iguchi and Meneghini*, 1994]. The space-borne radar has advantages over regional ground based radar networks because there are no range related problems like variations in resolution, minimum echo-height and sensitivity and radar calibrations. The main drawback of the TRMM-PR is that it has narrow (215km-247km) swath width that the data it provides tend are relatively scarce. This pose sampling problems for variability studies.

The TRMM-PR data has been used for regional inter-comparison of depth of storms of Amazon and various regions of African by *Geerts and Degene* [2005]. They found that African storms tend to be deep, vigorous and diurnally varying when compared to those of Amazon which tend to be shallow and more marine-like in nature. *Schumacher and Houze* [2005] also used this radar data to show that East Atlantic and West African storms have different composition in that stratiform rain is more prevalent over the ocean and convective storms over West Africa are about twice as strong as their eastern Atlantic counterparts. The implication of the distribution of convective and stratiform precipitation on the three dimensional latent heating and associated circulations are also investigated [*Schumacher and Houze*, 2004].

In this study surface rainfall, rainfall category (convective/stratiform) and vertical profile of reflectivity data from the TRMM-PR (2A25) data-set are used. The data is processed as follows;

- The orbital reflectivity and surface rain rate are classified into convective and stratiform categories. The rain type information provided in the (2A25) data-set is based on convective-stratiform separation algorithm in the TRMM product (2A23).

- The orbital echo-top height is defined as the highest level at which a 20dBZ signal is detected for an orbital data point which is categorized as convective. A storm with echo-top height 1km below the freezing level (taken to be 5km throughout) is defined as shallow convective.

- The data is put into weekly $0.5^0 \times 0.5^0$ grid boxes on which the mean stratiform, deep convective and shallow convective surface rain rate are calculated.

- The mean echo-top height is defined as the average of all the echo-top heights in the grid box with non-zero surface rain rate.

- The mean intensity of a storm is defined as the mean of the non-zero surface rain-rates in the grid box.

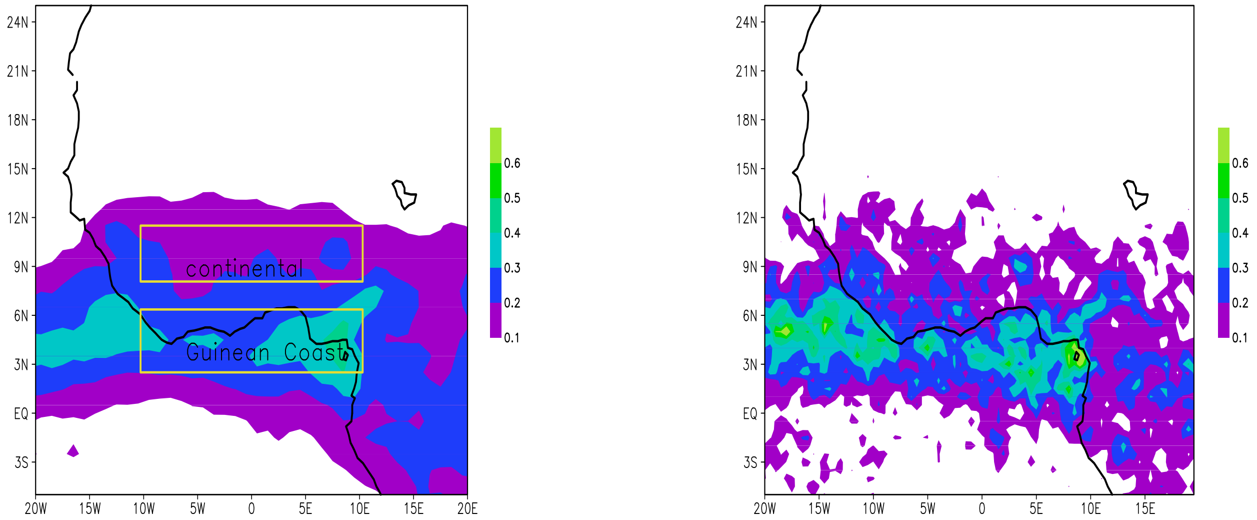
- This process is applied on April to August of all the 8-years data (1997-2005) over a rectangular domain shown in Figure 1.

Figure 1a and b show the comparison between the TRMM (3B42 $1^0 \times 1^0$, daily) and the gridded TRMM-PR (2A25 $0.5^0 \times 0.5^0$, weekly) during the pre-monsoon months (AMJ). In both cases, the precipitation is mainly concentrated along the coastline. There are precipitation maxima at the two corners of the continent i.e at 10^0E and 10^0W. Figure 1c and d show that during the months of July and August the precipitation band has shifted to about 10^0N. In both cases, again, the precipitation maximum at (10^0E, 5^0N) remains at its pre-monsoon position. In both the pre-monsoon and monsoon periods the magnitudes and distribution of precipitation are comparable.

The figure shows that the gridded TRMM-PR data reproduces the main climatological features very well that analysis of further information provided by the PR data is justified.

(a) TRMM 3B42 (AMJ)

(b) TRMM-PR 2A25 (AMJ)



(c)TRMM 3B42 (JA)

(d) TRMM-PR 2A25 (JA)

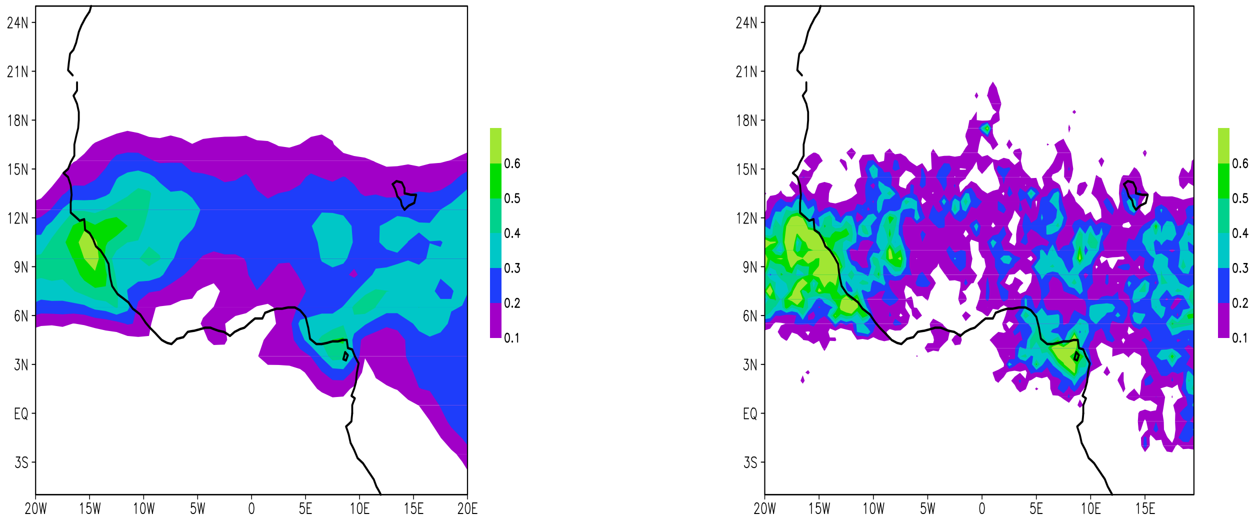


Figure 1. Comparison between 8-year average pre-onset (AMJ) precipitation (mm/hr) from (a) TRMM (3B42) and (b) TRMM-PR (2A25), (c) and (d) same for post-onset (JA)

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Results

Pre-monsoon vs monsoon storm characteristics

Figure 2a and b show the pre-onset and post-onset mean echo-top heights respectively. During April, May and June, there is remarkable contrast between oceanic and continental echo-top height. The continental storms are deeper by up to 2km. The mean echo-top height of storms at 10^0N reaches as high as 12km. After the onset of the monsoon, the relatively shallow convective systems have shifted northward into the continent. The deep storms are now located as far north as 15^0N.

Similar contrast in the intensity of the storms is also observed. Figure 2c and d show that in addition to being shallow, oceanic storms are also weaker (4-6mm/h on average) compared to their continental counterparts (whose mean could reach up to 12mm/hr). The continental storms, while intense, they tend to be short-lived. They are forced by strong surface heating during the day. The precipitation systems of the ITCZ tend to be weaker and wide spread and they don't appear to be influenced by diurnal variability as much. Continuous supply of moisture and heat appears to favor such systems. The onset of the monsoon is marked by the shift in this relatively weaker but wide spread convective systems of ITCZ into the continent.

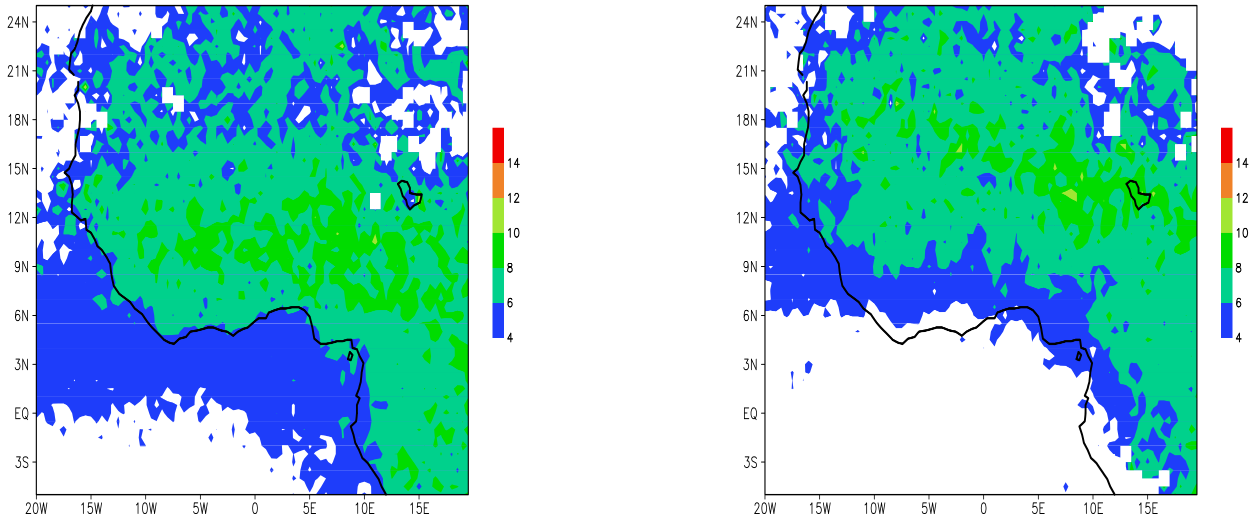
These observations suggest that the onset of the West African monsoon is indeed the shift of the relatively shallow, wide spread and moderately intense systems of the ITCZ moving into the continent as opposed to mere increase in the number of the existing continental storms. The northward shift of the deep intense continental storms suggests that they are favored by warm by relatively dry conditions, while their shallow counterparts of the ITCZ are favored by moist ocean-like conditions.

Precipitation Categories

During the pre-onset period, deep convective, stratiform and shallow convection have their maximum along the Coast of Guinea (Figure 3). Deep convection is the major contributor to the total precipitation throughout the coast. Shallow convection contributes less than 10% of the total precipitation and is essentially limited to the oceanic side of the coastline.

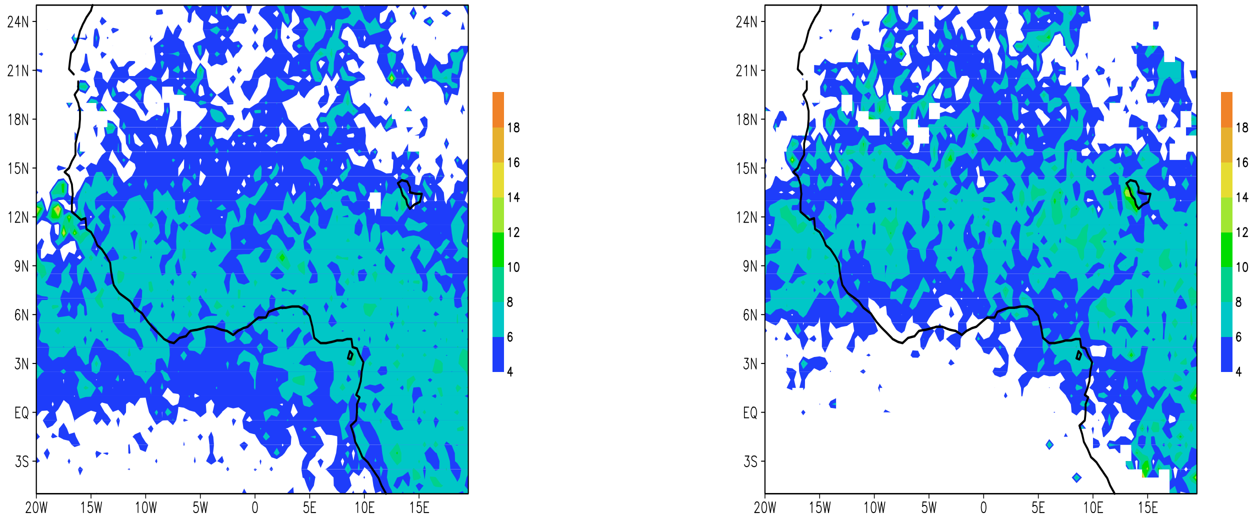
After the onset of the monsoon, the deep convective systems extend as far as 15^0N (Figure 3d). The most intense part of it is at about 10^0N, along the western coast. Stratiform rain has similar distribution. The contrast between stratiform rain inland and along the western coast however is more prominent (Figure 3e). This is could partly be due to abundance of moisture advected by westerly winds. With in the continental region, however, the AEJ and northerly advection of dry air might limit stratiform formation through evaporation and sublimation. Shallow convective precipitation remains to be a minute fraction of the total precipitation and it is limited to the coastline (Figure 3f).

Table 1 shows the composition of pre-monsoon and monsoon precipitation with in the continental region and the Coast of Guinea. Monsoon stratiform and convective precipitation over the continental region are about double their pre-monsoon value. Shallow convection is essentially absent in both periods. During the monsoon period the convective precipitation over the Coast of Guinea is about a third of its pre-monsoon value. The stratiform rain is reduced by about 40%. This makes it larger than the convective precipitation. Shallow convection doesn't show significant change.



(a) Echo-top height (AMJ)

(b) Echo-top height (JA)



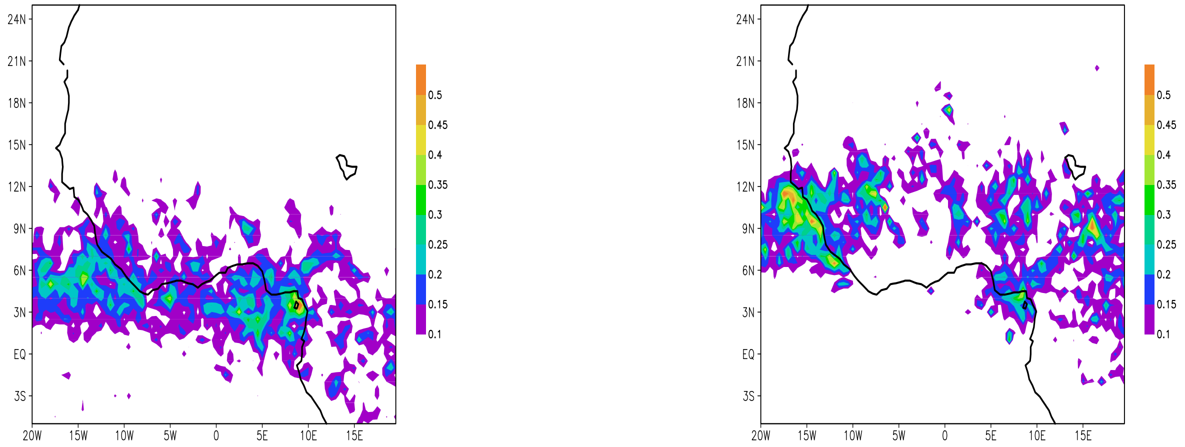
(c) Storm intensity (AMJ)

(d) Storm intensity (AMJ)

Figure 2. (a) Pre-onset and (b) Post-onset 8-year mean height (km) of the 2dBZ echo. (c) Pre-onset and (d) Post-onset 8-year mean storm intensity (mm/h).

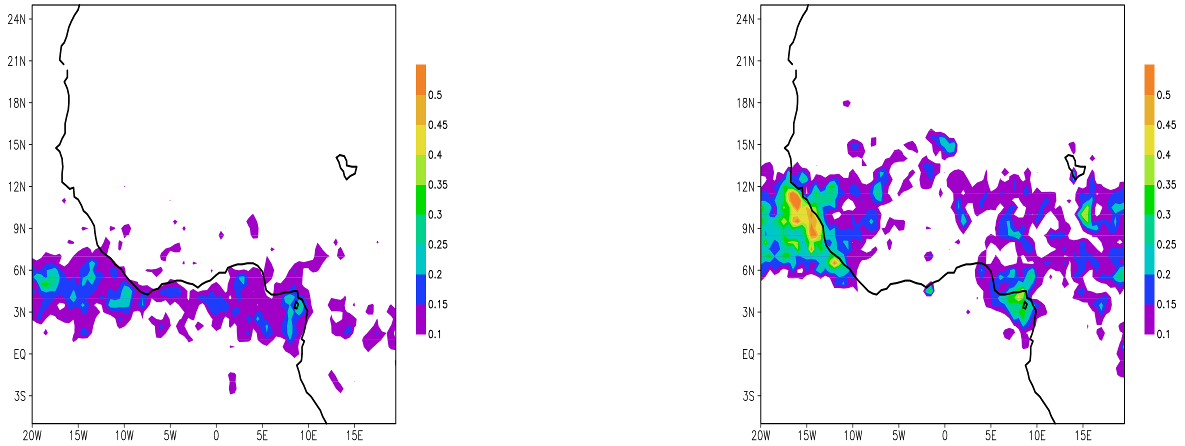
(a) Deep convective RR (AMJ)

(d) Deep convective RR (JA)



(b) Stratiform RR (AMJ) CMAP June

(e) Stratiform RR (JA)



(c) Shallow convective RR (AMJ)

(f) Shallow convective RR (JA)

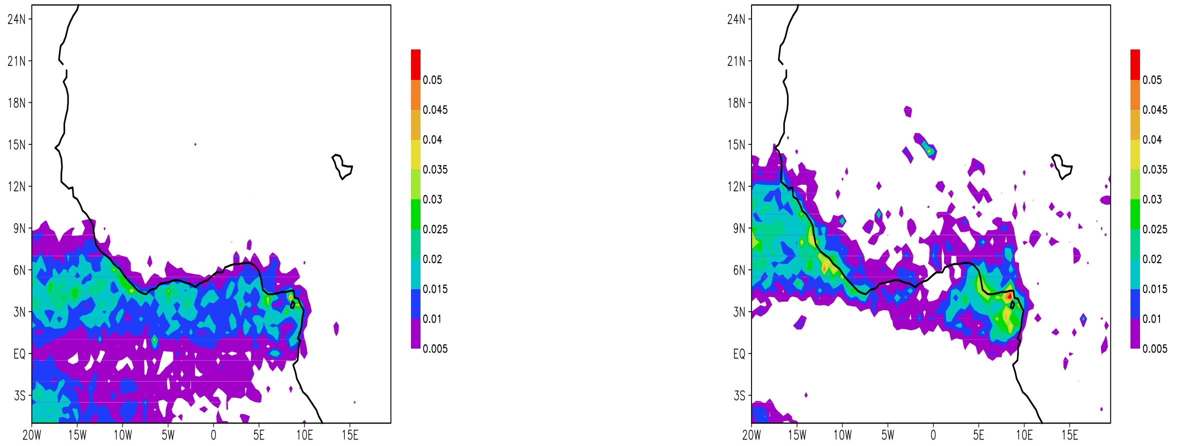


Figure 3. Pre-onset and post-onset composition of precipitation (mm/hr).

Table 1 Mean composition of areal surface rain rate

Region	convective (mm/h)	stratiform (mm/h)	shallow (mm/h)
Continental (pre-monsoon)	0.07	0.048	0.000
Continental (monsoon)	0.132	0.106	0.003
Guinean Coast (pre-monsoon)	0.176	0.123	0.013
Guinean Coast (monsoon)	0.067	0.076	0.013

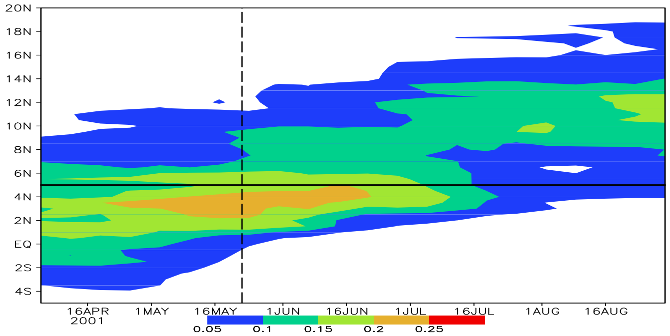
The monsoon onset

The onset of the West African monsoon is generally defined as the shift of the precipitation maximum from the Coast of Guinea (5^0N) to about (10^0N) at the end of June. To analyze the physical processes involved, the transitions of various components of the precipitation are considered.

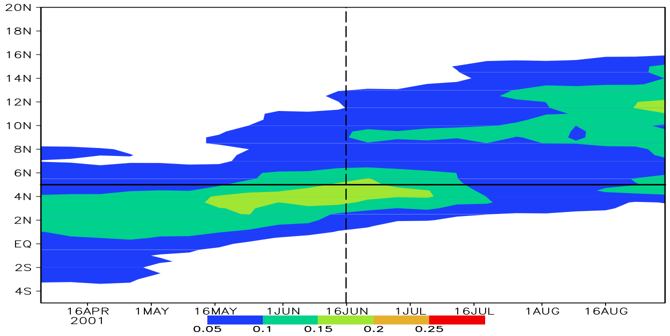
Figure 4a shows the evolution of deep convective precipitation during the monsoon onset. The solid line denotes the approximate latitude of the coastline. Significant amount of deep convective activity is observed around 8^0N starting at the last week of May. This is about one month ahead of the true onset of the monsoon. By the second week of July the entire convective precipitation has shifted into the continent. Significant amount of stratiform precipitation appears along 10^0N by mid-June (Figure 4a). The stratiform rain might be lagging behind the convective precipitation for stratiform rain use older convective materials to build and sustain themselves. While within the continent the rain drops grow large that they could fall too fast to produce stratiform. The stratiform rain along the Coast of Guinea disappears concurrently with the disappearance of convective rainfall. The shallow convective systems remain along the Coast throughout the transition period.

The thermodynamic aspects of this transition of various precipitation categories is assessed by considering the latent heat profiles associated with them and their contribution to the low-level latent heating which is the primarily driver moisture advection into the region. To estimate the latent heating associated with various precipitation categories, the convective-stratiform heating (CSH) algorithm developed by *Tao et al.* [2001] is used. Figure 5 shows the profiles associated with the precipitation categories. Stratiform precipitation supplies positive latent heating above the freezing level and cooling below with maximum and minimum at 8km and 3km respectively, while that of convective precipitation is positive everywhere and the maximum is at about 3km. Heating due to shallow convection has similar profile as that of deep convection but it essentially vanishes above the freezing level.

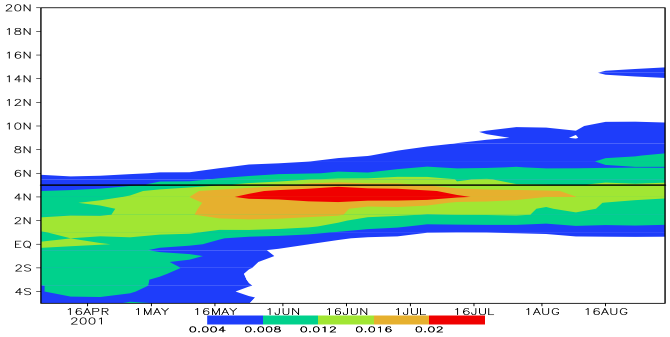
(a)



(a)) Deep convective RR



(b) Stratiform RR



(b) Shallow convective RR

Figure 4. Evolution of (a) deep convective, (b) stratiform and (c) shallow convective rain-rates (mm/h) during the monsoon onset.

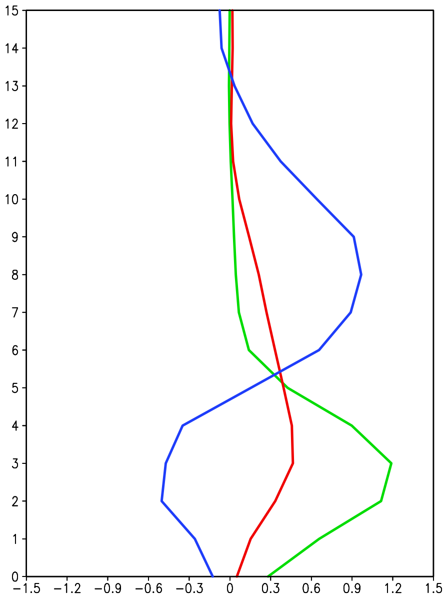
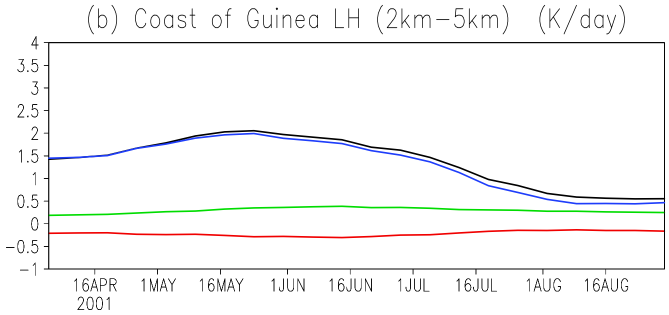


Figure 5. Latent heating associated with deep convective (green), stratiform (blue) and shallow convective precipitation (red) precipitation (K/mm) adapted from the CSH algorithm of *Tao et al.* [2001].

Using these profiles, the contributions of the precipitation categories to the total low-level heating are estimated. Figure 6 shows the evolution of latent heating at Coast of Guinea and the continental region (both defined in Figure 1a) averaged between 2km to 5km. At both latitudes, by far the largest latent heating is supplied by deep convective precipitation. In fact, during the pre-onset period (up to mid-June, the contribution of stratiform rain is negligible. With the onset of the monsoon, the shift of stratiform rain into the continent reduces the total low-level latent heating. The contribution of shallow convective precipitation at both latitudes as well as before and after the monsoon onset are very small.


(b) Coast of Guinea LH (2km−5km) (K/day)

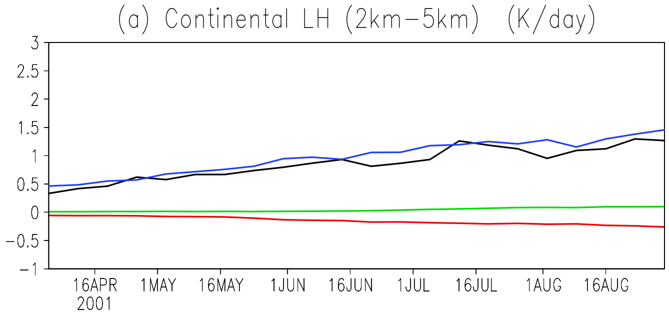

(a) Continental LH (2km−5km) (K/day)

Figure 6. Evolution of deep convective (blue), stratiform (red), shallow convective (green) and total (black) low-level latent heating at (a) 5^0N and (b) 10^0N. They are calculated using the CSH profile of Fig. 5.

Discussion

The new space borne radar observations of tropical precipitation have provided new perspectives in the regional characteristics of storms. In this study, the transition of the depth and intensity of storms as well as the precipitation categories during the onset of the West African monsoon are investigated. Thermodynamic implications of the composition of precipitation are also assessed.

Pre-monsoon continental convective storms are found to have their mean echo-top (20dBZ echo) at about 8km while those of the Coast of Guinea and Atlantic Ocean are at about 5km. After the onset of the monsoon the relatively shallow oceanic storms move into the continent, while the deep convective systems move further north up to 15^0N. Pre-monsoon continental storms are found to be more intense than their oceanic counterparts. After the onset of the monsoon, however, these relatively weak but wide-spread oceanic storms move into the continent.

These results suggest that the onset of the monsoon is associated the more ocean-like large-scale environment, with relatively weak but wide-spread convective systems, prevailing over the continental region. For the most part the pre-monsoon precipitation along the Coast of Guinea is composed of deep convection.

Using the CSH algorithm of *Tao et al.* [2001] the contributions of these precipitation categories to low-level latent heating are estimated. The pre-monsoon continental latent heating which is related to moisture advection into the continent is supplied by deep convection which starts to appear as early as one month ahead of the onset of the monsoon.

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References

Geerts, B., and T. Dejene, 2005: Regional and diurnal variability of the vertical structure of precipitation systems in Africa based on spaceborne radar data. *J. Climate.,* **18**, 893-916

Gu, G. and R. Adler, 2004: Seasonal evolution and variability associated with the West African Monsoon System. *J. Clim.* **17** 3364-3377

Houze, R. A., Jr.,1989: Observed structure of mesoscale convective systems and implications for large-scale heating. *Quart. J. Roy. Meteor. Soc.,***115**, 425-461

Iguchi, T., and R. Meneghini, 1994: Intercomparison of single frequency methods for retrieving a vertical rain profile from airborne or spaceborne radar data. *J. Atmos. Oceanic Technol., 11* 1507-1516.

E, M. Kalnay, and others, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*. 77 437- 471

Kummerow, and Coauthors, 2000: The status of the Tropical Rainfall Measuring Mission (TRMM) after two years in orbit. *J. Appl. Meteor.,* **39**, 1965-1982

Label, T., A. Diedhieu, and H. Laurent, 2003: Seasonal cycle and interannual variabiltiy of the Sahelian rainfall at hydrological scales, *J. Geophys. Res.,* **108(D8)**, 8389

Le Barbe, L., T. Label, and D.Tapsoba, 2002: Rainfall variability in the West Africa during the years 1950-1990. *J.Clim.* **15** 187-202

Schumacher, C., and R. A. Houze, Jr., 2004: The tropical dynamical response to latent heating estimates derived from the TRMM Precipitation radar. *J. Atmos. Sci.,* **61** 1341-1358

Schumacher, C., and R. A. Houze, Jr., 2005: Stratiform precipitation production over sub-Saharn Africa and the tropical East Atlantic as observed by TRMM. *Quart. J. R Meteor. Soc.* (submitted)

Sultan B and S. Janicot, 2003: The West African monsoon dynamics. Part II: The "preonset" and "onset" of the summer monsoon. *J.Clim.* **16** 3407-3427.

Sultan B and S. Janicot, 2000: Abrupt shift of the ITCZ over West Africa and intra-seasonal variability *Geophys. Res. Lett.,* **27** 3353-3356 **16** 3407-3427.

Tao ane Coauthors, 2001: Retrieved vertical profiles of latent heat release using TRMM ranfall products for February 1998. *J. Appl. Meteor.,* **40**, 957-982

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