THE REGIONAL AND DIURNAL VARIABILITY OF THE VERTICAL STRUCTURE OF PRECIPITATION SYSTEMS IN AFRICA, BASED ON TRMM PRECIPITATION RADAR DATA

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Abstract. *Several summer (JJA) and winter (DJF) seasons of 2A25 Tropical Rainfall Measuring Mission Precipitation Radar (TRMM PR) data are used to study the spatial and diurnal variability of precipitation, and the vertical profile of precipitation systems, over Africa. This continent is divided into several climatologically rather homogenous regions, and those regions are characterized and contrasted. A preliminary assessment, based on just one month of data, reveals a bi-modal pattern in the diurnal cycle of surface rain rate and reflectivity for the Sahel and Ethiopian highland regions. A very clear afternoon peak on convective activity occurs between 1800-2100 LT and a morning peak occurs between 0900-1200 LT in both these regions. On the other hand, there is a single afternoon maximum over most desert regions such as the Sahara. Frequency-by-altitude diagrams indicate that strong low-level reflectivities are more common in the Sahel region compared with the other regions in the northern part of Africa.*

INTRODUCTION

The economy of most African countries depends on agriculture, and the agriculture is mainly dependent on the performance of precipitation over the region; therefore extreme anomalies of precipitation such as drought and floods are associated with many socio-economic problems including substantial loss of property and life. Hence, it would be of great importance to improve understanding of the mechanisms and characteristics that relate to the precipitation in this region to be able to forecast the distribution and amount of precipitation ahead of time. One problem is the lack of surface and upper air weather observing stations over the region, including reliable rainfall measurements (Lebel and Amani 1999), hence NWP models and GCMs may err in their characterization of precipitation over Africa. The lack of data over that region also has global implications.

Spaceborne rainfall estimation, usually guided by raingauge data and also NWP output, has evolved dramatically over the last two decades (e.g. Huffman et al.. 1997). This is particularly important in Africa where large parts have a poor raingauge record. Spaceborne techniques have been developed based on IR brightness temperatures (e.g. Vicente et al.. 1996), multi-frequency passive microwave radiances (e.g. Kummerow and Giglio 1994), and 14 GHz radar reflectivities (e.g. Ferreira et al.. 2001). Often a combination of these is used to benefit from specific strengths, e.g. IR-based techniques using geostationary satellite data can be used continuously, day and night. Obviously IR-based techniques are much inferior to radar-based techniques, in principle at least, because the anvil of large convective systems is much larger than the radar echoes underneath, and its topography is more uniform. But large differences exist even between passive microwave and radar-based rainfall estimates, both on instantaneous and cumulative bases (Kummerow et al.. 2000). Much of the uncertainty appears to be related to differences in vertical structure of precipitation systems, specifically their depth and convective/stratiform nature (Masunaga et al.. 2002).

An understanding of the vertical structure of precipitating systems is important, especially in the tropics, not just because it implies differences in surface rainfall, but also because it has implications for the global atmospheric circulation. Different reflectivity profiles imply differences in latent heating profiles, and differences in the convective fraction. The convective-stratiform distinction is important because of differences in Z-R relationships (e.g. Steiner and Houze 1997), which affects not only the radar-based rainfall estimation, but also the latent heat release profile, and hence the energy balances of the tropical atmosphere.

The vertical structure of precipitation systems can be studied by means of reflectivity profiles derived from the Precipitation Radar (PR) aboard the Tropical Rainfall Measurement Mission (TRMM) satellite, launched in late 1997 (Kummerow et al.. 2000). One surprising discovery yielded by TRMM PR data is that the Congo Basin, as compared to the Amazon Basin, has deeper storms, a higher reflectivity above the freezing level in storms (e.g. at 7 km), a stronger 85 GHz ice scattering signature, and also more lightning activity (Boccippio et al.. 2000, Peterson and Rutledge 2001, Toracinta et al.. 2002).

Amazon rainfall patterns have been studied in some depth (e.g. Petersen et al.. 2002), in part thanks to the TRMM Large-scale Biosphere–Atmosphere (LBA) field campaign in the Amazon. None of the TRMM-based precipitation studies except one has focused on Africa. The one exception is a study by Adeyewa and Nakamura (2003), which compares various TRMM-based rainfall estimates to those based on other satellite data and rain gauges. There are also some studies of large convective systems in West Africa, mainly based on ground-based radar data, but these represent isolated case studies. In short, the typical vertical structure of precipitation systems in various climate regions of Africa remains undocumented. This is the motivation of the present study, which aims to describe the regional, diurnal, and seasonal variations of the vertical structure of precipitation systems in Africa, and to interpret these variations in terms of typical stability and shear profiles, i.e. parameters controlling storm dynamics.

After describing the data sources and analysis method, the structure of precipitating systems over Africa is presented, based on one month of TRMM radar data. I also plan to have extended this study to 5 years of summer and winter seasons (1998-2002), in order to describe both seasonal extremes, build statistical significance, and touch upon interannual variability.

DATA SOURCE

The TRMM satellite, operational since late November 1997, carries a suite of five instruments in a 35°-inclination non-sun-synchronous low earth orbit (Kummerow et al.. 1998) at about 350 km above the earth before August 2001, and 403 km afterwards. These instruments are the 13.8 - GHz precipitation radar (PR), the multi-frequency TRMM imager (TMI), a multi-frequency visible and infrared radiometer (VIRS), the lightning imaging sensor, and the Clouds and Earth's Radiant Energy System. The TRMM radar and passive microwave radiometers have been building a nearly homogeneous dataset of rainfall rate and vertical structure of precipitating systems over land and ocean since Dec 1997. In addition, the PR is being used to improve the overall TRMM precipitation retrieval accuracy by the combined use of active (PR) and passive (TMI and VIRS) sensor data (Kummerow et al.. 1998).

The non-synchronicity with the sun is rather unique compared to other Earth Observing Satellites (EOS), but it is important, because it enables the deduction of the diurnal variability, if a sufficiently large sample is collected. Spaceborne radar observations are superior to ground-based radar data for the description of the storm vertical structure, because of the near-nadir vantage point (Hirose and Nakamura 2002). For regional studies they are superior also to a network of ground radars, because there are no regional variations in radar calibration (Anagnostou et al.. 2001). The drawback of space borne radar observations is the data scarcity: the TRMM PR swath, 220 km wide, visits the same location only once or twice a day (Negri et al. 2002). The PR range resolution is 250 m (Figure 1). At high inclination angles, the vertical resolution decreases to 1000 m because of the relatively large footprint size, and the lowest 1-2 km above the ground become cluttered by ground return in the sidelobe. Therefore the low incidence angles are best, and for that reason we are confining our analysis to ±5 degrees from nadir. The trade-off here is that we retain even fewer data.

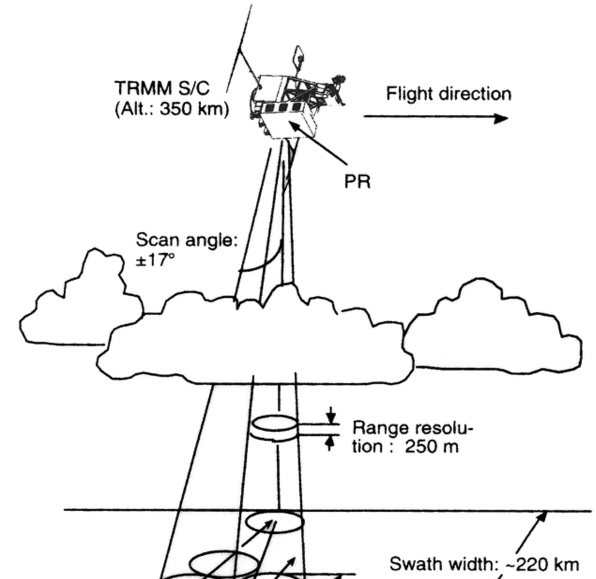

Figure 1. Schematic of TRMM platform scan strategy (following National Space Development Agency of Japan and National Aeronautics and Space Adminstration 2000)

The horizontal resolution of the PR is about 4.3 km at nadir and about 5 km at the maximum inclination of 17 degrees. This allows the TRMM PR to observe precipitation systems larger than about 10 km^2 (Wilcox and Ramanathan 2001). However less than a quarter of rain cells in Niger, Africa, have diameters larger than 5 km (Sauvageot et al. 1999), and this may generally apply to most continental regions in the tropics. The swath width of TRMM PR and other instruments on board is shown in Figure 1. The effects of limited horizontal resolution and low sensitivity (18 dBZ) combine to exclude isolated, small storm cells from the PR's view (Heymsfield et al. 2000). An attempt has been made to correct for this non-uniform beam-filling (NUBF) effect on PR-based surface rain estimation (Durden et al. 1998), but reflectivity profiles obviously are not ‘corrected’. All this suggests that our study is biased towards the larger precipitation systems, but then, they carry the bulk of the rain.

The primary dataset for this study is the TRMM-PR 2A25 volumetric radar reflectivities and surface rainfall rates (Kummerow et al. 1998; Iguchi et al. 2000). The 3B42 daily 1^o x 1^o TRMM is also used in this study to analyze the seasonal and inter-annual variability of precipitation over Africa. The 2A25 equivalent reflectivity profiles are corrected for attenuation by heavy rain, mainly using the surface reference technique, and the rain rates are corrected for NUBF. The combined instrument rain calibration algorithm (3B42) uses combined rain structure (2B31) and VIRS(1B01) as shown in Figure 2.

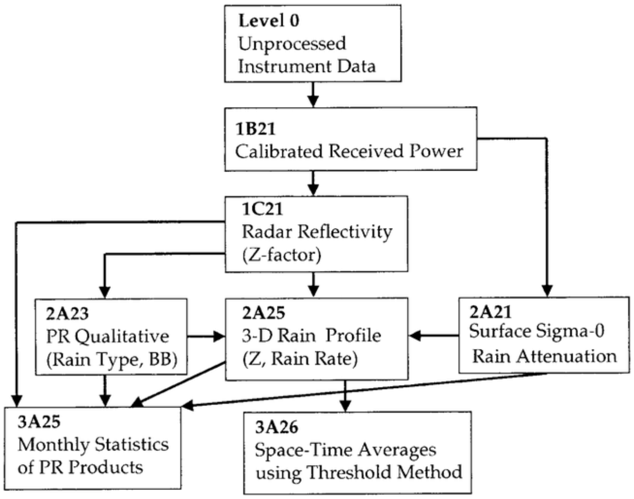

Figure 2. TRMM algorithm flow chart (following National Space Development Agency of Japan and National Aeronautics and Space Adminstration 2000)

DATA PROCESSING

In this study TRMM 2A25 reflectivity profiles and surface rain rate estimates are used at the original spatial resolution of the PR (4.5km at nadir) for July 2000. Five years of data (June 1998 to February 2003) is also used to characterize seasonal extremes and inter-annual variability over two pre-defined regions (by TRMM group): Congo and West Africa. The full vertical resolution of the 2A25 PR (250 m intervals) is retained as this study focuses on the reflectivity profile of precipitating systems. On the other hand, a 3-hr temporal resolution is chosen to capture diurnal variation, while still maintaining statistical significance.

The time resolution of 3 hours is rather course, but the sample size becomes too small at higher temporal resolutions. Negri et al. (2002) concluded that a temporal resolution of 1 hour, even using 3 years of PR data, is inadequate to describe the diurnal cycle of precipitation due to spatially inconsistent sampling. So, they suggested a 4-hour optimum period of sampling to study the diurnal variability using TRMM PR data, and spatial averaging over rather large regions. Considering the large size of the climatic regions selected for this study (Figure 3), temporal sampling was done every three hours, which is still adequate to highlight differences in the diurnal variability. Local solar time is used instead of universal time, because it is the relevant time in the description of the diurnal variation.

For further analysis and regional comparisons, Africa is categorized into nine broad climatic regions (Figure 3): Sahara (15ºN-30ºN, 11.5ºW-30ºE), Semiarid in the North (Sahel) (12ºN-15ºN, 11.5ºW-30ºE), Semiarid in the South (Okavango)(17ºS-22ºS, 17ºE-30ºE), Savanna in the North (8ºN-12ºN, 11.5ºW-30ºE), Savanna in the South (6.5ºS-17ºS, 14ºE-39ºE), Tropical wet (Congo) (6.5ºN-6.5ºS, 11.5ºW-30ºE), Horn of Africa (4ºN-14.5ºN, 31ºE-40ºE), Eastern Africa (4ºN-6.5ºS, 30ºE-39ºE) and Kalahari (22ºS-32ºS, 17.5Eº-26ºE). This classification has similarity with the classification done by Adeyewa and Nakamura (2003).

This regional classification is mainly based on the distinct rainfall climatology in these regions. The precipitation distribution for the two seasons (DJF & JJA) using the five years (1998-2002) data of 3B42 show the pattern of precipitation over these regions (Figure 4 & 5). The regions are not of the same size, nor do they have the same incidence of precipitation systems: the Sahara for instance encounters much fewer rain events per 5x5 km cell in July 2000, compared to the Sahel or other regions. Yet when it rains, the average surface rainrate is about the same in the three regions. The number of rain events per cell in July 2000 is clearly insufficient to establish a diurnal cycle or to characterize reflectivity profiles, certainly in the Sahara, with smaller rain events per cell. The use of 3 months per season, and 5 years of data, will increase the sample, and that should make the results statistically more significant. Hence, the diurnal variability of rainfall using the 5-year data over the pre-defined Congo and West Africa are included in this paper.

Figure 3. Climatic regions selected for this study

REGIONAL VARIABILITY OF THE VERTICAL STRUCTURE OF REFLECTIVITY

The nature and extent of convection varies from place to place depending on the time of the day and season, geographic location, and other factors related with the mechanism of the convection, etc. In the northern hemisphere of tropical Africa, strong convection occurs during the months of June-August along the latitudinal belt of ITCZ. However, the horizontal (Figure 6) and vertical extent, and intensity of the convection varies from region to region along the same latitudinal axis of ITCZ. Quite a number of factors such as the sources of moisture to the region, topography, interaction with the middle-latitude synoptic systems, etc could be responsible for the variation in the nature of convection in these regions.

The reflectivity probability density functions as a function of height in July 2000 is shown for the nine regions on Figures 7 and 8. Also, is shown the same density function for two regions (Congo and West Africa) using a 5-year data (Figures 9 and 10). Shown in these frequency-by-altitude diagrams (FADs) is the normalized probability for a given reflectivity at a certain height. The sum of all frequencies plotted equals 1. It can be inferred that a bright band, located at about 5.5 km, present for most of the region in Africa where rain is stratiform. The convective to stratiform classification is done based on the surface rain rate. If the surface rain rate is greater than 8mm/hr it is classified as convective otherwise it is stratiform. The storms over Sahara, Eastern Africa and Savana south have less number of occurrences of stratiform rain for July 2000. On the other hand, the stratiform rain over Congo, Sahel, Savanna North and Horn of Africa regions have a higher frequency and magnitude. The convective storms over most of the regions in Africa have a similar depth and intensity except over Congo and Savanna South where they have relatively deeper storms extending. This implies that when convective rain occurs at any region in Africa, it has somehow a similar characteristic in terms of depth and intensity.

Due to the decrease of reflectivity occurrence with a height below ~3 km is more rapid in the Sahara than elsewhere (Figures 7 and 8), the cloud base may be higher there, causing raindrops to evaporate. In the Sahel, Congo, Horn of Africa and Savanna (North), high reflectivity values are found close to the ground.

DIURNAL VARIABILITY OF RAIN RATE

Determining diurnal variability of precipitation matters, not only because it allows verification that other EOS-based rainfall estimates are not biased due to the orbit's sun-synchronicity (Bell & Reid, 1992), but also because it helps to understand the dynamics of precipitating systems in response to diurnally varying surface energy fluxes and wind profiles and to validate NWP models and GCM simulations.

The diurnal cycle of surface rain rate in July 2000 is shown in Figure 14. Rain is most common in the afternoon and evening over most regions in Africa. In addition, rain was also common early in the morning over most regions of Africa during this period (July 2000). However, a month data isn't sufficient enough to study the diurnal variability over a region. Then, there is a plan to consider a five-year data to study the diurnal variability over this region.

The result of a five-year data analysis for two pre-defined regions in Africa (by TRMM group at NASA): Congo and West Africa is also presented in this paper as shown in Figure 13. The diurnal cycle of rain rate over both these regions have a bi-modal pattern. The afternoon peak occurs at the same time for both regions around 19:30 LT. On the other hand, the morning peak occurs at different local times (at 10:30 am for west Africa and around 5a.m for Congo). The seabreeze effect from Atlantic Ocean could be the cause for this occurrence of morning precipitation over these two regions.

CONCLUSIONS

This study aims to describe the regional variability of the vertical structure of storms and the diurnal variability of rain rate in Africa, by means of five years of extreme-season (DJF and JJA) TRMM Precipitation Radar data. Regional differences were highlighted for regions with characteristically different rainfall regimes. . Key TRMM products used here are the radar-derived surface rain rate and the attenuation-corrected reflectivity profile, and the composited global precipitation data (3B42).

This paper describes the results for only one month (July 2000). Preliminary findings focus on the difference between the isolated storm events over the Sahara and the more frequent storms over Congo, Savanna North, Sahel and Horn of Africa in July 2000. Stratiform rain is relatively deeper and more frequent over Congo, Sahel, Horn of Africa and Savanna North. On the other hand, stratiform rain was less frequent over Sahara, east Africa, and Savanna south in July 2000. The convective rain is deeper over Congo and Savanna south compared with the other regions.

Vertical profile of reflectivity using a five-year data over Congo and West Africa doesn't show an observable or significant inter-annual variation. However, deeper and larger stratiform rain was observed in 1998 compared with the other years in both Congo and West Africa regions.

Though the sampling isn't sufficient to have a strong conclusion on diurnal variability for July 2000, it can generally be inferred that there are rain events both in the morning and in the afternoon for most regions in Africa. Diurnal variability of surface rain rate over Congo and west Africa (using a five year data) show that there are two rainfall peaks over the regions, one in the morning around 4:30am and another one in the afternoon around 7:30pm. Morning and afternoon peak over West Africa were observed at 10:30am and 7:30pm respectively.

FUTURE PLAN OF WORK

Five years of data will be used to analyze the diurnal variation of rain rate and vertical profile of reflectivity for the seasons December-January-February (DJF) and June-July-August (JJA). Regional differences in terms of the diurnal variability will be assessed for the nine homogeneous climatic regions over Africa.

Regional difference in the vertical profile of reflectivity will also be studied using the 5-

year data to understand the depth and intensity of storms over each region. Seasonal comparisons and inter-annual variability study will also be held based on the same five-year data.

The results of this work will be compared with the available observational data over the region. In addition, the result will be contrasted with re-analysis data from Global and regional climate model outputs.

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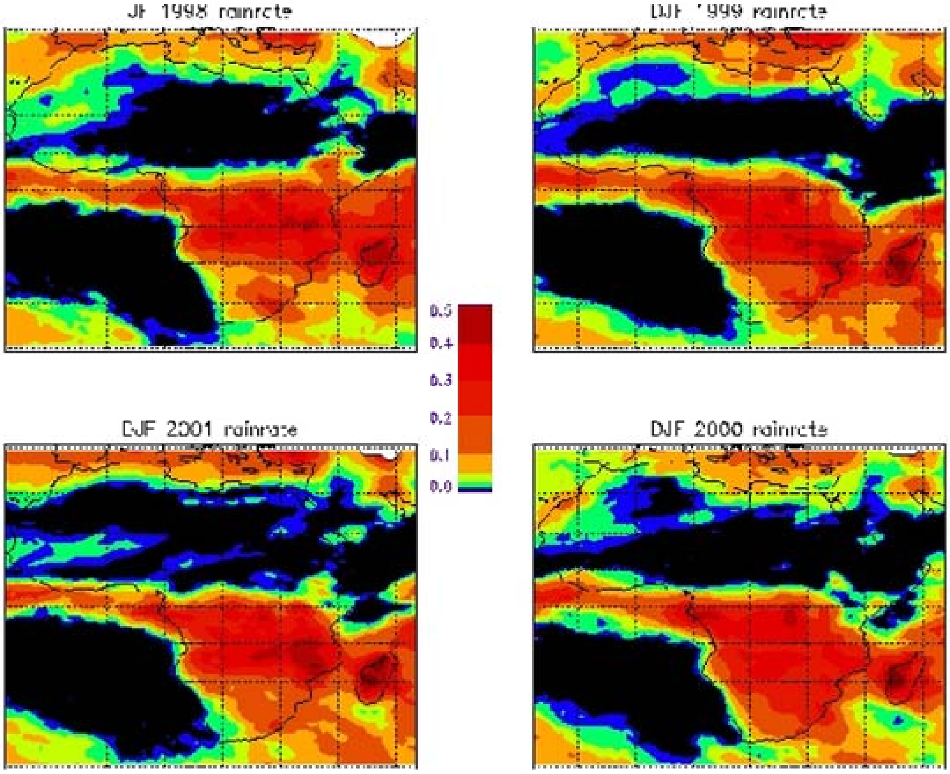

Figure 4. DJF mean rain rate (mm/hr) over Africa for 1998-2001

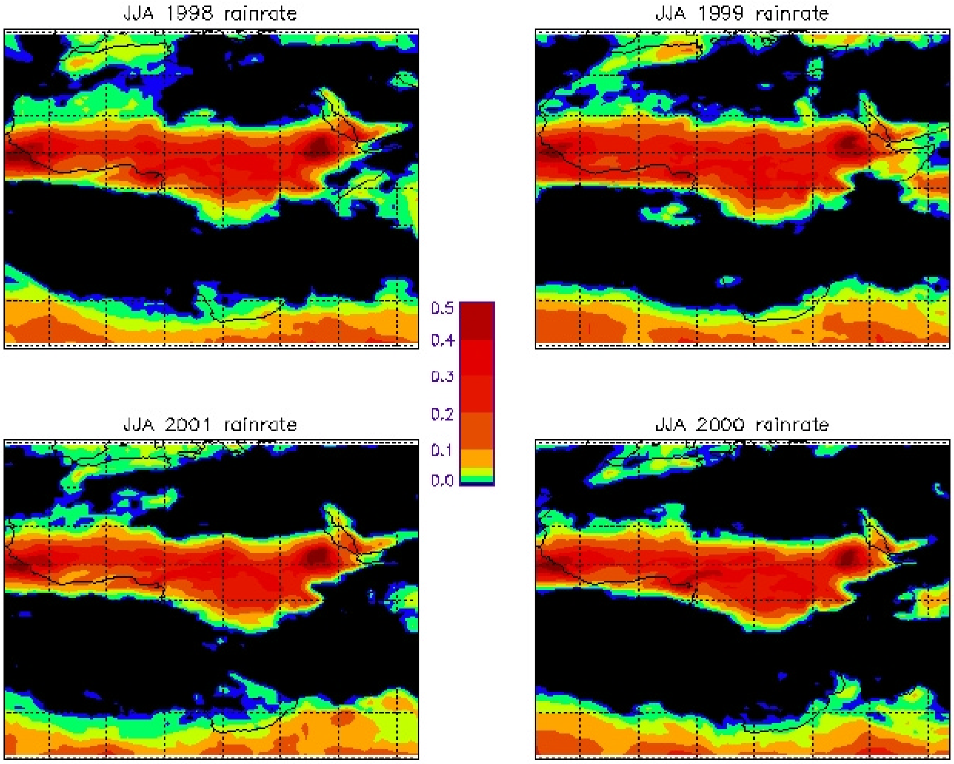

Figure 5. JJA mean rain rate over the African region 1998-2001.