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

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1. INTRODUCTION

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 (e.g. Lebel and Amani 1999). 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 the 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 balance 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 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, and there are no plans for a comprehensive atmospheric research experiment in or around the Congo Basin. 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 (Section 2) and analysis method (Section 3), the structure of precipitating systems over Africa is presented, based on one month of TRMM radar data. By the time of the conference (August 2003), we 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.

2. DATA SOURCE

The TRMM satellite, operational since late November 1997, carries a 13.8 GHz precipitation radar (PR) in a 35º-inclination non-sun-synchronous orbit (Kummerow et al 1998) at about 350 km above the earth before August 2001, and 403 km afterwards. 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 spaceborne 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 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

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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 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 2A25 equivalent reflectivity profiles are corrected for attenuation by heavy rain, mainly using the surface reference technique, and the rainrates are corrected for NUBF.

In order to interpret to reflectivity profiles, we also use the monthly-mean NCAR/NCEP global re-analysis of weather station, buoy and satellite data (Kalnay et al., 1996) (referred to as NNGR, and accessed at http://www.cdc.noaa.gov/). The NNGR spatial resolution is 2.5 degrees.

3. DATA PROCESSING

In this study TRMM 2A25 reflectivity profiles and surface rain rate estimates are composited at a spatial resolution of 50 km, for two seasons, DJF and JJA. Five years of data (June 1998 to February 2003) will be used to characterize both seasonal extremes. The 'compositing' is a counting of occurrences within certain bins, which are spatial (2D) and cover certain value increments. For instance, there is a bin that counts reflectivity measurements between 18-20 dBZ, at a given 50x50 km grid point, a given height (250 m intervals), a given time of day (3 hr intervals), and a given season. The size of the bin intervals is chosen to capture variation, e.g. geographic or diurnal variation, while still maintaining statistical significance. The full vertical resolution of the 2A25 data is retained, and the reflectivity interval (2 dBZ, starting at 18 dBZ) is small, because this study focuses on the reflectivity profile of precipitating systems.

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 (**Fig 1**), 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.

The surface rain rate is binned in 15 classes, with an interval of 2 dB (mm/hr). Reflectivity profiles are only included if the surface rain is classified as probable or certain.

For further analysis and regional comparisons, Africa is categorized into nine broad climatic regions (Fig 1). This regional classification is mainly based on the distinct rainfall climatology in these regions. 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 50x50 km cell in July 2002, compared to the Sahel (**Table 1**). 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 2002 is clearly insufficient to establish a diurnal cycle or to characterize reflectivity profiles, certainly in the Sahara, with about 4 rain events per cell (Table 1). The use of 3 months per season, and 5 years of data, will increase the sample by a factor of 15, and that should make the results statistically more significant.

Fig 1. Climatic regions selected for this study.

Table 1. Basic characteristics of three select climatic regions. The mean rain rate is based on 2A25 rainrate data for July 2002, and applies only to cases when rain occurs. The sample size is the average number of rain occurrences in a 50x50 km box in July 2002.

	area size	mean rain rate	sample size
units	10^3 km^2	mm/hr	#
Sahel	2,904	4.73	64
Ethiopia	2,420	4.68	96
Sahara	1,694	3.26	4

4. DIURNAL VARIABILITY

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-synchroneity (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.

The diurnal cycle of surface rain in July 2002 is shown in **Fig 2** for three select regions delineated in Fig 1. Rain is most common in the afternoon and evening. A bi-modal pattern exists for the Sahel and Ethiopia (the Horn), with a secondary peak in the morning. In the Sahara, the diurnal modulation is strongest, with a single peak earlier in the afternoon.

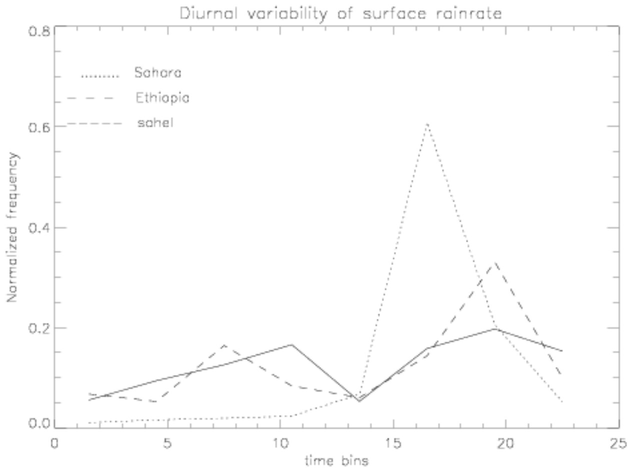

Fig 2. Diurnal variability of surface rain occurrence. The frequency is normalized by the total number of rain events in each region.

5. REGIONAL VARIABILITY OF THE VERTICAL STRUCTURE OF REFLECTIVITY

The basic seasonal swing of the zenithal rain in Africa is quite apparent in the 2A25 data. However, the vertical extent and intensity of African precipitating systems varies from region to region. We plan to map the mean and upper-percentile echo top height, as well as the mean radar reflectivity at a height of 7 km. This height is well above the influence of a bright band, and well below the top of most precipitation systems. Also to be mapped is a rain efficiency factor, which is the ratio of the surface rain to the vertically integrated liquid or frozen water (estimated from a Z-M relationship).

For now we examine reflectivity probability density functions as a function of height above sea level, for three regions (**Fig 3**). 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 4.5 km, is at least occasionally present for the Ethiopia and Sahel regions. On the other hand, a bright band, which indicates stratiform rain, is exceptional in the Sahara region (**Fig 4**). The storms over Sahel and Ethiopia are deep, with strong echoes at 7 km, while storms over Sahara tend to be more shallow. The secondary maximum in mean reflectivity above 7 km may be artificial, i.e. the result of the averaging procedure.

Because of the decrease of mean reflectivity with height below ~3 km is more rapid in the Sahara then

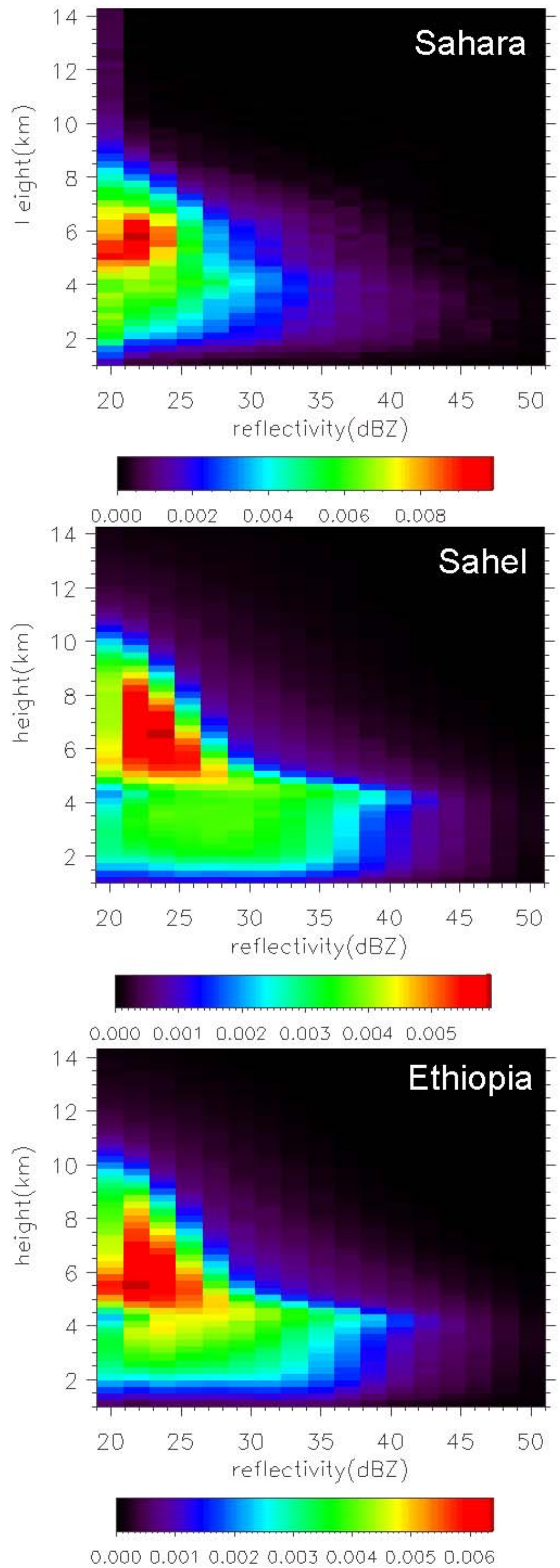

Fig 3. Reflectivity FAD for three regions in July 2003.

elsewhere (Fig 3), the cloud base may be higher there, causing rain drops to evaporate. In the Sahel, high reflectivity values are found close to the ground.

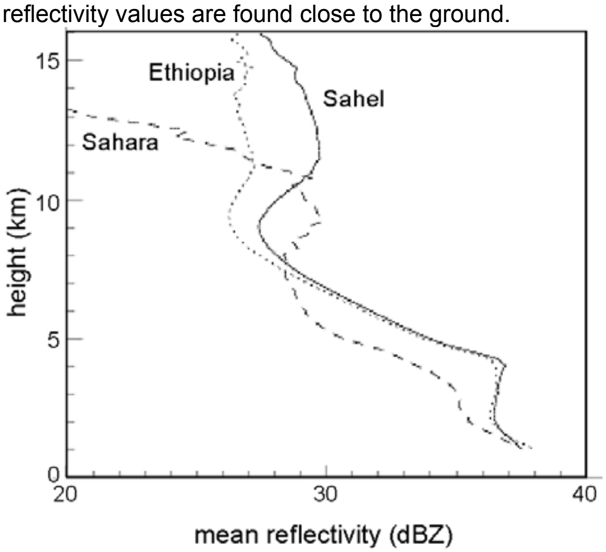

Fig 4. Average reflectivity profile based on the FADs in Fig 3. Reflectivity is averaged in units of $mm^6\ m^{-3}$.

6. CONCLUSIONS

This study aims to describe the diurnal and seasonal variability of the vertical structure of storms in Africa, by means of five years of extreme-season (DJF and JJA) TRMM Precipitation Radar data. Regional differences will be highlighted by means of statistics for regions with characteristically different rainfall regimes. The results will be interpreted in terms of climatological differences in the stability and shear profile. Key TRMM products used here are the radar-derived surface rain rate and the attenuation-corrected reflectivity profile.

This paper describes the results for only one month. Preliminary findings focus on the difference between the isolated storm events over the Sahara and the more frequent storms further south near the ITCZ in July 2002. At the radar conference we plan to present statistically more robust results, based on 15 months of data.

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