

# OBSERVED AND MODEL-SIMULATED INTRASEASONAL WAM VARIABILITY FOR THE 2005 RAINY SEASON

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## Abstract

Instantaneous (i.e., 15-minutes) rainfall intensities, as derived from a multi-sensor precipitation estimation approach, involving geostationary (MSG) and polar (SSM/I) satellite data, are used to investigate the dynamical mechanisms driving the African warm season precipitation episodes, and to evaluate the capability of a Regional Atmospheric Modelling System (RAMS) to reproduce this variability for the Sahelian area. Coherent precipitation patterns are presented for the 2005 rainy season, from June to August, with emphasis on a qualitative and quantitative inspection of intraseasonal variability of the West Africa Monsoon (WAM), investigating the longitudinal distribution of rainfall and the zonal component of motion. We also analyzed the periodicity and phase of precipitation within and beyond the diurnal cycle. Consistent with previous studies, the pattern of the diurnal cycle of summer precipitation is characterized by afternoon maxima, initiated mainly over the African highlands (Jos Plateau, Darfur, Ethiopian highlands).

Furthermore, a Regional Reanalysis strategy has been developed based on RAMS model forced by NCEP/NCAR Reanalysis. The RAMS better physical description, with respect to the NCEP/NCAR dataset, along with its higher spatial resolution (50km), provide a coherent and reliable atmospheric dataset especially for what concerns surface-atmosphere interaction governing monsoon dynamics. Diurnal precipitation patterns, produced by RAMS model, are investigated and compared with those obtained by MSG-based algorithm. Some guidelines, used on model setup, are presented as well. Statistical skill scores (POD, FAR, etc.), based on 3-hourly NOAA CMORPH rainfall data, have been evaluated to assess the reliability of this method for the whole rainfall season. Skill scores analysis reveals a good reliability of rainfall episodes detection.

## 1 INTRODUCTION

A reliable and detailed rainfall forecast system on West Africa, during the monsoon season, plays an important role for managing agricultural activities in such zones. Many large scale forecasting systems (Kalnay et al. 1996) have been developed and distributed, but, as any global model, its capability to correctly represent deep convection is very low. Lack of operational weather and environmental observations, combined with scarce and uneven monitoring ground network (raingauges), do not allow to determine the initial conditions for precipitation forecasting systems at short and medium-term, and prevent long-term monitoring for detecting the climate changes. The synergic use of satellite observations and numerical limited area models, based on the analysis of systematic satellite-based rainfall estimates at a very high spatial resolution and regional scale simulations, may result crucial in the comprehension and reconstruction of the monsoon dynamics.

In this framework, rainfall intensities, as derived from a multi-sensor precipitation estimation approach (Turk et al. 2000), involving geostationary (MSG) and polar (SSM/I) satellite data, are used to investigate

the dynamics and phenomenology associated with the African monsoon regime, in terms of propagation characteristics, intraseasonal variability and diurnal cycle of the rainfall episodes.

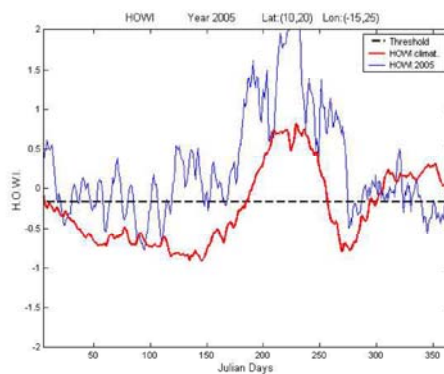
A Regional Atmospheric Modelling System (RAMS) forced by NCEP/NCAR Reanalysis, has been also employed to reproduce the African monsoon variability in terms of periodicity and phase of the organized convective systems, taking advantage of its better spatial resolution (50km) and physical description respect to the Reanalysis dataset.

## 2 DATA AND METHODOLOGY

### 2.1 Satellite observations

This preliminary case-study period spans from June to September 2005, the latter year chosen for its particular long-lived and strength monsoon characteristics (see Figure 1).

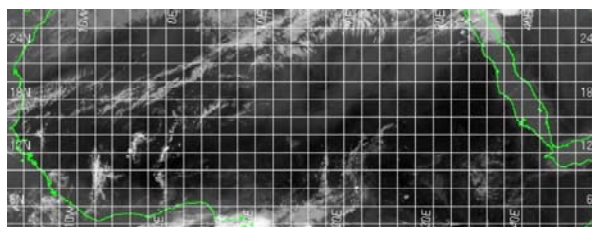
The 2005 African rainy season has been characterised by a positive precipitation anomaly in the northern part of Sahel area, more marked in August, while a negative anomaly characterised the coastal areas. Such behaviour is consistent with a weak negative SST anomaly in the Guinea Gulf along the whole season. In order to characterise the monsoon strength, we have used the HOWI prognostic index (Dalu et al. 2007; Figure 1) for the onset and the withdrawal of the West Africa monsoon (WAM).



**Figure 1: Climatological and 2005 behaviour of the HOWI index computed for the Sahelian area.**

When the index is positive, the WAM is active. An early WAM start-up followed by three intense (the more marked in August), distinctive phases are recorded. To be noticed the long-lived characteristics of the African monsoon, which finished its rainy phase in mid October.

Based on the ITCZ boundaries, the western Gulf of Guinea sea-land contrast and the prevailing low-level flow, the domain of interest (about 7200 x 2000 km<sup>2</sup>) spans from 3° to 20°N in the N-S direction, and from -18° to 48°E in the E-W direction. Figure 2 shows the domain of calculations.



**Figure 2: Computational domain for rainfall estimates Hovmöller diagrams.**

Our principal focus is to investigate the dynamical mechanisms driving the African warm season rainfall episodes. Half-hourly instantaneous rainfall maps have been used for this purpose, as produced by an automatic real time operational chain, which processes Meteosat Second Generation (MSG) infrared (IR channel @10.8 μm) and SSM/I microwave (MW) data (Antonini et al. 2007;

[http://www.lamma.rete.toscana.it/previ/eng/rain\\_msg\\_eng.html](http://www.lamma.rete.toscana.it/previ/eng/rain_msg_eng.html)). The procedure is a blended-technique based on that primarily developed by Turk et al. 2000, and then adapted for MSG data ingestion and processing. The use of MSG satellite in this operational chain certainly expands the spatial and temporal coverage of rainfall estimation and improves the consistence with the nature and development of precipitating systems.

The methodology used in this study to process rainfall data is similar to that of Carbone et al. (2002), Wang et al. (2004) and Laing et al. (2004), even if some modifications have been made to the way of identifying the convective cloud episodes. The domain of interest is firstly divided into 1650 narrow strips, each  $0.04^\circ$  wide in longitude and running from 3 to 20 in the N-S direction. Basically, the program identifies all the precipitation sequences (longer than 15 pixels) which have a rain rate greater than a choisen threshold along a certain latitude and then calculates the average. Finally, it considers only the coldest sequences and longitude-time Hovmöller diagrams are produced using time as the second dimension. To quantify the event coherency, longevity, and span, a two-dimensional (2D) autocorrelation function, uniform in one direction and cosine weighted in the other, was superimposed to the instantaneous rainfall estimates strips in the Hovmöller space to find their angle, duration and span. For a more detailed description of the mathematical aspects, see Carbone et al. (2002).

## 2.2 The Regional Atmospheric Modelling System (RAMS)

The latest Regional Atmospheric Modeling System–RAMS (Pielke et al. 1992, <http://www.atmet.com>) has been used for this study as instrument for a Regional Reanalysis simulation (for example Pasqui et al. 2004). In synthesis, the physical package of the model describes a large number of parameterizations for the description of atmospheric mechanisms: the Mellor-Yamada atmospheric turbulent diffusion scheme, the two moment cloud microphysics parameterization scheme, a modified Kain-Fritsch type cumulus parameterization, the Harrington radiative transfer parameterization short and long wave scheme and the Land Ecosystem Atmosphere Feedback scheme (LEAF-3) for soil – vegetation – atmosphere energy and moisture exchanges.

Due to the specific physical mechanisms acting in the tropics and the geomorphology sub – Sahelian Africa, in particular the Ethiopian high plains, the low resolution Global Reanalysis datasets cannot resolve many characteristics of atmospheric regional dynamics. The convective triggering mechanisms due to the interaction between large scale atmospheric dynamics, such as African easterly jet, and Ethiopian mountains are not well represented at that resolution. Thus, it is important to define a “downscaling technique” for catching local interactions and increase the atmospheric behavior description. We adopted a dynamic downscaling strategy using RAMS model nested into the NCAR/NCEP atmospheric fields, along with a weekly high resolution sea surface temperature datasets for a long period simulation run.

This long simulation period started on April up to October 2005 made by a single long RAMS run without any model restarts. Initial and boundary conditions are those of the Reanalysis global fields updated every 6 hours while the SST fields were updated only every 8 days (PODAAC–MODIS SST fields, <http://podaac.jpl.nasa.gov>). One single RAMS grid has been used with 50 km of grid spacing as reported in Figure 3 where the model domain is shown along with its topography. Vertical discretisation is ensured by 36 levels with a stretched spacing ranging from 300m (near the surface) to 1200m in the free troposphere.

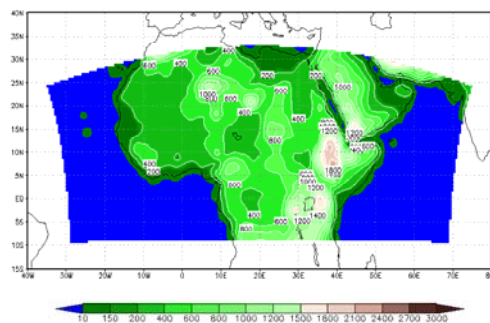
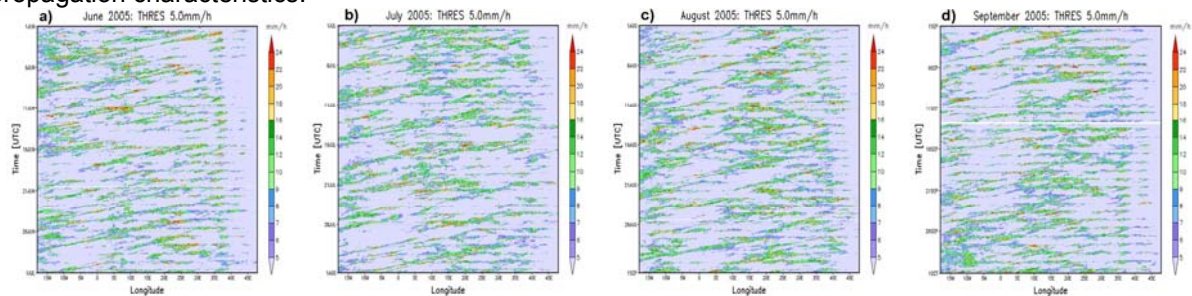


Figure 3:: RAMS model domain along with its topography.

Numerical stability issue has been ensured by typical RAMS configuration for what concerns a proper lateral nudging parameters set following previous seasonal simulations experience (Baldi et al 2003). Some special tests were performed in order to identify domain location and topography representation within RAMS. Since one of the key features for describing convection in the sub-Saharan area is the interaction between AEJ and Ethiopian high plains the final domain, shown in Figure 3, were set with the eastern boundary far away from the Africa coast. Furthermore the reflected envelope topography scheme in RAMS (see model documentation) has been applied to provide a reasonable representation of mountains.

### 3. CONVECTICVE CLOUD EPISODES

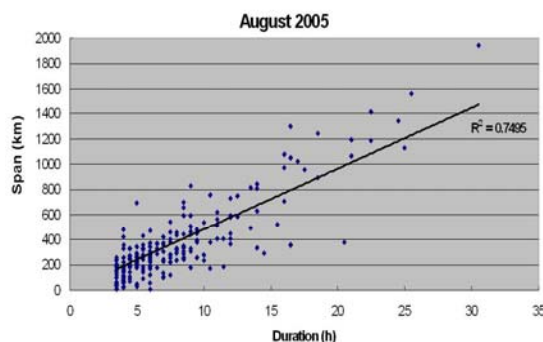
To investigate the coherent behaviour of precipitation episodes a set of Hovmöller diagrams have been created for the whole 2005 rainy season (see Figure 4). The scale represents the latitudinal-average rainfall estimates with a rain rate threshold value greater than 5.0 mm/h. In this domain, the well-organized precipitating systems appears as streaks of estimated rainfall rate, showing coherent eastward propagation characteristics.



**Figure 4:** Hovmöller diagram (longitude-time) of instantaneous rainfall estimates for a) June, b) July, c) August, d) September 2005. The white strips represents the missing data.

The travelling convection occurs daily, and it mainly initiates west of the Ethiopian highlands (west of 35°E). Second maxima of precipitation are also evident, influenced by the Darfur mountains (west of 20°E), Jos Plateau and by Cameroon mountains (west of 10°E), as by the elevated terrain along the western coast of Sahel. The dominant way of convection east of the Ethiopian highlands (east of 35°) is the non-propagating one, in phase with the diurnal heating. Moreover, convection is also linked to the African Easterly Jet (AEJ) in the low levels, which in turn becomes more and more stable as the rainy season progresses. Indeed, from June to September, we assist to a strengthens of the monsoon intensity, either in terms of a more marked organization and coherency of the MCS systems, or in terms of rainfall intensities and greater speed of event travelling.

Finally, the statistics of cloud streaks has been computed for August, as major signal of the strengthens of the African monsoon. Figure 5 shows the scatter plot of zonal span versus duration for August 2005, revealed by the application of the 2D function on the rainfall estimates streaks, in the Hovmöller diagram.



**Figure 5:** Scatter plot of zonal span vs duration of all convective episodes for August 2005.

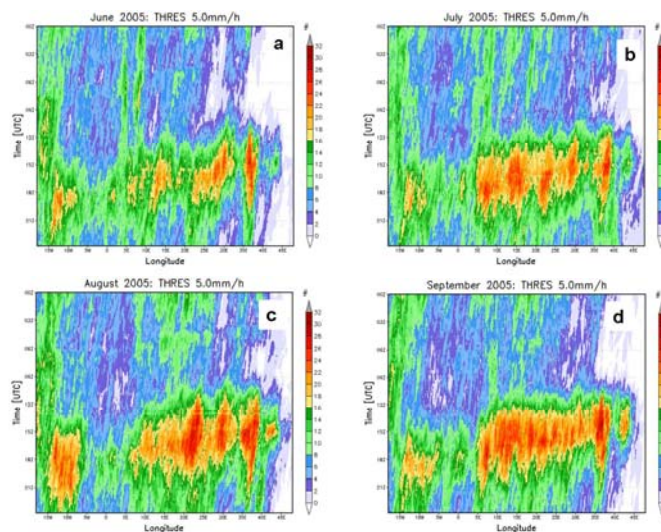
The mean zonal span, duration and phase speed for August were 352km, 7.8h and 12.7m/s, respectively. A few episodes spanned over 1000km and lasted longer than 20h. These results are coherent with those obtained for Africa by Laing et al. (2004), stressing the fact that our analysis have been conducted using rainfall estimates derived by a blended technique rather than IR Brightness temperatures, and that temporal periods and domains of calculation differ.

#### 4. DIURNAL CYCLE

The periodicity and phase of precipitation have been examined through coherent patterns related to average MSG-based rainfall estimates and RAMS modelled vertical velocity at 300hPa, the latter as a major signal for occurrence of modelled convection.

##### 4.1 MSG-based rainfall estimates

The zonal progression of rainfall, coupled with the diurnal cycle, is examined through daily histogram of rainfall occurrence. The regular occurrence of rainfall at a particular longitude, at the same time of day, can be seen as a maxima in the daily histogram. The number of days during which precipitation intensity was greater than 5.0 mm/h constitutes an event, for each longitude-time coordinate, with a temporal sampling of 15 minutes and spatial resolution of 0.04°. In this system of coordinates, the coherent rainfall patterns may represent a phase-locked occurrence of the precipitation events. Figure 6 shows the mean diurnal cycle for the 2005 warm season (JJAS) at a given longitude-UTC hour coordinate.



**Figure 6: Mean diurnal cycle for a) June, b) July, c) August, d) September 2005. The scale corresponds to the number of days during which precipitation is present (with a threshold value of 5.0 mm/h) at a given longitude-UTC hour coordinate.**

Generally, the persistency of the rainfall systems decreases toward west, while the signal due to the diurnal variations is generally evident across all longitudes between 0° and 40°E but becomes less evident westward. Several aspects are evident from this analysis:

- A daily oscillation across the African continent (maxima near 16-17 UTC)
- Maximum amplitude of diurnal cycle related to the Ethiopian highland (33°E-38°E).
- Easterly propagation of the maximum frequency related to the Ethiopian highland.

The convection in the eastern part of the domain mainly initiates in the lee of steep topography (maxima in correspondence to Ethiopian highlands, Darfur mountains, Jos Plateau and mountains of Cameroon), and it's consistent with the thermal heating due to the terrain elevation and studies in literature (Tetzlaff and Peters 1988; Laing and Fritsch 1993). Farther west, maxima can be found in correspondence to the late evening or night time hours. In the pre-monsoon phase (Fig. 6a), the convection exhibits 3 diurnal cycles,

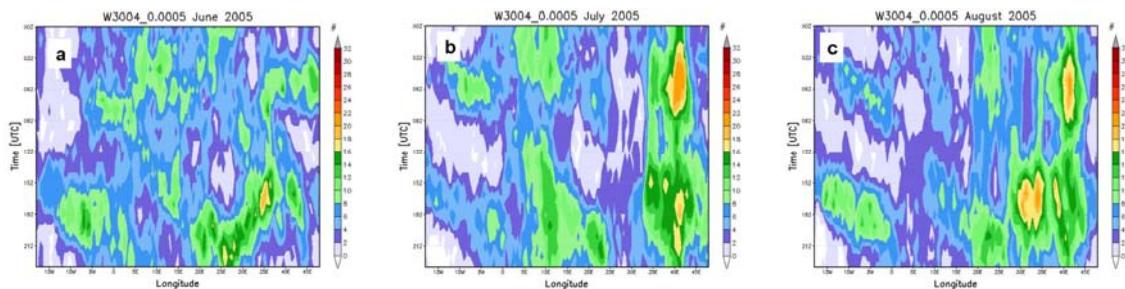
with diurnal maxima in the early afternoon, located mainly around 5°, 30°, and 35°E. With the strengthening of the monsoon, especially in the second half of July and August (see Fig. 6b and 6c), the diurnal cycle presents a major intensity, maxima in correspondence to the early afternoon in the eastern part of domain, while in the western part the convection born in the late evening hours. In this case the precipitation maxima are located around 10°W, 15°E, 25°E, and 38°E. The decaying phase of the monsoon (see Fig. 6d) is characterized by a more widespread distribution of rainfall, with 4 diurnal cycle of relevant intensity and maxima located in the late afternoon and early nighttime, in the eastern and western part of the domain, respectively.

#### 4.2 RAMS modelled vertical velocity

As a first step in setting RAMS simulations, we verified that the AEJ pattern in RAMS resembles closely the one in NCEP/NCAR Reanalyses (not shown). This must not be considered obvious, even if RAMS was forced (i.e. boundary conditioned) by the Reanalyses.

AEJ fine representation is in turn crucial for a correct simulation of WAM phenomena, as AEJ drives the occurrence and pulsation features of the WAM precipitation. The plus value of RAMS with respect to NCEP/NCAR Reanalyses is apparent on orography driven instabilities (as for the Ethiopian highlands, Darfur, Jos Plateau). The advantages of finer scale simulations begin from the enhanced description of mountain relieves: as a consequence precipitation becomes more reliable and diurnal cycle recognisable. Convective precipitation is however accounted by convection schemes also at our RAMS simulation resolutions, and it results affected by significant physical approximations. Vertical velocity at 300hPa is on the contrary a “cleaner” tracer of convection and it was preferred in the comparison with the precipitation estimations at higher resolution retrieved from satellite observations.

Figures 7a-c show the mean diurnal cycle of RAMS modelled vertical velocity at 300hPa for the months of June, July and August 2005, at a given longitude-UTC coordinate. According to satellite estimations we can see a stronger convective activity for the last two months, precipitation peaks near 16-17 UTC with maximum amplitude corresponding to the Ethiopian highlands (33°E-38°E). Less defined but still visible peaks are observable for latitudes corresponding to the other main relieves. Unrealistic precipitation peaks are however visible during morning time in the eastern part of the domain, that are maybe induced by the reanalysis lateral forcing.



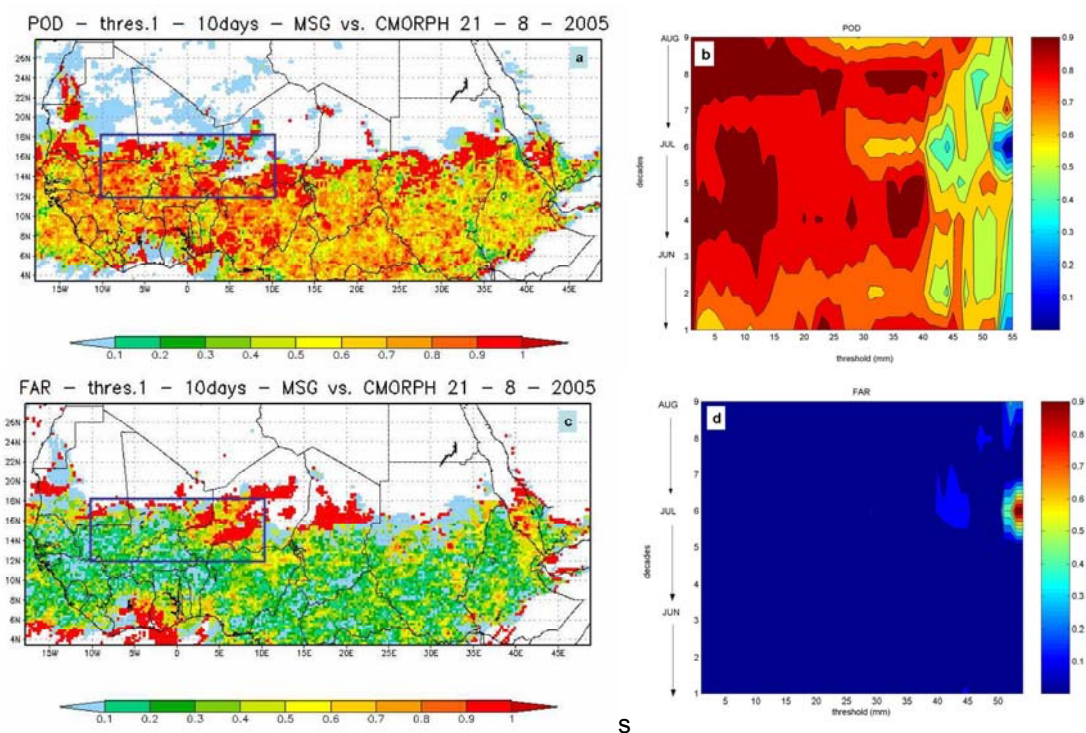
**Figure 7:** Mean diurnal cycle for a) June, b) July, c) August 2005. The scale corresponds to the number of days during which the vertical velocity at 300hPa is present (with a threshold value of 0.0005 m/s) at a given longitude-UTC hour coordinate.

#### 5. SKILL SCORES ANALYSIS

In order to assess the reliability of the proposed method for the 2005 rainfall season, some statistical skill scores, as POD and FAR, have been evaluated. The data used for this purpose are CMORPH (CPC MORPHing technique, Joyce et al. 2004) rainfall data, provided by NOAA. The CMORPH methodology produces global precipitation analyses using rainfall estimates that have been derived from low-orbit satellite microwave observations, and whose features are transported via spatial propagation information that is obtained entirely from geostationary satellite IR data.

The contingency tables are compiled, on a decadal basis, for different rain rate threshold values, taking into account the 3-hourly CMORPH rainfall data, as “ground truth” and the MSG-RU precipitation as the data whose reliability has to be evaluated.

The POD and FAR indexes, relative to the third decade of August 2005, are here presented (see Fig. 8a-d) in order to show the skilfulness of the proposed MSG-based precipitation algorithm. A good reliability (values near 1 for POD and around 0 for FAR) is reached in the Sahelian area, especially in some zones which are strategic from agricultural point of view. In particular, the temporal distributions of the POD and FAR mean values are shown for the area limited between 12°N-18°N and 10°W-10°E (Figure b,d). There are very few case of false alarms except for heavy rain events at the end of July, while as far as POD index concerned, the methodology shows a good reliability during all the rainy season, up to those events with intensity less than 40mm; for precipitation episodes with greater intensity, the POD index decreases especially in early June and end of July, probably due to intense isolated rainfall events which occur at the border with the desert, not revealed by one of the techniques.



**Figure 8 :** (a) POD (Probability of detection) and (c) FAR (False alarm ratio) for the third decade of August 2005, relative to the 1 mm threshold; (b) POD and (d) FAR temporal distributions for the 2005 rainy season, with respect to different thresholds.

## 6. CONCLUSIONS

Satellite observations, in terms of precipitation patterns estimated through a multispectral technique, have presented clear evidence of coherent rainfall patterns, associated with the monsoon regime. The methodology has correctly detected and followed the evolution of the intense dynamics of convection, in terms of organized rainfall events with coherent propagation in the longitude-time space, characteristics of those tropical areas (Melani et al. 2006). In this sense, the coherency characteristics has allowed to study the intraseasonal variability of the monsoon regime, the diurnal cycle and the zonal component of motion. These results acquired a relevant meaning in the global comprehension of the dynamics of monsoon precipitation genesis and evolution, and their impacts in the long-term forecasting and climatic changes. The reconstruction of the monsoon dynamics with a limited area model has shown good results in the

detection of some phase-locked behaviours, typical of those precipitation patterns, for a better comprehension and possible forecasting of the considered phenomenology. These dynamics will be investigated completing the statistics of the rainfall patterns with additional years and mathematical instruments as Fourier analysis. From a numerical modelling point of view, we intend to investigate the various components of the monsoon through sensibility tests to various factors (aerosol, SST, etc.) which could influence its complex dynamics.

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