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A climatology of Mesoscale Convective System from satellite

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A climatology of Mesoscale Convective System from satellite

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The deliverable presents a new database of MCS over West Africa obtained from a long time series of satellite measurements. The data have been made available in the AMMASAT server.

Summary

In West Africa, recent decades have shown significant climatic evolution. In particular, droughts conditions are continuously observed over the Sahel since the 70's while other regions exhibit a return towards neutral long term conditions. The intimate link between the rainfall and the Mesoscale Convective Systems calls for a concurrent analysis of the evolution of the MCS over the region. A first step is performed here by computing a homogeneous analysis of 24 years of METEOSAT data. MCS are hence detected and tracked in time using the infrared imagery. A simple MCS classification is developed based on the duration of the system and its speed of propagation. Four classes are formed using thresholds selected on a physical basis of 9 hour and 10 m/s, respectively. The long term average spatial distribution of the systems is presented as well as the interannual variability. A dedicated focus on the 2006 season is proposed. This work shows that in spite of its simplicity, the present MCS classification is useful to document convection in West Africa at various scales and should be of help to better understand the observed recent climatic variations over the region.

Introduction

West African rainfall is driven by a wide variety of convective clouds ranging from the isolated storms to the organized convective systems among which stands out the well known squall lines (Dhoneur, 1985). Over Sahel, in particular, organized convective systems appear to produce a large fraction of the summer rain yield (Mathon et al., 2002). The last century climatic history of the region is fully centered on the Sahelian drought which is lasting since the 1970's. Over the last 20 years, the situation has evolved with some regions revealing continued drought conditions (Lebel and Ali, 2009) and others showing "greening" associated with more rainfall per season (although still under the pre-drought climatic mean). Establishing the extent to which the different types of convective systems have evolved over this recent period over Sahel, and more generally over West Africa, would hence provide a way to link this climatic event with the processes at play in the rainfall. This would put a strong physical constrain on the ability to model such a past drought and the future evolution of rainfall in this sensitive area under climate change for which the current generation of GCM is still not showing much skills nor agreement (e.g. Douville and Terray, 2007). In this work, a systematic and homogenous analysis of 24 years of summertime METEOSAT satellite data is presented in order to offer the required observational support for such scientific investigations.

The natural spread of the expression of deep convection in the tropical atmosphere with various degree of organization (e.g., Houze and Betts, 1981 Redelsperger 1997), together with the multiple observational platforms deployed to characterize them (synoptic stations, rain gauges, ground radar, satellite infra red and microwave imagery,…) has yield to a large body of literature promoting a substantial nomenclature to characterize the rain events. The analysis of the satellite imagery in particular, based on the delineation of the convective systems generally using brightness temperature thresholds corresponding to optically thick cloudiness distributed at different altitudes in the atmosphere (e.g., Duvel, 1989) has raised a significant corpus. The classification of these loosely defined Mesoscale convective systems has indeed been the subject of many studies promoting various methods ranging from the Mesoscale Convective Complex (Maddox 1980), disturbance- or squall-line systems (Aspliden et al., 1976) to the Organized Convective Systems (Mathon 2001) and the Organized Tropical Storms and cyclones (Smith and Metha 1991). These classifications are based on experimental thresholds applied to some morphological parameters of the systems. For instance, the identification and analysis of the Mesoscale Convective Complex Systems (MCCs), defined by Maddox, has been generalised by Evans and Shemo (1996), and extended in four categories of organized and disorganized convective systems depending on their sizes, temperatures, lifetimes and eccentricities : Mesoscale Convective Complex (MCC), Convective Cloud Cluster (CCC), Disorganized Short-Lived convection (DSL), and Tropical Storms. Other studies focused on specific sub-category of systems like warm pool superclusters, convective clusters lasting longer than 2 days in the IR imagery (Mapes and Houze, 1993). Tropical convection penetrating into the upper troposphere and lower stratosphere is identified as cloud clusters detected at 245K on the IR imagery, if once in the lifecycle, a cold cluster (delineated by a 220°K threshold) is associated to it and furthermore, if a minimum temperature of 200°K corresponding to the cold point tropopause temperature is found in the system (Rossow and Pearl, 2007). Other approaches classify the system with respect to the global population of convective systems encountered during the period of study over the region of interest. Hence, Chen et al (1995) over the warm pool as well as Zuidema (2003) over the Bay of Bengal have classified convective systems in four classes, each class contributing to an equal amount of the cloud clusters cumulative size distribution.

Over West Africa, specific regional classifications have been applied on convective systems to characterize them according various criterion. Payne and McGarry (1977) have identified squall-lines by “explosive growth, high brightness, and a distinct and generally convex shaped leading edge”. In their study on the relationship between West African Squall-lines and African Easterly waves, any system consisted of a Western leading edge was considered as a squall-line by Fink and Reiner (2003). Aspiden et al (1976) has only classified the brightest clouds in squall-lines, depending on minimum size and lifetime thresholds. To analyse the generation of African Squall-lines, Rowell and Milford (1993), have applied thresholds on the temperature, the size and the propagation speed of the convective systems. In the study of Mathon (2001) about Mesoscale Convective Rainfall in the Sahel, Organized Complex Systems (OCS), associated to the most precipitating systems, are defined as areas colder than 233°K, containing at least one cluster at 213°K, and moving faster than 10m/s. The Global Atmospheric Research Program Atlantic Tropical Experiment (GATE), yield to MCS classification in three classes, only according to their speeds propagation speed (Barnes and Sieckman, 1984). In order to define convection over the Upper Ouémé Valley and to link it to the local dynamics, Fink et al (2006) have classified three types of rainfall events (advective cloud systems, local precipitation, and vortex related rainfall events), based on the genesis of the cloud clusters and the regional vertical winds. These three classes were then subdivided into OCS, MCS and instability storms, according to the temperature, the propagation speed, the area of the cloud cluster detected at 233°K, and the area of the convective cell, detected at 213°K, within it. Laing and Fritsch (1993) have used the Maddox (1980) definition of MCCs has been applied to the African continent and shown there to resemble closely to the tropical storms found elsewhere in the tropics (Laing and Fritsch, 1997). Hodges and Thorncroft (1997) have computed a 8-year climatology (1983-1990) of African Mesoscale Convective Systems based on Meteosat imagery. Convective cloud systems have been detected at a -15°C temperature, and then tracked through their entire life cycles. To compute statistics of organized convection, only systems with a lifetime longer or equal than half a day have been kept. In order to provide a simple and homogenized view of the convection organization over the whole West African continent, a simple four-class, two parameters convective cloud systems classification is introduced here. The 24 year climatology of these four classes of systems is presented and a focus on the 2006 season is offered as a large number of investigators are analyzing this season in details owing to the occurrence of the AMMA SOP (Redelsperger et al. 2006). This way, the convective activity during the AMMA SOP campaign is put in the context of the 24 years climatology.

The document is organized as follows. First the data are introduced together with some control quality indices. The cloud identification and classification is also discussed. The climatology is then presented as well as the interannual variability over the period.. A quick summary ends the manuscript.

Data and methodology

METEOSAT observations

Raw observations in the thermal window (10-12 microns) of the METEOSAT spacecrafts for the 1st June- 30st September over all the years 1983 :2006 included at full resolution (5km ; 30 minutes) have been acquired and processed at the Climserv data server of the Institut Pierre Simon Laplace, Palaiseau, France. The data originate from the EUMETSAT archive and from the Service d'Archivage et de Traitement Météorologique des Observations Spatiales located at the Centre de Météorologie Spatiale in Lannion, France. Calibration coefficients from EUMETSAT are then used to convert raw numerical counts to radiance and then to brightness temperature. METEOSAT-2 to METEOSAT-7 observations are used here and hardly differ in terms of spectral response. These characteristics constitute the basis of this long and homogeneous database. The summer 2006 is processed using Meteosat Seconde Generation data which have been degraded, temporally to mimic the METEOSAT first generation characteristics and to permit the extension of the database to the AMMA SOP period.

The seasonal availability of the data averages to 94.5% over the full period with a standard deviation of 4.2%. As shown in Figure 1a, the best year is 2003 with 0.7% in contrast with the worst sampling conditions of 1985 with 21%. The first 15 days of the season being missing. Of interest to the tracking of cloud systems discussed below is the return time between series of missing images. Indeed the tracking algorithm interpolates the missing slots up to 3 hours. If the imagery is not available for consecutive period greater than 2.5 hours then all the trajectories are stopped yielding to an artificial reduction in the cloud system estimated duration. Similarly, such events imply that some systems are initiated after the event while they could have started within the event. The figure 1b shows the fraction of the observed MCS that are concerned by such alterations at the seasonal scale along all the study period. It reveals that a marginal amount of the systems (less than 1.5%) are corrupted by this artificial interruption/initiation with better statistics after the

MFG satellite became operational with the advent of METEOSAT-4 during the year 1990. This indicates that the MCS statistical characteristics to be shown next are not affected by the availability of the imagery.

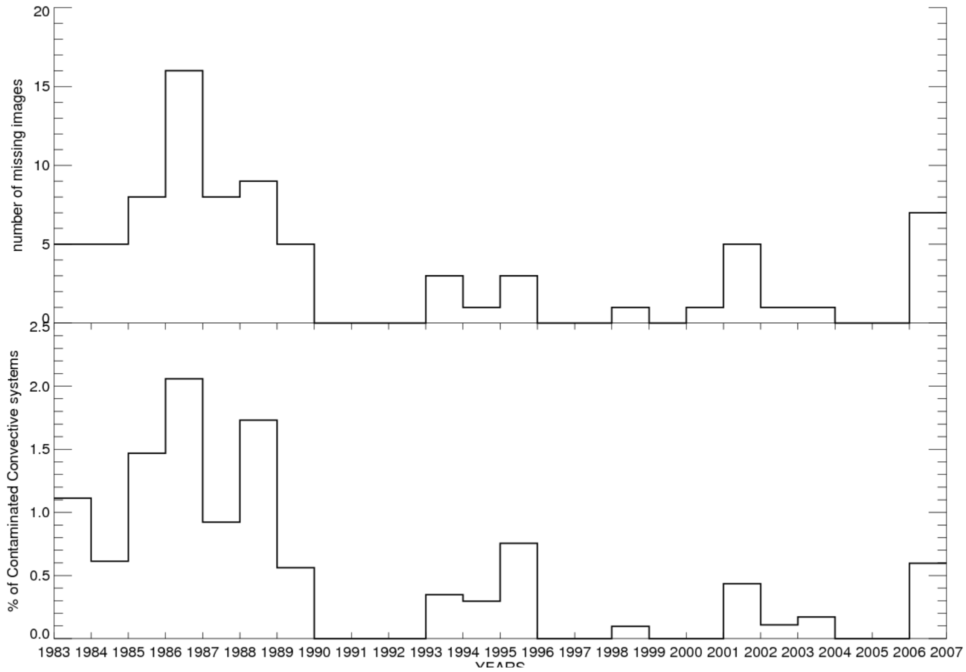

Figure 1 Number of missing images per season (top) Number of missing images per season (top). Percentage of the MCS population affected by missing series of images longer than 3 hours (bottom).

Cloud system tracking

The cloud system tracking algorithm is fully detailed in a number of papers (Williams and Houze 1987; Arnaud et al., 1992; Machado et al., 1992; Mathon et al. 2002). Here we only briefly summarize its functioning. It is composed of two steps: the detection of the cloud system at a given time and the tracking along the time. The cloud shield identification is performed simply with the raw IR imagery. It is indeed segmented using a clustering routine that delineates continuous region in space that is colder than a threshold. The labeling is performed using 8-connectivity and a threshold of 233K, well adapted for the study of convection and accumulated convective precipitation in the Tropics, (e.g., Arkin 1979) is chosen. The minimum size to characterize the cloud system is 5000 km^2 which is 200 pixels (555 pixels for MSG). The cluster tracking is performed when all the images of a given period are first segmented. Then the clusters detected in the image at time t+1 are matched with the ones in the previous image at time t based on the spatial overlap between the two segmented images. If the overlap is greater than 50% or 10000km^2 of the area of either the current cluster or the cluster from the previous image, the clusters are matched. When no overlapping occurs in the previous image, it is considered that the cloud system is generated. On the other hand, a convective system dissipates when there is no longer intersection with another cluster in the next image. The tracking can result in some clusters merging and splitting yielding to complex MCS life cycle. When several clusters merge to form a unique cluster in the next image, the larger cluster at this time is selected to continue the original track, whereas the tracks of the smaller clusters are considered to end. Similarly, splitting clusters are taking into account by selecting the larger cluster in the next image to continue the track and the smaller clusters are considered as split generation. For this study, a selection is applied to the MCS generated by a split, or dissipated by a merge, in order to keep convective systems which describe a complete life cycle. Consider that the cluster B in the current image is generated by a split of the cluster A in the previous image. If the lifetime of cluster B is longer than the lifetime of cluster A, from its genesis to the moment of its split, then the cluster B is considered as having describe a complete life cycle and is selected in our database. A similar process is applied for convective systems dissipated by a merge. This approach hence tracks each cluster along the time and allows building a life cycle of the mesoscale convective systems. The rejected MCS account for a few percent of the whole population and of the total cloud cloudiness and hence do not impact the following statistical analysis. Missing images in the time series are handled as follows: if few images are missing (< 10 images), a recovery process is run to continue the track of each convective system during the period of missing images. This process is based on the generation of the missing images, by extrapolating the behaviour of each convective system, like their locations and their sizes. As discussed earlier only a marginal amount of the systems indeed suffer from this issue (see

Figure 1b).

The morphological parameters of the so-defined convective cloud systems includes the surface of the system (km^2), the mean IR brightness temperature (°K), the speed of propagation (m/s) as a function of time along the MCS life cycle. Integrated MCS parameters like the duration (h), the cumulated surface (km^2), the average speed (m/s) are also computed. The location of the systems is defined by the center of mass weighted by the brightness temperature of each pixel. This definition of location is then required to compute the average speed, according to the average zonal displacement of the center of mass between the genesis and the dissipation of the convective system life cycle. Here, we focus on the use of the latter parameters (duration, cumulated surface, average speed) to analyze of the MCS population through the establishment of a classification of the systems.

Mesoscale Cloud Systems classification

As discussed in the Introduction, the rationale for the present new system classification is: simplicity and suitability to document the organized convective activity and associated rainfall encountered over the whole West African region. In light of the literature and after a series of tests, the duration D (hours) and the propagation speed V (m/s) were chosen as the basics parameters of the classification. Figure 2 shows the distribution of all the events detected with the tracking algorithm in this duration and speed propagation space. Most of the systems are short lived and do not propagate fast. The shortest systems reach the fastest average velocities while the speed of the longest systems asymptotes towards 12-15 m/s. Similar characteristics hold if the occurrence of the MCS is weighted by their cold cloudiness cover. Another major feature of the West African convective activity is the diurnal cycle. Most of the systems begin in the afternoon and dissipate before midnight A threshold of 9 hours is hence used to separate the MCS that vanish in the evening or early night from those that can sustain their activity through out part of the night or longer.

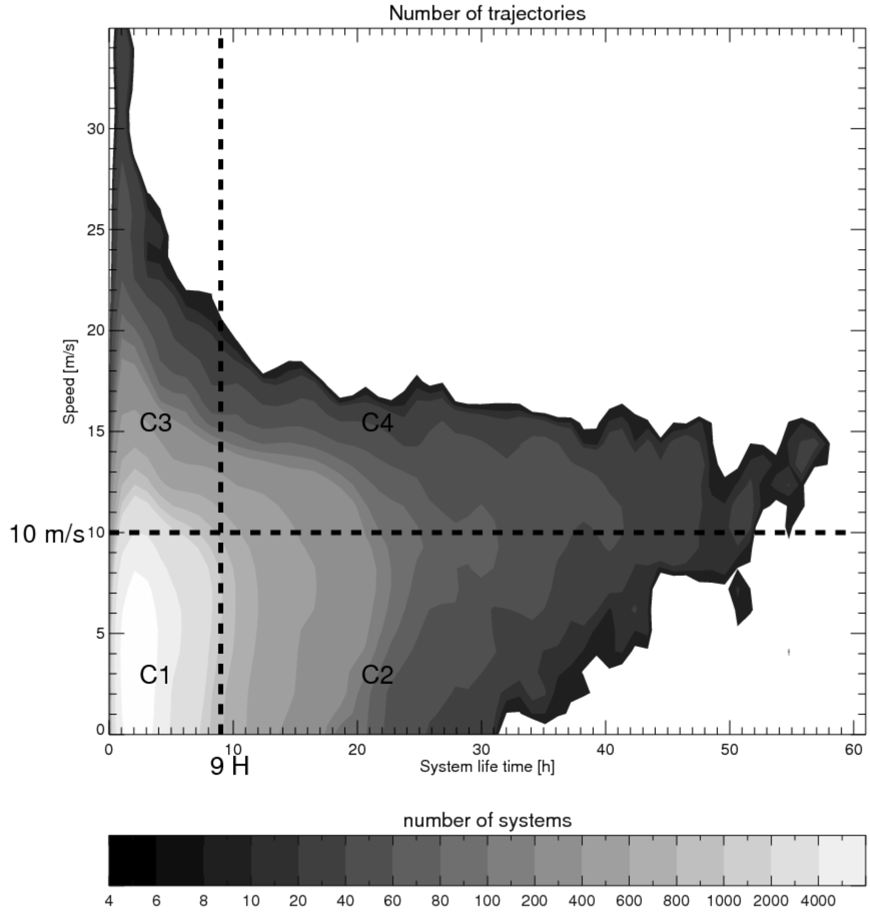

Figure 2 Histogram of the number of MCS as a function of the duration and speed of the system

The limit of the approach is coming from the use of hard thresholds and a limited set of parameters to characterize the diversity of organization of convection encountered in the West African monsoon. Such effort might hence not describe the convective processes as well as a local delineation might do (e.g. over the Niamey area, the multi parameter OCS from Mathon et al. 2001) but as advocated in the following sections, and in light of its simplicity, this classification is shown to be useful to document the convective activity in West Africa.

Other data

The Global Precipitation Climatology Project (GPCP) Version 2 surface rainfall estimates are used at a nominal resolution of 2.5°x2.5° at monthly mean over the period 1983-2006 to complete our description of deep convection over the region. The GPCP data (Huffman et al., 1997) is composed of rainfall estimates from geostationary satellite IR images, from polar orbiting microwave imagers and the rain gauges readily available from the Global Telecommunications Systems. Over the long time span considered here, the amount of data ingested by the merging algorithm fluctuates sensibly, for instance, with respect to the microwave imager availability (it only exists after 1987). The stability of the products with respect to other climatological rainfall products based on rain gauges only is nevertheless reasonable over West Africa. Indeed when carefully compared to Global Precipitation Climatology Centre observations (Beck et al., 2005), the GPCP V2 data has been shown to be well adapted for characterizing the annual and seasonal mean spatial distribution over the region as well as over sub latitudinal bands and to some extent of the interannual variability with emphasis on the sign of the anomaly; the magnitude being less certain (Lamptey, 2008). With respect to Sahel, recent investigation underscores the need for dedicated geographical and quality index to characterize the interannual variability and the recent (post 1993) evolution of the rainfall there (Ali et al., 2008). The computed interannual anomalies over Central Sahel for GPCP corresponds well to the one reported in Ali et al (2008). This indicates that GPCP is suitable to characterize the interannual variability of rainfall over our region of study for the sign of the interannual anomalies and to a certain extent, for the magnitude of this variability.

Climatology and inter-annual variability of the MCS

This section presents the climatology and the interannual variability of the MCS for the JJAS season over the period 1983-2006 included.

Long time mean statistics

Morphological parameters

Table 1 shows the long time mean morphological parameters of the MCS for each class over both the continent and the ocean. The C4 systems exhibit the larger average mean size of followed by the

C2, C3 and C1. The same ranking holds for the maximum system size recalling the strong relationship characterizing the MCS life duration and spatial extension (e.g. Mapes and Houze, 1993; Machado et al., 1992). The C2 and C4 systems have slightly colder average temperature as well as colder minima than the C1 and the C3 which is in agreement with the size parameters characteristics (Roca and Ramanathan, 2000; Roca et al. 2002). Most of the systems are propagating west wards (more than 80%) especially the C4 population (more than 97% of the cases). The only difference in the oceanic and continental MCS is the fact that for, each class, oceanic systems are systematically smaller and less cold than the continental ones indicating a lesser degree of organisation over the ocean.

	Land				**Ocean**			
Class	**C1**	**C2**	**C3**	**C4**	**C1**	**C2**	**C3**	**C4**
Average Mean Size (103km2)	11.6	64.8	17.2	82.5	9.3	35.4	12.9	48.0
Average Maximum Size (103km2)	16.0	137	26.1	175	12.1	69.6	18.2	94.5
Average Mean IR Temperature (K)	219	211	219	216	221	217	221	216
Average Minimum IR Temperature (K)	204	193	201	191	208	199	205	196
Fraction of Westwards population (%)	84	86	87	98	80	86	82	97

Tableau 1Long term mean morphological parameters of the MCS for the land and oceanic part of the region of study

Diurnal cycle

Figure 3 shows long time accumulated statistics of the local time of initiation of the cloud system for the 4 classes for a broad continental area roughly corresponding to West Africa (15°W-25°E; 5°N-20°N). All classes exhibit a strong diurnal cycle with most of the initiation taking place in the afternoon between 12h and 18h. C2 and C4 systems have very similar cycle while C1 appears similar but delayed by two hours. C3 systems cycle is marked with well defined activity between 14h and 18h. All classes show a minimum of initiation during the early morning between 6h and

10h but the C4. For this latter category the minimum of activity occurs in the middle of the night between 2h and 4h. More detailed analysis should be carried out to establish if these large scale results still hold true at regional and local scales which is out of the scope of the present paper.

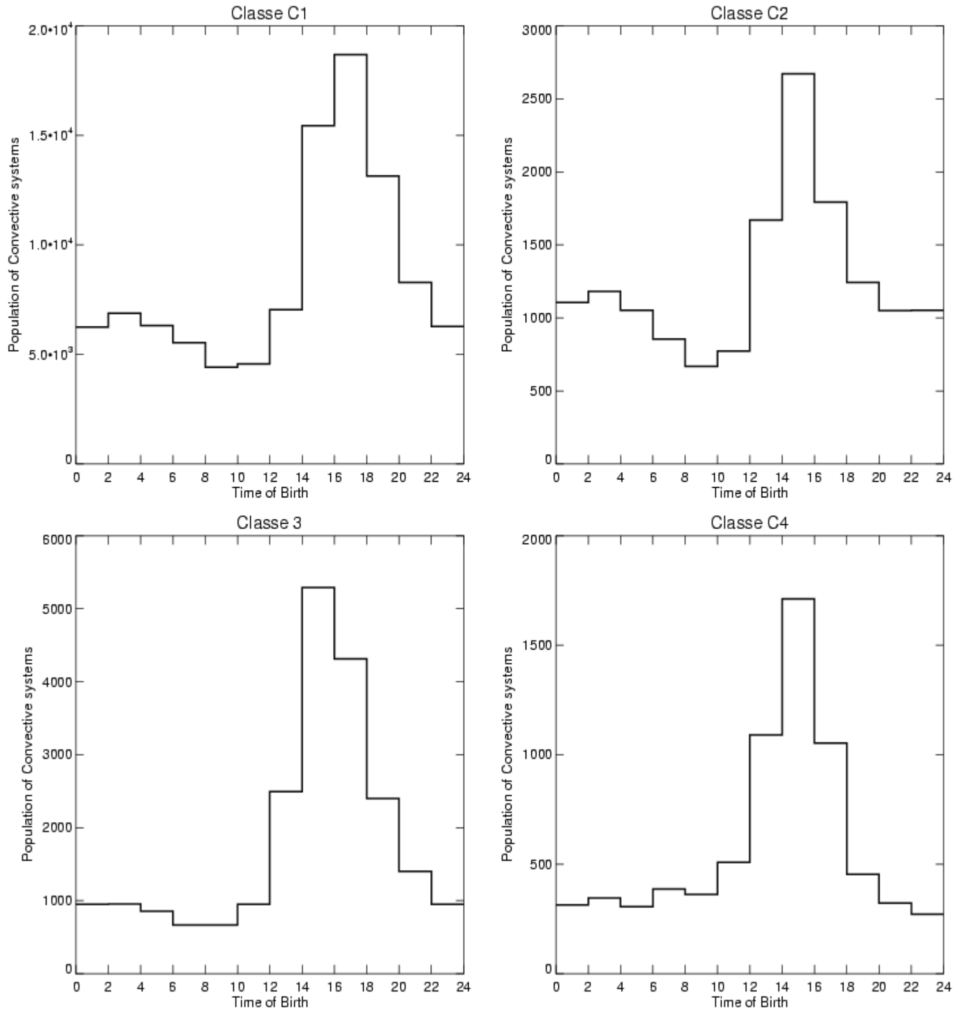

Figure 3Climatological averaged local time of genesis for the 4 classes. Only the continental system of the region of interest are kept.

Maps

Figure 4 reveals the spatial distribution of the convective systems. The cold cloudiness associated to the MCS cloud shield is accumulated over each season and for each grid point and normalized with respect to space and time and then expressed in hour per month. For instance, a value of 40 hour/month for the class 3 MCS indicates that for this grid point, cold cloudiness associated to the class 3 systems has been observed on average 40 hours per month. Figure 5 shows the relative contribution of each class to the total cold cloudiness. The C4 and C2 class are shown to be complementary; the C2 contribution being overwhelming over the Atlantic ITCZ area and over the Gulf of Guinea while the C4 dominates the cold cloudiness over the Sahelian band. Note that continental C2 contributes to a large fraction to the total over the Congo basin. The C1 systems contribution is smaller over the Sahel than else where and the C3 map reveals an equally distributed contribution of this population to the cold cloudiness.

In summary, the different MCS classes have the following characteristics:

- The C1 systems correspond to small, numerous, diurnal (short) and slow moving systems and a observed preferentially over the mountainous areas and over the ocean. This class overall does not contribute more than 20% of the total cold cloudiness with local minimum in the Sahelian band.
- The C2 systems are slow moving but long-lived MCS, bigger than the C1 systems. They are located over the ocean and over the slopes of the elevation where maximum of rainfall are found. While they contribute around a third of the total cloudiness over the Sahelian region, their contribution is overwhelming over the oceanic region.
- The C3 clouds are not very frequent and correspond to continental fast propagating and short lived MCS, dissipating in the evening with a very small contribution to the cold cloudiness.

- The C4 MCS are the long-lived, fast propagating systems. These are the biggest systems of the 4 classes and mainly located over the continent. There track is concentrated on the Sahel band (10-17°N) where they dominate the total cloudiness (up to 80% of contribution)

These summaries are in agreement with the arbitrary thresholds used to delineate the MCS categories. The long lived and fast propagating systems (C4), among which are the well known squall lines, are associated with this region of the west African monsoon where favorable conditions for these kind of systems are encountered in the summer. Indeed a warm low-level equivalent potential temperature, a strong wind shear to the African easterly jet located at 600 hPa (Lafore and Moncrieff, 1989) and a dry middle atmosphere (Roca et al., 2005) all facilitates the organization of convection into C4 systems (Barnes and Sieckman, 1984; Rotunno et al., 1988). The spatial distribution of the smaller and larger systems over ocean and land respectively was previously noted (Machado et al., 1992) so was the southward shift of the location of the small (C1) systems compared to the larger ones (C2).

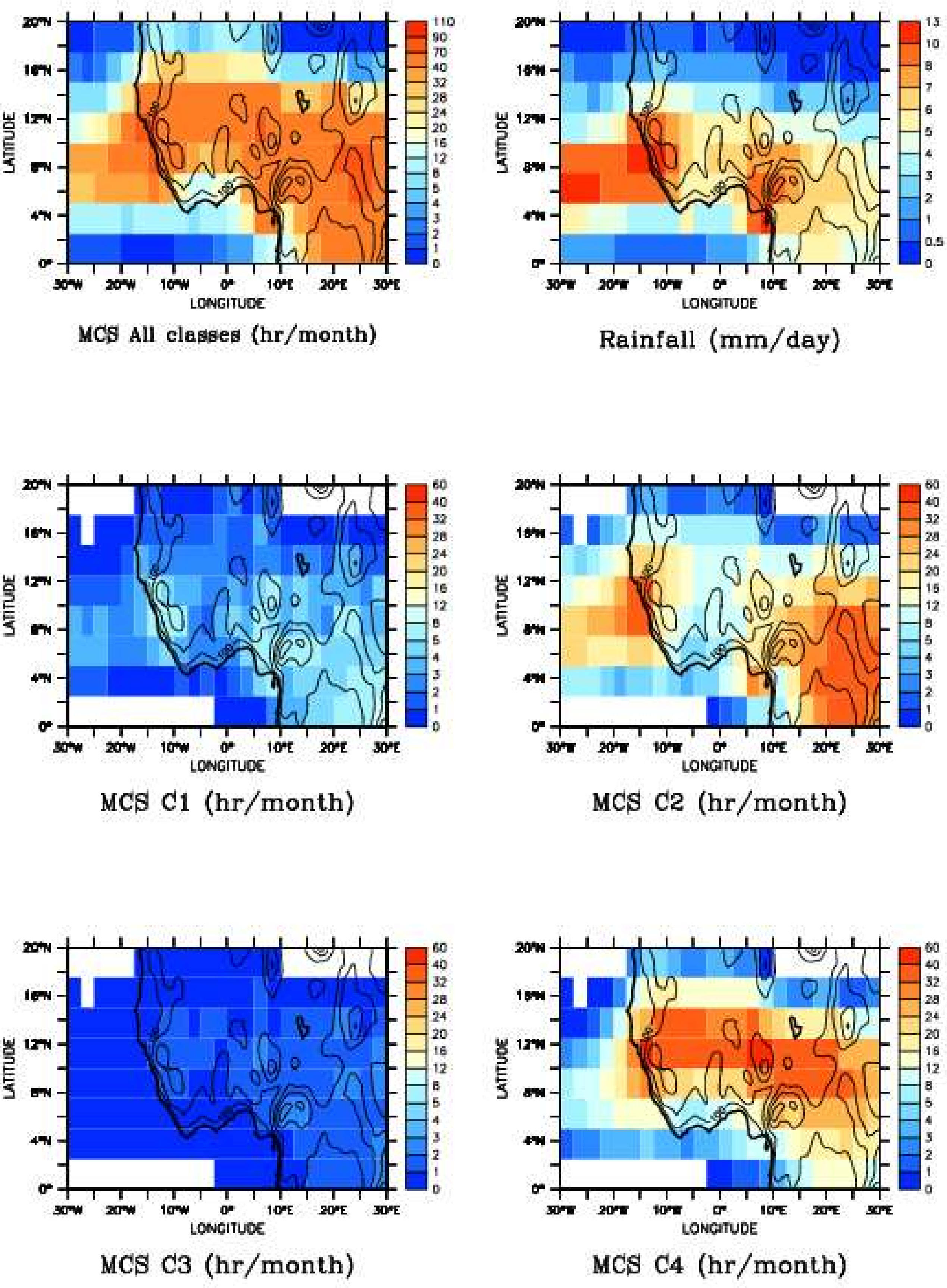

Figure 4 Long term average map of the convective systems cold cloudiness expressed in hr/month (see texte for details) for (a) All the systems (c) C1 (d) C2 (e) C3 (f) C4. The corresponding rainfall climatology is also shown (b). The contours correspond to the terrain elevation in meters.

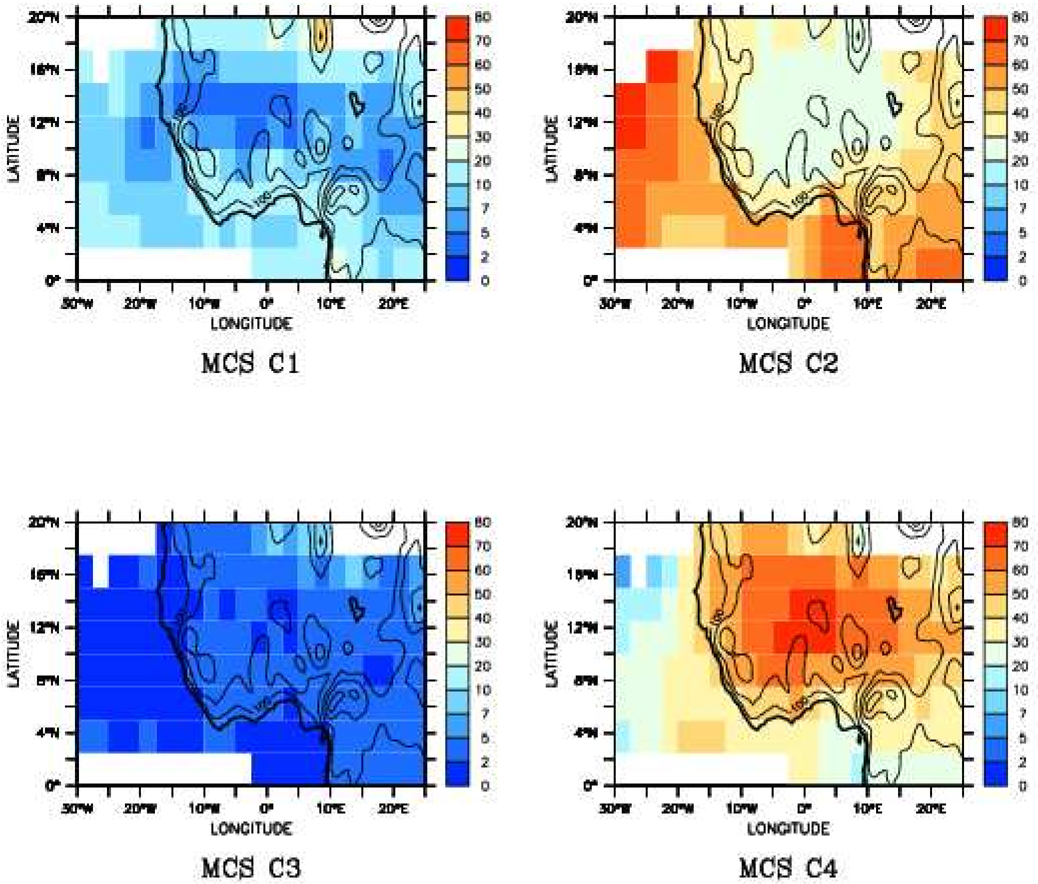

Figure 5 Long term average map of the convective systems contribution to the total cold cloudiness in % for (a) C1 (b) C2 (c) C3 (d) C4. The contours correspond to the terrain elevation in meters.

Interannual variability

The interannual variability is highlighted here over typical rain regimes of the West African monsoon.

Niamey and Dakar

Figure 6 shows the time series of the MCS over a 2.5°x2.5° region corresponding to Dakar (17.5°W-15°W and 12.5°N-15°N). The average cold cloudiness is around 50% contributed almost equally by the C2 and C4 classes; the two others classes contributing marginally. The interannual coefficient of variation (standard deviation normalized by the mean) of the cold total cloudiness is roughly 13%. The variability of contribution of the C2 (~20%) and of the C4 category (~19%) to the total cold cloudiness is comparable. The C2 and C4 hence seem to explain the interannual variability of the cold cloudiness over the Dakar area.

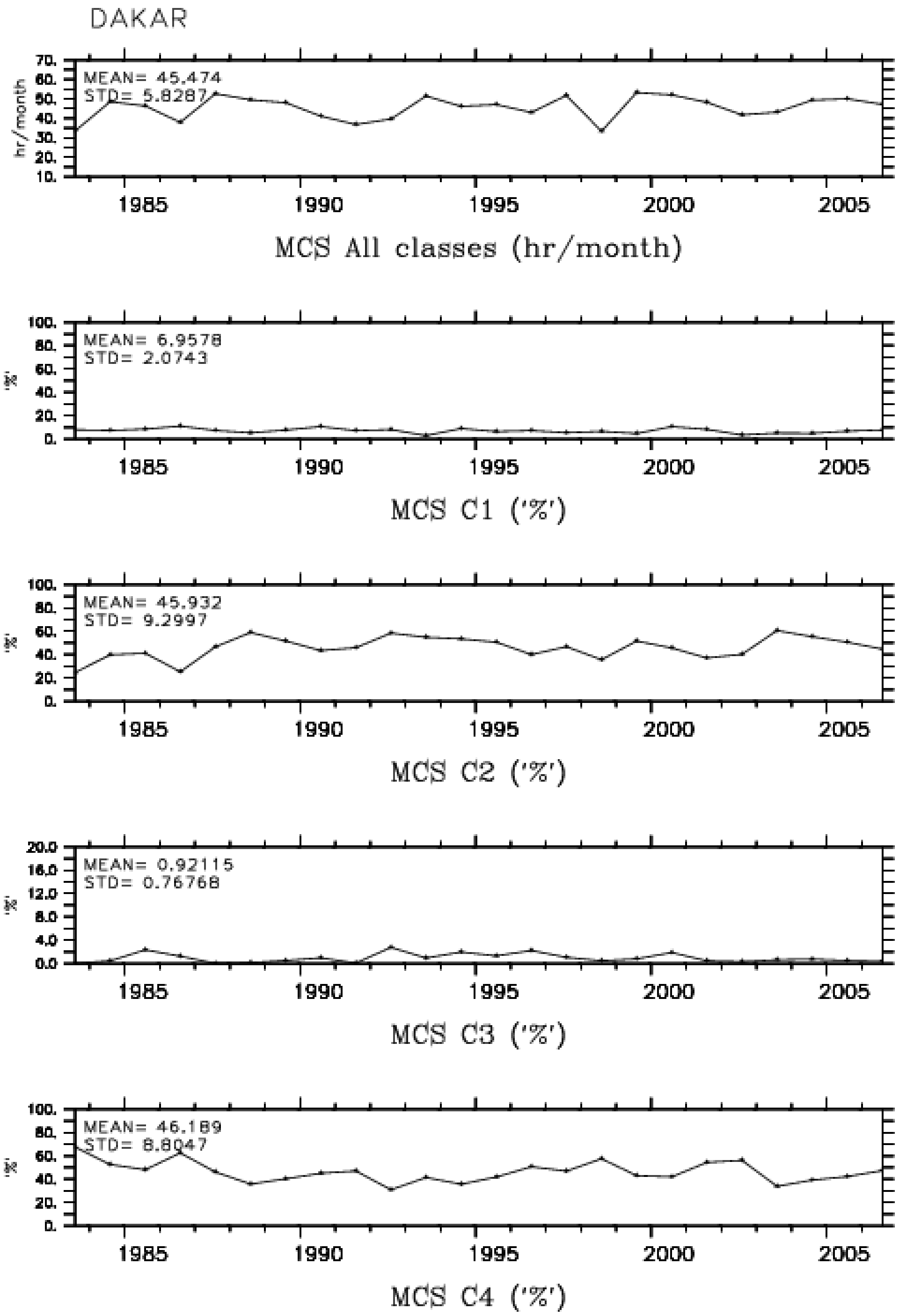

Figure 6 Time series for the Dakar area (°E-°E °N-°N). (a) All classes cold cloudiness in h/month. (b) Fraction of the cold cloudiness associated to Class 1. (c) Class 2. (d) Class 3 and (e) Class 4.

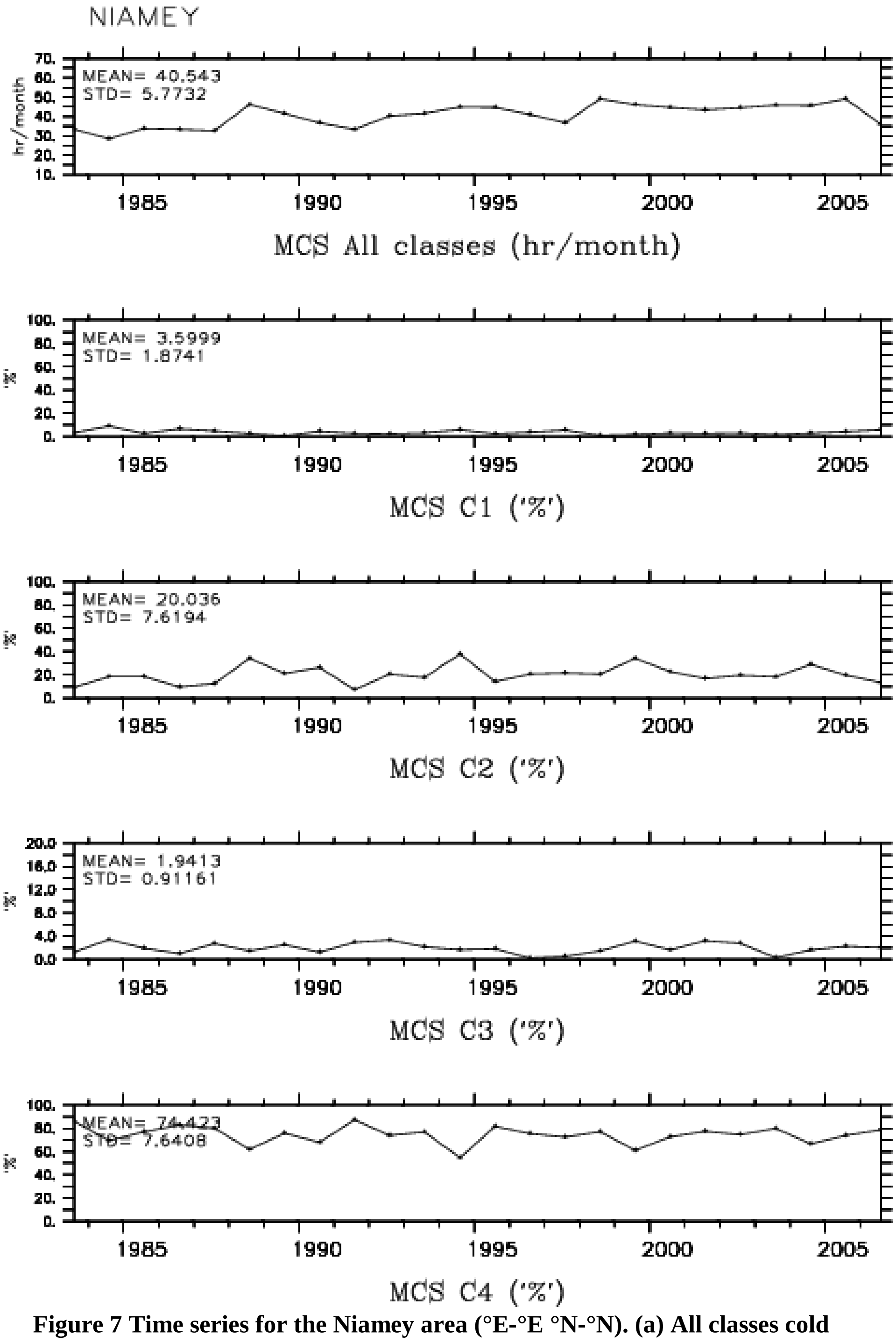

Figure 7 Time series for the Niamey area (°E-°E °N-°N). (a) All classes cold cloudiness in h/month. (b) Fraction of the cold cloudiness associated to Class 1. (c) Class 2. (d) Class 3 and (e) Class 4.

For the Niamey area (0°E-2.5°E and 12.5°N-15°N) the results are plotted in Figure 7. The cold cloudiness there is slightly less that that of Dakar (~40%) but reveals similar variability with a coefficient of variation of 15%. The C4 category dominates the contribution to the average cold cloudiness, and then comes the C2 with a small 20% contribution. The normalized interannual variability of the contribution of the C4 (10%) is less than that of the C2 (38%). In 1984, the C4 are less frequent than usual while all the other classes occurred in excess of the climatology, yielding to the less cold covered season of the period. In 1991, , the contribution of the C2 ceils to 5% while the C4 contributes up to 90%. The C4 hence seems to dominate the interannual variability of cold cloudiness in the Niamey region.

The AMMA 2006 SOP

During the 2006 season West Africa was the locus of a Special Observing Period of the AMMA project (Redelsperger et al., 2006). During the preparation phase of this campaign the MCS classification and climatology were used to qualify, in terms of MCS, the convective activity over a number of sites following a similar analysis as above (Lafore, 2006 personal communication). The analysis has been performed in more details (including day to day variations; intraseasonal and synoptic analyses, etc…) and was shown as an objective tool to discuss the location of the operational center of the flights operations (Lafore et al, 2007). The 2006 African summer monsoon was a near-normal rainy season with some excess rainfall north to 15°N compared to 2001-2005 (Janicot et al., 2008). Results in figure 8 are here computed with respect to 1983-2006 and confirm he overall near normality of the rain anomaly with a positive anomaly in the Western Sahel and a negative one on the Eastern Sahel. On the Mont Cameroun area, a significant positive anomaly is observed. The MCS occurrence anomalies also convey a near normal picture for 2006 with low anomalies. The C4 class exhibits an overall negative anomaly, like the total cold cloud cover, while the C2 anomaly seems to better correlate with the rainfall map. A more detailed analysis of the role of each class in the interannual variability of rainfall is nevertheless needed to further link the MCS distribution to the rainfall variability.

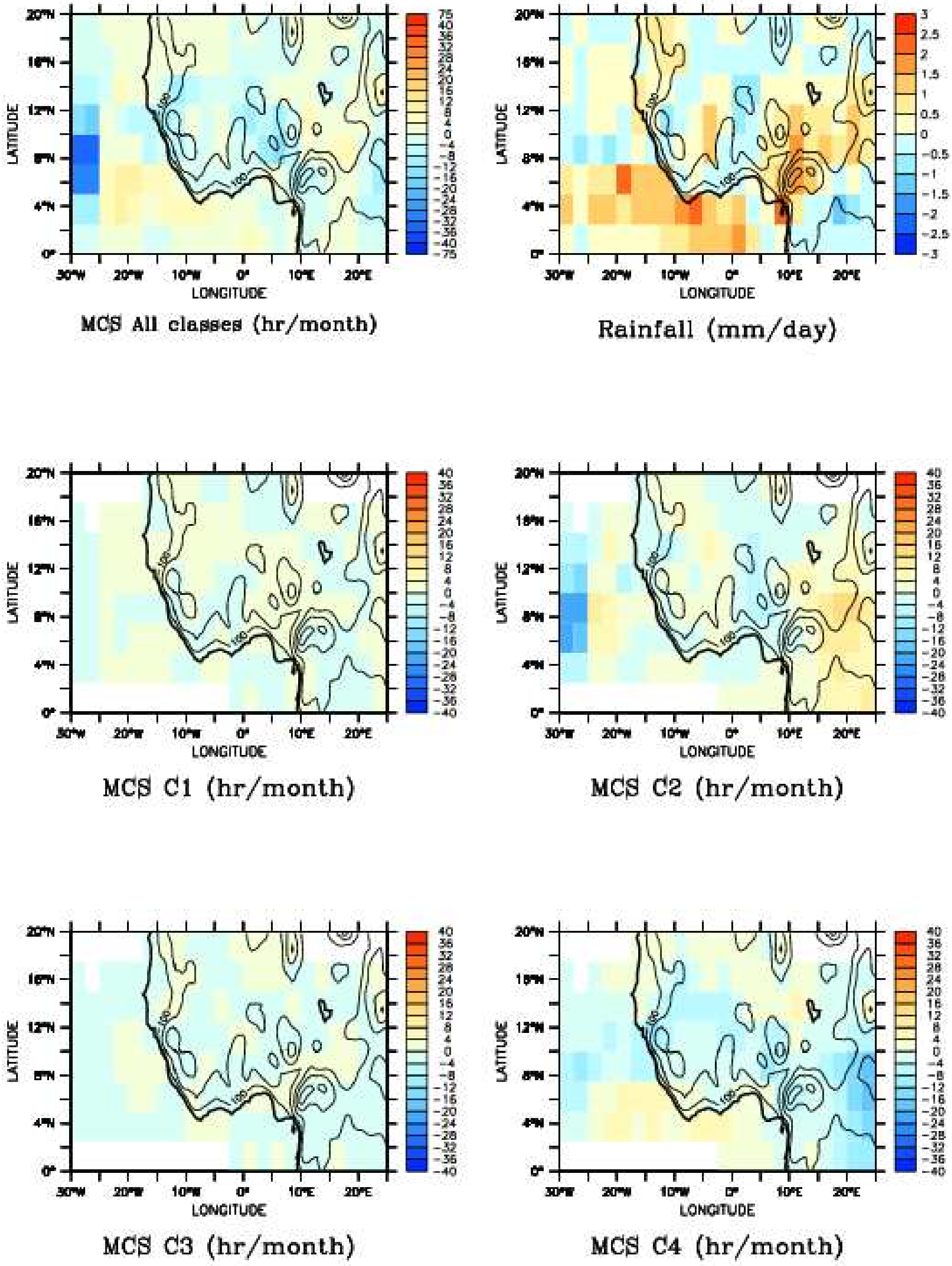

Figure 8 The maps of the anomaly of the season 2006 with respect to the climatology. (a) Cloud cloudiness for all classes (h/month) (b) GPCP rainfall estimates (mm/day) (c) cold cloudiness (h/month) for Class 1 (d) Class 2 (e) Class 3 and (f) Class 4. The contours correspond to the terrain elevation in meters.

Summary

A new data set is now available to the community and provides a homogeneous quality controlled simple classification of the cloud systems over the region. The data will be made available in the AMMA-SAT server. It will consist in netCDF files of each class's contribution in terms of cold cloudiness on a regular 2.5x2.5° grid for each month. The preliminary, rapid analysis of this new climatology reveals that:

- the C4, long lasting fast moving, dominates the Sahel region in terms of contribution to the cold cloudiness despite being, in numbers, less than all the other classes
- a weak relative interannual variability of the total cloudiness is observed over the Sahel (10%) which is well related to the variability of the C2 and the C2 MCS.
- 2006 is characterized by an overall negative to near normal anomaly in terms of MCS population.

More work is needed to link the MCS climatology to the rainfall climatology in some details.

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