TRACKING MESOSCALE CONVECTIVE SYSTEMS
IN THE SAHEL:
RELATION BETWEEN CLOUD
CHARACTERISTICS AND RAINFALL EFFICIENCY

Promoter:
Professor Nicole van Lipzig
Department of Earth and Environmental Sciences
Physical and Regional Geography

Master thesis
for the degree of
Master of Earth Observation
(Sciences)
Clémence Goyens

July – 2009
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Abstract

Mesoscale Convective Systems (MCS) can be broadly defined as an ensemble of strong convective cells which evolve into a single mesoscale cloud. These systems can reach spatial dimensions larger than 125 000 km² and a live duration of several days while producing heavy precipitation. In the semi-arid African Sahel region, MCS represent an important source of rainfall (70-90 % of the total annual rainfall). Understanding the behaviour of these systems is thus very important in this vulnerable region. Therefore, the present study aims to relate the convective initiation, development and structure of a MCS with their efficiency as a precipitation source. The study area is centred over the Lake Chad region, extending from 0 to 30°E and 5 to 20°N. Infrared (10.8µm) images from the geostationary satellite Meteosat-8 are used to track the MCS that occurred in the rainy season of 2006, June 1st till September 22nd. The radiance of the cloud tops in the infrared channel are converted into brightness temperatures in a way that convective clouds, which are characterized with very cold cloud tops, can be identified and delineated. For each cloud, several properties such as cloud area, cloud top temperature, life duration, mean propagation speed and coordinates of the cloud centre, are calculated and related to the cloud’s precipitation efficiency. The latter was estimated using images of NASA’s Tropical Rainfall Measuring Mission (TRMM) covering the same area and time period. In this way, we can get an in-depth understanding of the development and behaviour of MCS.
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<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AEJ</td>
<td>African Easterly Jet</td>
</tr>
<tr>
<td>BT</td>
<td>Brightness temperature</td>
</tr>
<tr>
<td>BT10.8</td>
<td>Brightness temperature in the Infrared channel centred on 10.8 µm</td>
</tr>
<tr>
<td>GMS</td>
<td>Geostationary Meteorological Satellite</td>
</tr>
<tr>
<td>GEOS</td>
<td>Geostationary Operational Environmental Satellite</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>IR10.8</td>
<td>Infrared channel centred on 10.8 µm</td>
</tr>
<tr>
<td>ISSCP</td>
<td>International Satellite Cloud Climatology Project</td>
</tr>
<tr>
<td>ITCZ</td>
<td>Intertropical Convergence Zone</td>
</tr>
<tr>
<td>MCC</td>
<td>Mesoscale Convective Complex</td>
</tr>
<tr>
<td>MCS</td>
<td>Mesoscale Convective System</td>
</tr>
<tr>
<td>MSG</td>
<td>Meteosat Second Generation</td>
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<tr>
<td>MW</td>
<td>Microwave</td>
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<tr>
<td>OCS</td>
<td>Organized Cloud Systems</td>
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<tr>
<td>PR</td>
<td>Precipitation Radar</td>
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<td>R</td>
<td>Rank Correlation Coefficient</td>
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<td>Rad</td>
<td>Physical Radiance</td>
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<tr>
<td>SEVIRI</td>
<td>Spinning Enhanced Visible and Infrared Images</td>
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<td>TEJ</td>
<td>Tropical Easterly Jet</td>
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<tr>
<td>TMI</td>
<td>TRMM Microwave Imager</td>
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<tr>
<td>TRMM</td>
<td>Tropical Rainfall Measurement Mission</td>
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<tr>
<td>VIRS</td>
<td>Visible Infrared Scanner</td>
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<td>VIS</td>
<td>Visible</td>
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<tr>
<td>WV</td>
<td>Water Vapour</td>
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1. Introduction

Non-experts in meteorology or climatology may never have heard about Mesoscale Convective Systems (MCS) or have only a very vague idea about what they are. Far more common than tropical cyclones but with lower intensity and destructive force, Mesoscale Convective Systems represent the largest of the convective storms in spatial dimensions and lifetime as well as a significant source of rainfall. MCS have been broadly defined as an ensemble of multiple intense convective cells accompanied by a stratiform region that quickly evolve into organized clusters forming a single mesoscale cloud. They are mostly concentrated in the tropics and mid-latitudes where they account for a large proportion of rainfall (Desbois et al., 1988; Carvalho and Jones, 2001; Houze, 2004; Wallace and Hobbs, 2006).

MCS are essential for the earth equilibrium as they modify the environment on a scale many times larger than the visible cloud (Moncrieff, 1995). They regulate the transport of energy, heat, moisture and momentum in the atmosphere (Laing and Fritsch, 1993; Schröder et al., 2009) and play an important role in the input of energy to the climate system through the radiative effect of the upper-tropospheric cloud and water vapour and enhanced surface fluxes (Moncrieff, 1995). Accordingly, features governing MCS may be considered as triggers of local and global climate changes. For instance, as the build up of Convective Available Potential Energy (CAPE) is closely related to the land surface (e.g. albedo) and surface fluxes (Mathon et al., 2002; Lauwaert et al., 2009), orography, land cover and land use changes are examples of factors that potentially modify the location of MCS and subsequent rainfall amount and pattern. Investigating the origin of changes in MCS and the impact of it on the climate requires a thorough understanding of the relations between the initiation, structure and development of such systems with their respective rain efficiency.

The Sahelian region is commonly defined as the region lying between 11-20°N in Africa and separating the hyper-arid Sahara desert from the rain forest band along the Gulf of Guinea and the Congo River Basin (Fig. 1.1.). MCS account for approximately 70 to 90% of the total annual rainfall in this vulnerable region explaining the interest of science in these systems (Laing et al., 1999; Mohr et al., 1999; Mathon et al., 2002). The annual rainfall varies from 200 mm to 600 mm and is concentrated during the rain season extending from June to September with strong year-to-
year variations (Kandji et al., 2006). Since the early 70’s, dry years have persist with a significant
decrease in rainfall for July and August (Le Barbé and Lebel, 1997; Kandji et al., 2006; Conway et al.,
2009). The meteorological station, Mao Meteo Chad (14.10° N, 15.32° E), recorded from 1960
to 1971, average monthly precipitation ranging from 25 to 155 mm over the rain season, while,
from 1971 to 2000, the average monthly precipitation for the same period didn’t exceed 100 mm
(Climate Explorer Web Site, n.d.). Improvements in understanding and forecasting MCS in
vulnerable regions such as the Sahel are hence crucial and will help to predict gains or losses in
rainfall and runoff (Laing and Fritsch, 1993; Laurent et al., 1998 b; Laing et al., 1999).

Throughout the years, numerous studies already aimed to analyze MCS in the Sahel (among others,
Desbois et al., 1988; Arnaud et al., 1992; Hodges and Thornicroft, 1997; Mohr et al., 1999; Mathon
and Laurent, 2001; Mathon et al., 2002; Schröder et al., 2009). Most of them identified and
classified convective systems using parameters such as the size, shape, velocity and/or height of the
cloud systems. As MCS often cover extremely large areas (exceeding 125 000 km²), it is not
surprising that space observations, in particular geostationary satellite images, are the primary tool
for MCS analysis (Machado and Laurent, 2004). Moreover, as the entire earth surface is not (yet)
densely and homogeneously covered by ground measurements, the high temporal resolution of
geostationary satellite images and their large field of view are an excellent alternative to study
continuously moving convective atmospheric circulation.

In the present study, MCS were tracked over the Sahelian region centred on the Lake Chad
extending from 0 to 30° East and from 5 to 20° North (Fig.1.1). The period of interest corresponds
to the rain season of 2006 extending from July until September. Since data were missing between
September 23rd and 25th, we have shortened the period of interest from July 1st until September 22nd.
The area is chosen large enough to make sure that a relevant sub sample of MCS is tracked and can
be considered as representative of the population of Sahelian MCS. The main objective is to relate
the structural and radiative cloud parameters of MCS, assessable from satellite images, with their
generated precipitation (total, maximum intense and average precipitation). The resulting
relationships will assist in providing a more detailed understanding of how the rain efficiency of
MCS varies and why. The selected cloud parameters, retrieved from geostationary Meteosat-8
satellite images, are considered as good indicators of the convective initiation, the development and
the structure of MCS. Precipitation is estimated from the 3-hourly Tropical Rainfall Measurement
Mission (TRMM) data over the same region and time period. Coupling the precipitation data with
the structural and physical cloud parameters computed for each MCS allow us to estimate the
rainfall efficiency of each system.
Figure 1.1. Sahel region and study area centred on Lake Chad, extending from 0 to 30°E and from 5 to 20°N (black square on both maps). Adapted from Millennium Ecosystem Assessment (2005).

The next chapter ‘context of research project’ outlines the structure, development and mechanics of MCS and reviews how MCS were identified in previous studies based on satellite images. In the same chapter, we also briefly describe the climatology of MCS in the Sahelian region and some common classification schemes of MCS in West Africa. Objectives and hypothesis are stated in the third chapter. A description the data and methodology used to achieve and verify the previously reported objectives and hypothesis are discussed in the fourth chapter. The results, including the outstanding relationships between the MCS’ structural and radiative parameters and their rain efficiency, are outlined in the fifth chapter and followed by a discussion. The report is finally wrapped up by a conclusion.
2. Context of the research project

2.1. *Mesoscale Convective Systems: Initiation, development and structure*

In a single MCS, two regions can be differentiated, the stratiform and convective region. The convective region corresponds to the leading edge of the system and is associated with maximum air updraft, while the stratiform region corresponds to an extensive trailing anvil cloud associated with air downdraft. Convection originates when warm and moist air is forced upwards by, among others, advection of cold air mass or due to the local orography. When the warm and moist air is forced upwards in a non-hydrostatic buoyant atmosphere (buoyancy exceeds the vertical gradient force) it will potentially attain a height at which it is warmer and subsequently less dense than the surrounding air. This height is referred as the local level of free convection (Fig. 2.1). The parcel of air will then continue its updraft but will cool while mixing with the relatively cold air from the surrounding. The vertical updraft velocity will therefore decrease with the altitude. This is illustrated by the temperature profiles of a typical convective region of a MCS shown in Figure 2.1.

The ascending air flow will cease when it reaches the so-called level of neutral buoyancy where the airflow is no longer warmer and moister than its environment. At this point, the remaining airflow will spread out horizontally forming a wide cloud area, the so-called anvil trailing stratiform region. In fact, the upward momentum carried by the updraft motion, may push the air flow slightly higher than the neutral buoyancy level. This will result in a slight introduction of the air flow in the stable stratosphere above the cloud anvil. Researchers call it the overshooting of the cloud top (Kurino, 1997; Houze, 2004).
Figure 2.1. Conceptual model of the convective region of a MCS (a), with associated temperature perturbation profiles at low level (AA') (b) and at middle level (BB'). From Roux et al. 1984.

The previous paragraph outlines the general air flow in MCS omitting important details. First, when the air is forced upwards, it experiences adiabatic cooling and at some point it will become supersaturated with respect to water. At this point water vapour may condense into cloud droplets or ice particles and eventually result in precipitation. During its updraft, rising air parcels may also entrain a certain amount of environment air via in-cloud turbulence which may potentially evaporate and sublime the raindrops again and which will decrease the Convective Available Potential Energy of the air flow (Houze, 2004). To counteract this decrease in potential energy, additional moist air, containing high potential energy, has to be added to the system. The flux of warm moist air into the system is governed by the updraft speed which is proportional to parcel buoyancy. In its turn, the latter is a function of the temperature difference between the parcel and its environment. When water vapour is converted into liquid droplets or ice particles it releases latent heat to the parcel and hence increases the temperature difference. The increase in buoyancy will thus finally enhance the updraft and increase the water vapour influx and positive feedback will occur as the increasing quantity of water vapour condenses and releases latent heat. It is thus not surprising that researchers related vertical updraft velocity profiles with heating profiles (among others Nuret and Chong, 1998; Houze, 2004; Wallace and Hobbs, 2006). Both are indeed similar. Hence, heating inside the convective region and vertical updraft are maximal during the mature stage and minimal at dissipation stage (Nuret and Chong, 1998).
In a MCS, the divergence of the updraft flow, the so-called front-to-rear flow, becomes more intense with the altitude (Fig. 2.1). This, as observed by Chong et al. (1987), is only significant at higher altitudes (above 3.5-4 km). It transports air into the trailing anvil which carries suspended particles that eventually may grow large enough to fall down as precipitation. Precipitation reduces the buoyancy by its drag force which counterbalances the upward velocity of the updraft and forces the air to descend (Chong et al., 1987; Houze, 2004). The descending air will carry low and mid-tropospheric air in its downward motion while cooling due to evaporation. Convection literally sucks up the surrounding air and therefore stimulates strong convergence in the boundary layer. The descending air will therefore be attracted towards the leading edge and participates to feed the so-called rear-to-front flow (Fig. 2.2). The rear-to-front flow will descend until the bottom of the leading convective line and spread out at the surface, increasing the low-level convergence. The cold air brought by the rear-to-front flow will enhance the updraft as it lifts up the warm boundary layer air in the front of the system when flowing underneath it (Roux et al., 1984; Chong et al., 1987; Houze, 2004). In Figure 2.2, a new cell is reproduced at the leading edge and the black arrows indicate the air flow. Additionally, cloud base, regions of heavy stratiform and convective precipitation are shown.

Figure 2.2. Conceptual model of a convective line with a trailing stratiform precipitation viewed in a vertical cross section perpendicular to the cloud propagation. From Houze et al. 1989 in Houze, 2004

The speed at which the rear-to-front flow enters the MCS depends on the thermodynamic processes, notably the cooling by sublimation, melting and evaporation of precipitation particles falling from the trailing-stratiform region. The higher the speed at which the rear-to-front flow converges towards the leading edge, the higher the strength of the leading updraft and the more intense the precipitation. Hence, the mesoscale updraft and associated front-to-rear flow maintains the anvil cloud by previously active convective cells transferred backwards. Meanwhile, mesoscale
downdraft and associated rear-to-front flow driven by evaporation or melting of precipitation, maintains the convection by strong convergence at the boundary layer (Chong et al., 1987; Houze, 2004). According to this and since the stratiform region mainly determines the size and shape of a MCS (Houze, 2004), structural parameters of MCS are dependent on the convective activity, or in other words, on the rate of formation of convective cells.

MCS move faster than the environmental air at all levels (Chong et al., 1987). The fast propagation speed of these systems is often explained by the cold pool dynamics (Houze, 2004). The cold pool refers to the cold layer of air underneath the stratiform cloud base and the cold pool dynamics can be broadly defined as the cold air in the trailing stratiform region spreading out at the surface by divergence. This lifts up the new convective cells at the leading edge. Accordingly, the cloud tends to move towards the new potential convective cells, which correspond to the low-level high potential temperatures (Laing and Fritsch, 1993). Therefore, as the propagation speed is related to the rear-to-front flow, it is not surprising that MCS are likely to propagate faster during their mature stage when convection is more pronounced (Mathon and Laurent, 2001). Looking back to Figure 2.1, we also observe that the intensity at which the rear-to-front flow reaches the leading edge is influenced by the zonal speed at middle height (see the easterly flow in Figure 2.1), such as for instance the African Easterly Jet in the Sahel. Hence, the propagation speed is also proportional to the zonal wind speed (Moncrieff and Miller, 1976 in Desbois et al., 1988).

It is not uncommon to see new cloud clusters forming also further ahead of the leading edge (Desbois et al., 1988; Houze, 2004). Meteorologist and climatologist assume that those new cloud clusters are induced by gravity waves (Moncrieff, 1995; Houze, 2004). The latter are generated by the combination of two opposing forces; on one hand, the convective updraft which forces the stable air to rise and, on the other hand, the stable atmosphere which forces the parcel of air to sink again. Because of the momentum of the rising and sinking parcels, the gravity waves propagate further away from the MCS. The new cloud clusters created by gravity waves influence the propagation speed and direction of propagation (Desbois et al., 1988). Given suitable conditions, gravity waves generated by MCS may propagate horizontally on a scale much larger than the MCS (Moncrieff, 1995; Houze, 2004).

Numerous studies showed how MCS are associated with a redistribution of water vapour and heat through the atmosphere (among others, Chong et al. 1984, Moncrieff, 1995; Hodges and Thorncroft, 1997). Therefore, researchers often make reference to the convective adjustment of the atmospheric instability by MCS. This is observed by the separations between the potentially warm
boundary layers and potentially cold mid-troposphere layers which are, after the passage of a MCS, no longer as pronounced. Also vertical profiles of water mixing ratio after a MCS indicate a better redistribution of the moisture with the height.

2.2. Analysis of MCS by satellite images

According to Klitch et al. (1985), “the best way to document convection, in general, might be to observe it explicitly via some remote sensing device such as radar or satellite” (pg. 326). Throughout the years, numerous studies already aimed to analyze MCS using infrared (IR) and/or visible (VIS) radiance images from geostationary weather satellites (among others Desbois et al., 1988; Arnaud et al., 1992; Hodges and Thorncroft, 1997; Laurent et al., 1998 a; Laing et al., 1999; Mohr et al., 1999; Carvalho and Jones, 2001; Mathon and Laurent, 2001; Mathon et al., 2002; Schröder et al., 2009). Those studies had as objectives to identify and classify convection systems from space observations using parameters such as the size, shape, velocity, temperature and/or height of the cloud systems. In the VIS channel MCS appears as oval, round or elongated shape (depending on the strength of the upper-level wind) which is relatively bright (reflective) compared to the non-cloudy pixels (Figure 2.3 (a)). However, the VIS channel is disadvantaged as it can only be used during daylight hours. Hence for tracking methods IR channels are more appropriate since they are a source of information at day and night time. Images in the VIS channels may also be affected by sun glint, in particular in warm areas such as the tropics, and clouds in the VIS band may be obscured by it (Kidder and Vonder Haar, 1995). Furthermore, in the IR channels, variations in radiance are mainly influenced by clouds and earth surface and little by atmospheric effects. In this part of the spectrum cloud droplets are Mie scattered. This means that the cloud droplets absorb almost all the incident IR radiation explaining the dark cloudy pixels in the IR images (Figure 2.3 (b)). Clouds thus act as blackbodies in the IR which favours the tracking in this part of the spectrum. It is thus not surprising that most authors used the IR channels in order to separate cloudy pixels from non-cloudy pixels. In meteorological applications, the most common IR channel corresponds to the 10-12.5 µm channel (Kidder and Vonder Haar, 1995).

Using the inverse of the Planck function, radiance measured by the thermal IR channels can be converted into equivalent brightness temperatures. This can be defined as the temperature of a black body which emits the same amount of radiation as the emitting body in the scene, in our case, the cloud top (Desbois et al. 1988; Kidder and Vonder Haar, 1995). Because the temperature decreases with the height in the troposphere, it is possible to derive the atmospheric processes, such as the cloud height, occurring in the scene (Kidder and Vonder Haar, 1995). According to Machado et al.
(1992) in a standard tropical atmosphere, a temperature of 253 K corresponds to 7.9 km, 230 K to 11.3 km, 218 K to 13 km and 207 K to 14.7 km height. Accordingly deep convection, which is characterized by a high vertical updraft, can be identified by low brightness temperatures and the strong contrast between the cold cloud tops and the warmer background can be used to delineate the spatial extent of the MCS (Kidder and Vonder Haar, 1995). Subsequently, differences in brightness temperatures inside the MCS reveal the structure of the system. The large trailing anvil cloud for instance, presents warmer temperatures than the very cold leading edge and the overshooting cloud top.

Other channels, often used for meteorological purposes too, are the water vapour channels which correspond to the water vapour absorption band (WV) centred around 6.2 µm (Kidder and Vonder Haar, 1995). In this channel, the water vapour absorbs nearly all the incident IR radiation from the Earth surface. Therefore, when high thick clouds occur, the only thermal energy reaching the sensor is originating from and above the cloud tops. Because of the high water vapour content in the lower layers of the troposphere, the radiation emitted by the earth surface is almost completely absorbed in the WV channel and hence does not contribute to the radiance measured by the satellite (Desbois et al., 1988). Previous studies have shown that the amount of energy originating from layers below 800 to 600 hPa is negligible in the WV channel (Georgiev, 2003; Krennert and Zwartz-Meise, 2003). In other words, this channel gives an indication of the relative humidity of the mid-troposphere as most of the radiation sensed by the satellite in this spectral band comes from the atmospheric layer between 600-300 hPa (Georgiev, 2003). Accordingly, high cloud tops appear as dark spots on the WV images (Figure 2.3 (c)). In deep convective systems, warm and moist air flows are forced upwards; this will thus correspond to lower brightness temperatures in the WV channel as the water vapour content is originating from the higher layers. Regions of low humidity will in contrast show higher brightness temperatures since the radiation originates from lower levels of the troposphere (Georgiev, 2003; Krennert and Zwartz-Meise, 2003). Accordingly, an increase (decrease) of brightness temperature in the WV channel reports a drying (moistening) of the mid-upper troposphere (Georgiev, 2003; Krennert and Zwartz-Meise, 2003).

Some authors also used the difference between the IR channel and the WV channel to identify deep convective clouds with precipitation (Kurino, 1997; Schmetz et al., 1997; Schröder et al., 2009). The authors showed that when overshoot occurred over deep convection, the brightness temperature in the WV channel can be larger than in the IR channel. The difference between the brightness temperatures in the two channels is explained by the non-linear behaviour of the Planck function. At the tropopause, higher brightness temperatures will be observed in the WV channel due to the
stratospheric water vapour above cloud top which re-emits absorbed radiation at warmer stratospheric temperatures (Schmetz et al., 1997; Feidas and Cartalis, 2005). Therefore, when the updraft momentum forces the layer at the tropopause, a rapid increase of the difference between the two channels is observed. When the air travels slightly higher than the tropopause, the difference decreases again because the water vapour at the cloud top decreases when the cloud rises (Schmetz et al., 1997).

![Images](a) (b) (c)

Figure 2.3. MCS identification by means of the Meteosat-8 VIS channel centred on 0.6 µm (a), IR channel centred on 10.8 µm (b) and WV channel centred on 6.2 µm (c). Images show the digital pixels values.

2.3. Thresholding, tracking methods and classification of MCS

From the literature, thresholding appears to be the most common way to define MCS on satellite images (among others, Klitch et al., 1985, Desbois et al., 1988; Machado et al., 1992; Arnaud et al., 1992; Laurent et al., 2002; Machado and Laurent, 2004; Schröder et al., 2009). According to Kidder and Vonder Haar (1995), this method is the oldest, simplest and still most frequently used method to extract clouds from images. However, setting the threshold is not an easy task. The threshold is indeed dependent on many factors such as the state of the atmosphere, the season of the year and the purpose of the study. Therefore, two different temperature thresholds are often used when MCS are delineated. A warmer threshold ensures that MCS are tracked over their entire life cycle (including the formative and dissipation state) and that some warmer parts of the anvil clouds are not excluded, while a colder threshold is used to delineate the most convective part of the MCS or the most convective cluster embedded in a MCS. Using both relatively warmer and colder temperature thresholds also ensures that relatively cold clouds, that don’t show any strong convective activity (such as cold cirrus clouds), are excluded. After thresholding, structural and radiative cloud parameters such as the average brightness temperature, the area and the eccentricity for each MCS can be estimated. These properties provide valuable information about the dynamics and the evolution of MCS (Carvalho and Jones, 2001).
Besides defining a temperature threshold, several scientists also imposed an area cut-off (Laurent et al., 1998 a; Carvalho and Jones, 2001; Mathon and Laurent, 2001; Laurent et al., 2002; Mathon et al., 2002; Machado and Laurent, 2004; Tomasini et al., 2006). Any system presenting an area below the area cut-off are not identified or tracked. Accordingly, it is a function of the used temperature threshold. Machado et al. (1992) tracked MCS with a cut-off area of 100 000 km² and 17 000 km². The authors observed that this was equivalent to a 20 K decrease in threshold. They also noted that with an area criterion of 5000 km² and a temperature threshold of 233 K only 7% of the MCS were lost due to the filtering of small clouds and that the initiation and dissipation time was close to what would be achieved by a visual tracking.

Numerous scientists also developed automatic tracking methods to study MCS (among others Arnaud et al., 1992; Machado et al., 1998; Mathon and Laurent, 2001; Wilcox, 2003; Feidas and Cartalis, 2005). As mentioned by Wilcox (2003), the Langrangian approach of the tracking algorithm presents the advantage (compared to cloud studies made over stationary grids or other Eulerian schemes) to register all the cloud parameters during its entire life cycle and hence taking into account the dynamical aspects of the clouds. Desbois et al. (1988), who used both an Eulerian and Langrangian approach to study MCS over the Sahel, also maintained that a Langrangian tracking method was necessary to study the diurnal cycle of MCS. Unfortunately, Langrangian methods also present a ‘no negligible difficulty’, notably the definition of ‘similarity criteria’, also called ‘match criteria’, which are the key for recognizing a single cloud through the successive images. Usually tracking methods outlined in the literature differ from each other only by their ‘similarity criteria’.

Table 2.1 gives an overview of the datasets, temperature thresholds, area cut-off and minimum life duration criteria used for the tracking and definition of MCS in several previous studies. In the early 80’s, Klitch et al. (1985) used Geostationary Operational Environmental Satellites (GOES) IR imagery to identify cold cloud tops with a brightness temperature threshold equal to 243 K. Desbois et al. (1988) used the International Satellite Cloud Climatology Project (ISCCP) dataset from the Meteosat IR (10.5-12.5 µm) and WV (5.7-7.1 µm) channels and a threshold of 233 K to analyze the MCS in the Sahelian region. The ISCCP has as objective to reduce, calibrate and uniformly format the original geostationary meteorological satellite images for climate studies (Machado et al., 1998). Original satellite images are therefore sampled at intervals of 3 hours and 30 km. Desbois et al. (1988) observed that the IR channel of Meteosat showed a good approximation of the motions of the large cloud clusters in the Intertropical Convergence Zone (ITCZ) and the temperate latitude. The authors also noted that the coldest cloud covers coincided with maximum precipitation.
Table 2.1. Overview of the datasets, threshold values, cut-off areas and minimum life durations, used for the tracking and definition of MCS in previous studies

<table>
<thead>
<tr>
<th>Sources</th>
<th>Materials</th>
<th>Channels</th>
<th>Thresholds, cut-off area and minimum life cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Klitch et al. 1985</td>
<td>GOES-5 (4 km and 1 km)</td>
<td>IR and VIS</td>
<td>≤ 233 K and bright appearance in VIS</td>
</tr>
<tr>
<td>Desbois et al., 1988</td>
<td>METEOSAT ISCCP (30 km, 3 h)</td>
<td>IR(10.5-12.5 µm) and WV(5.7-7.1 µm)</td>
<td>≤ 233 K</td>
</tr>
<tr>
<td>Machado et al., 1992</td>
<td>METEOSAT ISCCP (30 km, 3 h)</td>
<td>IR(10.5-12.5 µm) and VIS (0.4-1.1 µm)</td>
<td>≤ 253 K and ≤ 213 K</td>
</tr>
<tr>
<td>Arnaud et al., 1992</td>
<td>METEOSAT (5 km, 30 min)</td>
<td>IR(10.5-12.5 µm)</td>
<td>≤ 233 K</td>
</tr>
<tr>
<td>Hodges and Thorncroft, 1997</td>
<td>METEOSAT ISCCP (150 km, 3 h)</td>
<td>IR(10.5-12.5 µm)</td>
<td>≤ 258 K and life duration &gt; half a day</td>
</tr>
<tr>
<td>Laurent et al., 1998 a</td>
<td>METEOSAT (5 km, 30 min)</td>
<td>IR(10.5-12.5 µm)</td>
<td>≤ 233 K and 213 K, cut-off area = 5000 km²</td>
</tr>
<tr>
<td>Nuret and Chong, 1998</td>
<td>GMS-4 (5 km, 1 h)</td>
<td>IR(10.5-12.5 µm)</td>
<td>≤ 273 K, ≤ 235 K and ≤ 208 K</td>
</tr>
<tr>
<td>Machado et al., 1998</td>
<td>GOES-7 ISCCP (30 km, 3 h)</td>
<td>IR (~ 11 µm)</td>
<td>≤ 245 K and ≤ 218 K</td>
</tr>
<tr>
<td>Carvalho and Jones, 2001</td>
<td>GOES-8 (4 km, 1 h)</td>
<td>IR (~ 11 µm)</td>
<td>≤ 235 K, minimum radius =100 km</td>
</tr>
<tr>
<td>Mathon and Laurent, 2001</td>
<td>METEOSAT (5 km, 30 min)</td>
<td>IR(10.5-12.5 µm)</td>
<td>≤ 253 K, ≤ 233 K, ≤ 213 K and cut-off area = 5000 km²</td>
</tr>
<tr>
<td>Laurent et al., 2002</td>
<td>GOES-8 (4 km and 30 min)</td>
<td>IR(~11 µm)</td>
<td>≤ 235 K, ≤ 210 K and cut-off area = 3500 km²</td>
</tr>
<tr>
<td>Mathon et al., 2002</td>
<td>METEOSAT (5 km, 30 min)</td>
<td>IR(10.5-12.5 µm)</td>
<td>≤ 233 K, ≤ 213 K, cut-off area = 5000 km², life cycle &gt; 3 h</td>
</tr>
<tr>
<td>Wilcox, 2003</td>
<td>METEOSAT (5 km, 30 min)</td>
<td>IR(10.5-12.5 µm) and WV (5.7-7.1 µm)</td>
<td>≤ 240 K</td>
</tr>
<tr>
<td>Machado and Laurent, 2004</td>
<td>GOES-8 (4 km and 30 min)</td>
<td>IR (~11 µm)</td>
<td>≤ 235 K, 210 K and cut-off area = 3500 km²</td>
</tr>
<tr>
<td>Feidas and Cartalis, 2005</td>
<td>METEOSAT (5-6.5 km, 30 min)</td>
<td>IR(10.5-12.5 µm) and WV (5.7-7.1 µm)</td>
<td>≤ 233 K</td>
</tr>
<tr>
<td>Tomasini et al., 2006</td>
<td>METEOSAT (5 km, 30 min)</td>
<td>IR (10.8 µm)</td>
<td>≤ 233 K and cut-off area= 5000 km²</td>
</tr>
<tr>
<td>Schröder et al., 2009</td>
<td>METEOSAT (5 km, 30 min)</td>
<td>IR(10.8 µm) and WV (6.2 µm)</td>
<td>≤ 230K</td>
</tr>
</tbody>
</table>

Several authors used a second threshold to distinguish the wide anvil cloud area from the very deep convective region (Table 2.1) (Laurent et al., 1988 a; Mathon and Laurent, 2001; Laurent et al. 2002; Mathon et al., 2002). This second threshold varied usually between 210 and 213 K (Table 2.1). Laurent et al. (1998 a), who identified Sahelian MCS from Meteosat IR, mentioned that 233 K is a reliable threshold to identify convective rain-efficient clouds, while a threshold of 213 K shows the best correlation with rainfall during the core of the rainy season. Nuret and Chong (1998) used even 3 different thresholds to detect MCS; very deep convective towers were identified with a
temperature threshold of 208 K, high clouds associated with deep convection were defined with a threshold of 235 K and all pixels with a temperature threshold below 273 K and above 235 K were associated with middle height convection. Mathon and Laurent (2001) and Mathon et al. (2002) also used three thresholds (253, 233 and 213 K) but Mathon et al. (2002) included a duration and propagation criterion too; potentially rain-efficient MCS were considered to last for at least 3 hours and the most rain-productive MCS had to show a mean speed of at least 10 m s\(^{-1}\). Figure 2.4 illustrated how different IR temperature thresholds can be used for the identification of a MCS and the delineation of the most convective core within the system.

![Figure 2.4. IR satellite image and thresholding of a MCS over Missouri. From Houze, 2004](image)

Tomasini et al. (2006), who concentrated their study over West Africa, presented a way to detect and track cells using an adaptive temperature threshold from 263 K to 208 K. The threshold varied as a function of the temperature of the coldest pixel. Adding 3 K to the temperature of the coldest pixel allowed, according to the authors, to include not only the core of the convective cell, but also the cumulus tower. Furthermore, as the temperature thresholds vary during the development of the system, the threshold applied at early stages should be relatively warmer and enhance the detection of the initiation stage. However, the authors concluded that for MCS detection in West Africa, which are all of convective origin, a single threshold (233 K) and area criteria (5000 km\(^2\)) were sufficient to detect most of the MCS in the region.

Hodges and Thorncroft (1997), who described for the first time the 8-year climatology of the African summer convective systems, used a warmer temperature threshold than normal, notably
258 K. This warmer threshold was chosen since the authors only focused on very large MCS and therefore smoothed the ISCCP reduced resolution IR images onto a rectangular grid of approximately 150 km spatial resolution. Subsequently, the coldest gridded cloud-top temperature appeared warmer than the actual pixel value. Their results were consistent with results obtained 10 years before by Desbois et al. (1988).

Like Hodges and Thorncroft (1997), Machado et al. (1992) also used a warmer threshold than average. They showed a near linear independence between the size of the MCS and the chosen threshold varying from 253 ± 10-20 K. According to the authors the cloud parameters of MCS retrieved from the IR images, are insensitive to the precise value of the threshold used. However, Schröder et al. (2009), who used a temperature threshold of 230 K, noticed that, although a change of ±10 K in the temperature threshold only induced minor changes in the results, the 230 K threshold excluded from tracking some thinner parts of the trailing anvil cloud as well as very early stages of the MCS.

As with Klitch et al. (1985) and Desbois et al. (1988), Wilcox (2003) and Feidas and Cartalis (2005), used a combination of different channels for the detection of MCS. Both used the Meteosat-5 IR (10.5-12.5 μm) channel as well as the WV (5.7-7.1 μm) channel. However, Feidas and Cartalis (2005) mentioned that the WV (5.7-7.1 μm) band, used in the initial tracking as additional criterion for the detection of small MCS in Greece, didn’t improve the capacity of the method to detect convective cloud cells. Though, the WV (5.7-7.1 μm) channel gave additional information about the cloud top structure and in particular about the overshoot. This was also mentioned by Schröder et al. (2009).

Arnaud et al. (1992) tracked MCS over the Sahelian region during the rain season of 1989 based on the overlap between the MCS identified on an image at time ‘t’ and the MCS identified on the successive image at time ‘t+1’. The authors noted that imposing an overlap criterion of 50 % with a temporal resolution of 30 minutes generated some tracking errors, in particular when new cells were developing ahead the leading edge. In a more recent study, Carvalho and Jones (2001) determined from many tests performed with a temperature threshold of 235 K and minimum radius of 100 km, that a minimum overlap criterion of 30 % was satisfying for satellite images with 1 hour time interval. Similarly, Mathon and Laurent (2001) assigned a cloud to a detected cloud in the successive image any time when their position overlapped and when several systems overlapped the authors considered the pair with the largest overlap surface.
Overlap methods appear to be the most common methods for tracking. This was shown by Machado et al. (1998) who reviewed different tracking methods used in the past and evaluated these by comparing the results with a visual inspection of the MCS. Tracking was done with a slightly warmer temperature threshold than the average, notably 245 K, which according to Machado et al. (1998) corresponds to a cloud top altitude around 6-9 km. The authors also imposed that the contiguous areas presented a radius of at least 100 km and that the MCS showed at least once an embedded convective cluster with average brightness temperatures below 218 K. All methods defined a possible candidate as the evolution of a MCS when it was located inside a search domain of $5^\circ \times 5^\circ \approx 555 \times 555$ km around the MCS centre. Machado et al. (1998) found a total of 28 different match criteria encountered in the different tracking methods. The most common were maximum area overlap, minimum propagation speed and compatible direction, minimum difference in size and minimum in cloud top temperature differences. Finally, the authors claimed that the results were insensitive to the tracking method used and concluded that the simplest tracking method based on maximum area overlap gave satisfying results and was more objective and easily duplicated compared to the elaborated methods based on morphological and radiative cloud parameters.

The tracking method used in this study was developed by Schröder et al. (2009). In contrast with the conclusion of Machado et al. (1998), Schröder et al. (2009) assumed that using three parameters for the tracking algorithm instead of the overlap criterion only, is more robust and avoids ambiguities occurring with rapidly growing or dissipating deep convective systems. It also resolves problems that arise when merge and split events occur. Merge events makes that a cloud at time ‘$t+\Delta t$’ can overlap several clouds at time ‘$t$’, likewise, split events makes that a single cloud can evolve in several different clouds clusters. Using, in addition to the overlap criterion, the area difference and position difference, allows a unique label to be assigned to split or merge clouds. The tracking method of Schröder et al. (2009) is detailed further in the methodology.

Thresholding, together with cut-off area, life cycle and propagation speed criterion, is also used for the classification of MCS. For instance, Mesoscale Convective Complexes (MCC) as defined by Maddox (1980) are long-lasting, quasi circular (eccentricities equal to or larger than 0.7 at maximum extent) extremely cold topped MCS that persists for more than 6 hours. Maddox’s MCC, when identified with an IR brightness temperature threshold of 233K, should have an area of at least 80 000 km$^2$ and an embedded cloud core of at least 30 000 km$^2$ with an average brightness temperature lower than 213K. This definition has been adapted several times in later studies as the authors considered that Maddox’s MCC don’t correspond to the majority of the rain-efficient
systems (among others Laing and Fritsch, 1993; Laurent et al., 1998a; Mathon et al., 2002). An other example, are the Organized Convective Systems (OCS) defined by Mathon et al. (2002) as MCS lasting for at least 3 hours, having a horizontal propagation speed of at least 10 m s\(^{-1}\), containing clusters of pixels with IR brightness temperatures below 213 K and finally accounting for most of the rain over the Sahel during the core of the rain season. Similarly, Tomasini et al. (2006) defined the ‘fast-moving long-lived’ squall line type systems, which according to the authors, mainly occur in the Sahelian band between 10 and 15°N, as the MCS lasting for at least 9 hours, showing mean speeds exceeding 10 m s\(^{-1}\) and are the largest of all the MCS with an average area of 30 000 km\(^2\).

From the literature, one can easily remark that the different MCS classes are defined and named independently and are thus not necessarily mutually exclusive. Moreover, there is no universal definition of MCS that could be applied for tracking. Classification criteria used in the literature seem to depend on the study area, the period of interest and most of all on the objectives of the research.

### 2.4. Rainfall and MCS

As mentioned earlier, during the convective updraft, water vapour is transported at middle and upper troposphere where the water vapour either condensates, precipitates or remains suspended as cloud vapour. In section 2.1. (MCS: Initiation, Development and Structure), we also explained how the precipitation rate is proportional to the warm and moist mass fluxes that are pushed upwards at the leading edge. Mathon et al. (2002) showed that from 1990 to 1999, 72 % of the total rain in the Sahelian region fell during the core of the rainy season, namely from July to mid September. In an earlier study, Laurent et al. (1998b) already noticed that in the Sahelian region, 95 % of the annual rainfall is being produced by MCS. Of that 95 %, approximately 75 % is produced by very large and fast moving elongated MCS, often called squall lines. Mohr et al. (1999) concluded that MCS over 10 different tropical regions over the world accounted for at least 70 % of the wet season rain. There is therefore little doubt that rainfall and convective activity are closely related and that in the Tropics, MCS are the main source of precipitation (Arnaud et al., 1992; Houze, 2004). But the challenge remains to define the type of relationships that unites those two events.

Chong et al. (1987) analyzed a typical fast moving elongated MCS or squall line, in the Tropical West African region and recorded pressure, wind speed and direction, temperature and precipitation
rate during the passage of the MCS over a meteorological station. The meteorological measurements showed that the squall line was associated with a sudden drop in temperature, an increase in pressure and a rapid change in wind intensity and direction, but also a peak in precipitation rate (reaching almost 60 mm h\(^{-1}\)) (Fig. 2.5). Soon after the passage of the intense convective rainfall, the wind speed and pressure decreased and only light rain was recorded (approximately 2 mm h\(^{-1}\)). This, according to Chong et al. (1987) corresponds to the trailing stratiform rain. The authors estimated that the intense convective rain extended about 40 km from the centre of mass and perpendicular to the direction of motion.

![Figure 2.5. Series of meteorological parameters measured during the passage of a fast-moving elongated MCS (June 22nd, 1981). From Chong et al., 1987.](image)

Previous studies concluded that MCS generated more rain, not only as a function of the shape, life cycle and horizontal and vertical extents of the systems, but also as a function of the mean velocity, the direction of propagation and the origin time and location (among others Arnaud et al., 1992; Laurent et al., 1998a; Schröder et al., 2009). It also appears that the MCS produce more rain during their growth, estimated by maximum area expansion and vertical updraft velocity, than during their dissipation stage (Barrett and Martin, 1981 in Arnaud et al., 1992; Machado and Laurent, 2004; Schröder et al., 2009). This can be justified since it is expected that high-level wind divergence and the rate of condensation-evaporation are both related to the mass flux forced upwards at the leading edge and in-cloud turbulence in the convective region of the MCS (Machado and Laurent, 2004).
Larger mass fluxes entering in the convection region favour higher condensation rate, a strong area expansion at higher altitudes and a significant low-level moisture convergence. Accordingly, the expansion rate can be used as a good proxy to quantify the mass flux or condensation inside the system (Machado and Laurent, 2004). Systems with such strong internal dynamic enhance precipitation amounts while clouds that have a weak expansion rate during their initial stage usually have a short life cycle (Machado and Laurent, 2004).

2.5. Coupling rainfall data and Meteosat images

As we have seen previously, the IR channels are well suited for the detection and tracking of MCS. Accordingly, as MCS present the main source of rainfall in tropical regions (Le Barbé and Lebel, 1997; Laing et al., 1999; Mohr et al., 1999; Mathon et al., 2002), IR brightness temperature thresholds can be used for rainfall estimations in the tropics (Ba and Nicholson, 1998; Laurent et al., 1998 b). Indeed, precipitation and cold cloud tops show when averaging over larger scales and time periods, a good correlation (Laurent et al., 2002).

Laurent et al. (1998 b) selected in their study 3 different satellite based methods in order to estimate surface rainfall in Western Africa. The 3 methods use simple IR algorithms that are commonly used in tropical regions. The first method estimates the rainfall (Rf) as follow:

\[ R_f = \alpha \times P \]

Where \( P \) is the percentage of pixels showing brightness temperatures in the IR 10.8 channels below 233 K, cumulated over the life duration of the system and averaged over the total cloud area. The constant \( \alpha \) is equal to 3 mm h\(^{-1}\). The same equation and constant \( \alpha \), but a temperature threshold of 235 K was used by Nuget and Chong (1999) to estimate the so called precipitation index (Rf). The authors claimed that this method slightly overestimate the rain rate due to non-rainy extensive cold cirrus clouds. Wilcox (2003) also used the same equation with a temperature threshold equal to 240 K. The constant \( \alpha \) was determined by the least square regression between the cloud averaged rain rate from TRMM and the cloud area fraction colder than 240K from Meteosat-5 IR images.

The second method discussed by Laurent et al. (1998 b) estimates the rainfall (Rf) as follow:

\[ \begin{align*}
R_f &= \alpha + \beta D \\
\text{If} & \quad D > 0, R_f = \alpha + \beta D \\\n\text{If} & \quad D = 0, R_f = 0
\end{align*} \]

Where \( D \) is the life duration of the system and both calibration coefficients are updated taking into account the observations of rainfall of the previous year. The temperature threshold to discriminate rain cloud pixels from non-rain cloud pixels ranges from 233 to 210K and is estimated through a
regression preformed against observations. The last method estimates rainfall (\(R_f\)) as follow:

\[
\text{If } D > 0, R_f = \alpha * D + \beta * T + c \\
\text{If } D = 0, R_f = 0
\]

Where \(D\) is the life duration of the system identified with a temperature threshold of 233K and \(T\) is computed for each 10-day period as the average between the maximum IR brightness temperature recorded during the first 5-day period and the maximum IR brightness temperature recorded during the second 5-day period. According to the authors the value \(T\) accounts for the relationship between the surface temperature and rainfall. For each 10-day period the regression coefficients \(\alpha\), \(\beta\) and \(c\) are calculated using the available rain-gauge estimations. The last method showed the best results for 10-day cumulated rainfall over one year and for a spatial resolution of 0.5° x 0.5° over the Sahel area. But, in general those methods only showed good results when they are applied on large study areas and the rainfall estimates are averaged over large time periods; otherwise the methods gave poor results.

Similarly to Laurent et al. (1998 b), other studies also retrieved precipitation estimations from IR images. Among others, Fu et al. (1990) showed that the diurnal cycle of the core of the convective system, defined as pixels with IR brightness temperatures below 215 K, was similar to the diurnal cycle of precipitation. Likewise, Machado et al. (1992) claimed that a temperature threshold of 213 K in the IR (10.5-12.5 µm) is often chosen for precipitation evaluation. The authors noted a nearly linear increase in rainfall as the IR brightness temperature decreases below 220 K. Machado and Laurent (2004) found that the maximum area expansion derived from IR images, occurred at the same time as the maximum precipitation over the Amazonian basin.

Although rainfall estimates based on satellite observations doesn’t ensure a very high level of accuracy, in particular when estimated over a short period of time and at fine resolution, they are essential in regions where operational rainfall ground networks are sparse and not homogeneously distributed in time and space (Arnaud et al., 1992; Laurent et al., 1998 b; Laing et al., 1999; Machado et al. 2002). This is the case for the Sahelian region where often only daily readings are available while rain events typically last for a few hours (Mathon et al., 2002).

### 2.6. Behaviour of MCS in the Sahel

As mentioned in the introduction, this research will focus on the vulnerable region Sahel for which the study of MCS is crucial to help forecasting precipitation patterns and gains or losses in rainfall. It is during the annual rain season from July till September that MCS are the most common in the
Sahel. These are favoured by the strong solar insolation and the warm moist air originating from the Gulf of Guinea flowing below the much drier and hotter air coming from the northern Saharan region (Chong et al., 1987; Arnaud et al., 1992; Laing and Fritsch, 1993). During the same period, the ITCZ also shifts north to 20°N (Chong et al., 1987; Houze 2004). This is known to enhance the convection as it induces convergence of the water vapour flux in the lower layers (Desbois et al., 1988).

In West Africa, maximum activity of deep convection is observed between 10 and 15°N (Desbois et al., 1984; Chong et al., 1987; Arnaud et al., 1992; Laing and Fritsch, 1993). In contrast with the Saharan region, tropical African regions near the equator present low level of free convection which, together with the high low-level equivalent potential temperature, enhances the chances for instability and initiate increasing rainfall and storm activity (Hodges and Thorncroft, 1997). As already noticed previously, also the strong vertical wind shear near 700 hPa, generated by the African Easterly Jet (AEJ), activates the development of MCS (Desbois et al., 1998; Mathon et al., 2002). This is why tropical north African MCS follow the trajectory of the AEJ which propagates westward (Hodges and Thorncroft, 1997; Mathon and Laurent, 2001; Wallace and Hobbs, 2006). Several scientists reported that the mean propagation speed of MCS is similar to the magnitude of the AEJ (among others Laing and Fritsch, 1993; Mathon and Laurent, 2001; Mathon et al., 2002). The mean propagation speed in convective active regions such as the Sahel lies between 10 and 19 m s^{-1} with maximums where the AEJ attains the maximum magnitude, which is according to previous studies around Lake Chad, Burkina Faso, Mali and Niger (Chong et al., 1987; Desbois et al., 1988; Hodges and Thorncroft, 1997; Berry and Throncroft, 2005). This is illustrated in Figure 2.6 which represents the mean zonal wind at 700 hPa averaged over the period July 16^{th}-August 15^{th} 2000. Desbois et al. (1988) remarked that the AEJ directly influences the propagation speed of the MCS. In addition, Nuget and Chong (1998), who analyzed large-scale heat and moisture budget of a tropical convective system over the Western Pacific, observed that the maximum easterly winds were located at 200-150 hPa, which corresponds to the strong upper level Tropical Easterly Jet (TEJ) blowing from June to September. Accordingly, the AEJ and the TEJ are both responsible for the south-westward displacement of the MCS.
Desbois et al. (1988) makes the distinction between two main kinds of convective cloud development in the continental African region. The first one is characterized by isolated thunderstorms associated with local thermal contrasts and/or orography forcing the air ascendance. The second one is related to the flat areas of the Sahel and the Sudan. The authors claimed that the latter are the most rain-efficient and long-lived clouds and usually last longer than the diurnal events. MCS over the central Sahel initiate typically around 12.5°N while the lesser intensive clouds associated with local thermal contrast and orography, mainly initiate further south about 10.5N° (Mathon and Laurent, 2001). Several studies also showed that in general, MCS initiate more frequently over elevated regions (Desbois et al., 1988; Hodges and Thorncroft, 1997; Mathon and Laurent, 2001). Mathon et al. (2002) concluded in their study about Sahelian MCS that the areas between 10°W-15°E and 11-12°N and 15-16°N are privileged locations of large convective systems and that these contribute to 93 % of the cloud coverage. Similarly, Mathon and Laurent (2001) showed that MCS extending over areas larger than 30 000 km² accounted for approximately 60-90 % of the total cloud cover of the central Sahel.

In the previous section of this work it was noted that MCS could only develop if warm and moist air is present in the atmosphere. It is thus not surprising that solar heating is considered as the major physical driving force in MCS initiation. Large peaks of buoyancy and warm low-level equivalent
potential temperature may result from high daytime heating (Houze, 2004; Tomassini et al., 2006). Accordingly, most of the MCS initiate in the mid-afternoon when the solar heating is at maximum (Desbois et al., 1988; Machado et al., 1992; Laing and Fritsch, 1993; Schröder et al., 2009). Tomassini et al. (2006) added that in the Sahel, long-lived MCS (life times longer than 24 hours) typically develop 4 hours earlier, around 14:00 local time, than short-lived MCS (life duration shorter than 10 hours). As there is a lapse of time between initiation and mature stage, it is expected that the maximum convective activity occurs in the late afternoon and early evening, whilst the minimum occurs at noon (Mathon and Laurent, 2001; Schröder et al. in press) and during the morning (Desbois et al., 1988; Hodges and Thorncroft, 1996). Accordingly, and since maximum activity is related to high level divergence, maximum cloud cover occurs mainly at night time, soon after the maximum convective activity. This is supported by the results obtained by Mathon and Laurent (2001), who concluded that the mean MCS size is the largest at the end of the mature stage and the start of the dissipation stage and thus, according to the typical diurnal cycle of MCS, at night time. Similar to the conclusion of Mathon and Laurent (2001), Laing and Fritsch (1993) showed that very large MCS (similar to the MCC as defined by Maddox, 1980) reached their maximum extent around 01:00 local time and dissipated completely between 06:00 and 11:00. Like orography, coastal areas and large lakes also affects the initiation and development of MCS. Schröder et al. (2009) observed along the west coast of Africa, a local maximum in convective activity at noon and early morning.

Based on the diurnal cycle of MCS, authors usually distinguish different stages in the lifetime of MCS such as the 'initiation or formative stage', 'mature stage' (minimum brightness temperature), 'end of mature stage' (maximal horizontal extent) and finally ‘dissipation stage’ (Schröder et al., 2009). Split events are usually recognized as an indication of weakening of the MCS (Mathon and Laurent, 2001; Schröder et al., 2009). Accordingly, a maximum in split events corresponds to the dissipation stage and occurs in the evening. In contrast, the merging of systems results from a convection strengthening and occurs earlier in the afternoon during the initiation stage or the start of the mature stage (Mathon and Laurent, 2001; Schröder et al., 2009).
3. Objectives and hypotheses

The main objective of this study is to gain greater insight into how the dynamics and structural characteristics of MCS are related to their rain efficiency. Accordingly, we want to answer the question: Which of the structural and radiative cloud parameters determines most of the variations in rain efficiency?

From the literature review outlined in the first chapter of this study, it appears obvious that precipitation should be, at least partially, related to the convective initiation, the development and the structure of MCS. The difficulty lies in finding the right parameters that can serve as proxies for those cloud characteristics. In satellite images, radiative and structural parameters of MCS (e.g. brightness temperatures and cloud area) are relatively easy to retrieve and can be related to the internal cloud dynamic. For instance, the brightness temperature of a cloud top is a good proxy for deep convection as it is associated to the height of the cloud top. Similarly, the decrease in brightness temperature is a good proxy for vertical updraft velocity.

Hypotheses about the relationship between the cloud characteristics and their rain efficiency were formulated based on previous studies as well as on the theoretical description of MCS. Previous studies showed for instance that large, fast moving and long-lived systems were the most rain efficient MCS (among others Laurent *et al.*, 1998 a; Mathon *et al.*, 2002) and that maximum rainfall occurred close to the time of maximum area expansion (Machado and Laurent, 2004). Form both the literature and the theoretical description of MCS, we stated the following hypotheses:

The rain efficiency of MCS is related to:

- the size of the MCS at its maximum extent,
- the propagation speed,
- the life duration of the system and the time duration during which the MCS shows very deep convection,
- the brightness temperature of the system and in particular the brightness temperature of the convective core of the system.

We also expect that:

- a large decrease in brightness temperature in the convective core of the MCS coincides with maximum precipitation,
- maximum expansion rate is observed at or close to maximum precipitation.
Parameters not directly related to structural or radiative properties of the clouds may also be taken into account. As mentioned previously, solar heating is considered as one of the main drivers of convection (showed among others by Arnaud et al., 1992; Tomassini et al., 2006; Schröder et al., 2009). Also, the orography and local spatial features (e.g. lakes) play an important role on the initiation, development and rain efficiency of MCS too (Ba and Nicholson, 1998; Feidas and Cartalis, 2005). Subsequently, some additional hypotheses can be stated;

- the local time at maximum precipitation is related to the rain intensity, and
- a relationship exists between the location of the MCS and the rain intensity.
4. Material and method

4.1. Material

4.1.1. IDL: Programming, data analysis and visualization tool

Programming, data analysis and visualization of our images and results were done in the Interactive Data Language (IDL) environment Student Edition 6.2. This environment presents several advantages for projects related to imaging. Indeed, scripts can be compiled and executed and subsequent results can be displayed immediately in the same environment. This is very useful when working with images. The program also presents an extensive subroutine library. This strongly facilitates programming and reduces the programming time. Moreover, numerous programming tips and tricks are also available on the Internet. Finally, as the tracking algorithm computed by Schröder et al. (2009) and used in this study was written in IDL, it was more pertinent to use the same program.

4.1.2. Meteosat images

Meteosat Second Generation-1 (MSG-1) is the evolution of the first generation of European geostationary meteorological satellites which dates from 1977 (Schmetz et al., 2002). The MSG-1 satellite was launched on the 28th of August 2002 to its equatorial geostationary orbit at 0°N and 3.4°W. It is the eighth of the Meteosat satellites and when the satellite commenced its routine operations in January 2004, it was renamed Meteosat-8. The advanced Spinning Enhanced Visible and Infrared Imager (SEVIRI) radiometer aboard Meteosat-8’s platform scans the Earth in 12 different spectral channels from visible (VIS) to thermal IR (Table 4.1). The 12 spectral channels are known as either 'cold' channels (IR3.9, IR6.2, IR7.3, IR8.7, IR9.7, IR10.8, IR12.0, IR13.4) or 'warm' or 'solar' channels: HRV, VIS0.6, VIS0.8, NIR1.6 (Eumetsat, 2007 a). The satellite provides full-disk imaging of the earth at a spatial resolution of approximately 3.1 km at Sub Satellite Point (3712 x3712 pixels) and 1 km for the High-Resolution Visible (HRV) and at a repeat cycle of 15 minutes. However the spatial resolution of a pixel at the surface decreases with increasing off-nadir viewing angle (Schmetz et al., 2002).

The geostationary satellites, despite their broader spatial resolution compared to the polar satellites, allow the observation of ever-changing atmospheric processes and hence are valuable tools for
applications in climatology and meteorology. Subsequently, with a repeat cycle of 15 minutes, the multi-spectral observations of Meteosat-8 are a very good support to observe rapidly changing phenomena such as deep convection. All Meteosat-8 images are freely available for open research and education.

Table 4.1. The 12 spectral bands from MSG-1 with their respective central, minimum and maximum wavelength and common applications

<table>
<thead>
<tr>
<th>Channel No.</th>
<th>Spectral Band (µm)</th>
<th>Characteristics of Spectral Band (µm)</th>
<th>Main observational application</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>λ&lt;sub&gt;cen&lt;/sub&gt;</td>
<td>λ&lt;sub&gt;min&lt;/sub&gt;</td>
</tr>
<tr>
<td>1</td>
<td>VIS0.6</td>
<td>0.635</td>
<td>0.56</td>
</tr>
<tr>
<td>2</td>
<td>VIS0.8</td>
<td>0.81</td>
<td>0.74</td>
</tr>
<tr>
<td>3</td>
<td>NIR1.6</td>
<td>1.64</td>
<td>1.50</td>
</tr>
<tr>
<td>4</td>
<td>IR3.9</td>
<td>3.90</td>
<td>3.48</td>
</tr>
<tr>
<td>5</td>
<td>WV6.2</td>
<td>6.25</td>
<td>5.35</td>
</tr>
<tr>
<td>6</td>
<td>WV7.3</td>
<td>7.35</td>
<td>6.85</td>
</tr>
<tr>
<td>7</td>
<td>IR8.7</td>
<td>8.70</td>
<td>8.30</td>
</tr>
<tr>
<td>9</td>
<td>IR10.8</td>
<td>10.80</td>
<td>9.80</td>
</tr>
<tr>
<td>10</td>
<td>IR12.0</td>
<td>12.00</td>
<td>11.00</td>
</tr>
<tr>
<td>11</td>
<td>IR13.4</td>
<td>13.40</td>
<td>12.40</td>
</tr>
<tr>
<td>12</td>
<td>HRV</td>
<td>Broadband (about 0.4 – 1.1 µm)</td>
<td></td>
</tr>
</tbody>
</table>

Note: Adapted from Schmetz et al. 2002.

Figure 4.1 shows an example of the weighting functions of the thermal channels of Meteosat-8. It describes, in cloud free conditions, the contribution of each atmospheric layer to the radiance and thus gives information to retrieve vertical profiles of the atmosphere. Therefore, the maximum of the weighting function corresponds to the level where the maximum information comes from (Kidder and Vonder Haar, 1995). However, when a cloud obscures the area, the information retrieved by the satellite in the thermal IR channels originates merely from the cloud top and the layers aloft. Therefore, for convection phenomena, the different thermal channels and respective weighting functions give information about the temperature, associated height of the cloud top,
moistening and drying of the atmosphere and related atmospheric instability (Schmetz et al., 2002).

Tropical Nadir

![Figure 4.1. Weighting functions for the thermal IR channels of SEVIRI on MSG-1 for a tropical standard atmosphere at nadir view. From Schmetz et al. 2002.](image)

In the present study the Level-1.5 data-format was used. Level-1.5 data are the result of pre-processed and rectified raw satellite data which means that all unwanted radiometric and geometric effects have been corrected and the imagery data is ready to use with calibration and geo-location information appended in the metadata (Eumetsat, 2007 a). Eumetsat asserts that the Level-1.5 data is suitable for the derivation of meteorological products and further meteorological processing. As noticed by Schmetz et al. (2002), cloud tracking in successive images necessitates an accurate image-to-image relative accuracy requirement. The authors claimed that for Meteosat-8 this was met with a root mean square value of 1.2 km.

The pixel values of the Level-1.5 data are in engineering quantity ‘count’. These were firstly converted into the physical unit ‘radiance’ using two linear scaling parameters for each spectral band, the slope (C_slope) and the offset (C_offset). Both parameters were included in the metadata of the images. The physical radiance (Rad), expressed in mWm⁻²sr⁻¹ (cm⁻¹)⁻¹ was then calculated as follows:

\[ R = C_{\text{offset}} + (C_{\text{slope}} \times \text{PixelCount}) \]

In order to facilitate the conversion to radiance we used a single pair of scaling parameters for each channel (Table 4.2). But as identified by Eumetsat (2007 a), the slope and offset should be fixed scaling factors that normally don’t change. The error made by using the typical values for slope and
offset for each channel instead of those provided in the metadata of the images should thus be nil or very small.

Next, the physical radiance was converted into equivalent brightness temperature by inversing the Planck function and including two constants $A$ and $B$. The inverse relation used in this work corresponded to the analytical equation given by the Meteorological Products Extraction Facility of Eumetsat (Gieske et al., 2005):

$$ BT = \left[ c_2 v_c / \log (c_1 v_c^3 / R + 1) - \beta \right] / \alpha , \ v_c = \frac{10^4}{\lambda_0} $$

Where $\lambda_0$ is the central wavelength and the parameters $\alpha$ and $\beta$ are specific for each channel (Table 4.2). It is important to note that the equation is based on the effective blackbody radiance, which represents the integral over the spectral band and not the spectral black body radiance, which is estimated at a defined wave number. Eumetsat (2007 b) noticed an average error of ±1 K when this conversion formula is applied to the spectral black body radiance provided by the Level 1.5 images. However, this shouldn’t affect our results since, as shown in the literature, differences of ±10 K in the temperature thresholds doesn’t have a significant impact on the results of the tracking. Therefore we were confident that the formula given above gave satisfying results. Over all, Schmetz et al. (2002) asserted that onboard calibration of Meteosat-8 provides accuracy better than 1 K for the thermal IR channels.

Table 4.2. Coefficients and central wavelengths for the analytical equation used to derive the brightness temperature from the spectral radiance

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\Lambda_0$ (µm)</th>
<th>$V_c$ (cm⁻¹)</th>
<th>$\alpha$ (unitless)</th>
<th>$\beta$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>3.92</td>
<td>2567.33</td>
<td>0.9956</td>
<td>3.410</td>
</tr>
<tr>
<td>5</td>
<td>6.25</td>
<td>1598.103</td>
<td>0.9962</td>
<td>2.218</td>
</tr>
<tr>
<td>6</td>
<td>7.35</td>
<td>1362.081</td>
<td>0.9991</td>
<td>0.478</td>
</tr>
<tr>
<td>7</td>
<td>8.70</td>
<td>1149.069</td>
<td>0.9996</td>
<td>0.179</td>
</tr>
<tr>
<td>8</td>
<td>9.66</td>
<td>1034.343</td>
<td>0.9999</td>
<td>0.060</td>
</tr>
<tr>
<td>9</td>
<td>10.80</td>
<td>930.647</td>
<td>0.9983</td>
<td>0.625</td>
</tr>
<tr>
<td>10</td>
<td>12.00</td>
<td>839.660</td>
<td>0.9988</td>
<td>0.397</td>
</tr>
<tr>
<td>11</td>
<td>13.40</td>
<td>752.387</td>
<td>0.9981</td>
<td>0.578</td>
</tr>
<tr>
<td>C1</td>
<td>(1.19104 \times 10^{-5}) mW (cm⁻¹)⁻⁴m²sr⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>1.43877 Kcm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: From Eumetsat, 2007 b
The Meteosat-8 images corresponding to the study area, represented images of 1075 x 538 pixels. As we aimed to track the clouds during day and night we only used the thermal channels. Although, as noted previously, the spatial resolution of the pixels increases with the distance from the sub satellite point, we assumed that all pixels in the study area corresponded to a 3.1x3.1 km area. This was done in order to facilitate the projection and visualization of the images.

4.1.3. TRMM data

The Tropical Rainfall Measurement Mission (TRMM) satellite was launched in November 1997 in Japan and has been developed as a joint project between Japan and US (NASDA Earth Obs. Centre, 2001). The main concept of the TRMM project was to build a single platform with all the instruments used to retrieve precipitation estimates such that the measurements of the different instruments could be compared and combined. The TRMM was the first space mission dedicated to provide reliable rainfall data over the tropical and subtropical region retrieved from microwave, VIS and IR sensors and space borne rain radar. The satellite has an altitude of approximately 350 km, and an orbit period of 91.5 minutes. In the present study, we used the 3 hourly precipitation gridded estimations derived from the so-called ‘3B-42 – TRMM Merged HQ/Infrared Precipitation’ (referred hereafter as 3B-42) algorithm. ‘HQ’ in the algorithm-name, stands for the optimal active and passive precipitation estimates. The precipitation rate product has a spatial resolution of 0.25° x 0.25° (~27.78 x 27.78 km) in a global belt extending from 50°S to 50°N and from 180°W to 180°E.

The TRMM rainfall data is derived from 3 primary rainfall instruments. (1) The precipitation radar (PR) provides a 3-dimensional rainfall structure and achieves quantitative measurements of the rain rates based on the time delay of the precipitation backscattered return power (Kummerow et al., 1998). These are also known as active microwave estimates. The TRMM precipitation radar has a horizontal resolution of approximately 4 km and a swath width of 215 km. (2) The TRMM Microwave Imager (TMI) instrument provides data containing the information about the absorption-emission and scattering through the precipitating cloud along the sensor view path. Such precipitation retrieval techniques assume that the cloud droplets interact only slightly with the radiation while precipitation-size drops interact strongly (Kummerow et al., 1998). The rainfall rates based on passive microwave (MW) radiance are less reliable over land than over the ocean. The instrument utilizes 9 channels; the five channels have frequencies below 22 GHz for which the MW radiation is mainly affected by the rain absorption (Kidder and Vonder Haar, 1995), the two following channels have frequencies between, 22 and 60 GHZ for which MW radiation is both
affected by absorption and scattering by the rain drops and ice, and finally the remaining channels have frequencies above 60GHz for which ice scattering dominates the absorption (NASDA Earth Obs. Centre, 2001). (3) The third instrument used for the surface rainfall rate estimation is the Visible and Infrared Scanner (VIRS) which measures the scene radiance in five spectral bands. The VIRS mainly provides information on the cloud context, such as the cloud top temperature and structure, which can be used to complement the data from TMI and PR (Kummerow et al., 1998). VIRS data present the advantage of being available for long time periods.

The need for three rainfall instruments for retrieving precipitation is well justified. On the one hand, large underestimations will occur when retrieving precipitation with IR channels for warm rain, and on the other hand, large overestimations will occur for non-precipitating very cold anvil and thick cirrus clouds. Therefore, the measures of the radiance in the VIS and IR together with the MW data (PR and TMI), which sense the precipitation particles, will give more accurate precipitation estimates. Radar measurements, likely to provide the highest accuracy, however, usually have a small swath width compared to the other instruments and thus cover only a small fraction of the total area. Meanwhile, passive and active MW data also need a certain amount of correction and calibration. Radar, for instance, needs to be corrected with an attenuation correction when the amount of rain is large. Minimum detectable signal also affects the accuracy of the radar’s precipitation estimates. Passive MW present the disadvantage that over land the measure of rainfall is not as reliable due to the variation in surface emissivity but is a complement for radar data as it detects rainfall below the minimum detectable signal of the radar.

The 3B-42 estimates are produced in four stages. First, the microwave (passive TMI and active PR) estimates of precipitation are calibrated and combined on a 3-hourly 0.25° grid and averaged over the time range +/- 90 minutes from the nominal time. Secondly, brightness temperature in the IR is converted into precipitation estimates based on the calibrated microwave precipitation. Next, the microwave and IR estimates are combined. The latter is done by assigning every available physically-based microwave estimate to the corresponding grid box and filling the remaining grid boxes with IR estimates.

According to the TRMM data user handbook (NASDA Earth Obs. Centre, 2001) each precipitation field is best interpreted as the precipitation rate effective at the nominal observation time. In the present study, the overlay of the TRMM data and the tracked MCS based on the Meteosat images was thus done every 3 hours. The TRMM data corresponding to our study area represented an image of 120 x 60 TRMM pixels. Unfortunately, we couldn’t find ground rainfall data for the
summer of 2006 in our study area, and thus couldn’t verify the reliability of the TRMM data in our study area during the period of interest. Nicholson et al. (2003) showed that the TRMM data over West-Africa for the months May till September 1998, presented an excellent match with the ground data. The authors observed a correlation equal to 0.92 between the merged TRMM data and the rain gauges at a monthly resolution. The bias between both datasets at a monthly resolution was inferior to 1 mm h\(^{-1}\) for all months with the exception of June. As we used 3 hour data, it is highly probable that the bias in our dataset is larger than the one calculated by Nicholson et al. (2003). However, as the ground measurements over the study area are sparse (Arnaud et al., 1992; Laing et al., 1999; Machado et al. 2002) and usually correspond to daily readings (Mathon et al., 2002), we could neither calculate nor find in the literature the actual bias of the 3-hourly TRMM over West Africa.

4.2. Methodology

4.2.1. Meteosat IR10.8 channel for tracking

From the literature it appears that the most common channel for tracking is the IR10.8 channel or an equivalent channel from a previous Meteosat First Generation satellite or other platform (see Table 2.1 in section 2.3.). As with the literature, we also chose to use the IR10.8 for tracking MCS. This choice was justified by visualizing and analyzing a MCS in the eight different thermal channels of Meteosat.

Figure 4.2 shows a large mature MCS (reaching and area of approximately 300 000 km\(^2\)) observed in the early morning on August 5\(^{th}\) 2006. In the eight channels, the cloud is easily identified as a large circular field and follows the description of the West African MCS by Chong et al. (1987); “the region of intense precipitation appeared as an organized line extending mainly from north to south but bending toward the east in the southern part” (pg.676). Distinctive gravity waves are also noticed in the southern part of the MCS which indicates that the convective air flow has a significant vertical updraft velocity and subsequent significant upwards momentum.

Channel 4 from Meteosat 8 is centred at 3.9 µm (see Table 4.1 in section 4.1.2.). In this part of the spectrum the incident radiation is strongly absorbed by water vapour and liquid water (Kidder and Vonder Haar, 1995). In this channel the MCS can be identified by its cold cloud top temperatures but the MCSs’ boundary is not as clear. From the weighting functions of the IR Meteosat channels shown earlier in Figure 4.1 (section 4.1.2.), it appears that for cloud free conditions, the information
measured at the satellite in Channel 4, originates essentially from the lower layers of the atmosphere. When the scene is not overcast by high clouds, low clouds and atmospheric layers containing water vapour thus present cold brightness temperatures too. Hence, the fuzzy boundary of the MCS in Channel 4, results from the surrounding lower clouds and moist atmospheric layers.

In Channel 5 and Channel 6, which correspond to the channels centred on 6.2 and 7.3 µm respectively, the cloud looks narrower than on the other IR images (Fig.4.2). The two channels, as indicated by their respective weighting functions in a standard tropical atmosphere and for cloud free conditions (Fig. 4.1), provide information from a thin and relatively high layer of the atmosphere compared to the other IR channels. As indicated by the associated weighting function, with Channel 5 (WV6.2), often cited in the literature for tracking MCS, we can estimate the horizontal extent of the moist air in the upper troposphere. The boundary between moist and dry air is also clearly visible (sudden change in colour, from green-blue to red-orange).

In all the other IR channels (Channels 7 to 11) the MCS appears nearly identical. As described previously, a typical MCS shows a clear distinction between the convective region and the trailing stratiform region. In Figure 4.2 for the Channels 7 to 11, the core of the MCS shows colder brightness temperatures (darker blue) while the surroundings are slightly warmer (lighter blue). The spatial extent of the convective region as well as the stratiform region can thus be estimated in all channels. For the split window channels, centred on 10.8 µm (IR10.8) and 12 µm (IR12), the colour bar below the images indicates that the range in brightness temperatures is larger for these channels than for the other IR channels. The split window channels are also considered to give more valuable information on the temperature of the scene compared to the other channels (Kidder and Vonder Haar, 1995).
Figure 4.2. Identification of a MCS with the IR brightness temperature images of Meteosat-8. The range in brightness temperatures (K) is given by the colour bar, together with the minimum and maximum brightness temperatures of the scene. The channel number and central wavelength is given underneath each image.
From the literature, the IR10.8 channel appears to be the most common channel used for tracking and the WV6.2 channel is shown to be useful for retrieving additional information (see Table 2.1 in section 2.3.). Figure 4.3 shows a cross-section at 10°N (corresponding approximately to the centre of the cloud) of the brightness temperatures at the top of the atmosphere in the IR10.8 and WV6.2 channels. The cross-section asserts that the MCS shows colder brightness temperatures in both channels compared to its surrounds. The two horizontal lines shown in Figure 4.3 correspond to the two temperature thresholds used to define MCS in the present study (233 K and 210 K, see further in section 4.2.2). As observed on the previous figure (Fig. 4.2), in the WV6.2 channel the cloud area is slightly narrower compared to the cross section in the IR10.8 channel. In the latter, brightness temperatures show a lot more variation and we can easily define the external boundaries of the MCS (at 233 K) as well as the high convective region (below 210 K). In contrast, the extent of the entire system in the WV6.2 channel can’t be distinguished as easily. Overall, we can thus assume that the IR10.8 may be one of the most appropriate channels for the detection of MCS.

Figure 4.3. Cross section along a horizontal line at 10° N of the brightness temperatures in channel 5 (WV6.2) and 9 (IR10.8) of Meteosat 8 (refered to Fig. 4.2.). The used temperature thresholds for the detection of MCS are indicated on each plot; 233 (dashed line) and 210 K (dotted line).
4.2.2. Definition of MCS, temperature threshold and general guidelines for the tracking

Since there is no universal definition of MCS in terms of minimum area, shape and/or life duration, we defined MCS based on the literature and on the purpose of our research. As noticed in previous studies, rain efficient MCS were found to be relatively large and long-lived clouds. Therefore, we imposed in our tracking method that MCS had an area exceeding 30 000 km² for more than 3 hours. According to Tomassini et al. (2006), this corresponds to the largest continental MCS which occur mainly in the Sahel band between 10 and 15°N. Imposing the minimum area criterion over 3 hours, was based on the definition of Mathon and Laurent (2001), who focused on large MCS over the Sahelian region. Since we have rain data at a temporal resolution equal to 3 hours, this criterion also ensured that each cloud could be associated to rainfall data. For the tracking algorithm we defined an area cut-off equal to 3500 km² (360 Meteosat pixels). Systems showing an area smaller than the area cut-off were no longer considered. The small area cut-off allowed tracking the clouds from their initiation stage until their dissipation, while the large area criterion (here 30 000 km² for more than 3 hours) allowed selecting the MCS only.

Aside from the life duration and area criterion, MCS had also to be defined as a function of the selected channel chosen for the tracking. In the present study, we chose to use a brightness temperature threshold in the IR10.8 channel equal to 233 K, which is found to be the most common threshold in the literature (see Table 2.1 in section 2.3.). However, in order to ensure that the MCS presented at least once during its life cycle an embedded cloud cluster with strong convection, considered as triggers of intense precipitation, we defined a second temperature threshold equal to 210 K. The embedded cluster was defined as the 10 % coldest pixels of the system. This was based on the observations of Laurent et al. (2002). The authors observed that for a MCS detected with a temperature threshold of 233 K, the cloud area showing a temperature lower than 210K represented 10 % of the total cloud area whatever the lifetime or size. The low temperature threshold was also based on the observations of Machado et al. (1998), who mentioned that active convective clouds identified with brightness temperatures between 205 and 220K have a close correspondence with heavy precipitation.

Retaining the MCS that initiate spontaneously and end by dissipation only, ensures that the growth stage of the event is mainly due to internal dynamics and that the lifetime of the tracked MCS is representative of a complete life cycle (Machado and Laurent, 2004). However, as noted by Schröder et al. (2009), restricting our dataset to deep convective systems which neither merge not split during their life cycle, excludes a large fraction of the tracked clouds and in particular the large
systems. Over West Africa, Mathon and Laurent (2001) observed that the total number of splits is about 33 % at a threshold of 233K. Machado et al. (1998) observed 10 % split events and about 20 % merging events over the Americas, when tracking large MCS (~ 100 000 km²) at a temperature threshold of 245 K. Therefore, MCS presenting split and merge events were also included in our definition of MCS.

A last selection criterion concerned the motion of the MCS. Since MCS in the Sahel travel westward, (following the AEJ and TEJ), MCS in our study area had to present at initiation a longitude coordinate of the cloud centre larger than at dissipation. This allowed the exclusion of clouds such as very cold cirrus clouds that didn’t show a distinctive westward motion.

In summary we thus defined MCS as large contiguous clouds colder than 233 K and showing an area exceeding 30 000 km² for more than 3 hours. The MCS travel westward in the study area and have at least once during their life cycle, region(s) of very high convection with average brightness temperatures colder than 210 K.

The methodology was firstly applied over one week, notably from July 31st until August 6th 2006, which corresponds approximately to the core of the rain season. This was done in order to evaluate our tracking method and to increase our understanding of the tracking algorithm. The execution time for the one week analysis was indeed a lot shorter than for the three month analysis. The shorter execution time allowed us to investigate more easily the impact of variations in temporal resolutions and the influence of the different TRMM and Meteosat overlay methods on the results. From the one week analysis we also compiled numerous additional cloud parameters and selected out of those the one used for the three month analysis.

Each cloud tracked during the first week was also analyzed and visualized individually. This helped us to evaluate our definition of MCS and the hypotheses made in the third section of this work. Beside this, the one week analysis also showed that some clouds spent a large fraction of their life duration at the border of our study area and that the cloud parameters and rain variables associated to these clouds (referred hereafter as border clouds) were not representative. This was for instance the case for a border cloud which generated very intense rain while its area was relatively small. The latter was however unreliable since a large fraction of the cloud area fell outside our study area.

After visualizing all the clouds tracked from July 31st until August 6th individually, we defined the border clouds as clouds spending more than 65 % of their entire life cycle at the edges of the study.
These were then excluded from the cloud sample. This also included that the TRMM images had to be trimmed at the edges of the study area. Otherwise, the total rain induced by the MCS in the study area will be underestimated. Trimming the TRMM images, however, did not fully solve the problem but rather postpone it. Indeed, some of the clouds travelling close to the trimmed edges of the TRMM images generated more rain then actually calculated. This was because some of their rainy pixels fell in the trimmed edge and were subsequently excluded from the calculation. However, the trimming only affected a small fraction of the clouds (~20%). For most of these the underestimation of the calculated rain, generated by these clouds, was only small (underestimations up to 15% of the total rain of the system) as only a small fraction of their rain fell in the trimmed edges. Based on these observations, we thus concluded that the errors made when estimating the cloud parameters and rain variables, were smaller when excluding the ‘border clouds’ than when including them.

Once we were satisfied about our tracking method, we verified if our hypotheses could be considered as general and therefore applied our tracking method on the 84 days.

4.2.3. Optimal temporal resolution selection

The most appropriate time step between two successive images was tested for the first week of August. By appropriate we mean the best balance between the highest capability to track MCS and the smallest amount of data. To define this, the tracking algorithm was run 3 times with a temporal resolution of 15 minutes ($\Delta t_{15\text{min}}$), 30 minutes ($\Delta t_{30\text{min}}$) and 1 hour ($\Delta t_{1\text{h}}$). The Meteosat images were first downloaded every 15 minutes for an area slightly smaller than our study area (Meteosat images of 925 x 474 pixels). Testing the sensitivity of the temporal resolution on the number of MCS tracked was therefore done on this dataset. Images for the entire study area were downloaded hereafter dependent on the optimal temporal resolution.

When the tracking algorithm was run with a cut-off area of 3500 km² and a temperature threshold of 233 K but without imposing the different selection criteria of MCS (excluding that MCS should present an area larger than 30 000 km² for more than 3 hours, that the MCS shows at least once during its life cycle an embedded cloud core with brightness temperatures below 210K and a westward propagation), twice as many clouds were tracked with $\Delta t_{15\text{min}}$ than with $\Delta t_{1\text{h}}$ (280 out of 599 MCS). The clouds tracked with a $\Delta t_{30\text{min}}$ represented 75% of the clouds tracked with $\Delta t_{15\text{min}}$ (432 out of 599). In contrast, when the selection criteria were applied, the number of tracked clouds...
no longer varied as much. With a $\Delta t_{15\text{min}}$ the number of tracked clouds was 32, for $\Delta t_{30\text{min}},$ 30 and for $\Delta t_{1\text{h}},$ 29. We also evaluated if larger MCS were more or less sensitive to different temporal resolutions and therefore ran the tracking algorithm again for the 3 different temporal resolutions, but including only MCS that showed an area larger than 80 000 km² for more than 3 hours. In this case, more MCS were tracked with $\Delta t_{30\text{min}}$ then with $\Delta t_{15\text{min}}$ and $\Delta t_{1\text{h}}$. This resulted from the 3 hours threshold which leads in a decreasing number of MCS with an increase in temporal resolution. With $\Delta t_{15\text{min}},$ MCS have to show an area larger than 80 000 km² in at least 12 images, while with $\Delta t_{30\text{min}}$ and $\Delta t_{1\text{h}}$ the number of images in which the MCS have to show an area larger than 80 000 km² is reduced to 6 and 3 respectively. In contrast with the very large area criterion, we observed that the 3 hours threshold had no impact on the number of tracked clouds as a function of the temporal resolution when the area criterion is 30 000 km².

Previous results showed that in terms of the number of clouds, the results were sensitive to the temporal resolution. Figure 4.4 shows the cumulative sum of the average cloud cover of the MCS tracked for the 3 different temporal resolutions. The first plot (Fig. 4.4 (a)) shows the difference in cumulative cloud area for all MCS as defined in section 4.2.2 and the second plot (Fig. 4.4 (b)) includes only the very large clouds (MCS that shows an area larger than 80 000 km² for more than 3 hours). The largest cloud coverage was tracked with a $\Delta t_{30\text{min}}$ for the two cases. However, for both cases, more than 90% of the cloud coverage tracked with $\Delta t_{30\text{min}}$ was also tracked with $\Delta t_{1\text{h}}$. Hence, although different temporal resolutions may show small discrepancies, we estimated that these were not as significant to achieve the main goals of our study and that it was useful to reduce the amount of data by a factor of four and thus work with a $\Delta t_{1\text{h}}$.

![Figure 4.4. Cumulative sum of average cloud coverage of the tracked MCS. Considering all MCS (a) and considering only the MCS with an area larger than 80 000 km² for more than 3 hours (b). Dotted lines represent the result with $\Delta t_{15\text{min}}$, dashed lines with $\Delta t_{30\text{min}}$ and plain lines with $\Delta t_{1\text{h}}$.](image-url)
4.2.4. Tracking algorithm

The tracking algorithm used in this study was computed by Schröder et al. (2009) who depicted the diurnal cycle and life cycle of large convective systems in Africa using SEVIRI images from Meteosat-8. In Figure 4.5 the flowchart outlines the method step by step.

![Flowchart](image)

**Figure 4.5. Schematic overview of the tracking algorithm and selection criteria for the identification of MCS.** Data (parallelogram), processes (white boxes), decisions (diamonds) and decision criteria and retrieved cloud parameters (grey boxes) are represented. The dash-dot arrow indicates the loop when clouds are still present in the selected image ($I_t$) and the dashed arrow indicates the loop when there are no more clouds in $I_t$; the image $I_{t+\Delta t}$ becomes $I_r$. 

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### Table: Tracking Algorithm Criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brightness temperature</td>
<td>$&gt; 233 \text{ K}$</td>
</tr>
<tr>
<td>Eight-neighbor searching</td>
<td></td>
</tr>
<tr>
<td>Cut-off area</td>
<td>$= 3500 \text{ km}^2$</td>
</tr>
<tr>
<td>Successive images</td>
<td>$\geq 3$</td>
</tr>
<tr>
<td>Temperature differences</td>
<td>$\Delta t &lt; 2 \text{ h}$ and clouds overlapping for at least 5%</td>
</tr>
<tr>
<td>Cloud centroid</td>
<td></td>
</tr>
<tr>
<td>Number of pixels</td>
<td></td>
</tr>
<tr>
<td>Date and time in Julian day</td>
<td></td>
</tr>
<tr>
<td>Border flag</td>
<td></td>
</tr>
<tr>
<td>Cloud reach border</td>
<td></td>
</tr>
<tr>
<td>BT10.8, BT10.8c, BT10.8c, WV6.2, BT10.8, and $\Delta BT(WV6.2-IR10.8)$</td>
<td></td>
</tr>
<tr>
<td>Evolution of cloud centroid</td>
<td>Is cloud, with the smallest normalized $\Sigma$ of area difference change in position and overlap.</td>
</tr>
<tr>
<td>BT$<em>{e</em>{av}}$, BT$<em>{e</em>{2av}}$, BT$<em>{e</em>{1av}}$, Ae, life duration, flag</td>
<td>of merging and splitting and V$<em>{e</em>{av}}$.</td>
</tr>
<tr>
<td>Lon. at initiation</td>
<td>$&gt;$ Lon. at end (westward propagation)</td>
</tr>
<tr>
<td>Area $\geq 30000 \text{ km}^2$ for $&gt;3$ hours</td>
<td></td>
</tr>
<tr>
<td>Minimum BT$<em>{10.8</em>{1av}}$ $\geq 210 \text{ K}$ at least once</td>
<td></td>
</tr>
</tbody>
</table>

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39
In the present study, the tracking algorithm used as primary input data the IR10.8 images. First, in the image at time ‘t’ ($I_t$), all pixels presenting a brightness temperature below 233 K (threshold defined in section 4.2.2.) were set equal to 1, and all others equal to 0. Next, the contiguous areas were determined using an eight-neighbour searching algorithm. As illustrated in Figure 4.6, the eight-neighbour searching algorithm of the IDL program searches for all pixels which are horizontally, vertically and diagonally connected to the centre pixels in a 3x3 window and assigns a unique region index to all the connected pixels. The procedure is repeated for each connected pixel until no supplementary connected pixels are detected at the borders of the labelled area. All pixels excluded from the cloud mask or located at the edges of the study area are considered to belong to no region and therefore receive a region index of 0.

![Figure 4.6. Eight-neighbour searching algorithm. Grey boxes correspond to the cloud mask and the numbers to the unique region indices of each pixel.](image)

Afterwards the tracking criteria were verified for a single cloud (labelled region) (Fig. 4.5). If in both images $I_t$ and $I_{t-\Delta t}$ some pixels were colder than the threshold, if at least one system in $I_{t-\Delta t}$ overlapped a cloud in $I_t$ over more than 5 % of its area, if the time difference between the two images was less than two hours and if the cloud on $I_t$ showed an area smaller than 3500 km² (360 Meteosat pixels), the tracking criteria were verified and the cloud parameters were calculated for the cloud in both images $I_t$ and $I_{t-\Delta t}$ (Fig. 4.5). The overlap minimum is defined as a function of the propagation speed of a typical MCS, the chosen cut-off area (small MCS exhibit larger changes in area and position) and the temporal resolution of the dataset. In the present study, we run the tracking algorithm over the first week of August with an overlap minimum of 5 and 10 %. Both overlap criteria gave exactly the same results; the same clouds were tracked and retained. Therefore no further research was done in order to evaluate the optimal overlap criterion. The same overlap criterion as Schröder et al. (2009), notably 5 %, was used. We considered that an overlap of 5 % was small enough such that fast-moving and small systems were also tracked.
The calculated and saved cloud parameters are the latitude and longitude of the cloud centre and the cloud extremities, the area in number of pixels, the date and time in Julian day, the flag if the cloud reached the border of the study area, the brightness temperature in the IR10.8 image averaged over the entire cloud ($BT_{10.8\,av}$), over the 5 coldest pixels ($BT_{10.8\,5px}$) and over 10 % coldest pixels ($BT_{10.8\,10\%}$), the brightness temperature in the WV6.2 averaged over the entire cloud ($WV_{6.2\,av}$) and the difference between the brightness temperature averaged over the entire cloud in the IR10.8 and in the WV6.2 ($\Delta(BT_{10.8}-WV_{6.2})_{av}$).

In contrast, if the tracking criteria were not verified, the same step was repeated for the following cloud (indicated by the dash-dot line in Figure 4.5). If it didn’t present any additional cloud anymore, the next image $I_{t+\Delta t}$ became $I_t$ and the method returned to the first step ‘cloud mask and labelling’ (indicated by the dashed line in Figure 4.5).

A cloud on $I_t$ was considered as the evolution of a cloud on $I_{t-\Delta t}$ based on three parameters, area difference, spatial translation (difference in position between two clouds) and overlap. For each cloud in $I_t$, all clouds in $I_{t-\Delta t}$ that overlap it were retained. The area difference, the difference in position and the non-overlapping area between the cloud in $I_t$ and all the clouds in $I_{t-\Delta t}$ were calculated. The three parameters were normalized with values closer to 0 indicating a larger similarity between the two clouds. The cloud in $I_t$ presenting the smallest sum of the three normalized parameters was finally considered as the evolution of the cloud in $I_t$.

When split events occurred, the system that presents the most resemblance with the original cloud was labelled as the latter, and hence considered as the same cloud. The other split clouds were considered to initiate from splitting. When merging occurred, the system that presents the most resemblance with the original cloud was labelled with the original region index, while the other clouds were no longer tracked and therefore considered to have ended by merging. Finally, when a cloud that didn’t present any overlapping with a cloud detected at an earlier time, but showed an area larger than the area cut-off, the cloud was considered to have generated spontaneously. A cloud that merged with other smaller clouds received a negative ‘merge flag’. The absolute value of the ‘merge flag’ indicates the number of clouds that have merged. A positive ‘split flag’ was assigned to a cloud from which cloud clusters split and the absolute value of it corresponded to the number of split clouds. A flag equal to 1 corresponded to a cloud that neither split nor merged, and a flag equal to 0 indicated that the cloud reached the border of the study area.
Figure 4.7 illustrates the tracking method and shows 3 cases; a case that neither merged nor split, a merging case and a split case. The images on the left are the images at time ‘t-Δt’ while the images on the right are the images at time ‘t’. Black arrows indicate the evolution of a cloud, and the clouds surrounded with a circle with wide diagonals have the same region index at time ‘t’ and ‘t+Δt’. The other clouds, that merged (Fig. 4.7 (b)) or split (Fig. 4.7 (c)) at time ‘t+Δt’, are no longer tracked (die by merging) or receive a new unique region index (initiate by splitting).

After tracking, the ‘evolution parameters’ were estimated for each cloud and at each time step (Fig. 4.5.). These are the change in BT10.8_av, BT10.8_5px and BT10.8_10% between two successive images (BTe_av, BTe_5px and BTe_10% respectively), the expansion rate (Ae), the life duration, the merge or split flag and the propagation speed (V_av). The latter was based on the displacement of the centre of the cloud. Subsequently, MCS which merged or split during their life cycle often presented unrealistic speeds between two successive images due to a sudden displacement in the centre of the mass. In order to minimize this error, V_av was rather estimated by the displacement of the centre of the cloud between initiation and death divided by the life duration. The next step consist thus to relate these parameters and the previously saved cloud parameters to the rain variables. This is outlined in the following sections.
4.2.5. Overlaying TRMM and Meteosat images and retrieving rain variables

At each Meteosat time step and for each MCS, the latitude and longitude of the cloud centre and extremities were calculated (see previous section) and the area in number of Meteosat pixels (resolution of 3.1 x 3.1 km). The latter was then converted into the number of pixels at a resolution corresponding to the TRMM data. When TRMM data are available, which is every 3 hours, a box is drawn over the rain data with a spatial extent corresponding to the latitude and longitude of the extremities (Fig. 4.8 (a)). The sum of the rain that fell into the box corresponds to the rainfall induced by the MCS (corresponding to the box) at that time.

As the TRMM and Meteosat pixels had different spatial resolutions and because the coordinate system for the Meteosat images wasn’t entirely perfect (resulting from the assumption that the Meteosat pixels have a constant resolution for the entire study area), some inaccuracies were observed when both images were overlaid. Additional errors also emerged since we approximated the cloud area by a rectangular box. Therefore, a buffer was applied around the box drawn on the TRMM data. Two different ways to define an appropriate buffer width were tested; once as a function of the area of the cloud, and once as a fixed number of pixels.

A buffer based on the cloud area induced very large buffer widths when the cloud area was large. Figure 4.8 (b) shows, for instance, a buffer width corresponding to 50% of the area and that precipitation from neighbouring clouds is included in the box. This was even more obvious for very large clouds. For this reason a fixed buffer was preferred.

We often observed, when overlaying the two datasets, that the thinner parts of the trailing stratiform region and the subsequent rain (obviously induced by the MCS or associated gravity waves) were not included in the rectangular box (Fig. 4.8 (c)). Therefore, a better overlay between cloud area and precipitation data was obtained when a larger buffer was applied at the box side corresponding to the trailing edge. This was, as MCS in the Sahel travel westward, at the eastern side of the box. All in all, the southern, western and northern widths of the buffer were thus defined as relatively small but still large enough to correct the overlay errors (due to resolution differences and due to the approximation of the cloud area as a rectangular box) and the eastern width of the buffer was chosen as relatively large to correct the overlay errors and ensure that the larger extent of the trailing stratiform rain was included too (Fig. 4.8 (d)). Based on the visualization of the clouds tracked during the first week of August, the southern, western and northern buffer widths were set equal to 2 TRMM pixels (~55.58 km) and the eastern buffer width to 10 TRMM pixels (~277 km).
Figure 4.8. Overlay method for retrieving rain variables. Brightness temperature (K) IR10.8 below 233 K and cloud area reduced to a rectangular box (a). Precipitation (mm h$^{-1}$) with a buffer width equal to 50% of the cloud area (b), to 3 TRMM pixels (c) and to 10 pixels at the eastern side and 2 pixels at the other sides (d). Dashed lines in Figures (b), (c) and (d) represent the box without buffer.

After the Meteosat cloud information on the TRMM data was considered as satisfactory, three rain variables were calculated; the total rainfall ($p_{\text{tot}}$), which was the simple sum of all the rainfall that fell into the box, the maximum precipitation ($p_{\text{max}}$), which was the mean rainfall averaged over the 10 TRMM pixels that present the most intense rainfall inside the box, and the mean precipitation ($p_{\text{av}}$), which corresponds to $p_{\text{tot}}$ divided by the number of rainy pixels inside the box. The 3 rain variables were calculated for each cloud every 3 hours during its lifecycle. For a comparison between clouds, three additional rain variables were calculated for each cloud; the total rainfall ($P_{\text{tot}}$), which is the sum of $p_{\text{tot}}$ over the entire life cycle of the system, the maximum precipitation ($P_{\text{max}}$), which is the maximum of $p_{\text{max}}$ over the entire life cycle of the system and finally the mean precipitation ($P_{\text{av}}$), which is the sum of $p_{\text{av}}$ divided by the life duration of system.

4.2.6. Relationships between rain variables and structural and radiative cloud parameters

For the first week of August, the cloud parameters and the rainfall variables were plotted as a function of the local time for each cloud. Relationships between cloud parameters and rain variables
were thereby detected. Additionally, the evolution of the cloud parameters through the life cycle of each MCS and the rain variables were compared. Table 4 reviews the variables computed for each MCS during the tracking. Were relevant respective symbols, units, ranges and frequencies are also given.

Table 4.3 outlines all the variables computed for each MCS during the tracking and, where relevant, indicates their symbols and respective units, ranges and frequencies.

Table 4.3. Retrieved cloud parameters

<table>
<thead>
<tr>
<th>Calculated Parameters</th>
<th>Symbol</th>
<th>Units/Range</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud number</td>
<td>-</td>
<td>-</td>
<td>1 per cloud</td>
</tr>
<tr>
<td>Life duration</td>
<td>-</td>
<td>hours</td>
<td>1 per cloud</td>
</tr>
<tr>
<td>Width for merger and split events</td>
<td>-</td>
<td>10, 20, 30, 40, 50 km</td>
<td>hourly</td>
</tr>
<tr>
<td>Citation value</td>
<td>-</td>
<td>1</td>
<td>hourly</td>
</tr>
<tr>
<td>Longitude/Latitude cloud centre</td>
<td>-</td>
<td>0-30°W/5-20°N</td>
<td>hourly</td>
</tr>
<tr>
<td>Maximum Longitude/Latitude</td>
<td>-</td>
<td>0-30°W/5-20°N</td>
<td>hourly</td>
</tr>
<tr>
<td>Minimum Longitude/Latitude</td>
<td>-</td>
<td>1010-1015, 700-705N</td>
<td>hourly</td>
</tr>
<tr>
<td>Time and Date in Julian day</td>
<td>-</td>
<td>UT</td>
<td>hourly</td>
</tr>
<tr>
<td>Local Time</td>
<td>LT</td>
<td>hours</td>
<td>hourly</td>
</tr>
<tr>
<td>Area</td>
<td>-</td>
<td>km²</td>
<td>hourly</td>
</tr>
<tr>
<td>Average BT10.8</td>
<td>BT10 R&lt;sub&gt;ave&lt;/sub&gt;</td>
<td>K</td>
<td>hourly</td>
</tr>
<tr>
<td>Average BT10.8 for 10% coldest pixels</td>
<td>BT10 R&lt;sub&gt;10&lt;/sub&gt;</td>
<td>K</td>
<td>hourly</td>
</tr>
<tr>
<td>Average BT10.8 for 5 coldest pixels</td>
<td>BT10 R&lt;sub&gt;5&lt;/sub&gt;</td>
<td>K</td>
<td>hourly</td>
</tr>
<tr>
<td>Average WV6.2</td>
<td>WV6.2</td>
<td>K</td>
<td>hourly</td>
</tr>
<tr>
<td>Difference between BT10 R&lt;sub&gt;ave&lt;/sub&gt; and BT10 R&lt;sub&gt;max&lt;/sub&gt;</td>
<td>ΔBT</td>
<td>K</td>
<td>hourly</td>
</tr>
<tr>
<td>Change in BT10.8</td>
<td>BT&lt;sub&gt;200&lt;/sub&gt;</td>
<td>K.s&lt;sup&gt;−1&lt;/sup&gt;</td>
<td>hourly (not at time t&lt;sub&gt;1&lt;/sub&gt;)</td>
</tr>
<tr>
<td>Change in BT10.8 for 10% coldest pixels</td>
<td>BT&lt;sub&gt;10&lt;/sub&gt;</td>
<td>K.s&lt;sup&gt;−1&lt;/sup&gt;</td>
<td>hourly (not at time t&lt;sub&gt;1&lt;/sub&gt;)</td>
</tr>
<tr>
<td>Change in BT10.8 for 5 coldest pixels</td>
<td>BT&lt;sub&gt;5&lt;/sub&gt;</td>
<td>K.s&lt;sup&gt;−1&lt;/sup&gt;</td>
<td>hourly (not at time t&lt;sub&gt;1&lt;/sub&gt;)</td>
</tr>
<tr>
<td>Area expansion</td>
<td>A&lt;sub&gt;ave&lt;/sub&gt;</td>
<td>km&lt;sup&gt;2&lt;/sup&gt;</td>
<td>hourly (not at time t&lt;sub&gt;1&lt;/sub&gt;)</td>
</tr>
<tr>
<td>Average propagation speed</td>
<td>V&lt;sub&gt;ave&lt;/sub&gt;</td>
<td>m.s&lt;sup&gt;−1&lt;/sup&gt;</td>
<td>1 per cloud, every 3 hours</td>
</tr>
<tr>
<td>Total rain induced by the cloud per time step (sum of rain falling inside the box)</td>
<td>R&lt;sub&gt;ave&lt;/sub&gt;</td>
<td>mm h&lt;sup&gt;−1&lt;/sup&gt;</td>
<td>1 per cloud, every 3 hours</td>
</tr>
<tr>
<td>Average precipitation per time step (total precipitation divided by the number of raining pixels)</td>
<td>P&lt;sub&gt;ave&lt;/sub&gt;</td>
<td>mm h&lt;sup&gt;−1&lt;/sup&gt;</td>
<td>every 3 hours</td>
</tr>
<tr>
<td>Average precipitation (over entire life cycle)</td>
<td>P&lt;sub&gt;ave&lt;/sub&gt;</td>
<td>mm h&lt;sup&gt;−1&lt;/sup&gt;</td>
<td>every 3 hours</td>
</tr>
<tr>
<td>Maximum intensity precipitation (maximum of P&lt;sub&gt;ave&lt;/sub&gt; over the entire life cycle of the cloud)</td>
<td>P&lt;sub&gt;ave&lt;/sub&gt;</td>
<td>mm h&lt;sup&gt;−1&lt;/sup&gt;</td>
<td>1 per cloud</td>
</tr>
</tbody>
</table>

Note: Cloud parameters recorded per time step per cloud (hourly) or only once per cloud (referred as 1 per cloud in the table) and all rain variables recorded every three hours (indicated by a low case) or only once per cloud (indicated by an upper case). 45
The 5 coldest pixels were considered as the core of the convective region rather than the 10% coldest pixels. For very large MCS, the latter was indeed observed to correspond to a fraction of the cloud larger than the convective region, in particular at mature stage when the convective activity is concentrated over a small area, while the divergence at the cloud top is already important and the subsequent anvil cloud large. As a consequence, the difference between BT10.8_{av} and BT10.8_{10\%} was not as pronounced as the difference between BT10.8_{av} and BT10.8_{5px}.

For the three month analysis, the cloud characteristics, which refer to averages, minimum or maximum values of the different cloud parameters (P_{tot}, P_{av} and P_{max}), were correlated with the rain variables for each cloud. A quantitative measure of the strength of the relationships and the direction of it was computed using correlation coefficients. The most common correlation measure is Pearson’s correlation coefficient (r_s) (also known as the Product-moment correlation) (Ebdon, 1978) and is calculated as follows:

\[ r_s = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{n\sigma_x\sigma_y} \]

The nominator is the sample covariance of the variables x and y, and the denominator is the sample standard deviations for the two variables. However, this is a parametric test and hence assumes that both variables are normally distributed. The normality of the data was tested in this study by plotting the distribution of each variable and fitting a gauss function through it. However, as it was highly probable that all the variables did not follow a normal distribution, the use of a rank correlation was preferred. The rank correlation is less restrictive and is based on the probabilistic notion that a correlation exists between two variables if there is a high probability that an increase (decrease) in one variable will result in an increase (decrease) of the other variable (McPherson, 1990). Hence a continuously increasing or decreasing trend line will be reflected by a high rank correlation coefficient. For the rank correlation, the two sets of variables are ranked before the correlation coefficient (R) is calculated. First one set of variables is ranked from the smallest to largest. The corresponding values of the other variables are reordered such that the pairs for each observation remain unchanged. The rank correlation coefficient is than calculated as follow:

\[ R = \left[ \frac{\sum_{i=1}^{n} (Rx_i - \bar{Rx})(Ry_i - \bar{Ry})}{\sqrt{\sum_{i=1}^{n} (Rx_i - \bar{Rx})^2} \sqrt{\sum_{i=1}^{n} (Ry_i - \bar{Ry})^2}} \right] \]
The variables $R_x$ and $R_y$ are the magnitude-based ranks among $x$ and $y$, respectively. Those variables reflect the difference in ranking between the 2 variables. When the ranking of the variables $x$ from largest to smallest corresponds to the ranking of the variables $y$ from largest/smallest to smallest/largest, the correlation between both variables is perfectly positive/negative. A non-directional test is used in order to verify if the correlation is significant. Therefore the obtained correlation coefficient is converted into a probability factor indicating the probability of evidence to reject the hypothesis that the 2 variables are independent.
5. Results

5.1. Behaviour of MCS tracked from July 31st until August 6th

5.1.1. General facts

The 32 clouds tracked during the first week of August accounted for 77% of the total rain. Out of the 32 MCS, 15 systems had an area larger than 80 000 km² for more than 3 hours. Those systems, which represent 47% of the tracked MCS, accounted for 65% of the total rain that fell during the week. The average speed of the MCS tracked during the first week was 8.5 m s⁻¹. When considering only the very large MCS (systems showing an area larger than 80 000 km² for more than 3 hours) the average speed was slightly larger, notably 9.6 m s⁻¹. The mean and minimum in brightness temperatures averaged over the entire cloud were 218 K and 201 K respectively. The average life duration of a MCS was 15 hours.

Out of the 32 clouds tracked during the first week, we chose to outline four cases. The first case was chosen as it followed our expectation of MCS’ behaviours, visually on the satellite images as graphically on the plots. The second case presents a system which was amongst the fastest systems tracked during the first week of August and which lasted the longest between the fast moving clouds (V_{av} > 10 m s⁻¹). In the literature authors often consider large long-lived and fast-moving clouds as very rain efficient, so we judged that it was interesting to describe this system too. The third case outlines the MCS generating the most intense precipitation among all the clouds tracked during the first week of August (P_{max} = 47.3 mm h⁻¹). The last case shows a system that didn’t merge nor split. This ensures that variations in cloud parameters and rain variables are dependent only on the internal dynamic of the system and/or on external environmental factors.

For each case, a bar plot indicates the mean and maximum precipitation, the variables are plotted as a function of the local time in hours from 0 till 24 and the black arrows above the first plot indicate merging events. Red circles surrounding points-pair on the plots, correspond to the cloud-masked IR10.8 images and rain data images shown in the figures below.
5.1.2. MCS with typical behaviours

Figure 5.1 shows the area, BT10.8$_{av}$, BT10.8$_{5px}$ and rain variables for a MCS tracked at 1527 LT on August 5$^{th}$ and during the following 24 hours. The system showed an average area exceeding 95 000 km$^2$ and a maximal area equal to approximately 197 500 km$^2$. It moved westward with a propagation speed of 11.9 m s$^{-1}$ and showed a very cold convective core during its life cycle with BT10.8$_{5px}$ below 186 K. On average the systems induced a mean precipitation of 3 mm h$^{-1}$ and generated heavy precipitation with P$_{max}$ attaining 32 mm h$^{-1}$.

As noticed before, amongst the clouds tracked during the first week of August, this cloud shows trends and behaviours we expected. It initiated in the afternoon around 1500 LT when the solar heating was maximal. During its initiation phase the cloud presented a round shaped cloud area which grew continuously for approximately six hours. In the early evening, around 2027 LT, the system, as observed in Figure 5.1, showed a first peak in area and a drop in BT10.8$_{5px}$. Afterwards, the strength of the convective activity decreased (increase in BT10.8$_{5px}$) and the cloud area started dissipating and splitting (Fig. 5.1 (1) and (2)). However, three hours later, around 0127 LT, the cloud seemed to reinforce and started growing again. While growing, the cloud elongated slightly in the north-south direction and merged with surrounding small cloud clusters. As noticed in the literature, merging events often occur during the growing phase of systems (among others Schröder $et$ $al.$, 2009). After merging, the cloud showed a strengthening in convection. This is indicated by the decrease in BT10.8$_{5px}$ in Figure 5.1 (2). P$_{max}$ is observed when the difference between BT10.8$_{av}$ and BT10.8$_{5px}$ is nearly maximal and some hours before the maximum in cloud area. The maximum difference between BT10.8$_{av}$ and BT10.8$_{5px}$ is a sign of, on the one hand, strong vertical updraft in the leading edge and, on the other hand, low trailing anvil clouds. The maximum area occurs after maximum precipitation when, due to the drag force of the precipitation and the cooling of the air, the divergence from the leading edge to the anvil cloud increases.

No direct relationship between the rain variables and Ae or BTe$_{5px}$ is observed (Fig. 5.1 (3) - (4)). We can only notice in Figures 5.1 (3) and (4) that maximum precipitation occurs with a slight increase in BTe$_{5px}$ and Ae and that after maximum precipitation Ae decreases and shows negative values until dissipation. Figure 5.2 shows that at maximum precipitation, intense rainfall is concentrated over few pixels (Fig. 5.2 (a)). These pixels correspond to the most active part of the convective region, which induces intense convective rain. Three hours after maximum precipitation, the rainfall intensity drops below 10 mm h$^{-1}$ and the rain is more homogeneously distributed over the entire cloud clover (Fig. 5.2 (b)).
Figure 5.1. Cloud parameters and rain variables of MCS with typical behaviours as a function of the local time. Plain bars correspond to $p_{\text{max}}$ and dash-dot bars to $p_{\text{av}}$. Black arrows above plot (1) indicate when systems merged. Red circles indicate the time steps corresponding to the images below.

Figure 5.2. Brightness temperature IR10.8 (K) below 233 K and associated precipitation (mm h$^{-1}$) of MCS with typical behaviours. (a) and (b) correspond to 1$^{\text{st}}$ red circle in Figure 5.1., (c) and (d) to 2$^{\text{nd}}$. Boxes with plain line represent approximated cloud area and dashed boxes include the buffer.
5.1.3. Large long-lived and fast-moving MCS

Figures 5.3 and 5.4 show the cloud parameters and rain variables of a MCS tracked for 36 hours from July 31st at 0127 LT until August 1st at 1327 LT. This MCS can be considered as a large, long-lived and fast-moving cloud as it attains a maximal area of approximately 183 000 km² and an average propagation speed equal to 12.8 m s⁻¹. The system also presented once during its entire life cycle a very cold convective core with a minimum BT10.8px equal to 185 K. The MCS generated heavy precipitation with P_{max} equal to 23.75 mm h⁻¹ and P_{av} equal to 3.16 mm h⁻¹.

The system initiated before July 31st and began its dissipation after the first hours of tracking. This resulted in a decrease in cloud area and increase in BT10.8px (Fig. 5.3 (1) - (2)). After the first 9 hours of tracking, around midday, the convective activity reinforced. In Figure 5.3, we observe that three hours after the cloud area is minimal, BT10.8px quickly drops and the cloud induces a relatively large amount of rain compared to its area. At this time step, the TRMM image shows that the cloud area is indeed relatively small but very intense rain (up to 38 mm h⁻¹) is observed on a few numbers of pixels. The intense rain that occurred at 1330 LT may have induced high divergence rate in the upper troposphere which explains the large increase in area observed the following three hours. However, since at this stage the system also merged, we can’t ensure that the large increase in area is only related to the intense precipitation.

A second peak in maximum precipitation is observed at 0127 LT together with a small decrease in cloud area (Fig. 5.3). The maximum precipitation is also associated with a minimum in BT10.8px and a maximum in difference between BT10.8av and BT10.8px. After maximum precipitation, the cloud area increases again as well as BT10.8px (Fig. 5.3 (1) - (2)). Afterwards, the system starts its dissipation and the cloud area continuously decreases while BT10.8px increases.

Likewise for the system described previously, at maximum intense precipitation, the rainfall is concentrated over few pixels (Fig. 5.4 (a)), after, the rainfall is more homogeneously distributed over the entire cloud area (Fig. 5.4 (b)). Maximum intense precipitation also precedes a light increase in Ae (Fig. 5.3 (4)). However, as indicated by the black arrows in Figure 5.3 (1) and noted previously, at this time step the system merged too. In this case neither the minimum in BTe_{5px}, which is expected to be associated with high convection, nor the maximum in Ae coincide with the maximum intense precipitation (Fig. 5.3 (3)-(4)). However, we observe that a decrease in BTe_{5px} generally precedes intense precipitation, while an increase in area expansion is slightly delayed with respect to intense precipitation.
Figure 5.3. Cloud parameters and rain variables of large long-lived and fast-moving MCS. Same as for Figure 5.1.

Figure 5.4. Brightness temperature IR10.8 (K) below 233K and associated precipitation (mm h$^{-1}$) of large long-lived and fast-moving MCS. Same as for Figure 5.2.
5.1.4. Most rain efficient MCS

The MCS described in Figure 5.5 and 5.6 was tracked from 1927 LT on August 2\textsuperscript{nd} until 1427 LT on August 3\textsuperscript{rd}. The system lasted thus for 19 hours and travelled with an average propagation speed of 8.34 m s\textsuperscript{-1}. It showed during the tracking a minimum BT10.8\textsubscript{px} equal to 186 K and very intense precipitation with P\textsubscript{max} equal to 47.3 mm h\textsuperscript{-1} and P\textsubscript{av} equal to 3.9 mm h\textsuperscript{-1}. This system originated from splitting and consisted at the beginning of an ensemble of non-organized overlapping clusters that all split from a larger cloud. This explains why the maximal cloud area is observed at the beginning of the tracking (~ 330 000 km\textsuperscript{2}) (Fig. 5.5). When travelling away from the larger parent cloud, from which the clusters split, the different small convective clusters merged into a single compact MCS resulting in a decrease in area (Fig. 5.5 (1)). The compact MCS (Fig. 5.6 (a)) showed at 2227 LT very strong convection, which accounted for the heavy precipitation observed in Figure 5.6 (b). After maximum intense precipitation, the convection weakened and divergence towards the trailing area increased. This is consistent with the slight increase in cloud area observed on Figure 5.5 (1) and the subsequent increase in rain area observed on Figure 5.6 (c)-(d)). As expected, maximum precipitation is observed at the same time as a large difference between the BT10.8\textsubscript{av} and BT10.8\textsubscript{px} (Fig. 5.5 (2)). After the convective activity weakened, the difference between the two parameters decreased.
Figure 5.5. Cloud parameters and rain variables of most rain efficient MCS. Same as for Figure 5.1.

Figure 5.6. Brightness temperature IR10.8 (K) below 233K and associated precipitation (mm h\(^{-1}\)) of most rain efficient MCS. Same as for Figure 5.2.
5.1.5. Non-merge non-split MCS

Out of the 32 clouds tracked during the first week of August, only one MCS did neither merge nor split during its entire life cycle. The cloud is, in comparison to the other systems, relatively small (average area ~ 27 000 km²) and short-lived (8 hours). It reached a maximum area of 43 000 km² and a propagation speed of 9.56 m s⁻¹. The MCS induced only a small amount of precipitation ($P_{\text{max}}$ was 4 mm h⁻¹ and $P_{\text{av}}$, 2.33 mm h⁻¹) and initiated in the late afternoon and dissipated around midnight.

Since this system was short-lived and relatively small, it did not show as many variations in cloud parameters and rain variables as the three MCS described previously. The maximum precipitation occurred when the area was maximal (Fig. 5.7 (1)) and three hours after the minimum in BT10.8$_{\text{spx}}$ (Fig. 5.7 (2)). As neither merge nor split events were recorded, we may assume that the variations in BT10.8$_{\text{spx}}$ and Ae are strictly related to the internal dynamic of the system. At the time of maximum Ae and minimum BTe$_{\text{spx}}$, the intense precipitation is similar to the mean precipitation and not maximal as we would have expected (Fig. 5.7 (3) and (4)). However, these observations may be misleading as this system generated only little rain and didn’t show large variations in area (Ae varies between -0.15 to 0.1) compared to the previous described systems (Ae varies approximately from -1 to 1).
5.1.6. Summary

In summary, the analysis of MCS tracked during the first week of August showed that for 78 % (25 MCS out of 32) of the tracked systems, heavy precipitation is preceded or coincides with a local minimum in BT10.8_{px} and is followed by an increase in area or coincides with the maximum area. For these clouds, around the time of maximum precipitation, the difference between BT10.8_{av} and BT10.8_{px} increases and BT10.8_{px} remains below 200 K. Accordingly, we define the time interval for which BT10.8_{px} is below 200 K as the life duration of very deep convection. Resulting from the one week analysis, we also consider the difference between BT10.8_{av} and BT10.8_{px} a good proxy for studying the influence of brightness temperature, averaged over the entire MCS and averaged over the convective core, on the rain variables. The other 22 % corresponds to MCS which were usually very small in area (as shown in Figure 5.7) and/or showed significant merging and/or splitting events during their life cycle (as shown in Figure 5.7).

For the first week of August, the hypothesis that the maximum in Ae as well as the minimum in BTe_{px} will coincide with a maximum in intense precipitation, couldn’t be verified. However, P_{max}
usually coincided with a positive slope in area and a negative slope in BT10.8$_{5px}$. As seen in the previous figures, Ae and $\text{BTe}_{5px}$ often present sudden shifts and greatly in time. By smoothing these rapidly changing variables, we can bring the hourly Ae and $\text{BTe}_{5px}$ data onto the 3-hourly rain data and may exclude some noise most likely resulting from merge and split events.

Besides the first and last time step of the life cycle of MCS, the original value at each time step was replaced by the average of the original value and the two neighbouring values. Figure 5.8 shows the smoothed Ae and $\text{BTe}_{5px}$ as a function of the local time for the three MCS discussed in Figures 5.1, 5.3 and 5.5.

For the MCS with typical behaviours, $P_{\text{max}}$ occurred when $\text{BTe}_{5px}$ was minimal and close to the maximum Ae (Fig.5.8 (1)). In Figure 5.8 (2), which shows Ae and $\text{BTe}_{5px}$ for the large long-lived fast-moving MCS, the minimum in $\text{BTe}_{5px}$ and maximum in Ae occurs close to the first peak in precipitation but not to the second peak. For the most rain efficient MCS, the relationship is not as clear (Fig.5.8 (3)). This is probably due to the merging of the small cloud clusters into a single MCS at the beginning of the tracking. However, we can still observe a small decrease in $\text{BTe}_{5px}$ preceding $P_{\text{max}}$ and a positive Ae following $P_{\text{max}}$. Over all, for approximately 55% of the MCS tracked during the first week of August, a local minimum in $\text{BTe}_{5px}$ was recorded a couple of hours before $P_{\text{max}}$ while the time of maximum Ae usually coincided with the time of maximum rain or was close to it. A higher degree of smoothing did not give better results.
5.2. Three month study

5.2.1. General facts

358 MCS were tracked from July 1st until September 22nd and these accounted for 70% of the total precipitation fallen in the study area over the 84 days. The distribution of the maximum area indicates that a large fraction of the MCS (more than 90%) showed a maximum area below 200 000 km² (Fig. 5.9 (a)). The average maximum area was approximately 127 000 km², and standard deviation, 101 800 km². Hence, the maximum area varies largely from cloud to cloud. 136 MCS presented areas larger than 80 000 km² for more than 3 hours (later referred as the very large MCS) and accounted for 53% of the total rain. The proportion of very large MCS over the 3 months was...
thus smaller than over the first week of August (38% and 47% respectively). All 136 MCS merged or split at least once during their life cycle. For the 358 clouds, the longest lived MCS lasted for 58 hours and the fastest MCS had a propagation speed equal to 21.3 m s$^{-1}$.

The coldest convective core (estimated with BT10.8$_{5px}$) showed an average brightness temperature below 181 K and the maximum negative BT$_{5px}$ recorded was -0.0076 K s$^{-1}$. This is relatively fast as a BT$_{5px}$ of 0.0018 K s$^{-1}$ (estimated on basis of hourly images) correspond approximately to a vertical velocity of 0.22 m s$^{-1}$ assuming an lapse rate of 8 K km$^{-1}$ (Schröder et al., 2009). When considering all clouds, the minimum BT10.8$_{5px}$ showed a normal distribution centred around 190 K with a standard deviation of 4 K (Fig. 5.9 (b)).

The average life duration of a MCS tracked during the rain season of 2006 was approximately 13.5 hours (Fig. 5.9 (c)). As defined in the previous section, the time of deep convection corresponds to the life duration of the system during which it shows a BT10.8$_{5px}$ below 200 K. MCS tracked during the three months, presented deep convection during on average 9 hours (Fig. 5.9 (d)).

The propagation speed averaged over the all MCS was 9.6 m s$^{-1}$ and the standard deviation 3.6 m s$^{-1}$ (Fig. 5.9 (e)). This is smaller than the average speed estimated by Chong et al. (1987) and Desbois et al. (1988), who observed that the south-westward mean speed of squall lines over West Africa lies between 12 m s$^{-1}$ and 19 m s$^{-1}$. However, as noticed by Mathon and Laurent (2001), squall lines are considered as the fastest among the MCS. Therefore, a mean speed between 12 and 19 m s$^{-1}$ may be slightly overestimated for a more general classification of MCS. Mathon and Laurent (2001) estimated a mean propagation speed for MCS in the Sahel between 8 and 12 m s$^{-1}$, which is consistent with our observations.

Most of the MCS initiated in the late afternoon and very few in the early morning (Fig. 5.9 (f)). The time at dissipation was more variable, though peaks in dissipation occur mainly late in the night between 2200 LT and 0500 LT (Fig. 5.9 (g)).

The distributions of $P_{max}$ and $P_{av}$ are shown in Figure 5.5 (h) and (i). The mean and standard deviation of $P_{max}$ are equal to 12.3 mm h$^{-1}$ and 8 mm h$^{-1}$ respectively. For $P_{av}$ the mean is 1.97 mm h$^{-1}$ and the standard deviation, 1 mm h$^{-1}$. The maximum intense precipitation recorded during the period was 47.3 mm h$^{-1}$ and was generated by the ‘most rain efficient MCS’ described in section 5.1.4.
Figure 5.9. Distribution of cloud parameters. Area at maximum extent (a), minimum BT10.8$_{5px}$ (b), life duration (c), time interval during which the MCS shows BT10.8$_{5px}$ below 200 K (d), average propagation speed (e), time at initiation (f) and at dissipation (g), $P_{\text{max}}$ (h) and $P_{\text{av}}$ (i).

5.2.2. Correlations between cloud parameters and rain variables

In contrast with the one week analysis, the three month analysis aims to relate the cloud parameters to the rain variables ($P_{\text{max}}$, $P_{\text{av}}$ and $P_{\text{tot}}$). The matrix used for the three month study contains thus as many observations as the number of MCS, and as many variables as number of cloud characteristics chosen to verify our hypotheses. These are: (1) the maximum area, (2) the propagation speed, (3) the life duration of the MCS, (4) the time interval for which BT10.8$_{5px}$ < 200K, (5) the minimum in BT10.5$_{5px}$, (6) the maximum in ΔBT, (7) the minimum in BTe$_{5px}$ (after smoothing), (8) the maximum Ae (after smoothing), (9) the longitude at $P_{\text{max}}$ and (10) the local time at $P_{\text{max}}$. 
Table 5.1 shows the rank correlations between the ten cloud parameters cited above. Correlation coefficients significant at a 95% and 99% level are indicated by one star and two stars respectively.

A strong and significant rank correlation coefficient (0.78) is observed between the life duration of the system and the time interval during which BT10.8\(_{\text{spx}}\) is below 200 K (referred on the table as ‘Life with BT10.8\(_{\text{spx}}\) < 200 K’). This is coherent, since convective activity (approximated by BT10.8\(_{\text{spx}}\) below 200 K) is the ‘engine’ of MCS, maintaining the system alive. Both, life duration and the time interval during which BT10.8\(_{\text{spx}}\) is below 200 K, are significantly correlated with the area at maximum extent (0.59 and 0.67 respectively). Accordingly, long-lived MCS or/and MCS with long-lived convective cores present larger areas at their maximum extent than short-lived MCS or/and MCS with short-lived convective cores. However, this is only true when considering all clouds or all the very large MCS only. For MCS which doesn’t show areas larger than 80 000 km\(^2\) for more than three hours (referred hereafter as the smaller systems), the rank correlation between the life duration and the cloud area isn’t significant. For the 136 very large MCS, the correlation coefficient was 0.49 (not shown here).

The table also indicates that time interval during which BT10.8\(_{\text{spx}}\) is below 200 K is also correlated with the speed (0.33), the maximum in Ae (0.55), the minimum in BT10.8\(_{\text{spx}}\) (-0.70) and the maximum \(\Delta BT\) (0.64). Hence, deep convection lasting for a longer period of time goes together with larger and/or faster systems, colder convective cores and/or larger differences in brightness temperatures between the convective region and entire cloud. Similarly, the life duration also indicates, although slightly weaker, significant correlations with the speed (0.27), the maximum in Ae (0.45), the minimum in BT10.8\(_{\text{spx}}\) (-0.45) and the maximum in \(\Delta BT\) (0.52). An additional strong correlation, shown in Table 5, is the correlation between the maximum area and the maximum Ae (0.87). Hence, large expansion in cloud area goes together with a larger MCS.

Likewise the life duration, maximum area and maximum in Ae are negatively correlated with the minimum in BT10.8\(_{\text{spx}}\) (-0.58 and -0.50 respectively) and positively correlated with the maximum in \(\Delta BT\) (0.50 and 0.41 respectively). Hence long-lived and larger systems present usually colder convective cores and at some stage in their lifetime larger differences between BT10.8\(_{av}\) and BT10.8\(_{\text{spx}}\). Both, minimum BT10.8\(_{\text{spx}}\) and maximum \(\Delta BT\) are, as expected, also negatively correlated (-0.67).

The local time and longitude at maximum precipitation doesn’t show any significant correlation with any of the other cloud variables.
Table 5.1. Rank correlation coefficients between structural and radiative cloud parameters

<table>
<thead>
<tr>
<th></th>
<th>Max Area</th>
<th>Speed</th>
<th>Life duration</th>
<th>Min BT10.8&lt;sub&gt;px&lt;/sub&gt;</th>
<th>Max ΔBT</th>
<th>Life with BT10.8&lt;sub&gt;px&lt;/sub&gt; &lt;200K</th>
<th>Min Bte&lt;sub&gt;px&lt;/sub&gt;</th>
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Note: Correlations coefficients at a significant level of 95 % (*) and 99 % (**).

Table 5.2 shows the rank correlation between the three rain variables. It indicates that P<sub>tot</sub> is better approximated by P<sub>max</sub> (0.83) then by P<sub>av</sub> (0.44). Hence, the set of cloud parameters correlated with P<sub>max</sub> and should be also correlated with P<sub>tot</sub>. P<sub>max</sub> and P<sub>av</sub> also show a positive correlation. However, this is not as strong as the correlation between P<sub>max</sub> and P<sub>tot</sub>.

Table 5.2. Rank correlation coefficients between the three rain variables, P<sub>max</sub>, P<sub>tot</sub> and P<sub>av</sub>

<table>
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<tr>
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<th>P&lt;sub&gt;max&lt;/sub&gt;</th>
<th>P&lt;sub&gt;av&lt;/sub&gt;</th>
<th>P&lt;sub&gt;tot&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>P&lt;sub&gt;max&lt;/sub&gt;</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P&lt;sub&gt;av&lt;/sub&gt;</td>
<td>0.67**</td>
<td>1</td>
<td></td>
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<tr>
<td>P&lt;sub&gt;tot&lt;/sub&gt;</td>
<td>0.83**</td>
<td>0.44**</td>
<td>1</td>
</tr>
</tbody>
</table>

Note: Correlation coefficients at a significant level of 99 % (**).
5.2.3. Relationships between maximum intense precipitation and structural and radiative cloud parameters

Table 5.3 gives the rank correlations, when considering all MCS tracked over the three months, between all the structural and radiative cloud parameters and $P_{\text{max}}$. The highest correlation coefficient is observed between the $P_{\text{max}}$ and the time interval during which BT10.8$_{\text{5px}}$ is below 200 K (0.51). The latter can be related to strong convective life duration. Slightly lower correlations are observed with the area of the system at maximum extent (0.46), the life duration (0.49), the minimum in BT10.8$_{\text{5px}}$ (-0.44) and the maximum in $\Delta$BT (0.41). Weaker but still significant correlations are observed with the propagation speed (0.24) and the maximum Ae (0.34). In contrast, the minimum in BTe$_{\text{5px}}$ and $P_{\text{max}}$ are not significantly correlated.

<table>
<thead>
<tr>
<th></th>
<th>Max Area</th>
<th>Speed</th>
<th>Life duration</th>
<th>Min BT10.8$_{\text{5px}}$</th>
<th>Max $\Delta$BT</th>
<th>Life with BT10.8$_{\text{5px}}$ &lt; 200K</th>
<th>Min BTe$_{\text{5px}}$</th>
<th>Max Ae</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{max}}$</td>
<td>0.46**</td>
<td>0.24**</td>
<td>0.49**</td>
<td>-0.44**</td>
<td>0.41**</td>
<td>0.51**</td>
<td>-0.05</td>
<td>0.34**</td>
</tr>
</tbody>
</table>

Note: Correlation coefficients at a significant level of 95 % (*) and 99 % (**).

Figures 5.10 (a) and (b) show the relationship between $P_{\text{max}}$ and the life duration of the system as well as between $P_{\text{max}}$ and the strong convective life duration. Above each scatter plot the correlation coefficient (R) and the significance of its deviation from zero (Prob) are indicated. The latter is a value ranging from 0 to 1. A value below 0.01 and 0.05 indicate a significant correlation at a 99 % and 95 % level respectively.

The scatter plots (life duration and strong convective life duration versus $P_{\text{max}}$) show that the band of data points is angled upward, as indicated by the positive correlation coefficient, but the bandwidth is increasing with an increase in $P_{\text{max}}$. The correlations seem to results from the dense point cloud (corresponding to short-lived MCS generating low maximum intense precipitation) and a few number of longer-lived systems generating intense precipitation.

Figures 5.10 (c) and (d) show the same correlation as shown in Figures 5.10 (a) and (b) but when considering the very large systems only. For these systems, the correlations are positive and significant too. Although the bandwidth of data points is relatively large, the points definitely follow an upward direction. For the smaller systems the correlations are positive and significant too but not
as strong as the correlations when considering all the systems or the very larger systems only (Fig. 5.10 (e)-(f)). The scatter plots also show that the range in life duration and strong convective life duration for the very large cloud is twice as large as for the smaller clouds. This is coherent with the positive correlation coefficients given in Table 5.1 between the maximum area and the life duration and between the maximum area and the strong convective life duration.

As with the life duration and the cold convective core life, the correlations between the \( P_{\text{max}} \) and the maximum area as well as between \( P_{\text{max}} \) and the propagation speed are significant when considering
the very large clouds and not when considering only the smaller clouds. Figure 5.11 shows the correlations between $P_{\text{max}}$ and the maximum area and between $P_{\text{max}}$ and the propagation speed for all clouds ((a)-(b)) and for the very large clouds only ((c)-(d)). The data points in the scatter plots in Figures 5.11 (a) and (b) are much more spread out and the range in propagation speed is larger for MCS generating low maximum intense precipitation, than for MCS generating very intense maximum precipitation. For the correlations between $P_{\text{max}}$ and the maximum area, the data points are spread out too, although their upward direction is more pronounced.

![Figure 5.11](image)

**Figure 5.11.** Correlation plots between $P_{\text{max}}$ and the maximum area and between $P_{\text{max}}$ and the average propagation speed; for all MCS tracked ((a)-(b)) and for the very large MCS ((c)-(d)).

The significant negative correlation between the minimum in BT10.8$_{\text{spx}}$ and $P_{\text{max}}$ indicates that MCS showing strong convective activity (approximated by a very low BT10.8$_{\text{spx}}$) are more probable to generate intense precipitation. Indeed, the data points in the scatter plot shown in Figure 5.12 (a) follow a downward direction and, beside some outliers, they are not as dispersed. However, the steep slope of the band of data points shows that a large decrease in BT10.8$_{\text{spx}}$ will result in only a small increase in maximum precipitation. Figure 5.12 (b) also shows a positive and significant correlation between $P_{\text{max}}$ and the maximum in $\Delta BT$. Accordingly, MCS that show during their life cycle larger $\Delta BT$ are more able to generate heavy precipitation.
When considering only the smaller MCS, the correlation coefficients between $P_{\text{max}}$ and the radiative cloud parameters, minimum in BT10.8$_{\text{spk}}$ and maximum in $\Delta$BT, are smaller than when considering the very large MCS only. This is shown in Figure 5.12 (c), (d), (e) and (f). The data points in Figure 5.12 (e) and (f) are indeed more spread out compared to the Figures 5.12 (c) and (d). Moreover, for the very large MCS, the minimums in BT10.8$_{\text{spk}}$ are all below 200 K, while for the smaller systems, some of these are above 200 K.

Figure 5.12. Correlation plots between $P_{\text{max}}$ and the minimum in BT10.8$_{\text{spk}}$ and between $P_{\text{max}}$ and the maximum in $\Delta$BT; for all MCS tracked ((a)-(b)), for the very large MCS ((c)-(d)), and the smaller MCS ((e)-(f)).
As mentioned previously, the maximum in $Ae$ (after smoothing) has a positive correlation coefficient with $P_{\text{max}}$ (0.34). However, in the scatter plot showing the correlations between the two variables (Fig. 5.13 (a)), the data points show a cone-shaped pattern. This results from a very high concentration of data points around a maximum $Ae$ equal to 0 and only a few dispersed points with higher $P_{\text{max}}$ and maximum $Ae$ values. Hence, visually there isn’t a linear relationship between the maximum in $Ae$ and $P_{\text{max}}$. When we consider the very large and smaller systems separately, we observe that the high concentration of data points around the maximum $Ae$ equal to 0 results from the smaller systems (Fig. 5.13 (c)), while the cone-shaped pattern results from the very large systems (Fig. 5.13 (b)). Figure 5.13 (c) also shows that $P_{\text{max}}$ is insensitive to changes in maximum $Ae$ when the analysis is restricted to the smaller clouds. Hence, the relationship is function of the size of the MCS.

![Figure 5.13. Correlation plots between $P_{\text{max}}$ and the maximum in $Ae$: for all MCS tracked (a), for the very large MCS (b), and the smaller MCS (c).](image)

### 5.2.4. Relationships between mean precipitation and structural and radiative cloud parameters

Table 5.4 gives the rank correlations between all the structural and radiative cloud parameters and $P_{\text{av}}$ when considering all MCS tracked over the three months. The highest correlation coefficient is observed between $P_{\text{av}}$ and the propagation speed (0.26). In contrast with $P_{\text{max}}$, $P_{\text{av}}$ doesn’t show any significant correlation with the structural parameters, maximum area and life duration. However, it shows a small, but significant, correlation coefficient with the strong convective life duration (0.20). This is also the case for the correlation coefficients observed between $P_{\text{av}}$ and the radiative cloud parameters, minimum in BT10.8px and maximum in $\Delta BT$ (-0.24 and 0.19 respectively). Neither the minimum in BTe2px nor the maximum in $Ae$ are significantly correlated with $P_{\text{av}}$. 

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Table 5.4. Rank correlation coefficients between mean precipitation and the structural and radiative cloud parameters

<table>
<thead>
<tr>
<th></th>
<th>Max Area</th>
<th>Speed</th>
<th>Life duration</th>
<th>Min BT10.8&lt;sub&gt;5px&lt;/sub&gt;</th>
<th>Max ΔBT</th>
<th>Life with BT10.8&lt;sub&gt;5px&lt;/sub&gt; &lt; 200K</th>
<th>Min Bte&lt;sub&gt;5px&lt;/sub&gt;</th>
<th>Max Ae</th>
</tr>
</thead>
<tbody>
<tr>
<td>P&lt;sub&gt;av&lt;/sub&gt;</td>
<td>0.02</td>
<td>0.26**</td>
<td>0.08</td>
<td>-0.24**</td>
<td>0.19**</td>
<td>0.20**</td>
<td>0.00</td>
<td>-0.03</td>
</tr>
</tbody>
</table>

Note: Correlation coefficients at a significant level of 95 % (*) and 99 % (**)。

The correlations between maximum area and P<sub>av</sub> and between the life duration and P<sub>av</sub>, remain insignificant when considering the very large systems only, as well as when considering the smaller systems only. In contrast, P<sub>av</sub> shows not only significant correlations with the strong convective life duration for all MCS, but also when considering the very large MCS or the smaller MCS. Figure 5.14 shows the scatter plots of the correlations for the 3 cases; firstly when considering all the MCS (Fig. 5.14 (a)), secondly when considering only the very large clouds (Fig. 5.14 (b)) and finally when considering the smaller systems only (Fig. 5.14 (c)). The correlation coefficient is maximal when considering only the very large MCS (0.28).

Scatter plots in Figure 5.14 also shows that the range in strong convective life duration is twice as large for the very large systems then for the smaller systems. This is coherent with the positive correlation given in Table 5.1 between the strong convective life duration and the maximum area.

Like observed with the strong convective life duration, the propagation speed is significantly correlated when considering all MCS but also when considering the very large MCS (0.35) or the smaller MCS (0.20). However, by means of the scatter plot, we can observe that the variation in average speed for a given mean precipitation remains very large (Fig. 5.15). Here again, the correlation is maximal when considering only the very large MCS (0.35).
Figure 5.15. Correlation plots between $P_{av}$ and the propagation speed; for all MCS tracked (a), for the very large MCS (b), and the smaller MCS (c).

From the previous figures (Fig. 5.14 and 5.15) we can also remark that the range in $P_{av}$ is larger for the smaller clouds (ranges from 0 up to nearly 7) than for the very large clouds (ranges from 0 to 5). The difference in ranges is relatively small; nevertheless it indicates that either the convective region remains more or less constant when the cloud area changes or that $P_{av}$ is sensitive to the area of the MCS. However, the latter is unlikely to be true since $P_{av}$ and the maximum area are not correlated. Hence, the first assumption is more probable to be true and this supports the remark made by Houze (2004), notably that the anvil stratiform region actually defines the area of the cloud.

The radiative parameters, minimum BT10.8$_{5px}$ and maximum $\Delta BT$, are significantly correlated at the 99 % level when we take into account the very large MCS only. When considering the smaller clouds only the correlations are significant at the 95 % level (-0.17 and 0.14 respectively). Better correlations are however observed when we include all MCS tracked. Figure 5.16 shows the scatter plot for the correlation between $P_{av}$ and the minimum in BT10.8$_{5px}$ (-0.40) and between $P_{av}$ and the maximum in $\Delta BT$ (0.25) for all the MCS.
5.2.5. Relationships between total precipitation and structural and radiative cloud parameters

Table 5.5 shows the correlation coefficients between $P_{\text{tot}}$ and all the structural and radiative parameters. Like in Table 5.3, aside from the minimum in $B_{\text{Te}_{5px}}$, all cloud parameters are significantly correlated with the rain variable. This is coherent since $P_{\text{max}}$ and $P_{\text{tot}}$ are highly correlated (see Table 5.2). Accordingly, the correlations observed in Table 5.3 between the cloud parameters and $P_{\text{tot}}$ are similar to the correlations observed with $P_{\text{max}}$. However, compared to $P_{\text{max}}$, $P_{\text{tot}}$ shows stronger correlation coefficients.

Table 5.5. Rank correlation coefficient between total precipitation and the structural and radiative cloud parameters

<table>
<thead>
<tr>
<th></th>
<th>Max Area</th>
<th>Speed</th>
<th>Life duration</th>
<th>Min $B_{T10.8_{5px}}$</th>
<th>Max $\Delta BT$</th>
<th>Life with $B_{T10.8_{5px}} &lt; 200K$</th>
<th>Min $B_{Te_{5px}}$</th>
<th>Max $Ae$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{tot}}$</td>
<td>0.68**</td>
<td>0.26**</td>
<td>0.71**</td>
<td>-0.48**</td>
<td>0.54**</td>
<td>0.66**</td>
<td>-0.10</td>
<td>0.53**</td>
</tr>
</tbody>
</table>

*Note: Correlation coefficients at a significant level of 95 % (*) and 99 % (**) .

The strongest correlations are observed between $P_{\text{tot}}$ and the maximum area (0.68), the life duration (0.71) and the strong convective life duration (0.66). Figure 5.17 (a), (b) and (c) shows the scatter plots of the three correlations. When considering only the very large clouds, the correlations coefficients between $P_{\text{tot}}$ and the life duration and between $P_{\text{tot}}$ and the strong convective life duration are even stronger (Fig. 5.17 (e) and (f)). In contrast, when considering only the smaller clouds, the correlation coefficients between $P_{\text{tot}}$ and the three cloud parameters, maximum area, life duration and strong convective life duration, are weaker (0.26, 0.48 and 0.26 respectively; not
shown here). Accordingly, the high correlation coefficients between the rain variable and the three cloud parameters mainly results from the rain and cloud characteristics of the very large MCS.

![Figure 5.17. Correlation plots between $P_{tot}$ and the maximum area, the life duration and the time interval during which BT10.8 is below 200 K; for all MCS tracked ((a),(b) and (c)) and for the very large MCS ((d),(e) and (f)).](image)

The propagation speed is also significantly correlated with $P_{tot}$. However, the correlation is only significant when considering all clouds (0.26) or only the very large clouds (0.27). When visualizing the correlation between the rain variable and the propagation speed, the data points are widely spread out (Fig. 5.18 (a) and (b)).
Like observed for the correlation between $P_{tot}$ and the propagation speed, the correlations between $P_{tot}$ and the minimum in BT10.8 as well as between $P_{tot}$ and the maximum $A_e$, are only significant when considering either all clouds (-0.47 and 0.53 respectively) or all the very large MCS (-0.53 and 0.49 respectively). In contrast with these, the maximum in $\Delta BT$ present a significant correlation with $P_{tot}$ for the three cases; when considering all the MCS, when considering the very large clouds only and when considering the smaller systems only. However, the strength of the correlation decreases when considering the very large clouds only (0.49 versus 0.54) and even more when considering the smaller clouds only (0.30).

5.2.6. Concordance and discordance between the time at $P_{max}$ and the time at maximum $A_e$ and minimum $BTe_{5px}$

As mentioned in the section 5.1.6, for 55% of the systems tracked over the first week of August, a local minimum in $BTe_{5px}$ was recorded a couple of hours before $P_{max}$ while the time of maximum $A_e$ usually coincided with the time of maximum rain or was close to it. With the three month dataset, we can further explore this. In order to evaluate if the timing of the maximum precipitation coincides with the timing of maximum $A_e$ and minimum $BTe_{5px}$ (after smoothing), we plotted the normalized time at maximum precipitation versus the normalized time at maximum $A_e$ and minimum $BTe_{5px}$. This is shown in Figure 5.19.

In Figure 5.19 (a) we can remark that the maximum $A_e$ usually precedes $P_{max}$. This is indeed the case for 68% of the clouds. For 15% of the MCS the time at maximum $A_e$ and at $P_{max}$ coincided. The pattern is slightly different in Figure 5.19 (b). For 69% of the systems, the minimum $BTe_{5px}$
precedes $P_{\text{max}}$, but only for 0.1 % of the systems the time for the 2 events coincides. In both Figures 5.19 (a) and (b), the data points show that for several systems, the maximum precipitation occurred at the first time step of their life cycle (for 12 out of the 358) or at the last step of the life cycle (16 out of 358). Similarly, we also observed that for several cases (16 out of 358) the minimum in $BT_{\text{50}}$ occurred at the last step of the life cycle of the systems. This issue is examined in more detail in the discussion.

![Figure 5.19. Normalized time at $P_{\text{max}}$ versus normalized time at maximum $Ae$ (a) and at minimum $BT_{\text{50}}$ (b).](image)

### 5.2.7. Impact of the solar heating and local orography on the rain efficiency

As stated in one of our hypotheses, parameters not directly related to the structural or radiative properties of the clouds may also be related to the rain efficiency, in particular the solar heating and orography. As mentioned in the literature, these two factors play a role in the development and structure of MCS. Accordingly, we stated that the local time at maximum precipitation is related to the rain intensity, and that a relationship exists between the location of the MCS (approximated by the longitude of the MCS) and the rain intensity.

The role of the solar heating as a trigger for rain efficient MCS is neither depicted by the correlation between the local time at $P_{\text{max}}$ and $P_{\text{max}}$, nor by the correlation between the local time at $P_{\text{max}}$ and $P_{\text{av}}$ or $P_{\text{tot}}$ (-0.16, -0.13 and -0.18 respectively). The correlation coefficients are significant with $P_{\text{max}}$ and $P_{\text{tot}}$ at the 99 % level and with $P_{\text{av}}$ at the 95 % level. Nevertheless, the scatter plots don’t show any linear or identifiable pattern (not shown here). In contrast, the distribution of the local time at $P_{\text{max}}$ shows that heavy precipitation occurs preferentially from late in the afternoon until very early in the morning (Fig. 5.20). When comparing this figure with the Figures 5.9 (f) and (g) (showing
the distribution of the initiation and dissipation time), we observe that maximum precipitation occurs mostly immediately after the peak in initiation time (around 1500 LT) and meanwhile the dissipation time with maximums during the night around 2200 LT and early in the morning 0500 LT.

![Figure 5.20](image)

*Figure 5.20. Distribution of the local time at $P_{\text{max}}$ for all MCS tracked over three month.*

The local orography (estimated by the longitude of the cloud centre) showed an inverse correlation with the three rain variables, $P_{\text{max}}$ (-0.43), $P_{\text{av}}$ (-0.63) and $P_{\text{tot}}$ (-0.28) (Fig. 5.21 (a), (b) and (c) respectively). Like often remarked in previous sections, when a distinction is made between very large MCS and smaller MCS, the former show stronger correlations with $P_{\text{max}}$, $P_{\text{av}}$ and $P_{\text{tot}}$ then the latter (Fig. 5.21 (d), (e) and (f)).

For all cases (when considering all MCS as well as when restricting the correlation to the two subclasses), $P_{\text{av}}$ shows stronger correlations than $P_{\text{max}}$ and $P_{\text{tot}}$. Hence, the mean precipitation over the Sahel may be strongly determined by the orography while the maximum intense precipitation and the total precipitation are mainly determined by other factors. This observation is investigated in more detail in the discussion.
5.2.8. Summary

Over the three months, we tracked 358 clouds. From these, 136 clouds presented an area larger than 80 000 km² for more than 3 hours, while 222 systems did not. The former were referred as very large MCS and the latter as smaller MCS. The distinction between these two subclasses appeared relevant since we observed that correlations between the rain variables, $P_{\text{max}}$, $P_{\text{av}}$ and $P_{\text{tot}}$ and the cloud parameters, were function of these two subclasses.

First, the cloud parameters were correlated with each other. From this we identified that the area of a MCS at maximum extent is strongly correlated with the strong convective life duration of MCS and the maximum area expansion, and lesser with the life duration and minimum in BT10.8. When we restricted the correlation to the smaller systems only, the correlation between the maximum area and the strong convective life duration and life duration was no longer significant. Significant correlations were also observed between radiative cloud parameters and structural cloud...
parameters. Indeed, the maximum area and maximum area expansion was related to the minimum in BT10.8_{px} and the maximum in ∆BT.

Next, the correlations between the three rain variables showed us that P_{tot} was better approximated by P_{max} then by P_{av}. Indeed, for the former, the correlation coefficient with P_{tot} was equal to 0.83, while, for the latter, the correlation coefficient with P_{tot} was only equal to 0.44.

Afterwards, we analyzed the correlations between each rain variable and the structural and radiative cloud parameters. From this we observed that P_{max} and P_{tot} were significantly correlated with the maximum area, the maximum in Ae, the propagation speed, the life duration, the strong convective life duration, the minimum in BT10.8_{px} and the maximum in ∆BT. In contrast the two rain variables were not correlated with the minimum in BTe_{px}. P_{tot} and P_{max} were significantly correlated with the seven cloud parameters when considering all MCS tracked over the three months and usually even more when considering the very large MCS only. In contrast, most of the cloud parameters were no longer significantly correlated when the study was restricted to the smaller MCS.

Only the strong convective life duration, the minimum in BT10.8_{px}, the maximum in ∆BT and the propagation speed were significantly correlated with P_{av}. For P_{av}, we also remarked that the correlations were maximal when we restricted the study to the very large MCS only.

The maximum in Ae and the minimum in BTe_{px} precede in more than 60 % of the cases the time at which P_{max} occurred. However, the time between P_{max} and the maximum in Ae and between P_{max} and the minimum in BTe_{px}, varies largely. This was observed by plotting the normalized time at P_{max} versus the normalized time at either the maximum in Ae or the minimum in BTe_{px}. The resulting scatter plots also showed that for 12 MCS out of the 358, the maximum precipitation occurred at the first step and for 16 MCS out of the 358, the maximum precipitation occurred at last step of the life cycle of the MCS.

Finally, we evaluated the impact of the solar heating and the orography on P_{max}. From this we showed that the correlation between the local time at P_{max} and P_{max} was very weak. However, the distribution of the local time at P_{max} gave more relevant information. Indeed, when comparing it with the distribution of the initiation time and dissipation time, we observed that P_{max} usually occurs straight after the peak in initiation time and during the dissipation time from late in the evening until early in the morning. From the correlation between the rain variables and the orography
(approximated by the longitude at $P_{\text{max}}$), we observed that the longitude at $P_{\text{max}}$ was inversely correlated with the three rain variables and the correlation coefficient was maximal when correlated with $P_{\text{av}}$. The three correlation coefficients were also stronger when we took into consideration only the very large MCS.
6. Discussion

6.1. Agreements and disagreements between results and hypotheses

6.1.1. Relating rain efficiency with structural and radiative cloud parameters

In section 3, we stated that the rain efficiency of MCS (estimated by the maximum, average and total precipitation) is related to the size of the MCS at its maximum extent, the propagation speed, the life duration of the system and the time interval during which the MCS shows very deep convection. From the three month analysis, we observed that the total precipitation and the maximum intense precipitation are significantly correlated with the maximum area, the propagation speed, the life duration and the strong convective life duration of the MCS. As with Laurent et al. (1998a) and Mathon et al. (2002), we can also assume that large, fast-moving and long-lived MCS induce heavier and more precipitation than smaller, slow and short-lived MCS. However, it appears that these correlations are not significant when considering the smaller MCS. Accordingly, an increase in maximum cloud area, propagation speed and life duration, does not increase the probability of heavier and more precipitation when considering only smaller MCS (MCS that don’t present an area larger than 80 000 km² for more than 3 hours).

We also expected the rain variables to be related to the brightness temperature of the system and the brightness temperature of the most convective region of the system. This was verified by the correlations between the radiative parameters, minimum in BT10.8 and maximum in ∆BT, and the rain variables. These indicate that MCS presenting very low brightness temperature during their life cycle, as well as large differences in brightness temperatures averaged over the entire cloud, and averaged over the convective core, are more probable to generate more and heavier precipitation and higher average precipitation. The results also showed that the strength of the correlation increases when considering only the very large MCS.

6.1.2. Timing the maximum intense precipitation

The results showed that the hypothesis stating that maximum precipitation occurs when the system shows a maximal area expansion (as noticed by Machado and Laurent (2004)) and vertical updraft (estimated by a large decrease in BT10.8_{500}), is only partially true.
From the one week study we observed that for 78% of the MCS tracked during the first week $P_{\text{max}}$ coincided with a local minimum in BT10.85px and an increase in $\Delta BT$, but rather preceded the maximum area. This is, in our point of view, coherent with the development and structure of MCS. Indeed, deep convection results in heavy precipitation which, in turn, reduces the buoyancy by its drag force and counteracts the vertical updraft. Since precipitation cools the air layers, divergence increases. This explains why MCS attain their maximal area not long after they generated maximum intense precipitation. The increase in $\Delta BT$ at the time of $P_{\text{max}}$ indicates that, at this stage, the systems show very deep convection and subsequently significant updraft velocity in their convective core, while the anvil stratiform cloud remains lower. However, these relationships are not valid for all the MCS. Indeed, exceptions were observed in particular when split and merging events were recorded or when the MCS remained relatively small.

The three month study showed that for most of the cases, $P_{\text{max}}$ occurred at the time of minimum BT10.85px or slightly later and some time before the cloud area was maximal. However, the scatter plots in Figures 5.19 (a) and (b) showed that the time lapse between the minimum in BT10.85px and $P_{\text{max}}$ and between the maximum Ae and $P_{\text{max}}$ varies greatly. As mentioned for the one week analysis, these large variations may be related to merge and split clouds. Systems which reinforced during their life cycle may also influence the results. The distribution of the local time at $P_{\text{max}}$ indicated that several systems, which initiated in the afternoon, induced maximum intense precipitation more than ten hours later, around 0500 LT. These systems may present several sequences of initiation, mature and dissipation stages during their life cycle. A closer look at these systems may explain why we observed large variations in time intervals between the minimum in BT10.85px and $P_{\text{max}}$ and between the maximum Ae and $P_{\text{max}}$.

However, beside the merging and splitting events, we also believe that inaccuracies emerged due to the temporal resolution of our dataset. As noted by Schröder et al. (2009), a more accurate study of the vertical updraft and expansion rate of MCS requires a small time step between the successive images. In the present study, we showed that variations in temporal resolution between 15 minutes and 1 hour did not significantly alter the number of MCS tracked. However, we didn’t investigate the impact of variations in temporal resolution on the accuracy and continuity of our cloud parameters. ‘Evolution parameters’ such as Ae and BTe5px may be more sensitive to variations in temporal resolutions.
6.1.3. The influence of solar heating and orography on the rain efficiency of MCS

The last two hypotheses stated that the rain intensity could be explained by the local time and the location at maximum intense precipitation as a result of the orography and solar heating which are known to have an influence on the development and structure of MCS.

The first hypothesis was not verified. However, the distribution of the local time at maximum intense precipitation is consistent with the literature. According to previous studies, there is a lapse of time between initiation and mature stage and therefore convective activity occurs later in the afternoon and early in the evening (Desbois et al., 1988; Hodges and Thornicroft, 1996; Mathon and Laurent, 2001; Schröder et al. in press). This is consistent with Figure 5.20, which shows that maximum intense precipitation occurs preferentially late in the afternoon and evening. As mentioned in the previous section, another peak in maximum intense precipitation is also observed around 0500 LT. In section 6.1.2., we associated this to systems presenting several sequences of initiation, mature and dissipation stages during their life cycle. However, we may also relate this maximum in intense precipitation to the effect of coastal areas. Our study area includes a small area on the coast of Nigeria and the coastal areas of Togo and Benin (Fig. 1.1.). According to Schröder et al. (2009), along the west coast of Africa, maximum convective activity occurs at noon and early in the morning. Hence, the maximum in intense precipitation around 0500 LT may be explained either by systems which reinforced during their lifecycle or by systems influenced by the land-sea breeze which triggers the initiation of deep convection at coastal areas. This is also consistent with the strong inverse correlation between $P_{\text{max}}$ and the longitude at $P_{\text{max}}$ since the coastal areas are located in the south-west edge of our study area.

Aside from the coastal effect, the strong inverse correlations between the rain variables and the longitude at maximum intense precipitation can be justified by the Mount Cameroon region. One of the wettest places in the world, known as Debundscha point, is located around 4°N and 9°E on the foot of Mount Cameroon (NCDC/NOAA, 2008). Figure 6.1 shows the total precipitation during the period July 1st- September 22nd. In this figure, we can observe that the maximum total precipitation to fall during the three months is recorded in nearby Dedundscha around 6°N and 9°E. This follows the results of Schröder et al. (2009) who observed strong convective activity in the vicinity of the Cameroon highlands in June 2006. Hence, on average, more rain falls around Dedundscha explaining the strong inverse correlation between the longitude at maximum precipitation and $P_{\text{av}}$. The weaker correlation between the longitude at maximum precipitation and $P_{\text{max}}$ reveals that heavy precipitation is related to other factors more then the average precipitation.
When we look back to the ‘large fast-moving long-lived MCS’ described in section 5.1.3., we observe that the maximum intense precipitation occurred at a later phase of the mature stage (after a minimum in BT10.8$_{px}$ and after the MCS attained its maximum area). Additionally, Figure 5.4 showed that maximum intense precipitation occurred above the Mount Cameroon. Accordingly, at the end of its mature stage the system was forced upwards by the local orography, resulting in a reinforcement of its convective activity. This may also explain the evolution of the ‘most rain efficient MCS’ described in section 5.1.4. This system originated from several split clouds which merged together into a single convective system. As noted in the literature, the split events indicate a weakening of the convective activity and merge events result from a convective strengthening (Mathon and Laurent, 2001; Schröder et al., 2009). In Figure 5.6, we can observe that the convective strengthening and subsequent maximum intense precipitation, coincides with the time at which the system is forced upwards above the Cameroon Highlands.

![Figure 6.1. Total precipitation fallen during the period July 1$^{st}$ – September 22$^{nd}$ 2006.](image)

6.2. **General remarks when relating cloud parameters of MCS with rain efficiency**

From our results we observed that a significant correlation between a given cloud parameter and rain variable does not ensure that the correlation remains significant when considering a subsample of MCS. In other words, ‘under some conditions’ only, rain efficiency and structural and radiative
cloud parameters are significantly correlated. As has already been observed when analyzing the
MCS tracked over the first week of August, smaller clouds can be considered as exceptions to the
relationship between the cloud parameters and rain variables observed. Accordingly, further
research should be done in order to define and classify the ‘conditions’. This will lead to the
definition of subclasses of MCS. When considered separately, subclasses may present better
correlations coefficients between rain variables and cloud parameters.

Similarly, a significant correlation between a given cloud parameter and rain variable does not
ensure that the cloud parameter is significantly correlated with another rain variable. For instance,
while significantly correlated with $P_{\text{max}}$ and $P_{\text{tot}}$, neither the maximum area nor the life duration is
significantly correlated with the mean precipitation. Accordingly, larger and smaller MCS and long-
and short lived MCS present similar average precipitation. We even observed that the maximum in
$P_{\text{av}}$ was generated by a smaller MCS.

In the one week study we observed that the variations in average precipitation over the entire life
cycle of the MCS ($P_{\text{av}}$) were not as pronounced as the variation in intense precipitation ($P_{\text{max}}$) and
therefore the relationships between $P_{\text{av}}$ and the cloud parameters were not as noticeable. From the
three month analysis, we observed that the structural and radiative cloud parameters showed
stronger correlations with $P_{\text{max}}$ than with $P_{\text{av}}$. Moreover, $P_{\text{max}}$ is, in our point of view, a more reliable
variable than $P_{\text{av}}$. The latter is largely dependent on the applied methodology and in particular on
the buffer width. As a reminder, $P_{\text{av}}$ was estimated as the sum of the total rain that fell inside the
rectangular box (including the buffer) divided by the number of rainy pixels inside the box. Hence,
some rain variables are preferred to others.

As with the rain variables, some cloud parameters are preferred to others. For instance, the strong
convective life duration (which is defined as the time interval during which BT10.8$\text{_px}$ is below 200
K) is a more valuable cloud parameter than the life duration. In contrast with the life duration, this
parameter is not sensitive to the used methodology and in particular to the area cut-off and
brightness temperature threshold. Hence, it allows comparing the results with other studies based on
slightly different thresholds or area cut-off. Moreover, out of all the selected cloud parameters, it is
with the strong convective core life duration that we observed the strongest correlation with $P_{\text{max}}$
and $P_{\text{tot}}$. Furthermore, while $P_{\text{av}}$ isn’t related to the life duration, it is related with the strong
convective core life duration.

Finally, we also observed that comparing our results with results from the literature is not
straightforward. First as several studies focused on single MCS and, as shown in the present study, variations in behaviours and characteristics of MCS are large. Secondly, as there is no universal definition of MCS, we have to ensure that the definition of MCS in our study coincides with the definition made by the authors.

6.3. Short comings in tracking and overlay method

During the course of this study we identified several potential improvements to our methodology which could improve the level of accuracy.

(i) Threshold, minimum overlap, area cut-off and temporal resolution. When we examined the sensitivity of the results to variations in temporal resolutions, we observed that the number of clouds tracked, varied as a function of the temporal resolution. This is illustrated in Figure 6.2, in which two MCS, visually considered as two different clouds (indicated by the number 1 and 2 on the figure), are tracked differently depending on the temporal resolution. The black arrows between the figures of each row indicate the evolution of the MCS.

The first row of images (Fig. 6.2 (a)) corresponds to a MCS tracked with $\Delta t_{15\text{min}}$ at 12, 27, 42 and 57 minutes past each hour. Only the images taken 27 minutes past each hour are shown. Between 1527 LT and 1627 LT, two clouds merged into a single cloud. Between 1627 and 1727 LT, the tracked cloud split and the two resulting ‘split clouds’ were tracked separately. Cloud 1 was not retained as a MCS between 1527 LT and 1627 LT as it didn’t present an area larger than 30 000 km² for more than 3 hours. After 1627 LT, a new MCS initiated by splitting (Cloud 1 on the last image in Fig.6.2 (a)). Subsequently, between 1527 LT and 1727 LT, with a temporal resolution of 15 minutes, two clouds were recorded; Cloud 2 before merging and the new Cloud 1, which initiated by splitting.

The next two rows (Fig. 6.2 (b)) show the same MCS tracked every 30 minutes at 12 and 42 minutes past each hour. In these, the two clouds, which merged at 1627 LT, did not merge at 1612 LT or at 1642 LT (not shown here). Hence, as the 30 minutes resolution analysis could not make out that the two clouds merged at 1627 LT, both clouds were tracked separately.

The last row (Fig. 5.16 (c)) shows the same MCS again, tracked with $\Delta t_{1h}$ every 27 minutes past each hour. At 1627 LT, the two clouds merged again into a single cloud. In contrast with the case observed with $\Delta t_{15\text{min}}$ at the next time step the cloud that showed the strongest similarity
with the single merging cloud was Cloud 1. Cloud 2 was retained between 1527 and 1627 LT only, and after merging, the tracking method assigned the same region index to Cloud 1. Hence, between 1527 LT and 1727 LT with 1 hour temporal resolution only one cloud was counted while two clouds were tracked for both $\Delta t_{15\text{min}}$ and $\Delta t_{30\text{min}}$.

The assignment of a MCS differs thus, as a function of the image. As illustrated in Figure 6.2, images at 1612 LT and 1627 LT do not lead to the same assignment. The main assumption in tracking is that the cloud doesn’t change significantly (in brightness temperature and area) between two successive images (Schröder et al., 2009). Consequently, a high temporal resolution should be preferred. However, in order to reduce the computational work, further research should be done to evaluate the most appropriate threshold, minimum overlap and area cut-off as a function of the temporal resolution.
Figure 6.2. Differences in tracking resulting from differences in temporal resolution. MCS tracked with $\Delta t_{15\text{min}}$ (a), with $\Delta t_{30\text{min}}$ (b) and with $\Delta t_{1\text{h}}$ (c). Tracking date and local time are given underneath each image. The numbers 1 and 2 indicate the two clouds visually differentiated from each other. The black arrows indicate the evolution of the cloud as a function of the temporal resolution.

(ii) Overlay between Meteosat and TRMM data. Firstly, we observed that the overlapping of different boxes caused an overestimation of the total rain generated by the tracked MCS. Secondly, the lack of boxes in the Meteosat data may result in a misleading.
idea about the importance of MCS (as defined in the present study) as a rain source in the Sahel. Consequently, the rectangular-box approach used to retrieve the rain variables for each system could be improved. Another alternative, which may be more accurate, is to identify contiguous areas of rainy pixels and assign these to the overlapping MCS. Imposing a minimum overlap criterion may further improve the overlay.

(iii) *Split and merge events.* These events are amongst the most ‘annoying’ factors when studying the relationship between cloud parameters and rain variables. Indeed, low correlation coefficients are, in our point of view, often weakened by sudden shifts in structural and radiative characteristics induced by merging and splitting events. For instance, the calculated correlations between the rain variables and the propagation speed were smaller than expected (below 0.33). Since the propagation speed is estimated based on the displacement of the cloud centre, we believe that the results may be mistaken due to abrupt changes in the cloud centre after the cloud has merge or split. Research over a longer period of time may allow us to have a more significant number of MCS with no merging or splitting events (in the present study, only 13 clouds out of the 358 never merge or split). Our methodology may then be applied on these MCS which will ensure that changes in cloud parameters are merely initiated by internal cloud dynamics or external factors other than merging or splitting events.

(iv) *Data filtering.* Excluding outliers such as merging and splitting events as well as MCS tracked only over a fraction of their life duration, could also result in stronger correlations between cloud parameters and rain variables. As mentioned previously, further research could be done in order to identify the systems presenting maximum intense rainfall, maximum Ae or minimum BT_{5px} at the very beginning or end of their life cycle. If justified we may exclude them from the cloud sample or consider them separately. Examples of such systems are MCS which reinforced after dissipation or MCS which didn’t dissipate or initiate inside the study area and during the period of interest. Applying the tracking over a larger area than our study area and excluding all the MCS which don’t spend the majority of their life time inside the study area may present an alternative to get around the MCS which are tracked only over a fraction of their life cycle.
Conclusion

The vulnerability of the Sahel with respect to rainfall and the more frequent dry years occurring since the early 70’s, explain the importance of an in-depth understanding of the behaviour of MCS and their efficiency as a precipitation source. We proposed a way to improve this understanding by investigating the relationships between initiation, development and structure of MCS and their rain efficiency.

In the present study, MCS were tracked and cloud parameters were retrieved based on hourly IR10.8 Meteosat geostationary satellite images over the summer of 2006. Rain estimations for each MCS were derived from the 3-hourly Tropical Rain Measurement Mission (TRMM) data. The tracking method, developed by Schröder et al. (2009) and based on the difference in cloud area, on the spatial translation and the cloud area overlap, was slightly adapted to our definition of MCS: (1) large contiguous clouds colder than 233K, (2) showing an area exceeding 30 000 km² for more than 3 hours, (3) travelling west-ward in our study area, and (4) having at least once during their life cycle, region(s) of very high convection with average brightness temperatures colder than 210K. After tracking, we estimated for each system the generated maximum, average and total precipitation.

As the three month study required long computational efforts, our method was firstly tested on a single week, from July 31st till August 6th 2006. MCS tracked during the first week of August were visually analyzed and their rain efficiency and cloud parameters were plotted as a function of the local time. From this we concluded that maximum intense precipitation (average precipitation of the most intense rainy TRMM pixels) occurs during a later phase of the mature stage. Notably after an increase in vertical updraft strength, resulting in a drop in brightness temperature in the convective core (BT10.8₃px), and before an increase in horizontal extent. In the literature the area expansion rate was considered as a good indicator to estimate the mass flux in the convective core (Machado and Laurent, 2004); the minimum in brightness temperature change as a good indicator to approximate the strength of the convective activity. However, the large temporal resolution and the inaccuracies resulting from our threshold, tracking and overlay method didn’t allow us to directly relate these parameters to the rain efficiency of MCS.

From the literature it appeared that large, fast-moving and long-lived MCS induce heavier and more precipitation (among others, Laurent et al., 1998 a; and Mathon et al., 2002). In the study over the
three month period (July-September 2006), we showed that this assumption was only confirmed for very large clouds (MCS who presented an area larger than 80 000 km² for more than 3 hours). These clouds also confirmed the observed relationships between MCS rain variables and cloud parameters, whereas these relationships were not clear when investigating only smaller clouds.

Overall, the relationships between the rain efficiency of MCS and their structural and radiative parameters were only confirmed under certain conditions. This excludes systems with particular behaviours (among others, merging and split events, partially tracked clouds or systems which reinforce during their life cycle). Such systems should in further research be filtered out of the cloud sample or be considered separately.

Furthermore, relationships between rain variables and cloud parameters that were not addressed in the literature also emerged. We found that MCS showing convective cores that are particularly cold compared to the average brightness temperature of the system (a large $\Delta BT$) and that last for a longer time (longer time interval during which $BT_{10.8_{\text{px}}}$ is below 200 K), are more likely to generate heavier and more precipitation. In our point of view, these parameters are more reliable and less sensitive to the thresholding and tracking method than common cloud parameters like the brightness temperature averaged over the entire cloud ($BT_{av}$) and the life duration.

The present study emphasised advantages of thresholding and tracking methods for the analysis of MCS. However, it only outlined a glimpse of the capabilities of these methods. Exploring the impact of variations in matching criteria and temporal resolution and data filtering may lead to a more straightforward methodology and subsequently to more consistent results. The results of this thesis may aid movement in that direction.
References


