Cloud properties during active and break spells of the west african summer monsoon from CloudSat-CALIPSO measurements

E. Efon, A. Lenouo, D. Monkam, D. Manatsa

PII: S1364-6826(16)30095-5
DOI: http://dx.doi.org/10.1016/j.jastp.2016.04.001
Reference: ATP4399

To appear in: Journal of Atmospheric and Solar-Terrestrial Physics

Received date: 5 September 2015
Revised date: 31 March 2016
Accepted date: 1 April 2016

Cite this article as: E. Efon, A. Lenouo, D. Monkam and D. Manatsa, Cloud properties during active and break spells of the west african summer monsoon from CloudSat-CALIPSO measurements, Journal of Atmospheric and Solar Terrestrial Physics, http://dx.doi.org/10.1016/j.jastp.2016.04.001

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting galley proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.
Cloud properties during active and break spells of the West African Summer Monsoon from CloudSat-CALIPSO measurements

Efon E. 1,*, A. Lenouo 1,2, D. Monkam 1, D. Manatsa 2,3,4

1Laboratory of Environmental Physics, Department of Physics, Faculty of Science, University of Douala, P.O. Box 24157 Douala, Cameroon
2ICTP - Strada Costiera, 11, I - 34151 Trieste Italy
3Faculty of Science, Bindura University of Science Education, P. Bag 1020, Bindura, Zimbabwe
4Geography Department, University of Free State, Qwa Qwa Campus 9866, South Africa

*Corresponding authors : ericefon@yahoo.fr, lenouo@yahoo.fr

Abstract

High resolution of daily rainfall dataset from the Tropical Rainfall Measuring Mission (TRMM) was used to identify active and break cloud formation periods. The clouds were characterized based on CloudSat-CALIPSO satellite images over West Africa during the summer monsoon during the period 2006 - 2010. The active and break periods are defined as the periods during the peak monsoon months of June to August when the normalized anomaly of rainfall over the monsoon core zone is greater than 0.9 or less than - 0.9 respectively, provided the criteria is satisfied for at least three consecutive days. It is found that about 90% of the break period and 66.7% of the active spells lasted 3 - 4 days. Active spells lasting duration of about a week were observed while no break spell had such a long span. Cloud macrophysical (cloud base height (CBH), cloud top height (CTH) and cloud geometric depth (∆H), microphysical (cloud liquid water content, (LWC), liquid number concentration (LNC), liquid effective radius, ice water content (IWC), ice number concentration (INC) and ice effective radius) and radiative (heating rate properties) over South Central West Africa (5⁰- 15⁰N; 15⁰W - 10⁰E) during the active and break spells were also analyzed. High-level clouds are more predominant during the break periods compared to the active periods. Active spells have lower INC compared to the break spells. Liquid water clouds are observed to have more radiative forcing during the active than break periods while ice phase clouds bring more cooling effect during the break spells compared to the active spells.

Keywords: Cloud; West African monsoon; Active- break period; Intraseasonal variability

1 Introduction

Clouds greatly affect the radiation and hydrological budget of the earth-atmosphere system by reflecting, absorbing and transmitting radiation (Ramanathan et al., 1989; Wyser, 1998; Hirsch et al., 2012; Holl, 2013; Das et al., 2013). This is possible via feedback mechanisms on radiation, which depend mainly on cloud macrophysical properties (like cloud base heights, cloud top heights, geometric depths, cloud spatial distribution, etc) and microphysical properties (like
cloud number concentration, cloud effective radius, liquid water content, ice water content, optical thickness, etc). The region’s climate depends strongly on the surface energy balance and interaction with moist and dry convection (Stein et al., 2012). Due to cloud large spatial variability (Protat et al., 2010), their parameterization in climate models generate large uncertainty especially in estimating global warming (Das et al., 2013). As a result of these large uncertainties in climate models, further characterization of clouds will be of major importance in modelling the earth-atmosphere radiation budget (Das et al., 2013).

The West African Monsoon (WAM), according to the World Meteorological Organization (WMO) classification, starts from June to September. Central and West Africa receive between 70 - 85% of the total annual rainfall during the West African Summer monsoon season and therefore has a pronounced impact on agriculture (Janicot et al., 2009), which is the backbone of the economy of most of the countries in the region (Sylla et al., 2013). From June to August, which is the peak monsoon period (Sylla et al., 2013), the active and break spells of the monsoon rainfall is one of the interesting events corresponding to intense agricultural activities in West Africa. During the critical growth periods of vegetation, long break and active periods may lead to low agricultural yield due to water deficiency and flooding of farming lands respectively. These events are generally characterized by a poleward migration of intraseasonal oscillations (ISO) and cross-equatorial variability in sea surface temperature (SST) (Giannini et al., 2003; Lu and Delworth, 2005; Biasutti et al., 2009). The region bounded by (5 – 15°N, 15°W – 10°E) within the red rectangle in Fig. 1, receives 65-80% of all West African monsoon seasonal rainfall. We refer to this region as the West African core monsoon zone.

Generally, the active spell of monsoon is associated with cyclonic (anticlockwise) vorticity (Holton, 2004) and a decrease of surface pressure in the monsoon trough over the Sahara between the Hoggar and Atlas mountains (Lavaysse et al., 2009, 2010). The average life time of this synoptic disturbance marked with fast growing convective instability is about 3- 4 days. The strength of the cyclonic vorticity and rainfall is weak during the break phase. The atmosphere is more stable during the break phase, and this state persists until a synoptic scale system or northward propagating Intertropical Convergence Zone (ITCZ) comes over the monsoon zone. During the active spell, the African Easterly Jet (AEJ), which is a mid-tropospheric (600–700 hPa) core of strong zonal winds (up to 10 ms⁻¹) that propagates from East to West Africa, is most prominent among other features that produce rainfall. The African Easterly Waves (AEWs) intensify during the active phase of the monsoon as a result of the occurrence of deep, moist and shallow cumulus convection (Lenouo and Mkankam, 2008; Sylla et al., 2013). Most of the convective rainfall follows a south-north-south displacement of the ITCZ (Janicot et al., 2009) with a mean upward motion that reaches the height of 200 hPa. At this level during boreal summer, the Tropical Easterly Jet (TEJ), which is associated with the Indian Summer Monsoon (ISM) outflow, affects West Africa, and intensifies during the active period of the monsoon (Sylla et al., 2013). These features form the well-defined meridional structure of the WAM circulation (see Fig. 2 of Sylla et al., 2013).

During the break phase over the coast of Guinea, around 5°N, the monsoon trough shift northward, towards the Sahel region around May-June and produces heavy rainfall there (Lenouo et al., 2010; Sylla et al., 2013; Zebaze et al. 2015). Over Sahel during the break spell, the AEJ is more equatorward (Sally et al., 2013). Extended breaks can lead to drought
conditions; while on the other hand, extended active periods can result in floods. Therefore, examining vertical structures and microphysical properties of clouds during the active and break periods of the WAM is essential for understanding the role of clouds in precipitation.

Goswami et al. (2003) noticed that during the active and break periods of the ISM, there is contrasting behavior in the formation of weather systems and large-scale instability. Kiran et al. (2009) analyzed cloud and aerosol properties during the active and break spells of ISM using data from the Moderate Resolution Imaging Spectrometer (MODIS) and showed that there is more (less) frequent cloud occurrence over the Arabian Sea and West coast of India during the active (break) periods. Rao et al. (2010) investigated rainfall, circulation pattern and mesoscale convection during the active and break periods of the ISM (Rajeevan et al., 2010). Das et al. (2013) using CloudSat and Cloud Aerosol Lidar, and Infrared Pathfinder Observation Satellite (CALIPSO) showed that there is a large variability in the macrophysical and microphysical properties of clouds during the active and break spells of the ISM. The respective space based platforms use radar and lidar to detect hydrometeors and aerosols to define clouds vertical structure and microphysical properties. The lidar, which has a finer resolution, is used to detect clouds and aerosols while the radar employs a coarser resolution to sense clouds. The synergy between these two satellites gives a better insight into cloud macrophysical and microphysical properties (Sassen et al., 2009).

Stein et al. (2011), using CloudSat-CALIPSO dataset studied WAM cloud-macrophysical properties from 2006 to 2009, and reported clear diurnal signal in zonal mean cloud structure, dominated by deep convective activities. These were enhanced at night producing cirrus and anvil clouds, while more shallow clouds and congestus were observed during the day. They also noticed that a layer of altocumulus is omnipresent over the Sahara desert. Bouniol et al. (2012) analyzed WAM clouds macrophysical and cloud radiative properties using data collected over Niamey-Niger in 2006 with the Atmospheric Radiation Measurement (ARM) mobile facility and CloudSat-CALIPSO data. They found that mid-level and anvil clouds occur more frequently over the Sahara desert and have their largest impact on longwave and shortwave radiation respectively.

In this paper, we consider the region of West Africa between 5°N – 15°N and 15°W- 10°E (Fig. 1) to investigate the variability of cloud properties during the active and break spells of the WAM for the period 2006-2010 using the TRMM, CloudSat and CALIPSO datasets. This helps us understand the cloud-precipitation and cloud-radiation relationships during the WAM season. The paper is organized as follow: section 2 presents the data and methods used in order to compute the active and break periods of the WAM. It also presents atmospheric phenomena during the both monsoon periods. Results and discussion are provided in section 3. Finally, section 4 comprises of summary and concluding remarks.

2 Data and Methodology

In the present study, we used 3B42 version 7 data, which is a blended TRMM rain product for the monsoon season from June to September. It provides mean daily estimations of rainfall on a grid of 0.25° x 0.25°. The TRMM data is extracted between latitude 5° - 20°N and longitude 15°W – 10°E to represent W. Africa. The data are from 2006 - 2010 and have less than 5%
missing data. Averaging the regional data per day helps us calculate the rainfall anomaly necessary to determine active and break days. Active and break spells were identified when the standardized rainfall anomaly over the West African core monsoon region exceeds (less than) 0.9 (-0.9) with a sensitivity of 10% for at least three successive days during June 1 to August 31. The standardized rainfall anomaly time series for the years 2008 and 2010 are shown in figure 2. 2010 (Fig. 2b) was an excess monsoon year compared to 2008 (Fig. 2a). Due to early southward retreat of the rain belt (September-October) as documented by Le Barbe et al. (2002), the active and break spells were considered from June 1 to August 31.

After identifying the active and break periods for the WAM, we then used the corresponding CloudSat products to analyse the corresponding cloud properties. The data products used from CloudSat are the 2B-GEOPROF-LIDAR, 2B-CWC-RVOD and 2BFLXHR. The 2B-GEOPROF-LIDAR product identified hydrometeor layers and provided information about cloud base and top heights, and cloud geometric depth, the 2B-CWC-RVOD product provides information on cloud microphysical properties (cloud number concentration, cloud effective radius, liquid water content, ice water content, etc). The 2B-FLXHR is used to determine the heating rate for individual cloud profiles. Details on the algorithm and retrieval techniques of CloudSat data products can be found on the website http://cloudsat.atmos.colostate.edu/.

The normalized rainfall anomaly \( A_G \) for a given gridded data is computed as:

\[
A_G = \frac{R_G - R_m}{\sigma}
\]

where \( R_G \) is the rainfall total for the gridded point \( G \) during the season, \( R_m \) and \( \sigma \) are long-term mean and standard deviation of the seasonal rainfall total for the grid respectively.

To validate CloudSat and CALIPSO observations made during the active and break periods of the WAM, we used Re-analysis Data from the European Centre of Medium range Weather Forecast (ECMWF) data (available at http://data.ecmwf.int/data/) on a grid of 0.75° x 0.75°. Cloud cover for different cloud types, longwave radiation, shortwave radiation and mean specific cloud ice water content were derived from the ECMWF fields prior to sunrise (0600LST) and sunset (1800LST). Details of the ECMWF reanalysis dataset can be found in Dee et al. (2011).

3 Results and discussions

3.1 Active and break spells of the West African summer Monsoon

The active and break spells identified using TRMM are shown in table 1. It can be noted from this table that the active spells occur in two years only (2008 and 2010). 2008 has two active spells in August, with that occurring from the middle of the month being the longest, having 7 days of intense rainfall. On the other hand, all the years have at least one break period. It can be noticed that years without a single active spell have three break spells, except in 2007, which has only one break spell. Altogether, 13 active spells and 34 break spells were identified during the five years study period. All the active spells were in the month of August. This implies that August is the wettest month of the monsoon season, being characterized by rainfall spells that may last several days. From table 1, it is found that the value 4.4 (3.4) is equal to the sum of number of active (break) days/number of active (break) spells (e.g. 4.4 = (3+7+3)/3). The
standard deviation show the extent to which the number of active (break) days per period vary from the mean. The standard deviation of active spell (2.3) is much larger than that of the break spells (0.7). This suggests that the occurrence of the former vary far more than the latter (by at least an order of three). However during the season, more break spells were observed in June than in July and August.

Table 2 shows standard errors in cloud microphysical properties for the active and break spells of the WAM during the study period. These errors show fluctuations in the microphysical properties between active and break spells of the monsoon season. It is clearly seen in the table that for each cloud type, there is variability in microphysicial properties between the active and break spells. More variability is observed in INC for all cloud types. Table 3 shows the frequency distribution of duration of active and break periods (in per cent). It is noticed from the table that the mode is for short spells (3-4 days) for both active and break periods. Break spells tend to have a shorter lifespan (90%) than active spells (66.7%). 33.7% of active spells lasted about a week while only 10 % of breaks lasted for up to 6 days.

3.2 Variability in the macrophysical properties of monsoon clouds

West Africa is subjected to contrasting types of weather systems moving over the surrounding seas and creating a highly variable temperature and humidity structure over the region. Both the regional and the local meteorological conditions which determine the active and break periods in cloud properties were used, due to the advantage that the satellite passes directly over this region. CloudSat reflectivity from the granule 23026 (a) and 22689 (b) for segment 17 which crossed the study region during the days 26 August 2010 and 27 July 2010 for active and break periods respectively is show in the figure 3. Fields available in the 1A-AUX data set used by this algorithm include time (UTC) and spacecraft geodetic latitude/longitude (Lenouo, 2014). Convection is more intense during active periods where cumulonimbus clouds extend up to 20 km. Similar results were found by Lenouo (2014) using data from a different set of cloud data in Douala (4°N, 9.7°E) and neighbouring areas during the days of 26 January 2009 at 233525 UTC and 5 July 2009 at 233552 UTC. He showed that during the rainy season, the CloudSat profile shows intense convection characterized by cumulonimbus clouds which rise up to the stratosphere.

In this section, cloud macrophysical properties are investigated in terms of cloud top and base heights (GEOPROF-LIDAR product), and cloud geometrical depth. Figure 4 shows the occurrence (in percentage) of cloud base height (CBH) and cloud top height (CTH). It can be noted that the CBH distributions during the active and break spells are almost similar. However, CTH distributions and occurrence frequencies are different during both occasions. This could be explained by the differences in the corresponding large scale monsoon circulations. However, the CBH distribution is bimodal for both the active and break spells of the monsoon season. For both occurrences, the primary maximum in CBH frequency is in the range of 12-13 km, while the secondary peak is in the range 4-5 km and 6-7 km for the active and break period respectively. Although the CTH distribution also shows a bimodal distribution during the active and break spells, the bimodal structure is less prominent during the break period.
In the CTH distribution, the primary peak range from 13-14 km (14-15 km) for the active (break) periods and the secondary peak range from 7-8 km (9-10 km) for the active (break) spells. Using ground based lidar measurements, Protat et al. (2011) similarly reported a bimodal distribution in the CTH at Darwin (12.45°S, 130.83°E). They observed differences in CTH during both spells of the monsoon, with CTH rising up to 13.5 km and even higher (16 km) during the active spells. They attributed this difference to the local wind, which is westerly during the active and easterly during the break periods. Das et al (2013) used CloudSat geoprof-lidar data to study cloud macrophysical properties during the ISM. They observed similar results with the primary peak in CTH ranging from 16-17 km and the secondary maximum ranging from 2-3 km during the two different spells of the monsoon. These results were attributed to the wind flow (low level jet) that remains westerly during both active and break spells, but with their magnitude weakening during the latter.

However, over West Africa, the situation is different. Both the AEJ and the AEWs intensify during the active period. In addition, the TEJ, which is teleconnected to the ISM outflow, intensifies across West Africa during the active period (Sylla et al., 2013). The frequency of occurrence of CTH >16 km is about 8.6% (15.4%) during the active (break) periods. More CTH are at or above the tropopause during the break than the active spells. Clouds in this zone of the atmosphere play an important role in transporting water vapour to the lower stratosphere. Due to the strong and intense convective activities during the active period, more deep moist and shallow cumulus convective clouds were formed compared to the break conditions. Note that CBH (CTH) has a broad spectrum in the altitude range of about 9-14 km (12-16 km), and this is attributed to the presence of anvil and cirrus clouds during both conditions of the monsoon. The occurrence of CBH at higher altitude (> 13 km) is slightly more pronounced during the break (25.1%) spell than during the active (21.4%) spell. Similar differences are observed in the CBH occurrence at lower altitude (≤ 2 km), which is 6.8% for the break condition and 5.1% for the active period. In the mid troposphere (2-13 km) 73.5% of CBH occur during the active while 68.1% occur during the break spells.

We derived the geometrical depth (ΔH) by subtracting CBH from CTH. The distribution of ΔH during the active and break periods is shown in figure 5. From this figure, it is noted that the distribution of ΔH of clouds during both spells of monsoon display a Gaussian distribution. The distribution has a peak that ranges from 1 to 2 km for both active and break periods but with different occurrence frequency. 31.6% (36.9%) of the total clouds observed during the active (break) spells had vertical extension ranging from 1 to 2 km. The distribution of ΔH shows a higher peak frequency for geometrically thin clouds (with ΔH < 3 km) than for the geometrically thick clouds. About 72.9% (84.3%) of clouds with ΔH < 3 km were observed during the active (break) periods. Thick clouds (ΔH > 3 km) are more frequent during the active period (27.1%) than during the break period (15.7%). This could be explained by the formation of more thick anvil and cirrus clouds during the active spell (Sally et al., 2013). The results above indicate that during the active spell, large scale circulation is conducive for the formation of deep convective clouds that results in the development of anvil and cirrus clouds with thicker geometrical thickness compared to the break spell.

We later classified clouds into high- (CBH ≥ 6 km), mid- (2 km ≤ CBH < 6 km), low- (CBH < 2 km, and ΔH < 6 km) and vertically developed deep clouds (CBH < 2 km and ΔH ≥ 6 km). Based
on these criteria, as used by Stein et al. (2011), cloud classification occurrence (in percent) for both periods of monsoon is shown in table 4. This occurrence is calculated by dividing the number of observed high-, mid-, low- and deep clouds by the total number of observed clouds. Occurrence of high level clouds is predominant in both spells during the monsoon, but with a higher frequency during the break than the active periods. Both low and mid level cloud occurrence are not significantly different during the two phases of the season. Vertically extended clouds are more during the active compared to the break spells. This shows that convective activities are less intense during the break compared to the active periods. Figure 6 shows cloud cover during the break and active periods of the monsoon season. Fig. 6a-d shows low cloud cover, fig. 6b-e represent medium cloud cover and fig. 6c-f show high cloud cover during the break and active spells respectively. It is quite clear that high level clouds are dominant during both spells, but are more intense during the break spell (fig. 6c) compared to the active occurrences (fig. 6f) of the WAM. However it should be noted that the image is biased towards the dominance of high level clouds compared to other cloud types as the CloudSat is directed downward and hence resulting in most of the radar signal attenuated as it penetrates deep into the atmosphere.

3.3 Variability in the microphysical properties of monsoon clouds

In this sub section, we discuss the evaluation of cloud microphysical properties in terms of cloud liquid and ice water content, cloud liquid and ice effective radii and cloud liquid and ice number concentration of low-level, mid-level, high-level and deep convective clouds. Figure 7 shows the mean vertical profiles of liquid water content (LWC), liquid effective radius (R_{liq}) and liquid number concentration (LNC) of high- (top panel: Fig.7 a-c), mid- (middle panel: Fig. 7d-f) and low- (bottom panel: Fig. 7g-i) level clouds respectively, of the active and break spells during WAM. As noted by Chiu et al. (2012), this implies that uncertainties in zenith radiance measurements estimates may have a non-negligible impact on droplet size retrievals, and need to be accounted for in the retrieval method. These uncertainties in cloud-mode retrievals can be 15% based on simulation test (Chiu et al. 2012), and uncertainties in MODIS retrievals can be 5-20% due to cloud inhomogeneity (Platnick and Valero, 1995). During the active (break) period for low-level clouds, two peaks are observed, with the primary peak of about 451 mgm^{-3} (573 mgm^{-3}) at about 1 km followed by approximately 360 mgm^{-3} (370 mgm^{-3}) at about 5 km. The standard deviations are around 5, 15 and 60 mgm^{-3} at the high, mid and low level clouds respectively. In general, more LWC is recorded during the active spell compared to the break spell.

In addition, the increase in LWC at these peaks may be due to the collision-coalescence process among cloud droplets, as they grow larger by the condensation process. Generally, cloud particles during the active phase have higher R_{liq} compared to the break period, despite a maximum value of R_{liq} of about 13 μm (15 μm) at 1 km observed during the active (break) period for low-level clouds,. The LNC for low-level clouds is more at 1 km during the active (break) periods with values of about 73 cm^{-3} (82 cm^{-3}). Mid-level clouds have maximum LWC of about 155 mgm^{-3} (135 mgm^{-3}) at approximately 5.5 km (6.5 km) during the active (break) period. LNC and R_{liq} for mid-level clouds have maximum values of about 60 cm^{-3} (63 cm^{-3}) and 15.8 μm (13 μm) at approximately 2 km respectively during the active (break) period. With high-level clouds, the maximum LWC of about 65 mgm^{-3} (63 mgm^{-3}) , R_{liq} of about 11 μm (10.6 μm) and LNC of about 40 cm^{-3} (38 cm^{-3}) are noticed around 7 km during the active (break) period. Liquid
water existing above the freezing level (which is about 5 km) is due to the atmospheric and aerosols conditions (Das et al., 2013), which results in super cooled liquid phase clouds. We observed this metastable state up to about 8.4 km (corresponding to a temperature of -39.6°C). Low-level clouds have higher LWC, LNC and R_{liq} compared to mid- and high-level clouds. Microphysical properties of high-level clouds have narrower spectra compared to mid- and low-level clouds.

Ice water content (IWC), INC and ice effective radius (R_{ice}) of high- (top panel; Fig. 8a-c), mid- (middle panel; Fig. 8d-f) and low- (bottom panel; 8g-i) level clouds are shown in figure 8. For high-level clouds, there is no marked difference in the IWC, INC and R_{ice} during the different spells of the monsoon. However, clouds with top height up to about 24.5 km were observed during the active period compared to cloud top height of 17 km observed during the break spell. Clouds of such height were observed in August 20, 2008. Due to the large gradient in sea surface temperature between the coast of Guinea and the Sahara Desert, convective activities that develop have high convective available potential energy (CAPE), which may cause the clouds to grow rapidly and violently up into the stratosphere.

Mean specific cloud ice water content (ciwc) in August 20, 2008 is shown in figure 9. This figure shows that cloud ice particles were detected at altitude greater than 19 km. More ciwc is observed at noon but dropping as the sun sets. There is a clear difference between IWC and INC of mid-level clouds during both spells of monsoon. The maximum value of IWC of about 140 mg m^{-3} (20 mg m^{-3}) occurs at about 8.5 km (7 km) during the active (break) periods. R_{ice} maximum value is about 170 cm^{-3} (77 cm^{-3}) at 15 km (8.5 km) during the active (break) periods. The INC shows no clear distinction during both spells of monsoon. The IWC, INC and R_{ice} of low-level clouds show clear differences during the two epochs. The maximum value of IWC and INC is 68 mgm^{-3} (12 mgm^{-3}) and 72 cm^{-3} (32 cm^{-3}), respectively, during the active (break) spells. The R_{ice} of low-level clouds shows no significant differences during both phases of the season.

The increase in IWC, INC and R_{ice} from 5.6 Km level upward is due to the fact that at this height, decreasing temperatures favor the nucleation of hydrometeors into ice phase clouds. Generally, ice phase clouds have higher IWC, INC and R_{ice} during the active spells compared to the break spells. Clouds exist in three phases, the liquid phase which is made up of liquid water particles, the ice phase which is made up of ice water particles, and mixed phase that contain both the liquid and ice particles. Liquid phase clouds are classified as 'warm' and ice phase clouds classified as 'cold' clouds. The 'mixed-phase' clouds lie between the freezing point 0°C and the -40°C isotherm (the practical lower limit for liquid water to exist in the metastable state). The prevailing meteorological conditions and cloud microphysical properties throughout its life cycle determine which phase is more dominant (Das et al., 2013).

Deep convective clouds are made up of all the phases of clouds, and figure 10 shows the mean vertical profiles of (a) IWC, (b) R_{ice}, (c) INC, (d) LWC, (e) R_{liq} and (f) LNC of deep cloud of the active (solid gray line) and break (black broken line) periods of monsoon. It can be noted from figure 10 that during the active spell, the LWC, and LNC are higher compared to the break spell, while during the break period, the IWC, R_{ice} and INC are higher. The maximum values of LWC, and LNC of about 72 mgm^{-3} (64 mgm^{-3}) and 270 cm^{-3} (222 cm^{-3}), respectively, were observed at approximately 5 km altitude during the active (break) periods. Maximum values R_{liq} of about 12.7 μm (14 μm) of deep convective clouds occurred during the active (break) spells. During the
active phase, the unstable state of the atmosphere leads to an updraft that develop vertically extended clouds that are rich in moisture and this accounts for the observed high LWC and LNC. However, the $R_{\text{liq}}$ reaches up to the 5 km altitude during the active phase but goes higher during the break period. Table 4 shows that more cirrus clouds are observed during the break phase compared to the active phase, but with more IWC, INC and $R_{\text{ice}}$ noticed during the active period.

3.4 Variability in the radiative properties of monsoon clouds

Clouds greatly affect heating rates in the tropical lower stratosphere (Feuglistaler and Fu, 2006). The atmospheric heating due to clouds is an important factor in modeling WAM clouds in climate models. Clouds with different microphysical properties have different radiative forcing. We discussed clouds radiative forcing in terms of shortwave and longwave radiations. Top net longwave radiation and top net shortwave radiation during the active and break periods of the WAM are shown in figure 11. During the break spell (fig. 11b), more shortwave radiation is reflected back into space by the cirrus clouds compared to that reflected during the active spell (fig. d). Cloud albedo increases with increase in cloud cover, and this explains why there is more cooling of the upper atmosphere by cirrus clouds during the break period compared to the active period. Fig. 11a shows that there is more atmospheric heating by longwave radiation during the break spell compared to the active spell (fig. 11c). The higher cirrus cloud occurrence during the break spell absorb and reemit more longwave radiation back to the Earth leading to more heating of the atmosphere during the break spell compared to the active spell.

Clouds radiative heating rates (anomalies) profiles (K/day) during the active and break phases during the monsoon season is shown in figure 12. These anomalies are computed by subtracting the heating rate profiles during the break periods from the profiles during the active periods. Positive and negative anomalies indicate more heating and cooling during the active and break spells of monsoon respectively. Figure 12 shows that below 5 km, there are positive anomalies in the radiative heating rate. This is because during the active spell, clouds are highly concentrated in water vapor, which absorb more radiation compared to the break period. From 6 km upward, negative anomalies are observed. The analysis above indicates the effects of cloud types and percentage occurrence on the radiative heating rate of the atmosphere in terms of shortwave and longwave radiations. However, the complexity between cloud microphysical properties and atmospheric heating rates needs more detailed investigation.

4. Conclusion

The identification of active and break periods of WAM using gridded rainfall data from TRMM enabled this study to use CloudSat-CALIPSO data to quantify the differences between the active and break periods cloud macrophysical and microphysical properties, and radiating heating rate properties of clouds over the monsoon core zone (5-15° N; 15° W-10° E) from 2006 to 2010 during the monsoon season. The longest active spell was observed in 2008 (7 days) and more breaks in 2006. Over the 5-year study period, the averaged clouds macrophysical, microphysical and radiating heating properties vary significantly during both the active and break spells. In both epochs, CBH occurrence show bimodal distribution while CTH % occurrence show bimodal distribution only during the break period. More high-level clouds occurred during the break
period (53.5%) compared to the active period (46.5%). Deep convective clouds occurred more during the active period (9%) than the break period (3%). More geometrically thin clouds (ΔH < 3 km) are observed during the break (84%) than active (73%) spells. Geometrically thick clouds (ΔH > 3 km) occurred more frequently during the active period (27%) than the break period (15.7%). CBH > 13 km occur more during the break than active periods. Most clouds have thickness of about 2 km. High-level clouds have narrower spectrum cloud microphysical properties than mid- and low-level clouds during the WAM.

The LWC, LNC and Req of low-, mid- and high-level and deep convective clouds show relatively higher values during the active periods than the break periods of the monsoon season. The IWC, INC and R_{ice} of low-, mid- and high-level clouds have relatively higher values during the active periods compared to the break periods. Deep convective clouds have higher IWC, INC and R_{ice} during the break compared to the active periods. The formation of more thick clouds during the active spells of the season account for the higher values of microphysical properties observed. The decrease in convective activities during the break periods lead to an increase in the IWC, INC and R_{ice} of deep convective clouds.

The analysis of cloud radiative forcing in terms of shortwave and longwave radiation shows that more shortwave radiation is reflected back to space while atmospheric heating by longwave radiation is more during the break phase of the monsoon by cirrus clouds. The anomalies of mean net heating rate profile of clouds shows that below 2 km, between 2.2 - 6 km and 7 - 7.8 km, there is relative heating during the active periods than the break periods. Between 2 - 2.2 km and above 8 km, there is more cooling during the active spells than the break spells. The results obtained in this study provide information on the variation in macrophysical, microphysical properties and radiating heating rate of clouds over West Africa between the active and break periods of the WAM. Knowledge on this is important in parameterising clouds in climate models especially over West Africa. Generally we can conclude that cloud vertical distribution and the ice concentration in clouds change during the active/break phases of the WAM season. As noted by the work of Bouniol et al. (2012), which analyzed WAM clouds macrophysical and cloud radiative properties, the impact on longwave and shortwave radiation for the active and break periods should also be studied over the WAM region.

Acknowledgements
The authors are thankful to the entire staffs of TRMM and CloudSat Data Processing Centres for collecting, processing and providing TRMM and CloudSat data respectively. Lenouo and Manatsa were supported by ICTP, Trieste Italy through the Associate and Federation Schemes Program.
References


Dee and co-authors, 2011, The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Quarterly Journal of the Royal Meteorological Society. 137, 553–597


Lenouo A. and F. Mkankam Kamga, 2008: Sensitivity of African easterly waves to boundary layer conditions, Annales Geophysicae, 26, 1355–1363


Zebaze S., A. Lenouo, C. Tchawoua and S. Janicot, 2015, Synoptic Kelvin type perturbation waves over Congo basin over the period 1979-2010, Journal of Atmospheric and Solar-Terrestrial Physics, 130-131, 43-56
Figure 1: WAM core zone considered to identify active and break events and to analyze cloud macrophysical and microphysical properties. The rectangle corresponds to the region where the TRMM data were extracted to determine the active and break period during 2006-2010 (adapted from Microsoft encyclopaedia, 2008).
Figure 2: The standardized rainfall anomaly for the year (a) 2008 and (b) 2010, for the period 1 June to 30 September. The circles correspond to identified active and break periods for the months of June to August.
Figure 3: CloudSat reflectivity from granules 23026 (a) and 22689 (b) for the segment 17 which move crossing study region during the days 26 August 2010 and 27 July 2010 for active and break periods respectively. The vertical extension is from surface to 30 km whereas horizontal extension which corresponds to the length of the segment is around 1200 km. Also given down of this graphs date, type of product, granule number, time and reflectivity bar. The red horizontal lines show the height of the troposphere, which is about 16-18 Km.
Figure 4: Frequency distribution of cloud base height (top panel) and cloud top height (bottom panel) of the active periods (grey) and break periods (black) of monsoon. The curves represent moving averages to demonstrate bimodal nature of the CBH and CTH. The cloud base and top height is averaged for every 1 km interval.
Figure 5: Frequency distribution of cloud geometrical depth (ΔH) of the active spells (grey) and break spells (black) of monsoon. The ΔH is average for every 1km Interval.
Figure 6: Mean cloud cover of (a) low level cloud, (b) medium cloud, (c) high level cloud during the break and (d) low level cloud, (e) medium cloud, (f) high level cloud during the active spells of the WAM from 2006-2010.
Figure 7: Mean vertical profile of liquid water content, liquid effective radius and liquid number concentration of high- (top panel: a-c), mid- (middle panel: d-f) and low- (bottom panel: g-i) level clouds of the active (solid gray line) and break (dashed black lines) periods of monsoon.
Figure 8: Mean vertical profile of ice water content, ice number concentration and ice effective radius of high- (top panel: a-c), mid- (middle panel: d-f) and low- (bottom panel: g-i) level clouds of the active (solid gray line) and break (dashed black lines) periods of monsoon.
Figure 9: Mean specific cloud ice water content on August 20, 2008 at 00h00, 06h00, 12h00 and 18h00 over West Africa derived from ECMWF data.

Figure 10: Mean vertical profile of (a) ice water content, (b) ice effective radius, (c) ice number concentration, (d) liquid water content, (e) liquid effective radius and (f) liquid number concentration of deep cloud of the active (gray line) and break (black broken line) periods of monsoon.
Figure 11: Cloud radiative forcing (W.m$^{-2}$) in terms of longwave radiation (a-c) and shortwave radiation (b-d) of the break (a-b) and active (c-d) spells of the WAM from 2006 to 2009.
Figure 12: Anomalies (active-break) of mean net heating rate profile during WAM.

Table 1: WAM active and break spells, where J, Jy and A refer to the months of June, July and August respectively.

<table>
<thead>
<tr>
<th>Year</th>
<th>Active periods</th>
<th>Break periods</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>20-22 J</td>
<td>20-22 J</td>
</tr>
<tr>
<td>2009</td>
<td>-</td>
<td>4-7 J, 13-15 J, 25-27 J</td>
</tr>
<tr>
<td>2010</td>
<td>26-28 A</td>
<td>25-27 Jy</td>
</tr>
</tbody>
</table>

Table 2: Standard errors of cloud microphysical properties during the active and break spells of the WAM from 2006 to 2010

<table>
<thead>
<tr>
<th>Cloud types</th>
<th>Microphysical</th>
<th>High-level clouds</th>
<th>Mid-level clouds</th>
<th>Low-level clouds</th>
<th>Deep clouds</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Active Break</td>
<td>Active Break</td>
<td>Active Break</td>
<td>Active Break</td>
</tr>
<tr>
<td>LWC</td>
<td>5.33</td>
<td>5.28</td>
<td>10.67</td>
<td>9.66</td>
<td>27.04</td>
</tr>
<tr>
<td></td>
<td>2.81</td>
<td>2.76</td>
<td>4.48</td>
<td>4.92</td>
<td>5.72</td>
</tr>
<tr>
<td>R_{\text{liq}}</td>
<td>1.03</td>
<td>0.98</td>
<td>0.94</td>
<td>1.11</td>
<td>1.10</td>
</tr>
<tr>
<td>IWC</td>
<td>1.95</td>
<td>1.93</td>
<td>7.01</td>
<td>1.31</td>
<td>4.34</td>
</tr>
<tr>
<td>INC</td>
<td>6.22</td>
<td>2.67</td>
<td>8.40</td>
<td>4.86</td>
<td>3.75</td>
</tr>
<tr>
<td>R_{ice}</td>
<td>3.84</td>
<td>3.79</td>
<td>5.45</td>
<td>6.71</td>
<td>8.74</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Accepted Manuscript
Table 3: Frequency distribution of duration of active and break spells in per cent.

<table>
<thead>
<tr>
<th>Duration (day)</th>
<th>Active (%)</th>
<th>Break (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-4</td>
<td>66.7</td>
<td>90</td>
</tr>
<tr>
<td>5-6</td>
<td>00</td>
<td>10</td>
</tr>
<tr>
<td>7-8</td>
<td>33.7</td>
<td>00</td>
</tr>
</tbody>
</table>

Table 4: Percentage occurrence of cloud classification in terms of CBH and ΔH of the active and break spells of WAM from 2006 to 2010.

<table>
<thead>
<tr>
<th>Cloud types</th>
<th>Active (%)</th>
<th>Break (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-level clouds</td>
<td>46.5</td>
<td>53.5</td>
</tr>
<tr>
<td>Mid-level clouds</td>
<td>17.8</td>
<td>18.1</td>
</tr>
<tr>
<td>Low-level clouds</td>
<td>26.8</td>
<td>25.4</td>
</tr>
<tr>
<td>Deep clouds</td>
<td>9.0</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Highlights
- Clouds from CloudSat-CALIPSO satellites over West Africa during the summer monsoon were analyzed.
- The active and break periods are defined as the periods during the peak monsoon months.
- High-level clouds are most dominant and occur more during the break periods.
- Liquid water clouds are observed to have more radiative forcing during the active period.
- Active spells lasting about a week were observed.