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Active phases and pauses during the installation of the West African monsoon through 5-day CMAP rainfall data (1979–2001)

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[1] Objective diagnostic analyses based on PCA decomposition, Varimax rotation and low-pass filters ($\geq$1 month) are performed on the 5-day CMAP rainfall data over West Africa. The northward excursion of the rainbelt can be divided into 4 basic subperiods each composed of an equilibrium period (pause) followed by a rapid increase (active phase) of the system. We suggest easy criteria to automatically detect these events and propose a calendar for the 23 years. The pauses are centered around 27–28 March (pause #1), between 29 April and 2 May (pause #2), 11 June (pause #3) and 24 July (pause # 4) with standard deviations of 7–11 days. The phase of any pause impacts on the phase of other pauses. Pause #4, starting earlier, is preceded by earlier pauses #2 and #3, then is followed by an earlier annual rainfall maximum and more abundant June–August amounts. *INDEX TERMS:* 1812 Hydrology: Drought; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology. **Citation:** Louvet, S., B. Fontaine, and P. Roucou, Active phases and pauses during the installation of the West African monsoon through 5-day CMAP rainfall data (1979–2001), *Geophys. Res. Lett.*, *30*(24), 2271, doi:10.1029/2003GL018058, 2003.

1. Introduction

[2] This study comes within the research of the characterization of the intra-seasonal modulations of the West African monsoon (WAM) system during its annual cycle. Indeed, these fluctuations are not yet well understood and documented, particularly with regard to the main periods of installation of the various Western African rainy seasons and the phases of transition separating them. Also very few studies were interested in these onsets. Preliminary results were obtained through a meridional vision of the WAM. For example, *Sultan and Janicot* [2000] have shown, for the 1968–1990 period, that the northward migration of the Inter-Tropical Convergence Zone (ITCZ) is characterized, in late June, by an abrupt shift between 5°N and 10°N. Then, the monsoon system is really installed over the continent. This latitudinal shift is associated with intra-seasonal signals (10–60 day period) in the atmospheric circulation [*Janicot and Sultan*, 2001]. These studies have provided interesting results concerning periodic rainfall fluctuations of about 15 days in boreal summer. Other results on the modulation of the monsoon have been obtained for the spring season. *Grodsky and Carton* [2001] have shown, but for the year 2000 only, some rainfall fluctuations in connection with atmospheric circulation signals at similar time scales: a biweekly rainfall oscillation was highlighted in conjunction with fluctuations in the monsoon wind patterns. *Louvet and Janicot* [2003] have revealed that over the 1979–2000 period, the onset of the first Guinean rainy season should be associated with OLR (Outgoing Longwave Radiation) fluctuations (25–70 day period).

[3] The aim of this study is to focus more on CMAP rainfall time evolution linked to the WAM system throughout the year using objective analyses over the recent period. The precise objective is to examine whether or not this system is of continuous propagation, if there is a quasi symmetry between the installation and withdrawal of the monsoon, as suggested by the annual evolution of monthly means, and what are the typical intraseasonal fluctuations in the successive annual cycles.

2. Data Sources and Methodology

[4] Several types of rainfall datasets were considered first. The analyses derived from the 5-day period CMAP (CPC Merged Analysis Precipitation) file, analysed on a 2.5° × 2.5° grid from January 1979 to December 2001. This dataset comes from a merger of several kinds of information sources and has a better quality compared to the individual data sources [*Xie and Arkin*, 1997]. The version used has been constructed with rainfall measurements and several satellite observations but without forecasts of precipitation field generated by NCEP reanalysis. This version has been compared to in situ datasets, such as the daily rainfall amounts compiled by IRD (Institut de Recherche pour le Développement), ASECNA (Agence pour la Sécurité de la Navigation Aérienne en Afrique et à Madagascar) and CIEH (Comité Inter-africain d'Etudes Hydrauliques). Daily values were interpolated on the 2.5° × 2.5° [*Kalnay et al.*, 1996] grid of NCEP/NCAR reanalysis (National Center for Environnemental Prediction and National Center for Atmospheric Research), by assigning each station daily value to the nearest grid point and averaging all the values related to each grid point. In order to make the both datasets comparable, in situ daily values were transformed into 5-day averages. The comparison has been made for a northern and a southern region over the 1979–1992 period using simple descriptive statistics and linear coefficients of correlation computed on anomalies relatively to the mean annual cycle computed on raw values (see Table 1). CMAP data are very close to in situ values, both in rhythm (linear correlation coefficients) and in amplitude (means and standard deviations); indeed their

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Table 1. Linear Correlation Coefficients (*100) Between IRD and CMAP Rainfall Anomalies for the 1979–1992 Common Period Over Two Continental Key-Regions

	Northern region: 10°W–10°E: 10°N–15°N	Southern region: 10°W–10°E: 5°N–10°N
Correlation coefficients	+76**	+71 **
Standard deviations	IRD = 2.38, CMAP = 2.61	IRD = 2.82, CMAP = 3.01
Mean values	IRD = 2.45, CMAP = 2.60	IRD = 4.19, CMAP = 4.89

Standard deviations and mean values are in mm/day^{-1}; asters denote 0.05 levels of significance.

advantage is that they cover a larger period and geographic sector (including the ocean).

[5] To diagnose the most coherent and energetic rainfall evolutions over homogeneous regions we use Principal Components Analysis (PCA) Varimax orthogonal rotation on raw values [*Richman*, 1986]. This objective method allows us to well document the main modes of 5-day CMAP variability (main patterns and associated time components). A low pass butterworth filter [*Murakami*, 1979], which does not change the temporal phase, has then been applied on the time series to eliminate the shortest meteorological fluctuations (<1 month) and concentrate on the seasonal evolution with a climatological point of view.

3. Results

[6] PCA has been performed on a squared window (10°W–10°E/0°S–20°N) to get the same weight both in latitude and longitude, after other windows and other methods, in particular cluster algorithms using different linkage distances, have been used to test the robustness of the results. One of the main goals of this multivariate analysis was to examine if the window was representative of all the rainfall regimes in the region. The question was: could we retrieve Sahelian, Sudanian and Guinean rainfall cycle on the CMAP data? Two other reasons have guided the choice of the method: (1) we have noted that most of the classification methods was not always efficient to distinguish homogeneous regions inside the studied squared area except ascending classification with Ward criteria which has given about the same results than those obtained with Varimax rotation; (2) the advantage of the PCA is to provide a percentage of variance for each component.

[7] We have performed the rotation on two sets of PCs according respectively to the scree test [*Catell*, 1966] and the North's criteria [*North et al.*, 1982]. The first one has retained the first five principal components (74% cumulated explained variance) characterized by non-degenerescent eigenvalues. By contrast the second one takes into account degenerescent eigenvalues which correspond here to the 23 first principal components (94% cumulated explained variance). The results are very similar attesting the stability of the rainfall regimes and their spatial representation.

[8] Results of the Varimax orthogonal rotation will be presented in terms of maps of correlation coefficients between PCs and each grid point on a larger sector than the window submitted to the PCA (Figure 1). This method allows us to know if the variability detected modes are

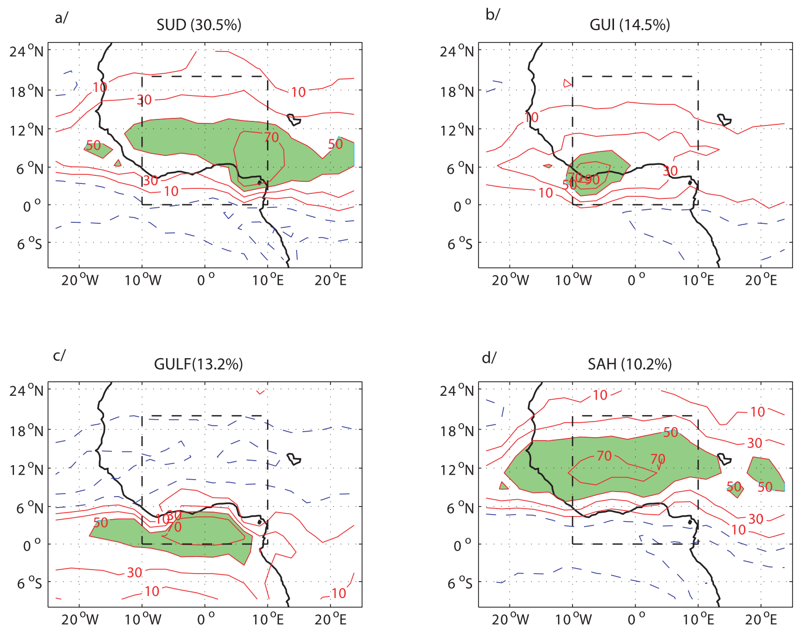

Figure 1. Correlation coefficient (*100) patterns between each grid point and the four main Varimax rotated PCs over the 1979–2001 period; Isolines every 20; shadings when >50 and dashed when <0. The geographical area submitted to the PCA Varimax orthogonal rotation is displayed (box in dashed lines).

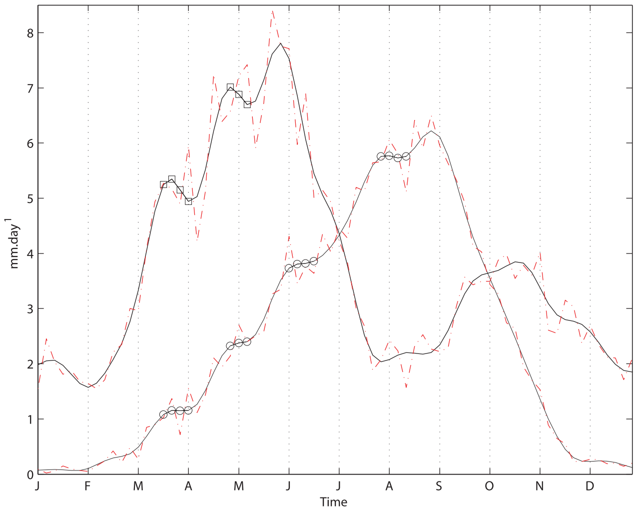

Figure 2. Interannual means of the successive 5-day rainfall amounts (mm/day^{-1}) averaged over regions where correlations in Figure 1 exceed 0.50: dashed/solid lines for raw and filtered data; circles and squares denote the main pauses (see text); Sudsah (circles) and Guigulf (squares). Period 1979–2001.

inside modes of the studied region or if they are of larger extension. The first rotated mode called SUD explains 30.5% of the total variance and is mainly associated with a continental rainfall variability mode over a large Sudanian region centered near Nigeria for the strong correlations (>0.7, Figure 1a). The second rotated mode (14.5% explained variance, Figure 1b) represents the Guinean coast (GUI), both over the continent and ocean. The patterns of the third mode (13.2%, Figure 1c), associated with the whole of the Guinean Gulf will be called GULF. The 4th mode refers to the Sahelian belt (10.2%, Figure 1d) and will be called SAH. The fifth mode (not shown) can be regarded as local and residual (5.6%): it is associated with the pluviometric regime of the Cameroon mount.

[9] The results of Varimax orthogonal rotation exhibit four basic variability modes: two over the continental parts (SUD, SAH) concerned by one unique tropical rainy season peaking in northern summer, and two others southward (GUI, GULF) over regions where there are two sub-equatorial rainy seasons. So, we will aggregate SUD and SAH and GUI and GULF, respectively, to define 2 main regional indexes (called SUDSAH and GUIGULF) by averaging the CMAP rainfall amounts (in mm.day^{-1}) over the area where correlation coefficients exceed +0.50 inside the 10°W–10°E/0°S–20°N window (Figure 1).

[10] Figure 2 shows the respective mean annual evolutions of the filtered (bold curve) and raw (dashed curve) indexes. The SUDSAH mean annual cycle peaks in August

Table 3. Linear Correlation Coefficients (*100) Between Dates of Pauses

	Sudsah/Guigulf		Sudsah		Guigulf
Pause n°	#1/1	#2/2	#1/2	#2/3	#1/2
Correlation coefficient	+43 *	+77 **	+75 **	+71 **	+89 **

For example, SUDSAH/GUIGULF #1/1 gives the correlation computed between the central dates of pause #1; SUDSAH #1/2 gives the correlation computed between the central dates of pause #1 and central date of pause 2. 1 and 2 asters denote the 0.1 and 0.05 levels of significance, respectively.

(6–7 mm.day^{-1}) but is not strictly monomodal and symmetrical: from spring to summer it clearly progresses by a succession of 4 active increases (strong slope on the bold curve) each followed by a pause (an equilibrium period with no slope) during which fluctuations of higher frequency (dashed curve) amplify, most often at the end of the pause. Such events do not occur during the monsoon withdrawal. The GUIGULF evolution is bimodal, due to the succession of two rainy seasons (peaking in April–June and October–November) separated by a relative minimum in August (the little dry season) in the region. Notice that GUIGULF progresses also step by step from spring to summer, as shown by the two active periods followed by two pauses, these events being in phase with those detected in SUDSAH (Figure 2).

[11] Can these pauses be objectively detected? We have computed the differences between all successive 5-day CMAP values computed from the beginning of each calendar year to the annual maximum on the 23 annual filtered SUDSAH series, positive/negative values meaning rainfall increases/decreases. Notice that 35% of these differences are negative while 43% exceed 0.15 mm.day^{-1} which corresponds to the upper threshold of the mode. The average of the differences is 0.16 mm.day^{-1} while the median is 0.14. So we will consider that any rainy period (>1 mm.day^{-1}) registering at least 2 successive differences <0.15 as a marked pause in the installation period: circles and squares in Figure 2 point to the 4 dominant pauses (in March–April, May, June and July) detected with these criteria, and Table 2 gives additional statistics on the timing. The 4 pauses have a mean duration of 3–4 weeks and tend to be centered on March 27–28, at the turn of April/May, on June 11 and July 24 with standard deviations ranging from 7 to 11 days. The 4 active phases which follow start on average by April 8–9, May 11–15, June 24 and August 5, respectively. Pauses #1 and #2 occur quasi-synchronously in mean over SUDSAH and GUIGULF (Table 3) and their phases are significantly and positively correlated over the 23-year period: these rainfall fluctuations tend to occur quasi-synchronously all over the West African region. Moreover, over a given region (SUDSAH, GUIGULF) the timing of successive pauses is strongly correlated (Table 3).

Table 2. Descriptive Statistics on Pauses in Days: Means and Standard Deviations (Underlined and *Italic*) of the Central Dates; Beginning and End Dates and Their Standard Deviations (Underlined and *Italic*)

Pauses	Pause #1 Sudsah	Pause #2 Sudsah	Pause #3 Sudsah	Pause #4 Sudsah	Pause #1 Guigulf	Pause #2 Guigulf
Central dates and standard deviations	28 March *7.5*	2 May *9.2*	11 June *9.7*	24 July *11.4*	27 March *10*	29 April *7*
Beginning and end dates of pause	16 March *7.8* 9 April *8.3*	19 April *9.4* 15 May *9.7*	29 May *10.2* 24 June *10.4*	12 July *11.2* 5 August *12.9*	15 March *9.9* 8 April *11.7*	17 April *7.1* 11 May *7.8*

Table 4. Central Dates and Durations in Pentads (Underlined and Italic) of the 4 Pauses in the SUDSAH Filtered Series Using Our Criteria Over the Period 1979–2001; ND = not Detected

	Pause #1	Pause #2	Pause #3	Pause #4		Pause #1	Pause #2	Pause #3	Pause #4
1979	◇3 apr *5*	◇15 may *4*	◇22 jun *5*	◇29 jul *4*	1991	ND	*20 apr *4*	*28 may *5*	*19 jul *6*
1980	*26 mar *6*	5 may *4*	9 jun *6*	◇29 jul *4*	1992	*16 mar *4*	*20 apr *4*	*30 may *6*	◇1 aug *7*
1981	29 mar *5*	◇10 may *6*	ND	24 jul *10*	1993	*24 mar *7*	◇10 may *6*	◇24 jun *4*	ND
1982	29 mar *5*	*30 apr *4*	7 jun *5*	*7 jul *5*	1994	◇8 apr *3*	8 may *5*	14 jun *4*	*19 jul *4*
1983	◇8 apr *5*	ND	14 jun *6*	ND	1995	29 mar *5*	3 may *5*	*4 jun *4*	*7 jul *3*
1984	*26 mar *6*	8 may *5*	9 jun *6*	◇13 aug *6*	1996	*21 mar *4*	*25 apr *6*	14 jun *6*	*19 jul *4*
1985	◇10 apr *6*	◇15 may *4*	ND	*14 jul *4*	1997	◇3 apr *5*	◇13 may *5*	◇24 jun *6*	◇1 aug *5*
1986	*19 mar *5*	*20 apr *6*	*2 jun *9*	◇1 aug *5*	1998	◇8 apr *3*	8 may *5*	◇17 jun *5*	◇11 aug *6*
1987	ND	ND	◇27 jun *5*	ND	1999	◇10 apr *8*	ND	*28 may *5*	◇29 jul *4*
1988	*24 mar *5*	3 may *5*	7 jun *3*	27 jul *5*	2000	29 mar *5*	*28 apr *5*	*2 jun *3*	*4 jul *4*
1989	29 mar *5*	◇10 may *6*	ND	*22 jul *5*	2001	ND	*25 apr *8*	◇22 jun *7*	ND
1990	ND	◇23 may *7*	ND	ND					

*and ◇ indicate the years used for the 'early' and 'late' composite analyses, respectively.

This suggests a possible connection implying that the phase of any pause could influence the time occurrence of the next one. This point requires further investigations and needs physical confirmation.

[12] Our results are coherent with those of *Louvet and Janicot* [2003] who pointed out a local increase in convection by the 10th of April, the mean onset date of the first Guinean rainy season, and of *Sultan and Janicot* [2000] who detected an abrupt northward shift of the rainbelt by 24 of June between Sudan and Sahel. However they allow to replace the approach of intraseasonal rainfall fluctuations in a more general context, showing that the onsets of the Guinean and Sahelian rainy seasons are in fact 2 local episodes of larger pulsations involving the whole monsoon region during the northward excursion of the rainbelt.

[13] Can this sequence of events be observed every year and impact on the annual rainfall cycle (phase, intensity)? Table 4 displays for SUDSAH the central dates and durations of pauses observed all over the period (1979–2001). Composite analyses, relative to the phase of each pause (#1, 2, 3, 4) have been conducted to contrast the mean annual cycles associated with the earliest and latest occurrences to examine if the dates of the pauses are statistically related to the successive 5-day rainfall amounts all over the annual cycle. The main results are reported in Figure 3 (see caption). Regarding the 'late' composite the results can be summarized as follows. Pauses in advance which occur early in the season (pauses #1, 2, curves with circles in Figures 3a and 3b) are of course linked to more/less rainfall just before/after the date of their normal timing (diamonds on the diagrams); more important, they seem to impact on the shape of all the CMAP annual cycle. For example, an 'early' pause #1 is significantly followed by a pause #2 in advance but by a late annual rainfall peak (Figure 3a). By

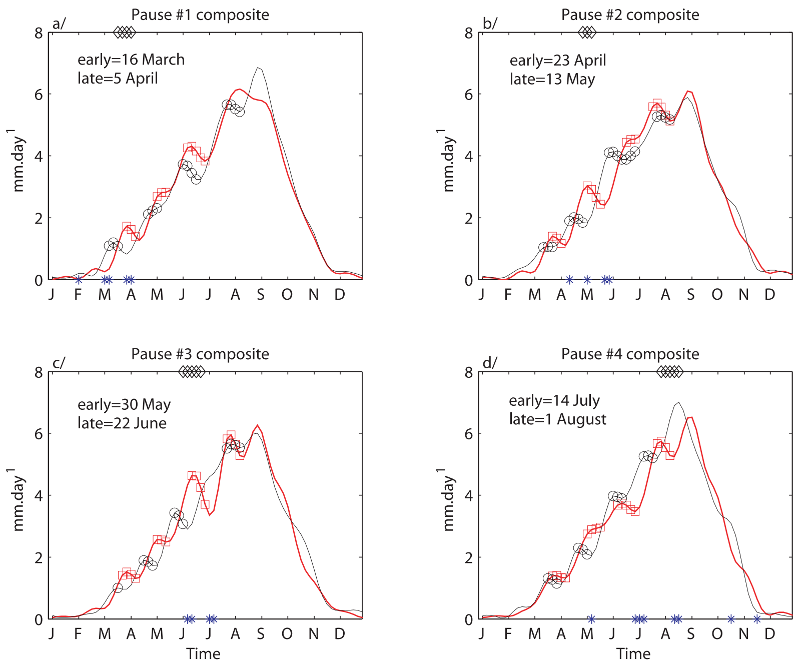

Figure 3. Same as Figure 2, but for the early (circles) and late (squares) composites regarding the central dates of the 4 pauses observed in the SUDSAH filtered series (see Table 3). Mean pause occurrences (diamonds, top) and significant differences between the two composite indexes (asters bottom) from the Student paired t-test (p = 0.05) are displayed. Period: 1979–2001. At left and top of each diagram: mean dates of the 'early' and 'late' pauses.

the end of May, a pause #3 occurring early (Figure 3c, thin curve) tends to be preceded by early and less marked pauses #1 and #2, and is associated to significant deficits at the turn of May/June and in the first days of June, followed by excesses in the last ones. This is due to the delay in the normal precipitation increase caused by the pause at a time of the year where rainfall gains 2 mm/day in some weeks. Finally, a pause #4 starting earlier than normal tends to be significantly preceded by earlier pauses #2 and #3, then to be followed by an advance in the annual rainfall maximum and more abundant amounts in June–August (Figure 3d). However the differences are poorly significant except for some pentads in late June and in August. For example, the correlation coefficient between the mean dates of pause #4 and seasonal rainfall amount in JAS is negative but not significant ($r = -0.41$).

4. Conclusion

[14] The mean annual cycle is not symmetric regarding the installation and withdrawal periods as often suggested by monthly means. The spring to summer excursion of the monsoon clearly progresses by a succession of active phases (rapid increases), and pauses (no increase); such events do not occur during the monsoon withdrawal. Even from a climatological point of view (fluctuations $\geq$1 month), the northward excursion of the rainbelt in the monsoon system is neither linear nor monotonous. It can be divided into 4 subperiods associating an equilibrium period (pause) during which meteorological fluctuations (<1 month) grow and a rapid increase of CMAP just after. We show that simple criteria based on the rainfall time-evolution are able to detect these events in the CMAP data. The first pauses in the annual cycle can be observed everywhere in the WAM region and tend to be centered on 27–28 March (pause #1) and between 29 April and 2 May (pause #2). The two other equilibrium periods are only observed in the Sudan-Sahel and are centered on 11 June (pause #3) and 24 July (pause #4). These mean dates have standard deviations ranging from 7 to 11 days. The active phases which follow the pauses tend to start around 8–9 April, 11–15 May, 24 June and 5 August. The dates of early occurring pauses are obviously significantly linked to more/less rainfall just before/after the date of their normal timing. However, they impact on the shape of the mean annual cycle: when pause #1 takes place earlier than normal, pause #2 is also in advance but the annual rainfall peak tends to occur late. A premature pause #3 is preceded by earlier and less marked pauses #1 and #2. It is also associated with significant deficits at the turn of May/June and in the first days of June and followed by excesses in the last ones. This is due to the delay in the normal rainfall increase caused by the pause at a time of the year where rainfall gains 2 mm/day in some weeks. An early pause #4 is clearly associated with an advance in the phase of the annual maximum and with more abundant rainfall all over the June–August rainy season.

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