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Abrupt shift of the ITCZ over West Africa and intra-seasonal variability

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Abstract. The onset of the monsoon system over West Africa is linked to the northward migration of the Inter-Tropical Convergence Zone (ITCZ) during the northern spring and summer. By using daily gridded rainfall data and NCEP/NCAR wind reanalyses over the period 1968-1990, we show that this migration is characterised by an abrupt latitudinal shift of the ITCZ in late June from a quasi-stationary location at 5N in May-June to another quasi-stationary location at 10N in July-August. A composite analysis based on the shift dates shows that this northward shift is associated with the occurrence of a westward-travelling monsoon depression pattern over the Sahel with characteristic periodicities of 20-40 days.

Introduction

Rainfall over West Africa is controlled by the advection of moisture from the Gulf of Guinea in the low-levels of the atmosphere. Following the seasonal excursion of the Sun, the monsoon develops over this part of the African continent during the northern spring and summer, bringing the Inter-Tropical Convergence Zone (ITCZ) and the associated rainfall maxima to their northernmost location in August. This is the time for the rainy season in the Sahel. The onset stage of the monsoon system over West Africa has not been studied in details up to now. This is the scope of this work, based on the period 1968-1990, a dry one over West Africa compared to the long-term mean [Hastenrath, 1995].

Two datasets have been used. Daily rainfall amount at stations located in the West African domain 3N-20N/18W-25E have been compiled by IRD (Institut de Recherche pour le Développement; ex ORSTOM), ASECNA (Agence pour la Sécurité de la Navigation Aérienne en Afrique et à Madagascar) and CIEH (Comité Interafricain d'Etudes Hydrauliques). These data are available for the period 1968-1990, including more than 1300 stations from 1968 to 1980, and between 700 and 860 stations for the period 1981-1990. These daily values were interpolated on the $2.5^\circ \times 2.5^\circ$ grid of NCEP/NCAR reanalyses (see below), by assigning

each station daily value to the nearest grid point and then averaging all the values related to each grid point. The greatest density of stations is located between the latitudes 5N and 15N. Data on latitude 17.5N can also be taken into account since between 30 and 40 stations are available. The NCEP/NCAR dataset consists of a reanalysis of the global observational network of meteorological variables (wind, temperature, geopotential height, humidity on pressure levels, and surface and flux variables) with the "frozen" state-of-the-art analysis and forecast system of the NCEP (national Centers for Environmental Prediction) at a triangular spectral truncation of T62 [Kalnay *et al.*, 1996]. Data are reported on a $2.5^\circ \times 2.5^\circ$ grid every 6 hours (00.00, 06.00, 12.00 and 18.00 UTC), on 17 pressure levels from 1000 hPa to 10 hPa. We used the data over the period 1968-1990, with one value per day, by averaging the four outputs of each day. As we have focused on the atmospheric circulation in the monsoon layer, we present results from the wind field at 925 hPa in this paper. A previous study [Diedhiou *et al.*, 1999] has demonstrated the accuracy of these two datasets.

The detection of the ITCZ shift

Figure 1 sums up the main features of the mean meridional excursion of the axis of maximum rainfall associated with the ITCZ. During the second part of May and in June, the ITCZ remains at a quasi-stable location around 5N (Fig. 1a). During the first part of July (Fig. 1b), it has already shifted abruptly to the north, and has reached a second quasi-stable state around 10N which persists during the second part of July and in August (Fig. 1c). This rapid shift of the ITCZ is highlighted when computing a time-latitude diagram of daily rainfall values averaged over the longitudes 10W-10E. Figure 2a depicts such an example for 1978. The zonal distribution of rainfall over West Africa (Fig. 1) enables to use such diagrams without any significant loss of information.

A quasi-objective method has been built up to define a date for the ITCZ latitudinal shift for each year between 1968 and 1990. An Empirical Orthogonal Function analysis (EOF) [Richman, 1986] has been performed on time-latitude diagrams of daily rainfall values averaged over 10W-10E, for each year from 1 March to 30 November (see Fig. 2a). Most of the rainfall variance decomposed by the EOF analysis is explained by

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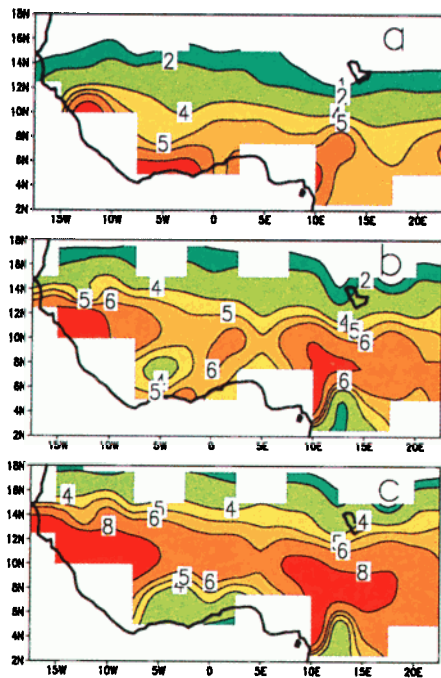


Figure 1. Mean 1968-1990 daily rainfall fields ($mm.day^{-1}$) averaged respectively (a) from 15 May to 30 June, (b) from 1 July to 15 July, and (c) from 16 July to 31 August. Rainfall values are from individual rain gauges gridded on a 2.5° mesh. White areas are due to missing data.

the two first components. The first one (about 91% of the variance on 1968-1990) is highly correlated with the rainfall time series at 10N (correlation of 0.9 on 1968-1990) and the second one (about 9% of the variance on

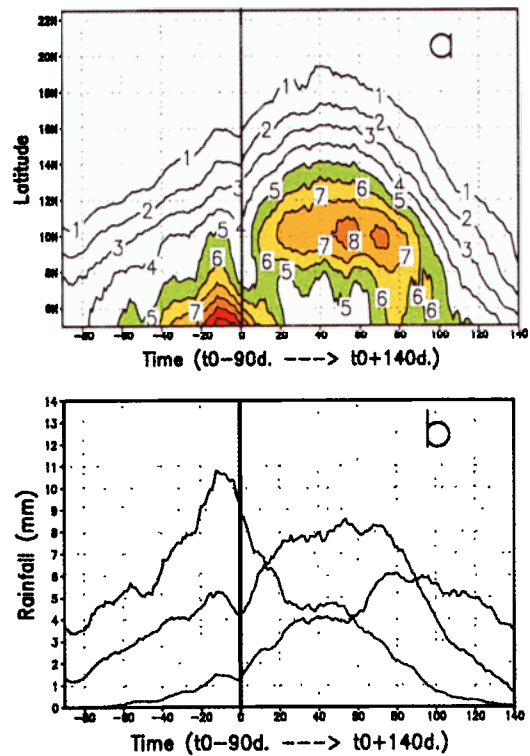
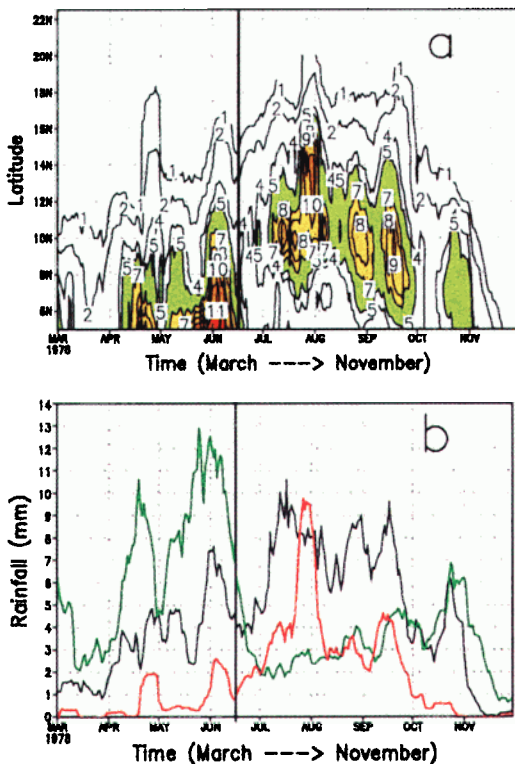


Figure 3. (a) Composite time-latitude diagram of daily rainfall ($mm.day^{-1}$) averaged over 10W-10E, filtered to remove rainfall variability lower than 10 days, and averaged over the period 1968-1990 by using as the reference date the shift date of the ITCZ for each year. Values are presented from t_0 (the shift date) minus 90 days to t_0 plus 140 days. Values greater than $5 mm.day^{-1}$ are shaded. (b) Time sections of diagram (a) at 5N (green curve), 10N (black curve) and 15N (red curve). On the two panels the vertical line localizes the date of the ITCZ shift at t_0 (the mean date over the period 1968-1990 is 24 June).



1968-1990) is highly correlated with the rainfall time series at 5N (correlation of 0.75 on 1968-1990). The rainfall indexes (i.e. the rainfall time series) at 10N and at 5N can then be used to sum up rainfall variability over West Africa and to define a date for the ITCZ shift. For few years, especially the dry ones like 1983 or 1984, we must have considered the rainfall index at 7.5N instead of 10N because the axis of maximum rainfall is located at a more southern location in summer. The time series of the rainfall indexes at 5N and 10N for 1978 are shown on Figure 2b. A rainfall maximum occurs during

Figure 2. (a) Time-latitude diagram from 1 March to 30 November 1978 of daily rainfall ($mm.day^{-1}$), averaged over 10W-10E and filtered to remove variability lower than 10 days. Values greater than $5 mm.day^{-1}$ are shaded. (b) Time sections of diagram (a) at 5N (green curve), 10N (black curve) and 15N (red curve). On the two panels, the vertical line localizes the date selected for the ITCZ shift (17 June).

May-June when the ITCZ is located at 5N. The abrupt shift of the ITCZ from 5N to 10N can be defined by simultaneously, a decrease of the 5N rainfall index and an increase of the positive slope of the 10N rainfall index. As there is most of the time a lag between these two moments, an uncertainty of few days remains. So we look for an increase of the positive slope of a similar rainfall index at 15N during this time to specify an only date (see the red curve on Fig. 2c). For 1978 the date of 17 June has been selected (see vertical line on Fig. 2). This method has been used to define a date of the ITCZ shift for each year from 1968 and 1990. The mean date found for this shift over the period 1968-1990 is 24 June and the standard deviation is 8.0 days.

Figure 3a shows the composite of the mean 10W-10E daily rainfall values averaged over the period 1968-1990 by using the ITCZ shift date for each year as the respective reference date. This figure points out latitude-time rainfall variations between the shift date (called t_0) minus 90 days and the shift date plus 140 days. Figure 3b shows the corresponding rainfall indexes at 5N, 10N and 15N. The rainfall maximum at 5N, also evident at 10N and at 15N, occurs about 10-20 days before t_0 (Fig. 3b). Then rainfall decreases slightly but over all of West Africa to a relative minimum value at the beginning of the ITCZ shift. At t_0 , the shift is first detected by a new positive slope of the rainfall index at 10N and by an increase of the rainfall slope at 15N. The ITCZ reaches the latitude 10N about 10 days after t_0 (Fig. 3a). The abruptness of the northward progression of the ITCZ is in sharp contrast to its withdrawal, which appears as a more orderly southward progression. It is in contrast also with the northern limit of the ITCZ (see the 1 to 4 $mm.day^{-1}$ isolines) which has a more gradual latitudinal variation during the onset than during the withdrawal.

An intra-seasonal atmospheric signal

Once a shift date has been defined for each year, we can study the atmospheric dynamics which could control the abrupt shift of the ITCZ. The role of the intra-seasonal variability in the monsoon layer has been investigated by filtering the wind at 925 hPa from variability lower than 10 days and greater than 60 days. The time sequence of the mean composite filtered wind field has been computed from t_0-90 days to t_0+140 days, by using as previously, the ITCZ shift date for each year as the reference time. To save space, the wind field sequence is not presented here. Instead, an index has been computed to sum up the time sequence, the difference of the relative vorticity of the 925 hPa 10-60-day filtered wind, computed between 10N and 17.5N. When a cyclonic circulation is located at 17.5N over West Africa, the wind field has a southerly component at 10N with the greatest anticyclonic curvature at this latitude (not shown). The index is then highly negative. Figure 4 shows the composite time-longitude diagram of

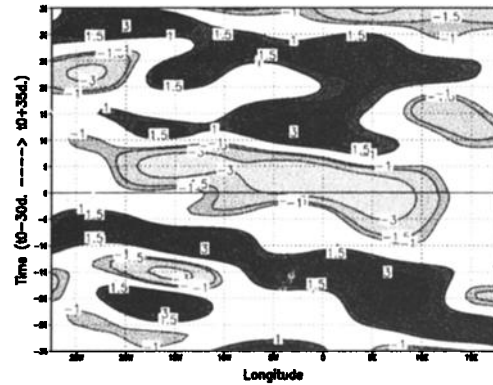


Figure 4. Composite time-longitude diagram of the difference of the 925 hPa relative vorticity ($10^{-6}.s^{-1}$) between 10N and 17.5N, from t_0 (the ITCZ shift date) minus 30 days to t_0 plus 35 days. This index has been computed from the 10-60-day filtered wind and averaged over the period 1968-1990 by using as the reference date the ITCZ shift date for each year.

this index from t_0-30 days to t_0+35 days. It highlights a westward propagation of an intra-seasonal scale atmospheric pattern, with successively anticyclonic (positive values) and cyclonic (negative values) circulations over the Sahel which develop between 0W and 10E before propagating westward at an approximate mean phase speed of 4° longitude per day. Figure 5 depicts the time series of this vorticity index averaged over 10W-10E, from t_0-90 days to t_0+140 days. This index has the greatest negative value at the time of the ITCZ shift (t_0+1 precisely). It depicts a clear quasi-periodic signal with a mean periodicity of 35 days on the whole sequence, and the highest amplitude around the shift date. The half-period of this index (from the minimum to the maximum value) is consistent with the interval of time taken by the rainbelt to move from 5N to 10N. More precisely (not shown), between t_0+5 and t_0+10 a large cyclonic circulation is located over the western part of the Sahel, controlling a southward pressure gradient and a northward moisture advection over West Africa, enhancing the mean monsoon winds. This circulation is still present at t_0+15 when the moisture advection becomes more vigorous through an extension of the cyclonic circulation over the whole West Africa and the Gulf of Guinea. The ITCZ get its final quasi-stationary stage at t_0+20 with the appearance of rainfall minima along the Guinean Coast. So we can argue that the abrupt meridional shift on the ITCZ responds not only to the seasonal march of the Sun, but also to an impulse due to a westward-travelling cyclonic circulation located over the western part of the Sahel.

The composite 10-60-day filtered rainfall index at 10N is superimposed on the vorticity index (Fig. 5). Around t_0 , this intra-seasonal rainfall change is the greatest, from +0.5 mm to -1 mm, and it is closely correlated with the vorticity index. This depicts at intra-seasonal time scale a close connection between the

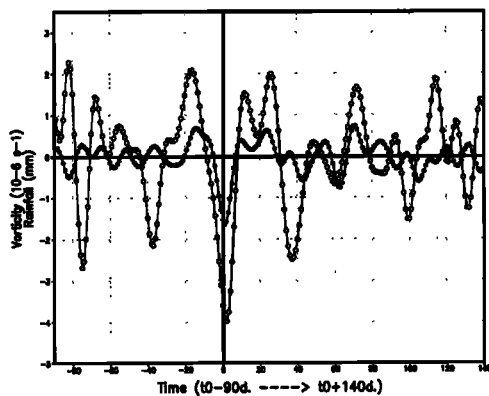


Figure 5. Time series of the composite intra-seasonal scale vorticity index shown on Fig.4 but averaged over 10W-10E. The time series (white dots) is computed from t_0-90 days to t_0+140 days. The associated mean 10-60-day filtered rainfall index (mm) at 10N, averaged over 10W-10E, is superimposed (black dots).

westward propagation of the atmospheric pattern and a rainfall decrease between t_0-10 and t_0+1 as well as a rainfall increase until t_0+15 , concomitant with the ITCZ shift from 5N to 10N. When considering each year, the respective vorticity indexes have a similar periodic variability but with a mean period varying from 20 and 40 days (not shown). A minimum of the vorticity index is always located near the shift date with a standard deviation of 5 days for the time lag distribution. This low dispersion, compared to the mean periodicity, enables to associate only one minimum of the vorticity index to the ITCZ shift.

Conclusion

By using gridded rainfall and wind data over the period 1968-1990, we have pointed out an abrupt latitudinal shift of the West African ITCZ in late June from 5N to 10N. This shift appears to result from an interaction between the seasonal cycle and a westward travelling intra-seasonal scale atmospheric circulation pattern in the monsoon layer, leading to an acceleration of the seasonal cycle. This result has been pointed out through the computation of composite means based on the ITCZ shift date for each year. This method assumes that the rate of development before and after each ITCZ shift is similar each year. At the time of the ITCZ shift, a large cyclonic circulation, centred over the Sahel, induces a southward pressure gradient and a northward moisture advection over West Africa. The enhancement of the monsoon winds is consistent with the simultaneous northward shift of the ITCZ. This shift seems to occur when the seasonal cycle has sufficiently progressed over the continent. Other sequences of positive vorticity patterns occur over the Sahel in the preceding

cycles (Fig. 5). For instance, 40 days before, rainfall in the ITCZ begins to increase but the ITCZ stays at 5N, may be because the intra-seasonal atmospheric pattern cannot induce a northward shift of the ITCZ.

Whereas the intra-seasonal atmospheric variability is present each year on the period 1968-1990, its origin is unknown and need more investigation. Is this an internal mode of the atmospheric variability as for the so-called onset vortex in the Indian monsoon [Krishnamurti *et al.*, 1981]? Or do interactions between land surface processes and deep convection, especially the impact of soil moisture and of the sensible heat input in the boundary layer, operate to create such circulation [Ferranti *et al.*, 1999]? Land surface processes have also been previously involved to explain the intra-seasonal variability of northward propagating rain bands in the Indian monsoon [Webster, 1983]. Atmospheric General Circulation Models as well as Limited Area Models must be used to understand better the different mechanisms involved. However these models have first to reproduce accurately the dynamics of the West African monsoon described here to be validated.

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