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Questions Relative to ITCZ Migrations over the Tropical Atlantic Ocean, Sea Surface Temperature and Senegal River Runoff

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With 8 Figures

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Summary

The ITCZ (Intertropical Convergence Zone) is an important parameter for climatic studies in tropical areas, and meteorological satellite imagery provides an original way to follow its location. Using archive imagery covering the 1971 – 1987 period, we attempted to study further some of the relationships (suggested by former studies) between ITCZ locations (followed here over the Atlantic ocean at 28 °W), and climate anomalies in the Sahel, an area affected by periodic drought for the last seventeen years. We also paid close attention to more frequently studied parameters, such as upper air data, wind at sea level, and sea surface temperature. As for relative drought estimates, we assumed that runoff from the Senegal River was representative of the sahelian area and we observed that its variations were consistent with the Lamb's rainfall index over the 1965 – 1987 period.

Since the onset of the rainy season for West Africa responds to wind changes, we assessed the link between ITCZ and wind at sea level and found the timing of northward ITCZ migration to be highly correlated ($r = 0.84$) with the date of zonal wind stress intensification.

On a general point of view, the relationships we found between rainfall amount and ITCZ position anomalies (or SST anomalies) agree with known results of precedent works, though better fit is found with the seventies than the eighties. We think this discrepancy is due in part to the fact that the parameters studied were not identical and, perhaps to a possible change in climatic conditions (on a long term basis, the data show a continuous trend for less intense equatorial upwelling in the gulf of Guinea, and our time series covers a more recent period than referenced works).

With a closer look on the first half of the year, it appears that typical (wet/dry) schemes of the ITCZ migration can be evidenced more clearly, than in reporting the northernmost ITCZ location, that we found to be a less significant index: in other words, a sooner (respectively later) northward ITCZ migration corresponds to dry (respectively wet) episodes during the rainy season in sahelian areas. Hence, we propose the "speed" of ITCZ northwards movement as a parameterization of this event.

Moisture content of the lower troposphere revealed that steady anomalies of this parameter may last several years over sahelian areas. Taking into consideration the relative strength African tropical and easterly jets, some limited results were obtained, in regard of climatic anomalies.

As first conclusions, moisture transportation over sahelian area (associated with larger negative SST anomalies) is more efficient for wetter rainy season, than the intensity of convective process linked to higher local SST in the equatorial Atlantic area. In joining moisture analysis and ITZ migration (1980 – 1987 period), wetter rainy seasons were observed each time that positive humidity anomalies coincided with a later northward ITCZ migration (or greater northward ITCZ speed).

1. Introduction

Periodic drought during the last seventeen years in West Africa has led several researchers to pay special attention to the variations of some climatic parameters monitored on a relatively long term basis. One of these is the Intertropical Convergence Zone (ITCZ), a major component of the general circulation of the atmosphere. Several studies have shown that anomalies in the ITCZ's location (coupled or not with other parameters) may be related to anomalous dry or wet rainy seasons in western Africa. Hastenrath (1984) found that the most abundant rainfall observed in sub-saharan Africa was associated with "a far northerly position of the near equatorial, low-pressure trough and associated features in wind, cloudiness, and sea surface temperature" (negative anomalies in the equatorial Atlantic region); the opposite conditions would also be true for ITCZ, wind, sea surface temperature, cloudiness and rainfall (data used cover the 1911 – 1982 period). Nicholson (1981; 1983) observed that only the monthly northernmost position of the 25 mm isohyets (we assimilated to the footpath of the inter tropical front) accounts for wetter years (data used cover the 1900 – 1980 period). Many oceanographers also determine ITCZ locations by confluence or convergence of wind at sea level.

It is clear from these different contributions that if a relative importance may be attributed to ITCZ location, the ways used to define it vary widely.

The purpose of this paper is to assess the level of significance that may be attached to ITCZ locations, as suggested by the aforementioned studies. In this study ITCZ has been tracked using meteorological satellite imagery, and its movement compared to climatic parameters and anomalies observed in sahelian area during last seventeen years.

2. Material and Methods

The data used in this study were ITCZ location, upper air wind and humidity, sea surface temperature (SST), and Senegal River runoff.

ITCZ observation was accomplished using either photographs, maps from polar orbital satellites (Noaa or Essa), or geostationnary satellite data [Goes-E and Meteosat received and processed at CMS (Lannion, Fr.)]. To establish ITCZ location we used the definition proposed by Frank (1983): "the prevailing eastwest line of maximum convection." We determined this line by using nephanalysis to locate the coldest clouds on satellite photographs, and through a similar (and more precise) computerized processing with numerical data. The ITCZ, a broad feature of general circulation and easily recognized when narrow and unique, was more complex to analyze when multiple convergence zones appeared. In these cases, only the northern, more stable zone was retained to establish our time series data: Noaa/Essa data provided two images daily during the 1971 – 1981 period, while during the period 1982 – 1987, eight Goes/Meteosat images per day were used. In order to avoid continental influences, which induce larger north-south migrations (due to diurnal warming), we tracked the ITCZ along 28 °W, that is, at a more or less equal distance between the coasts of West Africa and South America. This choice allowed us to determined, indirectly, the area of weak winds which limits the north and south subtropical anticyclones. Servain (1984) and others have shown that the dynamics of the equatorial ocean are particularly linked to wind changes in the western part of the Atlantic Ocean (remote forcing of wind being partly responsible through an oceanic Kelvin wave of the equatorial upwelling in the Gulf of Guinea).

Those factors introduced the need for both wind at sea level and sea surface temperatures, which we obtained from the climatic atlas of Picaut et al. (1985). These data, on a grid of 2 degrees square, were available on a monthly basis. Daily upper air data (humidity and wind), available from the European Center (ECMWF, Reading, U.K.), were available on seven levels from 1 000 to 100 hpa; since 1980 these data provide global coverage with a grid resolution of 2.5 degrees square.

As for drought estimates, we used Senegal River runoff records as primary data (Olivry, 1983), complemented by the Lamb rainfall index (Lamb, 1985). The source of the Senegal River is in the Guinean mountains; nonetheless, fairly good correlation ($r = 0.76$) was observed between its flow and the standard annual rainfall rate over the Sahel as a whole (Palutikoff et al., 1981; and Sircoulon, 1976). Research has also shown (Nicholson, 1980, 1981) that the African drought has extended simultaneously over a large area of intertropical Africa. And the fact that Senegal River runoff is generally similar to the Lamb index is more than a coincidence: Figure 1 shows updated values of the Lamb index and Senegal River runoff respectively, the latter being analyzed in terms of a normalized index (Ri) defined as follows: $Ri = (Di - D)/s$, where Di and D are runoff for

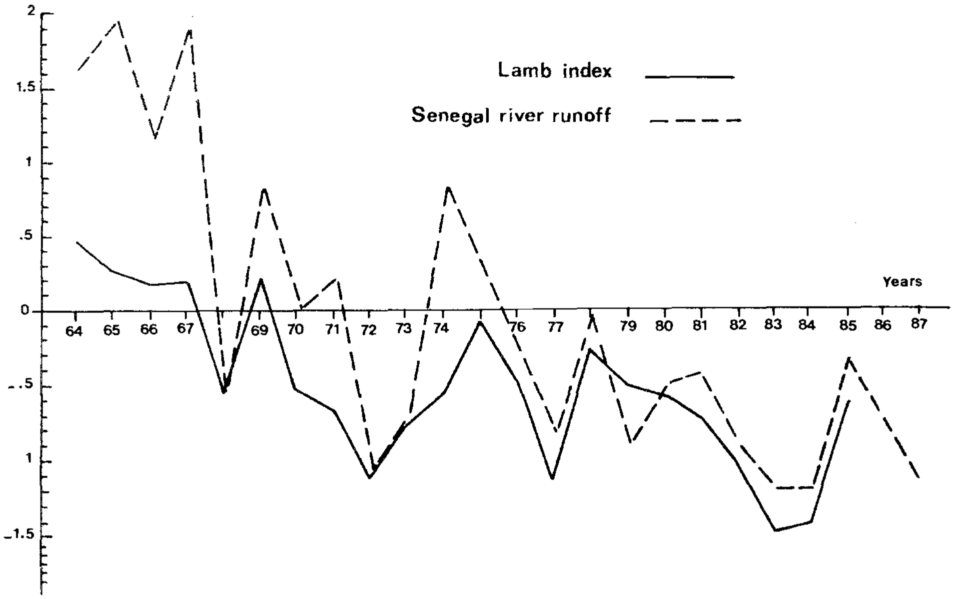

Fig. 1. Lamb rainfall index and standardized anomalies of Senegal river runoff

a year and the mean, "s", is the standard deviation. Only a few minor discrepancies between the two indices are of note: rainfall in 1974 seems to have been underestimated by Lamb's index, while in 1984 Senegal River runoff shows a steady drought. Apparently, at the end of the continuous drought experienced during these periods, the first available rainwaters were used to refill underground aquifers; thus, rainfall may be underestimated. The relative change in the tendency of the rainy season in 1984 is more realistic in the Lamb index, and other reports using water vapor channel of Meteosat (Desbois et al., 1987). Nevertheless, the variations of both indices since 1964 are generally coherent and, moreover, their general decrease is consistent with the linear downward trend observed in Agades (Niger) and Abeche (Chad) described by Hare (1983).

We shall focus only on inter-annual variations of these conditions, either by clarifying previous explanations or by suggesting new ones.

2.1 Report of ITCZ Locations for the 1971–1987 Period

In studying Figure 2, which shows the positions of the ITCZ along 28 °W plotted four times per month during the period under study, some interesting observations are possible. For example, as the ITCZ follows the apparent movement of the sun, two characteristics, namely the date at which the ITCZ began its northward migration and its northernmost position in boreal summertime, can be observed. It appears that northward displacement occurs either early in the year around February–March (as in 1973, 1976, 1982, and 1983), or later around April–May (as in 1974, 1984, and 1985). Observing the northernmost position reached by the ITCZ, one can see that the convergence zone was at rather low latitudes in July–August during 1972, 1973, 1977, 1979, and 1984. Since those years coincide with relatively severe drought periods (cf. Fig. 1), those results agree with the observations of Schupelius (1976), Lamb (1978) and Hastenrath (1984). On the other hand, the ITCZ was found in positions further north, in 1974, 1976, 1982, 1983, and 1985. But during those years, agreement with the aforementioned studies is not very satisfactory, because wetter years were not observed, as expected (except for 1974 and 1985). Since ITCZ migration has been the most commonly cited explanation for dry or wet episodes, some limitations to this interpretation appear. Nicholson (1981, 1983) also found that northernmost ITCZ positions may account for wetter years, though not exclusively.

The fact that our definition of ITCZ differs with those previously mentioned may explain, at least

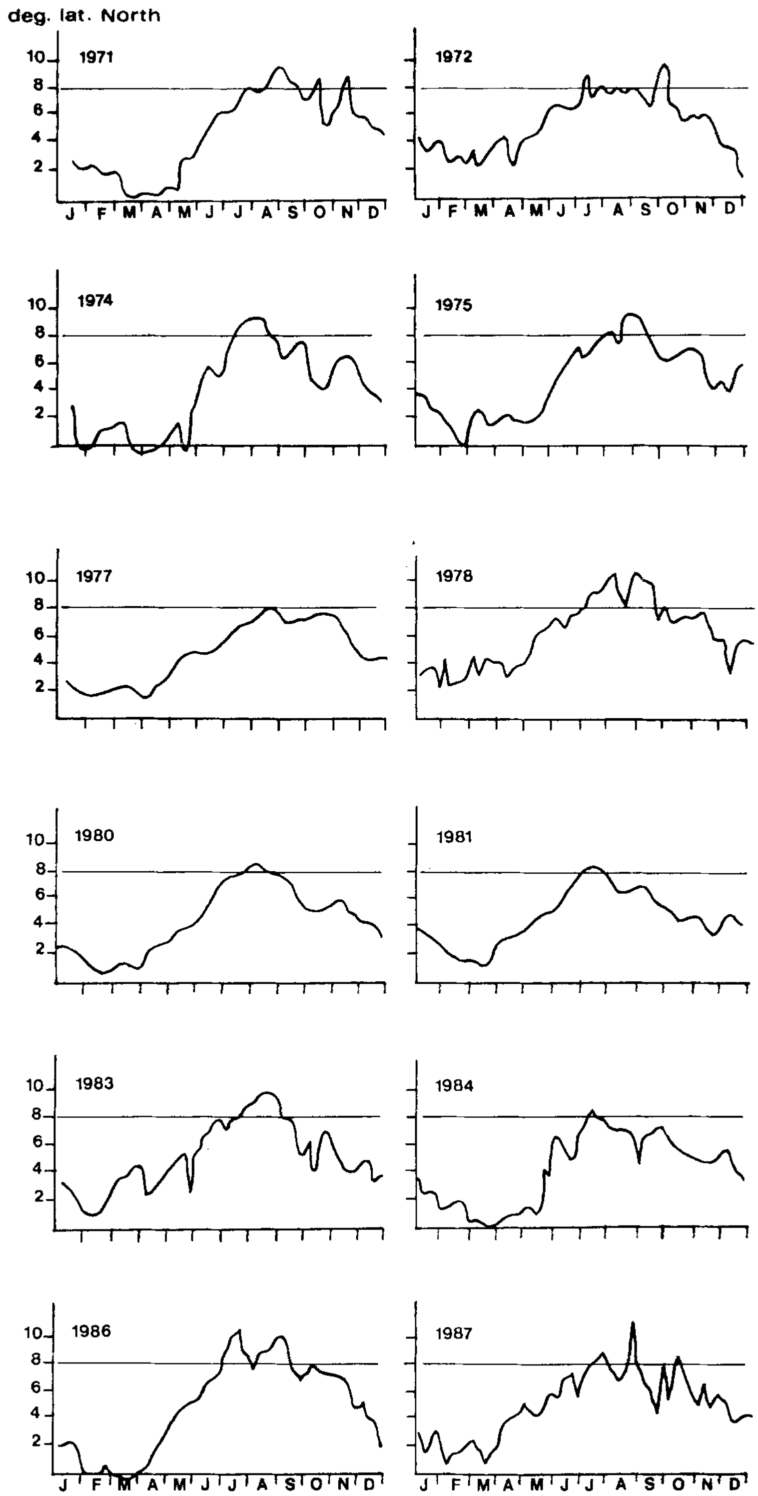

Fig. 2. Oberserved positions of ITCZ along 28 °W from 1971 to 1987

in part, some of the resulting differences in the analysis of ITCZ migration. While bearing in mind that major climate anomalies are usually evident on a global scale and in remote areas, we should also point out that our results are in closer agreement with the above mentioned studies during the seventies than during the eighties.

In order to improve the significance of this ITCZ watch, we studied some relationships with relevant wind observations at sea level.

2.2 Relationship between ITCZ and Wind at Sea Surface

Various studies (Air France, 1965; Hastenrath and Lamb, 1977) have already assessed the relationship between ITCZ and the location of minimum of wind at surface level. Since the satellite data we used did not permit us to make any wind computations, close attention was paid to the location of minimum of wind and its seasonal change. When looking more closely at the date of ITCZ northward migration, this one appears to be correlated with the date of zonal wind intensification observed in an analysis of the oceanographic data processed by Picaut et al. (1985) and updated by Servain et al. (1987). The results shown in Fig. 3 display a fairly good correlation between these two dates ($r = 0.84$). Moreover, it appears that the northward ITCZ movement generally precedes zonal wind intensification (at sea level) by approximately 25 days (slope = 0.99, intercept = 24.8).

This intensification of zonal wind is also well known by oceanographers as one of the parameters inducing the upwelling season in the eastern part of the Gulf of Guinea (Picaut, 1983; Servain, 1984) and allows an attempt of relationship between the latter and ITCZ position.

2.3 Relationship Between ITCZ, Equatorial Atlantic SST and Rainfall

The area where the equatorial upwelling in the gulf of Guinea take place may be well defined

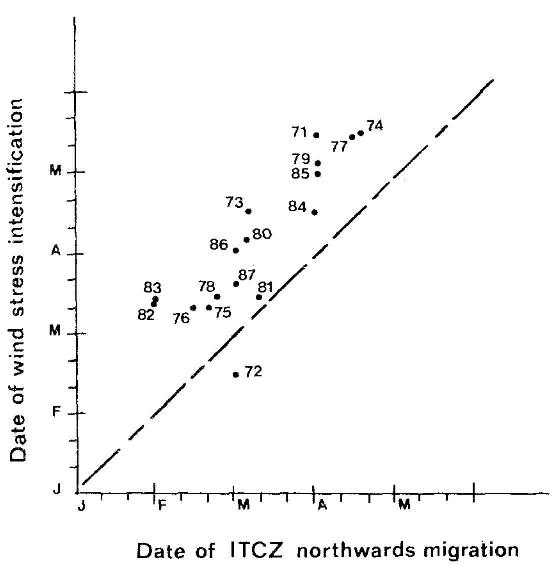

Fig. 3. Date of the onset of ITCZ northward migration versus the data of wind stress intensification at surface

using Meteosat imagery (Citeau et al., 1984), and we selected a limited area (2 N–2 S, 8 W–12 W), in which both the weak and the intense periods of this phenonenon have been well observed. Moreover, this area being crossed by the shipping route Dakar-Le Cap, has been well documented by sea surface measurements. Using the SST data set prepared by Servain (UBO-University of Brest, Fr.) for the tropical Atlantic Ocean, the mean SST anomalies in the area previously defined, were computed on a monthly basis and compared to simultaneous ITCZ location anomalies.

The three-year period from 1967 to 1969 (Fig. 4a and 4b) gives one of the best examples of simultaneous variations of both parameters in total agreement with Hastenrath and Lamb works: during the boreal summer of 1968 positive SST anomalies were observed in the equatorial Atlantic, and ITCZ was shown to be in a more southern position than usual (Hisard, 1980); by contrast, the years 1967 and 1969, during which northern anomalies of location for ITCZ were observed, showed negative SST anomalies. As for rainfall in sahelian areas, 1967 and 1969 were wet years and 1968 a dry one. This close agreement with Hastenrath and Lamb's scheme may also be extended to years from 1971 to 1987 with some noticeable exceptions:

In 1972, normal upwelling was observed in spite of a southern position of the ITCZ (linked to severe drought); later, in 1976, during which the ITCZ was located further north and related, negative SST anomalies were observed, rainfall amounts were again relatively low in sahelian areas. In 1980 and 1981 very similar northerly ITCZ positions and rainfall amounts were observed, in conjunction with quite different intensities of equatorial upwelling (positives anomalies in 1981). Then in 1982 and 1983, during which the northernmost ITCZ positions of this series were observed and, in addition, were well correlated with normal upwelling season in the Gulf of Guinea, a severe drought affecting not only the Sahel but the entire West African region was recorded. If the dryness of 1984 can be qualified of "normal" with regard to the observed signals in SST and ITCZ, the year 1985, which was wetter, led to unexplained positive anomalies of SST. In fact, a weak correlation exists between monthly anomalies of SST and ITCZ position (Fig. 4c), the "best" being derived ($r = 0.4$) when ITCZ position

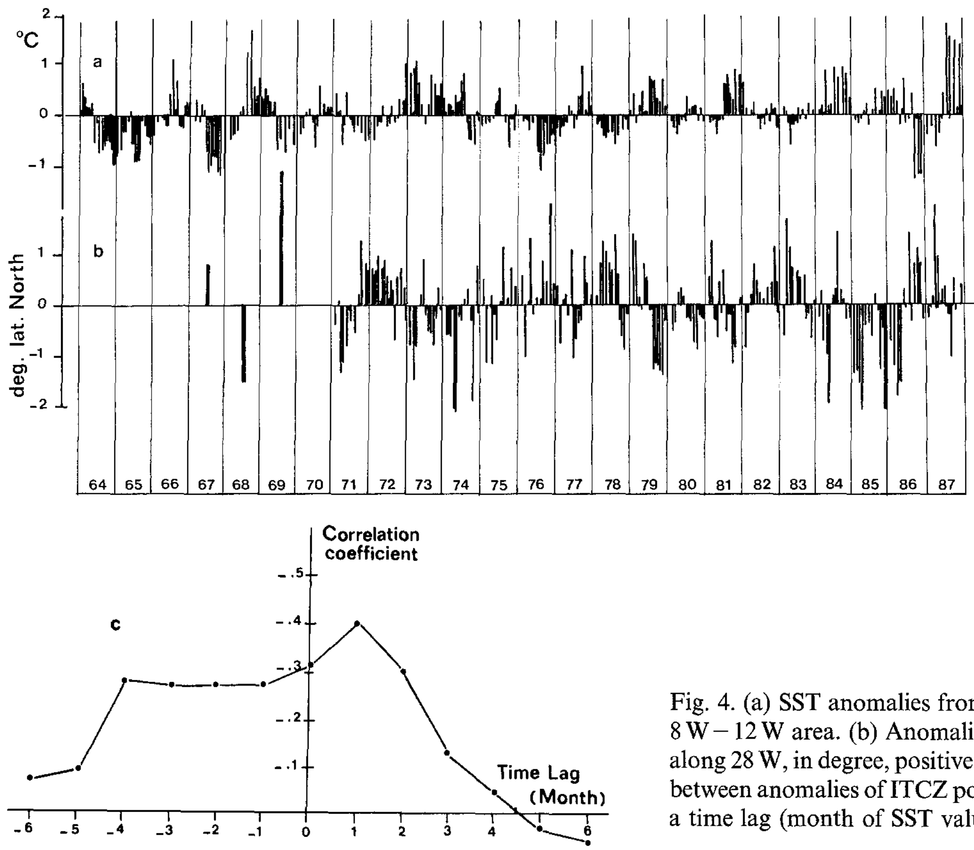

Fig. 4. (a) SST anomalies from 1964 to 1987 in the 2 N–2 S, 8 W – 12 W area. (b) Anomalies of the position of the ITCZ along 28 W, in degree, positive towards north. (c) Correlation between anomalies of ITCZ position and SST anomalies with a time lag (month of SST value – month of ITCZ value)

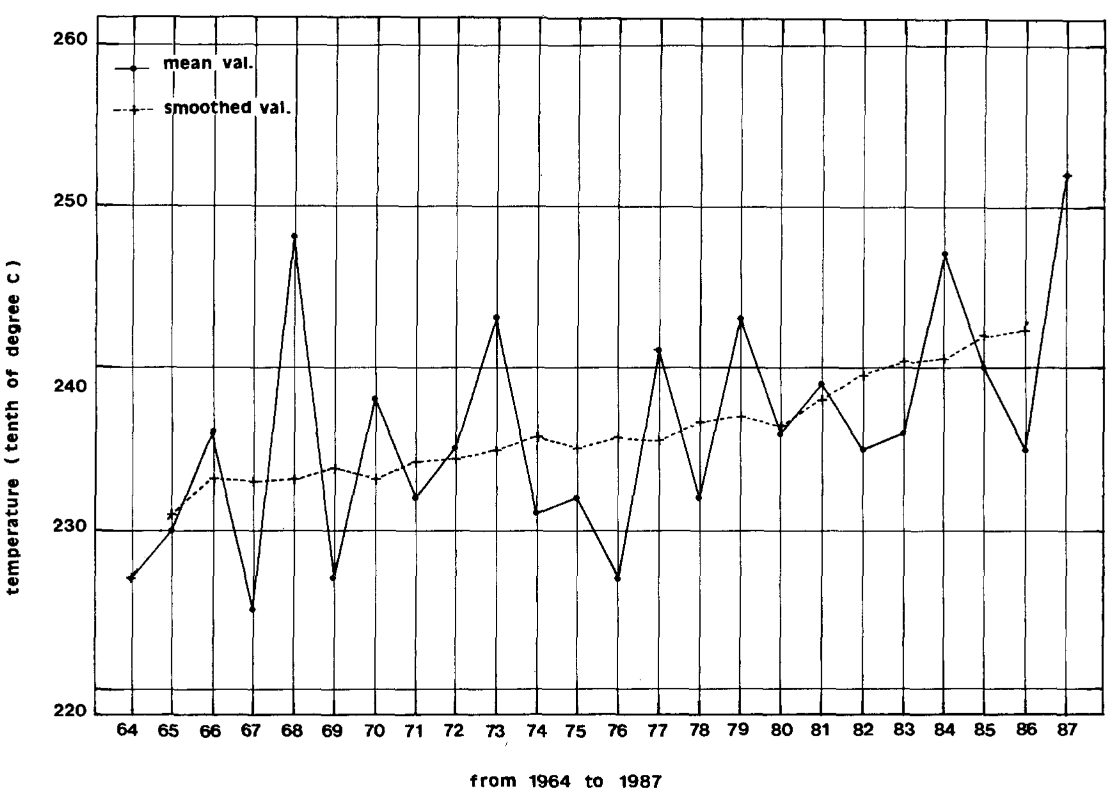

Fig. 5. Mean SST for July to September in the 2 N – 2 S, 8 W – 12 W area, from 1964 to 1987

anomalies are correlated with SST anomalies observed one month later. Some explanations to the fact that our results don't agree totally with aforementioned works must be found in the differences between the time series used, and in the period observed here which is more recent. Some large scale climatic change would also be taken in account as reported by Citeau et al. (1988 a), if we refer to the continuous trend for less intense upwelling in the equatorial area of the Gulf of Guinea (Fig. 5). It is clear that ITCZ location and SST anomalies alone, fail to explain the general and persistent rainfall decrease observed since 1964. As moisture content and transport are necessary conditions for rain process, we analyzed some of the upper air parameters which may be linked to the latter.

2.4 ITCZ Migration, Upper air Parameters and Rainfall

In order to study whether a pattern exists between ITCZ migration and dry or wet episodes, we plotted ITCZ positions for some characteristically dry years, such as 1972, 1982, and 1983 (Fig. 6 a), and, similarly, for the wetter years of 1974, 1985, and 1986 (Fig. 6 b). The resulting mean curve of northernmost and southernmost ITCZ positions is reported in Fig. 6 c for each group of data. The timing difference previously observed between wet and dry years for the ITCZ northward movement still remains evident in these figures but as far as the northernmost position reached by ITCZ during boreal summer is concerned, no significant differences appear. In order to assess the significance of the different timings observed for wet or dry years, it seemed interesting to determine the velocity of this seasonal change. In considering the February-May period and by applying smoothing procedures to our ITCZ time series, we may estimate a slope characterizing this northward movement; this can then be assimilated to an ITCZ migration speed that we represented in Fig. 7 a (in hundredths of degrees of latitude per day). Compared to rainfall index or Senegal River runoff, a fairly good parallel appears between the speed of northward migration and the variations in the drought index. Notwithstanding the encouraging results of this new ITCZ characterization, knowledge of the potential mechanism requires further study. Coupled with the SST signal

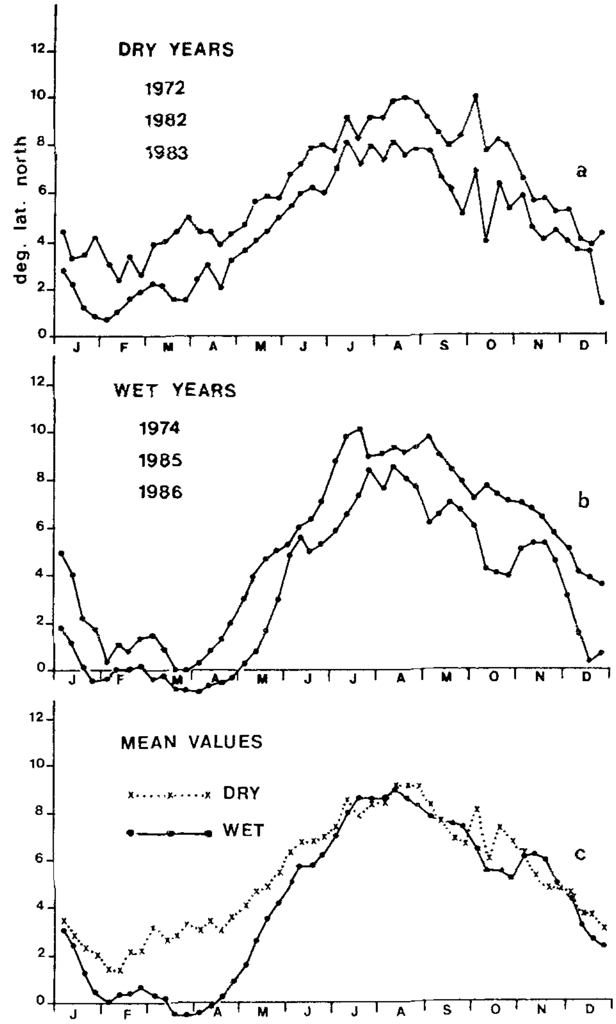

Fig. 6. Envelope of ITCZ's positions for driest years (a), wettest years (b) and mean values (c)

previously defined (Fig. 7 b), both may appear as some, but not the only, compounds adequate to support all explanations of climate anomalies.

Since the moisture of monsoon flux is expected to come from the Atlantic Ocean, it seemed useful to consider which has a greater influence on the rainy season: the amount of local convective processes (linked to warmer waters at the equator), or the transport of humid air, expected to be linked to more intense S–E trades and, by extension, to stronger upwelling in the Atlantic equatorial area.

A primary link to support any unexplained rainfall anomalies must also be looked for in an analysis of upper air parameters able to prevent or reinforce the convective process. This was done by Dhonneur (1985), Lambergeon et al. (1981), Leroux (1983), among other tropical meteorolo-

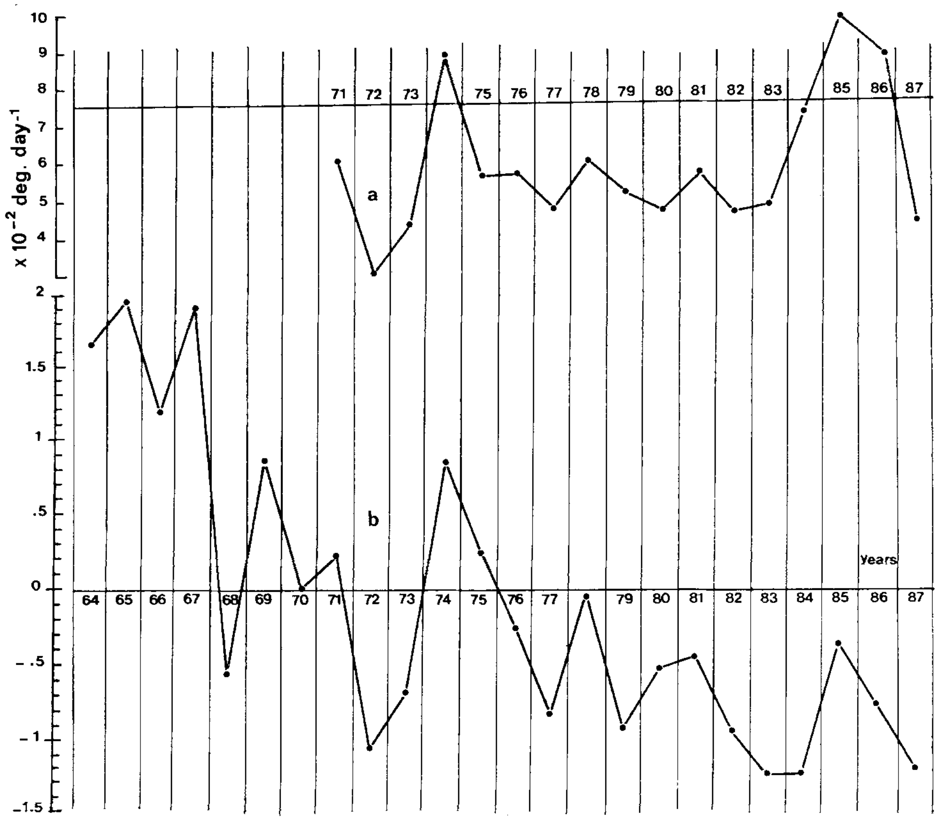

Fig. 7. (a) Mean value of the ITCZ northward speed, in 10^{-2} deg · day^{-1}, (b) Standardized anomalies of the runoff of the Senegal river

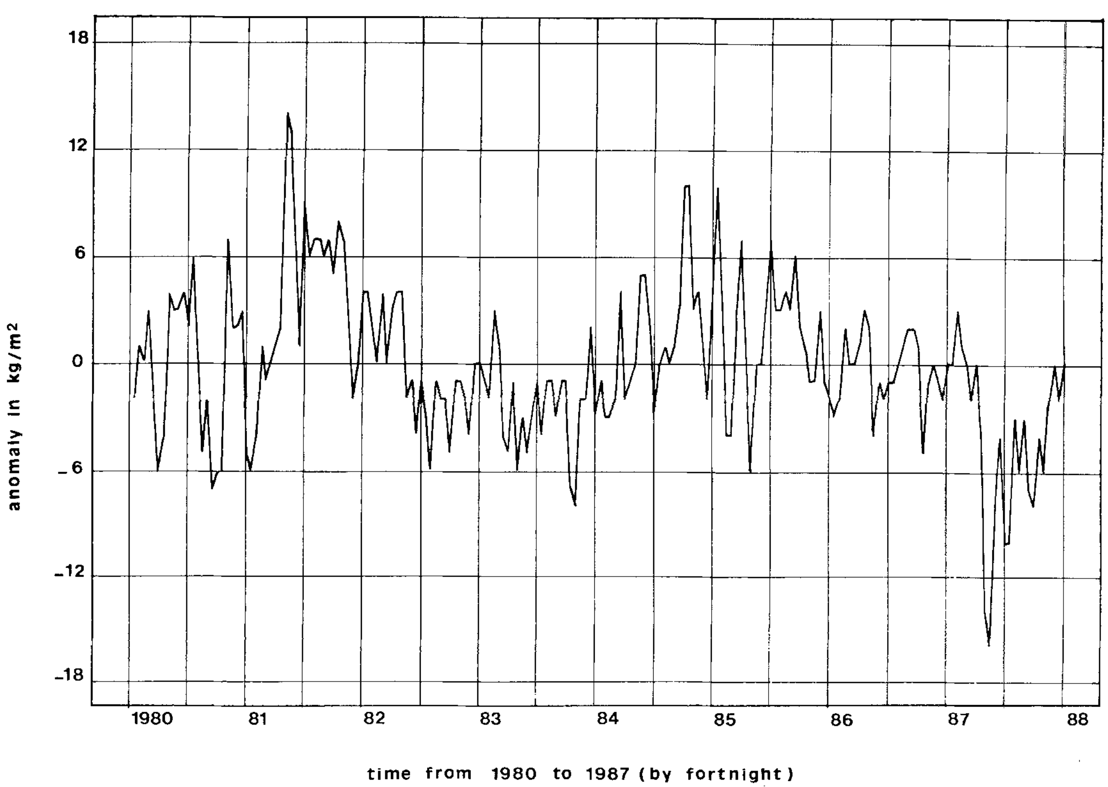

Fig. 8. Anomaly of water vapor content (in kg/m^2) from 1 000 to 300 hpa, in the 10 N − 20 N, 5 W − 20 E area, by fortnight from 1980 to 1987

gists who believe the monsoon flux coming from the Atlantic Ocean is dependent on the sea surface temperatures, and on the interaction between the St. Helena and Azores anticyclones and the Saharan through. The role of African and tropical easterly jets (AEJ and TEJ) has been well investigated by Dhonneur (1985), Tourre (1979) and Finaud (1977), who suggest that dryness over the sahelian area occurs when AEJ is stronger and migrates northward later and when simultaneously TEJ is weaker (the opposite conditions prevailing during wetter periods). This is understandable if one considers that a strong AEJ may hinder ascending movements. These conditions were observed in different sahelian stations, the best documented being Niamey during 1972, a dry year, and 1969, the wettest. But an attempt to extend this scheme to the data (analysis model) provided by European Center (ECMWF) since 1980 does not lead to clear conclusions, the range between weak or strong easterly jets being not very wide. By contrast, the timing of AEJ migration leads to more satisfactory results. When we represent zonal winds over Niamey in a time-scale diagram, wetter years show two cells of African easterly jets (1980, 1981, 1985, 1986) while dry years (1982, 1983, 1987) show only one.

Continuing our analysis of a potential use of upper air water vapor, we examined specific humidity (ECMWF data), computed the air mixing ratio [Goff-Gratch formula in Queney (1974)] from 1 000 to 300 hpa and integrated those in a "Sahel box" limited by 10 N–20 N, 5–20 E. Figure 8 (from Citeau et al., 1988 a) displays the anomaly of the water vapour content in the "Sahel-box" computed versus a climatology based on the 1980 – 1987 period. Notwithstanding the very short time scale of our "climatology" of water vapor content, one may observe that anomalies show long term variations lasting several years, either negative as from mid-1982 to early 1984, or positive thereafter until the end of 1986.

A closer look at each of these years demonstrates that each time the humidity content anomaly was negative, a drier rainy season was observed in the Sahel; this parameter may appear as a limiting factor (contrary to Dhonneur, 1985). The second observation for which we have no satisfactory explanation is that the wetter rainy seasons of the 1980 – 1987 period coincide with positive anomalies of humidity content (Fig. 8) and higher values of the meridional speed of ITCZ northward migration (Fig. 7 a).

3. Conclusion

From this short review, and from the different parameters we used to take a close look at past rainy seasons in West African countries, it appears that the timing of ITCZ and the African easterly jet may be linked to wet or dry anomalies in sahelian areas. Computation of the northward speed of ITCZ migration during the first half of the year is proposed as a new characterization of ITCZ timing. The northermost position reached by ITCZ (using our definition) is not very different in either dry or wet years. The ITCZ observed along 28 °W depicts large scale phenomena, just as the analysis we did over the Indian ocean (Citeau et al., 1988 b) revealed similar ITCZ migration schemes along 28 °W and 60 °E.

ITCZ and wind at sea surface are more closely correlated than ITCZ and SST. The intensity of equatorial upwelling gives some indication of the potential strength of SE-trades (turning to SW), which are responsible for the transportation of humidity over the countries of western Africa.

The humidity content in the upper air appears to be a limiting factor which may explain relative drought; while wetter episodes were observed when positive anomalies of the humidity content coincided with higher values of ITCZ meridional speed.

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