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Towards the prediction of Sahelian rainfall from sea surface temperatures in the Gulf of Guinea

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ABSTRACT

The possible link between sea surface temperature (SST) in specific areas of the Gulf of Guinea and summer Sahelian rainfall is investigated for the purpose of forecasting Sahelian rainfall. Analyses of data series of rainfall in the Sahel and SST in the Eastern Tropical Atlantic reveal that summer Sahelian rainfall is dependent on SST distribution, according to the period (dry or wet) and/or the specific oceanic area (coastal, equatorial or intermediate zone) under consideration. The occurrence of warm surface waters in the Gulf of Guinea is coincident with reduction of summer rainfall in the Sahel, mainly during dry periods. The same relationship does not hold during wet periods. It is suggested that summer Sahelian rainfall could be predicted: (a) from SST in the intermediate warm waters area and the equatorial upwelling zone 1–2 months earlier; (b) from previous quarterly rainfall data in the Sahel.

1. Introduction

The problem of drought in the Sahel is a major preoccupation of local populations, scientists, agriculturists, economists and administrators. Drought is still severe and has continued since 1968 (Lamb, 1982). Several hypotheses have been proposed to explain Sahelian rainfall anomalies. Most of the phenomena involved are termed external and may be related to large-scale climatic change. They include variations in the emitted solar radiation, human activity, volcanic eruptions and the subsequent processes (through northern hemisphere extratropical cooling) of the subtropical highs (e.g., Bryson, 1973a, b; Winstanley, 1973a, b), the intensification of the Hadley cell (e.g., Kanamitsu and Krishnamurti, 1978; Nicholson, 1981) and wave disturbances in the tropical easterlies (reviewed by Baker (1977), and Nicholson, (1981)). Other hypotheses deal with the biogeophysical feedback mechanism related to change in albedo (Charney, 1975; Charney et al. 1974) or the possible active roles of tropical circulation regimes. However, none of these hypotheses is accepted unanimously (for details, see for example Lamb, 1979) and several of them still remain controversial (e.g., Miles and Follard, 1974; Tanaka et al., 1975; Nicholson, 1979, 1980). The lack of sufficiently long series of observational data and the incomplete understanding of the behaviour of the tropical atmosphere lead to great difficulties when trying to relate droughts to large-scale circulation anomalies (Lamb, 1978). The incomplete knowledge of the tropical Atlantic Ocean behaviour is an additional difficulty in investigations about the Sahelian rainfall regime (Bah, 1978). The present study examines the relationship between the sea surface temperatures (SST) in the eastern tropical Atlantic and precipitation (P) anomalies in West Africa as the purpose of forecasting Sahelian rainfall. Local specific phenomenon in West Africa may influence the Sahelian rainfall regime. Of interest are the following:

1.1. Monsoonal wind regime

During the rainy season in north-west Africa monsoonal winds blowing from the ocean to the continent take up humidity in the Gulf of Guinea and bring it over the Sahel. Hirst and Hastenrath (1983) noticed that "local wind forcing contributes somewhat to the SST variance off the

Angola coast, and the SST variations in turn (presumably via atmospheric moisture and stability)" influence rainfall variability along the Angola coast.

1.2. ITCZ migrations

The existence of the Libyan anticyclone (Dhonneur, 1974; Bah, 1978) centered on the 15°E meridian and that of the equatorial depression lead to a thermal contrast between the Sahara and the tropical Atlantic Ocean. In summer this anticyclone is replaced by a (continental) thermal low which could eventually merge with the equatorial depression. Therefore the former existing thermal contrast is reversed leading to an inland flux of fresh and humid air from the nearby ocean. This mechanism in conjunction with the rapid evolution of the equatorial depression and of nearby subtropical anticyclones determines the position of the ITCZ and the northern limit of the rainy area in the Sahel (Bernard, 1974).

1.3. The upwelling phenomenon

The most important feature in summer in the Gulf of Guinea is the appearance of upwelled cold waters near the Equator and the northern coast of the Gulf (see for example Bakun (1978)). Years of intense upwelling in these areas could be coincident with years of drought in the Sahelian region while years of reduced upwelling should result in periods of relatively high rainfall in north-west Africa (Bah, 1978, 1981a–c). This seems to be more striking near the Gulf, south of 13°N than in the Sahel (e.g., Lamb, 1983).

1.4. Specific climatic features in West Africa and the Gulf of Guinea

Dry (wet) years in the Sahel are characterized by the presence of warm (cold) surface waters in almost all the Gulf of Guinea (Lamb, 1978, Figs. 6 and 8). This feature suggests that SST departure fields accompany the atmospheric circulation patterns (e.g., Lamb, 1978) through the enhancement or the weakening of the Hadley cell. On one hand, the reinforcement of the descending branch could result in a compression of the underlying air, a warming of this air and an ensuing dissipation of clouds over the region of the vicinity of 20°N (Bah, 1981a). On the other hand, the expansion of this descending branch is associated with a contraction of the equatorial "rainy" zone (see Nicholson (1981)).

2. Data

Rainfall data in the Sahel region for the period 1905–1973 consist of monthly means of obser-

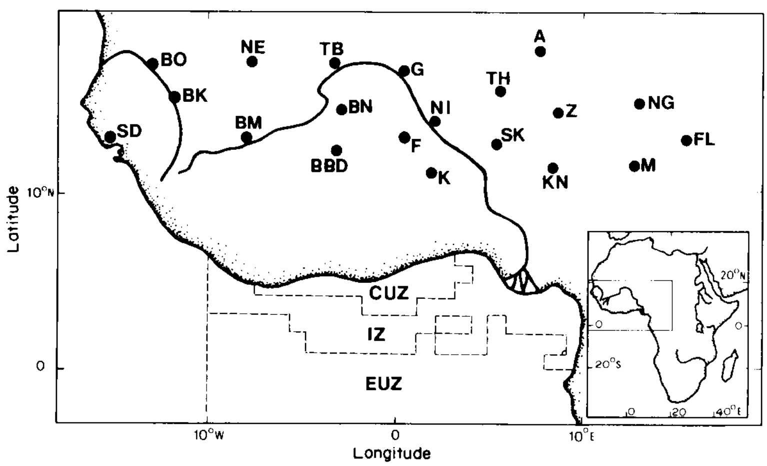

Fig. 1. Orientation map. Dots over continent are Sahelian rainfall stations: Agadez (A), Bakel (BK), Bamakc (BM), Bandiagara (BN), Bobo-Dioulasso (BBD), Boghe (BO), Fada N'gourma (F), Fort Lamy (FL), Gao (G), Kandi (K), Kano (KN), Maiduguri (M), Nema (NE), N'Guigmi (NG), Niamey (NI), Sedhiou (SD), Sokoto (SK), Tahoua (TH), Tombouctou (TB), Zinder (Z). Areas CUZ, IZ and EUZ in the Gulf of Guinea (GG) are outlined by broken lines. See text for further details on these areas.

vations averaged for twenty stations distributed in the area 16°59′N–10°47′N, 15°02′E–15°00′W (Fig. 1 and Table 1). Spatial averaging was performed by Helbig (1976) as follows: for each station, missing data (say X_{ijk}, where i refers to the station, j and k denote month and year respectively) were replaced by the average X_{ij} of values related to that month j over the remaining years, i.e., all the years of the series except year k. Then the area-averaged value for years k and month j were computed as

$$X_{jk} = \frac{1}{N_i} \sum_i X_{ijk}, \tag{1}$$

where N_i is the total number of stations. The reliability of this procedure and henceforth of these data (X_{jk}) are discussed in Section 3.

The SST data are based on ship observations and consist of individual monthly mean values for the period 1911–1972 relating to 1° subsquare in the eastern tropical Atlantic Ocean between 3°S and 7°N, 10°E and 10°W. They were extracted from a data set of marine observations from the National Climatic Centre, Asheville, USA stored on a magnetic tape at the German Weather Service in Hamburg. Because of large gaps in the data series during the early 1940's, only the period 1946–1972 was selected for computations. Here, SST fields were smoothed with a symmetrical 25-weight filter function discussed by Hantel (1970) and used by Lamb (1978) for the Tropical Atlantic Ocean data. Data were qualitatively controlled following WMO (1966) and Aivazian (1970). Stochastic independence was achieved through the squared successive differences test; normality was tested through skewness and kurtosis; doubtful values were removed whenever the standard normal deviate $v_n = |X_i - \overline{X}|/\sigma$ (where $\overline{X}$ is the mean over the entire series and σ the standard deviation) was significant at the 5% level. More details about these tests can be found in Snedecor and Cochran (1980) or Aivazian (1970).

3. Methods

Rainfall and temperature records are usually "noisy" and a normalization procedure must be adopted. The following index was developed:

$$I_{jk} = \frac{1}{N_i} \sum_i \frac{X_{ijk} - \overline{X}_i}{\sigma_i}, \tag{2}$$

Table 1. *Sahelian stations used in the present study*

Station	Station No.	Latitude	Longitude	Elevation (m)	Period	Gap
Agadez	61024	16°59′N	07°59′E	520	1921–72	
Bakel		14°54′N	12°28′W	36	1918–73	May 1922–July 1924
Bamako	61290	12°38′N	08°01′W	332	1919–73	
Bandiagara		14°20′N	03°36′E	426	1920–73	
Bobodioulasso	65510	11°10′N	04°18′W	460	1907–73	
Boghe		16°35′N	14°17′W	17	1919–73	
Fada N'Gourma	65507	12°04′N	00°21′E	301	1920–73	
Fort Lamy	64700	12°08′N	15°02′E	295	1932–72	
Gao	61226	16°16′N	00°03′W	258	1919–73	
Kandi	65306	11°08′N	02°56′E	290	1921–73	
Kano	65046	12°02′N	08°32′E	469	1905–73	1967
Maiduguri	65082	10°47′N	13°11′E	361	1909–73	1925, 67
Nema	61497	16°36′N	07°16′W	269	1922–72	
N'Guigmi	61049	14°15′N	13°07′E	289	1921–71	
Niamey	61052	13°29′N	02°10′E	320	1905–73	
Sedhiou		12°42′N	15°03′W	15	1905–73	
Sokoto	65010	13°02′N	05°14′E	354	1907–73	1967–69
Tahoua	61043	14°54′N	05°15′E	384	1921–72	
Tombouctou	61223	16°44′N	03°03′W	299	1897–1973	1915, 17–21
Zinder	61090	13°47′N	08°59′E	489	1905–73	

All data are gathered at the Meteorologisches Institute der Universität Bonn (after Helbig, 1976).

where I_{jk} is the index of the parameter X (SST or P) for month j and year k relative to the area of N_i stations (or N_i 1° subsquares). Such an index, with the standard deviation σ_i as the normalizing factor, instead of the mean $\overline{X}_i$, is useful and appropriate "because it gives somewhat less weight to desert stations which have a relatively large variance, but contribute little to the (amount of water parameters) of a region" (Kraus, 1977). However, since only spatially averaged values for Sahelian rainfall are presently available, expression (2) was used for the Sahelian area in the form

$$I_{jk} = \frac{X_{jk} - \overline{X}}{\sigma}, \tag{3}$$

where X_{jk} is defined by expression (1), and σ^2 is the variance of all values X_{jk}. Values for N_i are 25, 55, 95 and 175 for the coastal upwelling zone (CUZ), the intermediate zone (IZ), the equatorial upwelling zone (EUZ) and the entire Gulf of Guinea (GG) respectively as shown in Fig. 1. Annual totals during 1905–1973 were calculated to illustrate Sahelian rainfall variability using the following index:

$$I_k = \frac{y_k - \bar{y}}{\sigma_y}, \tag{4}$$

where $\bar{y}$ and σ_y are the mean and the standard deviation of annual rainfall respectively. Such an index was computed and served as a robust index of rainfall activity in coastal Angola (see Hirst and Hastenrath (1983)). The Sahelian rainfall index (I_k for year k) as defined by expression (4) and shown in Fig. 2 illustrates the pronounced interannual variability in rainfall. Fig. 2 resembles the corresponding one of Lamb (1983) except for years 1959–61, 63, 66, 69. The most extreme years in the Sahel were identified from Fig. 2 in the following way: 1946, 50, 52, 53, 54, 55, 57, 58 and 66 as WET; and 1948, 49, 68, 70, 71 and 72 as DRY. Year 1973 was deleted from the data set as no SST data were available for 1973. Most of these years are recognizable in the respective WET and DRY composites of Lamb (1978, 1982).

Several totals were selected for the study regarding Sahelian precipitation and coastal upwelling which occur mostly in summer. These totals are bi-monthly (for example, January–February, February–March etc.) or quarterly (January to March, February to April etc.). Finally, correlation analyses were performed with the Student t-test.

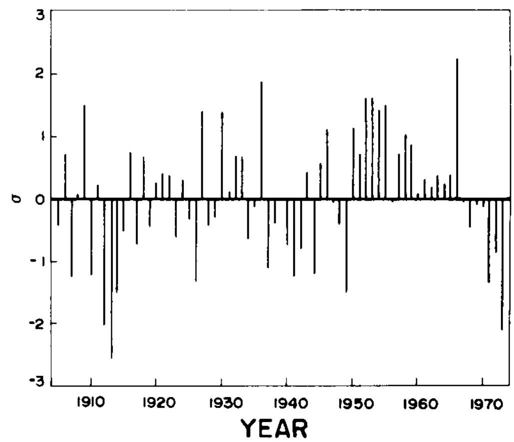

Fig. 2. Yearly average of normalized rainfall departures for the 20 Sahelian stations selected for the present study. See text for details of stations and computational procedure.

4. Results

4.1. Variability of rainfall and SST

The Sahelian rainfall regime and the temporal variation of SST in the Gulf of Guinea are characterized by a marked annual signal (e.g. Merle, 1980; Fleer, 1981) with a concentration of rainfall in July–September and a corresponding minimum of SST (Fig. 3). The spatial distribution of SST is not uniform. The coldest surface waters occur in the equatorial zone almost all the year long (Fig. 3a). In the summer season, the warmest surface waters are localized in area IWZ while cold surface waters are present elsewhere, suggesting the occurrence of coastal and equatorial upwellings in areas CUZ and EUZ respectively. In November–December upwelling is present only near the equator as already mentioned by Merle (1980) and the warmest surface waters are observed near the northern coast of the Gulf of Guinea.

The features noticed about the annual progression of SST are reflected in the departures (from the mean of the series under consideration) curves during the composite DRY and WET seasons and the whole period (1946–1972) as well.

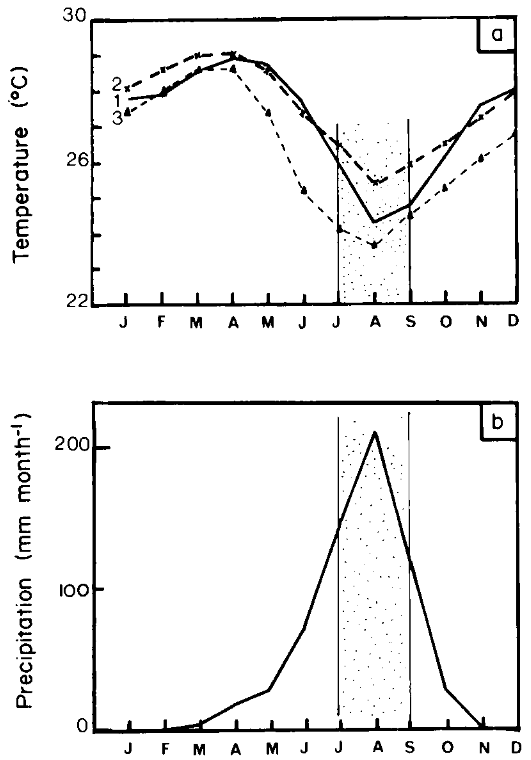

Fig. 3. March of the seasons for (a) SST in the Gulf of Guinea where indices 1, 2, 3 refer to coastal upwelling, intermediate warm waters and equatorial upwelling areas respectively, and (b) rainfall in the Sahelian region.

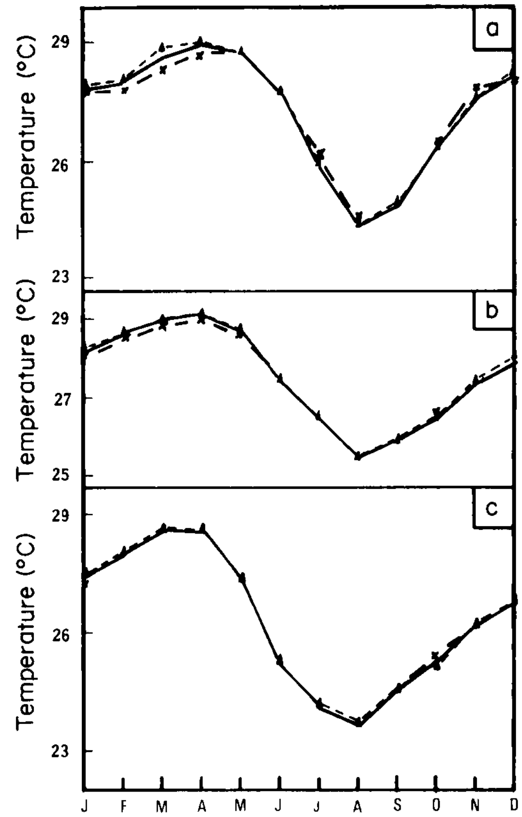

Fig. 4. Normals for SST in (a) the coastal upwelling area, (b) the intermediate warm water area and (c) the equatorial upwelling area, where curves refer to different composites as follows: (——) for the 1946–1972 average, (△--△) for the WET composite and (×——×) for the DRY composite.

The same results hold with corresponding index curves (not shown) and normals (Fig. 4). SST behaviour still is clearly different from one area to another (Fig. 5) and if we define departures as SST anomalies, positive anomalies are stronger in area EUZ in January–April, while negative ones are more important in area CUZ in August–September.

The differences between DRY and WET composites values are more pronounced for the coastal region, particularly from January to May. Moreover, in the whole Gulf of Guinea, surface waters are warmer in summer and cooler in late winter and early spring, during dry years. The opposite situation is not evident during wet years (Fig. 4). However, these results are not inconsistent with the fact that negative correlations occur between Sahelian rainfall regime and SST behaviour in the Gulf of Guinea (e.g., Lamb, 1978).

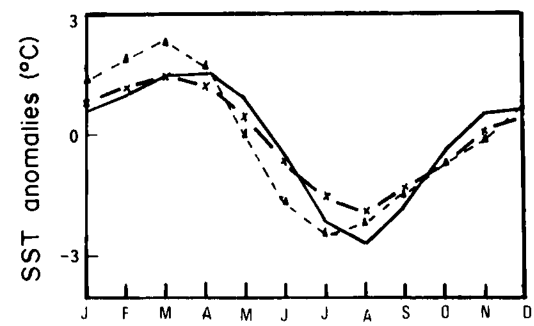

Fig. 5. SST anomalies as departures from the 1946–1972 mean, where curves refer to different specific oceanic areas as follows: (——) for the coastal upwelling area, (△--△) for the equatorial upwelling area and (×——×) for the intermediate warm waters area.

4.2. Spatial couplings

Correlations between the summer Sahelian rainfall and SST in the three specific zones of the Gulf of Guinea during all the 27 years are shown in Table 2. They are negative for both DRY and WET composites, except in the case of correlation between rainfall in the Sahel and SST in area EUZ relative to wet years. Correlations between SST are always positive. They are strong between the two upwelling areas for both composites, and only during wet (dry) years between areas CUZ (EUZ) and IZ. Thus, salient results noticed for the DRY composite hold whatever the specific zone (CUZ, IZ or EUZ), while the same is not true for the WET composite (see also Subsection 4.1). For more details, different series of bimonthly and quarterly sums of SST relative to the specific oceanic zones under study, were analyzed together with quarterly totals (June to August and July to September) of summer Sahelian rainfall. The results are summarized in Tables 3, 4 and 5.

Strong positive correlations occur between SST series (apart from some exceptions in spring), whatever the selected pair of marine areas, for the whole composite and to a small degree for the DRY one (Tables 3 and 4). The same is true for the WET composite (Table 5) but only in early spring and in summer (SST couplings in the upwelling zones and SST couplings in the upwelling areas and the intermediate warm waters zones). In any case, SST are negatively correlated in the spring season for the two upwelling zones, whatever the composite, DRY, WET or the whole one. The same holds for the equatorial cold waters and the warm waters in late spring (DRY composite), and in late summer (WET composite). For SST in the warm waters and the coastal cold waters zones, negative correlations

Table 2. *Correlation coefficients, in hundredths, between values of various indexes relative to Sahelian rainfall and sea surface temperatures in the Gulf of Guinea, where ISH denotes rainfall index for the Sahel, ICZ, IIZ and IEZ are SST indexes, respectively for the coastal upwelling zone, the intermediate zone of warm waters and the equatorial upwelling area*

Indexes		Correlation coefficient		
I	II	DRY (6 years)	WET (9 years)	Whole Period (27 years)
ICZ	ISH	−44***	−26**	
IIZ	ISH	−06	−57***	
IEZ	ISH	−10	45***	
IIZ	ICZ	17	56***	70***
IEZ	ICZ	46***	50***	76***
IEZ	IIZ	28***	08	71***

Two and three asterisks denote significance at the 5 and 1% levels respectively.

Table 3. *Correlation coefficients, in hundredths, between SST and rainfall where SAH denotes Sahelian total rainfall, from July to September, and CUZ, IWZ and EUZ denote quarterly sums of SST, in the coastal upwelling zone, the intermediate warm waters zone and the equatorial upwelling zone respectively*

	CUZ-SAH	IWZ-SAH	EUZ-SAH	SAH-SAH	EUZ-CUZ	EUZ-IWZ	IWZ-CUZ
January–March	20	23	38**	−25	88***	87***	88***
February–April	27	21	24	−37*	84***	88***	82***
March–May	44**	35*	07	−40**	10	46**	71***
April–June	47**	−13	−26	−44**	−31	31	49***
May–July	−13	−08	−34*	−02	72***	74***	72***
June–August	−30	−29	−42**	82***	82***	89***	73***
July–September	−33*	−31	−43**	100***	80***	95***	82***
August–October	−40**	−38**	−37*	81***	76***	92***	84***
September–November	−35*	−35*	−37*	39**	88***	95***	85***
October–December	−41**	−37*	−39**	−18	86***	90***	86***
November–January	−04	−09	−28	05	54***	58***	64***
December–February	01	03	12	−03	72***	61***	84***

One, two, three asterisks denote significant values at 10, 5 and 1% levels, respectively.

Table 4. *Correlation coefficients as in Table 3, except that DRY composites are considered and bimonthly, instead of quarterly sums are used for SST*

	CUZ-SAH	IWZ-SAH	EUZ-SAH	SAH-SAH	EUZ-CUZ	EUZ-IWZ	IWZ-CUZ
January-February	−09	−04	37	−45	72**	73**	95***
February-March	25	12	28	27	99***	85***	89***
March-April	70**	51	22	−81***	67**	90***	70**
April-May	83***	60*	−42	−65*	−43	34	59*
May-June	79**	60*	−60*	−48	−54	−68**	55
June-July	−70**	28	−66*	70**	98***	−44	−29
July-August	−79**	−22	−63*	100***	94***	45	24
August-September	−53	−52	−10	99***	34	79**	79**
September-October	−23	−43	−39	70**	95***	92***	78**
October-November	−67**	−78**	−62*	−89***	98***	90***	84***
November-December	−09	−84***	−81***	−77**	42	87***	55
December-January	47	−25	−22	−74**	69**	66*	65*

Significance of asterisks as previously given.

Table 5. *Correlation coefficients as in Table 4, but for WET composites*

	CUZ-SAH	IWZ-SAH	EUZ-SAH	SAH-SAH	EUZ-CUZ	EUZ-IWZ	IWZ-CUZ
January-February	48	70	31	26	09	62	−02
February-March	44	83**	58	−17	54	90**	64
March-April	57	79*	10	−82**	78*	62	89**
April-May	76*	−53	−94***	−87**	−62	59	05
May-June	73*	−91***	−97***	−16	−68	91***	−50
June-July	−76*	−89**	−98***	100***	84**	94***	89**
July-August	−85**	−91***	−94***	91***	85**	86**	85**
August-September	−19	68	−64	36	07	−47	−10
September-October	−47	−33	24	−54	14	−09	72*
October-November	−70	−66	06	−38	42	04	64
November-December	−68	−55	−50	29	47	03	58
December-January	−35	26	−12	08	−55	08	−21

occur in summer during dry years, and in winter, late spring and late summer during wet years.

The results are very different for pairs of SST and P data series. When analysing the entire 27-yr composite (Table 3) significant positive correlations occurred for CUZ-SAH and IWZ-SAH during the spring season. In winter, positive correlations between SST and P are significant only for EUZ-SAH. However, their values are too small (maximum explained variance = 22%) to provide any valuable forecasts of summer Sahelian rainfall from previous SST in the Gulf of Guinea. The same is true for the autocorrelation coefficients (SAH-SAH). Negative correlations are found in summer, autumn and early winter, as expected from previous results (see Subsection 4.1).

During dry years (Table 4), positive correlations occur between spring SST and summer Sahelian rainfall. However, among these positive correlations, only the one relative to coastal SST and Sahelian P series is significant (at least at the 5% level). The corresponding explained variances are 49, 69 and 62% for the March-April, April-May and May-June bimonthly totals respectively. This suggests that during dry years, Sahelian rainfall from July to September could be predicted from SST in the coastal upwelling zone 2 to 4 months earlier. The same suggestion holds with previous totals of Sahelian rainfall (March-April and April-May) since the corresponding explained variances are 66 and 42 percents. Strong significant values are found for negative correlation coefficients in autumn for all the specific zones, but only for CUZ–SAH and EUZ–SAH in summer, in good agreement with the results presented in Subsection 4.1 concerning the Sahelian rainfall regime and SST in the Gulf of Guinea. For the WET composite, significant positive correlations occur between Sahelian rainfall and SST in the coastal zone (Spring), the intermediate zone (early spring) and not the equatorial upwelling zone. The corresponding explained variances are 58% (April–May) for the CUZ–SAH series and 69% and 62% (February–March and March–April) for the IWZ–SAH data, suggesting that summer Sahelian rainfall could be predicted from SST in the coastal upwelling (intermediate warm waters) zone 2 (3–4) months earlier. However the largest values are found for negative correlations which occur basically in summer, in good agreement with the results in Subsection 4.1 (last paragraph). 83% of the variance is explained through the correlation between IWZ and SAH data in May–June; the corresponding values are 94 (88)% for EUZ–SAH data in May–June (April–May) and 76 (67)% for SAH–SAH in April–May (March–April). Summer Sahelian rainfall could therefore be predicted (1) for SST in the intermediate warm waters (equatorial upwelling) area one (1–2) months earlier, and (2) from previous quarterly rainfall in the Sahel region (2–3 months earlier).

5. Discussion and summary

Analyses of rainfall and SST data series have shown that summer Sahelian rainfall is dependent on the surface temperature distribution in the Gulf of Guinea. This distribution is spatially and temporarily not uniform and varies according to the period (dry or wet) and the specific oceanic area (coastal, equatorial or intermediate zone). Coastal and equatorial areas are characterized by the occurrence, mainly in summer, of cold waters due to upwellings, while warm waters appear in the intermediate zone, probably related to (advected by ?) the Guinea current. Positive SST anomalies are stronger in the equatorial zone from January to April, and negative ones are more important in the coastal area in August–September. Occurrence of warm waters in the Gulf of Guinea is coincident with reduction of summer rainfall in the Sahel, in accordance with the conclusions of Lamb (1978). This result however is true only for dry periods. It is not evident during wet ones, at least if one considers the entire Gulf. Indeed, distinct specific areas are observed in the Gulf and SST anomalies present in these areas may have important effects on the dynamics of processes occurring in the upper waters of the eastern tropical Atlantic and in the lower troposphere over North-West Africa, as can be inferred from spatial couplings and related cross correlation analyses.

Positive correlations are found between SST in the two upwelling zones, except in spring. This is consistent with the remote forcing hypothesis of Moore et al. (1978) as applied by Adamec and O'Brien (1978) and Bah (1981a, c) according to which variations of westward wind stress over the western Atlantic Ocean should induce upwelling (equatorial and coastal) in the Gulf of Guinea. Some other features could also be linked to the spatial distribution of SST anomalies: (1) cloudiness departures over the Eastern Tropical Atlantic could force SST departures through controlled insolation at the ocean surface (for more details see Hirst and Hastenrath, 1983); surface waters thus, could enhance or weaken convective activity on the regional scale depending on whether ITCZ is far away or not. However, this does not imply that continental rainfall anomalies would be associated with similar anomalies in offshore cloudiness (see, e.g., Hirst and Hastenrath (1983) for the Angola coast). (2) "Departures of local wind speed might force the development of SST departures by modulating the rate of evaporation and sensible heat loss from the air-sea interface and affecting the rate of turbulent mixing of surface waters with colder water from below" (Hirst and Hastenrath, 1983). However, the sub-Saharan drought does not seem to be associated with the inland flux of unusually dry surface air from the tropical Atlantic Ocean (Lamb, 1983).

Anyhow, whatever the cause (direct or indirect), or the causality chain of anomalies, links between Sahelian rainfall and temperature distribution in the Gulf of Guinea may be important, their strength depending on the period (DRY or WET) and/or the specific marine area (cold or warm waters zone). More specifically, it is proposed that summer rainfall in the Sahel could be predicted one to two months earlier from SST in the intermediate warm waters area and the equatorial upwelling zone. It is also predictable from previous quarterly rainfall data in the Sahel.

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