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Upper air characteristics of wet and dry days in tropical West Africa during the rainy season

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Abstract Many studies have been carried out to analyse monthly upper air meteorological data, trying to explain the dry or wet rainfall anomalies in tropical West Africa. Based on daily upper air data from seven stations in sub-Saharan Africa over a 30-year period we were able to show that the marked differences between dry and wet regimes are much better reflected in the differences between dry and rainy days, than between dry and wet years. Unambiguous differences were found for the zonal and meridional wind (both near the surface as in the middle and high troposphere), the thickness of the monsoonal layer, the specific humidity and the total precipitable water. Grouping the data into dry and wet years revealed that the marked daily differences occur both during dry and wet years, showing that the studies based on yearly differences are less suited to analyse different rainfall regimes.

INTRODUCTION

Recently abundant evidence has become available (Newell *et al.*, 1984; Fontaine *et al.*, 1995) documenting the downward rainfall trend observed during the second half of the 20th century in tropical West Africa. A number of studies have tried to characterize the anomalies of upper air observations in the Sahel during the earlier wet and the more recent dry period by means of average monthly and seasonal upper air data in order to find the relationship between Sahelian drought and regional or global circulation changes. Having noted the large inter-daily variability even during so-called wet or dry anomalous seasons and periods, we will focus in this paper on the statistics of daily upper air observations—separated for both dry and rainy days—for the rainy season from the beginning of May to the end of September. We report on work in progress regarding a comprehensive study of daily upper air statistics for a number of stations in tropical West Africa. We will concentrate on the summer period only, because it is only in summer that a significant amount of rainfall occurs in the Sahel.

The circulation in West Africa occurs along three main wind axes:

(a) The southwesterly monsoon flow at lower levels constitute an important source of humidity and its characteristics are to a large extent determined by the large scale atmospheric circulation and sea-air interaction over much of the tropical Atlantic sector (Lamb, 1983).

(b) The core of the African Easterly Jet (AEJ) at intermediate levels is situated between 12°N in June and 16°N in August and attains its maximum velocity between 700 and 600 hPa (Tetzlaff *et al.*, 1988). Figure 1 clearly shows the well

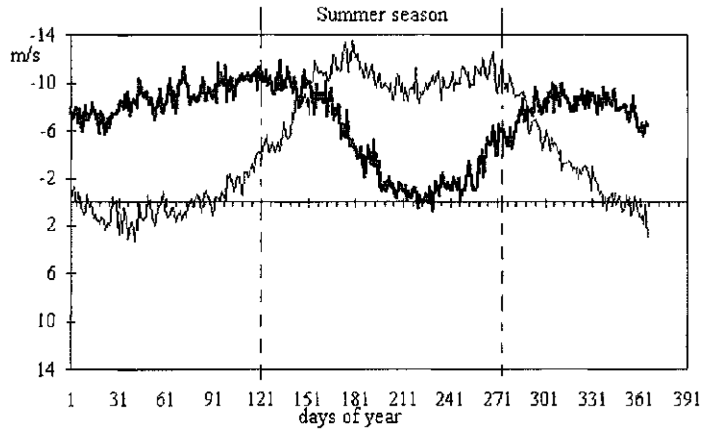

Fig. 1 The daily averaged zonal wind speed in m s^{-1} at 650 hPa. Negative values indicate easterly winds (in summer, African Easterly Jet). The thin line represents the average values for the three Sahelian stations (Dakar, Bamako and Niamey); the thick line represents the average value for the four stations at the Guinean coast (Lagos, Douala, Abidjan and Bangui).

developed African Easterly Jet in summer over the Sahelian latitudes only. This unstable and moderate jet reflects north–south thermal gradients near the surface between hot Saharan air masses and cooler Guinean and Atlantic ones. It appears limited to the Sudano-Sahelian belt (Fontaine *et al.*, 1995). Figure 1 also shows that during winter the easterlies are limited to the Guinean coast.

(c) The core of the Tropical Easterly Jet (TEJ) attains its maximum between 200 and 100 hPa around 15°N (Hulme & Tosdevin, 1989), but is situated further to the south in the exit area over West Africa. Figure 2 shows that the TEJ, although well developed over the Sudano-Sahelian region, is stronger at Guinean latitudes, where it also occurs earlier in the rainy season. Note also the existence of westerlies in winter above the Sahel.

Based on studies of monthly data Dhonneur (1974), Kidson (1977), Newell & Kidson (1984), Fontaine & Janicot (1992), Céron (1993) and Fontaine *et al.* (1995) have shown the existence of a negative (resp. positive) correlation between the monthly speed of the AEJ (resp. TEJ) and the precipitation in the Sahel. The deficient precipitation in boreal summer is associated with an abnormally rapid AEJ and an abnormally slow TEJ (and *vice versa*). The local inhibition of monthly precipitation is possibly, but by no means evidently, related to the strong shear induced under the axis of the AEJ.

DATA

In this paper we consider the upper air data from seven stations situated between 4°N and 15°N in West Africa (Dakar, Niamey, Bamako, Abidjan, Lagos, Douala and Bangui): the data were obtained from "Le Service de Météorologie National Français" (1951–1965), the National Oceanic and Atmospheric Administration (NOAA) (1964–1978), the West African Monsoon Experiment (WAMEX) (1979),

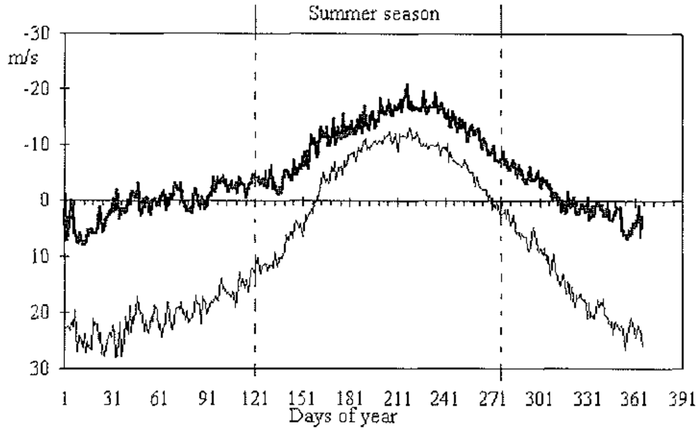

Fig. 2 The daily averaged zonal wind speed in m s[-1] at 200 hPa. Negative values indicate easterly winds (in summer, Tropical Easterly Jet). The thin line represents the average values for the three Sahelian stations (Dakar, Bamako and Niamey); the thick line represents the average value for the four stations at the Guinean coast (Lagos, Douala, Abidjan and Bangui).

and the European Centre for Medium Range Weather Forecast (ECMWF) (1980–1984). The period of investigation was the summer season (May–September) 1950–1980. Unfortunately many data were missing and it proved impossible—working with daily upper air data—to establish for the seven stations involved, and for the whole period, complete series. Accepting only individual years (rainy seasons) with less than 30% of missing data, we were able to establish a data set with on the average of 19% missing data. The main discussion will be limited to four stations only: Dakar, Niamey, Bamako and Abidjan.

Daily rainfall data, used to define rainy (≥0.5 mm) and dry days, were supplied by the International Data rescue Coordination Centre, Brussels (IDCC). The climate in the area of investigation varies from semiarid in the north to tropical humid in the south (Table 1). Bamako and Niamey will be taken as typical for the Sudano-Sahel area, Dakar for the coastal semiarid and Abidjan for the tropical humid climate near the Guinean coast, which is also characterized by a marked dry season in August (little dry season). In the semiarid area (Dakar) the number of rainy days during the rainy-season amounts to 12% (17 days in total), while in the Sudano-Sahel area the number of rainy days (25–30%) during the rainy season approaches the rainfall frequency at the Guinean coast during that same period. It should be realized that in

Table 1 General characteristic of selected stations.

	Lat.	Long.	Koeppen type	% of rainy days in rainy season:		Amount of rainfall (mm) per rainy day:		Amount of rainfall (mm) per day:	
				Dry years	Wet years	Dry years	Wet years	Dry years	Wet years
Dakar	14°,73	17°,50W	BS	12.1	17.8	18.0	25.7	2.2	4.6
Bamako	12°,53	07°,95W	Aw	24.7	31.2	24.6	33.1	6.1	10.3
Niamey	13°,48	02°,17E	BS	31.2	36.3	14.1	14.6	4.4	5.4
Abidjan	05°,25	03°,93W	Am	29.1	35.0	28.0	43.4	8.1	15.2

Rainy season: 1 May–30 September.

the latter area the amount of rainfall per rainy day remains however much higher, especially during the wet years (Table 1), and that no account was taken of the abundant rainfall outside the period May–September and that Abidjan witnesses a so called "little dry season" in August–September.

METHODS

From the raw aerosonde data a large number of statistics were calculated. Here we limit the discussion to the specific humidity q in g kg^{-1}, the zonal component of the wind u in m s^{-1}, the meridional component of the wind v in m s^{-1} and the precipitable water w in mm. The latter quantity was calculated by the trapezoidal method and expressed by:

$$w = \int_{Pt}^{Ps} q(\mathrm{d}p / g)$$

where q, g, Ps and Pt represent respectively, the specific humidity, acceleration due to gravity and the atmospheric pressure at the bottom and top of an isobaric layer of thickness dp. In this paper we will not consider the water vapour fluxes and instability criteria, which were also calculated but will be discussed elsewhere.

CHARACTERISTICS OF DRY AND RAINY DAYS

Zonal and meridional wind

Zonal wind:

(a) West coast semiarid: from the graph of the daily upper air data (Fig. 3(a), example Dakar), we observe—going from dry to rainy days—(i) the disappearance of the westerly component and an increase of the easterly wind speed between the surface and 805 hPa. (ii) a significant diminution of the speed of the easterly wind (AEJ) between 805 and 505 hPa. (iii) a drastic increase of the speed of the easterly wind from 505 hPa upwards (TEJ).

(b) Sudano-Sahel: a similar picture (Fig. 3(b), example Bamako) can be shown here with an increase of the easterly wind—going from dry days to rainy days—from the surface up to 750 hPa. The marked diminution of the wind speed of the AEJ takes now place between 750 and 400 hPa. Also the increase of the wind speed towards the TEJ is observed.

(c) Gulf of Guinea: the westerly zonal wind near the surface does not disappear but diminishes slightly in strength when going from dry to rainy days. From the level of 850 hPa upwards the wind becomes easterly, slightly diminished in strength at all levels during the rainy days as compared to the dry days (Fig. 3(c), example Abidjan).

Meridional wind:

The strength of the meridional wind component (Figs 4(b) and (c)) is generally much less (<1 m s^{-1}) than the strength of the zonal component in the middle and high

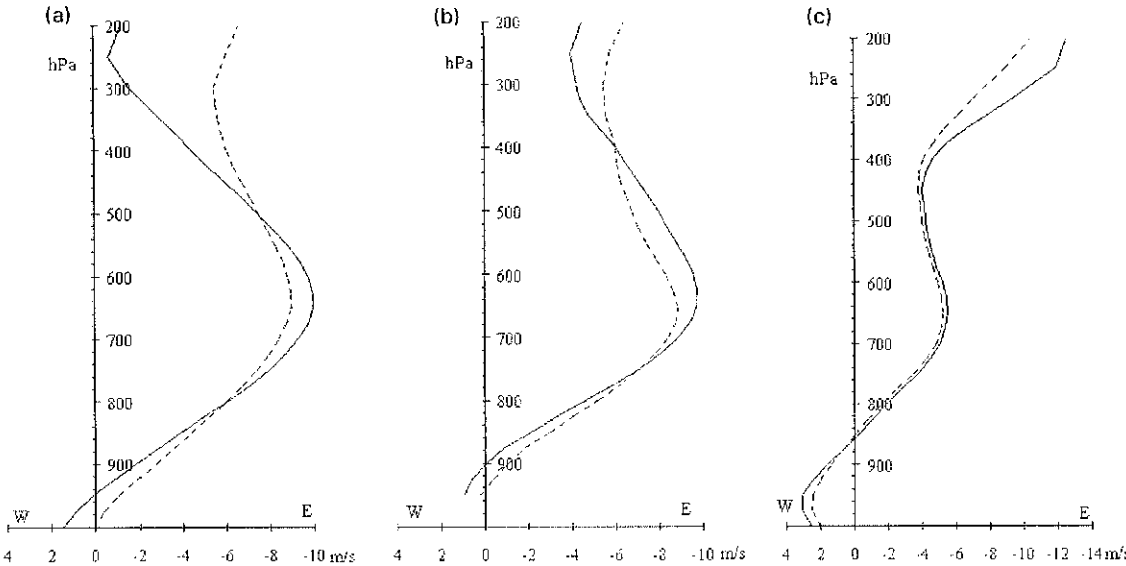

Fig. 3 The zonal wind speed in m s^{-1} for all years at (a) Dakar, (b) Bamako and (c) Abidjan. Full line: dry days; dashed line: rainy days. Positive value: western wind; negative values: eastern wind.

troposphere. Near the surface (from the surface to 800 hPa) the wind velocity is larger and one observes generally an increase of the southerly wind component during rainy days. In Dakar (Fig. 4(a)) the wind is northerly during dry days and switches to a southerly wind on rainy days. Niamey and Abidjan (Figs 4(b) and 4(c))

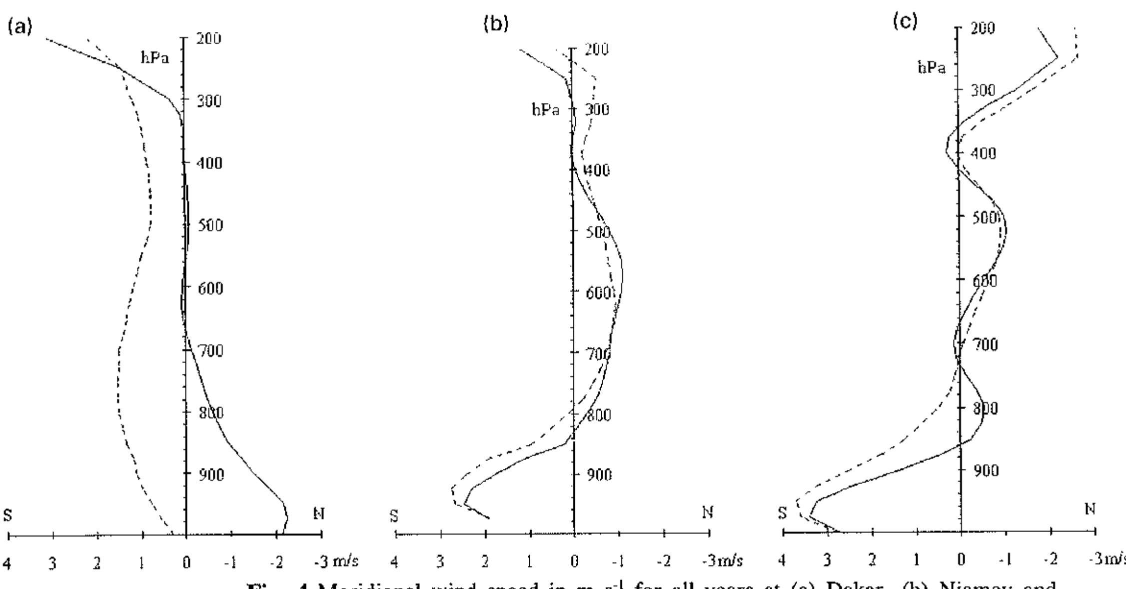

Fig. 4 Meridional wind speed in m s^{-1} for all years at (a) Dakar, (b) Niamey and (c) Abidjan. Full line: dry days; dashed line: rainy days. Positive value: southern wind; negative values: northern wind.

show a significant southerly flow (2–4 m s^{-1}) on dry days which increases during the rainy days.

These results (increase of the TEJ and decrease of the AEJ on rainy days) corroborate the findings of previous investigators dealing with dry and wet seasons. Furthermore we notice that near the surface and during wet days the southerly component of the southwest monsoonal wind increases compensating for the westerly decrease. In Dakar the meridional component of the wind is from the north during dry days and from the south during wet days and this over a significant portion of the atmospheric column. The southwesterly monsoon exists here only during the wet days.

Precipitable water

Integrating the amount of specific humidity over the total tropospheric column, the amount of precipitable water was calculated, again for the dry and wet days separately, and expressed in mm of water (Table 2). The precipitable water varies over the different stations between 40 and 55 mm (all years). However the values increased from dry days to rainy days everywhere with 5–10%, except at the west coast (Dakar) where a spectacular increase of 25% was observed. This aberrant increase at the west coast might be explained by the absence of a southerly wind component during the days without rainfall.

Thickness of southwesterly monsoon layer

It is well known that the southwestern moisture laden monsoonal inflow during the summer is caused by the curvature of the trade winds after crossing the equator. This

Table 2 Precipitable water in mm.

		Dry day	Rainy day	Difference
Dakar	All years	42.8	53.6	+10.8
	Dry years	41.7	52.7	+11.0
	Wet years	43.0	53.7	+10.7
	Wet – dry	***+1.3***	***+1.0***	***-0.3***
Bamako	All years	49.8	54.1	+4.3
	Dry years	50.4	54.4	+4.0
	Wet years	48.7	53.4	+4.7
	Wet – dry	***-1.7***	***-1.0***	***+0.7***
Niamey	All years	41.6	44.4	+2.8
	Dry years	42.1	46.1	+4.0
	Wet years	41.4	44.0	+2.6
	Wet – dry	***-0.7***	***-2.1***	***-1.4***
Abidjan	All years	49.0	54.4	+5.4
	Dry years	48.4	54.1	+5.7
	Wet years	49.8	54.6	+4.8
	Wet - dry	***+1.4***	***+0.5***	***-0.9***

Precipitable water in mm.

flux can clearly be seen in most stations of West Africa. In order to investigate the monsoonal flux near the surface in somewhat more detail we determined the height where the zonal wind changes from west to east and the meridional wind changes from south to north. In the continental Sahel (12°N–13°N), the thickness of southwesterly monsoon layer decreases with 30%, i.e. from 1000–1400 m during dry days to 700–1000 m during wet days. At the west coast (Dakar), as said above, it is only during rainy days that we can observe the southwesterly monsoon flow. At the Gulf of Guinea coast, we notice on the other hand an increase of the thickness of the southwesterly monsoon layer of about 10% going from dry days to rainy days. From this we conclude that in the continental Sahel, although we witness a southwestern influx of moist air near the surface related to a monsoonal effect, the rain forming mechanisms are not fundamentally related to this influx of moist air. This does not apply for the Guinean coast, where a relationship is suggested between rainy days and southwesterly moist air.

CHARACTERISTICS OF DRY AND WET YEARS

Dry and rainy days were again investigated during so called dry and wet years. A year was considered as dry (resp. wet), if its amount of rainfall during the rainy season was below (resp. above), its long term normal. Generally, the typical trends as noted above, when going from dry days to rainy days, are—as expected—more conspicuous during the wet years: i.e. the diminishing of the surface westerlies, the enhanced TEJ and especially the reduced AEJ (compare Figs 3(a) and 5(a), 3(b) and 5(b), 3(c) and 5(c)). In Abidjan the difference during wet and dry years is relatively reduced (Figs 3(c) and 5(c)).

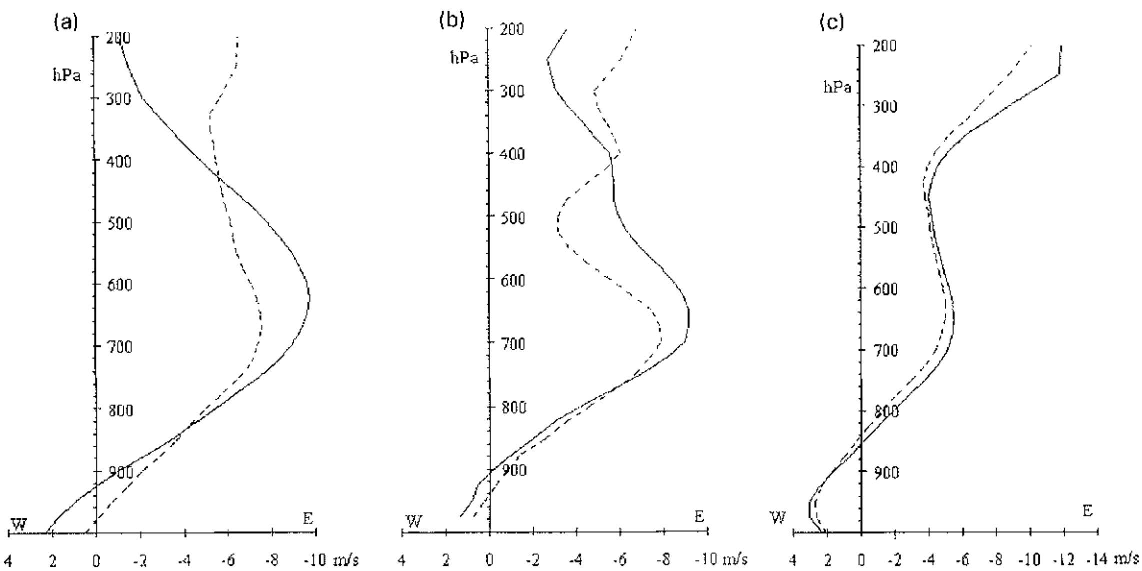

Fig. 5 The zonal wind speed in m s^{-1} during wet years (above average) at (a) Dakar, (b) Bamako and (c), Abidjan. Full line: dry days; dashed line: rainy days. Positive value: western wind; negative values: eastern wind.

The increase in precipitable water, going from dry days to rainy days remains significant both during dry years and wet years, especially near the west coast in Dakar (Table 2). The table shows moreover that this increase is slightly larger during wet years near the coast (Dakar and Abidjan) and smaller in the interior (Bamako and Niamey). This lower specific humidity in the Sahel during the wet periods is surprising and has been noted by other authors. It shows that the dominant feature between wet and dry conditions is best typified by dry and rainy days and not by dry and wet years.

CONCLUSIONS

In the past, in order to explain dry and wet regimes in West Africa, correlations have been sought between the amount of rainfall during dry and wet years and other climatic and circulation factors. In this paper we have shown that the significant differences to be explained are those related to dry and rainy days.

Compared to dry days, rainy days are unambiguously characterized by:

(a) near the surface: the decrease of the westerlies and the increase of the southerlies, which means that the monsoonal flow becomes more meridional. A decrease of the thickness of the monsoonal layer (except at the Guinean coast);
(b) in the middle troposphere: a decrease of the AEJ and consequently a decrease of the vertical windshear;
(c) in the higher troposphere: a significant increase of the TEJ;
(d) a very marked increase of the specific humidity in the lower and middle troposphere and hence of the total amount of precipitable water.

Grouping the data into dry and wet years revealed that these marked daily differences occur both during dry and wet years, showing that the studies based on yearly differences are less suited to analyse different rainfall regimes.

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