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THREE-DIMENSIONAL CHARACTERIZATION OF BOREAL SPRING-SUMMER CLIMATE VARIABILITY OVER WEST AFRICA

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1. INTRODUCTION

The climate of tropical West Africa, a subcontinent whose rural economy thrives predominantly on rain-fed agriculture, has received tremendous attention following the persistent and devastating drought that plagued the Sahel in the early 1970s (Lamb and Peppler 1992; Nicholson and Palao 1993). Efforts have been made to diagnose this extreme climate variability using empirical and modeling techniques, with the aim of understanding the attributions, and possibly, attempt to find pragmatic solutions that could inject new lease of hope to the people of this less developed subcontinent.

Two major seasons which characterize the West African monsoon (WAM) during boreal spring-summer are March-April-May-June (MAMJ) and June-July-August-September (JJAS). The MAMJ and JJAS seasons constitute the Gulf of Guinea Coast (GOGC) and the Sahel precipitation seasons, respectively. A comparison of the 3-dimensional climate anomaly patterns in association with the dominant precipitation modes of the two seasons involving June, the transitional month, has not been explored. This spurs us to undertake the study.

The current research is, therefore, intended to address the unique problem in order to improve our understanding of climate variability over this subcontinent. The results may be useful for modeling studies.

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2. DATA, METHODS AND ANALYSIS

2.1 *Data*

The data used for the research were monthly gridded University of Delaware terrestrial precipitation (Willmott and Robeson 1995), improved extended reconstructed sea surface temperature (ERSST; Smith and Reynolds 2004), and National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR)(Kalnay et al. 1996) reanalysis. These have spatial resolutions of 0.5^o latitude x 0.5^o longitude, 2.0^o latitude x 2.0^o longitude, and 2.5^o latitude x 2.5^o global grids, respectively. The essential climatic ingredients which were extracted from the reanalysis data were horizontal winds, vertical velocity (omega), and geopotential height fields at 1000 and 500 hPa isobaric surfaces.

2.2 *Methods and Analysis*

The general characterization utilized unfiltered (raw) data for the analysis, which spanned 1948-2006, constituting 59 years of continuous data for the two seasons. Empirical orthogonal function (EOF) analysis was performed on the precipitation data over West Africa, out of which the leading modes, which passed the delta-test (North et al. 1982), were retained. The total precipitation time coefficients (TPTCs) were decomposed into positive and negative phases at one standard deviation to increase the sensitivity of the experiment.

Anomalies from the horizontal winds, vertical velocity, geopential height, as well sea surface temperature (SST) fields bordering the continent (Mediterranean Sea, Atlantic and Indian Oceans) were computed and composited (Arguez et al. 2009) with the decomposed precipitation time coefficients. From the horizontal winds and precipitation anomaly composites, velocity potential and its associated divergent winds were computed (Krishnamurti 1971).

3. RESULTS

3.1 *West African Precipitation Variability: MAMJ vs JJAS*

In both MAMJ and JJAS seasons, the four leading principal components (PCs) of the unfiltered precipitation data, which were statistically separate according to North et al.'s (1982) delta-test and also physically realistic, were retained. These accounted for 45.22% and 54.70% of the total variances associated with MAMJ and JJAS, respectively. However, the first two modes are presented here. In MAMJ season, the two leading modes explained 26.41% and 8.31%, respectively, of the total variance. In JJAS season however, the first two modes contributed to 36.0% and 9.56%, respectively, of the total variance.

A visual inspection of the EOF 1 eigenvectors of the MAMJ season (Fig. 1a) depicts more or less ubiquitous positive weights over the region, which is reminiscent of a monopole or non-dipole structure, appearing to be dominated by Sahel. The TPTCs of the MAMJ EOF 1 (Fig. 1c) are dominated by interannual-like oscillations. Further, it is argued here that even though it does not typically rain over the Sahel in March-May (MAM), the transitional month, June, which commences and ends the major rainy season of the Sahel and GOGC, respectively, is fully captured by the EOF analysis. The June precipitation, a striking feature over the Sahel during the GOGC MAMJ season, is a manifestation of intraseasonal latitudinal monsoon shift (monsoon jump) from 5^{o}N to 10^{o}N (Hagos and Cook 2007), signifying the onset of the Sahelian rainy season. The eigenvectors of the MAMJ precipitation EOF 2 (Fig. 1b) are characterized by positive departure patterns weighted heavily over the GOGC, which show anti-phase variations with the Sahelian anomalies. Their time coefficients portray decadal variability (Fig. 1d).

In contrast, the JJAS precipitation EOF 1 spatial pattern (Fig. 2a) is the well-known Sahel mode/continental mode (SM/CM; Polo et al. 2008), depicting a dipole, in which positively weighted loadings are centered over the Sahel and negative loadings (precipitation deficits) over the GOGC zone. The temporal character of the SM depicts decadal or interdecadal oscillations (Fig. 2c). The JJAS EOF 2 spatial mode (Fig. 2b) depicts the spatial structure characteristic of the GOGC during which this humid zone receives relatively low precipitation (Giannini et al. 2005). Its temporal structures show interannual oscillations (Fig. 2d).

3.2 *Anomalous Boreal Spring-Summer Tropospheric Circulation over West Africa: MAMJ vs JJAS*

The climate anomaly patterns of the two seasons computed are presented in Figs.3-5. Positive (negative) events associated with the anomalous WAM circulations of the seasons are hereafter denoted by pos# (wet years) and neg# (dry years), where "#" denotes the mode of the decomposed precipitation time coefficients used for the composite analysis. The circulation structures associated with the first mode are presented here.

3.2.1 *Anomalous Surface Circulation*

The key anomalous circulation features associated with MAMJ pos1 (Fig.3a) may be described as the involvement of moisture supply created by contrasting SST anomaly (SSTA) patterns in the tropical Atlantic Ocean and the Mediterranean Sea, large-scale low-level cross-equatorial moisture flux convergence, and low-level cyclonic flows(Ward 1998; Giannini et al. 2005). Specifically, the mechanism leading to the ubiquitous positive rainfall anomalies over West Africa entails interactions among moderately, strong southwesterly surface winds, Tropical Atlantic dipole mode (TADM), substantiated by grid point and linear correlations (SST vs precipitation), moderately warm Mediterranean Sea SSTAs, a less developed cold tongue complex (CTC) in the tropical eastern Atlantic, and low-level cyclonic flow over West Africa, generated by diabatic heating, culminating in enhanced moist convection and precipitation over the region.

The key anomalous circulation features of the JJAS pos1 events (Fig. 3b) are similar to the MAMJ pos1 counterparts (Fig.3a). However, the former differs from the latter, in a depiction of an advanced form of CTC in the tropical equatorial Atlantic/southeastern Atlantic, accompanied by high pressure and strong momentum flux convergence, driven by intense westerlies or southwesterlies, which transport substantial moisture deeper into the Sahel. This is supplemented by moisture advection from warmer

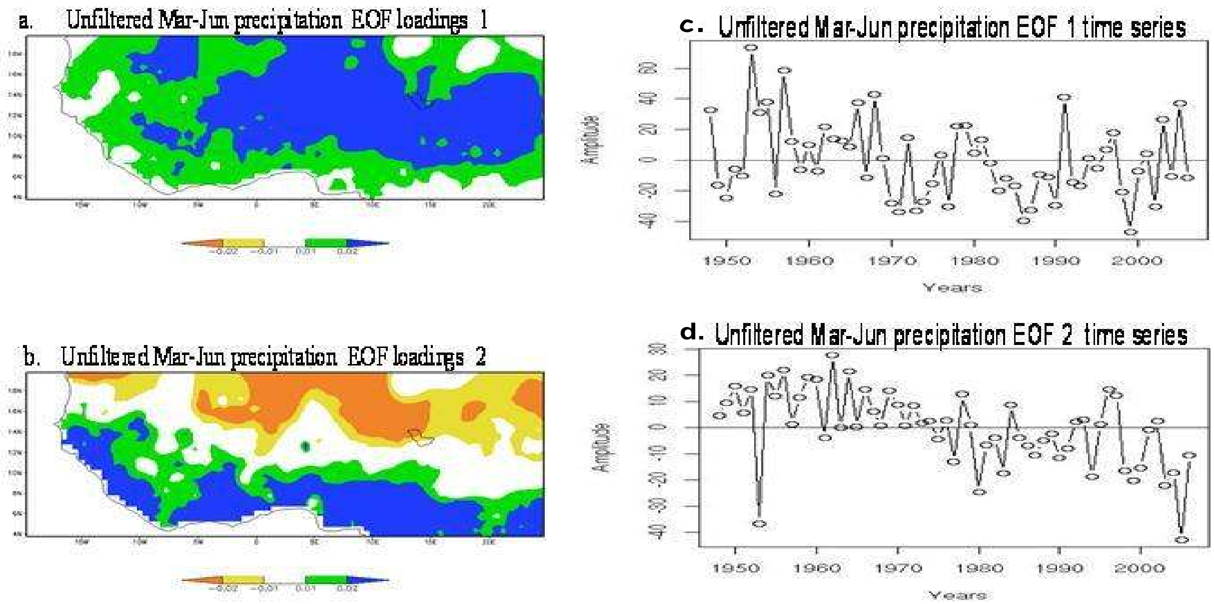


FIG.1. Unfiltered spatial patterns and their corresponding time coefficients of MAMJ rainfall during boreal spring-summer West African season.

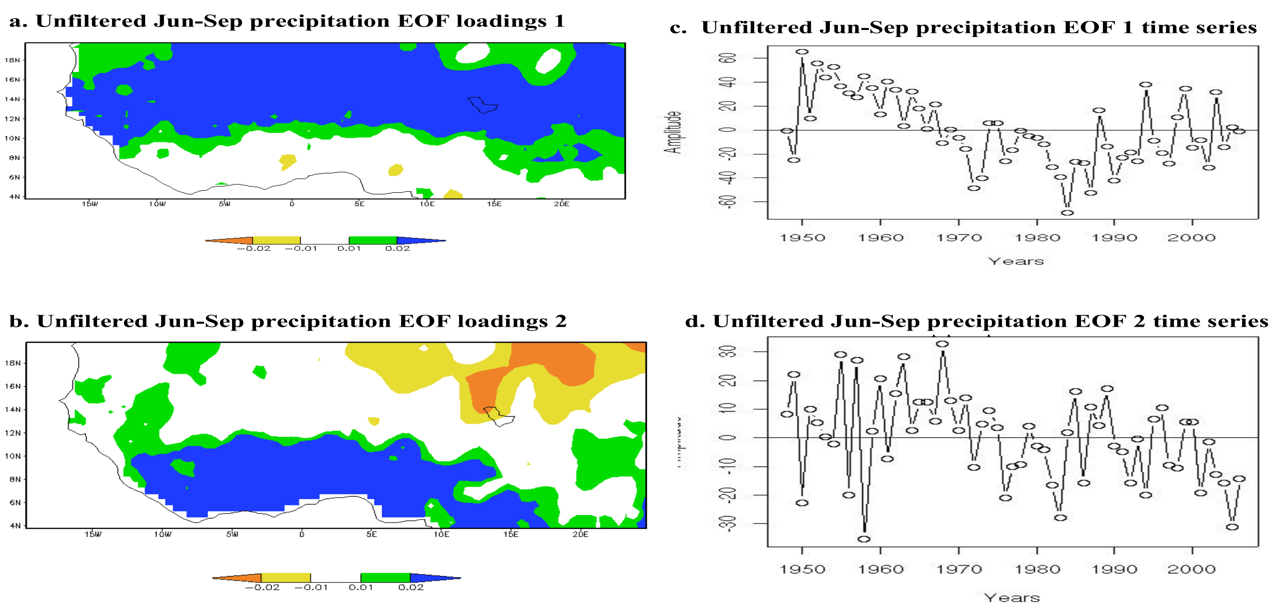


FIG. 2. As in Fig. 1a, except for JJAS season.

Mediterranean Sea SSTAs. These events deprive the humid GOGC of substantial precipitation. The wetness of the Sahel during the JJAS season is also found to coincide with colder Indian Ocean SSTAs.

The MAMJ neg1 and JJAS neg1 (Figs. 3c,d) events are the antitheses of their respective positive events. The precipitation deficits in both cases are characterized by obliteration of the CTCs, negative moisture advection and momentum fux from land into the Atlantic Ocean, warmer Indian Ocean SSTAs, reversal of surface winds, and the development of low-level anticyclonic flows.

3.2.2 *Velocity potential*, **d***ivergence, precipitation, vertical velocity, and geopotential height anomalies*

Figures 4 and 5 show the positive and negative events associated with the anomalous velocity potential and divergent circulations at 500 hPa (middle) and surface levels. It is observed that the centers of action of the middle (surface) level divergence (convergence) of the MAMJ pos1 is located roughly over Libya between latitude 20^o-30^oN of northern Africa (Figs. 4a,b). The associated vertical motions of the MAMJ pos1 events reveal relatively weak, anomalous ascent and descent, located over Sahel and the GOGC, respectively, and these are out-of-phase with the divergent circulation centers of action, neither do they synchronize with the MAMJ precipitation EOF 1 field**.** The 500 hPa geopotential height anomalies show positive center (ridge) over mid-Sahel, which is out-of- phase with the negative center (trough) over the GOGC. This anti-phase relationship does not seem to synchronize well with the positive monopole precipitation field.

In contrast, the anomalous middle (surface) level divergence (convergence) of the JJAS pos1 events is centered over the Sahel (Figs.5a,b), whose anomalous ascent (descent) is centered over the Sahel (GOGC), and thus, shows consistency with the JJAS divergent circulation field and the JJAS SM/CM. The 500 hPa geopotential height field shows stronger negative anomalies over the Sahel than the GOGC, thus, helping to explain the more intense pluvial conditions over the Sahel (Fontaine et al.1995).

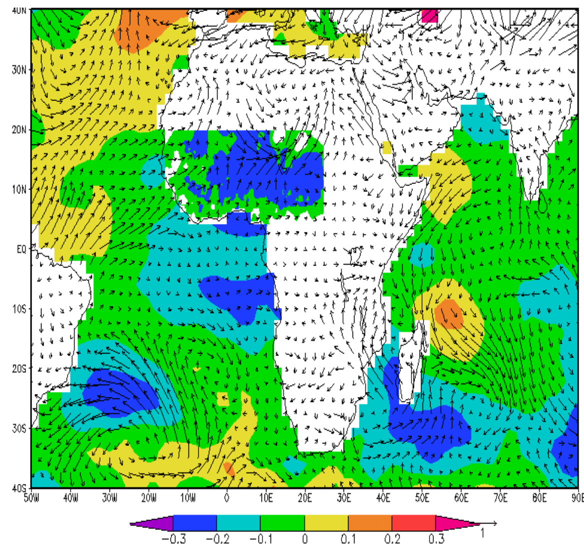
During the MAMJ neg1 events, the middle (surface) level convergence (divergence) is centered over Chad-Sudan region (Figs. 4c,d), which is a shift from the Libya center of action of the MAMJ pos1 events. However, the vertical motion field, which is dominated by anomalous subsidence, coincides with precipitation deficit observed in Fig. 3c. An examination of the JJAS neg1 events indicate that the anomalous surface level divergent field is overlain by middle level convergence centered over the Sahel (Figs. 5c,d). These fields are associated with strong anomalous subsidence and weak ascent over the Sahel and GOGC, respectively, which are also in coherence with JJAS neg1 precipitation field (Fig. 3d). In both seasons, the precipitation deficits observed are associated with positive 500 hPa geopotential height anomalies.

4. CONCLUSIONS

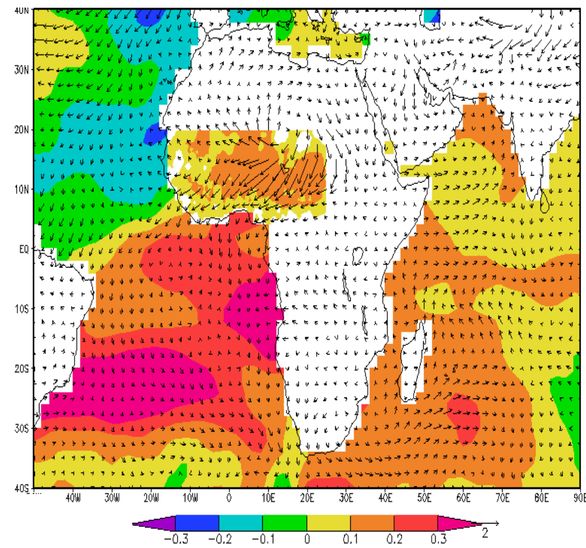
The study has demonstrated that JJAS precipitation fields generally show coincidence with the anomalous divergent circulation, geopotential height and vertical velocity anomaly fields. The MAMJ precipitation fields on the other hand, generally, were at variance with the anomalous divergent circulations. However, precipitation in both seasons appear to be linked to contrasting SST patterns in the Mediterranean Sea, Atlantic and Indian Oceans, as well as atmospheric wind anomalies.

The anomalous divergent circulations of the two seasons implicitly suggest that precipitation over Sahel and the GOGC appear to be driven by two competing mechanisms. These are momentum flux divergence/convergence(Sahel) and horizontal advection (GOGC).

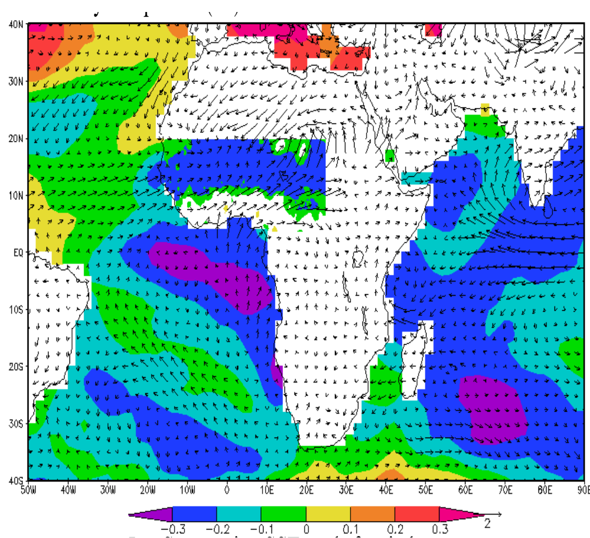
a. Unfiltered Mar-Jun precip., SST, and sfc winds composites (wet years: pos1)



c. Unfiltered Mar-Jun precip., SST, and sfc winds composites (dry years: neg1)



b. Unfiltered Jun-Sep precip., SST, and sfc winds composites (wet years: pos1)



d. Unfiltered Jun-Sep. precip., SST, and sfc winds composites (dry years: neg1)

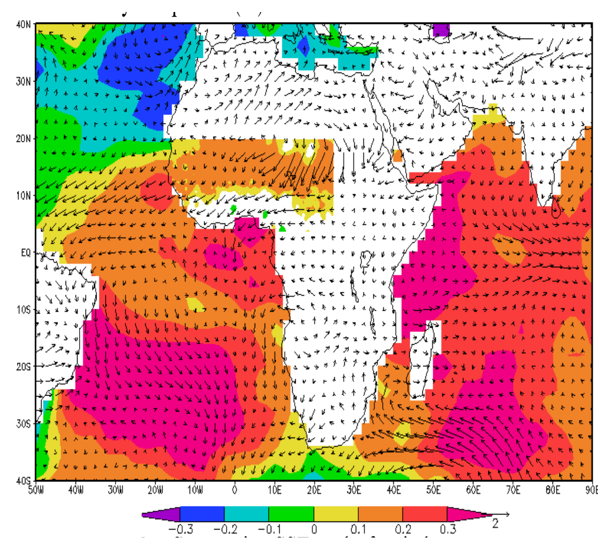
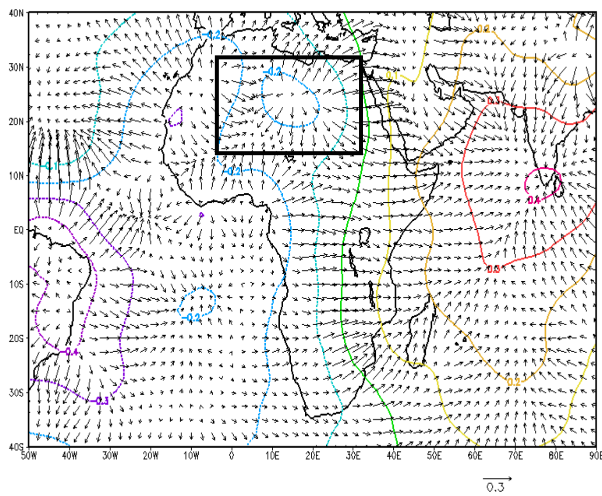
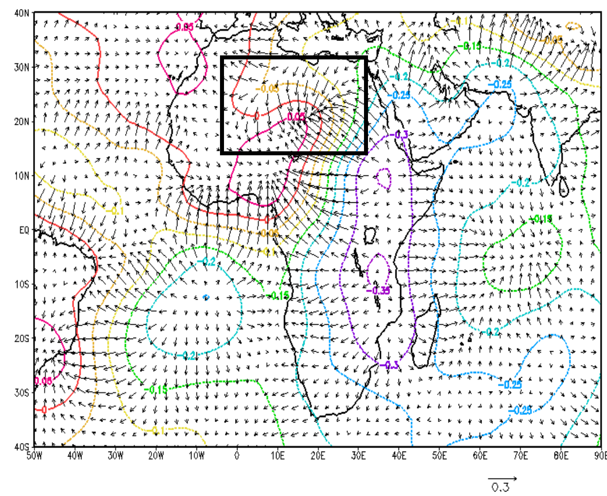


FIG. 3. Unfiltered tropospheric circulation anomaly composites associated with positive (negative) events of MAMJ and JJAS WAM at the surface level. Positive (negative) numbers denote positive (negative) phases of the decomposed precipitation time coefficients. The color bar denotes SST anomalies. Precipitation field over West Africa, has the following color notations: blue=very wet; green= wet; brown = very dry; yellow = dry; white= almost dry.

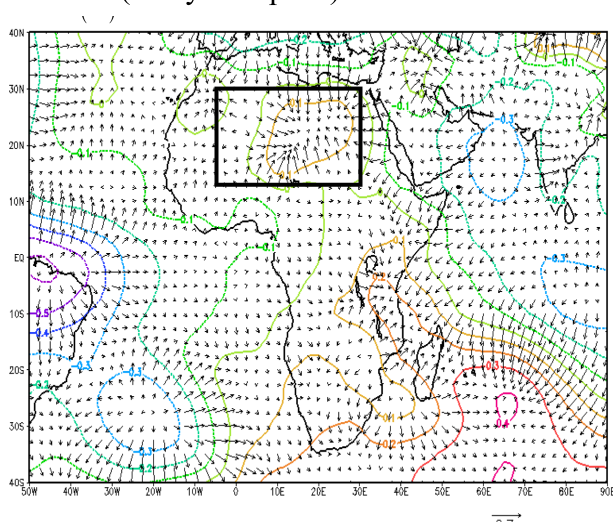
a. Unfiltered Mar-Jun 500 hPa vel. potential, divergent winds, and precip. composites (wet years: pos1)



c. Unfiltered Mar-Jun 500 hPa vel. potential, divergent winds, and precip. composites (dry years: neg1))



b. Unfiltered Mar-Jun vel. potential, divergent winds, and precip. composites at the sfc (wet years: pos1)



d. Unfiltered Mar-Jun vel. potential, divergent winds, and precip. composites at the sfc (dry years: neg1)

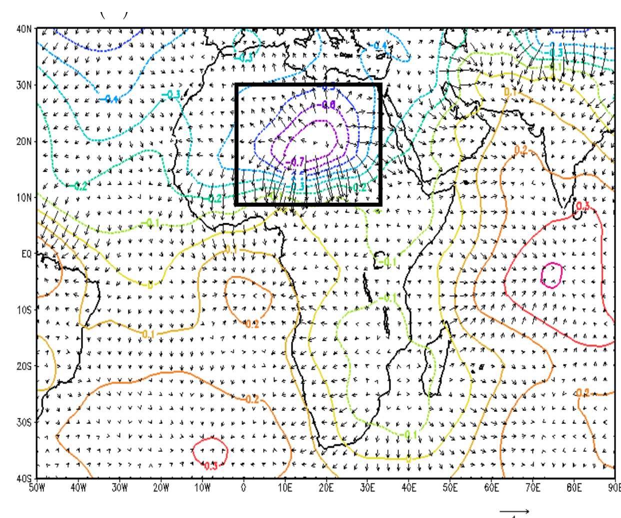
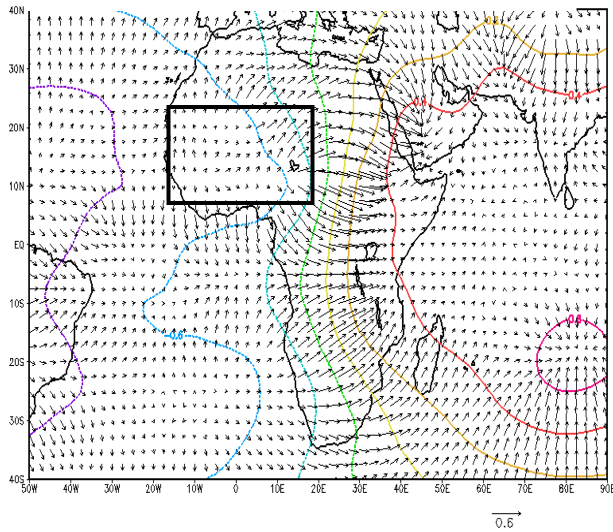
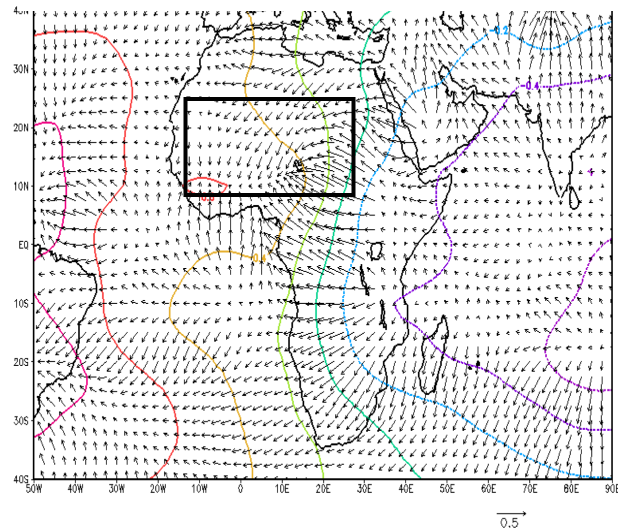


FIG. 4. Unfiltered MAMJ velocity potential, divergent winds, and precip. anomaly composites at 500 hPa and surface levels. Velocity potential (m^2/s), horizontal wind vectors (m/s); contour interval $x10^6$. Positive and negative numbers indicate the events. Boxes denote centers of action.

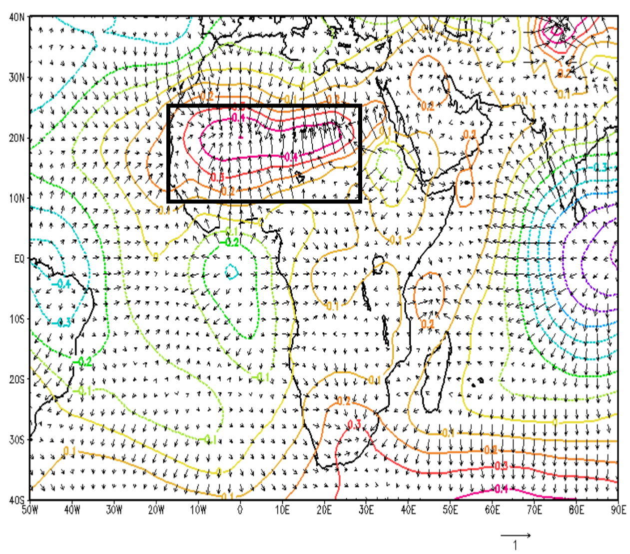
a. Unfiltered Jun-Sep 500 hPa vel. potential, divergent winds, and precip. composites (wet years: pos1)



c. Unfiltered Jun-Sep 500 hPa vel. potential, divergent winds, and precip. composites (dry years: neg1)



b. Unfiltered Jun-Sep vel. potential, divergent winds, and precip. composites at the sfc (wet years: pos1)



d. Unfiltered Jun-Sep vel. potential, divergent winds, and precip. composites at the sfc (dry years: neg1)

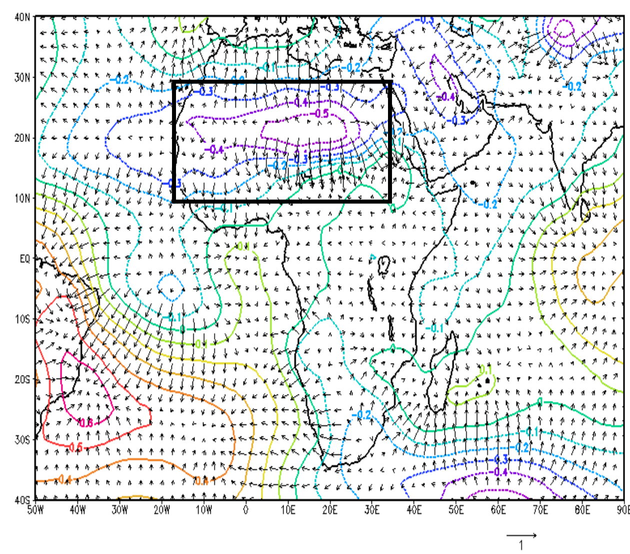


FIG. 5. As in Fig. 4, except for JJAS season.

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