29th Conference on Hurricanes and Tropical Meteorology, 10-14 May 2010, Tucson, AZ

6D.5 ANOMALOUS NORTHERN HEMISPHERIC SUMMER MIDTROPOSPHERIC CIRCULATION OVER WEST AFRICA

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1. INTRODUCTION

A great number of previous studies have contributed to our understanding of climate variability over Africa. For instance, Nicholson (1986) used linear correlation analysis to delineate six spatially coherent precipitation patterns over Africa. In that study, the role of Hadley and Walker circulations in modulating the principal dipole over the continent was highlighted. Janowiak's (1988) study, which appears to be an extension of Nicholson's (1986) work, used regular rotated empirical orthogonal function (EOF) solutions to isolate the dominant precipitation modes over Africa. In that study, three main spatially coherent precipitation departure patterns were delineated for the Northern Hemisphere (NH) summer (June-July-August-September; JJAS) season. The JJAS precipitation EOF 1 pattern, popularly known as the continental (Sahelian) mode, has positive loadings, relative to the negative loadings in Guinea coast. The EOF 2 pattern, a monopole, was mostly centered between equator and 10^o S, whereas the EOF 3 pattern consisted of a monopole confined to coastal West Africa, and a weak east-west dipole configuration whose axis was located at 20^o E. These modes were found to be associated with sea surface temperature (SST) patterns, e.g., the Atlantic SST anomalies. Also, the close link between global SST and precipitation variability over W. Africa has been established through observational and modeling studies (Lamb 1978; Lough, 1986; Semazzi et al. 1988).The mean annual cycle of rainfall and general circulation features over western and central Africa were investigated, where the roles, seasonal excursions and orientations of tropical easterly jet (TEJ) and African easterly jet of the NH (AEJ-N) were highlighted (Nicholson and Grist 2003; Nicholson 2008).

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Some limitations of previous works hinge on the use of a single or very few meteorological variables to investigate African climate variability(e.g.,Janowiak1988; Semazzi et al.1988). However, several atmospheric ingredients must be pooled together to help us better understand weather and climate. In instances where these were considered, the studies failed to consider simultaneous links between SST, dominant precipitation modes, and mid-tropospheric circulation anomalies, with special reference to wet and dry epochs. More especially, those studies invariably isolated two precipitation modes (the traditional Sahelian and Guinean modes) over West Africa (Giannini et al. 2005; Polo et al. 2008). In this study, four precipitation modes have been isolated over West African domain, using University of Delaware (UD) terrestrial precipitation data, corroborated by Climatic Research Unit (CRU) terrestrial precipitation data. This has led to a systematic empirical investigation and comparative description and documentation of eight distinct anomaly composite events and their corresponding rotational flows, all together, four dry and four wet patterns. A close inspection of the anomalous SST-surface wind-precipitation (SST-SW-P) composites shows that the positive events are antithetic to the negative events. However, a visual integration of the mid-level to surface rotational flow anomalies associated with the precipitation events into the SST-SW-P anomaly composites indicate that some of the physical mechanisms or processes underlying them are not merely a reversal of events, but encompass a myriad of processes characteristic to the events. Moreover, the choice of the mid-troposphere, delimited by 500 hPa isobaric surface, is of interest to us because this level, generally acknowledged as part of the mid-levels (i.e., 500-400 hPa) where maximum ascent is located, can act as a mid-level cap. This cap plays an important role in shallow convection whose train echoes, in tropical weather and climate, can produce comparable rainfall accumulation as deep convection. Therefore, by adding the current scope of study to previous works, such as Nicholson and Grist (2003), Giannini et al.(2005), Nicholson (2008), Polo et al. (2008), and García-

Serrano et al. (2008), will provide opportunity for comprehensive understanding of the W. African monsoon system during the boreal summer. The objectives of the study entail following:
(i) isolation of the dominant precipitation modes over the region during NH summer (JJAS) season,
(ii) obtaining the corresponding circulation anomalies (i.e., rotational flows) in the 500 hPa level, and
(iii) relating them to surface circulation and SST anomalies on the basis of the dominant precipitation modes.
By so doing will help us infer cause and effect relationship from, more or less, 3-D perspective.

2. DATA AND METHODS

Monthly unfiltered (raw) UD and CRU terrestrial precipitation and National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data are used for this study. The primary analysis tools utilized are regular non-rotated EOF, correlation, and composite analyses. EOF analysis is performed on precipitation over W. Africa, out of which the leading and physically realistic modes are retained. The corresponding standardized expansion coefficients (ECs) are decomposed into very wet and dry years, the selection of which is based on ECs whose values are at least one standard deviation (in absolute terms) from the mean. Anomalies from horizontal wind (1000 hPa and 500 hPa) and SST fields are computed and then composited with the decomposed ECs. From the horizontal winds, streamfunction and rotational wind anomalies are computed at the two levels for all the wet and dry events. Simultaneous linear correlations are computed between the total precipitation ECs and well-known teleconnection indices, e.g., obtained from Climate Prediction Center (CPC) website, as well as global SST EOF indices and NH summertime Indian Ocean Dipole (IOD) generated from our EOF analysis of extend reconstructed SST (ERSST) data. The purpose of this is to isolate the most important climate pattern(s) associated with the temporal character of the precipitation variability.

3. Results and Discussion

3.1 JJAS Precipitation EOF analysis

The EOF solutions for the UD precipitation data yielded four statistically separate modes, in accordance with North et al.'s (1982) delta-test. All together, they accounted for 54.7% of the total variance, with the individual contributions shown on top of the spatial patterns (Fig.1). Similar results were achieved with the use of CRU precipitation data (not shown).

The first mode (Fig. 1a), which is characterized by a meridional dipole pattern, is the well-known Sahelian mode in which the semi-arid zone receives maximum precipitation, whereas the Gulf of Guinea coast (GOGC) receives precipitation deficit during this time (Gianinni et al. 2005). The ECs of this mode are dominated by decadal variability (Fig. 1e). Further, this mode is strongly tied to three competing patterns (indices), namely multivariate ENSO Index, NH summertime IOD, and global SST EOF 3, which is the interhemispheric SST asymmetry, generated from the ERSST data. The EOF 2 (Fig.1b) depicts a departure pattern which is the GOGC mode. Its temporal structures (Fig. 1f), which demonstrate interannual to decadal variability, are associated with tropical Atlantic Dipole mode (TADM), an interhemispheric tropical Atlantic SST asymmetry which is not a coupled ocean-atmosphere variability mode as compared to Atlantic Niño (Sutton et al. 2000).

The EOF 3 identifies four main anomaly patterns (Fig. 1c), whereas EOF 4 identifies one main dipole (Fig. 1d). Their corresponding temporal structures are dominated by interannual to semi-decadal variability (Figs. 1 g, h).The anomaly patterns of EOF 3 may be described in terms of zonal or meridional configurations or orientations (Fig. 1c). Choosing the latter for convenience sake, the precipitation patterns are characterized by two dipoles: one centered over west coastal Africa (south-north gradient) and, the other, over eastern part of W. Africa (north-south gradient).Their temporal structures are closely connected to tropical South Atlantic mode (TSAM). EOF 4 consists of western Sahel-eastern W. Africa dipole. Its temporal structures are also associated with global SST EOF 3 index.

3.2 *SST, Surface wind, and Precipitation Anomaly Composites*

Before a discussion is presented on the mid-tropospheric circulation anomalies, it is instructive to display, first, the events captured at the mean sea level (Fig. 2), where a lot of botic and abiotic activities occurs, with aim of relating the features in the mid-troposphere to the surface to infer cause and effect from, more or less, 3-D perspective. Here, the events are classified on the basis of the precipitation modes, where *pos* and *neg* denote wet and dry events, respectively, yielding a total of eight events, four wet and four dry.

The key features (differences) which characterize the events include, but not limited to : i. contrasting SST patterns over the Mediterranean Sea, Atlantic and Indian Oceans, ii. damping or strengthening of the cold tongue complex (CTC), iii. strength or relaxation of the southwesterlies, southeasterlies, northeasterlies, and west-northerlies over the Mediterranean Sea, Atlantic Ocean, and NH African continent, iv. cross-equatorial flow determined by the strength of momentum flux convergence or divergence, v. strength of horizontal advection, and vi. strength of low-level troughs and ridges.

3.3 500 hPa Mid-tropospheric anomalous circulation in relation to mean seal level events

The fundamental factors governing the changes in the mid-tropospheric circulation anomaly composites in relation to their surface counterparts (Figs. 3, 4), as revealed by the streamfunction analysis, include, but not limited to: i. magnitude and spatial extent of ridges (troughs), ii. centers of action of the ridges(troughs), iii. shape, orientation and frequency (number) of troughs (ridges), iv. co-location or juxtaposition of troughs and/or ridges, v. magnitude of diabatic heating/cooling anomalies, and vi. strength of ascent(subsidence) from surface (mid-level). The mid-level to surface rotational flows, in conjunction with the surface patterns (Fig. 2), will enhance our understanding of the physical processes or mechanisms that govern the eight events. The differences and similarities in the events will be highlighted where necessary.

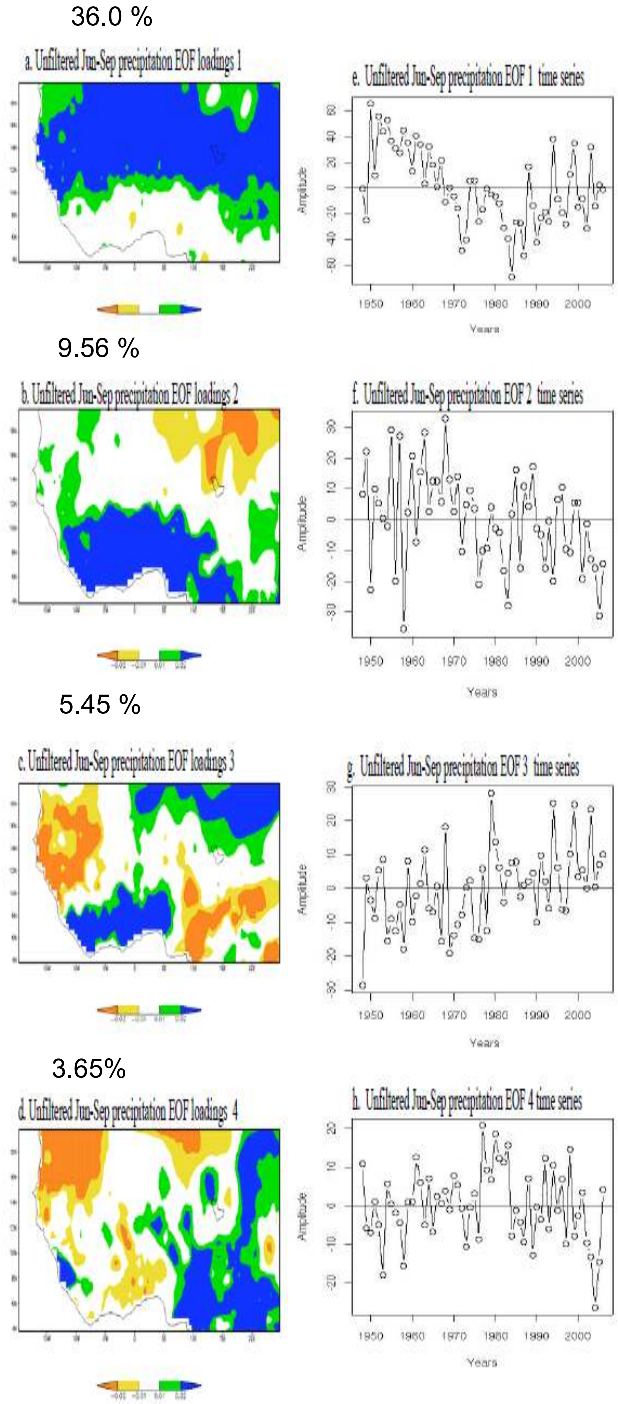

Figure1.Unfiltered West African JJAS precipitation spatial patterns and their corresponding time series during NH summer season.

Positive events **Negative events**

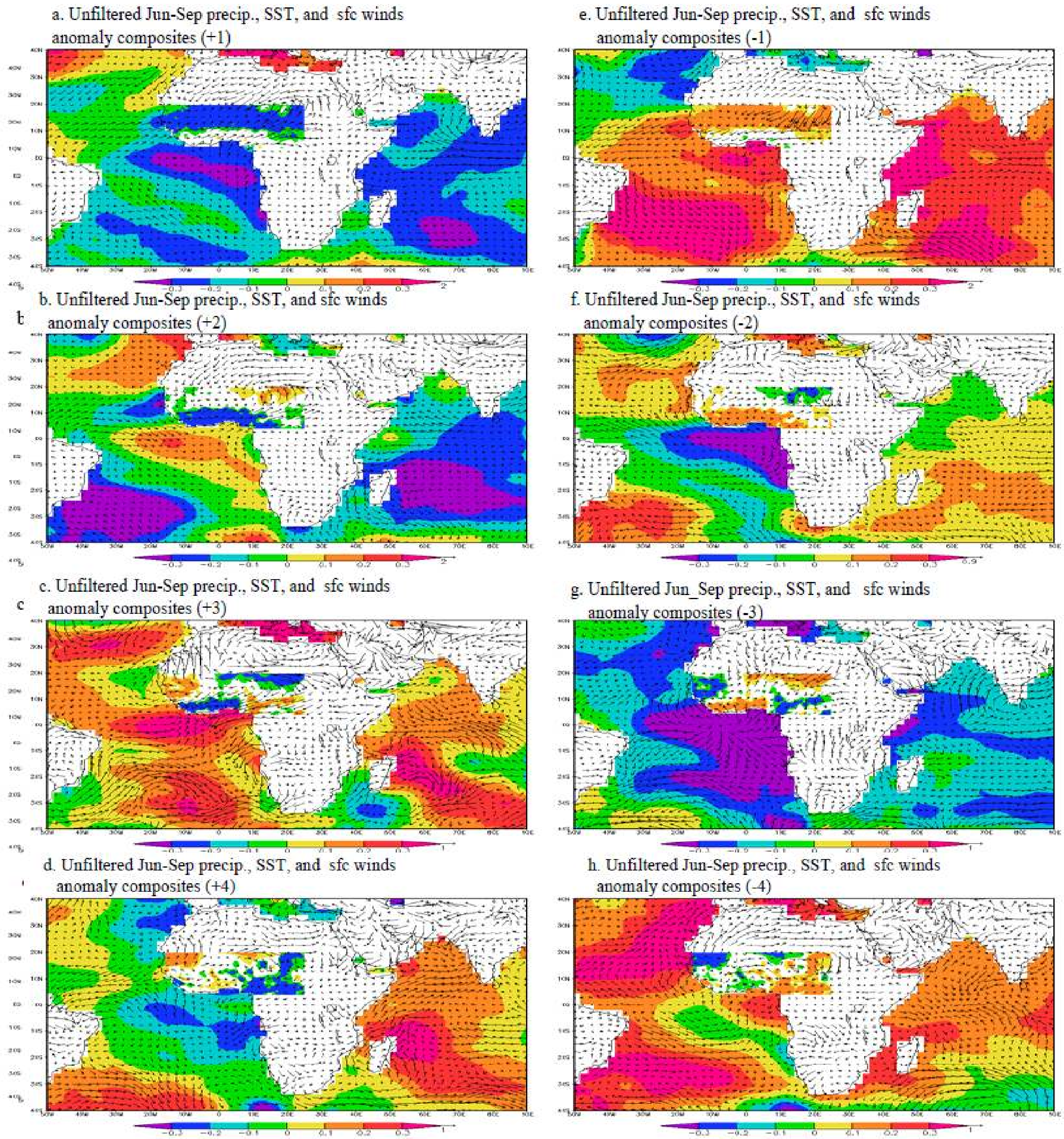

Figure 2. Unfiltered SST, surface wind, and precipitation anomaly composites. Positive (negative) numbers denote positive (negative) phases of the precipitation modes. The color bar denotes SST anomalies. Precipitation field over West Africa has the following color notations: blue=very wet; green= wet; brown = very dry; yellow = dry; white=almost dry.

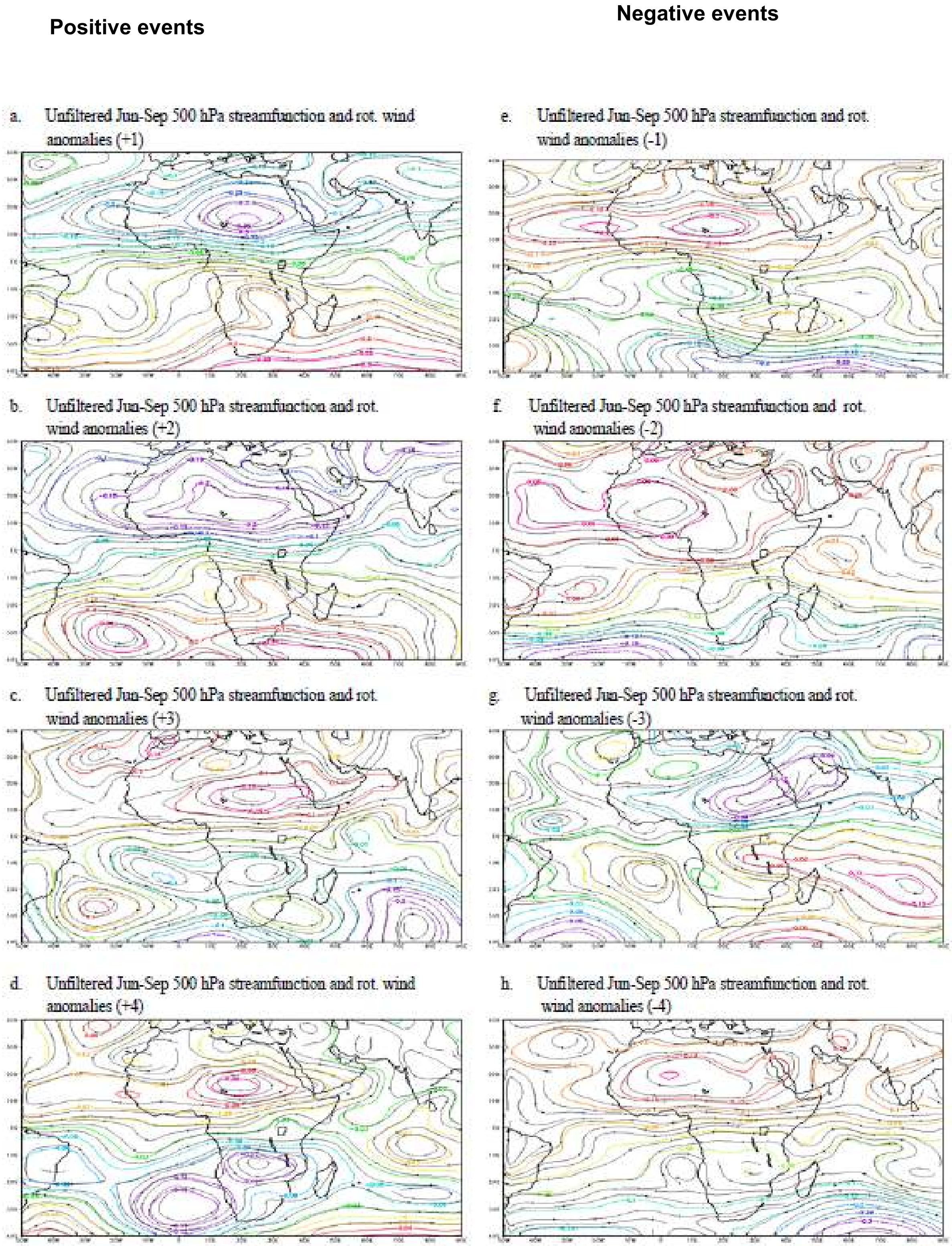

Figure 3. Unfiltered streamfunction (m^2/s), rotational wind, and precipitation anomaly composites at 500 hPa. Contour interval $x10^{6.}$

Positive events **Negative events**

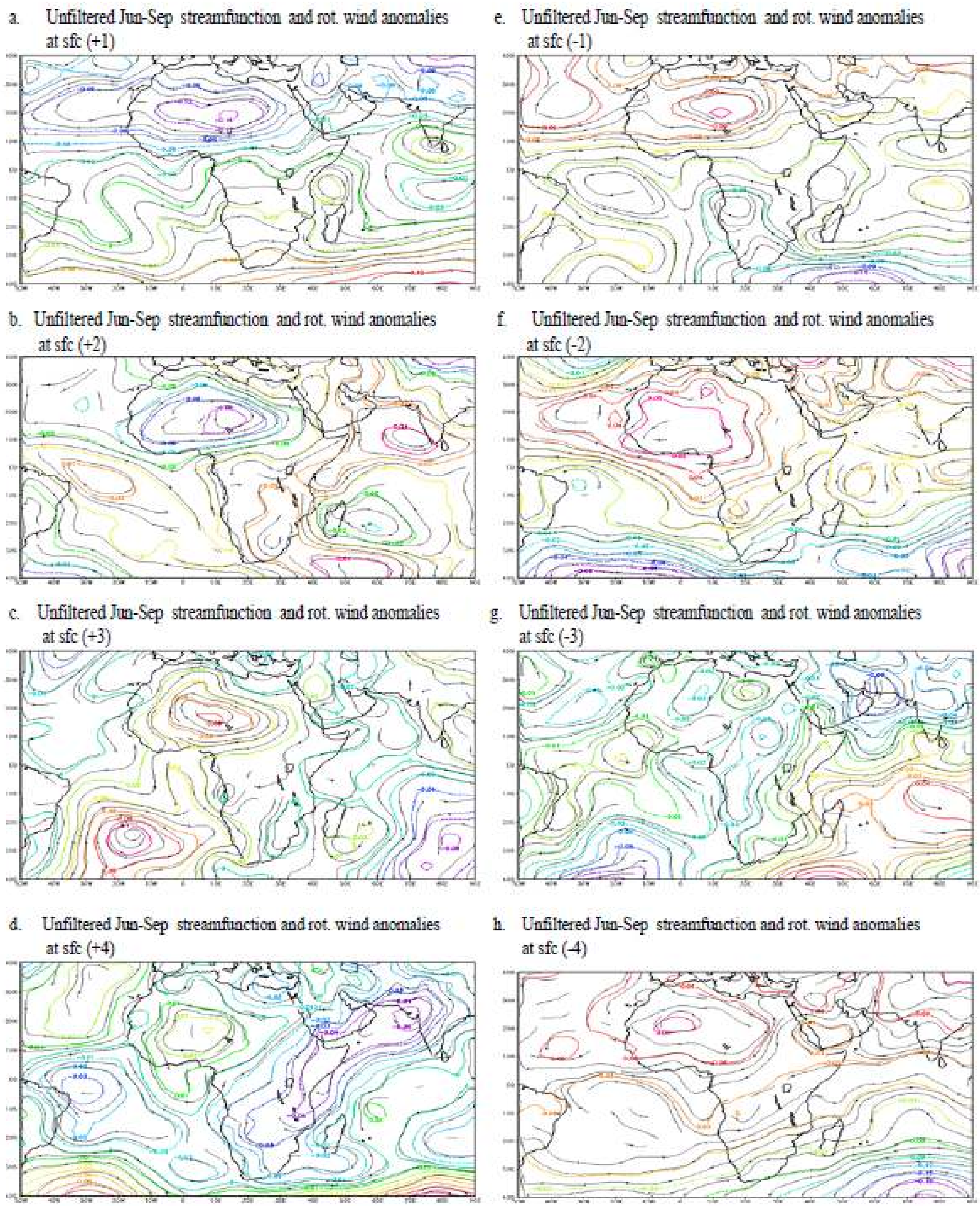

Figure 4. Unfiltered streamfunction (m^2/s), rotational wind, and precipitation anomaly composites at the surface. Contour interval $x10^6$.

The *pos 1* event (Fig. 3a) is characterized by a large-scale, anomalous, mid-level cyclone (trough), traversing NH tropical Africa, from east to west. This mid-level flow, though larger, demonstrates features reminiscent of its surface counterpart (Fig. 3a vs 4a). Its size, determined and maintained by an anomalously strong diabatic heating or convection emanating from the surface by which equatorial Rossby waves are excited to form cyclones (Vizy and Cook 2001), ensures that there is a strong connection between the two troughs in the atmospheric column from 1000-500 hPa isobaric surfaces. Interestingly, these troughs, coinciding with the North Atlantic Hurricane season, suggest a strong NH tropical Africa summertime, anomalous monsoonal flow that accompanies anomalously wet Sahel. These flows, confined to latitudinal bands between 10^{o}N and 30^{o}N, captures the geographic boundaries of the entire Sahel belt, excluding the GOGC, and thus, a reflection of the spatial extent of precipitation over W. African Sahel. Also, the flows escape off the west coast of Africa through the exit region of African easterly waves (the precursors of tropical cyclones), and extend over the tropical North Atlantic (TNA) Ocean as Atlantic troughs, in proximity to the main development region (MDR), which is the active site of tropical cyclogenesis.

The development of the low-level, large-scale Sahel monsoon trough, with its antitype aloft, is a manifestation of a fully-fledged CTC (Fig. 2a), arising from intense, oceanic upwelling over the tropical South Atlantic (Folland et al., 1996; Ward, 1998; Polo et al. 2008). Associated with this is a well-developed momentum flux convergence, emanating from the tropical North Atlantic (TNA) and tropical South Atlantic (TSA). This flux is enhanced by low-level, anomalous, cyclonic flow over TNA (Fig. 4a) that transports moisture into the interior of West Africa, reinforcing the northward displacement of the Intertropical Convergence Zone (ITCZ), leading to a wet Sahel and a relatively dry GOGC. The moisture convergence over Sahel is further sustained by anomalous cyclonic flow over the land (Figs. 2a, 4a). A small-scale subtropical North Atlantic (SNA) trough and its antitype aloft are seen juxtaposed to the large-scale TNA troughs, and thus also contributing to reinforcing the maritime ITCZ and precipitation enhancement over the Sahel. These convective developments coincide with anomalous cooling and warming of the Indian Ocean and the Mediterranean Sea (Folland et al. 1996; Semazzi et al. 1996; Ward 1998; Rowell 2003; Polo et al. 2008), respectively. The role of the former in precipitation variability over Sahel has been investigated by Giannini et al. (2005). The latter's contribution involves evaporation and subsequent southward horizontal moisture advection from its basin, leading to enhanced low-level moisture flux convergence over the Sahel (Folland et al., 1996; Ward, 1998; Polo et al. 2008). In *neg 1* event (Fig. 3e), which appears to be antithetic to the *pos 1*(Fig.3a), the mid-level Sahelian trough becomes entirely replaced by an anomalous strong, large-scale ridge (anticyclone) generated and maintained by diabatic cooling anomalies. The cooling initiates a correspondingly strong, mid-level subsidence where cooler, denser and drier air descends through adiabatic warming unto the surface, ensuring a weakening or suppression of ascending motion. Through these processes, the mid-level ridge induces a strong low-level ridge at the surface. Closely associated with these processes are the juxtapositions of mid-level SNA trough-ridge dipole and its counterpart below (not antithetic to the *pos 1*), the interactions of these appearing to inhibit vertical ascent needed to initiate convective development (Figs.3e, 4e). The anomalous rotational flows are accompanied by a damping of the CTC over the TSA and a general warming of the Indian Ocean (Fig. 2e). It is observed that, over the land surface of W. Africa, the area of strong, large-scale subsidence induced from the ridge aloft (Figs. 2e, 3e,4e) weakens the cross-equatorial flow responsible for a wet Sahel. The subsequent development of a strong momentum flux divergence over the land ensures the expulsion of atmospheric and soil moisture into the Atlantic, inhibiting convective development, and thereby creating drier conditions. The mid-level to surface atmosphere responds to the general surface warming of the two oceans, by creating a form of Bjerknes positive feedback loop (Zebiak 1993, Keenlyside and Latif 2007). The loop is perceived to be associated with an increase in local sea-level pressure and vertical wind shear, reinforcing and sustaining the drought events. We speculate that the Mediterranean Sea, in turn, responds (by cooling) to this feedback loop, and significantly reduces its evaporative water loss. The available moisture over the Mediterranean Sea is also prevented from moving inland by northward horizontal advection of south northerly winds over W. Africa, which also ensures the expulsion of atmospheric and soil moisture from the land to the sea (Fig. 2e). This effect of this is amplified by the westnortherly winds over the SNA.

In the *pos* 2 event (Fig. 3b), the mid-level patterns and processes over NH Africa are similar to *pos 1* (Fig. 3a). However, the processes involved in the *pos 2* are weaker, due to weaker diabatic heating emanating from the surface. The surface trough (Fig. 4b), whose center of action is mostly confined to the land alone (Sahel), is of much smaller spatial extent relative to its antitype aloft. Conspicuously missing in this event are the low-level TNA troughs which are prominent in *pos 1*. The absence of these troughs is, probably, a reflection of a stronger influence of the TADM than that of Atlantic Niño (Fig. 2b), as revealed by linear and grid point correlations between the total precipitation ECs, climatic indices, and global SST anomaly fields (the results of the grid point correlations not shown). The most significant features which appear to be associated with this event are, therefore, the absence of low-level TNA trough(s), the presence of a small-scale, oblique trough confined mostly to western equatorial South Atlantic, and the presence of a well-developed warm-phase of TADM (Folland et al. 1986; Xie et al. 2005), and a cold tongue in southwestern Atlantic and Indian Oceans. These developments, in the presence of dynamically active equatorial eastern Atlantic, favor convective development over the GOGC, suppressing Sahelian precipitation, even in the presence of firmly rooted troughs over the semi-arid zone. Thus, evaporation and northward moisture advection from the eastern Atlantic ensure a fairly strong low-level moisture convergence, leading to a wet GOGC. The wetness of the GOGC is seen to coincide with CTC in the southwestern Atlantic and the Indian Oceans. The dry Sahel may be attributed to its troughs which may have been generated from heat lows known to be actively involved in dry convection and/or dynamics. Also, the Mediterranean Sea dipole is associated with low atmospheric moisture, so that the southward horizontal advection is ineffective in supplying ample moisture for low-level convergence, and hence a drier Sahel. In the *neg* 2 event (Fig. 3f), a fairly strong mid-level ridge is centered over continental Sahel, extending into TNA Ocean. It induces a similar pattern in its antitype below (Fig. 4f), making these ridges, as a whole, not exactly the antitheses of the *pos* 2 (Fig. 3b). The mid-level ridge induces a relatively weak area of subsidence, and thus contributing to the sparse precipitation distribution over the land. However, the effects of SNA ridge aloft and its low-level trough appear to nullify each other to some extent. The drier GOGC, arising from the interactions of these ridges, is associated with a well-developed CTC in the equatorial Atlantic (the cold phase of TADM), which suppresses evaporation and horizontal advection of moisture and thereby, suppressing the development of rainbands. The inability of the CTC to initiate a convectively active precipitation over the Sahel, as with the case of *pos 1* (Fig. 2a), is associated with strong southeasterlies. These winds divert available moisture from the eastern Atlantic to the TNA Ocean, probably, in response to the cascading effects of the mid- to low-level, anomalous ridge observed over the region. The cold phase of the TNA meridional SST gradient (TADM) is also associated with northward moisture advection away from the Sahel, by strong, recurving, subtropical northwesterlies. The development of a fairly weak NH summertime Indian Ocean SST anomalies and a moderately warm Mediterranean Sea SST patterns (Folland et al. 1996; Ward 1998; Giannini et al. 2005; Polo et al. 2008) are associated with significant dryness over the region, with the GOGC experiencing a severer precipitation deficit than Sahel.

Generally, beyond the first four epochs, an inverse relationship between the numbers (frequencies) and sizes of troughs/ridges is observed. Contrary to the general expectation of detecting troughs in the mid-level in the *pos 3* event, three distinct ridges are, rather, seen over NH Africa, one of which projects onto the SNA Ocean (Fig. 3c). The ridges are accompanied by a juxtaposition of a trough and a ridge over the South Atlantic. At the surface, the main center of action of the ridge is confined to Sahel, with a smaller trough located over the SNA (Fig. 4c) whose effect appears to be antagonized by its counterpart flow aloft. The relatively weak areas of subsidence, from the mid- to surface level, appear to be compensated for by relaxation of surface winds, leading to warming events, especially over the Mediterranean Sea and the Atlantic, which contribute to the formation of pair of fairly weak dipoles (Fig. 2c). Horizontal moisture advection, similar to *the pos 1*, from the Mediterranean Sea is partially responsible for the wet part of eastern Sahel. Simultaneously, the anomalously strong thermal gradient between the land and the Atlantic that can be inferred from Fig. 2c, and the strong pressure gradient between the low-level ridge over the land and low-level trough over western South Atlantic (Fig. 4c), ensure momentum transport of atmospheric and soil moisture from land onto eastern Atlantic, the process of which results in partial wetness of the GOGC. This process, too, is similar to *neg 1*, though the latter is severer. In contrast, the *neg 3* event of the mid-level (Fig. 3g) is characterized by a system of small-scale and weak ridges over tropical NH Africa and SNA. This system is associated with a relatively large-scale trough inclined at an oblique orientation in eastern Sahel (East Africa), extending to India, a smaller trough over the TNA, and a trough-ridge dipole over the South Atlantic. At the surface, a system of small-scale troughs, at least six in number, is seen centered over NH tropical Africa and TNA/SNA. It can be inferred that the continental troughs may be dominated by heat lows, which may likely be responsible for the absence of convective development, leading to sparse precipitation pattern over the region. Of all the surface events over the South Atlantic, the strongest and most extended CTC is observed in *neg 3* (Fig. 2g). One may wonder why this anomalously cold SST pattern fails to invoke a precipitation pattern at least similar to the *pos 1* (Fig. 2a), but rather, maintaining small and unrealistic precipitation patterns confined to western Sahel and eastern part of W. Africa. One of the most obvious answers is that the CTC is closely tied to a very weak trough centered over the equatorial Atlantic, which fails to transport adequate moisture to Sahel (Figs. 2g, 4g). Another process observed is development of anomalously weak flux divergence centered over CTC, which is responsible for dispersing moisture mainly over the South Atlantic, a small portion of which is transported to eastern part of the GOGC, making it lightly wet. The Sahel is more affected because of the cold Mediterranean Sea SST anomalies (Folland et al., 1996; Ward, 1998; Polo et al. 2008), which are in-phase with the CTC.

In *pos 4 event*, a system of mid-level rides, especially over NH Africa and the Atlantic Ocean is a characteristic feature (Fig. 3d). The most prominent one is centered over Sahel, as with *neg* 1 (Fig. 3e). The mid-level flows are out-phase with the surface flows, whose centers are confined to Sahel and tropical equatorial/South Atlantic (Fig. 4d). This ridge-trough dipole inhibits convective development, leading to a precipitation dipole over the region. The SST asymmetries over the South Atlantic and TNA (Fig. 2d) are associated with the development of anomalously strong momentum flux convergence, originating from equatorial northeasterlies and southeasterlies, which transport moisture westward, and hence reinforcing the maritime ITCZ off the coast of West Africa, making Sahel drier. However, the moderately cold SST anomalies of the Mediterranean Sea are responsible for the partial wetness of the eastern part of West Africa. The *pos* 4 event is also accompanied by warm Indian Ocean SST anomalies, as with *pos* 3, *neg* 1, and *neg* 4 events. In *neg* 4 event (Fig. 3h), the mid-level ridges over NH Africa are similar to the patterns of the *pos* 4 (Fig. 3d). However, suppression of the surface troughs (Fig. 4h) by the *neg* 4 mid-level ridges appears to be more vigorous than those in *pos4,* culminating in a dry region. The dissimilarity between the rotational flows of the *pos* 4 and *neg* 4 rule the possibility of exact antithetical relationships. The relatively strong surface winds associated with warm SST anomalies over the TNA appears to suppress the horizontal advection from the Mediterranean Sea. The dry region is also closely linked to a warming of the Atlantic and Indian Oceans.

4. CONCLUSIONS

The study has utilized EOF, correlation, and composite analyses to describe climate anomaly patterns of boreal summer over W. Africa. Specifically, anomalous, mid-level, tropospheric, rotational flows delimited by 500 hPa isobaric surface, which plays an important role in shallow convection in the tropics, are related to the SST-SW-P anomaly event composites to infer cause and effect, from more or less, 3-D perspective. The regular non-rotated EOF solutions of the precipitation yield four distinct modes over W. Africa. Upon the decomposition of the precipitation ECs into very wet and dry phases, SST, precipitation, and wind anomaly fields were then composited with them, yielding eight distinct events, four wet and four dry.

The main findings are that the sizes, strengths, and centers of action of mid- and low-level trough-ridge systems, together with SST patterns over Mediterranean Sea, Atlantic and Indian Oceans can be used to gauge the spatial extent of the precipitation fields over W. Africa in the boreal summer. In particular, the wet phase of EOF 1: (Sahelian mode) is associated with well-developed CTC, large-scale, mid- and low-level trough traversing east to west of NH Africa, bounded by the Sahel belt and projects over TNA. The dry phase of Sahelian mode is associated with a damped CTC, and a large-scale, low-level ridge centered over mid-Sahel and TNA, and a large trough located over the TSA. Also observed is a large-scale mid-level ridge similar but opposite to its counterpart in the wet phase.

In EOF 2 (GOGC mode), the wet phase is closely linked to the warm phase of the TADM, a large-scale trough over Sahel, but thought to be a heat low, a large-scale ridge over TSA, and a very small-scale TNA trough. In the dry phase, the mode is associated with the cold phase of the TADM and a well-developed ridge similar but opposite to the trough in the wet phase of Sahel.

Generally, beyond the first four events, the frequencies and the sizes of the troughs and ridges exhibit inverse relationship. The wet phase of EOF 3 (west coastal Africa dipole and eastern part of W. Africa dipole) is characterized by a general warming of the two oceans and the Mediterranean Sea, large-scale, low-level troughs over land and the TSA, four mid-level ridges and a trough-ridge dipole over the TSA. During the dry phase, cold SST anomalies are observed over the two oceans and the sea, together with small-scale, low-level roughs on land and TNA. Finally, in the EOF 4 (western Sahel-eastern W. Africa dipole), the wet phase is associated with warmer Indian Ocean SST anomalies, large-scale, low-level troughs on land and over the TSA, and three mid-level ridges aligned in the southeast direction, from TNA to land. The dry phase is associated with a general warming of the two oceans and the sea, small-scale low-level troughs on land and tropical Atlantic Ocean, and a large-scale ridge centered over the land, and small-scale ridges centered over the TNA, respectively.

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