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Climate variability modes due to ocean-atmosphere interaction in the central Atlantic

By ROXANA BOJARIU, *National Institute of Meteorology and Hydrology, Sos. Bucuresti-Ploiesti no. 97, 71552, Bucharest, Romania*

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ABSTRACT

Sea surface temperature (SST) and surface wind patterns from the central Atlantic are studied using empirical orthogonal function and canonical correlation analysis. The data set, which consists of monthly means of SST, zonal and meridional wind components, spans the interval 1965–1987. North Atlantic Oscillation (NAO) effects are revealed by the analysis of the tropical Atlantic variability. The persistence of a NAO phase for several years seems to be related to the persistence of SST and wind anomalies through a feedback mechanism which takes place in the northern tropical Atlantic.

1. Introduction

A number of studies have revealed distinct climate variability modes due to air-sea interaction in the tropical Atlantic region. Analysis of the linkage between the Northeast Brazilian rainfall anomalies and sea surface temperature (SST) suggests a pattern of SST anomalies with opposite sign north and south of the intertropical convergence zone (ITCZ) (Hastenrath and Heller, 1977; Moura and Shukla, 1981). Using the patterns displayed by the tropical Atlantic SST anomalies, Servain (1991) has derived 2 indices related to SST variability. Houghton and Touree (1992) have shown that the Atlantic SST fluctuations north and south of the equator are uncorrelated in time although the tropical SST anomalies undergo low frequency behaviour. The results of Servain and Legler (1986), based on Atlantic SST and wind data analysis, have revealed that in some cases, northern and southern hemispheres oppose each other in contrast to other cases when the whole tropical basin act in phase. Several studies have investigated the fluctuations of the tropical and subtropical SST anomalies over Atlantic in connection with large scale phenomena (Namias, 1972; Hagen and Schmager, 1991; Servain, 1991; Kushnir, 1994). It has been suggested by Servain (1991) that the tropical Atlantic variability could be related to the El Nino-Southern Oscillation (ENSO).

Another possible way of approaching tropical Atlantic variability is to examine the relationship between the tropical Atlantic and atmospheric circulation patterns at higher north Atlantic latitudes. Namias (1972) has presented evidence to show that the interannual variability of rainfall over northeast Brazil is dependent on the cyclonic activity in the Newfoundland-Greenland area and on fluctuations in the Azores anticyclone, during the northern hemisphere winter and spring. These features suggest that North Atlantic Oscillation (NAO) could be related to tropical Atlantic variability modes.

NAO is the dominant mode of short range climate variability in the north Atlantic-European region and it is characterised by a dipole-like structure with north-south orientation in the sea

e-mail: bojariu@meteo.inmh.ro.

level pressure (SLP) anomaly field (Van Loon and Rogers, 1978) over the Northern Atlantic ocean and by an out-of-phase relationship in ground temperature between western Greenland and northern Europe. The southern part of Europe tends to be in phase with the Greenland region (Van Loon and Rogers, 1978). Complementary patterns of these and other parameters (zonal wind component over the Atlantic ocean, Atlantic sea surface temperatures (SST), latent and sensible heat flux anomalies over North Atlantic, precipitation over Europe and sea ice on the Greenland, Iceland and Baltic Seas) are associated with distinct modes of the NAO (Rogers and Van Loon, 1979; Cayan, 1992; Zorita et al., 1992; Wallace et al. 1990). The 2 opposing modes of NAO are firstly characterised by above normal temperature in Greenland and with temperatures in Europe below normal (GA) and secondly with temperatures in Greenland below normal and European temperatures above normal (GB). Van Loon and Rogers (1978) point out that the NAO modes are not randomly distributed in time, but one of them usually predominates for one or more decades. Roger and van Loon (1979) have shown that GA and GB modes occur relative frequently from October through April-May, and Glowienka-Hense (1990) points out that NAO is one of the dominant eigenmodes of SLP for all calendar months. However, during the summer, it has no direct influence on the central part of Europe south of about 50 °N. It seems that NAO phenomenon has a low frequency behaviour of decadal order and a seasonal behaviour with the strongest signature in winter.

The above-mentioned studies of NAO phenomenon have been focused mostly on mid and high latitude variability. A basic goal of this paper is to demonstrate that it may be a connection between north Atlantic oscillation and tropical Atlantic variability. The joint modes of SST and wind variability are obtained using canonical correlation analysis (CCA). The time series associated with the most significant CCA pairs are compared with the NAO index. The paper is organised as follows. Section 2 describes the dataset used. Canonical correlation analysis (CCA) and empirical orthogonal function (EOF) technique are briefly presented in Section 3. Section 4 describes tropical variability modes of SST and surface wind field over the Atlantic and their relationship with NAO. The conclusions are discussed in Section 5.

2. Data

The datasets used in this paper consist of monthly means of SST, zonal wind component and meridional wind component taken from the comprehensive ocean-atmosphere data set (COADS) (Woodruff et al., 1987). For this study, the COADS data extend from January 1965 to December 1987. Prior to analysis, the data are processed as follows. Using a $4° \times 4°$ grid the geographic domain has been defined as the Atlantic sector, from 29 °S to 31 °. The anomaly fields are calculated for the 1965–1987 period, for each month, at each grid point, and time series normalized by local standard deviation. The NAO SLP index is the difference of monthly normalized SLP anomalies between Akureyri (Iceland) and Ponta Delgada (Azores), for the interval 1965–1987. A NAO thermal index is also derived as the difference of monthly normalized temperature anomalies between Godthaab (Western Greenland) and Bergen (Norway), for the same time interval. The NAO indices use data extracted from the World Weather Records (1981) and Monthly Climatic Data for the World (1971–1987), edited by NOAA, Environmental Data Service.

3. Analysis methodology

Space and time variability patterns of SST, zonal and meridional wind anomalies over tropical Atlantic, are obtained using empirical orthogonal function (EOF) analysis (Preisendorfer, 1988; Von Storch, 1995). EOF analysis is a method designed to make an optimal representation of the covariance structure of a multicomponent dataset and it identifies patterns which maximise variances. The eigenvectors of the covariance data matrix represent the spatial patterns and the associated eigenvalues show the amount of variance explained by the eigenvectors. The corresponding time coefficients of the eigenvectors (principal components) describe the temporal behaviour of the data. The eigenvectors are orthogonal to one another and the principal components are uncorrelated.

The statistical analysis of the linkage between the ocean, represented by SST and the atmosphere represented by zonal and meridional wind fields, is carried out using canonical correlation analysis (CCA) (Preisendorfer, 1988; Zorita et al., 1992; Von Storch, 1995). The CCA selects a pair of spatial patterns of two variables such that their time evolution is optimally correlated. Prior to analysis, the original data are usually projected onto their EOFs, retaining only a limited number of them, in order to avoid noise. The canonical correlations tend to be overestimated if the number of EOFs is too large and a compromise is needed between the requirement of having a highly explained variance and the constraint regarding the noise from the data (Kharin, 1994; Von Storch, 1995). Preliminary CCA tests with different number of EOFs suggested that the first five EOFs of SST and seven EOFs of zonal and meridional wind could be retained in the present case. They explain 60%, 50% and 48% of the total variance of SST, zonal and meridional wind data, respectively.

4. Results

The EOF analysis of tropical Atlantic SST and surface wind fields have revealed the existence of distinct variability patterns. The correlation coefficients between the principal component associated to the first EOF of SST and the corresponding COADS SST anomaly field are presented in Fig. 1a. The tropical Atlantic (especially the equatorial and southern area) shows an upward shift in the mean values of the associated principal component after the late 1970's. Fig. 1b illustrates the principal component associated to the first EOF of tropical COADS SST and the time evolution of the anomalies averaged in a latitude belt from 5°S to 5°N but based on the Meteorological Office Historical Sea Surface Temperature (MOHSST6) (Folland and Parker, 1995; Parker et al., 1995). Using the monthly normalized values of SST averaged over the Atlantic basin from 30°N to 20°S, Servain (1991) has presented evidence of a similar trend. No local wind pattern was found to match this variability mode when a subsequent canonical correlation analysis was performed for the time interval 1965–1987. Bjerknes (1964) pointed out the distinct nature of decadal and inter-

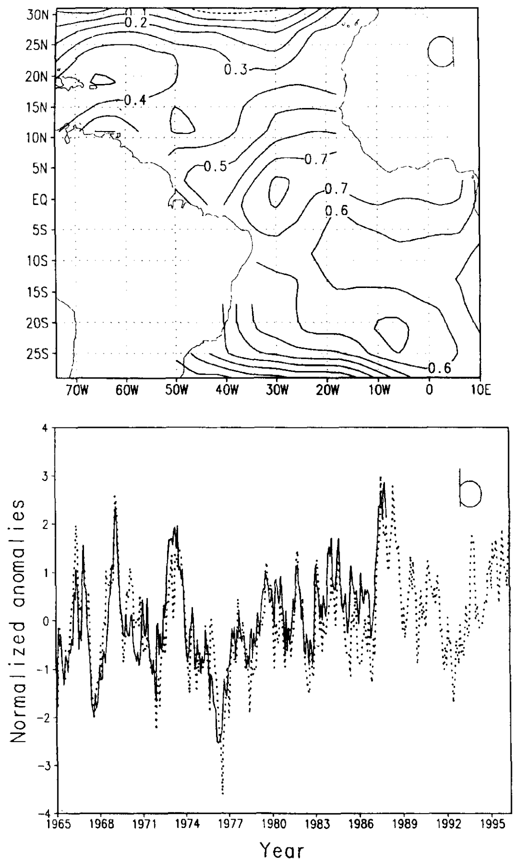

Fig. 1. The correlation coefficients (a) between the first principal component and the corresponding monthly normalized SST anomalies, for the time interval January 1965–December 1987. The normalized time series (b) represent the principal component associated to the first EOF of COADS SST (solid line) and the MOHSST6 anomalies averaged in a latitudinal belt from 5 °S to 5 °N (dotted line) for the time interval January 1965–May 1996.

annual Atlantic variability. He suggest that the interannual fluctuations of SST are maintained by the wind conditions through a local thermodynamic interaction. The decadal patterns of SST and winds that lack a similar coherent relationship may be related to a large-scale interaction between ocean circulation and the atmosphere. The upward trend, also shown by the tropical SST time series which are displayed in the global ocean surface temperature atlas (Bottomley et al., 1990) adds extra credence to the view that a global phenomenon may be involved.

The second EOF of Atlantic SST (not shown) is dominated by a dipole-like structure with the largest opposite polarity signals located over northern and southern tropical regions. The shape of the 2 main centres of variability shown by the 2nd EOF of tropical SST follows the trade winds orientation in the 2 hemispheres. This structure resembles that found by Servain (1991) and Hougton and Touree (1992) and is related to distinct meridional and zonal wind patterns over the tropical Atlantic. The pattern revealed by the second EOF of SST is very similar to the SST pattern of the first CCA mode of SST and meridional wind. The correlation coefficient of this CCA mode is 0.71 and the CCA patterns explain 18% of the SST variance and 11% of the meridional wind variance. The time series corresponding to the SST and meridional wind patterns of the first CCA mode (Fig. 2) are similar to the dipole-index which has been computed by Servain (1991) as the difference between monthly standardized SST anomalies spatially averaged in the northern and southern tropical Atlantic. The same low frequency behaviour of the north–south thermal difference is pointed out by Houghton and Touree (1992) when analysing SST normalized anomalies from the standpoint of rotated and unrotated EOF modes. Their results indicate that the dipole-like structure is not a real feature of the SST variability in central Atlantic although the low frequency fluctuation in the north-south temperature difference is certainly real. This type of structure, characterised by a thermal contrast between northern and southern tropical Atlantic, was analysed by Moura and Shukla (1981) in connection with the occurrence of severe droughts over north-eastern Brazil. Fig. 3 shows the correlation coefficients between the CCA time series and the corresponding SST and meridional wind anomalies. The CCA patterns show the linkage between the anomalies of the north-south thermal difference and meridional wind variability. An excess (deficit) of surface thermal energy in the northern tropics relative to the southern tropics, is associated with southerly (northerly) wind anomalies over western equatorial area. The interannual equatorial wind anomalies suggest the existence of interannual fluctuations in the position of ITCZ. It is therefore most likely that variations in the intensity of north-south thermal contrast are related to interannual changes in the Hadley circulation.

The first CCA of zonal wind and SST anomalies has also revealed some features of tropical variability although the linkage is not as strong as in the case of SST and meridional wind fields. The correlation coefficient of the first CCA pair of SST and zonal wind is 0.44. When zonal wind anomalies lead the SST anomalies in time by one month the correlation coefficient become 0.53 suggesting that a significant part of inter-monthly SST variability is driven by the wind. The SST and zonal wind patterns explain 18%, and 10% respectively of total variance. The SST pattern of the first pair

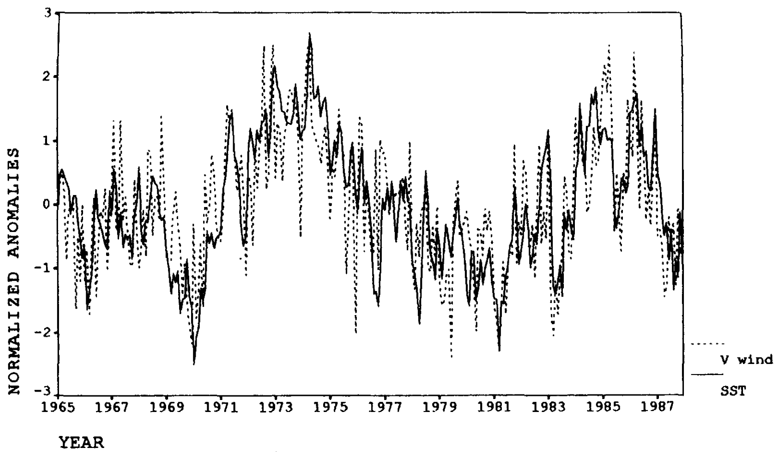

Fig. 2. Time series associated with the first CCA patterns of SST normalized anomalies (continous line) and meridional wind normalized anomalies (dotted line).

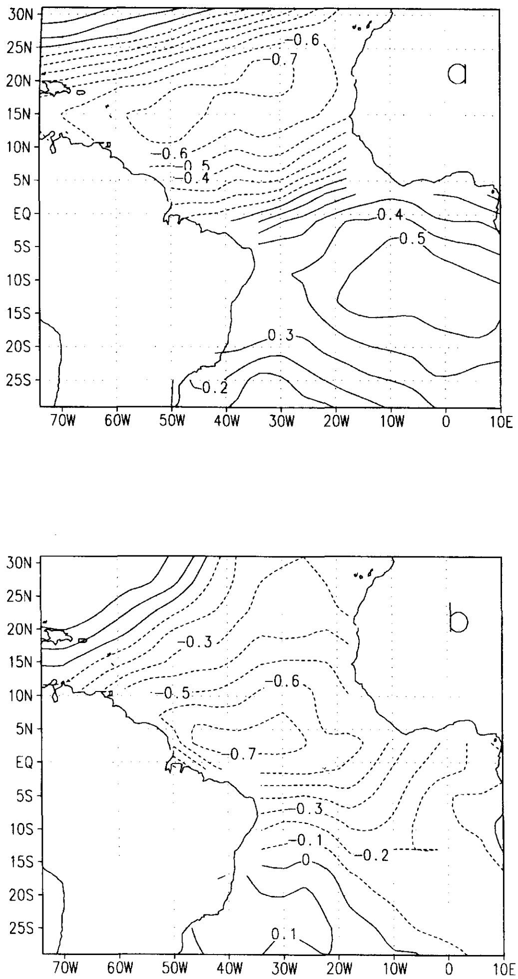

Fig. 3. The correlation coefficients between the CCA time series and the corresponding monthly normalized SST anomalies (a) and monthly normalized meridional wind anomalies (b), for the time interval January 1965–December 1987. Continous lines mark positive values and dotted lines negative values.

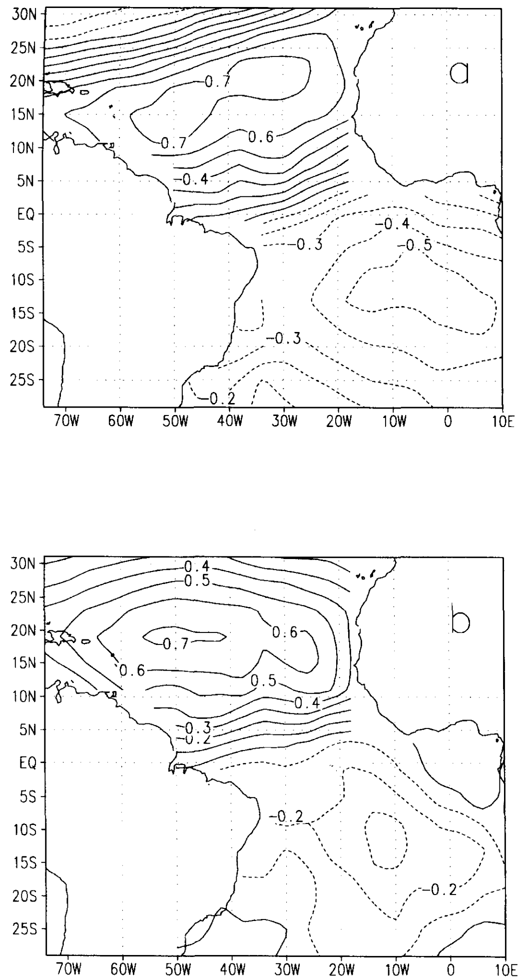

Fig. 4. The correlation coefficients between the CCA time series and the corresponding monthly normalized SST anomalies (a) and monthly normalized zonal wind anomalies (b) for the time interval January 1965–December 1987. Continous lines mark positive values and dotted lines negative values.

SST-zonal wind (not shown) bears a strong resemblance to the SST pattern of the first pair SST-meridional wind. Their associated time series have a correlation coefficient of 0.99. The correlation coefficient between the meridional wind time series of the first CCA pair SST-meridional wind and zonal wind time series of the first CCA pair SST-zonal wind is 0.60. Fig. 4 illustrates the correlation coefficients between the CCA time series and the corresponding SST and zonal wind anomalies. Positive zonal wind anomalies (reduced trade winds) are linked with positive SST anomalies and negative zonal wind anomalies (enhanced trade winds) are connected with negative SST anomalies. It seems that these features displayed by the CCA patterns of SST and zonal wind anomalies describe the effects of local interaction between ocean and atmosphere due to surface heat exchanges and wind mixing processes. However, spatial and temporal coherence between this CCA mode and the

CCA patterns of SST and meridional wind anomalies (which display non-local characteristics) suggests that the local interaction is coupled to a larger scale phenomenon. Servain (1991) pointed out a relationship between the interannual SST anomalies in the tropical Atlantic and the Pacific ENSO phenomenon. The linkage between the SST anomalies and the fluctuations in the Hadley circulation, shown by the first CCA patterns of SST and meridional wind, indicates a possible connection with North Atlantic Oscillation. Futhermore, the above discussed CCA modes show the signal to be stronger in the northern tropical Atlantic relative to the southern area suggesting that the link element between NAO and the tropical system may be the Azores High.

The correlation coefficients between the monthly NAO SLP index and the associated time series of the first CCA pairs of SST and surface wind components are presented in Table 1. Although the correlation coefficients are statistical significant at 5% level, their weakness is probably due to the strong high frequency component caused by internal atmospheric dynamics in mid and high latitudes. In the present study, this component is considered to be noise. The time evolution of SLP NAO and CCA indices become more coherent if the indices are initially low-pass filtered. Fig. 5 illustrates the filtered time series. Only the components with time scales longer then 48 months are retained. This is done in order to avoid, together with the high frequency components of mid and high latitude variability, the noisy influence of other tropical phenomena such as a mode similar to the ENSO occurence (Zebiak, 1993). It is noteworthy to point out the tendency of the time filtered NAO index to lead by about

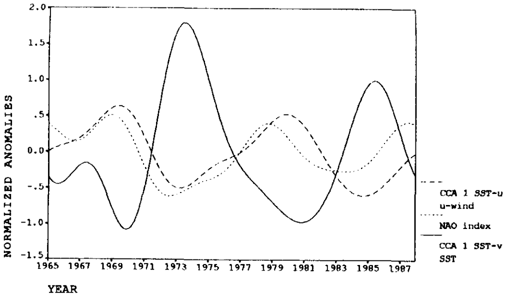

Fig. 5. The SST and zonal wind time series associated with the first CCA pair SST-meridional wind (continous line), the first CCA pair SST-zonal wind (dashed line) and the NAO SLP index (dotted line). The CCA and SLP NAO indices computed from monthly normalized anomalies are low-pass filtered retaining the components with time scale greater than 48 months.

11 months the time filtered coefficients corresponding to the first CCA pairs. The reason may be that NAO is generated in the extratropical atmosphere and the tropical ocean needs time to adjust towards a new state, however after the adjustment is reached the ocean acts to preserve the NAO conditions.

Table 1. *The cross correlation coefficients of the SLP NAO index and time series associated to CCA pairs of tropical SST and wind*

CCA pair	Variable	Correlation n coefficient	Lag L
SST-V wind	SST	−0.23	−1
	V wind	−0.22	−14
SST-U wind	SST	0.25	−1
	U wind	0.34	0

Lag −1 means that SLP NAO index leads CCA time series by 1 month.

It is interesting to analyse the time coefficients of the first CCA patterns from the standpoint of NAO mode occurrences. GA winters predominate in the time interval characterised by positive SST anomalies over northern tropics relative to southern tropics and by southerly equatorial wind anomalies. Westerly anomalies in zonal wind field over north-western tropical Atlantic are also associated with GA mode. The opposite patterns tend to be associated with the time interval characterised by GB winter occurrences. GA and GB winters are listed in Table 2. The classification has been made using the difference of winter SLP normalized anomalies between Akureyri (Iceland) and Ponta Delgada (Azores) together with the difference of winter thermal normalized anomalies between Godthaab (Western Greenland) and Bergen (Norway), for the interval 1965–1986. A GA (GB) winter is defined when the values of both thermal and SLP winter indices exceed 0.5 (-0.5) units of standard deviation. The definition of the two NAO mode winters presented here is different from that given by van Loon and Rogers (1978), but the basic idea is the same: GA and GB winters are associated with simultaneous

Table 2. *Winter classification using the difference of winter SLP anomalies between Iceland and the Azores and winter thermal anomalies between Godthaab and Bergen*

Winter	NAO SLP index	NAO thermal index	NAO mode
1965–1966	3.5	1.8	GA
1966–1967	−1.0	−0.1	—
1967–1968	0.6	0.7	GA
1968–1969	3.3	1.4	GA
1969–1970	0.3	1.2	—
1970–1971	0.2	−1.2	—
1971–1972	−1.1	−1.9	GB
1972–1973	−2.4	−2.0	GB
1973–1974	−2.1	−1.4	GB
1974–1975	−1.4	−2.3	GB
1975–1976	−1.2	−0.8	GB
1976–1977	2.0	1.8	GA
1977–1978	1.2	−0.1	—
1978–1979	2.7	3.1	GA
1979–1980	0.1	0.9	—
1980–1981	2.0	0.1	—
1981–1982	0.4	0.8	—
1982–1983	−2.1	−2.8	GB
1983–1984	−2.9	−2.6	GB
1984–1985	1.3	0.4	—
1985–1986	0.6	3.2	GA

All normalized anomalies were computed for the time interval 1965–1986.

anomalies in the thermal and SLP fields over the key regions.

The composite maps of SST and wind anomalies are derived using six GA and GB years (Table 2). A GA (GB) year is taken from the December of a GA (GB) winter to the following November. Due to a strong ENSO like episode occurrence in the tropical Atlantic in 1984, this year was not taken into account for the composites as its signal could overhelm the NAO signature. Fig. 6 shows the mean SST and wind difference between GB and GA years. The spatial distributions of a t variable, corresponding to the GB-GA difference in SST, zonal and meridional wind components were also calculated. Shaded and contoured areas indicate regions where the difference is statistical significant at 5% level (Fig. 6). The SST dipole structure is not so pronounced in the composite and its southern centre is shifted westward compared to the CCA mode. Differences probably arise because of inter-monthly variability which may influence the

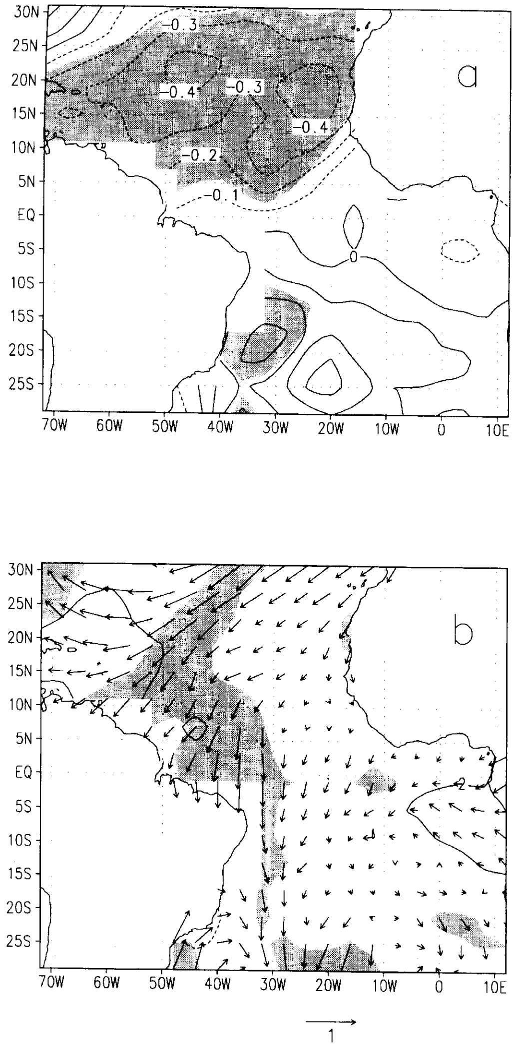

Fig. 6. Sea surface temperature differences in degree Celsius (a) and wind differences in m/s (b) for GB minus GA years. Shaded areas indicate statistical significant difference at the 5% level in SST field (a) and in meridional wind field (b). Contoured areas indicate statistical significant difference at the 5% level in zonal wind field (b).

CCA modes but is filtered out in the composites by the averaging procedure. However, mean difference patterns are consistent with the first CCA pairs of SST and wind normalized anomalies, especially in the northern part of the tropical Atlantic where the NAO related signal is stronger. It is noteworthy to point out the tendency for anticyclonic circulation to occur associated with colder SST anomalies over northern tropics in GB years relative to GA years.

Moura and Shukla (1981) used a simple primitive equation model to calculate the frictionally controlled and thermally driven circulation due to a heat source to the north, and a heat sink to the south, of the equator. Low-level cyclonic circulation and high-level anticyclonic circulation are generated to the north of the equator and low-level anticyclonic circulation and high-level cyclonic circulation are generated to the south of the equator. Although the mechanism described above makes no difference to the strength of northern and southern circulations, the CCA modes and NAO composites suggest that the northern region of tropical Atlantic is more active than the southern tropical area. Thus low-level cyclonic (anticyclonic) circulation associated with positive SST anomalies over northern tropical Atlantic may cause a decrease (increase) in the strength of the trade winds. The decrease (increase) in the strength of trade winds, linked to diminished (enhanced) Hadley circulation, determines further SST warming (cooling) north of the equator. The positive feedback described above could explain the persistence of SST and wind anomalies over the northern tropics through the combined effect of surface heat exchange and wind mixing process. The feedback influences on the Azores High may be further linked to the NAO mode persistence. The fact that NAO index tends to lead the tropical variability suggests the existence of extratropical factors that may also be involved in changing NAO modes.

5. Conclusions

The low-frequency variability in tropical Atlantic is affected by the NAO and the strongest NAO effects have been identified in the northern tropics. The presence of interannual meridional wind anomalies over the equatorial Atlantic could be related to the interannual fluctuations of the Hadley circulation which are also involved in the NAO development. A lagged relationship between the tropical patterns and NAO modes is revealed when the data are low-pass filtered. The existence of the lag supports the hypothesis that NAO is a preferred internal mode of the extratropical atmospheric variability, as atmospheric model results also suggest. However, the relationship between the tropical patterns and NAO mode persistence indicates that the ocean modulates NAO variability on a interannual to decadal time scale. The interannual persistence of SST and wind anomalies over the northern tropical Atlantic could be linked to the interannual persistence of the GA and GB winters. This could occur through a feedback mechanism in which local thermodynamic interaction in the northern tropics is coupled to larger scale processes such as Hadley circulation. Extratropical factors are probably involved in changing the NAO modes. Unlike El Nino/Southern Oscillation (ENSO) which is well defined as a tropical phenomenon, NAO has both tropical and high latitude implications. Most studies concerning NAO have analysed only the high and mid latitude characteristics of the phenomenon. A possible relationship between the tropical Atlantic processes and NAO modes has been shown in this paper but the description of NAO physical mechanism needs a more detailed understanding of the connection between the tropics and high latitudes. Further studies need to be carried out using longer data sets to describe the variability patterns associated with NAO. Coupled ocean-atmosphere models should be used in selecting possible mechanisms through which NAO signal is modulated on a interannual or decadal time scale.

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