North Atlantic Winter SLP Anomalies Based on the Autumn ENSO State

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ABSTRACT

The winter sea level pressure (SLP) anomalies in the Northern Hemisphere have been analyzed over the period 1873–2000 based on the ENSO state during the previous autumn. First, a set of extreme cold and warm ENSO events and periods that may be regarded as normal is selected using the SST data of the Niño-3 region. This selection is carried out for autumn and with the constraint that the ENSO event is well developed. For the winters following these selected autumn events, composites of Northern Hemisphere SLP anomalies have been obtained and compared to each other. A study of the consistency among events of the relationship between ENSO and SLP anomalies was also carried out. Results show the preference for a positive NAO-like SLP anomaly pattern in the North Atlantic region during the winters following autumns of strong cold ENSO events and, thus, suggest the existence of a potential source of predictability for the North Atlantic climate. An additional analysis of the winter North Atlantic Oscillation (NAO) index confirms this finding. The possible physical basis of this source of predictability for the North Atlantic climate is discussed.

1. Introduction

The association between ENSO and climate anomalies in the tropical Pacific region and the impact of ENSO on the climate of the extratropical regions, as well as the mechanism responsible, for which anomalies in the tropical Pacific SST have world-wide impacts, has been the subject of numerous studies throughout the last decades. Nevertheless, the impact of ENSO on the climate of the North Atlantic region remains open to debate (Hurrell et al. 2003). The early work of van Loon and Madden (1981) showed, in the North Atlantic European sector, a significant influence of ENSO on the winter SLP and temperature observational records. Similar evidence of ENSO's influence on the climate of the North Atlantic European sector were found by Fraedrich and Müller (1992), Fraedrich (1994), and Huang et al. (1998). Additionally, Dong et al. (2000), and Grötzner et al. (2000) provided model results indicating the influence of the 1997/98 El Niño and 1998 La Niña on the climate of the North Atlantic region.

In a previous work (Pozo-Vázquez et al. 2001), we examined the association between ENSO, Northern Hemisphere sea level pressure (SLP), and temperatures in Europe during the northern winter. In the North Atlantic region and during cold ENSO events, a significant SLP anomalies pattern, resembling the positive phase of the North Atlantic Oscillation (NAO), was found. The temperature analysis showed statistically significant anomalies consistent with the SLP anomalies. Most ENSO events begin between March and September and end between February and March, with the peak of the anomalies during the northern winter (Trenberth 1997a). Thus, if the ENSO event is well developed during autumn and is an extreme event, the event persistence to the following winter may be expected in most of the cases. Therefore, and taking into account the results of Pozo-Vázquez et al. (2001), an influence of ENSO on

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the Northern Hemisphere SLP anomalies during the winters following autumn ENSO events should be expected.

We explore this hypothesis in this work. Our aim is to study the SLP anomalies in the Northern Hemisphere during the winters following autumns of ENSO events over the period 1873–2000. We do not require that the ENSO events still take place during the winter, so this study gives certain forecasting information concerning the SLP anomalies during the winter following an autumn ENSO event. Our strategy is based on the study of the SLP anomalies associated with a set of cold and warm ENSO events selected following an optimal procedure in terms of an eventual influence of ENSO in the Northern Hemisphere extratropical regions. We analyze these SLP anomalies, their consistency among events, and also their statistical significance.

This study is structured as follows: In section 2, we discuss the criteria for the selection of the ENSO events and the data used in this work. In section 3, we obtain composites of Northern Hemisphere winter SLP anomalies for the selected autumn ENSO events. We also investigate the consistency among events of the relationship between ENSO and SLP. Finally, in this section, we carry out an analysis of the winter NAO index values based on the selected ENSO events. In section 4, we provide a summary and discussion of the results.

2. Methodology and data

The search for ENSO signals in the North Atlantic area presents several difficulties. First, there are different types of El Niño and La Niña events, with different characteristics that can lead to different responses of the extratropical atmospheric circulation. Second, climatological planetary atmospheric waves, natural noise, and the complexity of the numerous feedbacks (and possibly nonlinear relationships) can embed and hide the signal of ENSO in the extratropics (Trenberth 1997b). Some authors have argued that only when tropical SST anomalies are large can the ENSO signal be found in the extratropics (Trenberth et al. 1998; Huang et al. 1998). There is a lag of around 3 months between the beginning of an ENSO event and, eventually, the extratropical response in higher latitudes in the North Pacific area (Trenberth and Hurrell 1994). This response often resembles the Pacific–North American pattern (PNA). The perturbation can be propagated downstream, as a wave train, to other longitudes in the form of Rossby waves, eventually affecting locations far away from the Pacific, particularly the North Atlantic region. Consequently, the eventual propagation of such events to other longitudes takes place with a similar lag. As we are interested in the ENSO signal in the North Atlantic area during the northern winter, and bearing in mind the PNA hypothesis, we have to select those ENSO events that are considered extreme and that are well developed during the previous autumn.

The Niño-3 SST region (5°S–5°N, 90°–150°W) has been employed to monitor ENSO. Particularly, SST data for the period 1872–2000 from the Global Sea Ice and Sea Surface Temperature dataset, version 2.3 (GISST2.3; Rayner et al. 1996) have been used. A monthly standardized index was computed using the reference period 1951–80. Finally, seasonal values were calculated by averaging the corresponding monthly values: June–August for summer and September–November for autumn.

A set of moderate/extreme ENSO events have been selected basing the analysis on these seasonal SST normalized series. For El Niño (La Niña) events, we selected those years in which the current autumn and the preceding summer have an index value roughly equal to or greater than 0.7 standard deviations (years in which the preceding summer and the current autumn have an index value roughly equal to or less than −0.7 standard deviation for La Niña events). A similar threshold was used by Mason and Goddard (2001). The use of this relatively low amplitude threshold could be argued given the fact that the tropical east Pacific rainfall suppression during La Niña events tends to saturate and even moderate the amplitude of the cold SST anomalies. Thus, the teleconnection process for moderate and strong events would be quite similar, some evidence for which is shown in the GCM study of Hoerling et al. (2001). The criterion for the preceding summer ensures that, during the autumn, the ENSO events will be well developed. Since our purpose is to study an eventual climatic signal of ENSO in the North Atlantic area, we must be able to compare the situation during extreme ENSO events and during periods that can be regarded as normal. We consider normal years those that fulfill neither of the two criteria, and we will refer to these hereinafter as ''Normal'' years. Table 1 lists the selected cases. There are 23 El Niño and 25 La Niña events. The selected warm and cold events are consistent with those identified in other empirical studies (Mason and Goddard 2001; Trenberth 1997a; Hoerling et al. 1997; Kiladis and Diaz 1989; van Loon and Madden 1981).

The monthly mean SLP for the region 15°–85°N has been analyzed. The data are on a 5° by 10° latitude–longitude grid basis, covering the period 1873–2000, and have been provided by the Climatic Research Unit (CRU; Jones 1987). The 1873–2000 mean has been subtracted from the monthly data and seasonal averages for winter (December–February) were determined. With this database, composites of the Northern Hemisphere SLP anomalies during winter were obtained based on the selected autumn ENSO events. The Student's *t* test was used to compare the means of the different composites in each grid, and a 95% significance level was used. For completion of the composite analysis, we have examined the consistency among events in the relationship between ENSO and SLP, calculating the percentage of consistent signals, defined as the percentage of events

TABLE 1. List of El Niño, La Niña, and Normal autumn events selected using the Niño-3 region. The period of analysis is 1873–2000. For El Niño (La Niña) years, the current autumn and the preceding summer have an SST index value roughly equal to or greater than 0.7 (less than −0.7) std devs. For Normal years, the SST index value does not fulfil the criterion for autumn or summer.

El Niño	La Niña	Normal		
1877	1872	1873	1928	1980
1888	1874	1875	1929	1981
1896	1886	1876	1931	1984
1899	1892	1878	1932	1989
1902	1893	1880	1934	1990
1904	1903	1881	1935	1992
1905	1906	1883	1936	1993
1911	1909	1887	1937	1995
1914	1910	1890	1939	1996
1918	1916	1894	1943	1998
1930	1922	1897	1944	2000
1940	1924	1898	1945	
1951	1933	1901	1952	
1957	1938	1907	1953	
1963	1942	1912	1956	
1965	1949	1913	1958	
1969	1954	1915	1959	
1972	1955	1917	1960	
1976	1964	1919	1961	
1982	1970	1920	1962	
1987	1971	1921	1966	
1991	1973	1923	1968	
1997	1975	1925	1974	
	1988	1926	1977	
	1999	1927		

having anomalies with the same sign as that of the composite anomaly.

Finally, composite values of the winter NAO index during the selected ENSO events were analyzed. A seasonal index, proposed by Hurrell (1995) and covering the period 1873–2000, was employed.

3. Analysis

a. SLP patterns

Composites of SLP anomalies during the winters following the selected autumns of ENSO events (Table 1) have been obtained for the period 1873–2000; Fig. 1 shows the results. The consistency among events in the relationship between ENSO and SLP for El Niño and La Niña events are shown, respectively, in Figs. 2a and 2b.

A negative anomaly pattern is centered south of the Aleutian Islands during El Niño cases (Fig. 1a). This center reaches negative anomalies of −4 mb. During La Niña (Fig. 1d), positive anomalies, up to +3 mb, are found over this area. Both patterns are statistically significant when they are compared with the Normal situation (Figs. 1c and 1e) and show a consistence percentage that reaches 70% (Figs. 2a and 2b). These patterns are consistent with a deepening of the Aleutian low pressure center during El Niño events and a weakening during La Niña (Hoerling et al. 1997). Over the southeastern part of the United States, weak (but statistically significant) negative anomalies can be found when comparing El Niño and Normal years (Fig. 1c). This area also shows weak statistically positive anomalies when comparing La Niña and Normal years (Fig. 2e).

During La Niña cases (Fig. 1d), a relatively strong anomaly SLP pattern is found over the North Atlantic area. There is an anomalous high pressure band over the central Atlantic and an anomalous low pressure band over the area south of Iceland. The comparison of this pattern to that of Normal years shows that a region southwest of Iceland and other regions west of the Iberian Peninsula are statistically significant (Fig. 1e). This SLP anomaly pattern closely resembles the positive phase of the NAO, with an intensification of the Azores high and a deepening of the Icelandic low. Additionally, this pattern in the North Atlantic area shows a high coherence (Fig. 2b), reaching 90% over Iceland and between 70% and 90% over the central Atlantic area (roughly over the dipole centers of the NAO). This indicates that the SLP anomaly patterns over the North Atlantic area in Figs. 1d and 1e are not the result from a few major events but are due to the fact that the SLP anomaly in this area during the winters following autumns of strong cold ENSO events is quite stable and qualitatively similar to those found during the positive phase of the NAO.

Figure 1f shows the difference between El Niño and La Niña. Statistically significant areas are fundamentally those found in Fig. 1e.

b. Field significance

A field significance test, taking into account the spatial correlation of the data, that is, the lack of independence between the data, has been carried out. Particularly, the global field significance of the patterns in Figs. 1c and 1e was examined following Livezey and Chen (1983). A series of 1000 Monte Carlo composite patterns was first obtained in which 25 samples were selected randomly. It was found that 5% of these patterns had more than 6.8% of their area exceed the 95% confidence level of a t test when compared to the Normal case composites. As both El Niño and La Niña composites in Figs. 2c and 2e, respectively, were found to have greater than 6.8% of their area exceed the above requirements for a t test when compared to the Normal composites (11.8% for El Niño and 12% for La Niña), we can conclude that each of the spatial patterns in Figs. 1c and 1d does indeed pass the field significance test at the 95% confidence level.

Since the main goal of this work is to study the ENSO signal in the North Atlantic region, we have conducted an additional field significance analysis constrained over this area. Following the same procedure explained above, we have computed the field significance of the ENSO signal over the area extending from 15° to 85°N

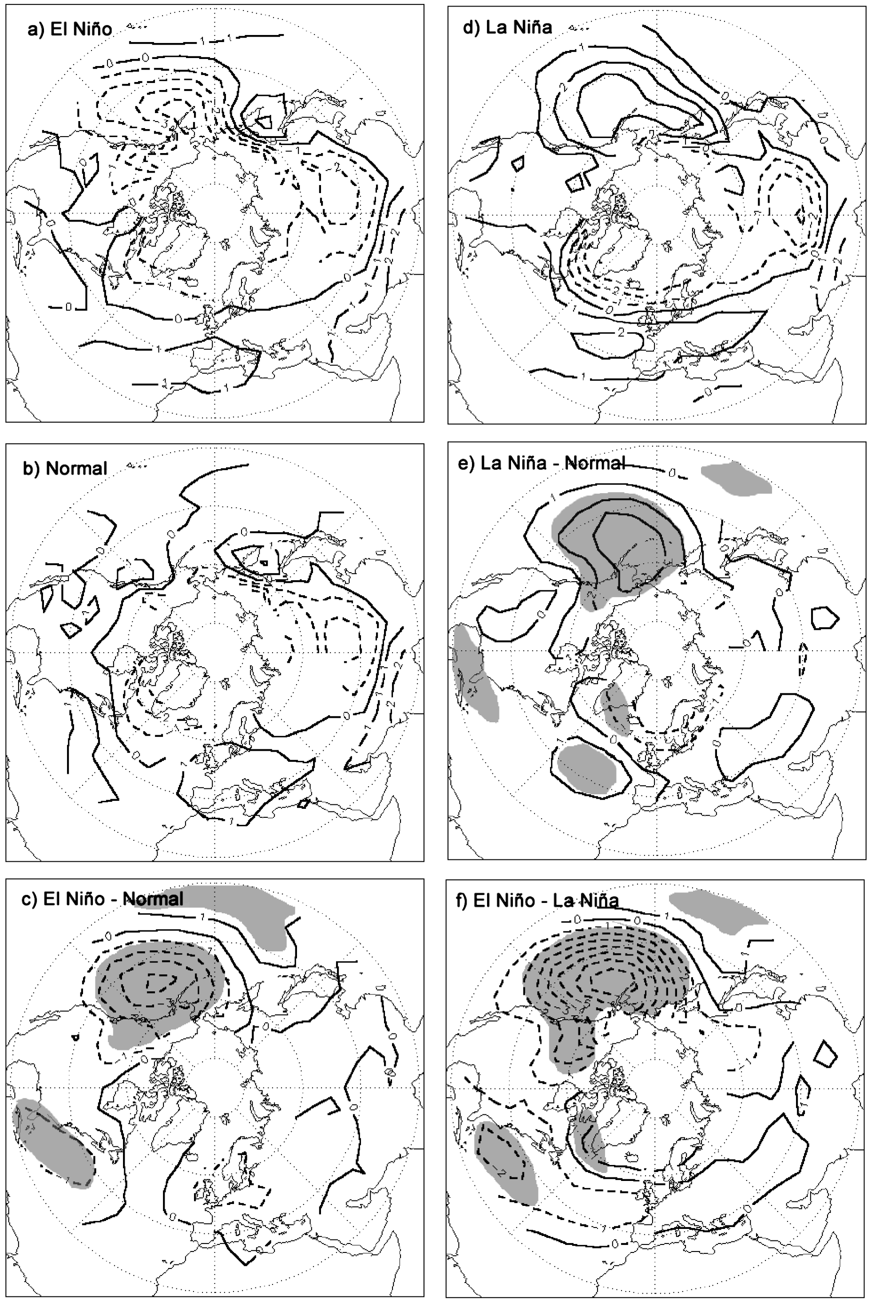

FIG. 1. Composites of the observed SLP anomalies during the winters following autumns of ENSO events. See Table 1 for the years included in the composites: (a) during winters following autumns of El Niño events, (b) during Normal, and (c) the difference of (a) minus (b). (d) Anomalies during winters following autumns of La Niña events, and (e) the difference of (d) minus (b). (f) The difference between El Niño and La Niña [(a) minus (d)]. The contour interval is 1 mb. The continuous lines indicate positive or zero anomalies, and the dotted lines indicate negative anomalies. Shading indicates local statistical significance of the difference at the 95% confidence level, based on a *t* test.

and 60°W to 40°E. For the La Niña composite in Fig. 2e, in this area it is found that 9.5% of the area exceeds the 95% confidence level of the *t* test when compared to the Normal composite cases. Therefore, accepting the same Monte Carlo results of the previous hemispheric analyses (6.8% of the area exceed the 95% confidence level), the La Niña signal in the North Atlantic area passes the field significance test at the 95% level. On

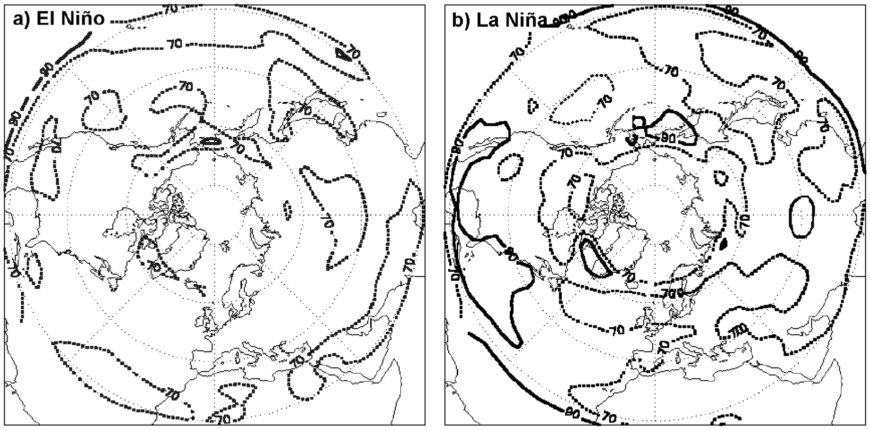

FIG. 2. Study of the consistency among events of the relationship between ENSO and SLP anomalies during the winters following autumns of ENSO events. (a) The percentage of events having anomalies with a sign consistent with the composite anomaly for El Niño events; (b) as in (a), but for La Niña events. The dotted line indicates 70%, and the continuous line indicates 90%.

the other hand, it is found that the El Niño signal does not pass the field significance test constrained to the North Atlantic region.

To complete the previous analysis presented in sections 3a and 3b, the analysis was repeated using the reference period 1951–80 for the SLP data. The results proved to be very similar to those presented here, so it can be concluded that the results do not depend on the reference period used.

c. *NAO index analysis*

We considered the association between the NAO and the ENSO phenomena through the analysis of the NAO index during the ENSO events. Composite values were calculated for El Niño, La Niña, and Normal cases during the winters following the selected autumn ENSO events in Table 1. For La Niña years, the mean value of the NAO index in winter was 0.68, while for El Niño it was 0.02 and for Normal cases it was −0.15. The mean of the NAO index for the period 1864–1984 is 0.089. In 18 of the 25 La Niña events, the phase of the NAO was positive; only for the winters of 1875, 1893, 1917, 1955, 1956, 1965, and 1971 was a negative winter NAO index value found (the year refers to the January year). The difference between the composite value for La Niña and Normal years is statistically significant at the 95% confidence level using a *t* test. Also statistically significant at the 95% level is the difference between La Niña and El Niño years. Nevertheless, the difference between El Niño and Normal years proved to be nonsignificant at this level.

TABLE 2. Composite winter NAO index values associated with autumn El Niño, La Niña, and Normal ENSO events. The values were computed by shifting the years of occurrence in Table 1. The year for the winter season Dec–Feb (DJF) corresponds to the year of Jan. Thus, the (−) and (0) rows correspond to the winter prior to the autumn ENSO event, and the (+) rows correspond to the winters following the autumn ENSO events. The statistical significance of the difference between La Niña series and Normal series and between El Niño series and Normal series has been computed using a *t* test. Significance levels greater than 90% and 95% are denoted by * and **, respectively.

Shift	La Niña	El Niño	Normal
−2	0.12	0.31	−0.30
−1	−0.18	−0.19	0.39
0	0.58	−0.62*	0.31
+1	0.68**	0.02	−0.15
+2	−0.25	0.53	0.07
+3	−0.18	−0.09	−0.14
+4	0.25	0.30	−0.14

We have carried out an additional analysis in order to study the significance of the ENSO signal in the NAO index. We have computed the NAO composite values shifting the years of occurrence in Table 1. If the La Niña signal in the NAO index is a true signal, an unclear signal in the NAO index should be obtained in these composites; Table 2 shows the results. Note that the highest NAO index value is found at lag +1 (that is, the winter following the autumn ENSO event) and for La Niña events. Furthermore, this is the only case in which the La Niña signal is statistically significant at the 95% confidence level when compared to the Normal cases. A high composite value is also found at lag 0 but it is just significant at the 76% confidence level.

4. Concluding remarks

a. *Summary*

The association between ENSO and SLP in the Northern Hemisphere has been analyzed during the period 1873–2000. A set of autumn ENSO events is selected with the constraint that the ENSO event must be well developed during the autumn. For the winters following these selected autumn events, composites of Northern Hemisphere SLP anomalies have been obtained and compared to each other. Results show that, in the North Atlantic area and for La Niña events, a statistically significant SLP anomaly pattern resembling the positive phase of the NAO can be found. No statistically significant patterns associated with El Niño events are found in this area. A consistency analysis shows that this SLP pattern is not the result of a few major events but is due to the fact that the SLP anomalies in this area during cold ENSO events are stable and qualitatively similar to those found during the positive phase of the NAO. A composite analysis of the NAO index provides further evidence of this result.

b. Discussion

Following the same procedure used to obtain the moderate/extreme autumn ENSO events, we have selected a set of moderate/extreme winter ENSO events. For El Niño (La Niña) events, we selected those years in which the preceding autumn and the current winter have an SST index value roughly equal to or greater than 0.7 standard deviation/(years in which the preceding autumn and the current winter have an index value roughly equal to or less than minus 0.7 standard deviation for La Niña events). It is found that all El Niño and La Niña events that were extreme during autumn (Table 1) were also extreme during the following winter. This may indicate that the existence of SLP anomalies in the North Atlantic area during the winters following autumns of extreme cold ENSO events could be simply due to the fact that the ENSO event continues to be an extreme event during the following winter and thus affects the climate of this region in the way indicated by Pozo-Vázquez et al. (2001). Additional evidence for this hypothesis is presented by Larkin and Harrison (2001) who, based on the analysis of SST anomalies in the equatorial Pacific, showed that the cold ENSO events tend to be fully developed between August and December of the year following the year of the first anomalies, while the anomalies tend to decay between January and May of the following year. Thus, if the cold ENSO event is well developed during autumn, the event persistence the following winter may be expected in most of the cases.

The physical mechanisms through which ENSO can affect the North Atlantic region circulation is still a matter under discussion. The PNA pattern has been proposed as one of the links between the tropical forcing and the extratropical circulation response in the North Atlantic area. This anomaly pattern disturbs the mean flow and can trigger a standing wave train that propagates downstream to the North Atlantic area and, particularly, can give rise to the stable SLP anomaly pattern resembling the positive phase of the NAO found to be associated with the cold phase of the ENSO. Evidence for this hypothesis is found in the recent work by Wu and Hsieh (2004), which showed the existence of a nonlinear response to the ENSO events on the Northern Hemisphere circulation; the response consists of the excitation of the positive PNA and NAO patterns. Nevertheless, this hypothesis must be considered cautiously, since other works, such as Strauss and Shukla (2002), argued that the effect of the ENSO events of the extratropical atmospheric circulation is to force distinct midlatitude patterns rather than to modify the probability of the internal variability patterns (such as the PNA).

On the other hand, several works showed the influence of the tropical Pacific SST anomalies in the tropical Atlantic SST variability (Wolter 1987; Curtis and Hastenrath 1995; Li 2000; Gallego et al. 2001; Alexander et al. 2002; Huang et al. 2002). Additionally, several studies, both using GCM experiments and observational records, suggested that changes in tropical Atlantic heating might affect Northern Atlantic circulation (Watanabe and Kimoto 1999; Robertson et al. 2000). In this sense, the tropical Atlantic SST has also been proposed to act as a link between the tropical Pacific SST anomalies and the circulation of the North Atlantic region.

It appears, therefore, that the response of the circulation in the North Atlantic region to ENSO events is some kind of mixture of tropical Atlantic forcing related to the tropical Pacific SST anomalies and the midlatitude atmospheric forcing through the PNA teleconnection. The difficulty in separating the influence of the tropical Pacific from those of the tropical Atlantic (Watanabe and Kimoto 1999; Dong et al. 2000) makes it difficult to assess which mechanisms are the most important for the North Atlantic circulation.

Since the signal in the North Atlantic area during la Niña events is more stable (Fig. 2b; 70%–90% of coherence between events) than the PNA signal (70%), our analysis suggests that the tropical Atlantic SST may play an important role in the preference for a positive NAO-like pattern in the North Atlantic during the winters following autumns of strong cold ENSO events, indicating that, even when the PNA pattern is no longer present in the North Pacific area, ENSO can influence the climate of the North Atlantic area throughout the tropical Atlantic SST anomalies. The influence of ENSO on the SST variability of the equatorial Atlantic (the equatorial Atlantic SST lags by about 6 months) reported by Latif and Grötzner (2000) also supports this hypothesis. Additional evidence is given by Larkin and Harrisson (2002), who showed the existence of cold SST anomalies in the Caribbean and the western tropical North Atlantic and negative SLP anomalies in the tropical Atlantic area during the peak and decay phases of the ENSO cold life cycles, usually during the winter. No counterpart anomalies are found during warm events in these areas.

Our analysis suggests the tendency for positive NAO-like climate patterns to exist in the North Atlantic region during the winters following autumns of strong cold

ENSO events and, thus, suggests the existence of a potential source of predictability for the North Atlantic climate. Nevertheless, the judgement of the possible significance of this source of predictability and its physical basis, founded only on the observational record analyzed, is difficult and must await further analyses with GCMs and other observational records.

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