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DECADAL AND LONGER CHANGES OF THE WINTER SEA LEVEL PRESSURE FIELDS AND RELATED SYNOPTIC ACTIVITY OVER THE NORTH ATLANTIC

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ABSTRACT

Long-term intensity changes in the winter synoptic activity over the North Atlantic are studied in relation to changes of the winter mean sea level pressure (SLP) fields. Analysis of linear trends has revealed a good agreement between long-term (interdecadal) changes in the intensity of synoptic processes and variations of the winter SLP. On the contrary, no such agreement was found between detrended and low-pass filtered anomalies. There are periods, that are characterised by the enhanced (reduced) synoptic activity attributed to the low (high) index of the North Atlantic Oscillation (NAO). It appears that low-passed anomalies of intramonthly root mean square deviations (RMSD) of SLP are negatively correlated with NAO and East Atlantic (EA) teleconnection patterns over most of the North Atlantic. The low-passed winter SLP anomalies demonstrate both propagating and standing patterns. The latter have a period of about 8 years. While meridional dipole-like structures formed by the winter SLP anomalies are shifted to the west (east) of the North Atlantic, the related anomalies of synoptic activity tend to be located in the eastern (western) part of the region. When decadally averaged, anomalies in the intensity of synoptic activity are strongly linked to the North Atlantic storm track position. The exception is the 1980–1990 decade, characterised by a very high NAO index. During this decade, enhanced synoptic activity is observed to the south of the North Atlantic storm track. Copyright © 1999 Royal Meteorological Society.

KEY WORDS: North Atlantic ocean; sea level pressure; North Atlantic Oscillation (NAO); climatic changes; winter anomalies; linear trends; low-pass filtering; correlation analysis

1. INTRODUCTION

Most of the climatic studies, that deal with the large-scale ocean-atmosphere interaction in the North Atlantic (Barnett, 1984; Wallace *et al*., 1990; Deser and Blackmon, 1993; Kushnir, 1994; Gulev, 1995) and such phenomena as the North Atlantic Oscillation (NAO) (van Loon and Rogers, 1978; Rogers, 1984; Palmer and Sun, 1985; Hurrell, 1995) are based on the analysis of monthly and seasonal means. It is obvious, however, that 2 months (seasons) having the same monthly (seasonal) means can at the same time be characterised by remarkably different intensities of synoptic activity (Zorita *et al*., 1992; Gulev, 1995). The short-period processes play a leading role in variations of the sea level pressure (SLP) fields over the North Atlantic, and their contribution to the total variance of SLP is up to 75% in this region (Zveryaev and Razoryonova, 1997). Hence, the study of long-term variations of the statistics of short-period processes and their relation to variations of climatic means can sufficiently improve understanding of the North Atlantic climate change. Zorita *et al*. (1992) used data from the Comprehensive Ocean–Atmosphere Data Set (COADS) to investigate relationships between intramonthly standard deviations of SLP, winter sea surface temperature (SST) and monthly SLP anomalies by means of

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canonical correlation analysis. It was indicated that intramonthly standard deviations of SLP vary simultaneously with SLP monthly means but lead monthly means of SST. On the basis of the North Atlantic Weather Stations (OWSs) dataset, Gulev (1997) studied long-term interannual variations of the intramonthly statistics in terms of linear trends and interannual oscillations with periods of several years. Rogers (1997) investigated the North Atlantic storm track variability and its association with monthly mean SLP fields and regional low-frequency teleconnections. It was shown that the primary storm track pattern does not suggest a strong storm track link to the NAO. Although some certain progress in this field has been made, nevertheless, the relationships between intensity of atmospheric processes at the different time scales and long-term variations of the averaged climatic variables are still practically unstudied.

In the present paper decadal and interdecadal changes of the winter SLP fields and related changes of the intensity of synoptic processes over the North Atlantic are investigated in terms of linear trends, low-pass filtered anomalies, and decadally averaged anomalies.

2. DATA AND METHODS

The data source for this study consists of time series of daily and monthly means of SLP taken from National Centers for Environmental Prediction (NCEP) operational analyses. These data, presented on the NCEP $47 \times 51°$ octagonal grid, were converted onto a 5° latitude × 5° longitude grid. The analysis covers the North Atlantic region from 20 to 70°N, and the period of observations includes the winters (December–February) between 1946 and 1994 (for daily SLP, the winters 1946–1989). Synoptic activity over the North Atlantic is essentially enhanced during the winter. At the same time, regional climatic signals such as NAO are more pronounced during this season. Therefore, the analysis is focused on the winter SLP variability. Based on daily data, intramonthly root mean square deviations (RMSD) of SLP have been calculated. At each grid point, anomalies both of monthly means of SLP and RMSD have been obtained by subtracting the long-term monthly mean and RMSD from the original values. These monthly anomalies were averaged into seasonal anomalies (December–February) to form winter mean departures from normal. The anomaly time series were then detrended by fitting a linear function to the records. Additional filtering was performed to highlight the longer periods by applying Potter's low-pass filter with half-window equal to 4 years to remove fluctuations with periods less than 7 years. The same procedures of seasonal averaging and low-pass filtering were applied to time series of NAO and East Atlantic (EA) indexes which have been taken from the website of the Climate Prediction Center.

3. RESULTS

3.1. Linear trends

As indicated above, linear trends were calculated for time series of winter seasonal anomalies of SLP and RMSD. Obtained trends were then plotted and are shown in Figure 1. The trends in time series of winter SLP anomalies (Figure 1(a)) are negative in high latitudes of the North Atlantic and positive in lower latitudes. According to Student's t-test (Bendat and Piersol, 1966) trends presented in Figure 1(a) are statistically significant at levels of 90% or greater. An exception is the narrow area along the zero isoline where trends are not statistically significant. In fact, this zero isoline presents a boundary between negative and positive trends that practically coincides with North Atlantic storm track position. Thus, in terms of linear trends, the last few decades are characterised by the increase of the SLP gradient between the Azores high and the Iceland low and by a related strengthening of westerlies. In view of this, one might expect the increase of RMSD values in the North Atlantic midlatitudes during the period considered. As is shown in Figure 1(b) the trends of RMSD over the most of North Atlantic are negative or close to zero. The only positive trends are observed in the eastern part of the region and they are not statistically significant.

With respect to the long-term changes of the NAO index (Hurrell, 1995), more careful analysis has been undertaken. Based on the earlier studies of Walker (1924) and Walker and Bliss (1932), Rogers (1984) introduced the NAO index for winter and defined it as the difference between the normalised mean winter (December–February) SLP anomaly for Ponta Delgadas (Azores) and that for Akureyri (Iceland). The NAO itself is a large-scale alternation of atmospheric mass between these two North Atlantic regions. The state of the NAO reflects the strength and orientation of the poleward pressure gradient over the North Atlantic and governs the speed and direction of the midlatitude westerlies (Lamb and Peppler, 1987). The NAO extremes, termed 'Greenland below' (high index) and 'Greenland above' (low index), are associated, respectively with strong and weak westerlies across the North Atlantic (van Loon and Rogers, 1978; Lamb and Peppler, 1987; Carleton, 1988).

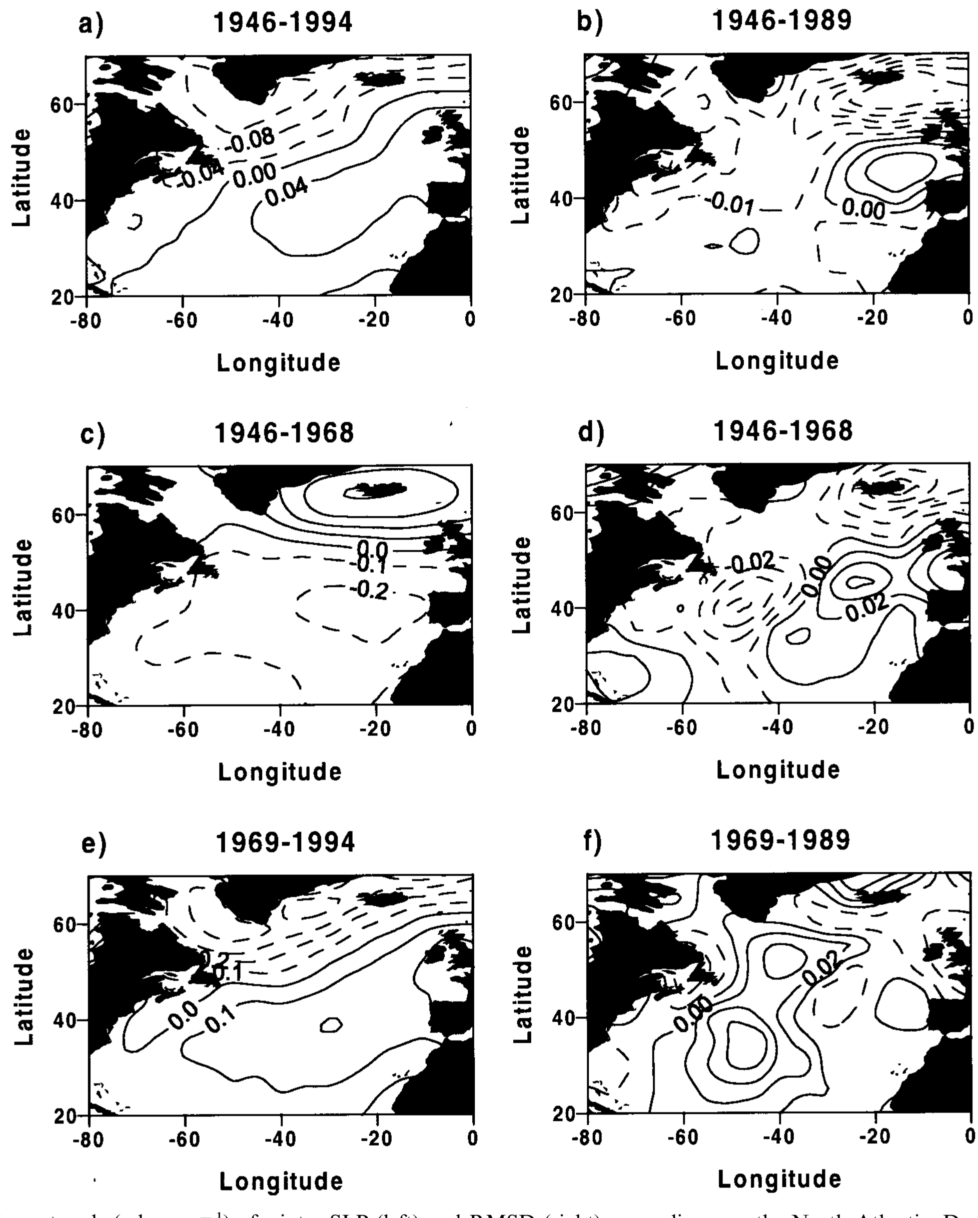

Figure 1. Linear trends (mb year^{-1}) of winter SLP (left) and RMSD (right) anomalies over the North Atlantic. Dashed contours indicate negative trends

The values of trends estimated for two subperiods characterised by a NAO index decrease (1946–1968) and a NAO index increase (1969–1994) are presented in Figure 1(c–f). Obtained trends are sufficiently stronger than those presented in Figure 1(a and b) and statistically significant at levels of 95% or greater. For instance, the values of positive trends in Figure 1(e) are up to five times higher than those presented in Figure 1(a). Maximum values of the estimated trends are 0.4 mb year^{-1} (Figure 1(c)). They demonstrate good agreement between climatic changes of SLP and RMSD, i.e. negative trends of RMSD (Figure 1(d)), that reflect a decrease in the intensity of synoptic processes that are related to a decrease of the NAO index (Figure 1(c)), and positive trends of the RMSD in the central part of the North Atlantic (Figure 1(f)) that are related to an increase of the NAO index (Figure 1(e)). The trends presented in Figure 1(e) are consistent with results of Robertson *et al.* (1998) obtained for 1963–1993. It is noted here that the values of positive trends in Figure 1(f) would be higher if the longer (1969–1994) time period was considered.

The values of estimated trends can depend on the date (year) that divides the time series into two subperiods (in the present study it is 1968–1969). As the choice of this year is rather subjective, to verify the results the calculations have been made for the dates shifted by ± 1 year (i.e. 1967–1968 and 1969–1970). The values of the newly estimated trends (not shown) were very close to those shown in Figure 1(c–f).

3.2. Decadal scale changes

To investigate the main features of decadal scale changes, time–latitude plots of detrended, filtered and zonally averaged North Atlantic anomalies of winter SLP and RMSD were constructed (Figure 2) after low-pass filtering. The actual time periods considered here are 1950–1990 for SLP and 1950–1985 for RMSD. Within this time period, three subperiods have been defined that are characterised by principally different behaviour of the long-term winter SLP anomalies. The first subperiod (1950–1954) is characterised by the domination of the positive winter SLP anomaly, which propagated from low and mid-latitudes to high latitudes of the North Atlantic (Figure 2(a)). Locations of this anomaly at the beginning and the end of considered subperiod are shown in Figure 3. They reveal very strong features of both meridional south–north and zonal west–east propagation of the winter SLP anomaly. This is very close to results obtained by Halliwell (1997) from the analysis of data from COADS.

During the second subperiod (1957–1971), a positive SLP anomaly in high latitudes and a prolonged negative one in lower latitudes are observed. Therefore, this period is characterised by decreased values of the NAO index. There are no obvious propagating features of the anomalies during this subperiod. It is remarkable that during this period anomalies of RMSD (Figure 2(b)) demonstrate both enhanced (1962–1966) and reduced (1967–1971) winter synoptic activity.

The third subperiod (1972–1990) demonstrates the standing patterns of the winter SLP anomalies with a period ('Greenland below' plus 'Greenland above') of about 8 years. As seen in Figure 2, there is no good agreement with related anomalies of RMSD. On the contrary, there are periods with high (1972–1976) and low (1977–1980) values of the NAO index, which are dominated, respectively by the negative and the positive anomalies of RMSD. Results for 1957–1990 are principally different from those presented by Halliwell (1997). The possible reasons for this disagreement will be discussed in the concluding remarks.

It is noted here that anomalies of annual means (not shown), which are considerably weaker than winter anomalies of SLP, demonstrate clear propagating features during the whole time period considered (1950–1990).

As the visual comparative analysis of Figure 2(a and b) has not revealed any certain relationship between anomalies of SLP and RMSD, possible links in terms of correlations with teleconnection patterns were examined. Correlation coefficients between low-passed anomalies of RMSD and low-passed indices of the most prominent patterns of low-frequency variability over the North Atlantic have been estimated. As the EA Jet pattern appears only during the summer season, the analysis has been limited to the NAO and the EA patterns. The EA pattern is structurally similar to the NAO, and consists of a north–south

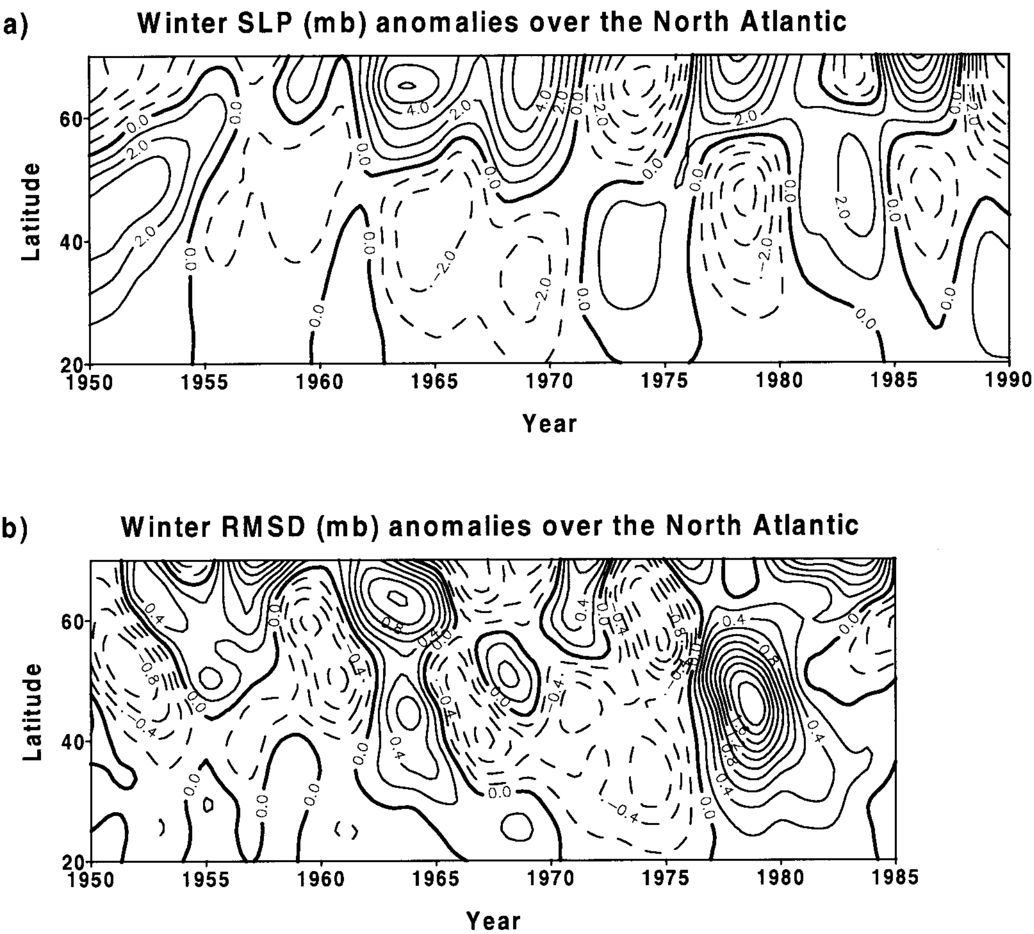

Figure 2. Time–latitude plots of detrended, low-pass filtered and zonally averaged winter anomalies of SLP (a) and RMSD (b). Dashed contours indicate negative anomalies

dipole of anomaly centres, but these anomaly centres in the EA pattern are displaced southeastward. Estimated correlation coefficients are shown in Figure 4. Correlations over most of the North Atlantic are negative both for NAO and EA patterns. For the NAO (Figure 4(a)) maximum negative correlations (up to -0.6) with RMSD are observed in south-western and north-eastern parts of the North Atlantic. Weak

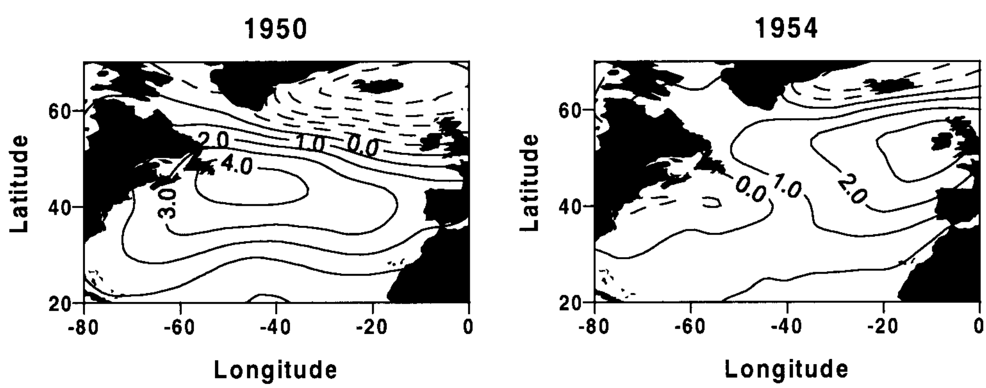

Figure 3. Maps of winter SLP anomalies for 1950 and 1954. Dashed contours indicate negative anomalies

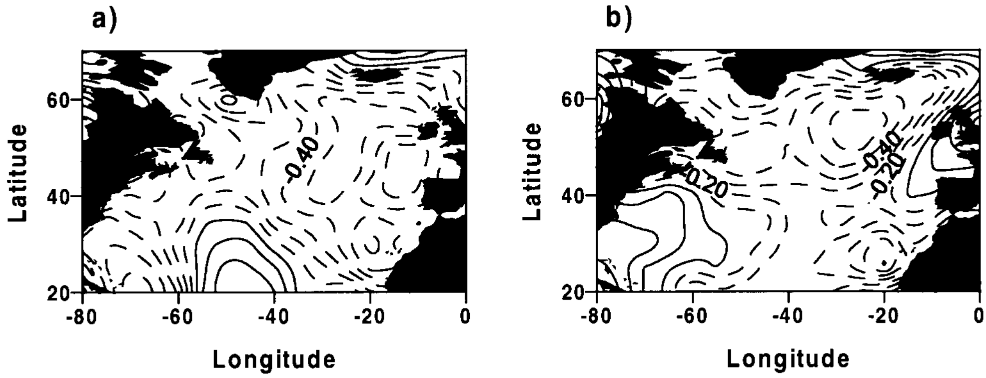

Figure 4. Correlation coefficients between low-passed anomalies of RMSD and indices of (a) NAO teleconnection pattern and (b) EA teleconnection pattern. Dashed contours indicate negative values

positive correlations are located in the central North Atlantic between 20 and 30°N and to the east of Greenland. According to the *t*-test, the correlation coefficients shown are statistically significant at the 95% confidence level in the eastern and the south-western parts of the ocean. In the case of the EA pattern, maximum negative correlations (up to -0.6) are observed along the North Atlantic storm track and to the west of Africa (Figure 4(b)). Correlation coefficients are positive over the British Isles and over western south-western North Atlantic. Correlation coefficients are statistically significant in the regions of their maximum values. Obtained negative correlations between anomalies of RMSD and indices of NAO and EA patterns will be discussed in the concluding remarks.

3.3. Decadally averaged anomalies

To analyse decade-to-decade evolution of the spatial structure of anomalies and their relationships, the anomalies of both winter SLP and RMSD have been averaged decadally for 1951–1960, 1961–1970, 1971–1980 and 1981–1990 (1981–1989 for RMSD). Although this approach is rather formal, it is noted here that the first two of the four decades considered practically coincide with the period of NAO index decrease, and 1971–1990 is the period of the NAO index increase. The spatial distribution of the decadally averaged anomalies of the winter SLP and RMSD is shown in Figure 5.

There are two possible situations concerning distribution of the winter anomalies of SLP and location of related RMSD anomalies. The first one is similar to that obtained for the linear trends (Figure 1), i.e. a high (low) value of the NAO index is associated with a positive (negative) anomaly of RMSD attributed to the North Atlantic storm track area. Another situation is presented by Zorita *et al.* (1992) for shorter time scales. In this case, locations of anomalies of RMSD are the same as those of SLP, and positive (negative) SLP anomalies are associated with reduced (enhanced) intramonthly variability of the atmosphere.

During the first two decades (1951–1960 and 1961–1970), positive anomalies of the winter SLP in high latitudes and negative ones in lower latitudes form meridional dipole-like structures (Figure 5(a and c)). Therefore, this period is characterised by decreased values of the NAO index, and the lowest ones are observed during 1961–1970. Related negative anomalies of RMSD are located in the North Atlantic storm track area (Figure 5(b and d)) and thus correspond to the first of the above described possible situations. Attention is paid here to the remarkable difference in relationships of anomalies during these two decades. While the meridional dipole is located in the western North Atlantic (Figure 5(a)), the negative anomaly of RMSD is observed in the eastern part of the North Atlantic (Figure 5(b)). During 1961–970 (eastern position of dipole), although there is still a negative anomaly in the eastern part of the ocean, the well-pronounced extensive negative anomaly of RMSD appears in the western North Atlantic (Figure 5(c and d)).

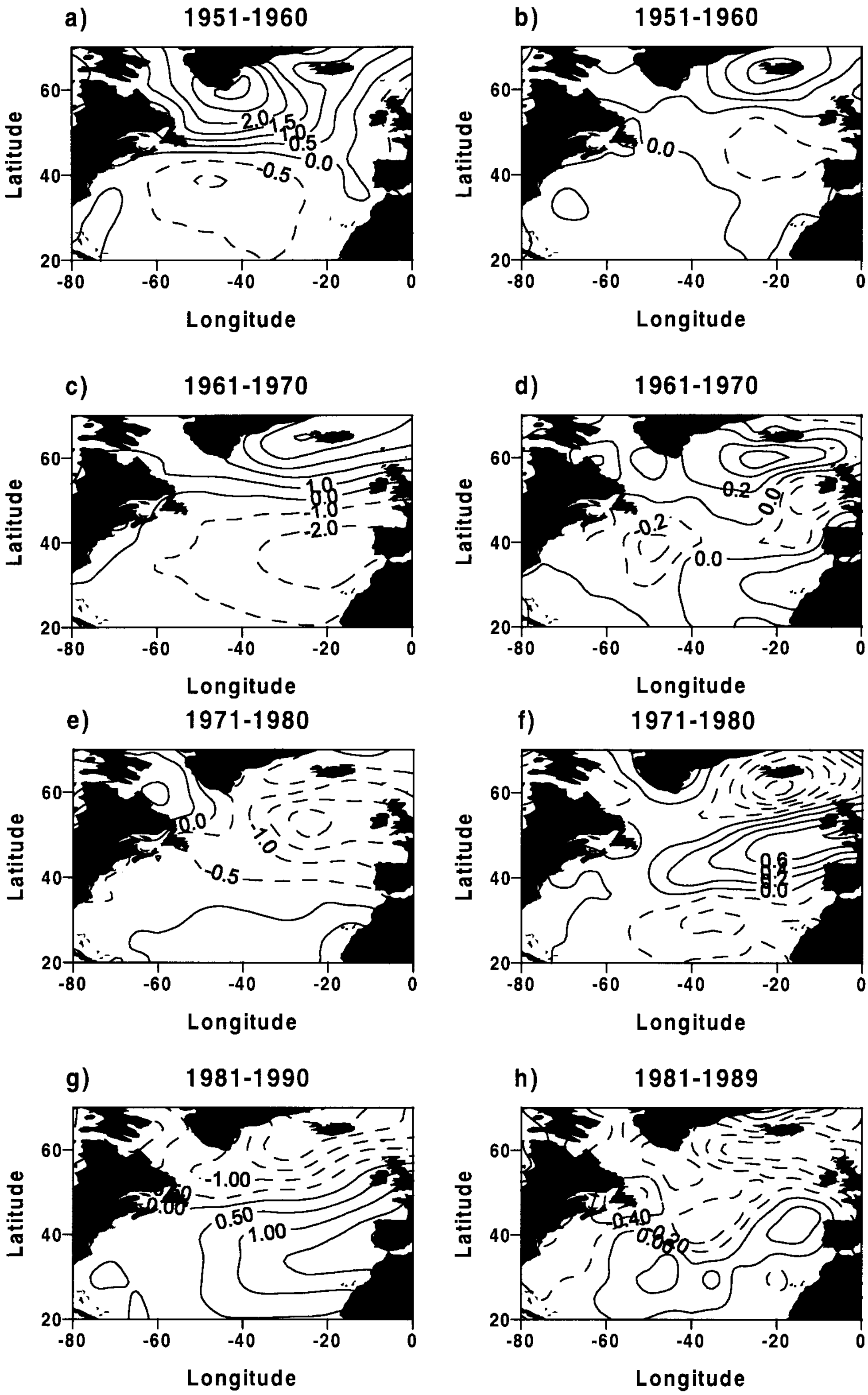

Figure 5. Decadally averaged winter anomalies of SLP (left) and RMSD (right). Dashed contours indicate negative anomalies.

The next two decades (1971–1980 and 1981–1990) are characterised by the reversed polarity of the dipole, i.e. the negative anomalies of the winter SLP, reaching -2 mb, are located in high latitudes and the positive ones (up to $+2$ mb in 1981–1990) in lower latitudes (Figure 5(e and g)). The NAO index is increased. Related positive anomalies of RMSD (maximum is $+0.6$ mb) in 1971–1980 are strongly linked to the North Atlantic storm track and reflect enhanced synoptic activity in this region (Figure 5(f)). During 1981–1990, values of the NAO index are the highest. As seen in Figure 5(h), the positive anomalies of RMSD are located to the south of the climatological North Atlantic storm track position and are not as great as the ones during the previous decade. Most of the storm track area and higher latitudes are occupied by the strong negative anomaly of RMSD, which reflects reduced synoptic activity in the region. The possible interpretation of the relationship of the winter SLP and RMSD anomalies is that during the periods characterised by the very high NAO index, North Atlantic midlatitude cyclones prefer to travel by more southerly tracks than usual. In particular, this is close to the situation described by Rogers (1997), when the Icelandic low is in its normal Denmark Strait location and cyclones move along the more southerly storm track toward the Mediterranean basin. This interpretation should be verified by further studies of the behaviour of individual cyclones during this period.

4. CONCLUDING REMARKS

Decadal and interdecadal changes of the winter SLP over the North Atlantic during 1950–1990 and related changes of the intensity of synoptic processes have been investigated in terms of the linear trends, low-pass filtered and decadally averaged anomalies.

Analysis of linear trends has revealed a very good agreement between interdecadal changes of the winter SLP and changes of the intensity of synoptic processes, i.e. the enhancement of synoptic activity in the central North Atlantic is associated with an increase of the NAO index and *vice versa*.

Low-pass filtered winter SLP anomalies demonstrate both propagating and standing patterns. The last ones have a period of about 8 years. While the propagating anomaly is very close to that obtained by Halliwell (1997), the standing patterns are somewhat different from his results for this time period. This disagreement can result from both data set and filtering technique differences. However, a very good agreement for propagating winter SLP anomalies at the beginning (1950–1954) of the considered time period makes the author believe that the main reason for the later disagreement is a difference between COADS and NCEP data sets. It is noted also that the analysis is extended to 70°N in comparison to that of Halliwell (1997) making winter SLP anomalies in high latitudes more pronounced. The preference of above considered data sets for climatic studies is arguable. Nevertheless, it was found recently that in contrast to COADS, data from NCEP analysis show interdecadal variability that is very similar to that obtained from OWS data (Gulev, 1997).

Analysis of the low-pass filtered and zonally averaged winter RMSD anomalies has not revealed their strong positive linkage to the winter SLP anomalies. Here, enhanced (reduced) synoptic activity can be associated with periods characterised by the low (high) values of the NAO index. Further analysis has shown that at this time scale RMSD anomalies are negatively correlated with NAO and EA indices over the most of the North Atlantic. It is noted here that Rogers (1997) in his study of the North Atlantic storm track variability and its association to the NAO has found that the primary storm track pattern does not suggest a strong storm track link to the NAO. A possible explanation of the relationships obtained can be found in Gulev (1997) and Gulev *et al.* (1998). It was shown that standard deviations calculated for different time scales demonstrate different tendencies. In particular, it was found that during the 1950s and 1960s, short-term synoptic and subsynoptic variability had a tendency of weakening, while the variability at time scales longer than 5–7 days strengthened. In the study, intramonthly RMSDs represent integrated intramonthly variability resulting from the joint effect of the variations of the background flow, synoptic-scale fluctuations, and subsynoptic high-frequency variability. Therefore, intramonthly RMSDs can demonstrate different tendencies of long-term changes depending on the relative role of the above mentioned processes in integrated intramonthly variability. In general, the obtained results suggest positive links between the intensity of winter synoptic processes and anomalies of mean winter SLP fields on an interdecadal time scale. As shown by correlation analysis, such links are negative on a decadal time scale.

Decadally averaged winter SLP anomalies form meridional dipole-like structures of different polarity related to periods of high (low) values of the NAO index. When meridional dipoles are shifted to the west (east) of the North Atlantic, related anomalies of RMSD tend to be located in the eastern (western) part of the region. During the decade characterised by the very high NAO index (1980–1990), positive anomalies of RMSD are located to the south of the North Atlantic storm track area. The assumption is made that during this decade North Atlantic cyclones tended to travel by the more southerly tracks than usual. Further studies of the behaviour of individual cyclones during this period are needed to verify this assumption.

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REFERENCES

Barnett, T.P. 1984. 'Long-term trends in surface temperature over the oceans', *Mon. Wea. Rev.*, **112**, 303–312.

Bendat, J.S. and Piersol, A.G. 1966. *Measurement and Analysis of Random Data*, J. Wiley and Sons, 390 pp.

Carleton, A.M. 1988. 'Meridional transport of eddy sensible heat in winters, marked by extremes of the North Atlantic oscillation, 1948/49–1979/80', *J. Clim.*, **1**, 212–223.

Deser, C. and Blackmon, M.L. 1993. 'Surface climate variations over the North Atlantic Ocean during winter: 1900–1989', *J. Clim.*, **6**, 1743–1753.

Gulev, S.K. 1995. 'Long-term variability of sea-air heat transfer in the North Atlantic Ocean', *Int. J. Climatol.*, **15**, 827–852.

Gulev, S.K. 1997. 'Climate variability of the intensity of synoptic processes in the North Atlantic midlatitudes', *J. Clim.*, **10**, 574–592.

Gulev, S.K., Jung, T. and Ruprecht, E. 1998. 'Interannual and seasonal changes in the intensities of the North Atlantic synoptic scale variability', *J. Clim.* (submitted).

Halliwell, G.R. 1997. 'Decadal and multi-decadal North Atlantic SST anomalies driven by standing and propagating basin-scale atmospheric anomalies', *J. Clim.*, **10**, 2405–2411.

Hurrell, J.M. 1995. 'Decadal trends in the North Atlantic oscillation: Regional temperatures and precipitation', *Science*, **269**, 676–679.

Kushnir, Y. 1994. 'Interdecadal variations in North Atlantic sea surface temperature and associated atmospheric conditions', *J. Clim.*, **7**, 141–157.

Lamb, P.J. and Peppler, R.A. 1987. 'North Atlantic oscillation: Concept and an application', *Bull. Am. Meteorol. Soc.*, **68**, 1218–1225.

Palmer, T.N. and Sun, Z. 1985. 'A modelling and observational study of the relationship between sea surface temperature in the north-west Atlantic and the atmospheric general circulation', *Q. J. R. Meteorol. Soc.*, **111**, 947–975.

Robertson, A.W., Ghil, M. and Latif, M. 1998. 'Low-frequency variability due to a North Atlantic sea surface temperature anomaly in an atmospheric general circulation model', *J. Atmos. Sci.* (submitted).

Rogers, J.C. 1984. 'The association between the North Atlantic Oscillation and the Southern Oscillation in the Northern Hemisphere', *Mon. Wea. Rev.*, **112**, 1990–2015.

Rogers, J.C. 1997. 'North Atlantic storm track variability and its association to the North Atlantic Oscillation and climate variability of Northern Europe', *J. Clim.*, **10**, 1635–1647.

van Loon, H. and Rogers, J.C. 1978. 'The seesaw in winter temperatures between Greenland and Northern Europe. Part I: General description', *Mon. Wea. Rev.*, **106**, 296–310.

Walker, G.T. 1924. 'Correlations in seasonal variations of weather IX', *Mem. Ind. Meteor. Dept.*, **24**, 275–332.

Walker, G.T. and Bliss, E.M. 1932. 'World weather V', *Mem. R. Meteorol. Soc.*, **44**, 53–84.

Wallace, J.M., Smith, C. and Jiang, Q.-R. 1990. 'Spatial patterns of atmosphere/ocean interaction in the northern winter', *J. Clim.*, **3**, 990–998.

Zveryaev, I.I. and Razoryonova, O.A. 1997. 'A comparative analysis of characteristics of sea level pressure and 500 hPa heights seasonal cycles in the Northern Hemisphere', *Meteorol. Hydrol.*, **1**, 27–36.

Zorita, E., Kharin, V. and von Storch, H. 1992. 'The atmospheric circulation and sea surface temperature in the North Atlantic area in winter: Their interaction and relevance for Iberian precipitation', *J. Clim.*, **5**, 1097–1108.

