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Synoptic and subsynoptic variability in the North Atlantic as revealed by the Ocean Weather Station data

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ABSTRACT

Surface meteorological records from Ocean Weather Stations are used to characterise interannual changes in the intensity of synoptic and subsynoptic processes over the North Atlantic mid-latitudes during the period from early the 1950s to 1990s. Individual 3-hourly data were filtered to separate ultra-high frequency variability (0–2 days) and synoptic scale variability (2–6 days). Joint consideration of the intensities at these 2 scales in mid-latitudes makes it possible to construct parameters which are highly correlated with the North Atlantic Oscillation index. In high latitudes, intensities of synoptic and ultra-high-frequency processes are strongly negatively correlated on interannual and decadal time scales. This phenomenon is discussed in the context of interaction between high and mid-latitudinal synoptic variability.

1. Introduction

Intensities of synoptic processes are as important as the monthly means for the understanding of the observed changes in the atmospheric circulation over the north Atlantic mid-latitudes. Interannual variations of the monthly means and intramonthly statistics may not be necessarily correlated. Moreover, different scales of synoptic variability can demonstrate different climatic tendencies. Recently, Ayrault et al. (1995) depicted the north Atlantic ultra-high frequency variability (UHFV), which was first found by Blackmon et al. (1984). UHFV is associated with the smaller than 1.5-day processes, and has the maximum, usually located downstream from the maximum of the synoptic scale variability (SSV), traditionally associated with the 2 to 6 days range (Ayrault et al., 1995). Gulev (1997), using Ocean Weather Stations (OWS) surface data from the late 1940s to early 1970s, showed that the long-term changes in the intramonthly variances of meteorological parameters are different for the original 3-hourly data and for the low-passed, with 72-h window, records. Considering interannual changes in the intensities of synoptic processes, we can better depict the North Atlantic Oscillation (NAO) associated with the strengthening and weakening of the zonal circulation in the north-east Atlantic (Van Loon and Rogers, 1978; Lamb and Peppler, 1987; Barnston and Livezey, 1987; Hurrell, 1995), and characterised by the sea-level-pressure (SLP) gradient between the normalised winter anomalies for the Azores high and Iceland low (NAO index) (Rogers, 1984; Hurrell, 1995). Although the NAO index accounts for the monthly mean parameters, it should have a reasonable link to the changes in the synoptic activity in the north Atlantic mid-latitudes. Recent analyses of cyclone frequencies (Schinke, 1993; Stein and Hense, 1993; Lambert, 1996) indicate changes in the number of the north Atlantic extratropical cyclones similar to those seen in the NAO index. On the other hand, there is a complicated nature beyond the NAO index, and it may not be necessarily successfully

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described in terms of SLP differences between the main north Atlantic centers of actions. Particularly, Rogers (1997) found weak correlation between the NAO index and variability of the storm track pattern in the north Atlantic. In this study, we use high-quality instrumental data in order to depict the long-term variability in the synoptic intensities over the north Atlantic midlatitudes for the period from the early 1950s to the late 1980s, which covers the development of primarily anticyclonic conditions in the 1950s and 1960s, the transition to the cyclonic conditions in the early 1970s, and the dramatic strengthening of the zonal circulation over the last 2 decades (Kushnir, 1994; Hurrell, 1995).

2. Data and methods

We used 3-hourly data from the 4 mid-latitudinal OWS (C, I, L, M) in the north Atlantic, which provide the records for the period from the 1950s to early 1990s. These are high-quality instrumental measurements, which are very complete and practically free of inhomogeneities inherent in the other data. Although these data are taken in only few locations, they have some advantages for the study of synoptic and subsynoptic variability in comparison with reanalyses, voluntary observing ship (VOS) data, and storm counts. Atmospheric analyses and recently-available reanalyses (Gibson et al., 1997; Kalnay et al., 1996) provide nearly global coverage, but have 6- to 12-h resolution, that results in the cut-off of a part of the UHFV. Intramonthly statistics for the VOS data, available from the COADS (comprehensive ocean-atmosphere data set) (Woodruff et al., 1998) account for the joint effect of the natural synoptic and error variance, and there is no way to distinguish these. Particularly, Zorita et al. (1992) used COADS statistics to study the interaction between the SLP and SST fields in the north Atlantic, and found a pronounced pattern in the intramonthly SLP variance in the north-east Atlantic, where the number of reports (and respectively error variance) indicate year-to-year changes within the range of 100%, that may affect the conclusions. Moreover, the VOS data provide the possibility to study the total intramonthly variance only. Cyclone counts are very useful for the description of synoptic processes, but might be influenced by the questionable quality of the weather maps and historical changes in the analysis technique (Agee, 1991; Ueno, 1993; Von Storch et al., 1993).

Fig. 1 shows the locations of OWSs, and periods of observations. The locations of OWS I and L are shifted from each other by only 200 km, and we have merged the data from these OWS to provide the time series of a climatic continuity. Locations of OWSs in Fig. 1 are overplotted by the frequencies of cyclones for the 2 selected winters, characterised by primarily blocking (1969) and zonal (1993) conditions. Cyclone counts were derived from the 6-hourly SLP data of the NCEP/NCAR reanalysis. With respect to the pathways of the atmospheric synoptic transients, the arrangement of OWS C, I/L, and M fit well with the necessity to depict both SSV and

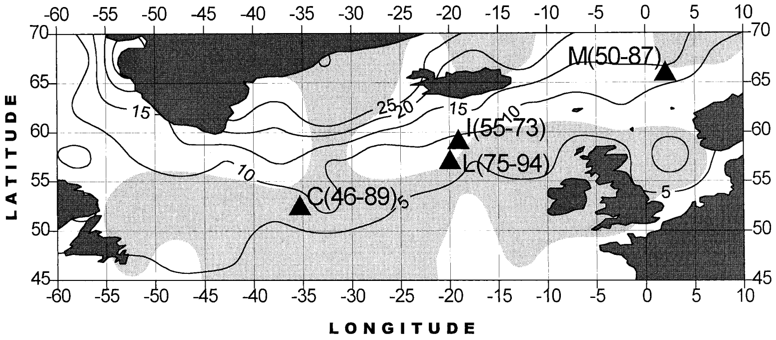

Fig. 1. Geographical locations of the north Atlantic OWSs used in this study and periods of observations at these OWSs. Solid contours show cyclone frequency (per 5° × 5° box) for the winter with primarily zonal conditions (1993); grey shading corresponds to the frequency higher than 10 cyclones during the winter with primarily blocking conditions (1969).

UHFV in the north Atlantic mid-latitudes. OWS C is influenced by synoptic transients in both zonal and blocking regimes (Ayrault et al., 1995; Hannachi and Legras, 1995), OWS I/L has to depict UHFV under the zonal regime, but it is also characterised by relatively high SSV, and the location of OWS M accounts for the propagation of synoptic disturbances to the North Europe.

To separate the SSV and UHFV, original 3-hourly records were filtered with low-pass and band-pass filters. We used the Lanczos filter (Lanczos, 1956; Duchon, 1979), which provides a very effective cut-off of the selected frequency in comparison with, say, the running mean or Tukey filtration. Gibbs oscillations created by the Lanczos filtering can be effectively reduced by the smoothing in the frequency range (Duchon, 1979). For every OWS and for every winter (December–February), 90 to 91 days' series of 3-hourly measurements were analysed by using spectral analysis and filtering procedures. To eliminate intraseasonal variations with the scale greater than 1 month, we have applied a 4-order polynomial detrending to the initial 3-monthly series. In practice, results do not depend strongly on this procedure, because 30- to 60-days variability is less pronounced in our data in comparison with the SSV and UHFV. To ensure the appropriate selection of the boundary between the UHFV and SSV, as well as between SSV and the background flow, we made calculations for all possible ranges with the limits varying from 1.5 to 2.5 days (UHFV), and from 5 to 7.5 days (SSV). Results of all runs made for the 45 possible combinations of limits are highly correlated with each other with seldom exceptions for OWS M in the 1980s. Although, the absolute values of standard deviations (SD) are reasonably different for different limits, application of a *t*-test could not pick up any differences in interannual variability patterns from one run to another. Thus, we used time ranges 6–48 h and 2–6 days, in agreement with Ayrault et al. (1995). Synoptic and subsynoptic variabilities were characterised by the SD of the decomposed series for every individual winter, which were then taken for the analysis of interannual variability.

3. Results

Figs. 2a–c shows interannual changes in the UHFV and SSV for the 3 locations in the north Atlantic during the periods of observations. OWS C does not demonstrate pronounced secular changes in SSV from the late 1940s to early 1970s, but shows weakening of the UHFV for this period. During the period from the mid-1970s to the late 1980s, there was a strong increase of both SSV and UHFV that is consistent with the intensification of zonal regimes over these 2 decades (Kushnir, 1994; Hurrell, 1995). The long-term behaviours of SSV and UHFV at OWS I/L are similar to those found for OWS C. Different scales of atmospheric synoptic variability may not be necessarily characterised by similar interannual behaviour of the intensities and can demonstrate different patterns of climate variability. If we consider linear tendencies, SSV at OWS C during 1946–1971 (primarily anticyclonic conditions) demonstrates slightly positive changes in contrast to a significantly downward tendency of approximately 0.25 mb/decade in UHFV. This disagreement is also visible for OWS I/L from the late 1950s to the early 1970s. Correlation between SSV and UHFV for this time period is small and insignificant for both OWS C and I/L. Alternatively, for the period from the late 1970s to 1990s, there are strong upward changes in UHFV and SSV for both mid-latitudinal locations. Correlation between UHFV and SSV for this period is 0.73 for OWS C and 0.65 for OWS I/L, and it increases up to 0.78 and 0.74 if the linear trends are removed from the time series. Short-period interannual variability at OWS C and I/L is represented by 2–4 year oscillations, which are visible on spectral functions (not shown here), although the continuity of series does not allow us to discuss them with confidence.

OWS M shows the changes in UHFV and SSV, which are nearly out of phase on both interannual and interdecadal scales. The correlation coefficient between the intensities of UHFV and SSV is -0.56 and becomes even more pronounced (-0.72) when the long-term changes are removed from the series. Fig. 3 shows normalised anomalies of the spectral power of the SLP for every individual winter from 1950 to 1987. These anomalies were computed as

$$S'(\omega) = [S(\omega) - \langle S(\omega) \rangle]/\sigma[S(\omega)], \tag{1}$$

where $S(\omega)$ is the spectral power at the frequency ω, $\langle S(\omega) \rangle$ is averaged over 37 winters' spectral power at this frequency, and $\sigma[S(\omega)]$ represents

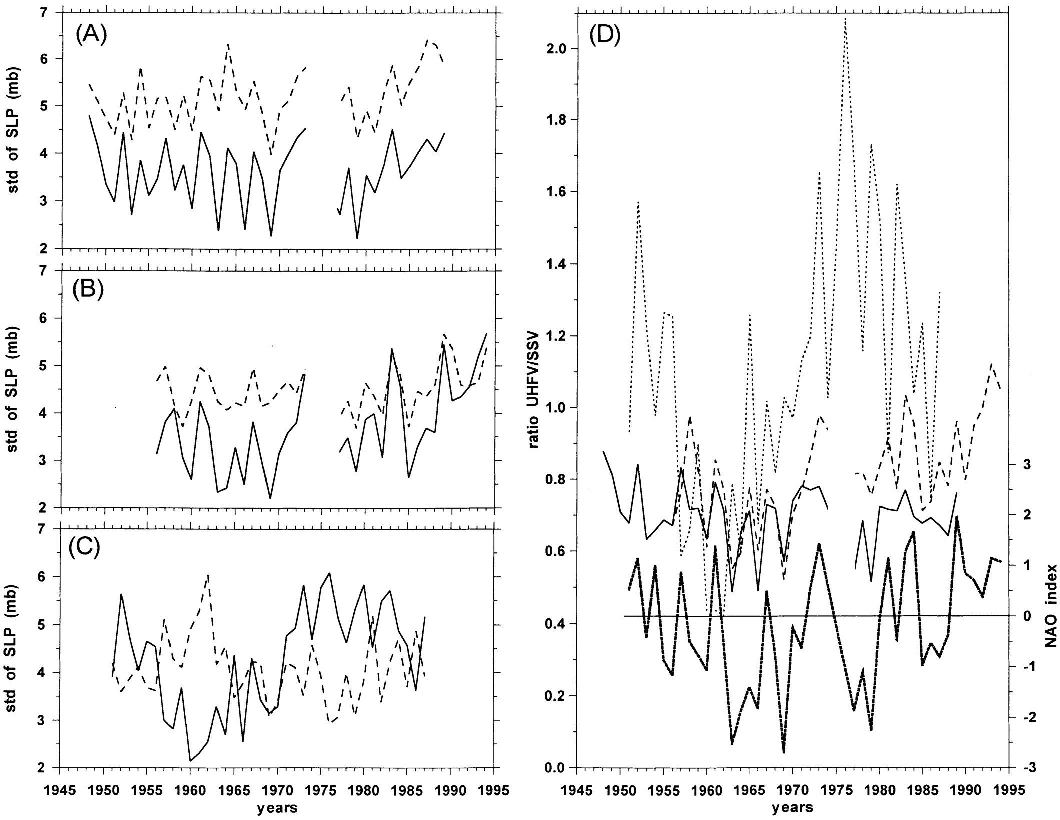

Fig. 2. Climatological time series of the SD of UHFV (solid lines) and SSV (dashed lines) for OWSs C (A) I/L (B), and M (C); D — interannual variability of the ratio between UHFV and SSV for OWSs C (solid line), I/L (dashed line), M (thin dotted line), and the NAO index (thick dotted line).

the SD of the estimates of spectral power at this frequency. The period from the mid-1950s to the late 1960s is characterised by the positive spectral anomalies in the synoptic interval and by primarily negative anomalies in the subsynoptic range. Alternatively, during the period of the 1970s and 1980s, positive spectral anomalies are observed in the UHFV range, and the SSV is characterised by decreased spectral power. Even within the SSV range, comparing the periods of the 1950s–1960s and 1970s–1980s, we can conclude that there has been a tendency of a shift of spectral maximum from the frequencies corresponding to the periods 4–6 days in the 1960s to somewhat a higher frequency range (2–4 days) in the 1970s and 1980s.

At OWS C and I/L, UHFV and SSV have their origin in the mid-latitudinal flow for both zonal and blocking regimes. OWS M is strongly influenced by the polar lows which have time scales smaller than for the mid-latitudinal cyclones and are sometimes considered as "Arctic hurricanes" (Emanuel and Ratunno, 1989; Rasmussen, 1985). These highly transient systems may contribute to a high-frequency variability range. Intensification of polar lows can occur, when the SLP pattern with centres of actions located over the Bay of Biscay and Barents Sea is intensified. Rogers (1997) showed that this pattern does not have any strong links to the NAO. Under the blocking regime, the Norwegian Sea is partly under the influence of the northward propagating mid-latitudinal cyclones from the central Atlantic and the Arctic pressure systems. Under the zonal regime, the UHFV in the Norwegian Sea results from the high-frequency variability associated with the polar lows rather than from the synoptic scale

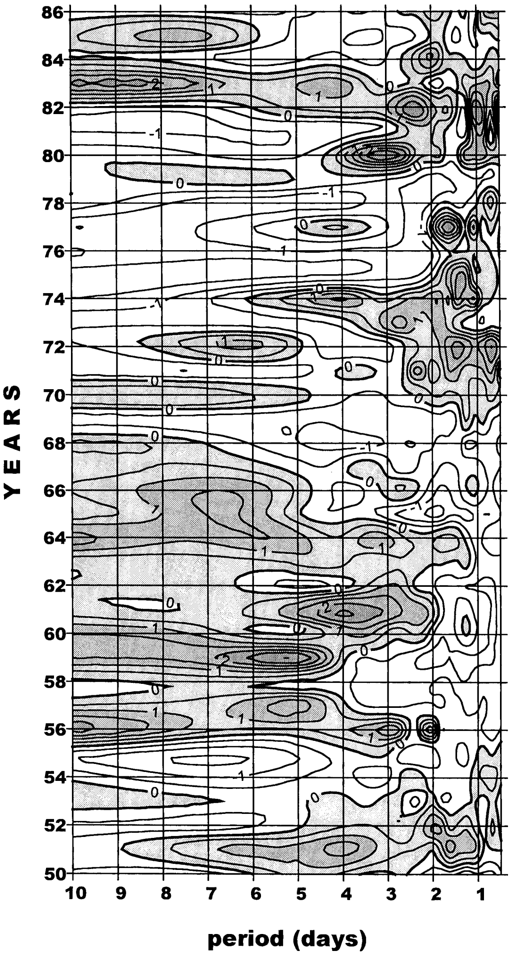

Fig. 3. Interannual variability of the "spectral anomalies" of the winter SLP for OWS M.

transients in the north-east Atlantic, which generate the associated maximum of the UHFV aligned south of the location of OWS M. During the Greenland anticyclone regime, highly transient polar lows propagating from Greenland to the east (Serreze and Barry, 1988), mainly contribute to the UHFV in the Norwegian Sea, and the impact of the Atlantic SSV is weakened, and is out of phase with the polar lows intensity. Thus, under all circulation regimes, we can expect that the UHFV in the Norwegian Sea has an origin which is different from the north Atlantic storm track, and can behave out-of-phase with the mid-latitudinal synoptic activity (Fig. 2c).

4. Discussion and conclusions

Analysis of the OWS data demonstrates that surface meteorological records can be effectively used to characterise synoptic and subsynoptic variability in the north Atlantic mid-latitudes. Although they do not depict spatial patterns of variability, they may help to quantify intensities of the processes on different synoptic time scales, due to better temporal resolution and higher accuracy of purely in-situ measurements, which are not influenced by the model as any kind of reanalyses or operational analyses.

Joint parameters of SSV and UHFV in the north Atlantic mid-latitudes can be effectively used to characterise changes in the mid-latitudinal circulation associated with NAO. Fig. 2d shows interannual changes of the ratio between the SD in the UHFV and synoptic-scale variability ranges, as well as the NAO index for the 3 winter months (December–February), taken from Hurrell (1995). For OWS C and I/L, this ratio varies from 0.5 to 1.1. During the late 1950s and 1960s, which are characterised by primarily anticyclonic conditions over the north Atlantic, ratios for OWS C and I/L are very close to each other. For the last 2 decades, they are less correlated and the ratio for OWS I/L is around 30 to 50% higher than for the OWS C. If we consider the intensity of the SSV computed from the OWS C and I/L records in the north Atlantic, it is not highly correlated with the NAO index, which is based on monthly mean values and does not account directly for the synoptic variability. Correlation coefficients for SSV are equal to 0.3 and 0.56 at OWS C and I/L, respectively. Correlation between the NAO index and the intensity of UHFV is higher and gives the coefficient values 0.62 for OWS C and 0.66 for OWS I/L. However, the highest correlation with NAO is obtained for the ratio between the intensities of UHFV and SSV (Fig. 4). Correlation coefficients are 0.74 for OWS C and 0.78 for OWS I/L, and both are significant at the 95% level. Enhanced SSV in the central and eastern mid-latitudinal north Atlantic can exist not only under the dominating zonal regime, but also during the blocking and Greenland anticyclone regimes, characterised by the relatively slow propagating systems of large magnitude which are not necessarily correlated with the NAO index. However, only intensification of the zonal flow is associated with

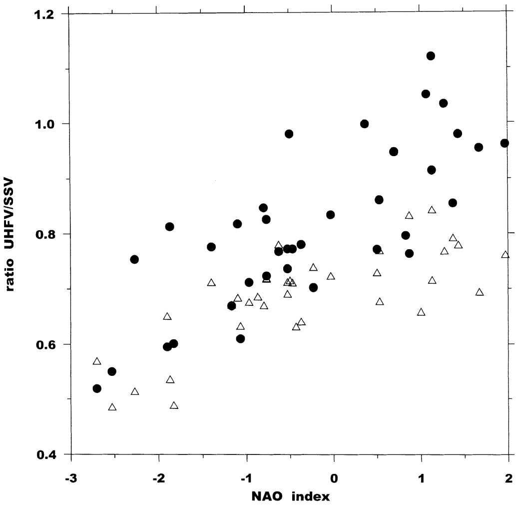

Fig. 4. Scatter plot of the NAO index and the ratio between the intensities of UHFV and SSV for OWS I/L (circles) and C (open triangles).

the enforced highly transient variability at the eastern end of the mid-latitudinal storm track, that is taken into account by the ratio between SSV and UHFV SD.

OWS M shows pronounced negative correlation between the SSV and UHFV on both interannual and decadal time scales. Decrease of the intensity of SSV during the period from the early 1970s to late 1980s, shows that NAO-related changes in the zonal flow may not necessarily be correlated in the north-east Atlantic and Norwegian Sea. If we assume that in high latitudes, variability in the time range 0–2 days may have an origin which is somewhat different from mid-latitudinal zonal flow and is probably associated with rapidly propagating polar lows, this fact is consistent with the cyclone counts published by Serreze et al. (1997). They show that the cyclone counts in the north Atlantic mid-latitudes north and south of 60N are out of phase during the period from 1966 to 1993, and that the number of polar lows increased strongly in the 1970s and 1980s. In other words, in mid-latitudes, UHFV as highlighted by Ayrault et al. (1995), serves as an effective additional characteristic of synoptic activity which has its origin in the instability of the same zonal flow, which is responsible for the synoptic scale transients. In high latitudes, UHFV may have 2 origins, associated with synoptic scale transients propagating from mid-latitudes, and with the fast polar lows, the intensity of which is out of phase with the intensity of mid-latitudinal synoptic activity. Therefore, one has to be careful to apply to the UHFV patterns in the high latitudinal regions, the concept of UHFV derived from the consideration of mid-latitudinal zonal flow.

It is a reasonable question to ask whether the relationships obtained are stable with respect to the selection of the winter season. We used the 3-month period from December to February, which is considered to represent well the winter conditions (Hurrell, 1995). Analysis of the cold periods combined from different sequential months from November to March shows relatively high correlation (0.82 to 0.88) between November–January and December–February data, as well as between the time series for December–February and January–March for both the SSV and UHFV parameters. However, correlation between the periods November–January and January–March is relatively low (0.4 to 0.52), and for OWS C underpredicts the level of significance. This problem has to be discussed in terms of the seasonality of long-term climate variability, which affects many climate parameters, including the NAO index itself (Shabalova and Weber, 1998; Jung and Ruprecht, 1999). In general, it is reasonable to assume that the characteristics of interannual variability will be dependent on the selection of season, even within the so-called cold period from November to March. On the other hand, this does not mean that the character of the relationships between the intensities of synoptic activity and the NAO index will be changed, because the NAO index will also be influenced by the seasonality (Jung, 2000).

Gridded data available from the reanalyses projects of NCEP and ECMWF give the possibility of more comprehensive investigations of the spatial patterns in the atmospheric synoptic and subsynoptic statistics. In this context, our work gives us the possibility to compare results from numerical weather prediction systems to in-situ data, if only in a few locations of the north Atlantic.

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