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The influence of the North Atlantic Oscillation on the regional temperature variability in Sweden: spatial and temporal variations

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ABSTRACT

A statistical analysis of the seasonal and interannual variations in the regional temperature anomalies of Sweden during 1861–1994 is performed. The study uses homogenized monthly temperatures averaged over 6 regions to minimize the non-climatic and local-scale climatic effects. It is found that the temperature variability shows a clear regional and seasonal dependency. The topography, the influence of the sea and the synoptic climatology may have determined the dependency. The anomaly is related to variations in the North Atlantic Oscillation (NAO) expressed by an index (NAOI) and the extent to which the temperature anomaly can be explained by the NAO is investigated. The results show that the NAO has an important effect on the regional Swedish temperature on the monthly and interannual scales. The relationship between the temperature and NAOI over the period 1985–1994 are strong, implying that the NAOI may be a suitable candidate for a statistical downscaling model of the regional temperature. However, correlation analysis over different 31-year periods shows that the strength of the association varies with time and region. The further north the weaker the association. On the other hand, the temporal variations of the moving correlations for the 6 regions are similar. Part of the temporal variations may be explained by the averaged strength of NAO during different 31-year periods. This is especially evident for southern Sweden. At last, the coherency spectrums between the temperature anomalies and the NAO index is determined, which enables an examination of the association over the frequency domain. The result supports the idea that the NAO has an important effect on the Swedish temperature, though the strength of the association varied with time. These results have implications for statistical downscaling.

1. Introduction

Within the framework of the Swedish Regional Climate Modeling Program (SWECLIM), there is an ongoing effort to examine linkages between regional climate in Sweden and large scale climate. Analysis of monthly temperature variability is a part of the effort. The documentation of temperature variations in Sweden started relatively early. Wargentin (1778) used monthly air temperature series from Stockholm (59°20′N, 18°03′E), beginning in 1756, and Uppsala (59°51′N, 17°37′E), beginning in 1722, to study climatic changes and variations. Additional studies of the Stockholm series were performed by Öfverbom (1808), Hamberg (1906), Brunt (1937), Liljequist (1943, 1949) and Wallén (1953, 1965). Bergström (1990) analyzed the Uppsala series and compared the monthly and yearly temperatures between 1722–1751 with the present day mean temperatures. Recently, the temperature records of

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Stockholm and Uppsala were homogenized by Moberg and Bergström (1997). A general description of variations and long-term changes in the series has also been made (Moberg and Bergström, 1997).

The first analysis of spatially averaged temperature series was made by Alexandersson and Eriksson (1989). Homogeneity tested temperature series from 5 stations in northern Sweden and 5 stations in southern Sweden were used to construct two averaged series for the two parts of Sweden for the period 1860–1987. The results show a high frequency of cold winters during the period after around 1930. The suggested explanation is a weakening of the westerly winds during that period, supported by a noted weakening of the pressure gradient between northern and southern Sweden.

Moberg and Alexandersson (1997) included homogenized temperature series from 132 stations, mainly in Sweden but also in Denmark, Norway and Finland, in the construction of six averaged air temperature anomaly series for the period 1861–1994 for Sweden. The temperature series were also adjusted with respect to urban warming trends. In a study of long-term trends, comparisons of the mean temperatures for the periods 1861–1890 and 1965–1994 indicate a significant positive change of the annual, spring and autumn temperatures between the 2 periods (Moberg and Alexandersson, 1997).

The temperature anomaly series can be considered as means for six $5^\circ \times 5^\circ$ regions covering the whole Sweden and enable analyses of regional variations, and are therefore suitable in studies in which local temperature patterns are of minor interest. The anomaly series will be used in this study which aims to identify regional differences in interannual and interdecadal monthly temperature variations in Sweden.

Sweden is positioned in the northern mid-latitudes and the temperature fluctuations are strongly governed by variations in air-mass advection (Rogers, 1985; Kozuchowski, 1993; Jönsson and Bärring, 1994; Hurrell, 1995; Jönsson and Holmquist, 1995; Johansson et al., 1998). The North Atlantic Oscillation, which is characterized by a quasi-cyclic mass alternation between the subpolar and subtropical parts of this region (Lamb and Peppler, 1987), significantly affects the advection, and hence the temperature in Europe (Van Loon and Rogers, 1978; Rogers and Van Loon, 1979; Hurrell, 1995) and climate in other parts of the world (Malmgren et al., 1998). As the NAO is the major mode of sea level pressure (SLP) variability in the North Atlantic sector, accounting for more than one-third of the total variance during winter months December, January and February (Wallace and Gutzler, 1981; Barnston and Livezey, 1987; Cayan, 1992), the connections may be of great importance in terms of predictability of the Swedish temperature.

The state of the NAO can be reflected by so-called NAO indices. Several such indices have been suggested and used (Rogers, 1984; Hurrell, 1995; Jones et al., 1997). The indices aim to capture the opposite variations in sea level pressure in the regions near the Azores high and the Icelandic low. The availability of long series of SLP instrumental observations has to a large extent controlled the development of the NAO indices. Data of SLP at Ponta Delgada, Azores and Akureyri, Iceland were used by Rogers (1984) to create an index which covers the period from 1894. The Akureyri data have later been replaced by data from Stykkisholmur, Iceland. Hurrell (1995) extended the index with another 30 years by using the SLP data from Lisbon, Portugal and Stykkisholmur. Jones et al. (1997) produced a new NAO index with an even longer temporal coverage (1823–1996) by substitution of the Lisbon SLP data with data from Gibraltar.

A positive relationship between the NAO and the Northern European/Scandinavian temperature has been pointed out by Rogers (1985) and Hurrell (1995). In those studies only a few Swedish stations are used. This study seeks to examine the connection between the NAO and the regional Swedish temperature in more detail and to investigate how it varies in time and space. Therefore the averaged regional temperature series including 132 stations are used. Focus is placed on the relationship between the NAO and temperature fluctuations in Sweden on monthly and interannual scales. The data sets used are described in Section 2. In Section 3, the variability of the NAO index and the temperature anomalies are described. Seasonal differences in variability and monthly persistence are examined as well as the differences between the 6 regions. Furthermore, the relationship between the temperature anomalies and the NAO index (Lisbon–Stykkisholmur) is evaluated. A summary and conclusions are given in Section 4.

2. Data and methods

The temperature data set consists of monthly temperature anomaly series representative of six 5° × 5° grid boxes (Moberg and Alexandersson, 1997). Since the monthly means are subtracted, the annual cycle of the temperature variation is to a large extent removed. The series cover the period 1861–1994 and the reference period is 1961–90. The six series represent the temperature anomalies for south-western (SW; stretches from 55°N 10°E to 60°N 15°E), south-eastern (SE; 55°N–60°N, 15°E–20°E), middle-western (MW; 60°N–65°N, 10°E–15°E), middle-eastern (ME; 60°N–65°N, 15°E–20°E), north-western (NW; 65°N–70°N, 15°E–20°E) and north-eastern Sweden (NE; 65°N–70°N, 20°E–25°E). It should be noted that there can be rather large differences in climate within the boxes, especially with respect to continentality. However, to some extent this is a desired effect for this study which focuses on regional scale variability. The results of the analyses should therefore be regarded as an averaged response of the regional climate.

Variability depends on the time scale considered and several measures of it have been suggested (Gibbs et al., 1978). The most frequently used is standard deviation (SD). Another measure is the absolute values of the anomalies. While SD describes mean variations around the mean over a certain period of time, the absolute values of the anomalies are more useful and straightforward in describing month-to-month variations. Since they can be directly translated to deviations from the mean, the variability of the regional temperature is here illustrated by this measure. If this measure is averaged over a period of time the mean is proportional to SD over the period.

A measure of the NAO is the NAO index (NAOI), which is based on the normalized sea level pressure difference between Lisbon, Portugal, and Stykkisholmur, Iceland, (Hurrell, 1995) and the monthly series are available for the period 1865–1994. The SLP anomalies at each station are normalized by division of each monthly pressure by long-term (1965–1994) standard deviation. This index will be used in this work to study the impact of the NAO on Swedish temperature anomalies. Monthly and annual correlation coefficients are calculated and their seasonal differences are discussed. Note that the index describes the pressure variation with respect to the standard deviation and is thus dimensionless.

To investigate the evolution of the connections between the NAOI and temperature anomaly, 31-year moving correlations are calculated. This is done by sliding a window along two time series and for each position of the window, Pearson's correlation coefficient is calculated for all observations within the window. The resulting correlation coefficient is assigned to the center point of the window. The window size is 31 years and the window is moved in one year steps.

To evaluate the use of NAOI as a measure of the strength of the westerlies over Sweden in summer, the index is compared with zonal indices for July. The zonal indices were calculated as the difference between the monthly means of the sea level pressure (SLP) along the latitude circles 40°N and 70°N, for a westerly area between 40°W and 5°W, and an easterly between 0° and 40°E. The gridded SLP data, received from the National Center for Atmospheric Research Data Support Section, USA, has a spatial resolution of 5° × 5° and covers the period 1899–1997.

3. Analysis and discussion

3.1. *Temperature variability*

An examination of the monthly temperature anomalies for the 6 regions shows that the month-to-month fluctuation is very important and there are clear seasonal differences in the variability. The maximum monthly absolute anomaly values for SW and SE are equal (7.7°C) while there are some east–west differences in middle (MW is 9.5°C and ME 8.9°C) and north Sweden (NW 10.2°C and NE 12.8°C).

To characterize the regional and seasonal differences in the variability, the mean of the absolute values of the anomalies are calculated for every calendar month and region. The results are shown in Fig. 1. The mean absolute values of the anomalies during the warm period (April to September) are relatively low and fairly constant, while the cold period (October to March) shows a varying and relatively high variability with the

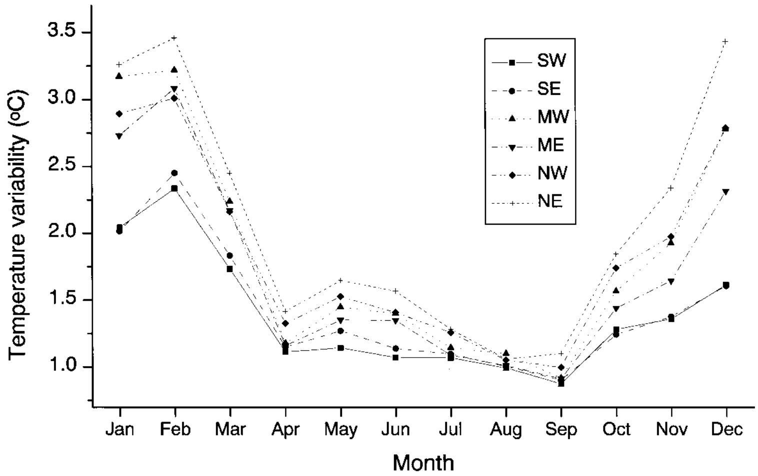

Fig. 1. The mean seasonal variation of the variability in the temperature (average absolute value of the anomaly) for the 6 regions in Sweden.

maximum in the winter months (December, January and February). The higher the latitude, the greater the temperature fluctuations. This difference is greater during the cold season. Moreover, the variability is generally higher in the eastern part than in the western and the difference increases with increasing latitude. However, the middle part of Sweden behaves differently in terms of the east–west differences.

The temperature fluctuations are highest in winter when the difference between the Swedish climate and the climate of the surrounding areas is largest and the atmospheric circulation is strong. Further, the temperature differences between the air masses affecting Sweden (maritime and continental) are largest in winter. The lowest variability occurs during the months with relatively high insolation, which means that the climate then is more locally controlled. The northern regions experience the largest fluctuations due to their position in the transition zone between the west wind belt and the Arctic climate. The temperature variations are generally lower in the western parts which are more exposed to the westerlies and hence more influenced by the advection of maritime air. The exception is the middle part of Sweden, where the variability is higher for the western region. This may be explained by its geographical setting in which the west part joins the Norwegian land mass and the east side has direct access to the Baltic sea. In fact, Ångström (1974) classified the west part as continental and the coast area in the east part as maritime.

As was shown by Moberg and Alexandersson (1997), the monthly temperature anomalies have a large range. Autocorrelation of the temperature anomalies reveals that there is virtually no correlation after lags longer than 2 months, i.e., the time scale of the variability is very short. This is mainly a reflection of the poor persistence of the synoptic circulation over the area. To make a regional comparison of the persistence, the sequential 2-month correlation of the temperature anomalies are shown in Fig. 2. Sequential 2-month correlation here means that the January temperature anomalies are correlated with the February temperature anomalies, the February anomalies with the March anomalies and so on. For southern Sweden the highest month-to-month correlations are found in winter, early spring and late summer. The persistence of the middle Sweden temperature anomalies is generally lower than for the southern parts. The monthly variations of persistence in northern Sweden are different from that in the southern, indicating that the two parts are affected by different circulation regimes. The highest sequential 2-month correlations for northern Sweden occur between February and March, late spring and between January and December. Studies of persistence of temperature in Europe (Schuurmans and Coops, 1984; Kozuchowski et al., 1994) and the United States (Van den Dool

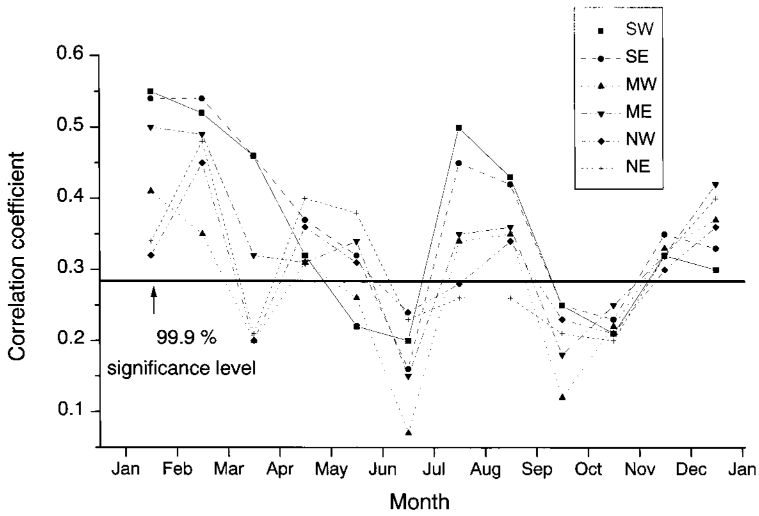

Fig. 2. The sequential 2 months correlations of the temperatures anomalies for the 6 regions. The correlation coefficient is assigned to the middle of the 2 months, i.e., the first correlation coefficient is that between January and February and the last one is that between December and January.

et al., 1986) have shown peaks in the month-to-month persistence in winter and summer. These peaks are present for southern and middle Sweden as well. However, the summer peak is much weaker or missing in the northern parts where a spring peak is more pronounced. The spring peak is to a lesser extent evident for the middle parts of Sweden as well. Suggested causes of the peaks found by Schuurmans and Coops (1984), Kozuchowski et al. (1994) and Van den Dool et al. (1986) are both of large and local scales. Winter and summer maximums of the month-to-month persistence of the monthly mean atmospheric circulation of the Northern Hemisphere have been revealed by Van den Dool (1983) and Van den Dool and Livezey (1984). Due to the regional scale of the temperature anomaly series in this study, it is questionable if local effects contribute to the persistence. However, the spring peak for northern and middle Sweden coincides with the period of snow melting in these parts. Temperature variations during this period may therefore be amplified by the positive feedback.

3.2. *Impact of the NAO on the temperature anomalies*

A short description of the NAO variations is given here to facilitate analyses of the impacts of the NAO on temperature anomalies. An examination of the monthly NAOI from January 1864 to December 1994 shows considerable short term fluctuations. This is supported by a spectrum analysis of the monthly index, showing that the power of the variance is concentrated on the higher frequency side (periods shorter than 12 months). The power spectrum of annual NAO index reveals that dominant periods of the NAO variability are 6–10 years and 2–3 years (Hurrell, 1996). Longer period oscillations with periods of 24 and 70 years have also been identified (Hurrell and Van Loon, 1997). By employing a linear regression to the data, the long-term linear trend of the NAO index during 1865 and 1994 is estimated to be 0.56 standard deviation change per 100 years. It is interesting to note that this long-term trend has the same sign as the long-term trend of the annual Swedish temperatures during the same period which was interpreted as the signature of the increasing concentration of greenhouse gases (Moberg and Alexandersson, 1997).

To simplify the analysis, we start with the monthly temperature anomaly for whole Sweden which is an average of the temperature anomaly from the 6 regions. This analysis shows that there is a reasonably good relationship between the monthly temperature anomaly and the NAOI and the relationship is fairly linear. The linear correlation coefficient is 0.46 which is statistically significant at the 99.9% level. The correlation coefficient of monthly temperature anomalies and monthly NAOI is 0.46, meaning the monthly fluctuations of the NAOI can explain 21% of the variance of the monthly temperature in Sweden.

To quantify regional and seasonal differences in the correlation, the analysis is applied to the 6 regions and every calendar month. Positive correlations are found for all the regions and months (Fig. 3) though considerable differences exist. The NAO seems to have the greatest influence on the temperature in March. It is evident that the effects of the NAO are of varying importance to the temperature of the 6 regions. Between September and March, the correlation coefficients are generally highest in southern Sweden, but between May and August they are highest in the northern parts. The seasonal differences in the coefficients are greatest for the southern parts, for which they vary from 0.07 to 0.67, whereas for the northern parts they vary from 0.31 to 0.55.

The high and positive correlation coefficients between temperature and the NAOI in autumn, winter and spring confirm that the NAOI reflects the state of the westerlies and hence the advection of relatively warm maritime air over the country in these seasons.

Earlier studies of the relationship between the temperature at a few Swedish stations and the zonal index have shown that in summer, station temperatures are negatively correlated with the strength of the westerlies (Kozuchowski and Marciniak, 1988; Kozuchowski et al., 1992 and Jönsson and Bärring, 1994). In this study positive correlation coefficients between the regionally-averaged temperatures and the NAOI are obtained for all of the summer months. This might be due either to the fact that the regionally-averaged temperatures are not negatively affected by westerly winds in summer or to the fact that the NAO-index does not serve as a good indicator of the strength of the westerly winds over Sweden in summer. Hurrell and Van Loon (1997) found that in spring and summer the Azores high is stronger over the ocean and therefore not well-captured by the Lisbon SLP and that the Lisbon–Stykkisholmur index fails to describe the negative pressure relationship between the subtropical and subpolar regions. To check if this is the reason for the positive connections between the regional Swedish temperature and the NAOI in summer the temperatures are correlated with another NAO-index which uses the SLP at Ponta Delgada (the Azores) to reflect the state of the Azores high. The correlations are calculated for the period 1899–1994. For June the correlation coefficient is 0.26 for the south-western region and increases to

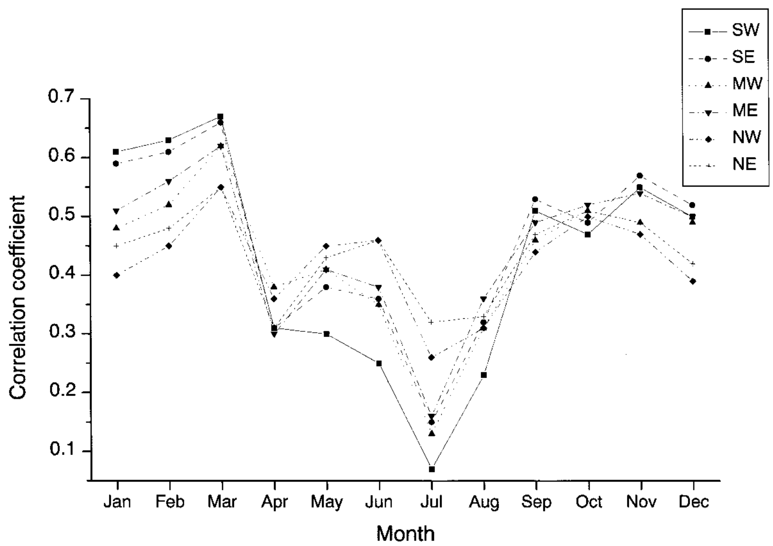

Fig. 3. Seasonal variation of the correlation between the monthly temperature anomalies and the NAOI for the 6 regions.

0.55 for the north-eastern part. Lower correlations are found for July (0.06 for SW to 0.37 for NE) and August (0.26 for SW to 0.32 for NE). These results are similar to those of the correlation analysis of the regional temperatures and the Lisbon–Stykkisholmur index. To test whether the regionally-averaged temperatures in summer are negatively affected by westerly winds, correlation coefficients of the temperatures and zonal indices for July was calculated. The zonal indices were also correlated with the NAOI. Two types of zonal indices were used, a westerly for the area between 40°W and 5°E and an easterly for the area between 0° and 40°E. The correlation coefficients of the zonal indices and the July temperatures of the 6 regions are shown in Table 1. The correlation coefficients of the westerly zonal index and temperature are similar to those of the NAO-indices and temperature. The easterly zonal index is negatively correlated with the July temperature of all regions. The correlation between the Lisbon (Ponta Delgada)–Stykkisholmur NAOI and the westerly zonal index is high, 0.84 (0.83), whereas the correlation between the easterly zonal index and the NAOI is much less, 0.34 (0.29). As expected, these results show that the regionally-averaged temperatures are strongly negatively effected by westerly winds in summer. It is also evident that the NAO-indices are not good indicators of the of state of the west winds over Sweden in summer and that the Swedish temperature is less effected by the atmospheric circulation over the North Atlantic in summer than in other seasons.

Due to the fact that the largest temperature fluctuations occur in wintertime and the most important period of the NAO variability is in winter, the relationship between annual temperature anomaly and the NAOI is expected to be even stronger. An examination of the averaged annual Swedish temperature anomalies together with the annual NAOI indicates that there is generally a good correspondence between the two time series, although the correspondence changes with time.

Variations in the influence of the zonal wind on Oslo (southern Norway) temperature (Rogers, 1985) and on temperatures of two stations in southernmost Sweden (Jönsson and Bärring, 1994) have been noted earlier. To investigate the evolution of the relationship over time and for all the regions, a moving correlation analysis is performed. Fig. 4 displays the results. There is a considerable fluctuation of the correlation for all of the regions when the correlations for southern parts are relatively high. However, the overall trends of the variations are about the same for all of the regions. This is especially true for the southern and middle parts. The correlation begun to decrease around the end of the last century. This declining trend continued until around 1930 when a rapid increase occurred. The increasing trend continued until around the 60s after which another decreasing trend appeared. The varying associations between the temperatures and NAOI imply that the relationship between the two is not stable and other processes not included may have undergone changes over time. An understanding of this change requires identification of all important processes and quantification of the role they played. It has also practical implications for development of statistical downscaling models. When such a model is developed, the stability of the model over various time periods or climate regimes should be tested in some way.

To investigate if the strength of the relation is connected to the strength of the NAOI, scatterplots of the 31-year moving averages of the annual NAOI versus the absolute values of the annual moving correlations over the same period were given in Fig. 5. There is some dependence of the correlation on the mean NAOI for the middle and southern parts. However, this dependency decreases quickly with increasing latitude and towards the east and there is virtually no such a

Table 1. *Correlation coefficients of zonal indices (westerly, easterly) and the July temperature of south-western, south-eastern, middle-western, middle-eastern, north-western and north-eastern Sweden.*

	SW	SE	MW	ME	NW	NE
ZI (westerly)	0.18	0.24	0.22	0.29	0.24	0.36
ZI (easterly)	−0.46	−0.42	−0.60	−0.49	−0.50	−0.45

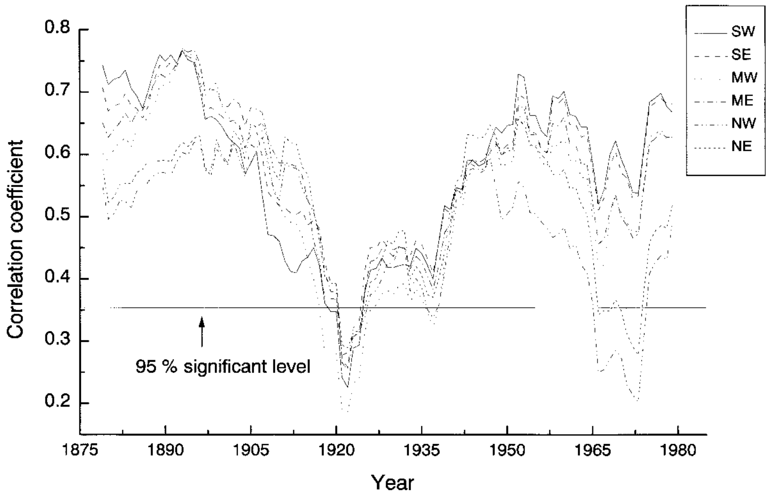

Fig. 4. The moving correlation between the annual NAOI and the temperature anomaly over a 31-year period. The correlation coefficients are assigned to the middles of the 31-year windows.

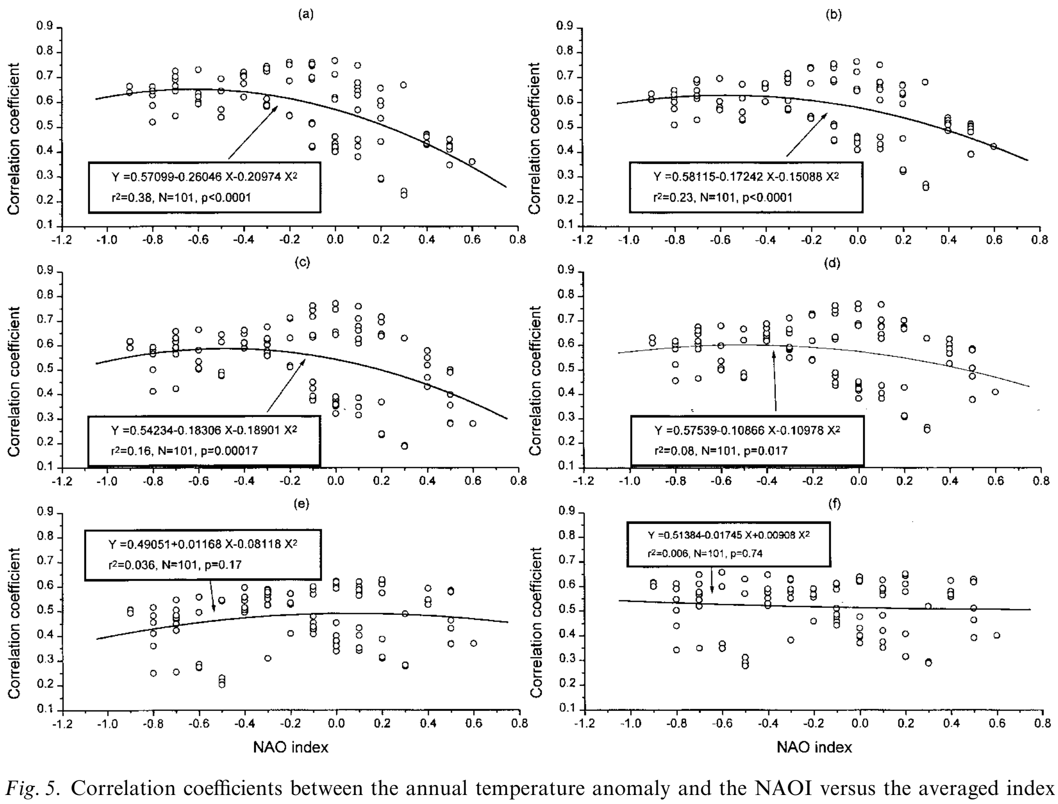

Fig. 5. Correlation coefficients between the annual temperature anomaly and the NAOI versus the averaged index over the window for the 6 regions: (a) SW; (b) SE; (c) MW; (d) ME; (e) NW; (f) NE.

dependency visible for the northern parts. For the middle and south parts, negative mean NAOI usually results in a fairly constant and high correlation. At the same time, the least scattering is found around the index value of -0.4 for all the regions, although there are only a few points around this value. Moreover, there seems to be a decreasing trend of the correlation with the increased positive NAOI for the two parts. Since the averaged NAOI is used, the dependency reflects the effect of the low frequency variability of the NAO. This is useful when an indication of the goodness of a statistical relationship is needed. It should be noted that the averaging implies an autocorrelation among the samples. A rigorous test on the significance of the relationship should take this reduction in the dimension into account.

From the discussion above, it is evident that not all of the variations in the connection between the NAOI and temperature can be explained by the size and sign of the NAOI. Some of the fluctuations might for example be related to variations in the oceanic processes. The underlying causes to the varying influence of the NAO on temperature pose a challenge to the whole community and modeling will most likely play an important role.

3.3. Cross-spectrum of the temperature and the NAOI

To examine the relationship between the temperature and the NAOI over the frequency domain, the cross-spectrum and the coherency spectrum between the two are computed and shown in Fig. 6.

Three peaks appear in the power spectrum of the temperature (Fig. 6a): 2.3, 7.7 and 52.6 years. Due to the length of series and the linear trend, the longest period found should be taken with caution. As found by Hurrell (1996), the power spectrum of annual NAO index (Fig. 6b) reveals that dominant periods of the NAO variability are 6–10 years and 2–3 years. Longer period oscillations with periods of 24 and 70 years have also been identified (Hurrell and von Loon, 1997).

The squared coherency can be interpreted as correlation coefficient between the two time series. There is a broad range of frequencies (3.5 to 12.5 years) where the correlation between the two is fairly high. The peak at the 2.3 years indicates the sole effect of the NAO. The correspondence of the coherency (Fig. 6c) and the NAO spectrum is fairly good, which implies that the importance of the variation in NAO on these time scales. The phase spectrum (not shown) also shows that there is practically no delay of the impact to temperature by NAO.

4. Summary and conclusions

The main purpose of this work is to describe features of regional temperature variability in Sweden in relation to the NAO using homogenized instrumental data. The influence of the NAO on temperature has been identified as important and significant. The following conclusions can be drawn.

- There are well defined seasonal and regional differences in the temperature variability, which is likely due to seasonal variations of solar radiation, temperature contrast, geography, and the dominating synoptic systems.
- In terms of persistence of temperature anomaly, southern Sweden is distinctively different from the middle and northern parts, which may point to a useful division for further studies.
- For the whole period studied, the temperature anomaly and the NAOI are positively correlated both on an annual and a monthly basis. The correlations are all significant at the 99% level, except for southern Sweden in July, indicating that the NAO is an important factor in determining month-to-month and year-to-year variations of the Swedish temperature. Therefore, the index should be useful for a statistical downscaling model.
- The correlation between the temperature and the NAO varies from region to region and from season to season. The influence of the NAO generally diminishes towards north and east, which demonstrates the influence of the advection by westerlies. The highest correlation is found in March.
- The correlation between the NAOI and summer temperature is positive, but the association between the summer temperature and a zonal index calculated for the area between 0° and 40°E is negative. The state of the westerlies over Scandinavia does hence affect the Swedish temperature negatively in summer. This indicates that

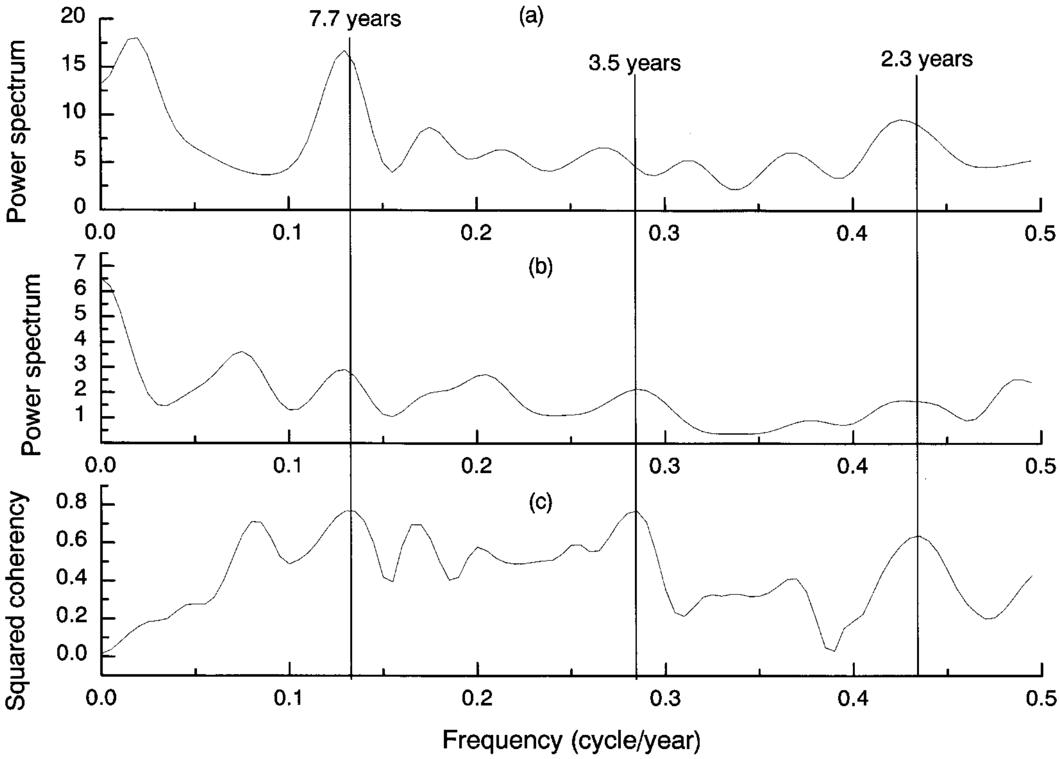

Fig. 6. Spectrum of the annual temperature anomaly averaged over the 6 regions and the NAO index (1864–1994) and their coherency: (a) the spectrum of the temperature; (b) the spectrum of the NAOI; (c) the squared coherency between the temperature and the NAOI.

the NAOI is not a good measure of the strength of the west winds over this area in summer.

• The moving correlation between temperature anomaly and the NAOI reveals that the correlation varies with time and the variations to some extent depend on the mean NAOI. However, there are considerable seasonal and regional differences in this dependence. This implies that the temporal variation in the usefulness of the index has to be taken into account when applying the index as a predictor in a statistical downscaling model.

• The coherency analysis shows that there are two frequency bands which contribute most to the temperature — NAOI correlation: one is between 3.5 and 12.5 years and another around 2.3 years. This confirms that the NAO is an important agent in determining the Swedish temperature.

5. Acknowledgement

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