Scale-dependent relationship between maximum ice extent in the Baltic Sea and atmospheric circulation

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Abstract

Previous studies have demonstrated the importance of large-scale atmospheric circulation on the maximum ice extent (MIE) over the Baltic Sea. The main objective of this study is to gain some understanding of the scale-dependent variability of the MIE in relation to the large-scale atmospheric circulation. Wavelet analysis was applied to the observed and modelled MIE observation to identify the association between them as a function of time scale. The model used is a statistical model linking a set of indices describing the large-scale atmospheric circulation and the MIE. The analysis enables verification of the statistical model regarding its ability to reproduce variability at various time scales. The analysis shows that for the both variables, the amplitudes and frequencies of the variations on all scales vary with time. The correlation between the MIE and the atmospheric circulation is strongest at the longer time scales (>64 years) and weakest at the time scale of 32 years. The correlation at the interannual and decadal scales lies in between and is fairly strong. Further, the linkage on all time scales becomes stronger after 1940.

1. Introduction

Sea ice is an important element in the climate system. As in other regions in the world, sea ice over the Baltic Sea has a great impact on both water and heat budgets (e.g., Omstedt et al., 1997). Like other climate variables in the region, the sea ice exhibits a large interannual variation. One of the most important indicators of ice variation is the maximum ice extent (MIE) that usually appears in late February or early March (Leppärenta and Seinä, 1985).

This indicator has been recorded since 1720 (Seinä and Palosuo, 1993) and represents one of the most well-documented climate records in the region. A number of studies have been undertaken using this record (e.g., Seinä, 1993). A detailed study regarding the variability, trend and frequency distribution of the record between 1720 and 1996 was carried out by Tinz (1996).

Large-scale atmospheric circulation plays an important role in determining regional climate in Northern Europe. A well-known example is North Atlantic Oscillation (NAO). NAO reflects the inter-annual
variability for both weather and climate (Hurrell, 1995). In a recent analysis of the NAO, Hurrell and Loon (1997) have shown that the winter NAO has tended to remain in one extreme phase (positive NAO index) since 1980, which has accounted for a substantial portion of the observed winter surface warming throughout Europe. It is established (Chen and Hellström, 1999) that there exists a close correlation between the NAO and the winter air temperatures in the Baltic Sea region, which points to a close correlation between the NAO and the annual maximum ice extent of the Baltic Sea.

Recently, Omstedt and Chen (2001) established a strong linkage between large-scale atmospheric circulation and the MIE. A statistical model linking a number of atmospheric circulation indices and the MIE has been developed. The model was developed and validated in a traditional way, i.e., without scale differentiation. Due to the dominant variability on interannual scales, the traditional methods of statistical modelling mainly reflect the skill of the model at this scale. However, climate varies on a variety of temporal scales. As a result, a model that describes the interannual variability well is not necessarily appropriate for other scales.

Different processes in the climate system are usually associated with different time scales. An examination of scale-dependent skill of a model may provide additional insight into the deficiency of the model, which may lead to further improvement of the model and better understanding of relevant processes. The focus of this work will be on identifying the scale dependence of the relationship between the MIE and the atmospheric circulation. The aim is to improve our understanding of the variability of the MIE in relation to atmospheric circulation on a variety of scales.

2. Data, model and method

2.1. The data and the statistical model

The MIE data were collected by the Finnish Institute of Marine Research. The collection of these data was first carried out in the 1920s and 1930s (Jurva, 1941) and has been continued by Palosuo and Seinä (Palosou, 1953; Seinä and Palosuo, 1993). In the beginning, the data are based upon the collection and analysis of all available archive materials, such as lighthouse diaries, ship reports, published studies, journals of travellers, newspapers, etc. (Seinä, 1993). The data are believed to be reliable from the 1840s on, while the data previous to 1840 should be regarded as rough estimates. The data from 1915 (Alenius and Makkonen, 1981) until present have been collected with the use of extensive observations, including regular coastal observations, ship reports, air reconnaissance and, in latter years, satellite data.

A set of circulation indices containing information about geostrophic wind and vorticity over Scandinavia was derived by Chen (2000). The indices were computed on a monthly basis using sea level pressure at 16 grid points covering northern Europe. Omstedt and Chen (2001) used westerly and southerly components of the geostrophic wind and the total vorticity to develop a statistical model linking the MIE and the atmospheric circulation. Fig. 1 gives a schematic description of the three indices and the study area. The statistical model predicts the MIE in terms of monthly indices as follows:

\[
A = 351.0 - 6.09u^{\text{Dec}} - 3.92u^{\text{Jan}} - 10.34u^{\text{Feb}} - 3.38v^{\text{Nov}} - 5.33v^{\text{Jan}} - 3.01\zeta^{\text{Jan}}
\]

where \(A\) is the maximum ice extent in 1000 km², \(u\) and \(v\) are the westerly and southerly wind indices, respectively, \(\zeta\) denotes the index of the total vorticity and all the superscripts indicate the month. All the indices have the unit of hPa per 10° latitude at 60° north.

The geostrophic wind is an idea surface wind representing transport of heat through air, while the vorticity describes strength of circular movement of air mass, i.e., high or low pressure systems. It is expected that the westerlies in December, January and February are negatively correlated to the ice extent, with February being the most important factor. The southerly wind in November and January have a similar negative impact on the ice extent. The vorticity in January also appears to be a factor; high pressure system is usually associated with strong radiative energy loss and extremely low temperature in the region (Chen, 2000), which favours development of ice and vice versa.
The model can account for a large portion (over 60%) of the total ice variability over the whole period.

2.2. Wavelet transform (WT)

Wavelet transform of a time series is its convolution with a local base function called wavelet. WT decomposes a series into time–frequency domains, which allows identification of temporal changes of dominant modes of variability (e.g., Datsenko et al., 2001). It has been proven to be a powerful tool suited for the analysis of the multi-scale structure, the time–frequency localization and non-stationary behaviour of temporal signals. WT has been introduced into climatic and oceanographic application since early 1990s (Gambis, 1992; Meyers et al., 1993; Lau and Weng, 1995). In this section, the wavelet analysis is described briefly. A comprehensive treatment of the wavelet subject can be found in Chui (1992), and references therein.

Let \( R \) and \( Z \) be a set of real numbers and integers, respectively. If \( L^2(R) \) denotes a space of square integrable functions, the inner product on \( L^2(R) \) is defined by:

\[
\langle f, g \rangle = \int_{-\infty}^{\infty} f(x)\overline{g(x)} \, dx
\]

where \( f, g \in L^2(R) \) and \( \overline{g} \) is the complex conjugate of \( g \).

Wavelets are families of functions that are produced by scaling and translating a single function called the mother wavelet:

\[
\phi_{a,b}(x) = |a|^{-1/2} \phi \left( \frac{x-b}{a} \right)
\]

where \( \phi \) is the mother wavelet, and the dilation and translation parameters \( a, b \) vary continuously over \( R \) with the constrain \( a \neq 0 \).

The continuous wavelet transform of a function \( f \in L^2(R) \) is defined by:

\[
Wf(a, b) = \langle f, \phi_{a,b} \rangle = |a|^{-1/2} \int_{-\infty}^{\infty} f(x) \phi \left( \frac{x-b}{a} \right) \, dx
\]

Function \( f \) can be reconstructed from its continuous wavelet transform using:

\[
f = \frac{1}{C} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} Wf(a, b) \phi_{a,b} \frac{dadb}{a^2}
\]

where \( \phi_{a,b} \) is the dual wavelet of the mother wavelet \( \phi \), and \( C = \int_{-\infty}^{\infty} \left( \left| \phi(\omega) \right| \right)^2 |\omega| \, d\omega \).

In order to make the wavelet framework computationally efficient, the most often used discretization of the parameters \( a \) and \( b \) is \( a = 2^j \), and \( b = k2^j \) with \( j, k \in \mathbb{Z} \). The dilated and translated wavelet is then:

\[
\phi_{j,k}(x) = 2^{-j/2} \phi(2^{-j}x - k)
\]
Parallel to the continuous wavelet transform, the discrete wavelet transform is defined by:

\[ W_f(j, k) = \langle f, \phi_{j,k} \rangle \]

and it can be shown that for function \( f \):

\[ f = \sum_{j,k \in \mathbb{Z}} \langle f, \phi_{j,k} \rangle \phi_{j,k} \]

This equation defines a reconstruction formula for \( f \) from its wavelet coefficients.

In this work, the compactly supported base-spline wavelet (BW) is employed to analyse the temporal variation of the MIE. BW possesses a number of good properties such as biorthogonality, compact support, smoothness, symmetry, good localization, efficient implementation, optimum flexible time–frequency window and linear-phase filtering (Chui, 1992), which makes it more effective and persuasive in hierarchical frequency structure of time series than other wavelets such as Haar, Morlet, Mexico-hat wavelets. In particular, the linear-phase filtering quality ensures the accurate decomposition and reconstruction of the time series.

3. Results

3.1. Wavelet transform of the MIE between 1720 and 1997

Fig. 2 shows the wavelet transform for the MIE anomalies. It is clear that there are three dominant bands of quasi-periodic oscillations: interannual (2–6 years), decadal and interdecadal (8–32 years) and century scales (64–256 years). The signals with large variability are mainly on the shorter, interannual time-scales. The contribution of the two interannual scales (2 and 4 years) in terms of variance exceeds 70% of the total.

A most remarkable feature in Fig. 2 is the coherent variability across the interannual and interdecadal bands. This is especially evident in the 20th century, as indicated by the arch-shaped isolines. Another noticeable feature is that these quasi-periodic oscillations at interannual time scales are intensified occasionally by dense isolines, especially between 1820 and 1880. In addition, MIE anomaly time series exhibits a strong non-stationarity at all

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Fig. 2. The wavelet coefficients of the MIE anomalies. The interval of the contour line is \( 50 \times 10^3 \) km², while the thick lines indicate isolines with the value of zero. The thin, solid and dashed lines denote the positive and negative values, respectively.
time scales, i.e., regular periodic oscillation hardly exists.

Fig. 2 shows that MIE has two main regimes of quasi-periodic oscillations. During the early part of the record (before 1850), the long-term oscillations are relatively strong, while the short-term oscillations, especially the 4-year oscillation is weak. In the beginning of this period, the magnitude of the decadal (around 8 years) variations is relatively large; it diminishes between 1750 and 1830 and, then, reaches its maximum around 1840. The intensities of the two interdecadal oscillations (16 and 32 years) vary with time too, but the changes are not simultaneous. During the last 150 years, the long-term oscillations (over 16 years) become weaker, and the 4-year oscillation is stronger than before. The 8-year variation has become stronger since 1850 and reached the second maximum in the last 20 years. On the other hand, the 16-year interdecadal and 32-year interdecadal oscillations have diminished since 1850. The interannual cycles are relatively stationary.

3.2. Scale-dependent relationship between the MIE and atmospheric circulation

WT is used here to reveal the scale-dependent similarity between the observed and modelled ice extent. Because there are only 123 years of data of the atmospheric indices, the analysis is limited to the period 1873–1995, which also sets the limit to seven time scales. Fig. 4 shows the time series of the wavelet coefficients for the seven different scales. Note that Figs. 2 and 3 can be compared in the corresponding scales, except that the longest scale in Fig. 3 should be considered as a sum of the first two time scales (256 and 128 years) in Fig. 2. This is due to the fact that the lengths of the two analysis are different.

Despite the small variability in the century time scale (64 and 128 years), the model reproduced the long-term variation surprisingly well. The model captured the decreasing trend and the two periods with low ice extent in the last decade and around 1930s. Compared to the interdecadal and interannual scales, the variability in this long-term band has been most ideally reproduced.

For the decadal and interdecadal variations, a common feature is that the model gave the realistic results for the last 30 years, but failed to simulate the variation for the earlier period. Especially, for the 32-year oscillation, the model produced the opposite phase before 1950s. Although the model succeeded in capturing the phases of the 16-year scale, the magnitudes modelled are much lower than the observed ones. In particular, for the period from 1900 to 1940, the modelled amplitude is simply too small.

As indicated in the previous section, the interannual variations are most important in the three frequency bands. Therefore, the modelled interannual variations dominate the final results when reconstruct-
Fig. 3. Temporal variation of the MIE anomalies (in $10^3$ km$^2$) associated with the dominant scales for the century bands (256 years (a), 128 years (b) and 64 years (c)), the decadal to interdecadal bands (32 years (d), 16 years (e) and 8 years (f)) and the interannual bands (4 years (g) and 2 years (h)). The number in the left part of the panel is the contribution of the scale in terms of the total variance. The last panel (i) shows the reconstruction of the original MIE time series using all the above decompositions.
ing the observed MIE time series using all the periodicities. The model performs satisfactorily at the interannual time scales. In particular, the model successfully simulates nearly all of the extreme events in terms of both phases and amplitudes. In addition, the modelled interannual variation after 1920 is much better than those modelled before 1920. This is true for almost all time scales, which may indicate an increasing role played by the atmospheric circulation in controlling the MIE. Similar results have also been
obtained by Busuioc et al. (2001). Alternatively, it can also be due to the fact that data quality in recent years is higher than previously.

4. Summary and conclusions

Wavelet analysis was applied to the MIE data and the indices describing the atmospheric circulation, enabling identification of the correlation between them as a function of time scales. The main objective of this study is to gain some understanding of the scale-dependent variability of the MIE in relation to the large-scale atmospheric circulation, and to verify the statistical model linking the MIE and the circulation indices regarding its ability to reproduce variability at various scales. The conclusions may be summarised as follows.

1. The wavelet transform of the MIE during 1720–1997 shows that the importance of the variability depends strongly on time scale and the dominant time scale is the interannual scale. Further, the amplitudes of the variations on all scales vary with time, demonstrating the strong non-stationary feature of the variability.

2. Despite the relatively small variance of the variability at the longest time scale, there appears a clear decreasing trend. This is consistent with the previous finding that there is a significant change point at about 1880.

3. Generally, the atmospheric circulation has a varying effect on the MIE depending on time scale. Specifically, the correlation between the MIE and the atmospheric circulation is stronger at the longer time scales than the short ones. However, the poorest correlation is found at the interdecadal scale (32 years). This underlines the importance of other factors other than the direct influence of the atmospheric circulation at that scale. The reproduced MIE based on the statistical model are fairly satisfactory at the interannual and decadal scales.

4. If the period 1873–1995 is divided into two sub-periods, 1873–1940 and 1940–1995, the correlation between the circulation and the MIE is stronger in the later sub-period, which may point to either a genuinely stronger correlation or to improved data quality during the later sub-period.

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