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# Climatic turning points and regime shifts in the Baltic Sea region: the Baltic winter index (WIBIX) 1659–2002

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The derived climate index is based on monthly values of the first principal component of (i) winter anomalies (January–March) of air pressure difference between Gibraltar and Reykjavik to describe the North Atlantic Oscillation, (ii) sea level anomalies of Landsort (Sweden) to characterise the filling level in the Baltic Proper, and (iii) maximum Baltic ice cover to include the influence of continentally dominated alignments of atmospheric centres of action (1897–2002). Resulting time coefficients were regressively completed by corresponding winter anomalies in air temperature over central England (1659–1896). The power spectrum of the obtained index (WIBIX 1659–2002) exhibits five significant quasi-cycles (2.2, 3, 6, 8, and 14 years), but also suggests periods of about 40 and 100 years. Severe (continental, WIBIX < 0) and mild (maritime, WIBIX > 0) winter types alternate and associated turning points characterise regime shifts affecting the ecosystem. Consequences for the Baltic fishery are discussed.

## Introduction

On the geological time scale, the Baltic Sea is relatively young and its environment has always been subject to changes on different spatio-temporal scales. It is located in the humid climate belt of the mid-latitudes. On the climate scale, two types of the general weather situation may be distinguished. The continental type advects dry air masses from Eurasia towards the Baltic Sea, while the maritime type conveys humid air masses in the belt of westerlies from the North Atlantic towards western Europe. The impact of the maritime type decreases with increasing eastern longitude while that of the continental type increases. The resulting Baltic water balance is mainly characterised by a surplus of freshwater from river discharges (HELCOM 1986). A smaller contribution of about 11% derives from net precipitation (Meier and Döscher 2002). Consequently, Baltic salinity is much lower than oceanic salinity. According to Stigebrandt and Gustafsson (2003) the Baltic Sea renews most of its heat, but only three percent of its salt during the annual cycle. Near-surface layers show typical values of three PSU in the northernmost part of the Gulf of Bothnia, seven PSU in the central Baltic Sea, and about ten PSU in the connecting straits between the south-western Baltic Sea and the Kattegatt (Fig. 1). Thus, relatively light brackish water feeds the main outflow through the Belts and the Sound towards the North Atlantic through the North Sea, the Skagerrak, and the Kattegatt via the Baltic Current along the Swedish, Danish, and Norwegian coasts. Intrusions of saline, dense, and frequently well oxygenated water follow the contours of bottom topography to overflow several topographic sills

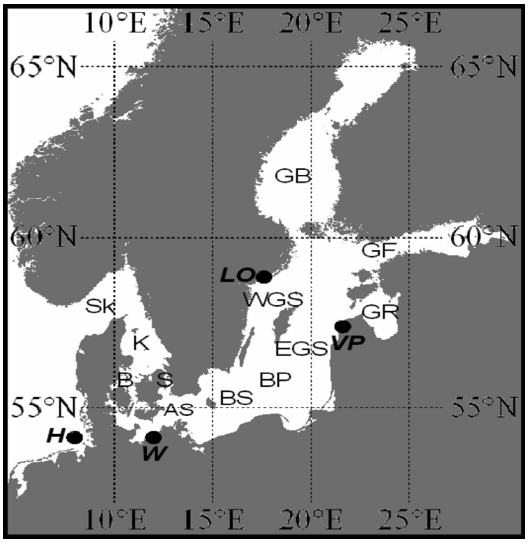


**Fig. 1**. Map of the Baltic Sea with the Gulf of Bothnia (GB), the Gulf of Finland (GF), the Gulf of Riga (GR), the Baltic Proper (BP) comprising the western/eastern Gotland Sea (WGS/EGS), Bornholm Sea (BS), and Arkona Sea (AS); connecting straits of the Belts (B) and the Sound (S); transition zone of the Kattegatt (K) and the Skagerrak (Sk); station positions of Helgoland (H), Warnemuende (W), Ventspils (VP), and Landsort (LO) are given by dots.

from one deep basin to the next. The new inflowing deep water is rarely dense enough to replace the older deep water completely. Vertically, the resulting salinity distribution controls that of density, and the brackish water of upper layers is separated by a pronounced halocline/pycnocline from more saline water of deep layers (Møller and Hansen 1994).

Variability in Baltic climate peaks during the winter season due to intensified westerlies. From January until March, there exists an exceptional positive correlation between the North Atlantic Oscillation (NAO), which describes changes in intensity of the geostrophic component of westerlies over the North Atlantic Ocean and western Europe, and the filling level of the Baltic Proper (Andersson 2002). The latter integrates the Baltic water budget. Its temporal fluctuations are well depicted by changes in sea level recorded at the Swedish coastal station Landsort (Svansson 1972), however, they are negatively correlated with the total Baltic ice cover on the decadal scale, cf. Omstedt and Chen (2001) and Hupfer (2003). On shorter time scales of several days and few weeks, drastic anomalies in sea level changes of the Baltic Proper well reflect exceptional in-outflow conditions via gradients in sea level between the south-western Baltic Sea and the Kattegatt (Hagen and Feistel 2001). However, major Baltic inflows affect the hydrographic state of intermediate and deep layers in the whole Baltic Sea modifying the ecosystem on much longer time scales. Associated trends in hydrographical, chemical, and biological conditions are considered to be climatic regimes. They were not only observed in the Baltic Proper (Möllmann *et al*. 2003), but also over adjacent shelves, in small Baltic gulfs (Dippner and Ikauniece 2001), and in lakes of the surrounding hinterland (George *et al*. 2004, Nõges 2004). Therefore, it seems to be justified to search for a summarising winter index which sufficiently describes changes in climate on interannual and decadal scales. It should reflect well known interrelationships between the NAO, the filling level in the Baltic Proper, and the maximum Baltic ice cover. Consequently, such a winter index should be able to describe already detected “regime shifts” and associated “turning points” in the Baltic ecosystem.

## Data sources and processing

### Basic long-term series

The following variables were used as input series for the principal component analysis: (i) monthly sea level records of the Swedish coastal station Landsort, (ii) monthly differences in sea level air pressure between Gibraltar and Reykjavik, and (iii) maximum ice coverage of the Baltic Sea.

#### Monthly sea level records of the Swedish coastal station Landsort

Basin-scale fluctuations of wind forcing and of the Baltic water budget initiate natural oscillations of the sea level (SL) along the main axis of the Baltic Proper (Wübber and Krauss 1979). Therefore, the filling level of the central Baltic should be recorded at coastal stations which are

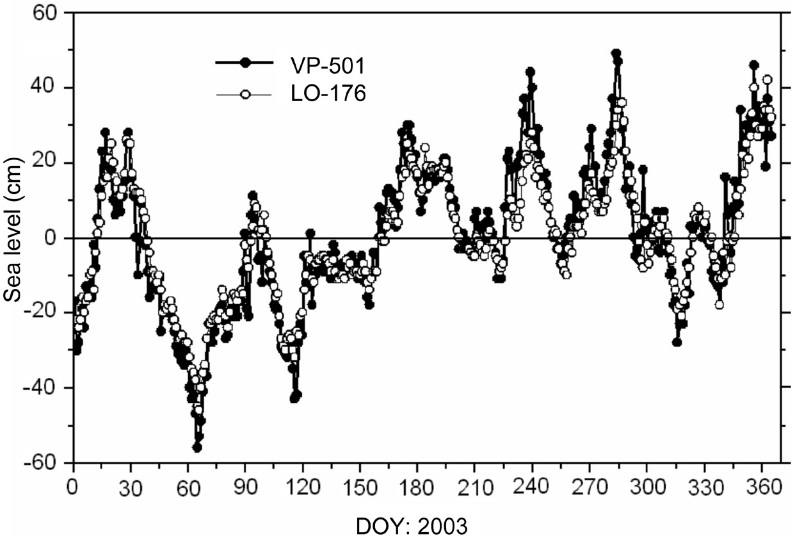


**Fig. 2**. Daily sea level anomalies (cm) at Ventspils (VP, dots) and Landsort (LO, circles) during 2003 (day of the year = DOY). Positions are shown in Fig. 1 and the annual averages of 501 and 176 cm result from differently used calibration scales.

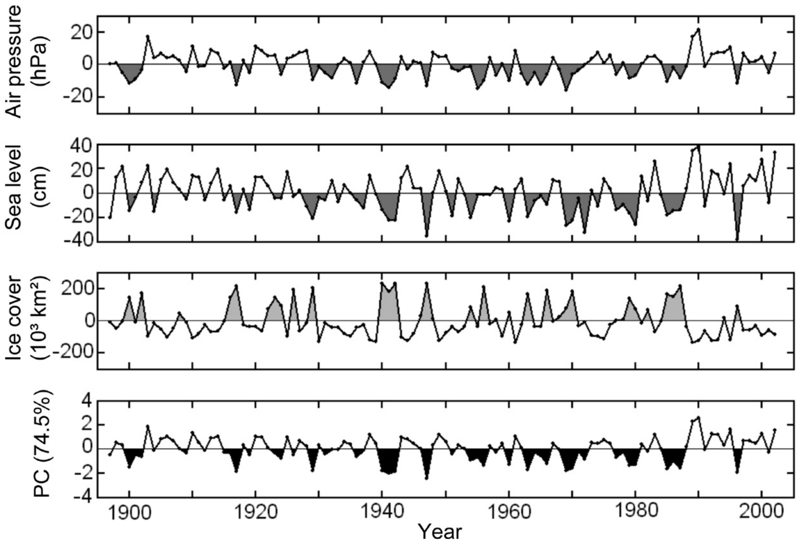


**Fig. 3**. Centred or detrended winter anomalies (December–March) of the difference of sea level air pressure (hPa) between Gibraltar and Reykjavik, sea level of the Baltic Proper at Landsort (cm), and maximum Baltic ice cover ($10^3$ km$^2$). The first principal component (PC) of these three anomaly series explains 74.5% of the total variance (1897–2002) (Table 1).

located in the vicinity of associated nodal points. This precondition is approximately fulfilled at the coastal stations Ventspils (57°24´N, 21°33´E) in the east and Landsort (58°45´N, 17°52´E) in the west (Fig. 1). Daily sea level records of Ventspils were available for the year 2003 from the website http://www.meteo.lv/pdf_base/juras_2003.html. Corresponding data sets of the coastal station Landsort were provided by the Swedish Meteorological and Hydrological Institute, Norköpping. When subtracting the annual means of both series it becomes evident that there is a high degree of similarity in resulting sea level anomalies (SLA) across the central Baltic Sea (Fig. 2). The squared correlation coefficient is 0.89 between both SLA series. Because day-to-day changes in sea level show the lowest standard deviation at Landsort — *see* figure 13 in Jacobsen (1980) — we only used monthly data of this station to describe changes in the filling level of the Baltic Proper. This record starts in December 1897 and ends in December 2003. On the base of monthly means, averaged winter values (January–March) were computed. Then, the decreasing trend was subtracted to obtain related anomalies (LO´) as described in more detail by Hupfer (2003) (Fig. 3). Investigating the effect of sea level air pressure on long-term changes in Baltic sea level, Heyen *et al.* (1996) concluded that the observed decreasing trend is primarily caused by geologically originated upward movements of the surrounding hinterland.

### Monthly differences in sea level air pressure between Gibraltar and Reykjavik

The phenomenon of the North Atlantic Oscillation (NAO) and its importance for the description of climatic changes over the North Atlantic Ocean and western Europe has been recently reviewed by Meincke (2002). In the simplest case the NAO can be described by changes in differences of sea level air pressure (SLP) between single meteorological stations in the south (Azores, Portugal, Gibraltar, etc.) and in the north (Iceland). Associated atmospheric centres of action are the well known Azores High and Icelandic Low. Using the thermal wind equation, the gradient between both air pressure centres describes the strength of the geostrophic zonal component in the belt of westerlies. Positive values correspond to enhanced west winds due to increasing core pressure of the Azores High and/or decreasing core pressure of the Icelandic Low and vice versa. Hurrell (1995) and Jones *et al.* (1997) updated monthly SLP values for Gibraltar (36°07´N, 05°21´W) and Reykjavik (64°09´N, 21°56´W). Both time series were available for January 1897–December 2002 (http://www.cru.uea.ac.uk/cru/data/nao.htm). These two stations were selected because the monthly SLP difference between Gibraltar and Reykjavik is more adequate to describe climatic changes over western Europe than the commonly used SLP difference between the Azores and Iceland. Values of the three winter months (January–March) were averaged for Gibraltar and Reykjavik and their difference computed. Its overall mean of 19.1 (± 0.7) hPa was subtracted to obtain corresponding anomalies (NAO´) (Fig. 3).

### Maximum ice coverage of the Baltic Sea

Peak values in the ice coverage of the Baltic Sea mainly occur between January and March. Extreme winters result either from the westward inflow of continentally transformed cold, dry air masses, which are formed under the influence of the Siberian High, or an enhanced eastward advection of warm, humid air masses originating all around the Icelandic Low over the North Atlantic Ocean. The series of maximum Baltic ice was obtained from Seinä and Palosuo (1996). It starts in 1720 and ends in 1995. This series was supplemented until 2002 by data of the Finnish Institute of Marine Research (FIMR, http://www2.fimr.fi/en/palvelut/jaapalvelu/jaatalvi2002-2003.html). The overall average of 187 000 (± 10 000) km$^2$ of the overlapping period (1897–2002) was subtracted to obtain corresponding anomalies (BI´) (Fig. 3). This mean value reflects about 49% ± 3% of the overall surface of the Baltic Sea, as estimated by Hagen and Feistel (2001) equivalent to 382 500 km$^2$.

## Comparative data

For comparison with the statistically relevant first principal component (PC) of the anomalies LO´, NAO´, and BI´, we used the following variables to show how they react on local, regional, and global scales: anomalies of (i) the Helgoland sea-surface temperature, (ii) the cold sums of air temperature at Warnermuende, (iii) the air temperature over central England, and (iv) the averaged air temperature of the northern hemisphere.

### Local scale

Monthly values of Helgoland sea-surface temperature (SST) were provided by H. Dooley from the data bank of the ICES (International Council for the Exploration of the Sea, Copenhagen). This series describes changes in SST at the Helgoland Island (54°11.30´N, 07°54.00´E) of the eastern North Sea (Fig. 1). It starts in January 1873 and ends in December 2001. Winter season averages (January–March) have been calculated and the overall mean of 3.59 (± 0.11) °C was subtracted to obtain corresponding anomalies (SSTA) (Table 1).

Cold sums summarise daily averages of dry air temperatures lower than 0 °C for each month to characterise mild or severe winters at a given meteorological station. The used data set results from records of the weather station Warnemuende (54°10´N, 12°08´E) in Germany (Fig. 1). It was provided by the German Weather Service (DWD, http://www.dwd.de/de/FundE/Klima/KLIS/daten/online/nat/index_standardformat. htm). This time series clearly demonstrates fluctuations of mild and severe winters over the western Baltic Sea. It starts in January 1947 and ends in December 2003. For comparison of its overall negative values with those of other time series all values have been standardised (mean = 0, standard deviation = 1) to obtain comparable numerical levels.

### Regional scale

Monthly averages of air temperature over central England were originally compiled by Manley (1974) for the period between 1659 and 1973. A revised version was presented by Parker *et al.* (1994) for 1772–1991 while the completed series (1659–2001) is available at http://www.met-office.gov.uk/research/hadleycentre/CR_data/Monthly/HadCET_act.txt. Averages of three winter months (January–March) were computed. The linear trend has been subtracted to obtain corresponding winter anomalies (MT´). The 343 years lasting trend (1659–2001) suggests increasing air temperatures over central England with a slope of 0.4 °C per 100 years on the regional scale (Table 1).

### Global scale

Monthly anomalies of land-surface temperature could be obtained from ftp://ftp.ncdc.noaa.gov/bub/data/anomalies. This updated data set is based on 5° resolution gridded values of Jones (1994) which cover the northern hemisphere between 20° and 90°N. Resulting anomalies point to a 30-year reference period (1961–1990). Such an area-weighted temperature anomaly has been the most commonly used parameter in climate change studies due to enhancement of the underlying signal-to-noise ratio by considering large spatial scales (Braganza *et al.* 2003). Winter season averages (January–March) were computed and detrended by linear regression between 1880 and 2003. The associated slope suggests a rise of 1.2 °C per 100 years over land surfaces on the hemispheric scale (Table 1). It exceeds that of regional changes over central England by a factor of about three, probably due to the more maritime climate over western Europe and dominating continental climate over intrinsic land surfaces of the northern hemisphere. For comparison, detrended anomalies have been standardised (mean = 0, standard deviation = 1).

## The winter Baltic climate index

Lengths of used time series and regression coefficients for overall trends are compiled in Table 1. Due to the global nature of interannual changes, we like to follow Feistel *et al.* (2003) and accept the working hypothesis that variabilities in the NAO´, the LO´, and the BI´ involve a joint component in the parameter domain. It should be well reflected by loading factors and time coefficients of unrotated, principal components. This method is described in more detail by Wilks (1995). It reduces a data set containing a certain number of variables to a data set containing fewer new variables (empirical modes) which represent a large fraction of the variability con-

**Table 1**. Abbreviations, time span, duration, and coefficients of linear regressions ($y = A + B \times \text{Year}$) which were used to compute winter anomalies (January–March) for (i) the filling level in the Baltic Proper expressed by sea level changes at Landsort (LO´), (ii) the North Atlantic Oscillation (NAO´) given by the difference in sea level air pressure between Gibraltar and Reykjavik, (iii) maximum Baltic ice coverage (BI´), (iv) sea surface temperature at the Helgoland Island, North Sea (SSTA), (v) sums in air temperature lower than 0 °C at the coastal station Warnemuende, Germany (Cold Sum), (vi) air temperature over central England (Manley Temperature, MT´), and (vii) globally averaged air temperature of land surfaces of the whole northern hemisphere (20–90°N) (NHL´); the corresponding correlation coefficient *R* is significant at the 95% confidence level (*t* distribution).

| Abbreviation | Time | Years | *A* | *B* | *R* |
|---|---|---|---|---|---|
| LO´ | 1897–2002 | 106 | 686.36 | –0.2536 | –0.45 |
| NAO´ | 1897–2002 | 106 | – | – | – |
| BI´ | 1897–2002 | 106 | – | – | – |
| SSTA | 1873–2001 | 129 | – | – | – |
| Cold Sum | 1947–2003 | 57 | – | – | – |
| MT´ | 1659–2001 | 343 | –2.48 | 0.0036 | 0.27 |
| NHL´ | 1880–2003 | 124 | –23.14 | 0.0119 | 0.63 |

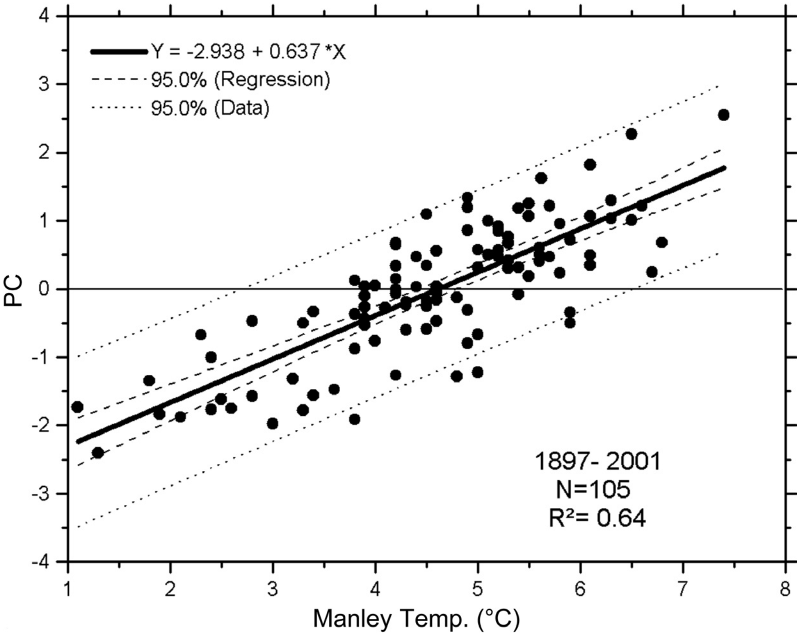


**Fig. 4**. Linear regression between the averaged winter (December–March) temperature (°C) over central England and the first empirical mode (PC) shown in Fig. 3 for the overlapping 105 years (1897–2001). The coefficient of determination is $R^2$ = 0.64 and statistically justifies the backward extension of the PC until the little ice age.

tained in the original data. Applied to the Baltic Sea data discussed before, the remaining first empirical mode explains 75.4% of the total variance. Its loading factors are 0.87 for the NAO´, 0.88 for the LO´, but –0.85 for the BI´. These loadings provide the common correlation coefficient between the input series and, suppressing their noisy fluctuations, the resulting time coefficients (PC). The latter are considered to be the base for the deduced winter index (Fig. 3). Due to the applied method, this index is given with an overall zero mean and unit standard deviation. The positive loading factors correspond to enhanced westerlies over the North Atlantic and western Europe (NAO´ > 0), higher filling levels in the Baltic Proper (LO´ > 0), but reduced maximum ice cover in the Baltic Sea (BI´ < 0) and vice versa. Underlying regressions suggest that, for instance, changes of ± 0.5 units account for ± NAO´ ~ 3 hPa, ± LO´ ~ 5 cm, and ± BI´ ~28 000 km$^2$. The last value reflects about seven percent of the overall surface of the Baltic Sea.

From the statistical point of view, the frequency resolution of the power spectrum could be essentially improved by backward extension of the obtained first empirical component. As climate changes over the Baltic Sea should be well mirrored in long lasting changes of air temperature over western Europe, the well-known "Manley Temperature Series" is a promising candidate for such a regression. This series describes monthly air temperatures over central England for 343 years (1659–2001). Its time period overlaps with that of our PC for 105 winters (1897–2001). Positive values of the PC coincide with mild winters over central England (MT´ > 0) and vice versa (Fig. 4). The resulting regression explains 64% of the total variance on the 95% confidence level (*t* distribution). This confirms that winter season anomalies in the air temperature over central England are very informative about hydrographic conditions in and around the Baltic Sea. Both the regressively computed and the original PC series are drawn in Fig. 5. The resulting series covers 344 years, but maintains the PCs for the last 106 years (1897–2002). Its overall standard error is 0.05 units (1659–2002) (Table 2). In the following, this extended series will be named **Win**ter **B**altic Climate **I**nde**x** (WIBIX). It follows a Gaussian frequency distribution sufficiently well and fulfils all statistical prerequisites for the power spectrum analysis (Fig. 6).

## Quasi-periods and regime shifts

Due to the use of detrended input series, the general shape of the resulting WIBIX spectrum

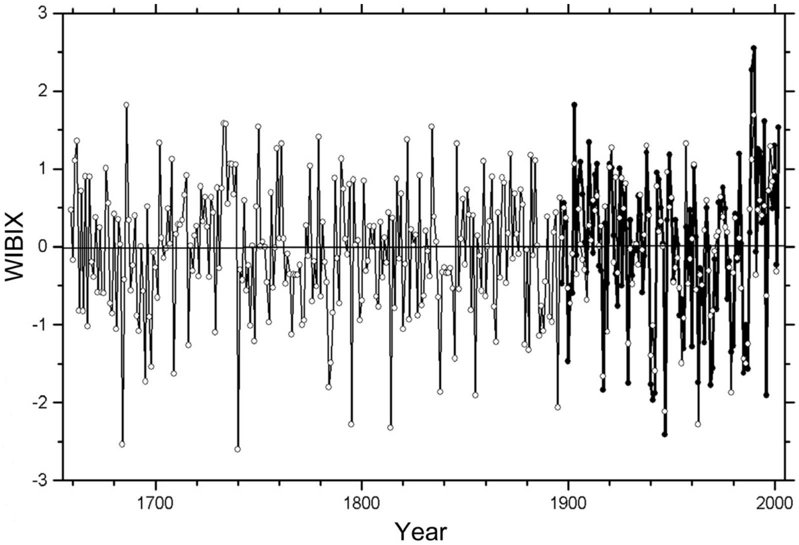


**Fig. 5**. The Winter Baltic Climate Index (WIBIX) for December–March resulting from the first principal component (PC) (thick line, 1897–2002) and regressively extended coefficients (thin line, 1659–1896).

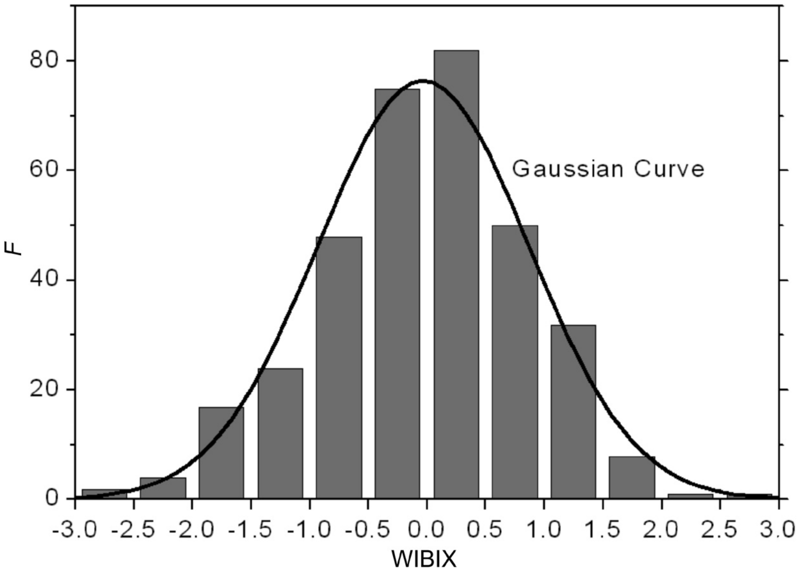


**Fig. 6**. Frequency distribution (*F*) of the WIBIX (1659–2002) for *N* = 344 years (Fig. 5); it follows a Gaussian distribution (bold line).

describes that of "white noise" with a constant energetic background level and superimposed peak values. It exhibits four significant peaks exceeding the 95% confidence level (*t* distribution) (Fig. 7). They cover a relatively wide range of quasi-periods. The shortest of them points to the well-known cycle of the Quasi-Biennial Oscillation (QBO) with the averaged length of 26 months (Naujokat 1986). The next one reveals the three year cycle, which was observed not only in the Baltic Sea (Börngen 1978), but also world-wide (Wagner 1940). The level of power increases towards the next peaks of six

**Table 2**. Basic statistics of the first principal component (PC) and the WIBIX; skewness and kurtosis vanish for the Gaussian distribution.

| Parameter | PC (75.4%) | WIBIX |
|---|---|---|
| Time | 1897–2002 | 1659–2002 |
| Years | 106 | 344 |
| Mean | 0 | –0.05 |
| Standard deviation | 1 | 0.877 |
| Standard error | 0.097 | 0.047 |
| Maximum | 2.55 | 2.55 |
| Minimum | –2.41 | –2.60 |
| Skewness | –0.235 | –0.273 |
| Kurtosis | –0.247 | 0.096 |

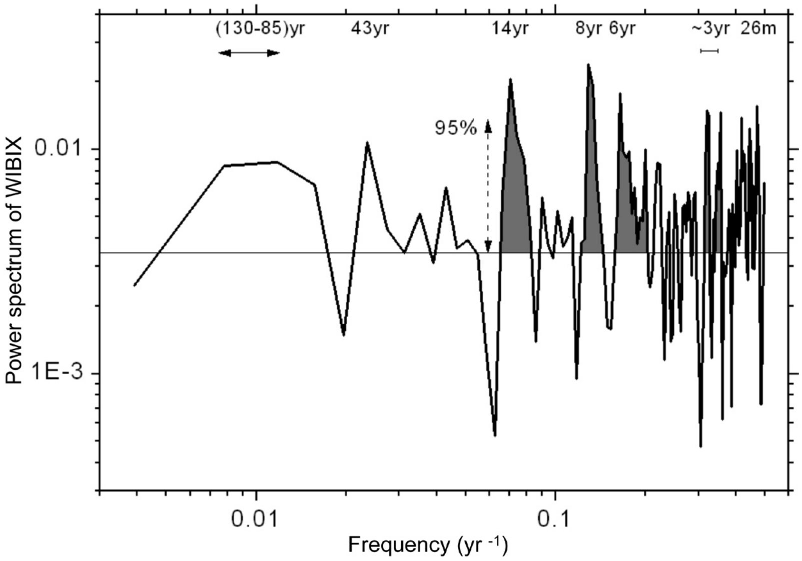


**Fig. 7**. Power spectrum of the WIBIX (Fig. 5). Peak values above the constant "white noise level" (horizontal line) characterise quasi-cycles of 2.2, 3, 6, 8, and 14 years exceeding the 95% confidence level (*t* distribution, dashed arrow). Squared amplitudes were scaled on the overall variance and the resulting confidence interval is constant for all spectral estimates plotted versus logarithmic ordinates since its interval widths are proportional to estimated amplitudes.

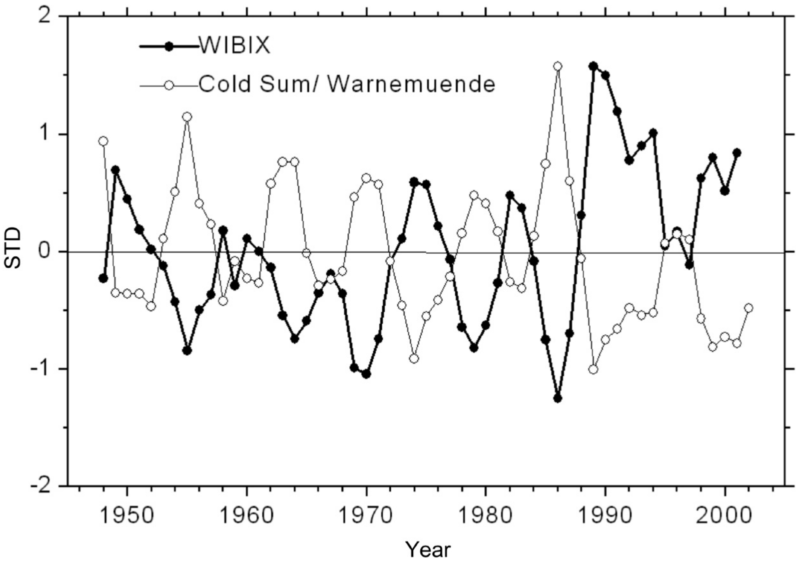


**Fig. 8**. Three years running means of standardised series (mean = 0, standard deviation = 1, 1947–2003) resulting from the first principal component (PC, dots) and the winter (December–March) cold sums at Warnemuende/Germany (open circles).

and eight years. These most energy-rich peaks reveal characteristic changes of the winter NAO (Meincke 2002). Comparable quasi-periods are clearly seen in plots of three-year running means of the WIBIX and those of standardized anomalies of three-monthly averaged (January–March) cold sums observed in air temperature at Warnemuende (Fig. 8). The energetic level of the spectrum perennially decreases towards longer periods. Related peaks of 14, 43, and about 85–130 years should be of global origin (Grötzner *et al*. 1998). However, the significance is relatively poor for quasi-periods longer than 40 years because they are only 3–8 times represented in the series of 344 winters. Nevertheless, the WIBIX is able to explain 55% of fluctuation in corresponding anomalies (January–March) of sea surface temperature (SSTA), which was measured between 1873 and 2001 at the coastal station of Helgoland, North Sea (Fig. 9). That means this index reflects climatic changes in the transition zone between the North Sea and the Baltic Sea, too.

When focussing attention at possible regime shifts in the Baltic climate it seems to be necessary to oppress relevant short periods in the

WIBIX series. The simplest way is to use cumulative plots of standardised anomalies (mean = 0, standard deviation = 1), cf. Jacobeit *et al.* (2001). The changing sign of accumulated values exhibits turning points by relative peak values. For the case of standardised series, they are given by multiples of the underlying standard deviation. Between neighbouring turning points, the obtained curve should once intersect the line standard deviation = 0. The enclosed time interval characterises a certain climatic regime through ascending (positive anomaly) or descending curve segments (negative anomaly). Applying this concept, a total of six turning points could be identified (Fig. 10 and Table 3). They separated three mild (maritime) from three severe (continental) winter modes lasting between 25 and 163 years. However, there was a slight tendency for longer continental modes including the longest period of time (1739–1902). With the exception of this exceptional long-lasting climatic regime, the average of remaining climate modes is 37 ± 5 years. Such a value confirms the estimated quasi-period of about 43 years (Fig. 7). Here, we only may speculate that such long quasi-cycles probably attribute to so-called teleconnection processes which control climate changes on the hemispheric scale. Apparently, decadal scale changes in the WIBIX are controlled by winter anomalies in the land-surface temperature averaged over the northern hemisphere (20–90°N) (Fig. 10). They contribute about a quarter of the total variance. This follows from the associated coefficient of determination resulting from the cross-correlation of both series. However, most of the WIBIX variability originates from atmospheric processes which are regionally controlled (Figs. 4, 5 and 9).

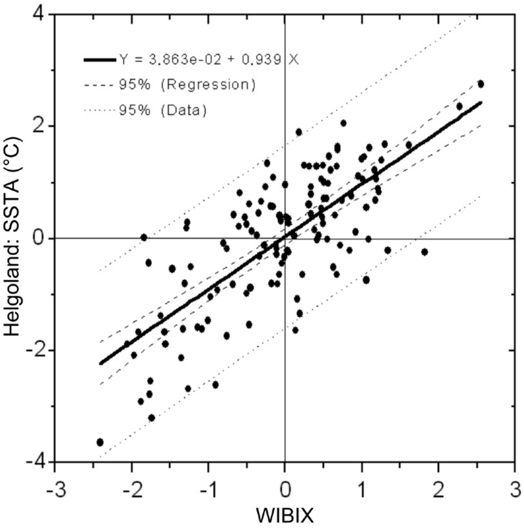
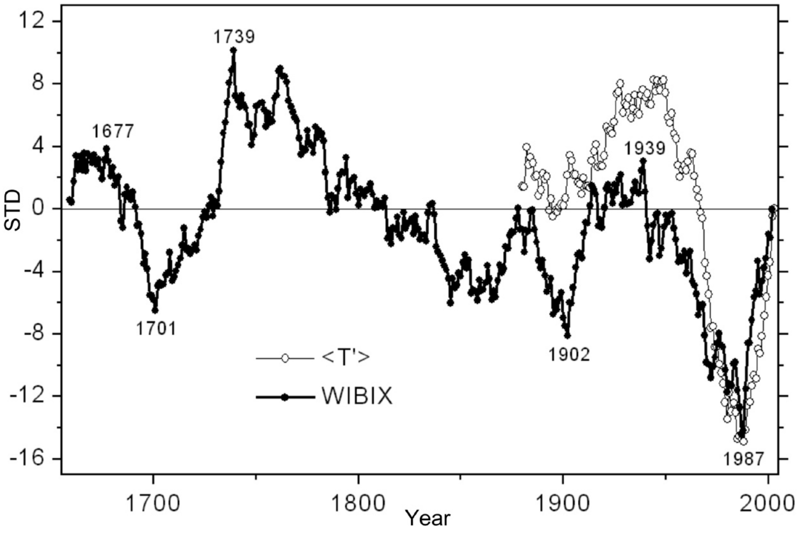


**Fig. 9**. Regression between the WIBIX (Fig. 5) and the winter anomalies (December–March) in sea surface temperature (SSTA) observed at the North Sea Island Helgoland (Fig. 1) for the $N$ = 129 overlapping years (1873–2001). The coefficient of determination is $R^2$ = 0.55.

**Fig. 10**. Cumulative series of the standardised WIBIX (mean = 0, standard deviation = 1) drawn in Fig. 5 and corresponding winter anomalies (December–March, 1880–2002) of the land air temperature (< $T'$ >, open circles) averaged over 20–90°N. Relative peak values indicate turning points (years) between subsequent climatic regimes which are marked through increasing (mild regime) or decreasing curve segments (severe regime).



## Discussion

So-called major Baltic inflows are able to renew completely the deep water of the entire Baltic Proper, mainly during the winter season, cf. Matthäus and Franck (1992) and Kouts and Omstedt (1993). They occur on the interannual time scale. Including the Gulf of Finland and the Gulf of Riga, the volume of the Baltic Proper is about 70% of the total volume of the Baltic Sea (Winsor *et al.* 2001). It represents the Arkona Sea, Bornholm Sea, and western/eastern Gotland Sea (Fig. 1). Sporadic renewals of deep water strictly depend on adjusted changes between prevailing easterly and westerly winds over the North Atlantic and the Baltic Sea on the scale of several days up to a few weeks (Schinke and Matthäus 1998). Such relatively short changes in weather conditions over the Baltic Sea are embedded in climatic trends, which determine the sequence of mild or severe winters (Wagner 1940). Alternating predominance of maritime and continental types of the general weather situation forms a climatic transition zone with quasi-oscillations on interannual and decadal scales (Hupfer and Klige 1991). This follows from the analysis of relatively long observation series dating back over more than one century. Meteorological and hydrographic key parameters are given by air temperature, sea level air pressure, precipitation, river discharge, maximum ice cover, sea level, water temperature, salinity, dissolved oxygen, and currents in the whole water column. In the past, homogeneous long-term series were mainly recorded on board of anchored light vessels, but with a significant gap during World Wars I and II (Matthäus 1995). Thereafter, auxiliary hydrographical, chemical, biological, and geological quantities have been observed more frequently by research cruises of many riparian countries (Fonselius and Valderrama 2003). The analysis of these interdisciplinary data sets completed the recent picture about climatic development tendencies in the Baltic Proper (Winsor *et al.* 2001).

**Table 3**. Climate regimes of continental (severe) and maritime (mild) winter modes (January–March) over the Baltic Sea derived from the cumulatively plotted WIBIX (Fig. 10).

| Number | Regime | Type | Years |
|---|---|---|---|
| 1 | 1677–1701 | continental | 25 |
| 2 | 1702–1739 | maritime | 38 |
| 3 | 1740–1902 | continental | 163 |
| 4 | 1903–1939 | maritime | 37 |
| 5 | 1940–1987 | continental | 48 |
| 6 | 1988– | maritime | ? |

Reviewing Baltic Sea physics, Omstedt *et al.* (2004) recently concluded that further research is needed to link our understanding of the large-scale atmospheric circulation over the Baltic Sea with that of globally occurring processes in order to obtain a deeper insight into dynamics controlling climate changes on year-to-year, decadal, and long-term scales. Associated variabilities are inherently linked with fluxes between ocean and atmosphere, mainly via the exchange of heat. Over the Baltic Sea, the alternating advection of maritime or continental air masses produces climatic episodes in general weather situations, cf. Gerstengarbe and Werner (1993) and Weisse *et al.* (1994). Their study required well homogenised data sets with a sufficient grid resolution not only in space but also in time. Simple climate indices are frequently used to overcome this problem. In contrast to the usually applied index of the North Atlantic Oscillation (NAO), which mainly describes changes in the climate over the North Atlantic Ocean and western Europe, the Winter Baltic Climate Index (WIBIX) developed in this study also incorporates the impact of continentally originated climate fluctuations via maximum ice cover and filling level of the Baltic Proper. It is based on the working hypothesis about alternating dominance of maritime and continental climate modes with their own characteristics in atmospheric circulation patterns. Such patterns are assumed to be superimposed on the removed trend of warming, which occurs at the whole northern hemisphere on the century scale. According to Michaels *et al.* (2000), this tendency of warming mainly results from the increasing winter temperature in cold, dry air masses of the Siberian anticyclone. That means not only enhanced westerlies but also more intense easterlies may contribute to the observed trend of decreasing Baltic ice cover. Independently of this trend of warming, the resulting WIBIX is considered to be a robust quantity to categorise given meteorological, hydrographical, chemical, and biological time series of limited length in the context of decadal scale changes in the winter climate over the Baltic Sea. It elucidates climatic "regimes" and associated "turning points" for winter environmental conditions (January–March). The maximum ice cover frequently peaks during February–March and the so-called "Major Baltic Inflows" mainly occur during the winter season to renew the deep water with drastic consequences for the ecosystem.

The WIBIX sufficiently reflects changes in local, regional, and global parameters. It covers 344 winters (1659–2002), and the obtained power spectrum points to quasi-cycles of 2.2, 3, 6–8, 14, 43, and 80–130 years. However, the two longest cycles do not reach the required statistical significance of the 95% confidence level. We may expect that different processes, which work on different spatio-temporal scales, force different quasi-cycles with fluctuating intensity. For instance, Jaani *et al.* (1999) reattempted to explain decadal scale changes in Baltic ice cover by changes in solar activity. In general, the alternating sign of the WIBIX describes two different winter modes. The maritime (mild) mode (WIBIX > 0) stands for an enhanced North Atlantic Oscillation with pronounced westerlies over western Europe. The increased advection of relatively warm, humid air masses is responsible for mild winters over the Baltic Sea. Via wind-induced surges, intensified precipitation in the catchment area of the Baltic Sea, and higher river discharge this mode is accompanied by increasing filling levels in the Baltic Proper, but decreasing peak values in the maximum Baltic ice cover. According to Zorita and Laine (2000), this mode also effects decreasing salinities and increasing values of dissolved oxygen within near-surface layers of the Baltic Proper. Here, this may be caused by intensified downward mixing in reaction on weakened stratification and enhanced wind-stirring. However, intensified downward convection ventilates the whole water column much deeper during the continental (severe) mode. Thus, both modes are expected to significantly influence the development of the ecosystem in the Baltic Sea as well as that in transition areas towards the North Sea. Furthermore, it became evident that there is a strict correspondence between long-term changes in the derived WIBIX and those of anomalies in air temperature over central England. That means the central England temperature is very informative about hydrographic conditions in and around the Baltic Sea. For instance, it correlates well with the maximum Baltic cover. The correlation coefficient $R = 0.55$ exceeds the 95% confidence level for 282 overlapping years (1720–2002). However, a somewhat stronger correlation ($R = 0.74$) was found between the WIBIX and anomalies in sea surface temperature observed at the island station Helgoland, which is located in the south-eastern North Sea. Comparing changes in sea-level height, sea-surface temperature, wind speed, and sea-level atmospheric pressure in the Mediterranean Sea, the North Sea, and the Baltic Sea for five years (1992–1997), Fenoglio-Marc (2001) concluded that there is a high correlation between sea-level height and the wind speed in the North Sea and the Baltic Sea on the year-to-year scale. This is due to the relatively large extent of atmospheric circulation patterns travelling eastward in the belt of westerlies.

Strong phases of increased ice cover in the western Baltic Sea are characterized by frequent blocking situations (relaxed westerlies), and the phases of reduced ice cover may be regarded as phases of increased zonal circulation (Koslowski and Glaser 1999). In the recent past, mild winters occurred between 1900 and 1940 and since the late 1980s. During both climatic regimes, river run-off into the Baltic Sea increased and salinity decreased at the 200 m horizon of the Baltic Proper due to freshening of the whole water column (Matthäus 1995). Such changes in salinity non-linearly follow the total freshwater run-off to the Baltic Sea with a relatively short lag of several months (Hänninen *et al.* 2003). In context of long-term changes of the Baltic hydrography, the Baltic Sea Index (BSI) of Lehmann *et al.* (2002) cannot be considered to be typical for one of the identified winter modes. It is based on monthly differences in sea level air pressure between Szczecin (Poland) in the south and Oslo (Norway) in the north to describe the more regional wind forcing from 1979 until 1999. This time window is centred near the detected turning point of 1987. On the year-to-year scale, the first eight winters belong to the last continental mode while the rest is subject to the persisting maritime mode. Consequently, the climatic tendency exhibits a parabolic shape all around the winter 1987. Nevertheless, these authors also concluded that large-scale atmospheric patterns have a strict impact on regional atmospheric conditions.

Inspecting statistics of corresponding types of general weather situations, cf. fig. 2 in Jacobeit *et al.* (2001), it becomes clear that the mild (maritime) winter mode is characterised by increasing frequencies of west-southwest types, but decreasing frequencies of east-northeast types. Opposite conditions dominate the severe (continental) winter mode with the WIBIX < 0. Such a mode started with the exceptionally severe winter 1739–1740 and lasted more than one and a half centuries (Lutebacher *et al.* 2002). The next cold regime only controlled 48 years (1940–1987). This period of time was accompanied by cooling of the northern hemisphere (20–90°N). Such a correspondence between decadal scale changes of the WIBIX and those in anomalies of land surface temperature of the northern hemisphere confirms that climate changes over the Baltic Sea are remarkably influenced by globally detected fluctuations. Furthermore, it must be expected that associated environmental changes also control the development of the whole Baltic ecosystem, up to the food chain level of fishes.

Fisheries landings have been systematically recorded since the 1920s in the Baltic Sea (Mackenzie *et al.* 2002). Here, the cold water favouring herring is one of the most important fish species. In the past, different severe winter modes were also responsible for an extraordinary herring fishery along the Swedish Bohuslän coast in the Skagerrak. Concerning the overlapping period with the WIBIX, exceptional herring landings were reported from this transition zone around 1780 and 1890 (Alheit and Hagen 1997). Associated climate regimes were marked by negative peak values of the cumulative WIBIX indicating the temporary dominance of the severe mode. Somewhat later a similar situation was observed in the Baltic Proper during the beginning of the 1940s, but on a much lower level (Parmanne *et al.* 1994). However, this increase was also supported by application of modern fishing technologies and it seems to be extremely difficult to distinguish properly between the effect of climate modes and that of changed fishing efforts. Nevertheless, the observed turning point between the ending mild mode and the beginning severe mode caused increasing landings in herring and cod while those of plaice decreased significantly, cf. Meyer and Kalle (1950) and MacKenzie *et al.* (2002). This tendency lasted until the end of the 1980s when the mild mode returned (Kalejs and Ojaveer 1989). The superposition of mentioned quasi-cycles of different length excited specific hydrographic conditions of limited length, especially in fishing grounds of the deep Baltic basins. For example, intrusions of saline deep water shortly peaked in the Bornholm Basin and all around the Gotland Deep during the early 1950s, cf. Schemainda (1956) and Kalejs and Ojaveer (1989). The cumulative WIBIX marks this by positive peak values, which indicate an interim period of mild winters occurring during the prevailing severe mode. Furthermore, this index series suggests that adjacent mild episodes of comparable duration excited conditions for alternating cod stocks with a decreasing tendency in the Bornholm Basin between the early 1970s and the mid 1980s (Berner *et al.* 1989). Thereafter, the turning point of 1987 shifted the central Baltic fish community from a cod dominance during the 1980s to a sprat dominance during the 1990s (Bagge *et al.* 1994, Möllmann *et al.* 2004). MacKenzie and Köster (2004) concluded that a warmer Baltic Sea could be favourable for an increasing sprat population. In addition to the prevailing mild mode in the late 1980s until the early 1990s, the overall cod stock was reduced by intensified fishery activities to a very low level of biomass. However, it finally benefited from the high productivity of herring and sprat supplying its major prey (Gislason 1999). Independent of such changing fishery efforts and biologically originated feedback mechanisms, we conclude that the deduced WIBIX may be employed as a robust index for the description of climate variability over the Baltic Sea and adjacent areas from the little ice age (1670–1700) until now. In a simple fashion, it may also be used to characterise mild or severe winter conditions in the Baltic hydrography as well as associated consequences for the Baltic fishery. By utilising the statistical persistence of the WIBIX, it also could be employed for creating statistically based forecasting concepts to evaluate climatic development tendencies for a few winters in advance.

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