REPORT

A Multivariate Baltic Sea Environmental Index

Joachim W. Dippner, Georgs Kornilovs,
Karin Junker

Received: 28 April 2011 / Revised: 5 August 2011 / Accepted: 18 February 2012 / Published online: 20 March 2012

Abstract Since 2001/2002, the correlation between North Atlantic Oscillation index and biological variables in the North Sea and Baltic Sea fails, which might be addressed to a global climate regime shift. To understand inter-annual and inter-decadal variability in environmental variables, a new multivariate index for the Baltic Sea is developed and presented here. The multivariate Baltic Sea Environmental (BSE) index is defined as the 1st principal component score of four z-transformed time series: the Arctic Oscillation index, the salinity between 120 and 200 m in the Gotland Sea, the integrated river runoff of all rivers draining into the Baltic Sea, and the relative vorticity of geostrophic wind over the Baltic Sea area. A statistical downscaling technique has been applied to project different climate indices to the sea surface temperature in the Gotland, to the Landsort gauge, and the sea ice extent. The new BSE index shows a better performance than all other climate indices and is equivalent to the Chen index for physical properties. An application of the new index to zooplankton time series from the central Baltic Sea (Latvian EEZ) shows an excellent skill in potential predictability of environmental time series.

Keywords Baltic Sea · Climate indices · Environmental prediction

INTRODUCTION

Various climate indices have been developed in the last decades to understand inter-annual and inter-decadal climate variability and to identify the response of ecosystems to climate variability. Studies have been performed correlating biological variables to climate indices for various regions. In the Atlantic sector, the North Atlantic

Oscillation (NAO) index (Hurrell 1995) has been widely used to identify the response of climate variability in terrestrial (Myrsterud et al. 2003), freshwater (Straile et al. 2003) and marine ecosystems (Drinkwater et al. 2003; Dippner 2006 and references therein). However, there is evidence that the correlation of NAO and biological variables, e.g. macrobenthos communities in the southern North Sea fails after 2001/2002 (Dippner et al. 2010) which might be addressed to a climate global regime shift (Swanson and Tsonis 2009). The same regime shift has been observed in the Baltic Sea (Möllmann et al. 2009).

The Baltic Sea is an intra-continental brackish water basin with a total area of 415,000 km² (including Kattegat, Fig. 1). The catchments area is four times larger and populated by ~85 million inhabitants. Climate variability in the last 150 years overlaps with human activity in the drainage basin leading to considerable change in the biogeochemistry of the semi-enclosed sea. The Baltic Sea is characterized by a closed basin circulation (Voss et al. 2005) strong horizontal as well as vertical salinity gradients, and pronounced heterogeneity in ecosystem variables. The horizontal salinity gradient is responsible for the unique situation in the Baltic Sea with marine species in the transition area to the North Sea and freshwater species at the end of the Gulf of Finland and the Bothnian Bay (Fig. 1).

The inter-annual and inter-decadal variability of the Baltic Sea is characterized by the climate variability on the northern hemisphere and major Baltic inflows of water with relatively high salinity propagating from the North Atlantic through the North Sea into the deeper parts of the Baltic Sea (Matthäus and Frank 1992).

A statistical analysis (Chen and Hellström 1999) of the seasonal and inter-annual variations in the regional temperature anomalies of Sweden during 1861–1994 shows a

Fig. 1 Depth distribution of the Baltic Sea and its basins: Bothnian Bay (BoB), Bothnian Sea (BoS), Archipelago Sea (AR), Gulf of Finland (GF), Gulf of Riga (GR), Gotland Sea (GS), Bornholm Sea (BS), Arkona Sea (AS), Danish Sounds (DS) and Kattegat (KT). The red asterisk marks the position of Landsort gauge. The red lines mark the area of ICES subdivision SD 28

strong relation to the NAO for the period 1985–1994. However, correlation analysis over different periods shows that the strength of association varies with time and region (Chen and Hellström 1999). To improve statistical downscaling models, Chen (2000) derived circulation indices for Scandinavia from monthly sea level pressure data based on the classification system of Lamb (1950). These indices allow a reproduction of 70 % of the total variance in the January air temperature for Sweden during 1887–1994.

The large-scale atmospheric circulation patterns in the Arctic and North Atlantic described by the Arctic oscillation (AO) and NAO significantly control ice extent and ice thickness in the Baltic Sea (Omstedt and Chen 2001). AO and NAO are highly correlated if the atmospheric dynamics is driven by the North Atlantic (Deser 2000); however, the AO appears to describe more of the dynamics of the Baltic Sea ice conditions than the NAO (Jevrejeva et al. 2003).

Atmospheric forcing also influences the general circulation and the sea level. Approximately 85 % of the variability in sea level anomalies can be explained by the NAO and 10 % by the Vb storm track (Heyen et al. 1996), the only persistent cyclone pathway in Europe which may

cause extreme precipitation and huge flooding of central and eastern European rivers during summer time (Mudelsee et al. 2004). A more detailed analysis indicates regional differences in winter sea level variations (Hünicke et al. 2008). In the central and eastern Baltic Sea, the sea level variation is correlated to the North Atlantic sea level pressure similar to Heyen et al. (1996). In contrast, in the southern Baltic Sea, sea level variation is best explained by area averaged precipitation (Hünicke et al. 2008).

A linear correlation analysis reveals the NAO accounts only for about 10 % of the general volume exchange of the Baltic Sea with the North Sea (Lehmann et al. 2002). This was the reason for Lehmann et al. (2002) to develop the regional Baltic Sea index which has a much better performance than the NAO index itself.

Salinity and oxygen concentration in the Baltic Sea also depend strongly on large-scale atmospheric circulation (Zorita and Laine 2000). A strong meridional sea level pressure gradient over the North Atlantic causes positive rain fall anomalies, increasing river runoff and decreasing salinity. Due to the weakened stratification, deep water oxygen concentrations increase (Gerlach 1994; Zorita and Laine 2000). An increase in precipitation will also result in

higher input of nutrients or dissolved organic matter by rivers and enhanced eutrophication in near coastal areas with higher phytoplankton and benthic biomass (Dippner and Ikauniece 2001).

A long-term analysis of 100 years of hydrographic data with focus on the freshwater budget (Winsor et al. 2001, 2003) indicates that freshwater supply to the Baltic Sea has large variations on time scales up to several decades. A similar result has been obtained by Omstedt et al. (2004). They argued that it is rather problematic to clearly define ‘trends’ or ‘regime shifts’ on shorter time scales because the Baltic Sea has decadal climate modes on the order of 30–60 years. Analysis of a cumulative Baltic winter index shows that during the last 350 years six climate regime shifts have occurred (Hagen and Feistel 2005).

Recently, Dippner et al. (2010) showed that since 2001/2002 the high correlation between climate predictors and environmental response variables failed due to a non-linear regime shift. In such a situation, the response of the biological system to climate variability cannot be predicted any longer with linear methods or simple indices such as the NAO. To overcome this problem two possibilities exist, the development of alternative climate predictors or the application of nonlinear prediction methods. The development of a new multivariate index and first applications to physical and biological time series are presented here.

MATERIALS AND METHODS

Data

The following data sets have been used in this study:

- (1) Monthly mean values of the AO index from 1899 to 2007 (Thompson and Wallace 1998) which describe the leading Empirical Orthogonal Function (EOF) of monthly geopotential height anomalies at the 1,000 hPa level on the northern hemisphere poleward from 20°N;
- (2) Monthly mean values of the NAO index from 1864 to 2009 (Hurrell 1995) defined as the difference between the normalized sea level pressure anomalies between Lisbon and Stykkisholmur;
- (3) The Atlantic Multidecadal Oscillation index from 1856 to 2009 (Enfield et al. 2001) defined as the monthly mean sea surface temperature (SST) anomalies in the North Atlantic area weighted from 0° to 70°N;
- (4) Monthly mean values of the Baltic Sea index (Lehmann et al. 2002). An extended version (1948–2009) of the Baltic Sea index is used here which is combined from data from the Swedish

Meteorological and Hydrological Institute (SMHI) and data from the National Centre of Environmental Predictions (NCEP; Kalnay et al. 1996) There are no inhomogeneities between these two data sets.

- (5) Monthly mean values of the updated (1780–2010) Chen index (Chen 2000). The Chen index consists of three time series: the components of the geostrophic wind and the relative vorticity of the geostrophic wind over the area 50°–70°N and 0°–30°E.
- (6) Monthly mean SST fields derived from the comprehensive ocean atmosphere data set (COADS) on a 2°×2° grid for the period 1900–1992 (Woodruff et al. 1987). In addition, an updated version of the COADS for the period 1960–2010 is also used (<http://icoads.noaa.gov/data.icoads.html>).
- (7) Monthly mean salinity on oceanographic standard depth has been compiled on 1°×1° grid for the whole Baltic Sea (Feistel et al. 2008). We average the data from 1900 to 2005 between 120 and 200 m in the area of the central Gotland Sea 16°–22°E and 55°–59°N (Fig. 1) to a salinity time series.
- (8) Monthly mean runoff data for the whole Baltic Sea area for the period 1921–1993 has been compiled by Bergström and Carlsson (1994). The data set for river runoff consists of the data from Mikulski (1982) for the period 1921–1949, and the data compiled by the SMHI for the period 1950–1993 and extended later up to 2002. There are no inhomogeneities between these two data sets.
- (9) Monthly mean SST from 1902 to 2005 in the Gotland Sea area averaged between 16°–22°E and 55°–59°N (Feistel et al. 2008);
- (10) Monthly mean values from Landsort gauge (Fig. 1) for the period 1897–2002 from SMHI;
- (11) Annual average sea ice extent for the period 1720–2006 (Feistel et al. 2008);
- (12) Seasonal (May, August, October) time series of mesozooplankton for the period 1960–1997 from the Central Baltic Sea in the area of ICES subdivision SD 28 (Fig. 1).
- (13) Seasonal time series of mesozooplankton for the period 1960–2008 from SD 28 (Fig. 1).

Zooplankton Sampling

The samples were collected with Juday net, the opening diameter of 0.36 m and the diameter of the middle section 0.5 m, mesh size 0.16 mm. The hauls were carried out vertically from the depth of 100 m or from the bottom at the stations shallower than 100 m and from different depth layers: mainly 0–25, 25–50 and 50–100 m. Taking into

account some sampling deeper than 100 m, it could be considered that mesozooplankton is distributed till the depth of 100 m and only some smaller part of adult *Pseudocalanus elongatus* can be met deeper. The sampling is conducted throughout the daytime. Zooplankton samples are preserved in formaldehyde and later treated in the laboratory under binocular microscope. All zooplankton specimens are determined as to species or in some cases to genus, and, for Copepoda species, seven stages—nauplii, five copepodite stages and adults—are distinguished. The biomass per cubic metre is calculated assuming that the filtered volume was 1 m³ per 10 m of the water layer and the filtering coefficient was regarded as 1 (UNESCO 1968). Biomasses are estimated from values of individual wet weights (Hernroth 1985). Averages are calculated for the shallow and deep (>100 m) stations separately. The adult stages of all zooplankton species with sufficient abundance are considered for our experiment. These are *Acartia* spp., *Bosmina longispina*, *Evadne nordmanni*, *Pseudocalanus* spp., *Syncheata* spp. and *Temora longicornis*. These data have been used in a previous article (Dippner et al. 2000) to show the climate-driven variability in a downscaling experiment using COADS SST as climate predictor.

From the 1960–2008 monitoring data, we select the average biomass and abundance of the adult and copepodite stages of the three major species (*Acartia* spp., *T. longicornis* and *Pseudocalanus* spp.) of the depth interval 0–100 m for the deeper stations, and 0-m bottom of the shallower stations.

Statistical Downscaling

In modern time series modelling two approaches are used regarding the treatment of auto-correlations. If the invariant dynamics of an ergodic system is of interest, the auto-correlation in the time series must be removed (e.g. Dippner et al. 2002). In contrast, in the case of time series prediction, auto-correlation is an essential part of the contained information and must be preserved. The statistical downscaling technique, a multivariate method used here, has been developed by von Storch et al. (1993). The idea is to correlate the potential climate predictor variables with the regional observations and to look for high correlations. The predictands are the anomalies (against the seasonal cycle) of the regional observations, i.e. Landsort gauge, ice extent or mesozooplankton. The predictors are the anomalies of climate observations, i.e. AO, NAO, Baltic Sea index, Chen index and BSE index. Possible time lags of 1 month up to 1 year between the signals in climate and the local variables are taken into account. As the time series are auto-correlated, we restrict the time lag to this span. In a second step, the combinations with the highest skills that are detected automatically are selected and tested

for their statistical significance. Finally, the physical and biological plausibility of the remaining combination has to be evaluated.

Information from fields of climate predictors and regional predictands can be related to each other in the following way: first, empirical orthogonal functions (EOFs, also known as ‘principal components’) of the anomalies of climate predictors $\vec{C}'(x, t)$ and the anomalies of regional predictands $\vec{R}'(x, t)$, both are functions of space x and time t , are calculated.

$$\vec{C}'(x, t) = \sum_i \vec{C}_i(x) c_i(t) + \text{noise}$$

$$\vec{R}'(x, t) = \sum_i \vec{R}_i(x) r_i(t) + \text{noise}$$

Thus, the major part of the variance from a multidimensional vector is concentrated in few new dimensions, the leading eigenmodes $C_i(x)$ and $R_i(x)$ which are functions of space only. The advantage is to keep the dimensionality of the model low. Second, a canonical correlation analysis is performed between the leading eigenmodes of the climate predictor and the regional time series. The canonical correlation analysis identifies patterns $C_i(x)$ and $R_i(x)$ and time series $c_i(t)$ and $r_i(t)$ which are optimally correlated to each other. Hence, the regional time series can be regressed from predictor data as $\vec{R}'(x, t) = \sum_i \vec{R}_i(x) \rho_i c_i(t)$, where ρ is the correlation coefficient of the time series. A detailed description of the method is given in Dippner et al. (2001).

Validation

As canonical correlations analysis is optimized with respect to the used sample, it is necessary to validate the correlation with independent data. In contrast to von Storch et al. (1993) who split the records into a fit and a validation period, we use a cross-validation technique (Michaelsen 1987) and Monte Carlo simulations. In the cross-validation, if n time steps of data are available, n models are fitted by using $n - 1$ different time steps each. For each model, the n th step of the predictand is regressed from the predictor. Finally, the n estimations are compared with the observations of the predictand.

Skill Factors

From all tested combinations, the results with the relatively highest skills were selected. The skill for all combinations is computed considering all possible time lags. As skill factors, correlation coefficient r between the regional

observations and the cross-validated estimations and Brier-based score β are used. The Brier-based score skill is defined as: $\beta = 1 - \sigma_E^2 / \sigma_O^2$, where σ_E^2 and σ_O^2 are the variances of the error (i.e. observation minus model) and observations. $\beta = 1$ means that model and observation are identical, $\beta = 0$ that the error of the model has the same size as the variance of the observations (Livezey 1995). The significance level of selected results was calculated with Monte Carlo technique. Thousand series of random numbers with the same statistical properties (mean, standard deviation and autocorrelation) as the EOF coefficients of the predictands were generated.

Construction of the BSE Index

We select four time series to construct the BSE index: the AO index, the salinity in the deep Gotland Sea, the integrated river runoff of all rivers draining into the Baltic Sea and the relative vorticity of geostrophic wind over the Baltic Sea area. All these time series have different length

and the salinity time series is infrequent before World War II. To construct a consistent index, we select the period 1948–2002. Canonical correlation analysis has the tendency to over fit peaks (Heyen and Dippner 1998). To avoid such an over fitting, a moving average filter with (1–2–1)-filter weights has been applied to all time series. An EOF analysis of the normalized anomalies of these four time series is computed and the 1st Principal Component score of the 1st EOF mode serves as the new multivariate BSE index (Fig. 2).

Performance Tests

To test the performance of the new BSE index, we use statistical downscaling technique. In the first test, Atlantic multi-decadal oscillation, AO, NAO, Baltic Sea index, Chen and BSE index serve as climate predictor and SST in the Gotland Sea, Landsort gauge and sea ice extent serve as environmental response variable. To test the performance of the BSE index with biological data, in addition to the

Fig. 2 Monthly values of the Baltic Sea Environmental Index (dashed grey line). The blue filled line shows the time series filtered with a cut-off period of 25 month

climate indices, COADS SST is used as climate predictor and the various mesozooplankton time series from Latvian monitoring as regional predictands.

RESULTS

The BSE Index

The new multivariate BSE index (Fig. 2) is a combination of a large-scale index, the AO and local indices: the vorticity from the Chen index, deep water salinity and total river runoff. The 1st EOF has an amount of explained variance of 38.5 %, the 2nd EOF of 28.8 %, the 3rd EOF of 17.3 % and the 4th EOF 15.4 %. The EOF patterns show that the first mode is dominated by the river runoff, the second mode by the AO, the third mode by the vorticity and the fourth mode by the deep water salinity. In Fig. 2, the BSE index is drawn until 2005, however, in the last 3 years the influence of river runoff is absent. Due to the fact that the 1st EOF is controlled by the river runoff which ends in 2002, the downscaling experiments can only be performed until 2002.

Performance Test with Physical Data

No significant correlation has been found between the Atlantic multi-decadal oscillation and the physical data. The regional Baltic Sea index has a better performance than the global indices AO and NAO. The same holds for the Chen and the BSE index. A comparison of Baltic Sea index, Chen index with three EOFs and BSE index with four EOFs shows similar results for the SST in the Gotland Sea and the ice extent for winter time. Concerning Landsort gauge, all indices show a clear correlation for winter data. The Baltic Sea index has a highly significant correlation ($r = 0.66$), but, the Chen index ($r = 0.84$) and the BSE index ($r = 0.87$) are significantly better. The Chen and the BSE index, both indicate high correlations and skills throughout the year in the case of Landsort gauge (Fig. 3). The only exceptions are April for the Chen index and April, May and June for the BSE index. During these period no correlations can be identified (Fig. 3). Altogether, the performance test with the above-mentioned physical data indicates that the BSE index has a better correlation and a better skill than global indices and the Baltic Sea index and is equivalent to the Chen index with respect to the model skill (Table 1).

Performance Test with Biological Data

In the second step, the performance of the BSE index is tested using Latvian zooplankton time series. In a previous

Fig. 3 Correlation coefficient and Brier-based score skill as function of the month of the year for the downscaling projections of BSE and Chen index on Landsort gauge

article, Dippner et al. (2000) have demonstrated that a major amount of inter-annual variability in zooplankton time series can be explained by climate variability using COADS SST as climate predictor. We repeated this downscaling experiment using COADS SST and BSE index as predictor for the period 1960–1992 (Table 2). The results indicate that the prediction is equivalent in case of *Acartia* spp. whereas for *E. nordmanni*, the BSE index has a higher correlation. For the period 1960–1992, a downscaling experiment using COADS SST as predictor shows a better correlation and skill for *Synchaeta* spp. and *T. longicornis*. No meaningful correlation has been found for *B. longispina* and *Pseudocalanus* spp.

In the final step, all considered climate indices like Atlantic multi-decadal oscillation, AO, Baltic Sea index, BSE, Chen, NAO and an updated COADS SST are used as predictor for the Latvian mesozooplankton time series for the period 1960–2002. The BSE index is used twice, with one and with four considered EOFs, respectively (Table 3). This experiment shows that the BSE index using only the 1st EOF as predictor performs better than all other indices

Table 1 Correlation coefficients and the Brier-based score skill in parentheses between the climate predictors: Atlantic multi-decadal Oscillation (AMO), Arctic Oscillation (AO), North Atlantic Oscillation (NAO), Baltic Sea index BSI), the Chen index, the BSE index and Baltic Sea predictands: the SST in the Gotland Sea (GS), the mean sea level at Landsort gauge (LG) and the ice extent (IE)

	SST-GS (2/-1)	LG (1/0)	IE (1/0)
AMO	ns	ns	ns
AO	0.64 (0.39)	0.62 (0.37)	0.61 (0.34)
NAO	0.62 (0.35)	0.65 (0.41)	0.54 (ns)
BSI	0.71 (0.49)	0.66 (0.42)	0.67 (0.43)
Chen (1)	ns	0.59 (0.31)	0.37 (ns)
Chen (2)	0.61 (ns)	0.84 (0.63)	0.46 (ns)
Chen (3)	0.75 (0.45)	0.84 (0.64)	0.72 (0.42)
BSE (1)	0.69 (0.45)	0.73 (0.51)	0.67 (0.44)
BSE (2)	0.72 (0.48)	0.87 (0.67)	0.68 (0.44)
BSE (3)	0.73 (0.48)	0.87 (0.67)	0.70 (0.44)
BSE (4)	0.73 (0.48)	0.87 (0.68)	0.70 (0.45)

Bold numbers mark significant correlations with respect to the 99.9 % confidence level for the correlation coefficient and for the 99 % confidence level for the skill. The number in parentheses in the predictor column denotes the number of considered EOFs. The numbers in parentheses in the predictand row display the considered month of the years and the time lag in month

ns no significance

Table 2 Correlation coefficients and the Brier-based score skill in parentheses between climate predictors and zooplankton biomass as used in the previously performed downscaling experiment (Dippner et al. 2000)

	BSE (1960–1992)	COADS-SST (1960–1992)
Acar (S1/M2)	0.70 (0.37)	0.70 (0.37)
Bos (S2/M7)	ns	ns
Evad (S1/M2)	0.80 (0.55)	0.78 (0.60)
Syn (S1/M3)	0.75 (0.32)	0.76 (0.50)
Temo (S1/M2)	0.64 (0.27)	0.71 (0.42)

The fitting period is 1960–1992. *Acartia* spp. (Acar), *Bosmina longispina* (Bos), *Evadne nordmanni* (Evad), *Syncheata* spp. (Syn) and *Temora longicornis* (Temo) as predictands. The season is denoted with an “S” and the season number, with S1 as spring (May values) and S2 as summer (August values). The month of the predictor is denoted with an “M” and the number. Bold numbers mark significant correlations with respect to the 99.9 % confidence level for the correlation coefficient and for the 99 % confidence level for the skill

ns no significance

except the Chen index. However, one should keep in mind that the Chen index is considered three EOFs. The BSE index with four EOFs shows the best prediction with respect to the correlations. The only meaningful correlation with the Atlantic multi-decadal oscillation was found for summer *Acartia* spp. copepodites and the climate index in April. Whether this lag of 2 to 4 months is meaningful or not, cannot be answered seriously. Also in this experiment,

no meaningful correlation has been found for *B. longispina* and *Pseudocalanus* spp. and any potential predictor. The reason why no index is able to predict *Pseudocalanus* spp. might top down control of fish grazing (Kornilovs et al. 2001).

Figure 4 shows the *Acartia* spp. copepodite and *T. longicornis* copepodite spring biomass anomaly observed and predicted using the BSE index and Chen index. The observation indicates a negative biomass anomaly from 1960 until the 1989/1990 regime shift (Dippner et al. 2010). Amplitude and trends are well reproduced by the BSE index including the 1989/1990 regime shift, whereas the amplitudes reproduced by the Chen index are too small. The strong peak in 1998 is neither reproduced by the BSE index nor by the Chen index. In summary, the BSE index performs very well compared to the other tested indices regarding the predictability of zooplankton.

DISCUSSION

The new BSE index is developed and presented here as a tool for a better prediction of inter-annual and inter-decadal variability in environmental variables of the Baltic Sea. The index consists of four time series: the AO, the salinity between 120 and 200 m in the Gotland Sea, the integrated river runoff of all rivers draining into the Baltic Sea, and the relative vorticity of geostrophic wind over the Baltic Sea area. Each time series represents a specific forcing to the Baltic Sea in time and space and all relevant physical processes which are responsible for the forcing of inter-annual and inter-decadal variability of the Baltic Sea are incorporated. The AO index represents the northern hemisphere climate variability of both, the North Atlantic and the North Pacific. Therefore, AO is a better index than NAO which considers only the climate variability of the North Atlantic. Major Baltic inflows strongly influence the salinity in the deeper layers of the Gotland Sea which contributes with 15.4 % to the inter-annual variability of the Baltic Sea. The counterpart of major Baltic inflows is the hydrological cycle which is influencing the surface salinity. The effect of large-scale atmospheric blocking situations is considered by using the vorticity from the Chen index (Chen 2000). In the case of blocking, westerly winds disappear and meridional winds dominate. In such a case, the AO index and the NAO index do not contribute to the northern hemisphere climate variability. Therefore, the best way to consider the contribution of climate variability in case of blocking is the use of the relative vorticity of the geostrophic wind (Chen 2000). Each of the four considered time series contributes to the inter-annual and inter-decadal variability of the physical and biological system of the Baltic Sea.

Table 3 Correlation coefficients and the Brier-based score skill in parentheses between climate predictors as in Table 1 and different stages of *Acartia* spp. (Acar), and *Temora acuspes* (Temo) with fitting period 1960–2002

	BSE (4)	BSE (1)	AMO	AO	BSI	Chen (3)	NAO	COADS-SST (1)
AcarAb (S1/M2)	0.66 (0.32)	0.60 (0.32)	ns	0.57 (0.28)	0.57 (0.29)	0.64 (0.32)	0.56 (0.29)	0.43 (0.13)
AcarAa (S1/M2)	0.65 (0.32)	0.59 (0.32)	ns	0.57 (0.28)	0.55 (0.27)	0.61 (0.29)	0.56 (0.29)	0.42 (0.13)
AcarCb (S1/M1)	0.58 (0.16)	0.45 (0.18)	0.17 (ns)	0.37 (0.11)	0.37 (0.09)	0.41 (0.03)	0.33 (0.07)	0.65 (0.40)
AcarCb (S1/M2)	0.69 (0.26)	0.54 (0.26)	0.22 (ns)	0.57 (0.3)	0.59 (0.32)	0.67 (0.37)	0.51 (0.25)	0.56 (0.28)
AcarCb (S2/M4)	0.53 (ns)	ns	0.53 (0.24)	ns	ns	ns	ns	0.18 (ns)
AcarCa (S2/M4)	0.51 (ns)	ns	0.55 (0.26)	ns	ns	ns	ns	0.14 (ns)
AcarCb (S3/M10)	0.57 (0.13)	0.12 (ns)	0.48 (0.19)	0.37 (0.1)	0.33 (0.03)	0.35 (ns)	0.12 (ns)	0.14 (ns)
TemoCb (S1/M2)	0.72 (0.36)	0.61 (0.35)	0.23 (ns)	0.59 (0.33)	0.61 (0.34)	0.68 (0.38)	0.54 (0.27)	0.56 (0.27)
TemoCa (S1/M2)	0.78 (0.45)	0.67 (0.43)	0.17 (ns)	0.73 (0.51)	0.66 (0.4)	0.70 (0.41)	0.66 (0.41)	0.59 (0.31)

The number in parentheses in the predictor row denotes the number of considered EOFs

A adults, C copepodites, a abundance and b biomass

Bold numbers mark significant correlations with respect to the 99 % confidence level for both

Fig. 4 *Acartia* spp. copepodite (top) and *T. longicornis* copepodite (bottom) spring biomass anomaly observed and predicted using the BSE index and Chen index

Two unexpected results have been found: first, no meaningful combination has been found if Atlantic multi-decadal oscillation is considered as climate predictor for the physical response variable. This is rather surprising

because various authors (e.g. Knight et al. 2006) have shown a strong correlation of Atlantic multi-decadal oscillation with the air temperature in central England and the precipitation over the Baltic Sea catchment area. This finding needs further investigations.

Second, correlation coefficients and skills indicate that a regional index like the Baltic Sea index or a multivariate regional index such as the BSE have a much better performance than a large-scale hemispheric index. This result is a clear contradiction to the prediction paradox of Hallett et al. (2004). The prediction paradox says that large-scale climate indices seem to be better predictors of ecological processes than local climate. This might be perhaps the case in terrestrial ecosystems considered by Hallett et al. (2004). But, our results indicated that this is surely not the case in marine areas such as the North Sea (Dippner et al. 2010) and the Baltic Sea (Möllmann et al. 2009). Our results indicate that the multivariate BSE index combined of large- and regional-scale indices has an excellent performance and a high versatility much better than each single large-scale index only. Especially, the regime shift at the end of the 1980s and the extreme cold winters 1978/79 and 1995/96 are well reproduced.

Limitation

We also have to consider weak points in the development of the BSE index. At the moment we cannot say anything on the 2001/2002 regime shift, because we cannot provide down-scaling experiments longer than 2002. The reason is the cumulative river runoff. This time series is the shortest and ends in 2002, but unfortunately it dominates the 1st EOF of the BSE index. It was unexpected that the signal of the shortest time series dominates the first mode. Therefore, to overcome this disadvantage, an update of the river runoff

time series would be desirable because it would allow a prolongation of the BSE index and, hence, an improved potential predictability of Baltic Sea environmental properties. An update of the river runoff data is currently under debate and we will strongly support such activities.

Outlook

The human desire to look into the future requires investigations of the potential predictability of the system. In principle, the development of the BSE index is a step in this direction. The possibility to predict ecosystem structure and development is a necessary prerequisite for a fundamental understanding of the climate-induced ecosystem variability and for assessing the limits of predictability. This knowledge is particularly important in developing strategies for marine resource management. We hope that this new multivariate BSE index might be useful for colleagues working in the Baltic Sea.

Acknowledgments The authors are indebted to Tina Henrich for tremendous data processing. The time series of Landsort gauge has been provided by the Swedish Meteorological and Hydrological Institute (SMHI) Norrköping, the time series of ice cover by the Finnish Institute for Marine Research (FIMR), the updated Chen index by Deliang Chen and Thorsten Blenckner, the updated river runoff by Miguel Rodriguez, and the updated Baltic Sea index by Andreas Lehmann. The COADS update in the NCEP Marine data have been provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at <http://www.esrl.noaa.gov/psd/>. All these contributions are greatly acknowledged. The zooplankton monitoring was performed and the data were prepared by the Institute of Food Safety, Animal Health and Environment, Riga, Latvia. This paper is a contribution to the BONUS+ ERANET Project AMBER (BMBF Project No. 03F0485A).

REFERENCES

- Bergström, S., and B. Carlsson. 1994. River runoff to the Baltic Sea: 1950–1990. *Ambio* 23: 280–287.
- Chen, D. 2000. A monthly circulation climatology for Sweden and its application to a winter temperature study. *International Journal of Climatology* 20: 1067–1976.
- Chen, D., and C. Hellström. 1999. The influence of the North Atlantic Oscillation on the regional temperature variability in Sweden: Spatial and temporal variations. *Tellus* 51A: 505–516.
- Deser, C. 2000. On the teleconnectivity of the “Arctic oscillation”. *Geophysical Research Letter* 27: 779–782.
- Dippner, J.W. 2006. Future aspects in marine ecosystem modelling. Special WKFDPI issue. *Journal of Marine System* 61: 246–267.
- Dippner, J.W., and A. Ikaunieca. 2001. Long-term zoobenthos variability in the Gulf of Riga in relation to climate variability. *Journal of Marine Systems* 30: 155–164.
- Dippner, J.W., G. Kornilovs, and L. Sidrevics. 2000. Long-term variability of mesozooplankton in the Central Baltic Sea. *Journal of Marine Systems* 25: 23–31.
- Dippner, J.W., J. Hänninen, H. Kuosa, and I. Vuorinen. 2001. The influence of climate variability to the zooplankton abundance in the Northern Baltic Archipelago Sea (SW Finland). *ICES Journal of Marine Science* 58: 569–578.
- Dippner, J.W., R. Heerkloss, and J.P. Zbilut. 2002. Recurrence quantification analysis as a tool for characterisation of non-linear mesocosm dynamics. *Marine Ecology Progress Series* 242: 29–37.
- Dippner, J.W., K. Junker, and I. Kröncke. 2010. Biological regime shifts and change in predictability. *Geophysical Research Letters* 37: L24701. doi:10.1029/2010GL045696.
- Drinkwater, K.F., A. Belgrano, A. Borja, A. Conversi, M. Edwards, C.H. Greene, G. Ottersen, A.J. Pershing et al. 2003. The response of marine ecosystems to climate variability associated with the North Atlantic Oscillation. In: *The North Atlantic oscillation, climatic significance and environmental impact*, eds. Hurrell, J.W., Y. Kushnir, G. Ottersen, and M. Visbeck, 134: 211–234. Washington, DC: AGU Geophysical Monograph.
- Enfield, D.B., A.M. Mestas-Nunez, and P.J. Trimble. 2001. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental US. *Geophysical Research Letter* 28: 2077–2080.
- Feistel, R., G. Nausch, and N. Wasmund (eds.). 2008. *State and evolution of the Baltic Sea 1952–2005—a detailed 50 year survey of meteorology and climate, physics, chemistry biology, and marine environment*, 703. Hoboken NJ: Wiley-Interscience, Wiley.
- Gerlach, S.A. 1994. Oxygen conditions improve when the salinity in the Baltic Sea decreases. *Marine Pollution Bulletin* 28: 413–416.
- Hagen, E., and R. Feistel. 2005. Climatic turning points and regime shifts in the Baltic Sea region: The Baltic winter index (WIBIX) 1659–2002. *Boreal Environmental Research* 19: 211–224.
- Hallett, T.B., T. Coulson, J.G. Pilkington, T.H. Clutton-Brock, J.M. Pemberton, and B.T. Grenfell. 2004. Why large-scale climate indices seem to predict ecological processes better than local weather. *Nature* 430: 71–75.
- Hernroth, L. (ed.). 1985. *Recommendations on methods for marine biological studies in the Baltic Sea. Mesozooplankton biomass assessment*, 10: 1–32. Baltic Marine Environment Protection Commission.
- Heyen, H., and J.W. Dippner. 1998. Salinity variability in the German Bight in relation to climate variability. *Tellus* 50A: 545–556.
- Heyen, H., E. Zorita, and H. von Storch. 1996. Statistical downscaling of monthly mean North Atlantic air pressure to sea level anomalies in the Baltic Sea. *Tellus* 48A: 312–323.
- Hünicke, B., J. Luterbacher, A. Pauling, and E. Zorita. 2008. Regional differences in winter sea level variations in the Baltic Sea for the past 200 yr. *Tellus* 60A: 384–393.
- Hurrell, J.W. 1995. Decadal trends in the North Atlantic oscillation regional temperature and precipitation. *Science* 269: 676–679.
- Jevrejeva, S., J.C. Moore, and A. Grinsted. 2003. Influence of the Arctic Oscillation and El Niño–Southern Oscillation (ENSO) on ice conditions in the Baltic Sea: The wavelet approach. *Journal of Geophysical Research* 108: 4677. doi:10.1029/2003JD003417.
- Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, et al. 1996. The NCEP/NCAR Reanalysis 40-year project. *Bulletin of the American Meteorological Society* 77: 437–471.
- Knight, J.R., C.K. Folland, and A.A. Scaife. 2006. Climate impact of the Atlantic multidecadal oscillation. *Geophysical Research Letter* 33: L17706. doi:10.1029/2006GL026242.
- Kornilovs, G., L. Sidrevics, and J.W. Dippner. 2001. Fish and zooplankton interaction in the Central Baltic Sea. *ICES Journal of Marine Science* 58: 579–588.
- Lamb, H.H. 1950. Types and spells of weather around the year in the British Isles. *Quarterly Journal of the Royal Meteorological Society* 76: 393–438.

- Lehmann, A., W. Krauss, and H.-H. Hinrichsen. 2002. Effects of remote and local atmospheric forcing on circulation and upwelling in the Baltic Sea. *Tellus* 54A: 299–316.
- Livezey, R.E. 1995. The evaluation of forecast. In *Analysis of climate variability*, ed. H. von Storch, and A. Navarra, 177–196. Berlin: Springer.
- Matthäus, W., and H. Frank. 1992. Characteristics of major Baltic inflows—a statistical analysis. *Continental Shelf Research* 12: 1375–1400.
- Michaelsen, J. 1987. Cross-validation in statistical climate forecast models. *Journal of Climate and Applied Meteorology* 26: 1589–1600.
- Mikulski, Z. 1982. *River inflow to the Baltic Sea 1921–1975*. Warsaw: Polish Academy of Science, Polish National Committee of the IHP UNESCO.
- Möllmann, C., R. Diekmann, B. Müller-Karulis, G. Kornilovs, M. Plikshs, and P. Axe. 2009. Reorganization of a large marine ecosystem due to atmospheric and anthropogenic pressure: A discontinuous regime shift in the Central Baltic Sea. *Global Change Biology* 15: 1377–1393. doi:[10.1111/j.1365-2486.2008.01814x](https://doi.org/10.1111/j.1365-2486.2008.01814x).
- Mudelsee, M., M. Börngen, G. Tetzlaff, and U. Grünewald. 2004. Extreme floods in central Europe over the past 500 years: Role of cyclone pathway “Zugstrasse Vb”. *Journal of Geophysical Research* 109: D23101. doi:[10.1029/2004JD005034](https://doi.org/10.1029/2004JD005034).
- Mysterud, A., N.C. Stenseth, N.G. Yoccoz, G.O. Ottersen, and R. Langvatn. 2003. The response of terrestrial ecosystems to climate variability associated with the North Atlantic Oscillation. In: *The North Atlantic oscillation, climatic significance and environmental impact*, eds. Hurrell, J.W., Y. Kushnir, G. Ottersen, and M. Visbeck, 134: 235–262. Washington, DC: AGU Geophysical Monograph.
- Omstedt, A., and D. Chen. 2001. Influence of atmospheric circulation on the maximum ice extent in the Baltic Sea. *Journal of Geophysical Research* 106: 4493–4500.
- Omstedt, A., C. Pettersen, J. Rodhe, and P. Winsor. 2004. Baltic Sea climate: 200 yr of data on air temperature, sea level variation, ice cover, and atmospheric circulation. *Climate Research* 25: 205–216.
- Straile, D., D.M. Livingstone, G.A. Weyhenmeyer, and D.G. George. 2003. The response of freshwater ecosystems to climate variability associated with the North Atlantic Oscillation. In: *The North Atlantic oscillation, climatic significance and environmental impact*, eds. Hurrell, J.W., Y. Kushnir, G. Ottersen, and M. Visbeck, 134: 263–279. Washington, DC: AGU Geophysical Monograph.
- Swanson, K.L., and A.A. Tsonis. 2009. Has the climate recently shifted? *Geophysical Research Letters* 36: L06711. doi:[10.1029/2008GL037022](https://doi.org/10.1029/2008GL037022).
- Thompson, D.W.J., and J.M. Wallace. 1998. The Arctic oscillation signature in the wintertime geopotential height and temperature fields. *Geophysical Research Letter* 25: 1297–1300.
- United Nations Educational, Scientific and Cultural Organisation. 1968. Zooplankton sampling. Monographs on oceanographic methodology. Paris: UNESCO.
- von Storch, H., E. Zorita, and U. Cubasch. 1993. Downscaling of global climate change estimates to regional scales: An application to Iberian rainfall in wintertime. *Journal of Climate* 6: 1161–1171.
- Voss, M., K.C. Emeis, S. Hille, T. Neumann, and J.W. Dippner. 2005. Nitrogen cycle of the Baltic Sea from an isotopic perspective. *Global Biogeochemical Cycles* 19: 1–16. doi:[10.1029/2004GB002338](https://doi.org/10.1029/2004GB002338).
- Winsor, P., J. Rodhe, and A. Omstedt. 2001. Baltic Sea ocean climate: An analysis of 100 yr of hydrographic data with focus on the freshwater budget. *Climate Research* 18: 5–15.
- Winsor, P., J. Rohde, and A. Omstedt. 2003. Erratum: Baltic Sea ocean climate: An analysis of 100 yr of hydrographical data with focus on the freshwater budget. *Climate Research* 25: 183.
- Woodruff, S.D., R.J. Slutz, R.L. Jenne, and P.M. Steurer. 1987. A comprehensive ocean-atmosphere data set. *Bulletin of the American Meteorological Society* 68: 1239–1250.
- Zorita, E., and A. Laine. 2000. Dependence of salinity and oxygen concentrations in the Baltic Sea on large scale atmospheric circulation. *Climate Research* 14: 25–41.

AUTHOR BIOGRAPHIES

Joachim W. Dippner (✉) is a senior scientist at the Department of Biological Oceanography. He is a physical oceanographer and expert in numerical and statistical modelling. His research interests are ecosystem theory and modelling and climate-induced variability in marine biological systems. He was coordinating lead author of the book ‘Assessment of Climate Change for the Baltic Sea Basin’. Currently, he is coordinator of the BONUS+ ERANET Project AMBER (<http://www.io-warnemuende.de/amber.html>).

Address: Leibniz Institute for Baltic Sea Research Warnemünde, Seestr. 15, 18119 Rostock, Germany.

e-mail: dippner@io-warnemuende.de

Georgs Kornilovs is a fisheries biologist and the head of Fish Resources Research Department in the Institute of Food Safety, Animal Health and Environment. His research interest is stock dynamics of the pelagic fishes in the Baltic Sea and the relationships between fishes and zooplankton.

Address: Fish Resources Research Department, Institute of Food Safety, Animal Health and Environment, Daugavgrivas 8, Riga 1048, Latvia.

e-mail: georgs.kornilovs@bior.gov.lv

Karin Junker is a Ph.D. student in the BONUS+ ERANET Project AMBER at the Department of Biological Oceanography. She is a physical oceanographer and her research interests are time series analysis, modelling and climate impact assessment.

Address: Leibniz Institute for Baltic Sea Research Warnemünde, Seestr. 15, 18119 Rostock, Germany.

e-mail: karin.junker@io-warnemuende.de