Correlation analyses of Baltic Sea winter water mass formation and its impact on secondary and tertiary production

OCEANOLOGIA, 49 (3), 2007.
pp. 381–395.

KEYWORDS
Baltic Sea
Winter water temperature
Baltic Sea Index
Fish egg survival
Zooplankton stage
development

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Received 3 May 2007, revised 21 August 2007, accepted 23 August 2007.

Abstract

The thermal stratification of the upper water layers in the Baltic Sea varies seasonally in response to the annual cycle of solar heating and wind-induced mixing. In winter, the stratification down to the halocline is almost completely eroded by convection and strong wind mixing. Monthly averaged temperature profiles obtained from the ICES hydrographic database were used to study the long-term variability (1950 to 2005) of winter water mass formation in different deep basins of the Baltic Sea east of the island of Bornholm. Besides strong interannual variability of deep winter water temperatures, the last two decades show a positive trend (increase of 1–1.5°C). Correlations of winter surface temperatures to temperatures of the winter water body located directly above or within the top of the halocline were strongly positive until the autumn months. Such a close coupling allows sea surface temperatures in winter to be used to forecast the seasonal development of the thermal signature in deeper layers with a high degree of confidence. The most significant impact of winter sea surface temperatures on the thermal signature in this depth range can be assigned to February/March. Stronger solar heating during spring and summer results in thermal stratification of the water column leading to a complete decoupling of surface and deep winter water temperatures. Based on laboratory experiments, temperature-dependent relationships were utilised to analyse interannual variations of biological processes with special emphasis on the upper trophic levels (e.g., stage-specific developmental rates of zooplankton and survival rates of fish eggs).

1. Introduction

The Baltic Sea can be regarded as a unique, large estuarine basin. Its circulation is governed by a huge amount of river runoff (about 470 km^3 yr^{-1}) and a compensating inflow of highly saline water from the North Sea, which results in a permanent salt stratification, i.e., density is almost entirely determined by salinity. A permanent halocline at 50–80 m depth separates the less saline surface water from the more saline bottom water, and during summer a thermocline develops in the surface layer (Kullenberg 1981). The thermal stratification in the upper water layers varies seasonally in response to the annual cycle of solar heating and wind-induced mixing. In autumn and winter the stratification is eroded by convection and strong wind mixing.

The distribution and intensity of vertical exchange is the key to many processes affecting physical as well as biological processes in stratified ecosystems like the Baltic Sea. It is more common to consider exchange across and along isopycnal surfaces rather than vertical and horizontal exchange, since density stratification sets up a barrier to fluid exchange. Mixing across isopycnal surfaces can only occur if there is sufficient energy to overcome the potential energy of the density stratification: cooling of sea surface temperatures (SST) increases the density of the surface layer and reduces the energy required for mixing. In the eastern Baltic, the maximum density of sea water occurs at $\sim$2.5°C. During autumn and winter, surface cooling triggers vertical convection and therefore cross-isopycnal mixing until the temperature of the density maximum is reached. Further cooling leads to the stabilisation of the water column. If the winter temperature is <2.5°C seasonal surface warming in early spring will result in an unstable water column with convective overturning (Eiola & Stigebrandt 1998). If the water temperature is >2.5°C, warming leads to the development of a thermocline.

Temperature-dependent processes are numerous across species and marine ecosystems (e.g., Campana 1996, Fowler & Jennings 2003, Zeldis et al. 2005), but they often involve a multitude of interrelated mechanisms. Weak year-classes of fish species have often been associated with severe winters accompanied by low water temperatures during peak spawning. In many cases, the temperature effect of enhanced larval fish survival through higher growth rates is probably augmented by temperature-dependent zooplankton dynamics (Limburg 1996). For *Acartia* spp. and *Pseudocalanus elongatus*, Klein-Breteler & Schogt (1994) and Klein-Breteler et al. (1995) used the Belehrádek function to estimate the development time from eggs to adults, showing that the higher the temperature, the faster the stage development. They further demonstrated a physiological temperature optimum leading to higher mortality rates if the temperature rises (or falls) dramatically beyond this optimum.

As in estuaries, marine and fresh water organisms in the Baltic Sea are found in a regional succession with different species-specific ranges of distribution. Depending on their specific adaptation to and tolerance of hydrographic property levels (e.g., temperature, salinity and oxygen), many species approach the limit of their general area of distribution in the Baltic Sea. Thus, they may also show increased vulnerability related to changes in environmental conditions. For sprat, significant temperature effects on recruitment strength have been attributed to the limited tolerance of sprat eggs and early larvae to low mid-water temperatures after severe winters (Nissling 2004). The interaction between temperature and sprat egg buoyancy is important for the survival of sprat eggs (Nissling 2004, Köster et al. 2005). This interaction is important because sprat eggs are neutrally buoyant at depths where the water temperature is affected by winter cooling (Wieland & Zuzarte 1991); thus, if the temperature is too low, successful egg development may not be possible. Laboratory experiments on sprat egg survival performed on board research vessels revealed no difference in viability between 5 and 13°C (Nissling 2004). Viable hatching decreased significantly with temperature, which indicated that water temperatures of $< 4°$C may seriously reduce the level of reproduction. The interannual variability of copepod abundance and biomass in the Baltic was shown to depend to a large extent on hydrographic conditions controlled by climate factors (e.g., Dippner et al. 2000, Hänninen et al. 2000, Möllmann et al. 2003). Decreasing salinities since the late 1970s have been responsible for the declining biomass of *Pseudocalanus acuspes*, the dominant copepod in the Baltic Sea (Dippner et al. 2000, Möllmann et al. 2000). The abundance and biomass of *Acartia* spp. depend mainly on the prevailing temperature conditions: this species showed a general increase in biomass in the 1990s, in response to relatively high temperatures (Möllmann et al. 2000). Older copepodites and adults of *Acartia* spp. were also found to inhabit for preference the vertical range of the winter water mass (Schmidt 2006).

This paper presents a correlation analysis of the influence of the severity of atmospheric winter forcing conditions on water mass generation and the strength of convection in the eastern part of the Baltic Sea. The primary aim of this study was to examine the vertical distribution and temporal evolution of the winter water body and to demonstrate the predictive power of temperature data time series for forecasting the stability of winter water mass temperatures in time. The highly temporally and vertically resolved temperature data time series were also used to consider depth-specific temperature trends on a decadal time scale.

As a second line of analysis, relationships between secondary and tertiary production variability and month-depth-specific temperature conditions were evaluated on the basis of more than 30 years of observations in the eastern Baltic.

2. Material and methods

Temperature data in the Baltic Sea were compiled from the International Council for the Exploration of the Sea (ICES) Oceanographic Database containing depth-specific CTD (conductivity-temperature-depth) and bottle measurements. From the database, all available temperatures were selected between 1950 and 2005 in ICES subdivisions (SD) 24 to 30 (Fig. 1). Similar analyses could not be performed for ICES SDs 31 and 32, where SST data during the winter months was insufficiently resolved temporally owing to

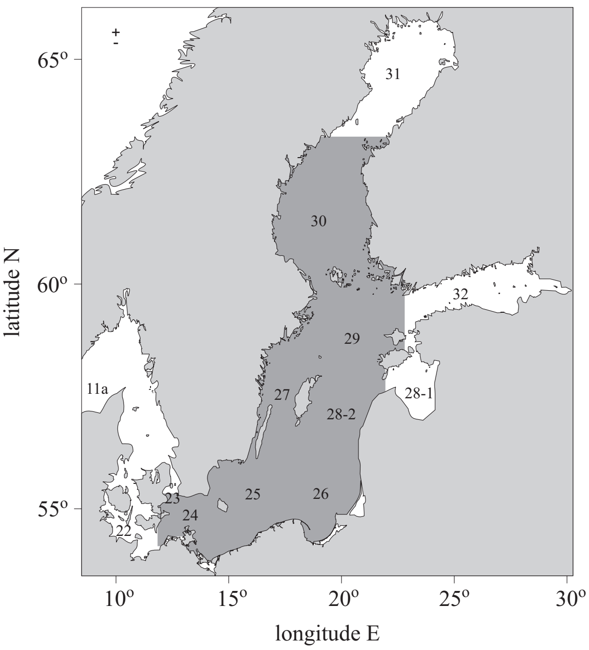

Fig. 1. Map of the Baltic Sea with ICES subdivisions

ice coverage. Data were subsequently aggregated to obtain monthly means per year and per 5 m depth stratum down to 140 m.

In order to backtrack the influence of winter water masses generated during winter months at the sea surface, vertically resolved temperature data time series were correlated to SST data for all ICES SDs. Correlations between time series of the different temperatures were studied for 12 months a year and with respect to different numbers of depth layers dependent on the specific depth strata in the ICES SDs. Additionally, the data were used to analyse the long-term dynamics of the winter water mass temperatures and to hindcast temperature-dependent rate processes on secondary and tertiary production (e.g., sprat egg survival, stage development of calanoid copepods).

To obtain a general impression of how atmospheric conditions over the Baltic Sea influence winter water mass formation patterns, the Baltic Sea Index (BSI) was applied (Lehmann et al. 2002, Hinrichsen et al. 2002a): this is defined as the difference of normalised sea level pressure anomalies between Oslo (Norway) and Szczecin (Poland). These anomalies were normalised by dividing them by the long-term mean (1948–1999) standard deviation. During winter months, positive indices correspond to anomalous sea level pressures associated with westerly winds (warmer periods), whereas negative indices indicate predominately easterly winds (colder periods) over the Baltic Sea. BSIs were recorded at 3 h intervals, but later averaged over the desired periods of temporally resolved temperature profiles (one month).

3. Results

Monthly mean temperatures at various depths in many areas of the Baltic Sea are significantly associated with the severity of the previous winter. The interaction between the temporal evolution of water mass formation according to discrete monthly mean temperatures at the sea surface can be facilitated by use of simple linear regression models. Figure 2 shows the temporal distributions of the correlation coefficient R of the cross-correlation between SST for specific months and the corresponding temporally and vertically resolved temperature data for ICES SD 28 (Gotland Basin). This figure shows a sequence of distributions of R for SST ranging from January (Fig. 2a) to June (Fig. 2f). Cross-correlation between SSTs from January to March and temporally and vertically resolved temperature data revealed high positive values down to 70 m. Positive correlations are indicative of an increase in winter water temperature with increasing SSTs and vice versa. For example, in the Gdańsk Deep, the highest correlations between 50 and 70 m indicate that these water

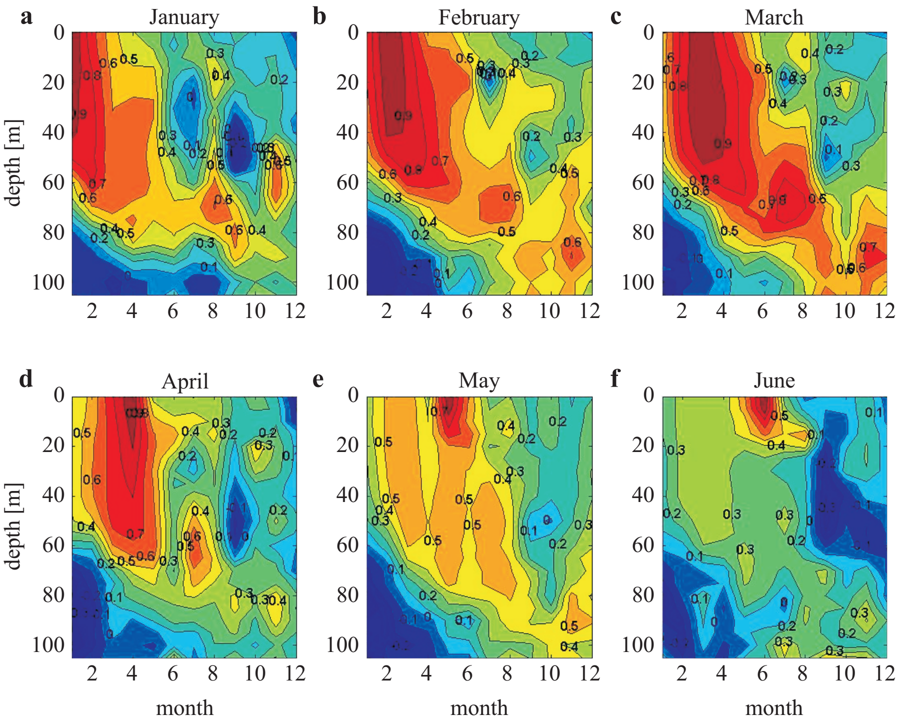

Fig. 2. Correlation coefficients between January to June (2a–f) SSTs and deeper water mass temperatures for all months of the year in ICES SD 28 (Gotland Basin)

masses were formed as a result of sea surface convection, mainly during March (Fig. 2c). In general, weaker to negative correlations were found for temperatures within the halocline and deeper than 70 m until June/July. Another depth range displaying only low correlation values was found in the upper water layers for time periods after the development of the thermocline (spring to winter); this begins with the onset of seasonal warming in April (Fig. 2d). Thus, higher correlations between SSTs and the temperatures of deeper water masses (down to 60 m) exist only for limited time periods and become less influential for SSTs in May and June (Figs. 2e+f). Generally, the analysis showed that for SD 28 the interaction between SSTs and the temperatures of deeper water masses above the halocline later in the year was highest for March.

Similar correlation analyses were done for ICES SDs 24, 25, 26, 27, 29 and 30: similar results were obtained as for SD 28. Figure 3 shows that correlations between SSTs and temperatures of deeper water masses later in the year were highest in March for SDs 24, 25, 26, and 27 (also 28; see Fig. 2c). Farther north (SDs 29 and 30), high correlations were delayed until April (Fig. 3e–f). The impact of SSTs on winter water temperatures

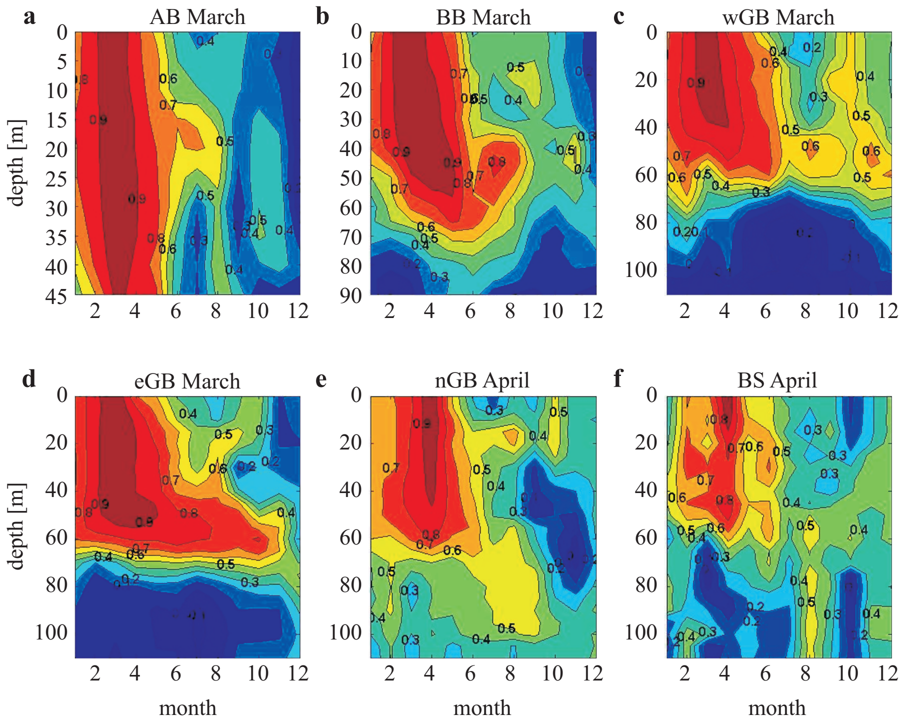

Fig. 3. Correlation coefficients between winter SSTs and deeper water mass temperatures for all months of the year in ICES SDs a) 24 (Arkona Basin), b) 25 (Bornholm Basin), c) 26 (Gdańsk Deep), d) 27 (western Gotland Basin), e) 29 (northern Gotland Basin, and f) 30 (Bothnian Sea)

was less pronounced in SD 24, with highest correlations in the whole water column until May and weaker correlations only in the 10–25 m range until August.

Assessment of the long-term development of Baltic Sea temperatures reveals significant positive trends. The interannual variabilities of winter water mass temperatures resemble those of the SSTs (Fig. 4). Thermal conditions between 40 and 60 m in May and July are comparable to those at the sea surface. All three months show a marked regime shift, such as an increase in temperature (1–1.5°C) since the late 1980s. The correlation coefficients between SSTs and mid-water temperatures are extremely high: 0.96 for March SSTs and May temperatures, and 0.87 for March SSTs and July temperatures.

The impact of temperature on the survival of sprat eggs (Nissling 2004, Petereit et al. 2007) was calculated on the basis of average ambient temperatures (40–60 m) in the Bornholm Basin at the main spawning time in May as well as on predictions based on mean SSTs recorded during

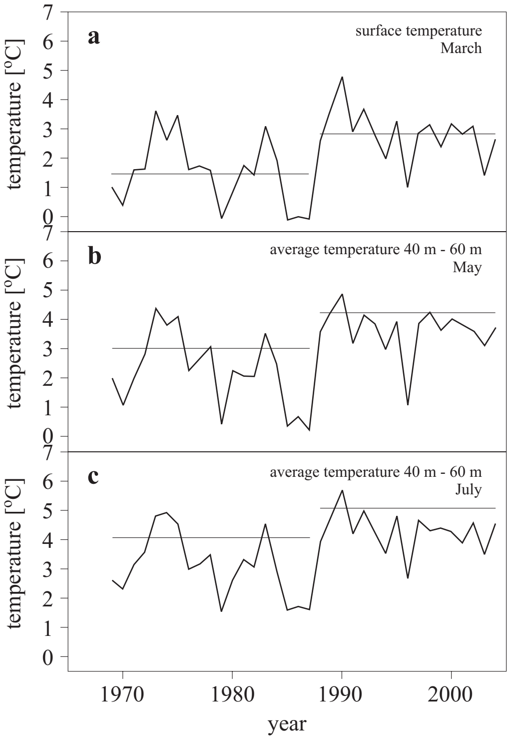

Fig. 4. Time series of a) SST in March, b) average temperature 40–60 m in May, and c) average temperature 40–60 m in July in ICES SD 25 (Bornholm Basin)

March. Extremely low temperature-dependent egg survival (Fig. 5a) has been associated with severe winters accompanied by low water temperatures during peak spawning (1979, 1985–1987). In this respect, the absence of severe winters since the middle of the 1980s indicates favourable thermal conditions for sprat egg survival and most likely contributed to the generally high recruitment (Köster et al. 2003). Figure 5b and c show the generation times of *Acartia* spp. and *P. acuspes* in July and May. Because of the high variability in the winter water mass, the time-series exhibits strong variations in the developmental times of the copepods, particularly for *Acartia* spp. The generation time varied between 50 and 150 days, but the thermal effect on stage development was less pronounced in *P. acuspes* (50 to 100 days). Generally, the coincidence between observed and predicted temperature-dependent rate processes is quite high. These exercises resulted in a $>90\%$ explained variance between observations and predictions.

Monthly average BSIs were calculated in order to estimate the probability of intra- and interannual changes in the BSIs. For all the SDs under consideration, the positive correlation coefficients between the BSIs

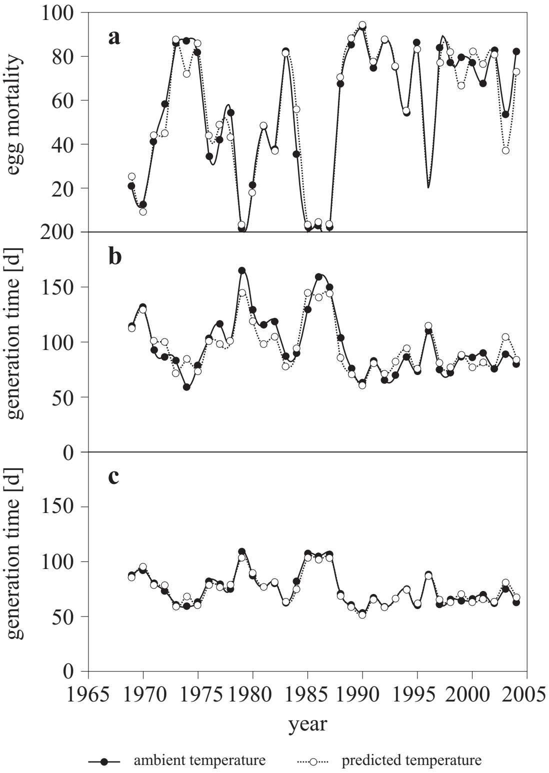

Fig. 5. Time series of temperature-dependent rate processes in ICES SD 25 (Bornholm Basin), a) sprat egg survival, b) generation time of *Acartia* spp., and c) generation time of *Pseudocalanus acuspes*

and the successive monthly means of SSTs of the year indicate that correlations between January BSIs and February/March SSTs are much higher than between subsequent monthly mean SSTs later in the year (Table 1). Generally, the correlation coefficients between February or March and subsequent monthly mean temperatures are much less strongly correlated. This indicates a time lag of about two months for the impact of local atmospheric forcing conditions on SSTs and hence, subsequent winter water mass formation. Furthermore, the correlations between BSIs and SSTs become less, the farther apart the SDs were located from the BSI baseline (Fig. 6).

4. Discussion and conclusions

Our analyses indicate that basin-wide monthly means of vertically resolved temperatures can represent conditions throughout an entire basin, at least for the purpose of following the fate of winter water masses in

Table 1. Correlation coefficients between BSI and SST for different months in different ICES SDs

BSI/SST: SD24

	January	February	March	April	May	June
January	0.61	0.77	0.80	0.60	0.55	0.36
February		0.58	0.74	0.61	0.67	0.35
March			0.48	0.48	0.50	0.38

BSI/SST: SD25

	January	February	March	April	May	June
January	0.60	0.78	0.84	0.71	0.80	0.71
February		0.47	0.67	0.43	0.61	0.47
March			0.52	0.48	0.50	0.29

BSI/SST: SD26

	January	February	March	April	May	June
January	0.58	0.81	0.79	0.61	0.67	0.61
February		0.55	0.67	0.31	0.45	0.29
March			0.49	0.06	0.52	0.29

BSI/SST: SD27

	January	February	March	April	May	June
January	0.39	0.65	0.73	0.56	0.67	0.34
February		0.59	0.76	0.64	0.54	0.21
March			0.40	0.41	0.28	0.33

BSI/SST: SD28

	January	February	March	April	May	June
January	0.52	0.77	0.83	0.62	0.76	0.49
February		0.54	0.61	0.50	0.58	0.16
March			0.46	0.27	0.29	0.24

BSI/SST: SD29

	January	February	March	April	May	June
January	0.42	0.52	0.60	0.56	0.65	−0.06
February		0.55	0.73	0.68	0.49	0.015
March			0.42	0.35	0.16	0.40

BSI/SST: SD30

	January	February	March	April	May	June
January	0.32	0.16	0.73	0.53	0.60	0.30
February		0.41	0.66	0.49	0.27	0.28
March			0.50	0.15	0.10	0.14

the Baltic Sea. Strong correlations among long-term data suggest that atmospheric processes at the sea surface appear to be closely coupled to the temporal temperature development in the interior of the Baltic Sea. Furthermore, their significant relationships with mid-water temperatures

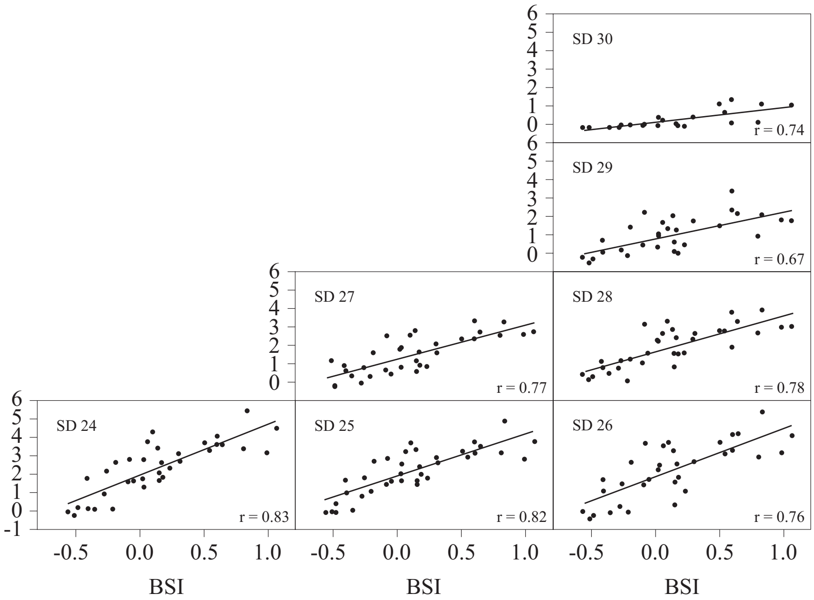

Fig. 6. Baltic Sea Index (January) and SST (March) for ICES SDs 24, 25, 26, 27, 28, 29, and 29

could have a considerable influence on the description and prediction of processes affecting the development, growth and survival of species representing different trophic levels.

Our study has demonstrated a correlative link between SST during winter months and mid-water temperatures until the autumn months. This is exemplified by the changes in the vertical distribution of sprat eggs during the spawning season: eggs were distributed mainly in the deep layers early in the season, occurring in and above the permanent halocline during peak spawning, and above the halocline towards the end of the spawning season (Nissling et al. 2003). Consequently, poor oxygen conditions in the deep layers and low temperatures in the layers between the halocline and the developing thermocline may affect egg development. Thus, conditions for egg development vary over the spawning season and between spawning areas, and depending on the severity of winters, between years. In conjunction with an index that reflects factors affecting recruitment, such as the degree of larval transport or depth-specific temperature conditions (Baumann et al. 2006), this information can, for instance, be used in short-term projections of Baltic sprat egg mortality and thus be fed directly into assessment procedures. Climate-driven change in temperature is associated with dramatic changes in the stage developmental progress in zooplankton communities.

The results of our analyses suggest that the temperature conditions affect both the egg mortality rates in the Baltic sprat and the developmental rate of zooplankton species/stages. The differences in developmental time between the two major species *P. acuspes* and *Acartia* spp. suggest a shift in the species composition as well as a shift in the peak occurrence of different stages. This might lead to changes in larval prey fields, potentially leading to a mismatch and thus worse conditions for survival, or vice versa. Results obtained from laboratory experiments could be validated by data from specifically designed field campaigns that include a realistic description of the temporal and spatial distribution (mesoscale to small-scale patchiness) of the abiotic and biotic property fields.

The local atmospheric circulation pattern has a strong influence on most environmental processes in the Baltic Sea. A significant correlation of inter-annual changes in SST with changes in the BSI has clearly been demonstrated in this study. Because of the correlation of the BSI with the North Atlantic Oscillation Index (Lehmann et al. 2002), the impact of large-scale atmospheric conditions on the dynamics of the Baltic Sea is clear. Thus, the influence of the North Atlantic Oscillation (NAO) is to a high degree manifested in the local atmospheric conditions, which constitute the direct impact.

The assessment of climate change in the Baltic Sea reveals significant positive trends in the annual mean temperature for the northern and southern basins (BALTEX 2006). Westerly airflows have intensified, especially during winter, contributing to higher winter temperatures and greater precipitation. Especially during the last 10 to 15 years, extremely high NAO+ phases have been registered, showing high SSTs and hence the potential to cause an increase in winter water temperature. Increasing greenhouse gas concentrations are expected to lead to a substantial warming of the global climate during this century (Cubasch et al. 2001). In the Baltic Sea, the increase in temperature, especially during winter, will affect the growth and reproduction rates of fauna and flora. Studies of past and recent ecosystem changes have demonstrated the sensitivity of the Baltic Sea ecosystem to changing temperatures. They have been related to various effects, in particular to the composition of species: for instance, higher temperatures during the 1990s were associated with a shift in dominance within the open sea copepod community from *Pseudocalanus acuspes* to *Acartia* spp. (Möllmann & Köster 2000). The results of a coupled biophysical modelling study have suggested that sufficient food to ensure the high survival of Baltic cod larvae is strongly dependent on the occurrence of *Pseudocalanus acuspes* in the prey field (Hinrichsen et al. 2002b). Increased production and survival rates of sprat and herring populations during the last 5–10 years have co-varied with high temperatures and high BSI and NAO indices (Köster et al. 2003). These trends are expected to continue into the future, because the identified trends in temperature and related variables are consistent with regional climate change scenarios prepared with climate models (BALTEX 2006).

In general, the information on basin-wide resolved monthly averages of SST can be employed in the short- and medium-term projection of temperature-related rate processes for species from various trophic levels by coupling SSTs measured relatively early in the year to the thermal environments and habitat quality in deeper layers later in the year. The utilisation of these relatively simple parameters allows a general examination of, for example, how habitat and environment affect the survival and stage development of species, and are inexpensive compared to field observations. Furthermore, it might be of interest to find out whether the predictive power of process-oriented models can benefit from simplified but 'online' accessible physical forcing parameters, such as the Baltic Sea Index.

Acknowledgements

Funding for this study was obtained from the BMBF-financed GLOBEC-Germany program. The study was also carried out with financial support from the Commission of the European Communities, Agriculture and Fisheries (FAIR), specific RTD-programme CT98 3959 (STORE) as a contribution to EU FP6, TP 8.8 Specific Targeted Research Project 513670 (PROTECT) and the Baltic Sea Region INTERREG III B Neighbourhood Programme BALANCE. This paper does not necessarily reflect the view of the Commission. This is also a contribution to the BALTEX Phase II.

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