Spatial and interannual variations of seasonal sea surface temperature patterns in the Baltic Sea

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Abstract

On the basis of monthly averaged satellite data, this study examined how the annual cycle of the Baltic Sea surface temperature (SST) varied spatially and temporally during the period 1986–2005. We conclude that there are two main thermal seasons in the Baltic Sea separated only by short transitional periods – spring lasting about one month, and autumn lasting two months. Generally speaking, summer covers the part of the year from June to October with the highest monthly mean SST in August. Winter, with a minimum monthly mean SST in February in shallow waters or in March in deeper areas, lasts from December to April. As a result of climate changes over the Baltic Sea region, strong positive trends in SST occur in the summer months. In consequence, the period with extremely high sea surface water temperatures has become slightly longer in the central Baltic. In the last decade winter changes in SST display zero or even negative tendencies. The investigated period was characterized by an annual increase in mean temperatures of about 0.03–0.07°C. However, the rates of monthly mean SST changes were sometimes more than three times as high.

1. Introduction

The past one hundred years have witnessed changes in the thermal regime of Baltic Sea waters. Identified trends in temperature are consistent with regional climate changes and are expected to continue into the future (e.g. Stigebrandt & Gustafsson 2003, EEA 2004, BALTEX 2006, Meier 2006, Siegel et al. 2006). Scientists predict a further warming of the climate over the Baltic Sea, but indicate a regional diversity in this respect. In the northern Baltic, the greatest warming is generally predicted for winter; in the south, the seasonal cycle of warming is less clear (BALTEX 2006, Meier 2006).

The responses of a wide range of marine organisms to oceanic warming, visible through changes in biomass distribution, biodiversity and shifts in the dominance of certain species, have already been documented (e.g. Beaugrand et al. 2002, Walter et al. 2002, Müren et al. 2005, Pilkaitytè & Razinkovas 2006, MacKenzie et al. 2007). In the Baltic Sea, increasing water temperatures in summer may intensify cyanobacterial blooms (Wiktor & Pliński 1992, Witek & Pliński 1998, Wasmund & Uhlig 2003). Higher temperatures in winter mean that diatoms are often replaced by dinoflagellates during spring blooms (Pliński & Dobroń 1999). A shift in the dominance of the open sea copepod community in association with higher temperatures during the 1990s (BALTEX 2006) has also been observed. Changes in sprat and herring populations during the last 5–10 years co-varied with high temperatures as well (MacKenzie & Köster 2004). One of the possible changes caused by future temperature rises may be an increase in the ratio of bacteria to phytoplankton biomass (BALTEX 2006). The effects of climate change may be immediate or delayed in time: Gröger & Rumohr (2006), for example, showed that temperature changes can influence macrobenthic fauna (species richness) even after a four-year delay.

Biological responses to temperature variations can be either direct, by influencing physiology, or indirect, by affecting food web interactions (Stenseth et al. 2004). An important feature of the thermal regime that influences marine biology is the seasonality of temperature. Regular, seasonal changes in temperature are environmental signals regulating the life-cycles of the majority of organisms. There are two periods in the biology of the phytoplankton and phytobenthos: the growing season and the period of quiescence. The seasonal cycle of marine fauna is directly or indirectly connected with the seasonal cycle of marine flora. As a result, thermal seasonality and its changes can significantly influence biological processes in the sea (Kröncke et al. 1998, Stenseth et al. 2004, Kirby et al. 2007). The aim of this study is to examine how the annual cycle of the Baltic Sea

surface temperature (SST) varied spatially and temporally during the 20 years from 1986 to 2005 in the context of global climate change.

2. Material and methods

In this study, we used monthly averaged SST fields from the PO.DAAC database (Physical Oceanography Distributed Active Archive Centre; on line service: http://podaac.jpl.nasa.gov/DATA_CATALOG/sst.html). The data consist of two sets for the period between February 1985 and October 2006. The first one is the NODC/RSMAS Pathfinder Advanced Very High Resolution Radiometer (AVHRR) dataset (version 5.0), based on historical AVHRR data (1985–2003), provided in a longitude-latitude grid with a resolution of $0.09°$. The second dataset of SST (2003–2006), with a spatial resolution of $0.045°$, is from the Moderate–resolution Imaging Spectroradiometer (MODIS) instruments aboard the NASA Terra and Aqua satellites. Satellite data are processed using consistent SST algorithms, an improved satellite and intersatellite calibration, quality control and cloud detection (Armstrong 2002, Vazquez et al. 1998). Detected clouds and ice coverage are coded by *NoData* value. For the purpose of this work, SST fields were resampled to the common grid of 4×4 km pixels in UTM zone 33N projection (datum WGS1984) using natural neighbour interpolation (Smith et al. 2007).

To perform time series analysis it is crucial to have a complete data set for each pixel, but the availability of satellite data for the Baltic Sea is limited owing to frequent cloudiness and ice cover in the north. There were no data for December 2003 and 2005, and the remaining fields had some gaps covering 3–75% of the sea area (less than 20% for most fields). Only those pixels were analysed for which valid data were available for at least 80% of time steps and missing data were randomly distributed over a year (Figure 1). For the area of investigation, incomplete time series were reconstructed using empirical orthogonal functions (Alvera-Azcárate et al. 2004) as follows: 1) (temporal analysis for each pixel). Data for the months of December 2003 and 2005 were partially reconstructed using polynomial regression based on data from the three preceding months and the three following months. 2) (spatial analysis for each map). Each map was allocated to have a nearest neighbour monthly averaged SST as a first-order approximation of data in the remaining gaps and the mean value calculated for each pixel was subtracted. 3) (spatiotemporal analysis). EOF decomposition of the new time series was carried out but only the first k EOFs, which explained over 80% of the variance, were extracted. 4) A set of EOFs and multiple regression was used to reconstruct originally missed data. These new approximated values replaced the previous ones.
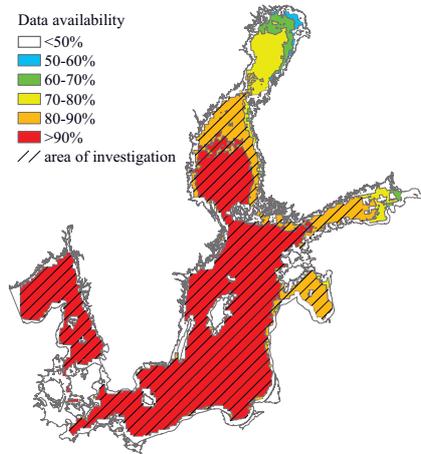
Figure 1. Availability of monthly averaged SST data and the area of investigation

To prevent an artificial border from being set up between the estimated and real data, a fuzzy algorithm was applied to mix them in a buffer zone of 10 km width. 5) Steps 3–4 were then repeated until convergence was achieved. Finally, to convert the completed anomalies back to the monthly averaged SST data, the mean values calculated in step 2 were added back.

In situ water temperatures (no deeper than 1 m below the surface) from the ICES (International Council for the Exploration of the Sea) database were used to verify the analysed data. Monthly mean SSTs were compared with averaged in situ data for pixels where at least 5 measurements were made per month (Figure 2a). The mean difference was $0.58°C$ with standard deviation $0.93°C$ (126 pairs compared). This is good agreement, given that the data from these two sources differ in spatial scale and temporal distribution over a month. Monthly averaged satellite data assigned to the date in the middle of the month form a mean cycle of temperature that shows the general pattern of local sea surface temperature changes during a year (Figure 2b).

The annual statistics for each pixel were calculated from the monthly mean SSTs and analysed to characterize interannual variations and trends. Interannual variability was characterized by the standard deviation related to the average (coefficient of variability expressed in [%]). In trend analysis a simple linear model with the error terms assumed to follow an autoregressive structure was used (Piegorsch & Bailer 2005). Analysis of normal probability plots for residuals enabled their normal distribution to be assumed. The statistical significance of the slope coefficient was tested using Student's t-test. The linearity of the time series was given by the
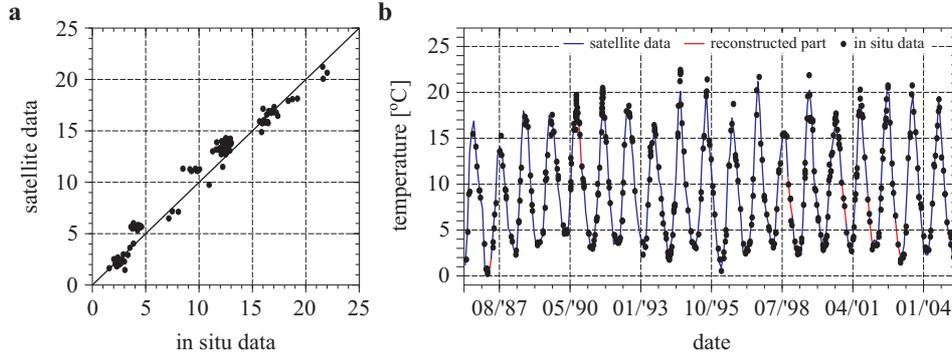
Figure 2. Comparison of satellite data with in situ temperatures (data from the ICES database): monthly mean SSTs versus temperatures measured in surface waters, averaged over one month (a), the monthly mean SST cycle from satellite data with temporal in situ values at 16°E, 55.25°N (b)

coefficient of determination r^2 and Mann-Kendall statistics τ, which describes the degree to which a trend is consistently increasing or decreasing (Kendall & Gibbons 1990).

There is no standard method for distinguishing thermal seasons in the sea. For the purposes of this work, the duration of each season in the annual cycle was determined on the basis of SST time series standardized according to

$$SST' = \frac{SST - \overline{SST}}{SD_{SST}}, \tag{1}$$

where SST' – standardized SST, $\overline{SST}$ – annual mean of SST, SD_{SST} – standard deviation of SST in the annual cycle. This enabled the seasonal character of SST to be analysed independently of long-term changes, taking into account only relative changes of SST over a year. Standardized SSTs have a slightly positively skewed distribution and a range between -1.5 and 1.5 ($\sim 95\%$ of the dataset). It was assumed that spring and autumn are characterized by monthly means close to the annual mean SST. The summer and winter seasons differ with respect to the monthly mean SST from the annual mean by more than 0.5 standard deviation. Periods with temperatures higher or lower than the annual mean by more than 1.5 standard deviation were treated as extremely hot or cold (Figure 3). This is a simple but objective method – its results do not change when the analysed SST time series is lengthened or shortened, which is the limitation of many statistical methods, e.g. cluster analysis. Assuming the point where the annual SST cycle curve to reach a value equal to the annual
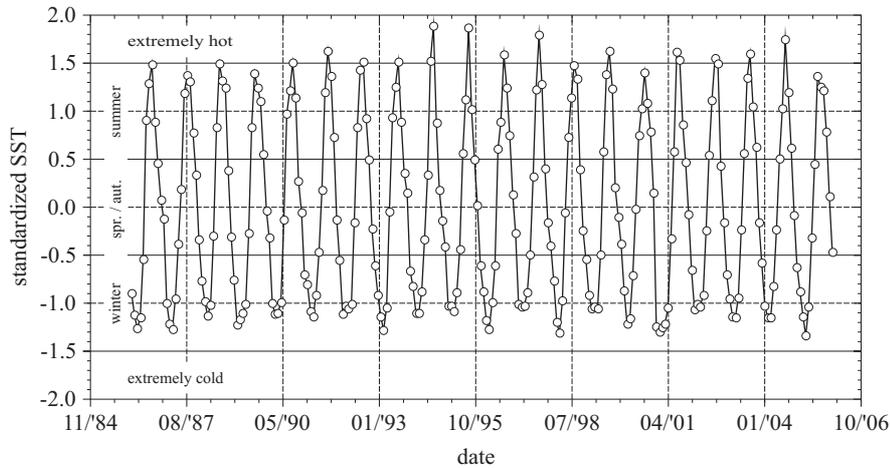
Figure 3. An example of a standardized SST time series (16°E, 55.25°N)

mean ±0.5 standard deviation at the turns of the seasons, the lengths of the seasons were calculated using linear interpolation.

Surface air temperatures extracted from the reanalysis database of the U.S. National Center for Environmental Prediction (NCEP) (provided online by the NOAA/OAR/ESRL Physical Sciences Division in Boulder, Colorado, USA; Kalnay et al. 1996, NCEP 2007) were used to interpret the SST analysis results. The monthly and seasonal mean air temperatures over the Baltic Sea region were calculated from the six-hourly air temperature fields covering the period 1958–2006 with a spatial resolution of 2.5°. Recent SST trends could be thus analysed in the broader context of the air temperature changes in the entire Baltic Sea region, over a longer period than the one for which SST data are available.

3. Results

3.1. Annual and monthly means

SSTs averaged over 20 years period ranged from about 5.5°C in the Bothnian Sea to 9.5°C in the southern Baltic (Figure 4a). The warmest part of the investigated area is the entrance to the Danish Straits with a 20-year mean SST of ca 10.5°C. The standard deviation (SD) of the annual means was between 0.5 and 0.9°C, with the highest values in the Baltic Proper. However, relative to the long term average SST, the Bothnian Sea seems to be the most variable (Figure 4b). The considerable interannual variations of the yearly mean temperatures, averaged over the whole study area, show a slightly positive trend with an increase of about 0.5°C per
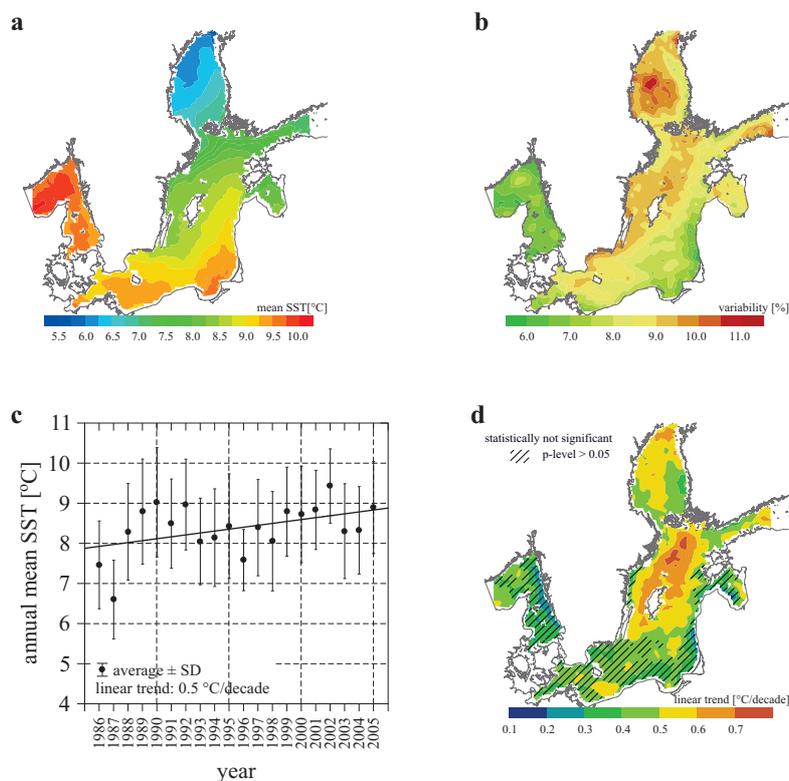
Figure 4. Statistical characteristics of the annual mean SSTs in the period 1986–2005: 20-year average (a), interannual variability (b), SST averaged over the study area (c) linear trends (d)

decade (p-level < 0.05) (Figure 4c). This is the result of tendencies recorded to the north of Gotland (0.4–0.8°C per decade, p-level < 0.05, $\tau > 0.3$). The southernmost interannual variations are more random ($\text{r}^2 < 0.2$, $|\tau| < 0.3$), so a 20-year period is too short to yield statistically significant trends (Figure 4d). However, the summer seems to be affected by the warming tendency in the whole Baltic Sea. The trend line slopes calculated for each month show an evident warming in August and September with an increase in temperature even three times as much as that predicted from the yearly means (Figures 5a,b). On average, the mean August SST increased during the period investigated by 1.5°C along the southern Baltic coast (τ between 0.25 and 0.35) and by as much as 4.8°C in the Gotland Basin and Bothnian Sea (τ between 0.35 and 0.55). In the winter seasons, zero or even negative tendencies have been reported since 1990, especially in March (p-level < 0.05, τ between -0.65 and -0.35) (Figure 5c). The highest interannual variations of the monthly mean SSTs are observed in May and
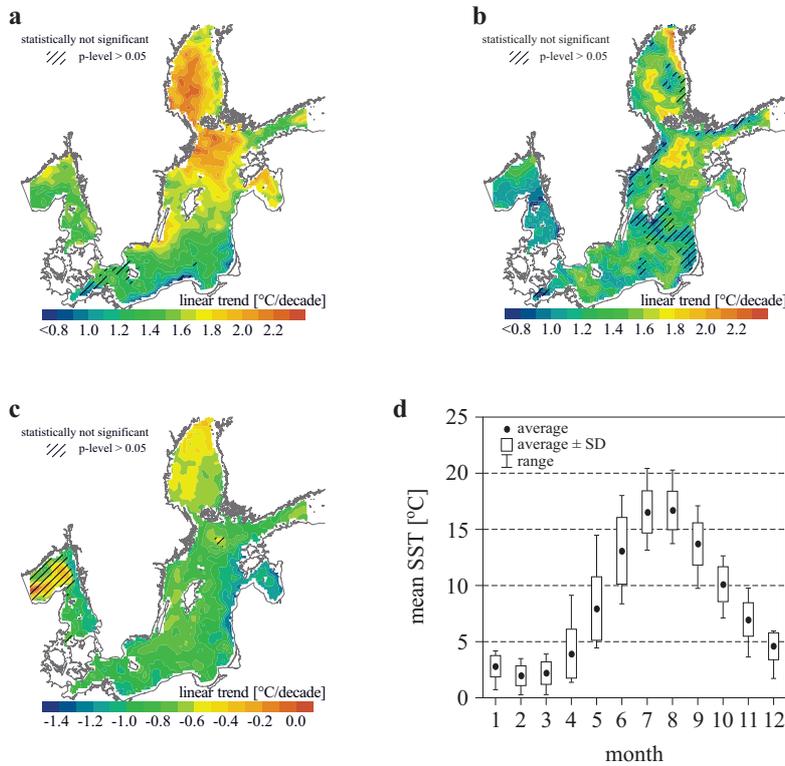
Figure 5. Spatial distribution of August (a) and September (b) SST mean positive trends from 1986 to 2006, March SST mean negative trends from 1990 to 2006 (c), and variations in monthly mean SST from 1985 to 2006, averaged over the study area (d)

June (Figure 5d). However, SSTs increased and decreased in turns ($r^2 < 0.2$, $|\tau| < 0.3$), so a longer time series would have to be examined to establish the potential (statistically significant) trends for these months.

3.2. Seasonality

The annual cycle of mean monthly SSTs in the Baltic Sea generally drops to a minimum in February–March and rises to a maximum in July–August (Figure 5d). Figure 6 shows the spatial variability of the turns and durations of the seasons. There were interannual variations of time and SST of the turns of the seasons, but there were no statistically significant trends in the period 1986–2005. The average SST at the beginning and end of the winter season varied from about 3.0°C (SD: 0.5°C) in the north to 5.5–6.5°C (SD: 0.7–0.9°C) in the Baltic Proper. SST at the beginnings and ends of summer was between 9.0–10.0°C (SD: 0.8–1.0°C) in the Bothnian

Sea and 12.0–12.5°C (SD: 0.7–1.0°C) along the southern coasts and in the Danish Straits.

The winter, spring and summer seasons start first in the shallow waters of the Danish Straits and Pomeranian Bay, 10–15 days later in the Baltic Proper and finally in the north-eastern regions. In contrast, autumn starts first in the north-west, and the latest in the south-east (Figure 6a). As a result, the winter season (the time when the averaged annual SST cycle lies below the mean by more than 0.5 standard deviation) is the longest in the Bothnian Sea (Figure 6b). In the whole Baltic it lasts at least 4.5–5.5 months. In the period 1986–2005, SSTs did not drop below the annual mean by more than 1.0 standard deviation, except for some local situations, e.g. in the coldest year of 1987 in the Danish Straits. Interannual variations of the duration of the winter season ranged from 6 to 11% of the average.
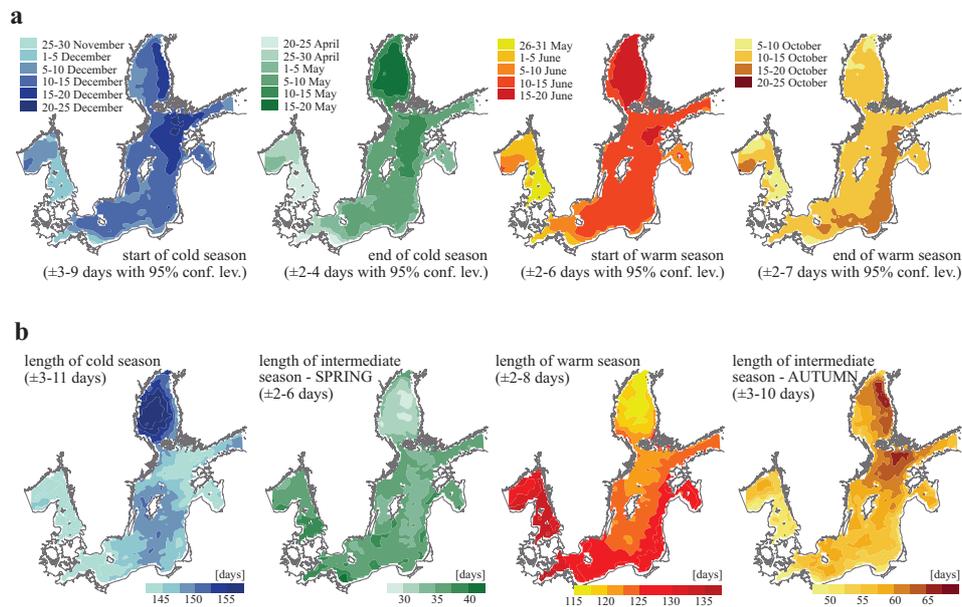
Figure 6. Average time of the beginning and end of the warm and cold seasons (the point where the standardized monthly mean SST curve exceeds 0.5) (a), and average duration of all seasons (the half-width of the 95% confidence intervals is given in brackets) (b) in the period 1986–2005

The summer season generally lasts 4–4.5 months. In the Danish Straits, southern Baltic and along the eastern coast up to the Gulf of Riga, monthly averaged SSTs remain above the annual mean by more than 0.5 standard deviation for about 10 days longer than in the northern part of the sea.
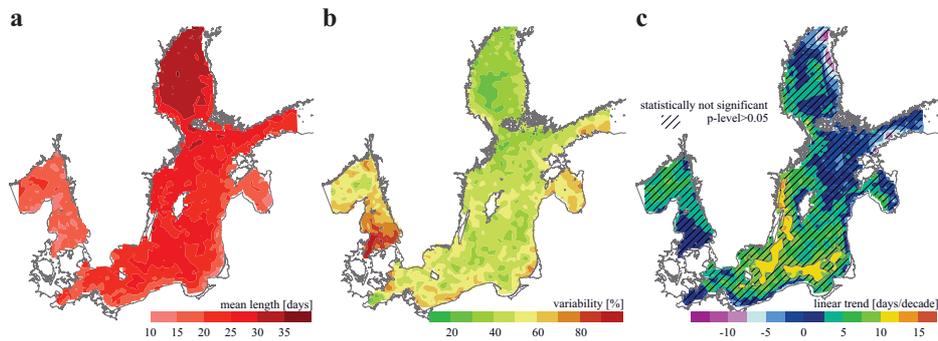
Figure 7. Statistical characteristics of the duration of extremely hot periods in summer from 1986 to 2005: 20-year average (a), interannual variability (b), linear trends (c)

Interannual variations of the duration of this season ranged from 4 to 11% of the average, with smaller values in the shallowest regions. In the warmest period of this season, monthly mean SSTs are higher than the annual mean by more than 1.0 standard deviation. Almost every year extremely warm surface waters were recorded in the Gotland Basin to the north and east. This phenomenon is least often observed in the Danish Straits and along the southern and south-eastern coasts; it did not occur at all in over 75% of the study area, either in the coldest year (1987) or in warmer years (1992, 1998, 2000). The calculated duration of this extremely warm period is 0.5–1 month on average, but it exhibits a high interannual variability (Figures 7a,b). However, for the small area of the Baltic Proper a statistically significant increase in the duration of the warmest period (p-level < 0.05) was found: on average, it was 10 days per decade (Figure 7c).

Short intermediate periods when the monthly mean SST is close to the annual mean are characteristic of SST seasonality in the whole Baltic Sea. The annual cycle of monthly mean SSTs remains in the range of the annual mean ± 0.5 standard deviation for no longer than one and a half months during the spring warming and for two and a half months during the autumn cooling (Figure 6). In the north the spring warming of surface waters is the shortest, whereas the autumn cooling is the longest. Changes of SST in these intermediate periods occur much faster than in summer or winter. During summer the rise in temperature by 1 standard deviation takes 10–20 days more than during spring. Reaching the minimum temperature of a year from the beginning of winter (a change in temperature usually of less than 1 standard deviation) takes 10 to 20 days more than the duration of the autumn cooling (change in temperature equal to 1 standard deviation).

The biggest difference occurs in the Danish Straits and along the southern and south-eastern coasts.

3.3. Annual extremes

In the period 1985–2006 the coldest month in the year was always marked by a monthly mean SST no higher than 2.5°C in the northern- and easternmost parts of the Baltic, 5°C in the Baltic Proper and 6.5°C in the Danish Straits (Figure 8a). In the whole area the coldest month was usually March, except in the shallow Danish Straits and along the coasts, where February was usually the coldest month. Very rarely and rather locally, an annual monthly mean temperature minimum occurred in January or April.

Interannual changes of the coldest month temperature do not show any statistically significant trends if the whole investigated period is taken into account ($r^2 < 0.1$, $|\tau| < 0.2$). But, on average, the decade 1996–2005 was characterized by annual minimum SSTs lower than those of the previous decade by 0.2–0.9°C. The differences were greatest in the Danish Straits, the Gulf of Finland and the Gulf of Riga. This is the result of a reversed tendency of the coldest month water temperature that has been present since 1990, with a decrease of approximately 0.6°C decade^{-1} in the Bothnian Sea, 1.0°C decade^{-1} in the Baltic Proper and up to 1.4°C decade^{-1} in the Gulf of Riga (p-level < 0.05, $\tau < -0.3$).

The warmest month of each year investigated was generally August. Only in 1987–1989, 1992, 2001 and 2005 was the maximum monthly mean SST recorded in July over the larger part of the area. Surface waters along the southern and south-eastern coasts display the highest temperatures with
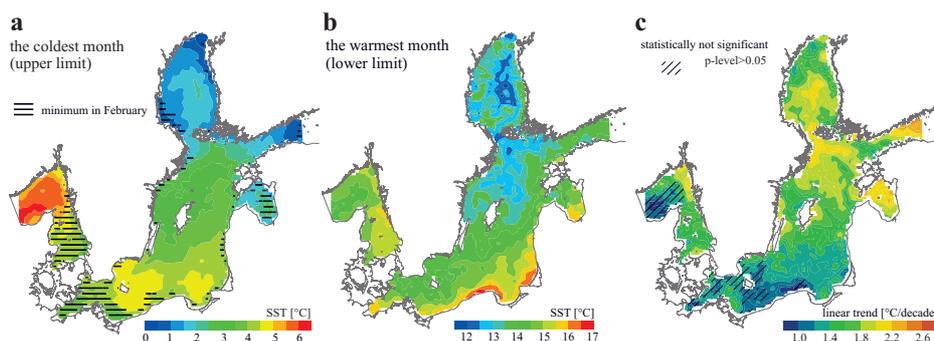
Figure 8. Spatial distribution of the upper limit of monthly mean SST for the coldest month in the year (a), the lower limit for the warmest month (b) and linear trends of the annual range of monthly mean SSTs in the period 1986–2005 (c)

annual maximum monthly means no lower than 16.5°C. Towards the north these mean temperatures decrease but only to 11.5°C (Figure 8b).

The earlier mentioned rising tendencies of temperature changes in August resulted in a wider range of temperatures during the year. This observation is reinforced by the opposite tendency, recorded in the winter seasons since 1990. Averaged over decades, the annual range of monthly mean SSTs changed from 11.4–17.9° (1986–1995) to 12.4–20.4 (1996–2005). According to the linear trend, the difference between annual extremes between 1986 and 2005 rose by 2°C along the Polish coast to over 4°C in the Bothnian Sea, the Gulf of Finland and the Gulf of Riga (Figure 8c).

4. Discussion

The annual cycle of monthly-mean sea surface temperature is strongly correlated with monthly-mean surface air temperature changes over the Baltic Sea (Figure 9a). The relation to the mean air temperature of the preceding month is about 1.5 times weaker, which shows that the response time of heat is rather short and that the surface layer responds quickly to changes in local atmospheric conditions. The atmospheric circulation affects the SST both directly – through the parameters influencing air-sea heat exchange (air temperature, humidity, cloudiness and wind speed) – and indirectly, by inducing a specific water circulation and the associated vertical mixing, advection etc. Intense three-dimensional hydrodynamic processes can explain the weaker influence of the air temperature on thermal conditions in the surface waters of the Bornholm and Gdańsk Basins (Figure 9a). The regions with a lower correlation between the air and sea-surface temperatures are dynamically the most active, with the highest annual average surface current velocities (Lehmann & Hinrichsen 2000a) and a highly stable circulation (Lehmann & Hinrichsen 2000b). An analogous situation in the Gulf of Finland is caused by the winter ice cover (e.g. Granskog et al. 2006), which partially cuts off the direct influence of the atmosphere on the surface water layers. Hence, although there is a statistically significant correlation between the Baltic Sea SST and the various regional (e.g. the North Atlantic Oscillation) and local (e.g. the Winter Baltic Climate Index) atmospheric circulation indices (e.g. Omstedt et al. 2004, Siegel et al. 2006), no straightforward relationship between the two has been found.

The seasonal SST pattern shows two main thermal seasons with short intermediate periods between them (Figure 6). The interannual variability of thermal conditions over the Baltic Sea can cause some shifts in the general SST seasonality pattern – up to 10 days at a 95% confidence level. These seasons are not homogeneous in temperature, especially in
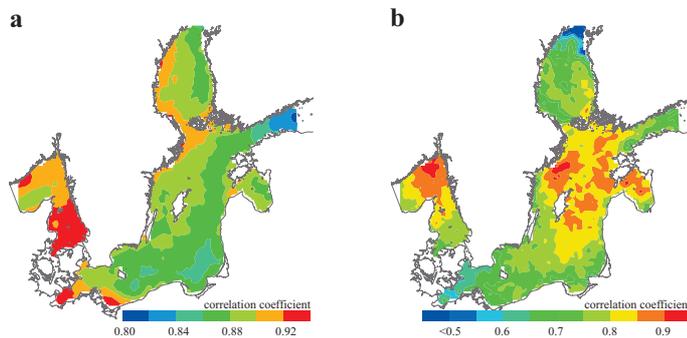
Figure 9. Correlation coefficients between 20-year time series of monthly (a) and annual (b) averaged sea and air surface temperatures (p-level < 0.05)

summer, when monthly mean SSTs can rise above the annual mean by more than 1.5 standard deviations. Generally, SST variability due to the three-dimensional hydrodynamic processes in the sea is the highest in the summer, when the vertical temperature differences reach their maximum, and the lowest in late winter and spring, characterized by the relatively uniform temperature profiles in the upper layers. Faster SST changes during spring and autumn are the result of intensive mixing.

The method applied here to distinguish seasons cannot guarantee the division of the year into seasons in accordance with the phytoplankton growing seasons. Temperature is only one of the parameters affecting the conditions supporting phytoplankton growth. Spring blooms in the Baltic Sea usually start in March when temperatures are lower than those prevailing here at the turn of winter. A distinctive feature of these blooms is the shift in the time of their appearance in the southern Baltic. The mass occurrence of phytoplankton is first observed in the Bay of Mecklenburg, mainly in the middle of March, after which the blooms move to the east, through the Arkona Basin in early April and the Bornholm Basin in mid-April, reaching the Gotland Basin in May (Wasmund et al. 1998, Fennel 1999, Siegel et al. 1999). Spatial differences in water column stability, rather than temperature alone, are responsible for this state of affairs at the beginning of the growing season (Fennel 1999). During the winter stratification of the Baltic Sea, cold waters (temperature below the temperature of the maximum density of water) form a surface layer above the warmer and denser ones (inverted stratification). Thus, the initial warming of surface waters in early spring at first causes this stratification to disappear and convectional mixing to appear. The process forming the summer stratification starts from the moment the water temperature rises above the maximum water density

temperature. However, the temperature of the maximum density of Baltic waters varies from the Danish Straits to the east (with decreasing salinity). The spatial differences during thermal season transitions shown on Figure 6 can influence the spatial variability of the later phytoplankton taxa changes.

Climate change modelling suggests that the warming from the present to the last decades of the 21st century will be in the 3–5°C range in the case of the annually averaged air temperature and 2–4°C in the case of the sea surface temperature over the Baltic Sea (Rummukainen et al. 2001, EEA 2004, BALTEX 2006, Meier 2006). According to the EEA report (2004), warming in the last 15 years occurred at the rate of about $0.33°$ decade^{-1}. Siegel et al. (2006) calculated a slightly higher trend – $0.53°$C decade^{-1} – for the same period. The trend calculated here for the yearly mean SST, generally ranging between 0.3 and $0.7°$C decade^{-1} (Figure 4), corresponds well to these findings. The greatest warming of surface waters in the Gotland Basin is well explained by the local increase in air temperature (Figure 9b). However, air temperature changes are not stable in time, so tendencies will vary over a long period (e.g. EEA 2004, Karlén 2005, MacKenzie & Schiedek 2007). The changes recorded during 1986–2000 were the highest in the last 200 years (Jones & Moberg 2003, Omstedt et al. 2004); hence, the relatively large increase in surface water temperature. The air temperature trends calculated for 1985–2006 and 1958–2006 reveal an appreciable increase in the rate of warming in the northern Baltic (Figure 10). However, this may be only a temporary exception, because climate change simulations predict maximum values of surface warming at the end of the 21st century in the central and southern basins of the Baltic Sea, regardless of the adopted climate change scenario (Meier 2006).

Two-decadal trends of monthly mean SST in the Baltic Sea show that warming occurs mainly in the summer months. Statistically significant trends were found for almost the whole Baltic Sea in August and September (Figure 5). Similar observations were reported by Siegel et al. (2006) or MacKenzie & Schiedek (2007). These authors emphasized the significantly faster temperature rise in the period from June to October than in the rest of the year. MacKenzie & Schiedek (2007) claim, moreover, that the rates of warming in summer since the late 1980s are exceeding the ranges of habitat preferences and the scopes for thermal acclimation and adaptation. The weaker response of SST to global warming in winter can be explained by the increased thickness of the mixed homogeneous surface layer in comparison to the summer, and by the additional heat supply required to melt the sea ice before the water column can start to warm up (Meier 2006). However, the data analysed here even showed negative trends of the winter monthly mean SST in recent years (Figure 5); the same applies to the air temperature
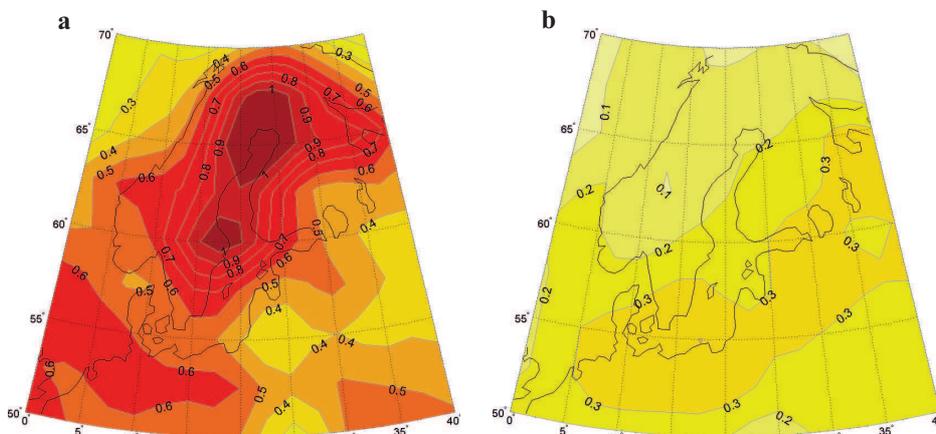
Figure 10. Spatial distribution of the annual mean air temperature trends [°C decade^{-1}] calculated for two long-term periods: 1985–2006 (a) and 1958–2006 (b)
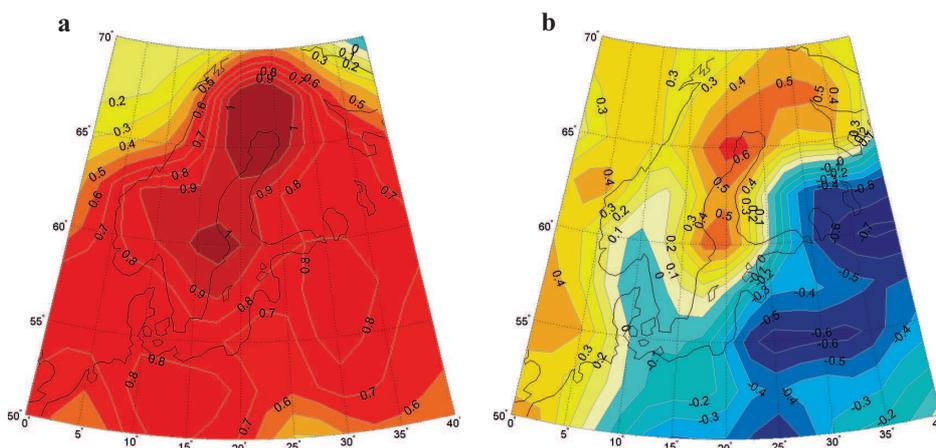
Figure 11. Spatial distribution of the air temperature trends [°C decade^{-1}] calculated for the period 1985–2006 and averaged over the June–October (a) and the December–April periods (b)

(Figure 11). Similarly, slight negative trends of monthly mean SST were recorded by Siegel et al. (2006) in the three main basins of the Baltic Sea in February and March. Winter cooling was mentioned in the EEA report (2004) as well, but only with reference to the 1990–1998 period. Later, warming was again reported. As a consequence of both winter cooling and summer heating, a wide range of the monthly mean temperatures occurs on the annual scale (Figure 8).

Climatologists point to the lengthening of the summer season as a result of both an earlier start to spring and the delayed onset of autumn (Sparks & Menzel 2002, BALTEX 2006). In the 20-year period analysed here, the interannual variations of the beginning dates of seasons and the duration of seasons did not show any statistically significant trends. However, there was a slight tendency for the warmest part of summer to be prolonged (Figure 7), which may be the first evidence of such changes and a possible reason for the intense summer blooms of cyanobacteria in central Baltic waters (Wasmund & Uhlig 2003). The high interannual variability of the duration of this period, which reflects the highly variable character of the atmospheric circulation patterns over the study area, require longer time series of data to demonstrate that this tendency will spread over a wider area and continue into the future.

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