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ORIGINAL RESEARCH ARTICLE

Spatial and temporal variability of sea surface temperature in the Baltic Sea based on 32-years (1982—2013) of satellite data[☆]

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Summary Satellite measurements provide synoptic view of sea surface temperature (SST) and can be used to trace global and regional climate trends. In this study we have examined the multiyear trends and variability of the Baltic Sea SST using 32-years (1982—2013) of satellite data. Our results indicate that there is a statistically significant trend of increasing SST in the entire Baltic Sea, with values ranging from 0.03 to 0.06°C year^{-1}, depending on the location. SSTs averaged over the entire Baltic Sea increase at the rate of 0.05°C year^{-1}. Higher values of SST trend are generally present in the summer months, while trend is not statistically significant in the winter months. The seasonal cycle of SST in the Baltic Sea is characterized by well-defined winter and summer seasons. The average amplitude (16—18°C) of this cycle is significantly larger than in the North Sea waters located at the same latitudes as the Baltic Sea. The analyzed data set also highlights considerable interannual SST variability, which is coherent in different regions of the Baltic Sea and significantly correlated with interannual variability of the air temperature. SST variability in the Baltic Sea in winter can be linked to the North Atlantic Oscillation index.

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1. Introduction

The Baltic Sea (BS) is a semi-enclosed brackish sea located in Northern Europe (Fig. 1). The sea is quite shallow and has an average depth of only 56 m. The hydrography of the BS is strongly influenced by the fact that annually about 480 km^3 of freshwater are added to the Baltic Sea by river runoff and atmospheric input. The river runoff is about one order of magnitude larger than the net atmospheric flux (precipitation minus evaporation, Leppäranta and Myrberg, 2009). Significant influx of freshwater from rivers promotes a permanent two-layer salinity structure in the Baltic Sea with a persistent halocline and an estuarine-like water exchange with the North Sea. Water residence time in the Baltic Sea is about 30 years. Low salinity waters coming out of the Baltic Sea have significant influence on the hydrography of the North and Norwegian Seas (e.g., Leppäranta and Myrberg, 2009). Most of the time, however, there is only limited inflow of dense and salty water to the Baltic Sea from the North Sea (through the Danish Straits, Skagerrak, and Kattegat) because of shallow topography. The intensity of this inflow can sporadically, at irregular intervals of time, increase significantly. Such events, called the Major Inflows depend on weather patterns, which control the sea-level difference between the Baltic and the North Seas (e.g., Gustafsson and Andersson, 2001; Omstedt et al., 2004). The Major Inflows are difficult to predict, but have a vital influence on the state of the Baltic Sea (e.g., Leppäranta and Myrberg, 2009).

Because of its geographical location, the BS region has some arctic characteristics with a pronounced seasonality (Leppäranta and Myrberg, 2009). At irregular intervals of time this region is under the influence of continental or marine climate forcing. In general, the westerly winds dominate, but the atmospheric circulation has a strong annual cycle component, with more intense westerlies during the autumn and winter seasons. The mean near-surface air temperature in the Baltic Sea region is usually several degrees higher than in other geographical regions located at the same latitudes. The reason for this is that atmospheric circulation and the warm North Atlantic Current bring heat to Western Europe (e.g., Bigg, 1996). The transport of warm water masses in the North Atlantic has significant effects on climate even much further north, including the Arctic Ocean (e.g., Beszczynska-Möller et al., 2012; Holliday et al., 2008).

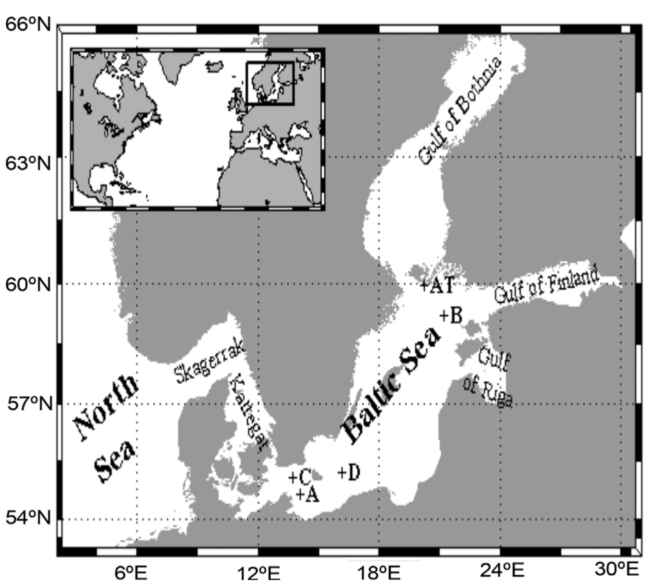

Figure 1 Map showing the geographical location of the Baltic Sea. The letters A and B indicate the positions of the time series data displayed in Fig. 3, the letters C and D show the positions of data sets in Fig. 4, and the AT is for the air temperature data presented in Figs. 7, 9, and 10.

A characteristic feature of the Baltic Sea hydrography is the seasonal surface layer with relatively warm and low salinity water embedded in the upper layer of water. This seasonal layer is formed in the spring due to seasonally increased freshwater input, ice and snow melt, and more efficient solar heating. Optical properties of this water layer are closely linked to river discharge of water with optically active components (dissolved and suspended matter, e.g., Babin et al., 2003; Stramska and Świrgoń, 2014). In deeper parts of the Baltic Sea a permanent halocline persists throughout a year at depth of about 40—80 m. Below it anoxia is common and interrupted only by the Major Inflows of the North Sea water (Leppäranta and Myrberg, 2009). The hydrography of the Baltic Sea is further complicated by the fact that the sea is partially covered by ice in winters. The extent of sea ice in the Baltic Sea varies from year to year. In average winters, the ice-covered region in March includes the Gulf of Bothnia, Gulf of Finland, Gulf of Riga, northern parts of the Baltic Proper, and shallow coastal waters, including those located in the southern part of the sea. In extremely cold winters almost all of the BS can freeze (Leppäranta and Myrberg, 2009). More details about the physical oceanography of the BS can be found in a recent review published by Omstedt et al. (2014).

Scientific efforts undertaken to understand past and present changes in the climate of the Baltic Sea region have been intensified in the past two decades. It has been shown that during the past century the increased frequency of both anticyclonic circulation and westerly winds has resulted in a warmer climate with reduced sea-ice cover. Significant increase in surface air temperatures in the Baltic Sea region has been also documented (e.g., BACC Author Team, 2008; Rutgersson et al., 2014).

In the present paper we have focused on satellite sea surface temperature (SST) data records covering 32-years (1 January, 1982 to 31 December, 2013). Our main goal is to analyze long-term SST trends and their regional and seasonal variations. In addition, our objective is to review characteristic features of the annual SST cycle and patterns of interannual variability. Sea surface temperature is an important oceanographic parameter, linked to many processes that occur in the upper ocean. For example, studies on primary productivity, exchange of energy with the atmosphere, climate change, ocean and weather modeling and forecasting require information about the SST. As a result, SST has been classified as one of the Essential Climate Variables that support the work of the UN Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC, 2007). The information about SST in the Baltic Sea gained through our analysis will contribute to improved understanding of the hydrography and climate trends in this region. Similar analyses of SST in the Baltic Sea published before have been based on significantly shorter time series. For example, Darecki et al. (2008) demonstrated good agreement between in situ and satellite derived SST in the Baltic Sea. Siegel et al. (2006) have analyzed 15-years of the Advanced Very High Resolution Radiometer (AVHRR) data and described seasonal and interannual SST variability in 1990–2004. Karagali et al. (2012) carried out an analysis of the diurnal SST cycle based on hourly satellite SSTs, which are only available from 2004 onwards. Bradtke et al. (2010) have performed a thorough analysis of spatial and interannual SST variations based on 20-years long data series (1986–2005). Longer data sets were simply not available at that time. However, long-term trends in geophysical data can be detected with good confidence only if sufficiently long observations are available. For example, Beaulieu et al. (2013) concluded that approximately 27 years of continuous satellite observations are required to detect global trends in surface chlorophyll concentrations. Therefore, we believe that it is worthwhile to revisit SST analysis in the Baltic Sea using the recently available 32-years long time series data.

2. Data and methods

Over the years satellite remote sensing has established itself as an indispensable technique of acquiring global and regional information about oceans. Our study is based on 32-years long data series (years 1982–2013) known as the National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation SST (OISST) Version 2 data set (Reynolds et al., 2007). These data have been made available by the NOAA Earth System Research Laboratory Physical Science Division (ESRL/PSD) through their Web site at http://www.esrl.noaa.gov/psd/. These are daily SST records (one daily value for each pixel), with spatial resolution of $0.25^\circ \times 0.25^\circ$, based on the Advanced Very High Resolution Radiometer (AVHRR) infrared satellite measurements (Pathfinder data in September 1981 through December 2005; operational AVHRR from January 2006). The final data set has been derived using satellite SST retrievals, SST observations from ships and buoys, and proxy SSTs generated from sea ice concentrations. Full description of data processing methods and comparisons between the NOAA OISST SST and in situ data can be found in Reynolds et al. (2007) and at www.ncdc.noaa.gov/sst/description.php. NOAA OISST SST data are currently the longest satellite data record that can be used to study long-term SST variability and trends. This data set has been approved by NOAA as the research quality data set, which can be used by oceanographers for further scientific analyses.

The infrared satellite remote sensing SST algorithms can provide either a skin SST if they are based on radiative transfer models or a subskin SST if in situ observations have been used to adjust satellite retrievals (Merchant and LeBorgne, 2004). In the NOAA OI SST Version 2 data set the bias correction of the satellite data has been based on data from ships and buoys, therefore it can be interpreted as the bulk SST at about 0.5 m depth (Reynolds et al., 2007). In order to apply the correction for bias, the satellite data have been classified into daytime and nighttime bins and corrected separately using in situ data. Then, all the data have been reanalyzed jointly using the optimum interpolation (OI) procedure. The final data represent the daily mean SST values. In the IO SST data set there are no missing data. Missing data have been interpolated using OI method or, if there was a significant sea ice coverage (ice fraction between 0.5 and 1), the SSTs have been calculated using statistical relationships between SST and sea ice coverage established regionally (Reynolds et al., 2007). Minimum SSTs for ice concentrations of 1 have been assumed to equal the freezing point of water (-1.8°C for seawater and 0°C for freshwater). In our data set in the Baltic Sea we have assumed that the freezing temperature is -0.33°C, which corresponds to the freezing point of seawater with salinity of 6 PSU (Leppäranta and Myrberg, 2009, page 221). We have carried out sensitivity tests, which indicated that our results presented in the figures and described in the Results section would not change significantly if we change the freezing temperature by $\pm 50\%$.

Our main interest in this paper is in the Baltic Sea (Fig. 1), but maps presented in the Results section also cover a vicinity of the Baltic Sea (parts of the North Sea) to show a better perspective for the analyzed SST variability. For discussion of SST variability and to show time series plots we have also used spatial SST averages representing small geographical regions. For this purpose we have subjectively defined four regions displayed in Fig. 2a. The exact positions of these regions do not have any special significance, the regions have been defined mainly to illustrate temporal patterns of SST variability. The area of each region is a square of 1° by 1° and the upper left corners of the regions have following geographical coordinates: region 1: 5.625°E and 57.125°N; region 2: 17.125°E and 55.875°N; region 3: 20.125°E and 59.375°N; region 4: 19.875°E and 62.875°N. For brevity we will use in this paper terms such as 'region 1 averages'. If we refer to the Baltic Sea averages, we consider the sea area located east from the 12°E. In all cases the regional averages were calculated only from pixels representing ocean surface. The Reynolds SST data set includes complementary information about the total SST error derived from the random sampling and bias error (Reynolds et al., 2007). We have plotted the average error for years 1982–2013 in Fig. 2b. As can be noticed, the errors assume larger values near the coasts in comparison to the open sea region. The largest errors are associated with the Gulf of Bothnia and Gulf of Finland, most likely because of frequent cloudy days and because sea surface in these regions is covered by sea ice over in the winters.

Validating data records from operational SST satellite instruments requires substantial volumes of high quality in situ data. Such data, covering the entire time period of satellite observations (1982–2013) were not available to us. Nevertheless we have compared the Reynolds SST data with in situ data that we were able to acquire. The first data set includes daily water temperature data from buoys and was obtained from the Baltic Operational Oceanographic System (www.boos.org). In this paper we present as an example data from two sensors deployed at 2-m depth (geographical positions are indicated in Fig. 1a by letters A and B, respectively). The second set consists of data collected from ships, and as an example we have plotted data for two stations: BY2 and BY5 (data downloaded from the Swedish Meteorological and Hydrological Institute, SMHI, http://produkter.smhi.se/pshark). These data have lower temporal resolution (on average one water temperature profile per month), but they cover the entire 32-years time period (1982–2013) represented in the Reynolds OI SST data. When comparing the in situ and satellite derived water temperatures one has to remember that both kinds of water temperature measurements are subject to errors. Errors in in situ data can be due for example to instrument drift, errors in

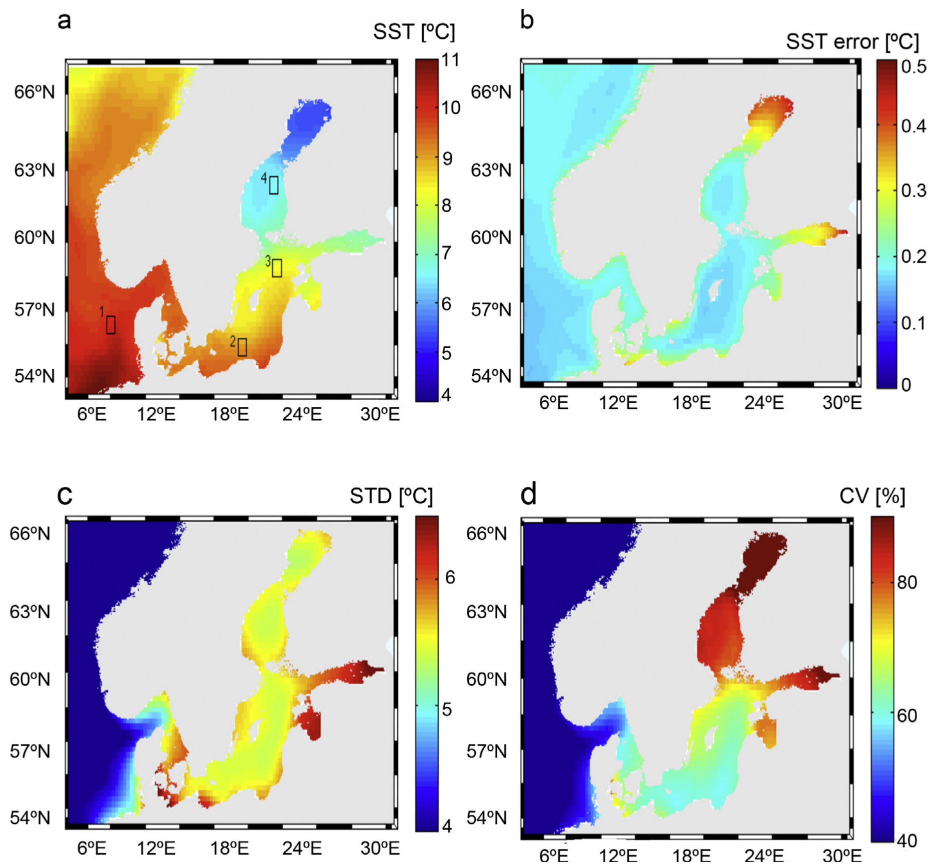

Figure 2 (a) The 32-year mean SST, (b) total SST error averaged in 32 years, (c) standard deviation (STD), and (d) coefficient of variation (CV). All estimates are based on Reynolds data from 1982 to 2013. Four study regions discussed in the text are indicated by black boxes in panel a.

calibrations or instrument malfunctioning. Errors in satellite data can be due to errors in imperfect atmospheric corrections. For brevity, in this paper, we refer to in situ SST estimates as 'observation' and to the differences between satellite-derived and in situ SST estimates as 'errors'.

The differences between in situ and satellite-derived SSTs have been quantified as follows:

- the absolute average error (AAE)

$$\mathrm{AAE} = \frac{1}{N}\sum_{i=1}^{N}|O_i - P_i|, \tag{1}$$

- the root mean square error (RMSE)

$$\mathrm{RMSE} = \left[\frac{1}{N-1}\sum_{i=1}^{N}(P_i - O_i)^2\right]^{1/2}, \tag{2}$$

- the bias (B)

$$B = \frac{1}{N}\sum_{i=1}^{N}P_i - \frac{1}{N}\sum_{i=1}^{N}O_i = \overline{P}_i - \overline{O}_i, \tag{3}$$

- the mean absolute percentage error (MPE)

$$\mathrm{MPE} = 100\frac{1}{N}\sum_{i=1}^{N}\left|\frac{P_i - O_i}{O_i}\right|, \tag{4}$$

where N is the number of measurements, O_i is the water temperature from in situ observation and P_i is the predicted value (satellite SST determination).

We have also examined meteorological data from the NOAA-CIRES Climate Diagnostic Center NCEP/NCAR (National Centers for Environmental Prediction and National Center for Atmospheric Research) Reanalysis 1. The Reanalysis Project employs a state-of-the-art analysis/forecast system to assimilate global meteorological data from various available sources from 1948 to the present. These data have coarser spatial resolution than SST data and are provided on the $2.5^\circ \times 2.5^\circ$ spatial grid. In this paper we have included comparisons of SST data with daily mean 2-m air temperature (AT). We have also analyzed the net latent and sensible heat fluxes, along with the net longwave and net shortwave radiation estimates, used to calculate the net heat flux at the sea surface. Because of the low spatial resolution of the NCEP data for our comparisons of SST and NCEP data we have used the NCEP data from a grid point located in the middle of the Baltic Sea (at 20.625°E 60.0°N, near region 3).

To examine the influence of the North Atlantic Oscillation (NAO) on SST we have used the Hurrell principal component (PC) based index, obtained from http://climatedataguide.ucar.edu/guidance/hurrell-north-atlantic-oscillation-nao-index-pc-based. These indices are provided as time series of the leading Empirical Orthogonal Function (EOF) of the sea level pressure (SLP) anomalies over the Atlantic sector at 20°–80°N and 90°W–40°E. An advantage of the PC time series approach is that such indices are more optimal representations of the spatial patterns of NAO than the station-based indices (fixed in space). Station-based indices can be affected by small-scale and transient meteorological phenomena not really related to the NAO. For a more detailed discussion of issues related to the NAO indices see Hurrell et al. (2003) and Hurrell and Deser (2009).

In addition to SST and meteorological data, we have used satellite ocean color data from MODIS Aqua (2003—2013) to show the spatial distribution of water turbidity in the Baltic Sea. The Baltic Sea waters are optically classified as Case 2 waters due to high CDOM and suspended matter concentrations (e.g., Babin et al., 2003). In Case 2 waters the standard NASA algorithms generally do not perform well, but the performance of the semianalytical algorithm for the diffuse attenuation coefficient for downwelling irradiance (K_d) is acceptable (Lee et al., 2005a,b). The average of absolute percentage difference between the in situ measured and the semianalytically derived $K_d(\lambda)$ in the Baltic Sea has been estimates as 14% for $\lambda = 490$ nm and 11% for $\lambda = 443$ nm. Therefore, in this paper we have used the semianalytically derived $K_d(490)$, obtained from the NASA's Ocean Color Web (www.oceancolor.gsfc.nasa.gov/) as the annually averaged Level 3 data (reprocessing version 2013). From these annual data we have calculated the 11 year average $K_d(490)$ distribution in the Baltic Sea. Recall, that the spectral vertical attenuation of downwelling irradiance, $K_d(\lambda,z)$, is defined as:

$$K_d(\lambda, z) = -\frac{d \ln[E_d(\lambda, z)]}{dz}, \quad (5)$$

where $E_d(\lambda,z)$ is the planar downwelling irradiance, z is the water depth, and λ is the light wavelength in vacuum (Mobley, 1994). Importantly, K_d influences the radiative heating of the ocean (e.g., Mobley and Boss, 2012; Stramska and Dickey, 1993; Stramska and Zuzewicz, 2013; Zaneveld et al., 1981) and can have a significant effect on SST.

Standard statistical methods have been used to examine the correlations between different quantities, and a simple linear model for trends has been assumed and tested for statistical significance (Ostasiewicz et al., 2006).

3. Results

3.1. Average SST

The spatial distribution of the 32-year averaged SST in the Baltic Sea is shown in Fig. 2a. Note that the geographical distribution of SST is characterized by a significant gradient between the southern and the northern parts of the Baltic Sea, with the 32-year averaged SST decreasing from about 9°C in the southern Baltic to 5—6°C in the Bothnian Bay. The average SSTs in the North Sea shown in Fig. 2a assume higher values than in the Baltic Sea. This can be linked to the influence of advection of warm water by the North Atlantic Drift Current, which is considered to be an important moderating factor for the climate in Western Europe (e.g., Bigg, 1996; Moron et al., 1998). In contrast, standard deviation (STD) calculated from 32-year long time series of SST is significantly larger in the Baltic Sea than in the North Sea (Fig. 2c). Coefficient of variation (CV) calculated as the ratio of STD and mean SST is also larger in the Baltic Sea and assumes the largest values in the northeastern regions (Fig. 2d), where mean SSTs are the lowest. Most of the SST variability characterized by STD and CV displayed in Fig. 2c and d can be attributed to the annual cycle, which will be discussed later.

In Fig. 3 we have compared the Reynolds OI SST data with in situ data collected at 2 m depth from two oceanographic moorings. The location of the first buoy (13.87°E 54.88°N) is indicated by the letter A and the location of the second buoy (20.0°E 59.25°N) is indicated by the letter B in Fig. 1. We were unable to find any public domain daily in situ data covering exactly the same time period as the Reynolds OI SST data, therefore time series shown in Fig. 3 are only few years long. In Fig. 4 another comparison is presented using data from ships. These data extend over the same 32 years as the Reynolds OI SST, but they have not been collected at regular time intervals, usually there is only one data point per month. When comparing the data in Figs. 3 and 4 one has to keep in mind the issue of mismatch in scales in the data sets. The Reynolds OI SST data represent mean daily value averaged in a pixel of 0.25 by 0.25 degree. The in situ data represent water temperature measured at a given point in space and valid for a given hour of the day. In addition both data sets are subject to instrumental errors. Given these issues, our comparison presented in Figs. 3 and 4 has to be treated with caution and cannot be understood as a true validation of satellite data. Such validations are done routinely by institutionally funded programs (NASA, NOAA, ESA) with detailed quality controlled data sets, and are out of the scope of this paper. Nevertheless, data shown in Figs. 3 and 4 indicate that Reynolds OISST and in situ water temperatures in the Baltic Sea agree reasonably well. Additional analysis (not shown here) indicated that there is no statistically significant trend in the differences between the long-term water temperature records shown in Fig. 4. The error statistics for data displayed in Figs. 3 and 4 is summarized in Table 1. For comparison, the mean difference between in situ and monthly satellite data presented in Bradtke et al. (2010) was 0.58°C.

Maps of the median and maximum SSTs observed in the entire 32-year long time period (1982—2013) are displayed in Fig. 5. The median SSTs are generally lower and the maximum SSTs are higher in the Baltic Sea basin than those observed in the North Sea near the entrance to the Baltic Sea. This suggests a stronger impact of the local weather forcing on the Baltic Sea SST in comparison to the nearby oceanic regions, influenced by advection of water with the North Atlantic Current. In the Baltic Sea, the highest 32-year SSTs are observed in the southern Baltic and in the shallow waters of the Gulf of Riga and the Gulf of Finland, with the maximum temperatures exceeding 24°C (Fig. 5b). Generally, the temperatures decrease from the south to the north and the lowest mean, median and maximum temperatures are observed in the northern regions.

3.2. Seasonal cycle

Variability of SST in the Baltic Sea is characterized by an outstanding seasonal cycle. This is illustrated in Fig. 6. In Fig. 6a and b we have plotted spatial distribution of the 32-year averaged annual minimum and maximum SST, respectively. Note that the color scale is different for every figure, to better show the range of observed SST values.

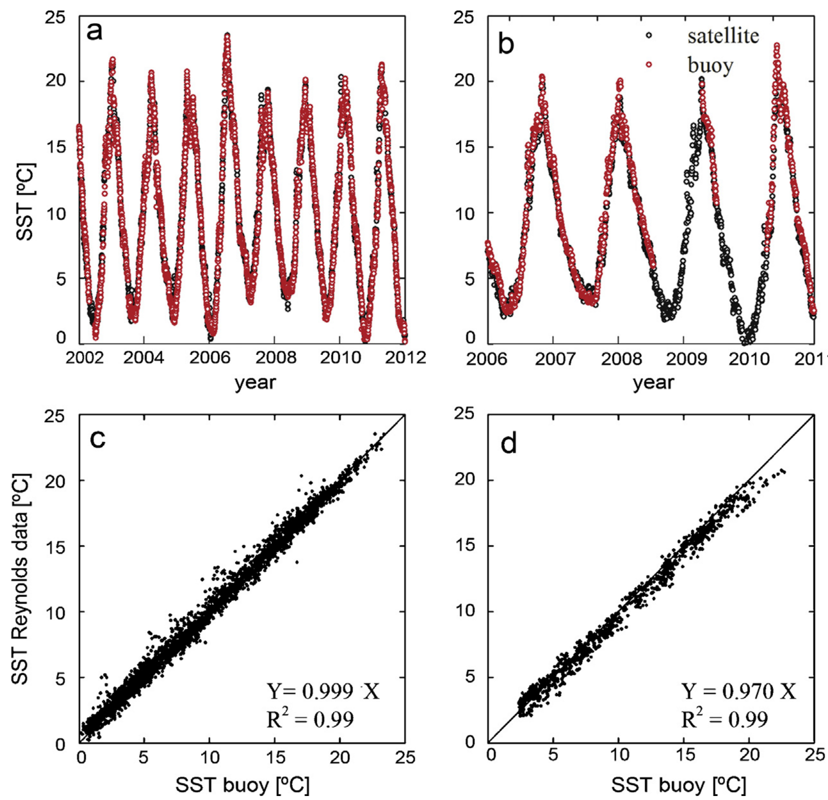

Figure 3 Comparison of Reynolds SST data with water temperatures measured at 2 m depth from buoys deployed in the Arcona basin (13.87°E 54.89°N, data shown in panels (a) and (c)) and in the northern part of the Baltic Proper (21.0°E 59.25°N, data shown in panels (b) and (d)). The geographical positions of the buoys are indicated in Fig. 1 by letters A and B. The solid lines in panels c and d indicate the *Y* = *X* line (see Table 1 for error statistics).

Fig. 6c and d indicates when the minimum and the maximum SSTs are observed (year day). The highest minimum and maximum SST values (2—3°C and 18°C, respectively) occur in the southern part of the sea. The minimum SST values of the 32-year averaged annual cycle are usually observed in February—April (Fig. 6c), while the maximum values are generally present in July—August (Fig. 6d). In Fig. 6e, the amplitude of the annual cycle is presented. This amplitude has been calculated as the difference between the maximum and minimum SST values plotted in Fig. 6a and b. The most striking observation is that the amplitude of the SST annual cycle in the Baltic Sea is considerably larger than in the North Sea. This is due to significantly lower annual minimum SST and higher annual maximum SST in the Baltic Sea in comparison to the North Sea (Fig. 6a and b). It is also striking that even if the maximum and minimum temperatures cover a broad range of variability (depending on the geographical location), the annual SST amplitude does not change much over the entire Baltic Sea. As can be seen in Fig. 6e the greatest amplitude of the seasonal SST cycle (more than 17°C) occurs in shallow bays such as the Gulf of Riga and the Gulf of Finland. Comparison with Fig. 6f, where the spatial distribution of the vertical attenuation coefficient for downwelling irradiance, $K_d(490)$, is presented, leads us to the conclusion that larger amplitude of SST can be associated with regions where waters are more turbid. Note, that higher concentrations of optically active water components, responsible for larger values of $K_d(490)$, are often associated with considerable runoff from rivers. Therefore, these are the regions where waters can be more stratified due to significant amounts of low salinity waters spreading on the surface, and such stratification likely also induces more pronounced annual cycle of SST.

To better illustrate the development of the seasonal cycle we have extracted SST time series in the four locations shown in Fig. 2a. Comparison of the 32-year averaged annual cycle of SST at these four locations is displayed in Fig. 7a. Fig. 7a in

Table 1 Estimates of the bias (*B*), absolute average error (AAE), mean absolute percentage error (MPE), and root mean square error (RMSE) obtained for comparison of Reynolds SST with in situ water temperature measured at sites A, B, C, and D (see Fig. 1). N is the number of observations. The relevant data sets are shown in Figs. 3 and 4.

Sites	A	B	C	D
B [°C]	−0.05	0.38	0.02	0.09
AAE [°C]	0.42	0.56	0.83	0.8
MPE [%]	7.7	7.4	13.1	10.8
RMSE [°C]	0.57	0.71	1.05	1.05
N	3000	1034	324	309

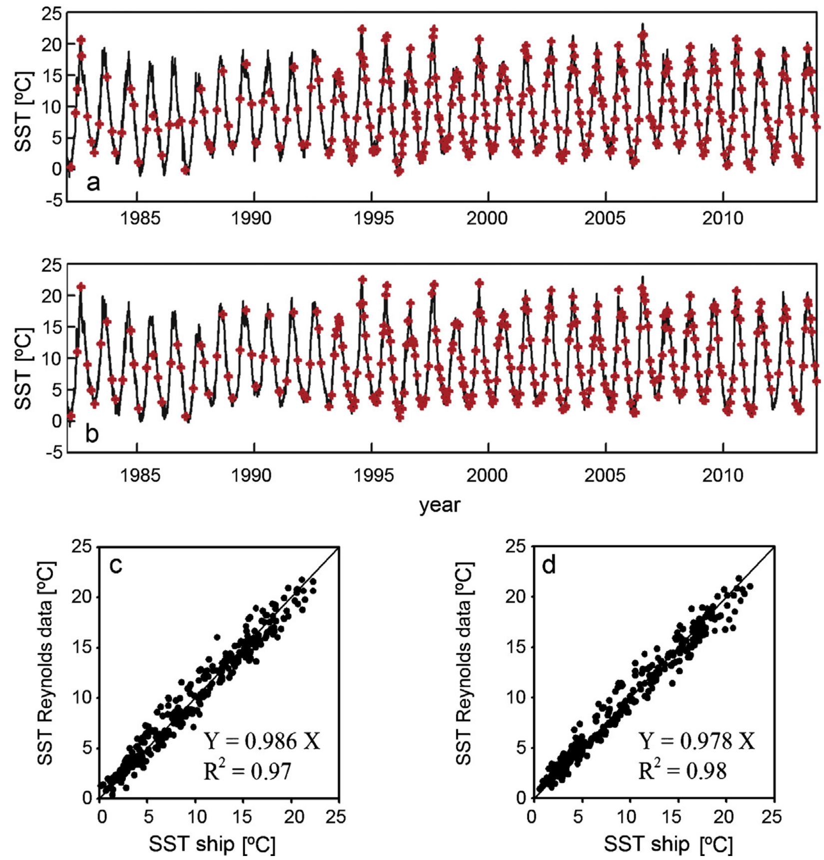

Figure 4 Comparison of Reynolds SST data with surface water temperatures measured at 0.5 m depth from ships at stations BY2 (14.1°E 55.0°N, data shown in panels a and c) and BY5 (15.99°E 55.25°N, data shown in panels b and d). The geographical positions of the stations are indicated in Fig. 1 by letters C and D. The solid lines in panels a and b indicate the *Y* = *X* line (see Table 1 for error statistics).

addition to Fig. 6 highlights a significant difference in the SST cycle in the North Sea (location 1) and in the Baltic Sea (locations 2, 3, and 4). The North Sea location is characterized by smaller amplitude of the annual SST cycle than the three Baltic Sea locations. This can be at least partly explained by the fact that SST in the North Sea is influenced by water advection with warm current while the Baltic Sea is surrounded by land. As a result oceanic water inflow into the Baltic Sea is restricted by topography and the variability of SST is mainly due to local air-sea exchange processes. In addition, sea surface in the Baltic Sea is exposed relatively more often to air masses advected from land than in the North Sea. Continental air masses typically have a more pronounced temperature variability compared to the oceanic air masses, and this can be reflected in the Baltic Sea SST variability. Moreover, the Baltic Sea is strongly influenced by the freshwater inflow from rivers. This inflow increases water column stability and water turbidity (Stramska and Świrgoń, 2014). Increased water turbidity in turn likely causes more efficient heating of the surface layer of water (e.g., Stramska and Dickey, 1993).

Comparison of SST and air temperature (AT) data presented in Fig. 7a shows that the seasonal cycle of AT is leading the seasonal cycle of SST in winter with the minimum AT occurring in the end of January/beginning of February. The minimum AT is on average lower than the minimum SST by about 5°C, while the maximum SST and AT have similar values and both are featured in July/August (day 210—225).

Based on the 32-year time series of daily SST data, we have also documented (Fig. 7b) a characteristic annual cycle of the SST standard deviation (STD) in our four geographical locations. Fig. 7b shows that in all four locations the daily SST standard deviations assume higher values (~1.5—2°C) in the summer and lower values (~1.3°C and less) in the winter. The daily SST standard deviations in region 1 (North Sea) have on average lower values in comparison to the Baltic Sea regions, which again is consistent with the fact that region 1 is more influenced by the advection of the oceanic water and air masses than the Baltic Sea. In comparison to SST, the standard deviation of the air temperature (Fig. 7d) has an opposite annual cycle with the largest STD values observed in the winter (6°C) and smaller STD values in the summer. Such a difference in the STD patterns of SST and AT can be explained by the fact that during winters surface waters in the Baltic Sea undergo efficient wind-induced and convective mixing. Therefore cooling of the water involves large volumes of water (not only surface layers) and this decreases the temporal variability of SST. In Fig. 7c spatial patterns in the standard deviation of SST are shown after the annual cycle has been subtracted at each pixel. This caused a substantial decrease of STD in comparison to STD shown in

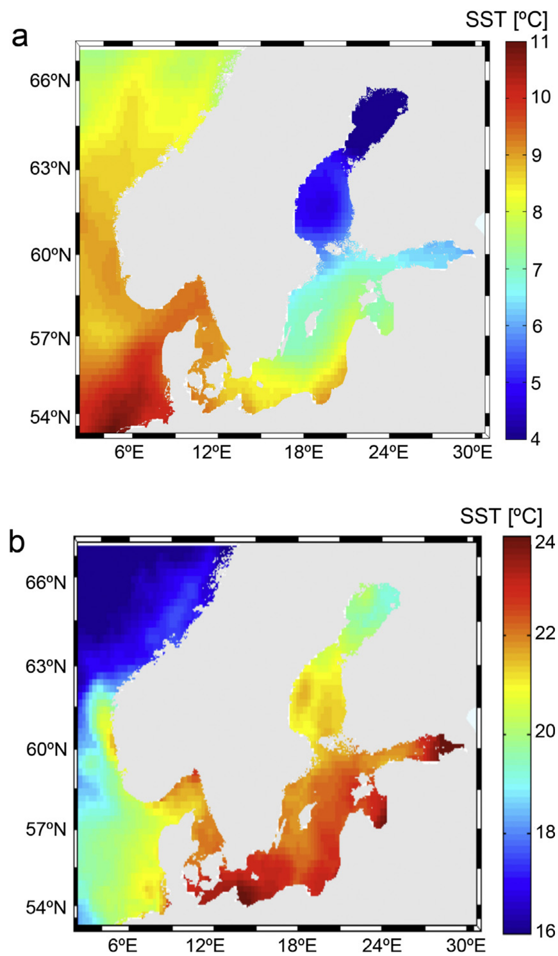

Figure 5 (a) Median and (b) maximum SST values in the time period between January 1, 1982 and December 31, 2013. Note that the color scale is different for each plot. (Figure in color is provided in the web version of this article.)

Fig. 2c, where annual variability was included. As can be seen, STD values in Fig. 7c are greater in the southern part of the Baltic Sea than in the northern part. This can be explained by the fact that water in the north is partly covered by sea ice in the winter. In addition, larger STD values can be associated with regions more influenced by variability in the water circulation patterns and advection (Omstedt et al., 2014).

3.3. Long term trends and interannual variability

Time series of annual SST data have been used to estimate regional SST trends presented in Fig. 8 (statistically significant at 95% confidence level, $p < 0.05$). Trends of increasing annual mean SST have been detected everywhere in the Baltic Sea and in the North Sea near the entrance to the Baltic Sea. These trends in the Baltic Sea are generally greater than 0.04°C year^{-1} and sometimes assume values of about 0.06°C year^{-1}, for example in the Gulf of Finland. Our analysis indicates that SST averaged over the entire Baltic Sea increases at the rate of 0.05°C year^{-1} (or 0.5°C per decade). Similar SST trend has been estimated by Bradtke et al. (2010), who used a different data set. For comparison, the globally averaged SST trend calculated by Good et al. (2007) using 20 years of Advanced Very High Resolution Radiometer Pathfinder data (January 1985 to December 2004) has been estimated as 0.18°C and 0.17°C per decade from daytime and nighttime data, respectively. Thus, the warming trend estimated by us for the Baltic Sea is greater than these global trends. Trends higher than the global SST trend were reported before for other coastal regions, for example in the Arctic (e.g., Nghiem et al., 2014; Peterson et al., 2002). They have been explained by an increasing water runoff from land, which intensifies water column stratification in the ocean (e.g., Morison et al., 2012) and supplies more terrigenous material, at the same time amplifying surface water heating (Fichot et al., 2013). Similar effects can be expected to play a significant role in the Baltic Sea.

We have observed large range in SST variability due to a relatively strong annual cycle in the Baltic Sea. The annual mean SSTs can be significantly affected by extreme SST values. Therefore we have also used annual SST data to estimate trends for medians, 25th and 75th percentiles (Fig. 8b, c, and d). Note that these estimates are completely independent on our assumptions about the temperatures in the sea ice covered pixels. Our results indicate that the annual median SST values have been increasing stronger in the southern Baltic than in the Botnic Sea, but trends are statistically significant in the entire Baltic. The 75th percentiles in the annual SST data have been increasing faster than the mean and median SST (note that the scale in Fig. 8c is different than in Fig. 8a and b). Similar trends for the 25th percentiles were low and statistically not significant (not shown). This indicates that the mean SST in the Baltic Sea increases mainly due to changes occurring in the warm season of the year. This conclusion is also supported by Fig. 8d, where trends based on monthly SST data have been presented. Fig. 8d shows that the multiyear SST trends are strongest in the summer months (July—September). Bradtke et al. (2010) also reported larger SST trends in the summer. Interestingly, Bradtke et al. (2010) observed negative SST trends in the winter, but such negative trends have been not confirmed by our analysis. In addition we have checked that trends for maximum annual values were statistically significant, but trends for the amplitude of the annual cycle (taken as the difference between maximum and minimum SST) were not significant, probably because there was no trend in the minimum SST values.

In addition to multiyear trends the SST data allowed us to analyze patterns in interannual variability. As an example, time series of annual SST anomalies averaged in the four study regions are shown in Fig. 9a. The annual anomalies were defined as the difference between the annually averaged SST minus the 32-year average SST calculated at each pixel. Next, the anomalies for all pixels within each region were averaged to obtain the regional anomalies shown in Fig. 9a. For comparison, annual AT anomalies at 20.625°E 60.0°N are also included in this figure. The data displayed in Fig. 9a indicate that the lowest annual SST values in all four regions were observed in 1987. Patterns of interannual SST variability are coherent in different regions of the Baltic Sea and in the North Sea in region 1. There is also a good

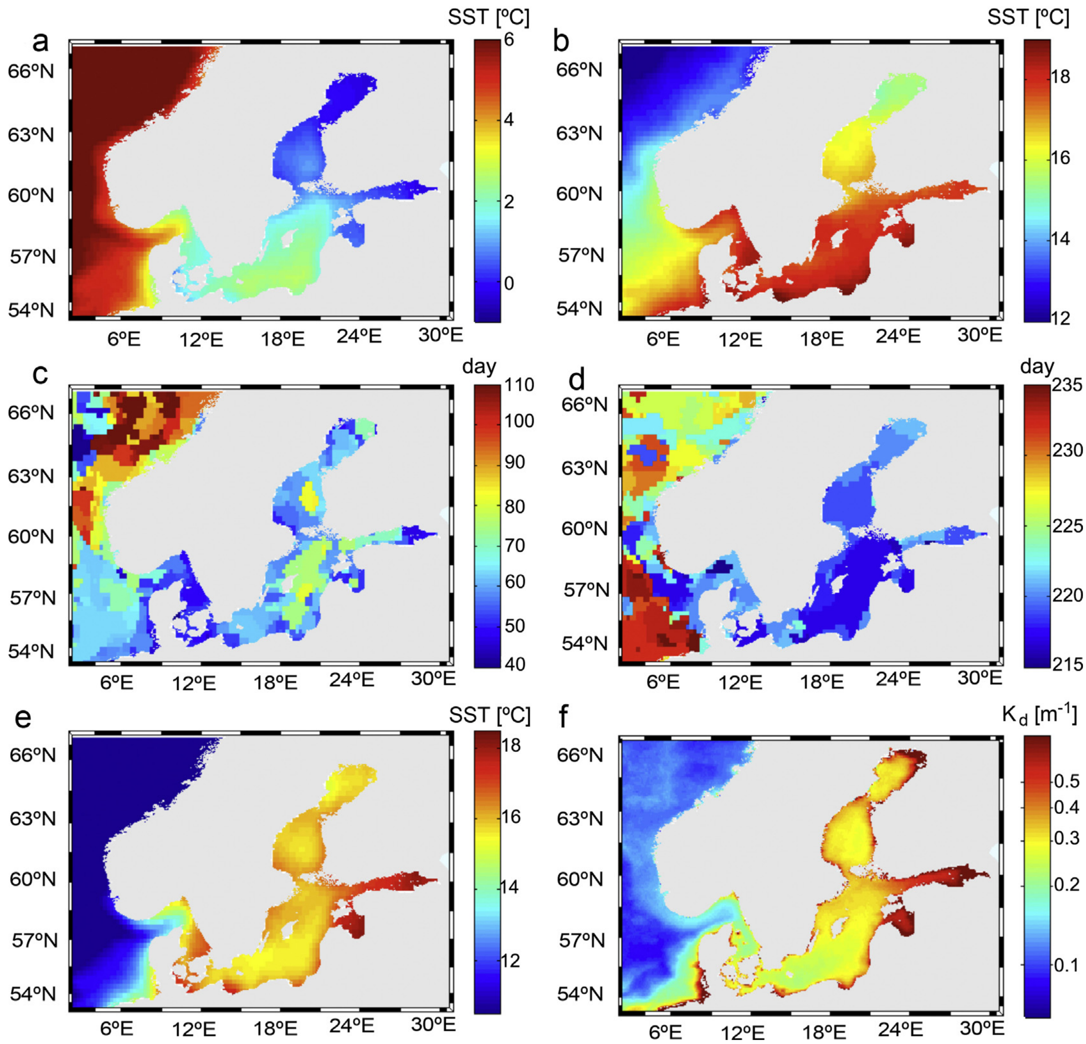

Figure 6 Summary of the 32-year averaged annual cycle of SST: (a) minimum, (b) maximum SST values, (c) day of the year when the minimum SST is observed, (d) day of the year when the maximum SST is observed, (e) amplitude of the annual SST cycle, and (f) the vertical attenuation coefficient K_d(490) averaged in 11 years (2003—2013) based on the MODIS Aqua data. (Figure in color is provided in the web version of this article.)

correspondence between the 2-m annual air temperature anomalies and SST anomalies. To illustrate the relationship between the AT and SST anomalies, a scatter plot including data from region 3 is shown in Fig. 9b, as an example. Correlation coefficient (R) for these data is 0.88. Analogous correlation coefficients for AT and SST anomalies in regions 1, 2 and 4 (scatter plots not shown), are 0.69, 0.88, and 0.89, respectively. Similar correlation was lower but also statistically significant when we compared the anomalies of SST and the net shortwave radiation flux ($R = 0.61$, data not shown). Correlation between SST and the net heat flux anomalies was not statistically significant ($R = -0.16$, data not shown).

The North Atlantic Oscillation (NAO) index (e.g., Hurrell and Deser, 2009; Hurrell et al., 2003) is often linked to climate variability in Europe. Positive NAO index values are associated with low-pressure anomalies over the Iceland and anomalously high pressure in the subtropical Atlantic, and indicate stronger than average westerlies. The NAO variability has been linked for example to the precipitation (Hurrell, 1995) and sea surface temperature patterns in the northeast Atlantic (Planque and Taylor, 1998), and has been also shown to influence the variability in the Baltic Sea (BACC Author Team, 2008; Hänninen et al., 2000, 2003; Kauker and Meier, 2003). The atmospheric circulation can affect SST directly through processes of air-sea energy exchange and indirectly by forcing specific patterns of water circulation and advection. Therefore we have included in Fig. 10 the winter anomalies of SST (in region 3) and AT plotted as a function of the winter (DJF) Hurrell principal component (PC) based North Atlantic Oscillation (NAO) index (Hurrell and Deser, 2009; Hurrell et al., 2003). The results were comparable if we plotted in a similar way SST data from other regions (results not shown). The correlations between NAO and SST as well as NAO and AT in winter are statistically significant, but similar correlations are not statistically significant for the annual data (not shown). The correlations can be explained by the fact that a positive NAO index in winters is accompanied by strong westerly winds and advection of humid and warm air masses from the Atlantic, while a negative NAO index is associated with the northerly winds advecting cold

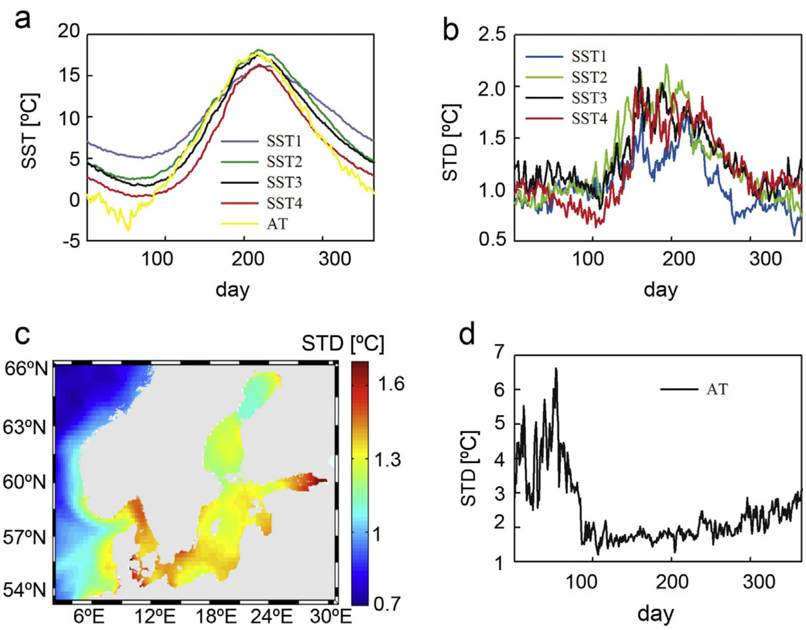

Figure 7 (a) The 32-year averaged annual cycle of SST in the four study regions. The geographical position of each region is indicated in Fig. 2a. For comparison, the 32-year averaged annual cycle of the air temperature (AT) at 20.625°E 60.0°N is also plotted. (b) Annual patterns in the standard deviations calculated from daily SST data in the four study sites. (c) Spatial distribution of the standard deviations calculated from daily SST data after subtracting the average annual SST cycle at each pixel. (d) Annual pattern in the standard deviation of the air temperature (AT) at 20.625°E 60.0°N.

arctic air masses. These continental and marine climate influences are most likely reflected in SST anomalies.

4. Summary and conclusions

Our main goal in this paper was to characterize multiyear SST variability and trends in the Baltic Sea. For this purpose we have used the NOAA Optimum Interpolation SST (OISST) Version 2 data (Reynolds et al., 2007), which provide long-term, consistent synoptic view of the thermal state of the ocean surface and can be used to assess regional climate trends and variability. The analysis of SST variability in the Baltic Sea can lead to a better understanding of this marine environment, including

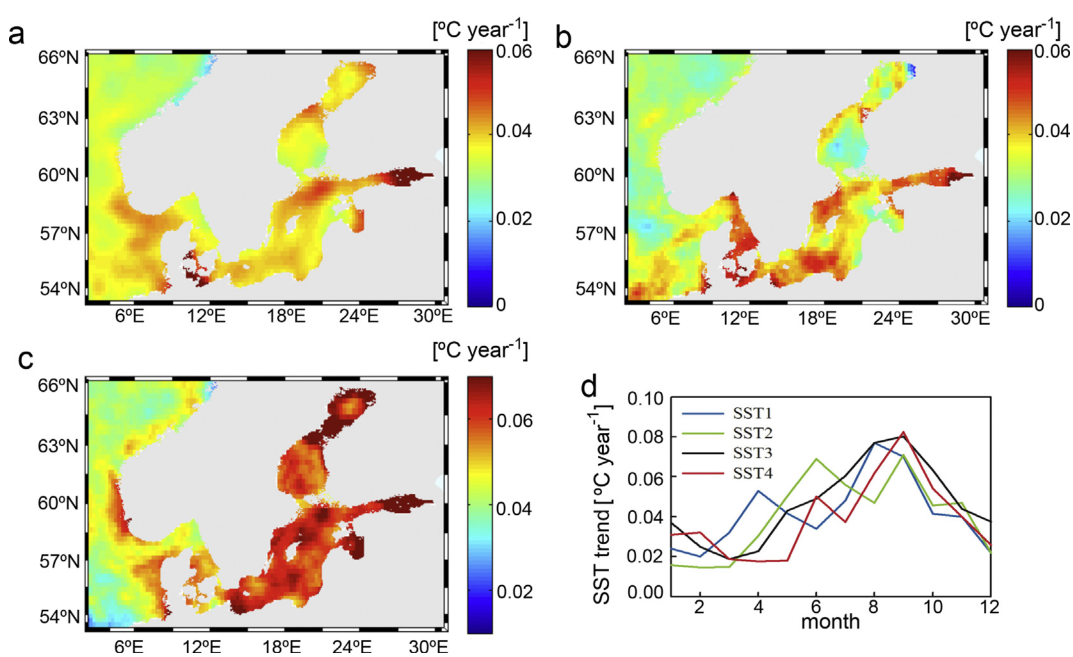

Figure 8 Trends in the annual (a) means, (b) medians and (c) 75th percentiles of SST in years 1982—2013. Trends are statistically significant ($p < 0.05$, 95% confidence level). (d) Trends in the monthly SST data averaged at the four study sites displayed in Fig. 2a.

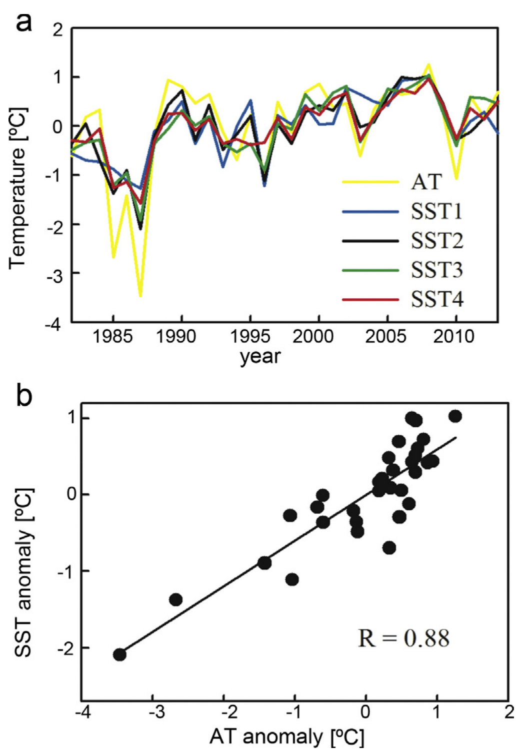

Figure 9 (a) Time series of the annual SST anomalies averaged in the four study regions. For comparison, the annual air temperature anomalies at 20.625°E 60.0°N are also shown. (b) Annual anomalies of SST in region 3 plotted as a function of AT anomalies at 20.625°E 60.0°N.

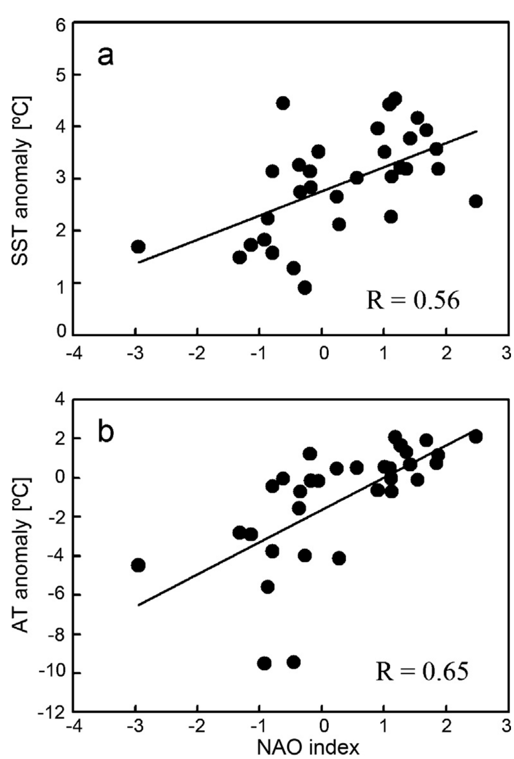

Figure 10 Winter anomalies of (a) SST in region 3 and (b) air temperature at 20.625°E 60.0°N, plotted as a function of the Hurrel winter (DJF) principal component (PC) based North Atlantic Oscillation (NAO) index.

climate related hydrographic and ecosystem trends and dependencies.

Our most important findings can be summarized as follows:

- The 32-year averaged annual mean and minimum SSTs in the Baltic Sea (5 to 9°C and −0.3 to 3°C, respectively) are significantly lower than in the North Sea (10 to 11°C and 8°C, respectively) near the entrance to the Baltic Sea.
- Annual maximum SSTs are higher in the Baltic Sea than in the North Sea. On average, the maximum SSTs of about 19°C in the southern Baltic are observed in July—August, but in some years SSTs can exceed 24°C. In comparison 32-year averaged maximum annual temperature in the North Sea at similar latitudes is about 16°C.
- There are large regional differences between the annual mean, median, maximum, and minimum SSTs in the southern and northern regions of the Baltic Sea. They can be explained by the latitudinal extent of the Baltic Sea (from about 53°N to 66°N).
- In spite of this large range of regional SST values the average amplitudes of the seasonal cycle have similar value almost everywhere in the Baltic Sea (16—17°C). The amplitude has slightly higher values in shallow bays and coastal regions, where bathymetry prevents water mixing and circulation. Optical properties of more turbid coastal waters are also likely an important factor causing more efficient heating of surface waters. This can be even more reinforced if waters are strongly stratified due to the freshwater runoff.
- Amplitudes of the annual SST cycle are significantly larger in the Baltic Sea than in the North Sea at the same latitudes (~10—12°C).
- Overall SST variability reflected in standard deviations and coefficients of variation is greater for the Baltic Sea SSTs (5.5—6°C and 60—90%, respectively) than for the North Sea SSTs (~4°C and 40%, respectively).
- Patterns in interannual SST variability are coherent in different regions of the Baltic Sea and in the North Sea near the Baltic Sea.
- The interannual SST anomalies are significantly correlated with 2-m air temperature anomalies and net shortwave radiation.
- Interannual SST variability in the Baltic Sea in the winter is significantly correlated with the North Atlantic Oscillation index.
- We have documented statistically significant 32-year long trends ($p < 0.05$, 95% confidence level) of increasing annual mean, median and 75th percentiles SST. Trend for the Baltic Sea averaged annual mean SST is estimated as 0.05°C year^{-1}, but depending on the exact geographical position its values range from 0.03 to 0.06°C year^{-1}.
- Trends indicate stronger warming in the summer months. Trends are not statistically significant for annual minimum and 25th percentiles SST.

It is worth noting that our analysis indicates that SST warming trend in the Baltic Sea is greater than the globally averaged SST trend. This finding is consistent with earlier results published by Bradtke et al. (2010) and Siegel et al. (2006). Similar to our findings, Bradtke et al. (2010) indicated that warming is stronger in the summer. However, Bradtke et al. (2010) also postulated a negative SST trend in the winter months. This negative trend has not been confirmed in our analysis. The observed large differences between the variability of SST in the North and the Baltic Seas can be explained by stronger impacts of the oceanic water and oceanic air advection on the North Sea SST than on the Baltic Sea SST. Because of the limited inflow of oceanic water, SST in the Baltic Sea is mostly under the influence of local air-sea interaction processes. In addition, atmospheric circulation brings at times continental air masses over the Baltic Sea, and this intermittent influence of oceanic/continental air masses increases the variability of SST in this sea. Alternating between continental and marine influences is typical for the Baltic Sea region. This is also reflected in the variability of the North Atlantic Oscillation Index. Positive NAO index in winters is associated with strong westerly winds and advection of humid and relatively warm air masses from the ocean. Negative NAO index is associated with cold winters due to the northerly winds advecting cold arctic air masses. Our results are in agreement with the notion that Baltic Sea climate system memory is characterized by two important time scales of variability (Omstedt and Hansson, 2006a,b). The first scale is associated with the water balance and salinity and has an e-folding time of about 30 years, while the second scale is associated with the heat balance and has an e-folding time of approximately one year. This means that on the annual time scale the Baltic Sea is almost in thermal balance with the atmosphere. This is reflected in the variability of sea ice extent and water temperatures. In contrast we can expect that it will take longer before we can detect changes in parameters related to the water balance, such as water salinity.

In the Baltic Sea, the combined system of rivers, estuaries, and oceanic water inflows, creates a complex hydrodynamic environment, governed by variable atmospheric forcing (wind, heat fluxes, sea ice processes), irregular river discharge, and variable bathymetry. The sea is surrounded by nine countries, and the quality of life of about 85 million people is affected by the environmental problems in the Baltic Sea. One of the important aspects of the Baltic Sea research is the goal of remediating the eutrophication of this marine environment (HELCOM, 2009). This requires a better understanding how this system reacts to global climate and human induced changes. Progress in oceanographic understanding of the Baltic Sea has been hampered by a limited number of free access databases with systematic, large-scale in situ measurements. We believe that in this light, the significance of information gained from long-term satellite observations cannot be overestimated.

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