Sea surface temperature development of the Baltic Sea in the period 1990–2004

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Abstract

Sea Surface Temperature (SST) maps derived from NOAA weather satellites for the period 1990–2004 were used to investigate seasonal and inter-annual variations in the Baltic Sea. A comparison between monthly mean SST and *in situ* measurements at the MARNET station 'Arkona Sea' showed good agreement with differences in July and August. Monthly means reflect strong seasonal and inter-annual variations. The yearly means show a slight positive trend with an increase of 0.8 K in 15 years. In particular, summer and autumn months contribute to this positive trend, with stronger trends in the northern than in the southern Baltic. The winters are characterised by a slightly negative trend. The winter minimum SST in the Arkona Sea correlates best with the WIBIX climate index derived for the Baltic region.

1. Introduction

Sea Surface Temperature (SST) is an important quantity in the study of the ocean and the atmosphere, because it is related directly to the exchanges of heat, momentum and gases. Therefore, knowledge about its spatial and

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temporal development is of special interest. Satellite-derived SST delivers the synoptic temperature distribution of large areas with a high temporal resolution over a long period, something that cannot be done by other methods. This is a further reason for the application of SST to different studies, including climatological investigations.

The application of satellite-derived SST maps in Baltic Sea research covers a wide range of topics, such as the support of monitoring programmes, studies of dynamic processes, coastal zone/open sea interactions in river discharge areas, and climatological phenomena. Furthermore, water temperature is one of the factors affecting the development of phytoplankton. The particular topics analysed include: the dynamic features and processes like eddy development, fronts or coastal upwelling (Horstmann 1983, Gidhagen 1984, Lehmann 1992, Hansen et al. 1993, Siegel et al. 1994, Kahru et al. 1995); the water exchange between coastal zones and the open sea in the south-eastern Baltic Sea (Horstmann et al. 1986, Brosin et al. 1988, Horstmann 1988); the Oder River discharge in the Pomeranian Bight to determine the transport directions and the accumulation areas for the sediment load (Siegel et al. 1994, 1996, 1998, 1999a); the discharge and dynamic processes along the entire German Baltic Sea coast (Siegel et al. 2005); seasonal and inter-annual variations in the Baltic Sea in the 1990s on the basis of monthly mean SST-maps (Siegel et al. 1999b).

The 15-year SST satellite data with a spatial resolution of 1×1 km for the entire Baltic Sea is a unique data set that can contribute to a large number of research topics. The investigation in this paper focuses on the development of the yearly mean SST in the entire Baltic Sea for the period 1990–2004 to identify potential trends. The investigation period lies in a warming phase of the northern hemisphere, which began in the mid-1970s (Jones & Moberg 2003, Jones et al. 2006). Furthermore, regional, seasonal and inter-annual particularities were elaborated. Because the SST contains information on the skin the presentation of the results begins with a comparison between monthly mean SST and surface temperature means measured at 2 m depth to identify differences.

2. Area of investigation and data sets

The area of investigation shown in Fig. 1 includes a transect consisting of 25 stations through the central parts of the Baltic Sea. The numbering starts in the south-western Baltic and ends in the Bothnian Bay. Position P6 represents the Arkona Sea, P11 the Bornholm Sea, P15 the Gotland Sea, P19 the Bothnian Sea and P23 the Bothnian Bay. The positions of the Arkona, Gotland and Bothnian Seas are marked because they have been

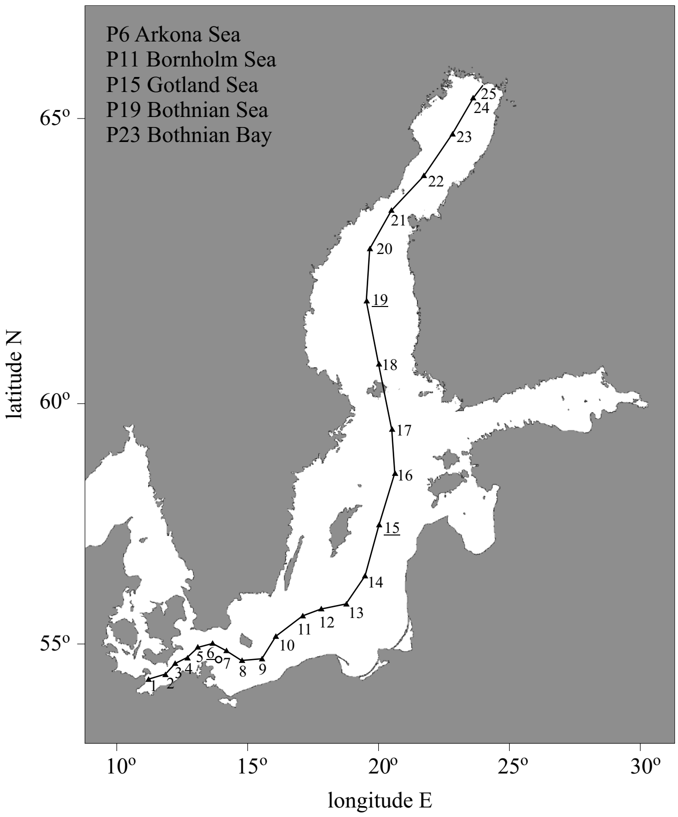

Fig. 1. Area of investigation, including the transect through the central basins of the Baltic Sea and the MARNET station 'Arkona Sea' (marked by a circle)

used for detailed analyses. The location of the IOW-MARNET (**Mar**ine Monitoring **Net**work of the BSH) station 'Arkona Sea' is also shown.

The SST-maps of the investigation period 1990–2004 were derived from the infrared channels of the Advanced Very High Resolution Radiometer (AVHRR) of the weather satellites of the National Oceanic and Atmospheric Administration (NOAA). The German Federal Maritime and Hydrographic Agency Hamburg (Bundesamt für Seeschifffahrt und Hydrographie Hamburg, BSH) operates a SeaSpace-HRPT (High Resolution Picture Transmission) receiving station and the TeraScan image processing system. During the 15 years, 6 different NOAA satellites were used, always two in parallel. The procedure for SST evaluation using the standard NOAA algorithms implemented in the TeraScan software is described in Siegel et al. (1994), and the applicability of SST data and the interfering factors are discussed in Siegel et al. (1996).

Monthly mean SST maps were calculated on the basis of all cloud-free pixels of the available scenes (overpasses) during each month, depending on the number of satellites from which the data were received. Over the period January 1990–December 2004, always two NOAA-satellites served as the major data sources for the BSH. The number of overpasses per month varied between 60 and 180, which are 2–7 per day and about 30 000 scenes with a spatial resolution of 1 km throughout the investigation period. The number of usable data per image pixel contributing to the monthly means varied seasonally, depending on cloud coverage, misinterpretation of readings, and especially on ice coverage in winter. Siegel et al. (1999b) gives examples for the number of usable scenes. The monthly mean SST was used to calculate seasonal and yearly mean values for each pixel and also the yearly means for the entire Baltic Sea.

Water surface temperature data for 2003 measured at the permanent MARNET station 'Arkona Sea' were included for methodological investigations. The measurements were performed continuously at 2 m water depth every hour averaged over 10 minutes and a temperature precision $\Delta T < 0.01$ K.

3. Results

3.1. Methodological findings

Monthly mean SST values for 2003 were compared with measured means from the MARNET station 'Arkona Sea' at 2 m water depth to examine seasonal differences. The mean SST data of a 3×3 pixel area at the location of the MARNET station, the values at point 6 of the transect through the Baltic Sea (see Fig. 1) and the mean *in situ* temperatures are presented in Fig. 2.

The two SST curves are rather similar so that patchiness does not influence the average values significantly. The comparison with the *in situ* data started in March because of the sensor performance at the station. The SST and *in situ* data are in rather good agreement ($R^2 = 0.995$). Differences occurred particularly in the summer months July and August with higher SSTs of approximately 0.92 and 1.09 K, respectively. One reason for the differences is the development of a diurnal thermocline during calm conditions and high solar radiation during the daytime. This results in higher SSTs in summer as compared to the in situ values. The lower SST in winter is due to cooling effects (March). Additionally, the water temperature is overlain by the skin effect in the upper 100μm layer due to evaporation, which is of the order of -0.2 K. Another reason for the differences in the monthly mean values in the summer months could be the

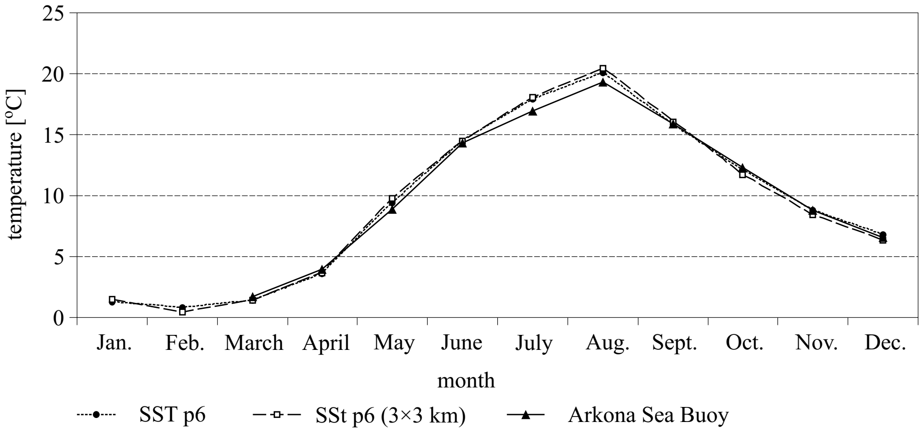

Fig. 2. Monthly mean SST at point 6 (Fig. 1, 1 × 1 km), and of 3 × 3 km square, and surface temperature measured at the MARNET station 'Arkona Sea'

consideration of all *in situ* measurements, also below clouds, where the water temperature can be lower than during cloud-free periods. To investigate this effect only the *in situ* measurements for available cloud-free SST scenes were analysed. In 2003 the respective differences of 0.51 and 0.35 K for July and August were due mainly to the daily warming. A detailed comparison of the data in August showed two phases of low wind speed (< 3 m s^{-1}), where the SST was much higher than the temperature measured at 2 m water depth. The differences between SST and 2 m measurements partly exceeded 2 K in this period and on 3 August reached the maximum of 3 K. The temperature gradient was established down to 5 m water depth. Between 2 and 5 m a maximum difference of 2 K was measured. To eliminate the daily warming, only nighttime data were compared. These nighttime SST are closely related to the surface temperatures and give an indication of the quality of the applied algorithm. For this data set the correlation between SST and 2 m temperatures increased ($R^2 = 0.98$). The differences between the mean nighttime SST and comparable *in situ* data were -0.09 K and 0.07 K for July and August, which implies a reliable accuracy of the derived SST. This methodical investigation described the reasons for the existing differences between SST and *in situ* surface temperature. Further studies will show whether the derived differences are typical values or special signatures for this particular summer.

3.2. Yearly mean SST and their temporal development

The yearly mean SST maps of the Baltic Sea in the investigation period from 1990 to 2004 are presented in Fig. 3. Considerable inter-annual variations occurred in all Baltic regions. Colder years were recorded in

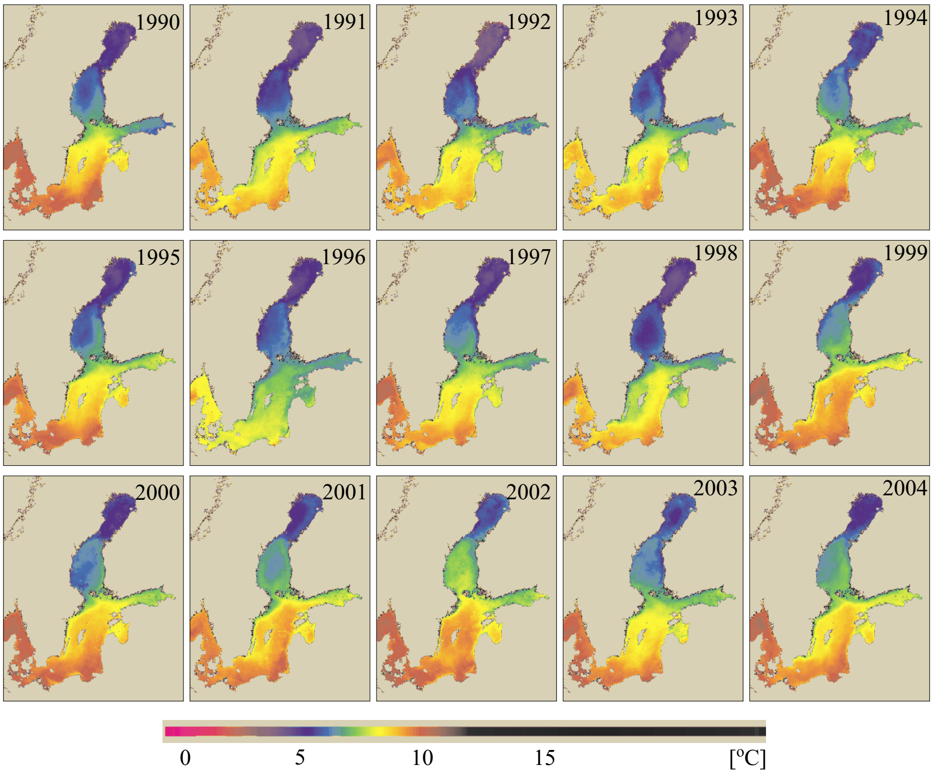

Fig. 3. Yearly mean SST of the Baltic Sea in the period 1990–2004

the early nineties and in 1996, the year with the severest winter in the southern Baltic Sea in the last 15 years. The temperatures in these years varied between 8 and 9°C in the Baltic Proper. The number of warmer years increased at the beginning of this century. The warmest years in the Baltic Proper were 2002, 1999 and 1994 with temperatures between 9 and 10°C. Particularly in the Bothnian Sea, the temperature rose in the second half of the investigation period.

The mean SST of the entire Baltic Sea was calculated from these yearly mean values to examine potential trends of the 15-year observation period. Time series, anomalies and trends are shown in Fig. 4.

The mean value for the entire period is 7.37°C. The minimum of the yearly means (6.55°C) was observed in 1996. The warmest year was 2002 with 8.05°C. A further peculiarity is the occurrence of positive anomalies in every year starting from 1999. This results in a slight positive trend with an increase of approximately 0.8 K in the 15-year period. This trend corresponds to the findings in the EEA Report (2004) with an increase of 0.5 K in the last 15 years.

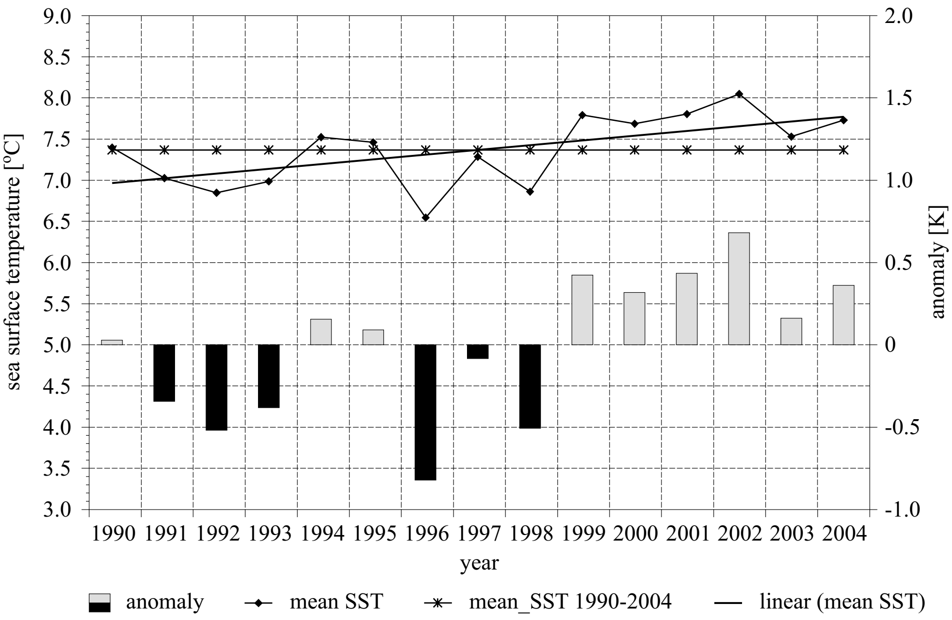

Fig. 4. Development of the yearly mean SST of the Baltic Sea in the period 1990-2004 with long-term means, anomalies and trend

3.3. Regional differences in the mean SST

3.3.1. Regional differences in the yearly mean SST

In the yearly mean SST shown in Fig. 2 regional differences were already visible. Fig. 5 shows the SST on the transect through the central Baltic from the south-west to the northern regions, as mentioned in Fig. 1. The mean differences between the western and northern parts of the Baltic Sea are approximately 3–4 K. The coldest year in the Baltic Proper and the western part (points 1–18) was 1996; in the northern parts it was 2001 (points 20–25). The warmest year in the entire Baltic Sea was 2002.

The SST of the central points of different basins was used to investigate the correlation between the different basins and the mean temperatures of the Baltic Sea. The results are presented in Table 1. Correlations are very high ($R^2 > 0.9$) between the areas in the western Baltic from the Darss Sill (P3) to the Słupsk Channel (P12), lower to the Gotland Sea (P15; $0.7 < R^2 < 0.8$), and low to the northern parts (P19, P23; $R^2 < 0.6$). The correlation of the mean value of SST (MV SST) with coefficients of determination between 0.8 and 0.9 is high for all regions except the Bothnian Bay (P23). The results underline that the northern Baltic (P19, P23) is subject to meteorological forcing different from that in the southern basins.

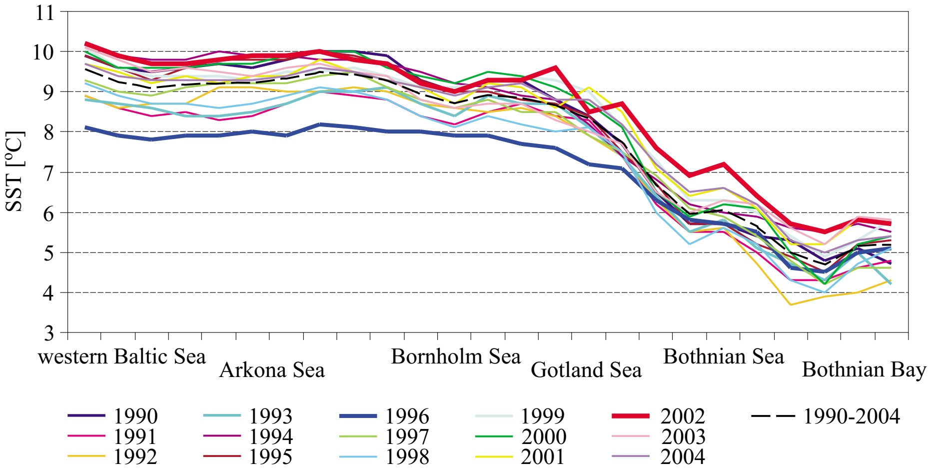

Fig. 5. Yearly mean SST along the transect through the Baltic Sea for the whole year of the investigation period; the coldest and warmest years are marked

Table 1. Correlation analysis between different basins (P3–Darss Sill, P6–Arkona Sea, P10–Bornholm Sea, P12–Słupsk Channel, P15–Gotland Sea, P19–Bothnian Sea, P23–Bothnian Bay) and with the mean SST of the Baltic (MV SST)

	P3	P6	P10	P12	P15	P19	P23	MV SST
P3		0.95	0.95	0.92	0.78	0.57	0.62	0.90
P6			0.93	0.91	0.73	0.55	0.53	0.83
P10				0.90	0.79	0.42	0.48	0.82
P12					0.85	0.58	0.51	0.85
P15						0.65	0.47	0.86
P19							0.77	0.80
P23								0.68

3.3.2. Regional differences in mean SST of February and August

The seasonal development of SST is characterised by a minimum in February and a maximum in August. Therefore, Fig. 6 shows the transect of February and Fig. 7 that of August. In the northern Baltic Sea, particularly in the Bothnian Bay, the SST is below 0°C every year in February, and the sea surface is often covered by ice. Therefore, empty pixels, where water identifications did not exist, are visible in the mean SST images of February in some years (pixel value −1 for ice). From the western part (P1) to the northern Gotland Sea (P16) the mean SST is around 2°C. The warmest February was in 1990 with SST between 3°C and 4°C in the main

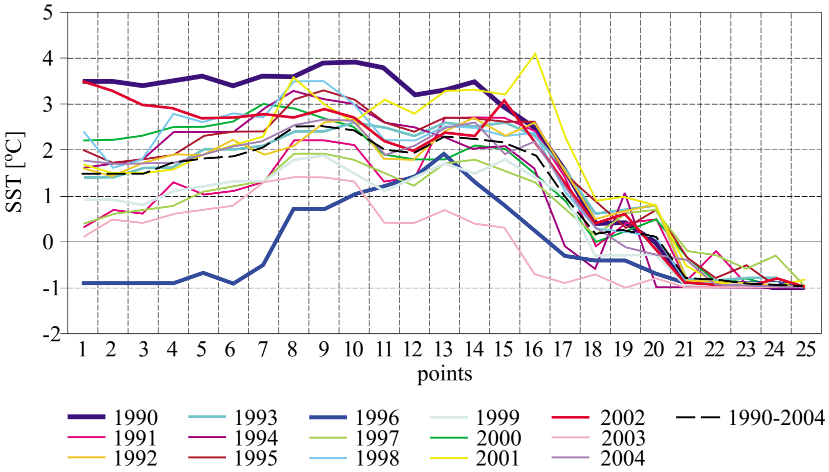

Fig. 6. Inter-annual variations in SST in February for the entire Baltic Sea along the transect through the central parts: 15 years mean, coldest and warmest February are marked

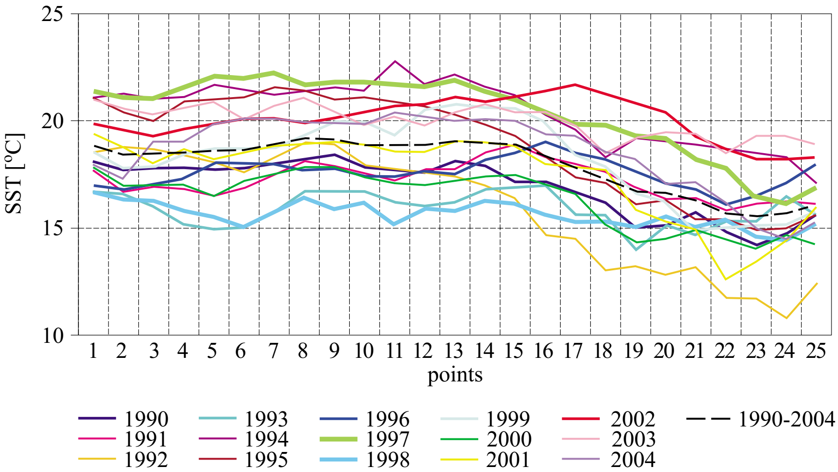

Fig. 7. Mean August SST along the transect through the Baltic Sea: 15-year mean, the coldest and warmest February are marked

parts. The coldest was in 1996 in the south-western Baltic and 2003 in the Baltic Proper.

The August temperatures also show strong inter-annual variations. The mean temperatures in the 15 years vary between around 19°C in the western Baltic and Baltic Proper and 15–16°C in the Bothnian Bay. The coldest August in the Baltic Proper was in 1998 without a north-south gradient, followed by 1993, whereas 1992 was extremely cold in the Bothnian Sea and

Bay. The highest temperatures were recorded in the western and southern Baltic Sea in 1997, in the Bothnian Sea in 2002 and in the Bothnian Bay in 2003. In 2002 and 2003 the temperatures were rather similar in the entire Baltic Sea. It seems that the number of warm summers has increased, particularly in the northern Baltic Sea.

3.3.3. Seasonal and regional trends

The yearly mean SST of the Baltic Sea in Fig. 4 shows a weakly positive trend in the mean temperature development in the entire Baltic Sea. To investigate seasonal and regional differences a trend analysis was performed for three characteristic regions in the Baltic Sea – the Arkona Sea (6), the Gotland Sea (15) and the Bothnian Sea (19) – represented by the points shown in Fig. 1. The results are displayed in Fig. 8, separately for the different months. The slopes of the linear trends show slight negative trends, particularly in the winter months of February and March. Strong positive trends occurred in the summer months of July and August but also in September and October. The maximum was found for July in the Bothnian Sea with a slope of > 0.3 K a^{-1}, which means an increase of more than 4 K in the investigation period (1990–2004).

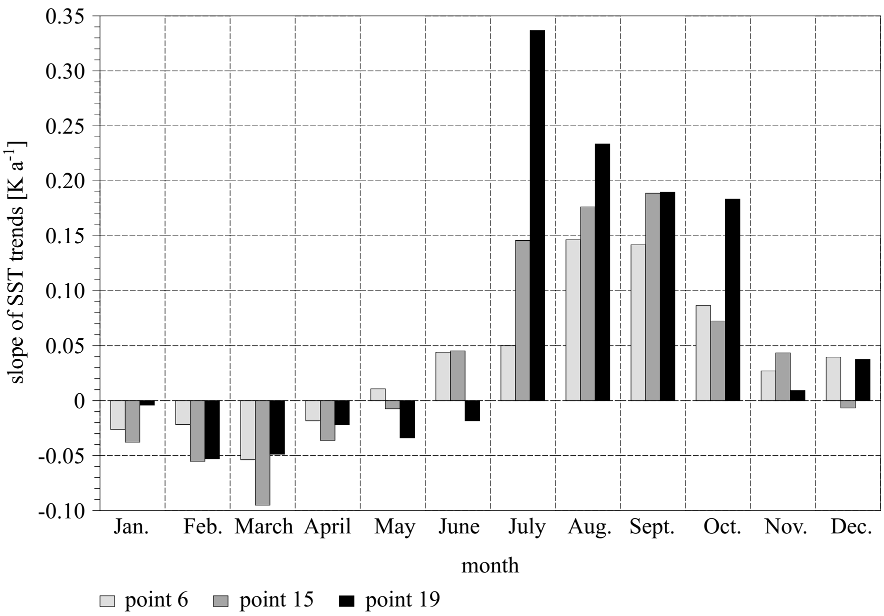

Fig. 8. Slope of the trends in different months in the Arkona Sea (6), Gotland Sea (15) and Bothnian Sea (19)

3.3.4. Relation to climate indices

The 15-year time series of SST was compared to different climate indices, like the North-Atlantic Oscillation (NAO), the Arctic Oscillation (AO) and the Baltic winter index (WIBIX). The NAO data were taken from Jones et al. (2006), the AO data from the Thompson Web page (Thompson & Wallace 1998), and the WIBIX data were provided by Hagen (Hagen & Feistel 2005). The winter means and winter minimum SST from different regions like the Arkona Sea, eastern Gotland Sea and Bothnian Sea were compared with the climate indices. The best correlation was found for the winter minimum SST of Arkona Sea and the WIBIX with a coefficient of determination of $R^2 = 0.665$.

4. Summary and conclusions

The monthly mean SST showed good agreement with the mean *in situ* temperatures measured at 2 m water depth. The differences in the summer months were investigated in detail to identify the different contributory processes and conditions. Future investigations of other years will have to show the significance of these differences in relation to the course of the summer. Located in a warming phase of the northern hemisphere, the investigation period was characterised by a positive trend in the yearly mean SST of the Baltic Sea with an increase of 0.8 K in 15 years. Summer and autumn dominate this positive trend. The winters show a slightly negative trend. The positive summer trend is highest in the northern Baltic Sea. The best correlation with climate indices exists between the winter minimum temperature in the Arkona Sea and the Baltic winter index (WIBIX). The results have been implemented in the German assessments of the environmental state of the Baltic Sea and the HELCOM Indicator fact sheet.

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