# Regional change of seasonal temperature regimes do exceeds the prognosed global climate change effect in inshore Baltic ecosystems –implications for fisheries management

Rainer Oeberst and Patrick Polte

Johann Heinrich von Thünen Federal Research Institute for Rural Areas, Forests and Fisheries, Institute of Baltic Sea Fisheries, Alter Hafen Süd 2, D - 18069 Rostock, Germany

## Abstract

Today, spatial patterns of sea surface warming become increasingly evident in the context of climate change processes. Therefore, adjustment of knowledge on temperature variability is very important to predict and model biotic responses. The Greifswalder Bodden is the main spawning area of Western Baltic spring spawning herring. This shallow, semi-closed estuary is highly susceptible to be affected by a changing temperature regime. Time series of mean daily sea surface temperatures (SST), mean daily air temperatures and mean number of sunshine hours were compared in weekly intervals from 1976 to 2006. In addition, the effects of large scale oceanographic and atmospheric indices (NAO and BSI) on the regional climate development were analyzed over the same 30 yrs period. Results indicate that mean SST and mean air temperatures are highly correlated (R = 0.91). Air temperatures however, correlate with the number of sunshine hours only during the summer month. Overall, mean SST in 2006 was 1.1°C higher than in 1976. Additionally the seasonal flux of SST differed significantly between 1976 and 2006. Whereas over the decades only a minor increase was observed for winter temperatures, a maximum increase of more than 2.8°C was observed for spring and summer seasons with the exception of a short period in June showing a slight decrease of SST. Additionally we observed a lower mean SST in November during recent years. Although mean SST in the Greifswalder Bodden correlates with NAO and BSI during winter (R ~ 0.7), both indices do not explain the variability of summer air and water temperatures. This study clearly shows that strong increases of sea surface temperatures actually do occur in shallow inshore waters where high seasonal climate variability cannot directly be linked to global indices. Although geographically on a small scale, those regional increases of SST can have immense ecological and economical consequences, when they affect the reproduction center of an important fish stock. The regional climate change effects in this case might affect reproduction success of spring spawning herring and should be incorporated in future research and management actions.

*Keywords*: temperature, SST, climate development, estuary, Baltic Sea, Greifswalder Bodden

**Corresponding author**: Rainer Oeberst, Johann Heinrich von Thünen Institut, Federal Research Institute for Rural Areas, Forests and Fisheries, Institute of Baltic Sea Fisheries, Alter Hafen Süd 2, 18069 Rostock, Germany; Phone +49 381 8116 125; email rainer.oeberst@vti.bund.de

## Introduction

Depending on the type of emission scenario applied in climate models, average global surface temperature increase per decade is estimated to range from 1- 4°C until the end of the century (IPCC, 2007). Recently however, concerns were published about increases of regional temperature extremes exceeding predicted average global warming by several magnitudes (Clark *et al.*, 2010). Especially on higher latitudes of the northern hemisphere, regional climate change impacts might not only promote extreme events but also affect the seasonal temperature gradients structuring biological processes in aquatic ecosystems.

Knowledge of the variability and trends of climate regimes is fundamental to predict biotic responses to temperature rise (Drinkwater, 2006). Spatial patterns of sea surface warming, as it is evident today (IPCC, 2007; Christensen *et al.*, 2007), will probably result in geographically differing responses in marine ecosystems.

Direct impacts can be expected for primary production because various phytoplankton species are limited by specific temperature regimes (Fromentin & Planque, 1996; Heath *et al.*, 1996; Corten, 2000). This might indirectly influence the productivity of fish stocks by cascading effects in the trophic web eventually changing food availability (Möllmann *et al.*, 2005). On the other hand global warming results in changes of the species composition and spatial distribution of species (Beare *et al.*, 2004) and, higher water temperatures during fish reproduction might result in shorter egg incubation periods (exemplary: Klinkhardt, 1986; Wieland *et al.*, 1994) and faster growth of hatched larvae (e.g. Peck *et al.*, 2006; Oeberst *et al.*, 2009b). Pörtner & Peck (2010) discussed cause-and effect understanding and described different model approaches to assess the effect of climate changes on fishes and fisheries.

However, mechanistic knowledge of climate effects on fishery resources is still fragmentary because climate change may affect fish populations differently at various life-history stages (Rijnsdorp *et al*., 2010). Brunel & Boucher (2007) showed that recruitment of different demersal and pelagic fish stocks is related to climate changes. Various studies demonstrate a link between herring production and temperatures. Toresen (2001) found significant relation between recruitment and temperature for Norwegian spring spawning herring and pointed out that other herring stocks showed an enhanced recruitment at higher temperatures. Axenrot & Hansson (2003) demonstrated that the North Atlantic Oscillation index together with the spawning stock and the young-of-the-year age class explains 93 % of the variability of the age 2 herring in the Baltic Sea. Melvin *et al*. (2009**)** observed a decline of the spring spawners in the recent years and pointed out that general warming trend favors autumn spawning herring in the western Atlantic.

The poor recruitment of the autumn-spawning North Sea herring recently observed was linked to ocean warming (Payne *et al*., 2009; Dickey-Collas *et al*., 2010), but, the mechanisms behind this link are still unclear (Brunel & Dickey-Collas, 2010). In contrast to this Gröger *et al*. (2010) suggested that the recruitment of North Sea herring depends on climate oscillations and is independent of the spawning stock.

Year-class strength of Atlantic herring (*Clupea harengus*) appears to be determined mostly prior to metamorphosis of the larvae (Heath & Gallego, 1997; Nash & Dickey-Collas, 2005). The variability in the production of larvae largely accounts for major fluctuations in stock abundance (Nash *et al*., 2009), but, significant relations between spawning stock and recruitment were not found (Lough *et al*., 1985).

The Western Baltic spring-spawning herring (WBSS) aggregates on several coastal spawning grounds, of which the Greifswalder Bodden together with the Strelasund is considered as very important (Biester, 1989). The shallow waters of the Strelasund and the Greifswalder Bodden (mean depth of 5.6 m) with limited connection to the open Baltic Sea is especially sensitive against climate change impacts because surface temperature is strongly coupled with the atmosphere above it. This is especially evident ad mid-latitudes, where migrating cold fronts and warm fronts can cause relatively large shifts in surface temperature (IPCC, 2007**).** Therefore, the reproduction success of WBSS herring might be directly influenced by increasing water temperatures during the spawning season because year-class strength of WBSS herring is already determined when the larvae are 20 mm long and 20-40 days old, depending on temperature (Oeberst *et al*., 2009a).

The principal objective of this paper is to determine whether a) the seasonal temperature regime in the Greifswalder Bodden changed significantly between 1976 and 2006 and b) whether the change of water temperatures can be explained by regional factors such as air temperature and / or the duration of sunshine rather than oceanographic factors such as currents and upwelling events.

## Materials and methods

Different sources were used to estimate the mean daily water temperature in the Greifswalder Bodden between 1976 and 2006 (Figure 1). The "Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommern" has conducted measurements of the surface water temperature at fixed stations within a spatial sampling grid ("Meßnetz Küstenmonitoring MV") in the Greifswalder Bodden since 1976 (http://www.lung.mvregierung.de/insite/cms/umwelt/wasser/kuemo/ kuemo_messnetz.htm). In rare occasions when sampling was not possible, mean water temperature was estimated by linear interpolation based on neighboring data points to describe the temperature development from 1976 to 2006 for each defined day of the year. The interval between subsequent sampling points varied between 1 and 166 days within the first six month of the year. Large intervals between subsequent sampling points can result in underestimations of the water temperature, especially, if measurements were taken out between November and March/April. Additional data sources were only used as a back up in rare cases assuming that interpolation between sample points in the Greifswalder Bodden represented the trend of the temperature development with higher accuracy.

Periods of ice coverage in the Greifswalder Bodden were made available by the Federal Maritime and Hydrography Agency, Hamburg (BSH, www.bsh.de). The time series range over a period from 1976 to 2009 and presents the periods of ice coverage at six locations in the area of the Greifswalder Bodden. During these periods water temperature could not be measured *in situ*, but it can be assumed that water temperatures were below 0 °C. The periods of ice coverage were defined as data points with a temperature value of zero.

Measurements of surface and bottom temperatures have been carried out *in situ* during the herring larvae surveys (Oeberst *et al*. 2009b) since 1992. The time interval between the measurements varied between 5 and 7 days respectively between April and June. Previous studies showed that surface and bottom temperatures in the Greifswalder Bodden are highly correlated (Oeberst *et al*. 2009a).

Surface temperature values are available from satellite data taken between 1990 and 2006 which represents the surface temperature of the upper ~ 20 cm (www.bsh.de). One data point represents the mean temperature of an area of 1.6’ N x 1.4’ E. From periods with sea ice or cloud cover present, there are no data available. Data sampled at the same time were averaged. Mean temperature measured at different times during the same day showed clear diurnal gradient due to the solar altitude. Therefore, only data were used that were sampled before 8 p.m. In addition, water temperature data from a depth of 3 m, continuously measured stationary at a pile close to the Oderbank between 1997 to 2006 were used as alternatives if the intervals between available data points were more than 14 days **(**Figure 1).

Estimates of the monthly mean water temperature of the rectangle north of the island of Rügen (center 13° 30’ E, 54° 30’ N) were used for the period from 1976 to 1990 in cases of large intervals between subsequent data points (Feistel *et al*., 2008, http://www.io-warnemuende.de/ projects/baltic/index.htm). In these cases temperature values were assigned to the middle of the month. Based on a synthesis of available data a time series was created describing the change of the water temperature from 1976 to 2006.

In addition, daily mean air temperatures and the number of sunshine hours on three stations in the area of the Greifswalder Bodden (Greifswald, Putbus and Greifswalder Oie) were used to explain the development of the mean water temperatures between 1976 and 2006. The data were made available by the German National Meteorological Service (“Deutscher Wetterdienst”). Mean values of temperature data of all stations were used during the analyses because of differing starting points (Putbus from 1/1/1976, Greifswald from 1/1/1978, Greifswalder Oie from 1/7/1999) and occasional missing data at single stations. It was assumed that the change of the water temperature within a period of x days beginning with day t is influenced by the mean air temperature and the mean sunshine duration during the same period. Different periods (10 and 30 days) were used to reduce the effect of variability of daily values.

The patterns of atmospheric variability over the North Atlantic region is represented by the North Atlantic oscillation (NAO) which is widely used to study climate effects. Since 1865 the monthly NAO index  is based on the difference of normalized sea level pressures (SLP) between Ponta Delgada, Azores and Stykkisholmur/Reykjavik, Iceland (Hurrell, 1995) and is publicly available online (http://www.cgd.ucar.edu/cas/ jhurrell/Data). An additional index was used for studying climate effects related to the mean air and water temperatures of the Greifswalder Bodden which directly reflects the impact of climate in the central Baltic Sea, the Baltic Sea Index (BSI, Lehmann *et al*. 2002). The BSI is defined as the difference in normalized sea level pressure anomalies between the positions 53° 30’ N, 14° 30’ E (Szczecin, Poland) and 59° 30’ N, 10° 30’ E (Oslo, Norway).

Following notations were used:

| | |
|---|---|
| t | date of the beginning of the period |
| x | duration of the period in days |
| $T_w(t)$ | Mean water surface temperature at day t |
| $T_a(t)$ | Mean air temperature at day t |
| $S_h(t)$ | Number of hours with sunshine |
| $\bar{T}_w(t,x)$ | Mean water surface temperature from t to t + x - 1 |
| $\bar{T}_a(t,x)$ | Mean air temperature during the period from t to t+x - 1 |
| $\bar{S}_h(t,x)$ | Mean number of hours with sunshine during the period from t to t+x - 1 |

The beginning of the period was always defined as the first day of each month. Consequently, the 31th day of the month was not taken into account as illustrated by the sequence for x = 10 days: 1/1/1976, 11/1/1976, 21/1/1976, 1/2/1976, 11/2/1976, 21/2/1976, 1/3/1976, etc. In all cases only 28 days were used in February.

Multiple linear regression models and time series analyses have been applied using STATGRAPHICS (Statgraphics Centurion, Version XV, StatPoint, Inc.). Time series models where linear trends were adjusted, mean was removed and tapper of =% was used to evaluate long term periods and autocorrelation processes in the data.

## Results

### *Shifts in seasonal sea surface temperatures*

Estimates of the mean daily water surface temperature, $T_w(t)$, of the Greifswalder Bodden in 2005 showed similar seasonal development as stationary measurements taken at the pile close to the Oderbank and the satellite data respectively (Figure 2). However, $T_w(t)$ did not reflect the high variability within short periods due to the interpolation between the sampling points. Similar results were also found for other years. Large differences of estimates of the mean water temperature were found based on the measuring points provided by the different sources which were sampled at the same day or temporally close (2 – 5 days). Mean temperatures in the Greifswalder Bodden and estimates in the Arkona Sea differed by more than 5 °C in spring due to faster heating of the Greifswalder Bodden ,but, differences of more than 2 °C were observed in both winter and summer. Temperature data were relatively close by in autumn. Water temperature close to the Oderbank (Fig. 1, pile) increased slower in spring and reached lower maximum values in summer. In addition, water temperature was lower in the Greifswalder Bodden in winter. Differences of more than 2 °C were observed in many cases. Based on satellite data, estimates of winter water temperatures were lower by up to 3 °C in most cases. However, estimated values by both sources were comparable in spring and summer. Mean water temperature was estimated based on satellite data, data logger close to the Oderbank and *in situ* measurements in the Greifswalder Bodden in November and December.

A pronounced seasonal development of $T_w(t)$ with year to year variations was observed in the shallow Greifswalder Bodden (mean depth of 5.6 m, maximum depth of 13 m) **(Fig. 3**). In January and February $T_w(t)$ varied between 0 °C and 4 °C followed by a rapid, nearly linear increase in spring up to values between 18 °C and 24 °C in summer. In autumn a nearly linear decrease was observed. Figure 3 also illustrates the high inter-annual variability of $T_w(t)$ at the particular season. Variations within a range of ~ 4 °C were observed in most periods with maximum variations in March, August and December.

The means of $Tw(t)$ of 10 day periods, $\overline{T}_w(t,10)$ were used to describe the variation between 1976 and 2006. Different trends (mean change in °C per year) of the $\overline{T}_w(t,10)$ were found for the period from the first to the tenth day between January and June (February not presented) (Figure 4). Low positive trends of $\overline{T}_w(t,10)$ were observed in January and March. These trends did not significantly differ from zero due to a slight increase in relation to the high inter-annual variability of $\overline{T}_w(t,10)$. A significant positive trend was observed at the beginning of May whereas no trend was found in June, but, in eight of ten years between 1997 and 2006 $\overline{T}_w(t,10)$ was above the mean of the total period in April and May. In spring also the highest differences between minimum and maximum of $\overline{T}_w(t,10)$ were observed with values above 8 °C. In contrast to this the differences were below 5 °C during the first five ten day periods of the year and between middle of November and beginning of December.

Trends of the $\overline{T}_w(t,10)$ by 10 days and 30 days intervals from January to December are presented in Figure 5. Positive trends were observed during most periods with maximum trends in spring and autumn. From the end of May to the middle of June as well as from lateNovember to early February trends were close to zero. The mean increase of water temperatures from 1976 to 2006 ranged from 1.5 °C to 3 °C between February and May as well as between July and October. The seasonal development of the trend indicates that spring water temperatures did increase faster during the last decade compared to the beginning of the time series. Consecutively the increase of water temperatures between end of May and middle of June was lower during the last decade because significant trends of $\overline{T}_w(t,10)$ were not observed in the same period. The period of strong increase of $\overline{T}_w(t,10)$ shifted from May – June to April – May from 1976 to 2006. After the period of stable $\overline{T}_w(t,10)$ in early June it increased again from 1976 to 2006 with a mean of more than 2 °C. Similar results were observed for the trends based on 30 day periods. Mean values based on these longer periods resulted in lower maximum trends and lower fluctuation between the subsequent periods. Although in this case significant trends of water temperature changes between 1976 and 2006 were not found in June and between November and January.

To reduce the effects of strong inter-annual variability, five year periods were used to describe the long term change in mean water temperature, $\overline{T}_w(t,10)$ calculated based on ten day periods, over the seasons (see Fig. 4). Data of the periods 1976 – 1980, 1986 – 1990, 1996 – 2000 and 2001 – 2005 are given in Figure 6. The period 1976 – 1980 was used as baseline. A strong increase of water temperatures was observed for the winter season between 1986 and 1990 in relation to the baseline period due to low ice coverage. With a maximum of 2 °C at the end of April the increase of spring water temperatures was higher than the five year period before. The maximum difference between end of June and end of July was -1.5 °C. The temperature in late summer and at the end of the year was similar to the standard period with a maximum difference of -1 °C in late November. The total mean water temperature between 1986 and 1999 was 0.5 °C higher than between 1976 – 1980.

A further increase of water temperatures was observed between 1996 and 2000. The mean temperature was 2.8 °C higher in late February and early March and again at the beginning of May. In June the temperature was similar to the standard period and at the end of June a slight difference of -0.7 °C was observed. The water temperature was then again higher between July and beginning of November with a maximum difference of 1.9 °C followed by a short period of lower temperature. The mean annual water temperature in that period was 1.0 °C higher than the baseline 1976 – 1980. The seasonal gradient of the mean water temperature between 2001 and 2005 was similar to the period before. The difference at the beginning of the year was partly smaller, but the temperatures in summer increased again to a maximum difference of 2.4 °C. In late June the water temperature was -0.5 °C lower than earlier in the month. The annual mean temperature between 2001 and 2005 was 1.1 °C higher than between 1976 and 1980. The five year periods which are not presented here all show seasonal developments of the mean water surface temperature which are located between the surrounding periods demonstrated.

During the major part of the year, mean water temperatures were higher in the period of 2001 to 2005 compared to the period from 1976 to 1980. The increase was more than 2 °C in spring as well as in summer. The increase of the water temperature was observed in all five year periods with different extend in different periods of the years. Negative temperature developments were found in June and early winter. Mean water temperature was 1.5 °C lower in July between 1986 and 1990 and 0.5 °C lower between 2001 to 2005 compared to the period from 1976 to 1980.

### *Long term trends of seasonal air temperatures and number of sunshine hours*

Trends of mean air temperatures of the subsequent 10 days periods between 1976 and 2006, $\overline{T}_a(t,10)$, strongly varied (Figure 7). Positive trends were observed during spring with a maximum increase of 4.2 °C from 1976 to 2006 followed by very small trends end of May to the beginning of June and strong positive trends from July to September. The trends of the mean number of sunshine hours, $\overline{S}_h(t,x)$ also highly fluctuated within the year using 10 day periods (Figure 8). Positive trends were found end of March followed by a strong negative trend in the middle of April. Again, strong changes from a negative to a positive trend within short periods were observed from the beginning to the middle of July.

An increase of the time interval from 10 to 30 days as base line for estimating mean values resulted in a more stable seasonal development of trends. However, month with strong positive trends and low positive trends alternated. The high positive trends in January, February and April corresponded with the high positive trend of $\overline{T}_w(t,x)$ during the same month. However, the trends in March are different. Again similar developments of air and water temperatures were observed between July and September. A high positive trend of $\overline{S}_h(t,x)$ was only observed in March. During the other month the trends were close to zero.

The seasonal development of the mean air temperature of five year periods, $\overline{T}_a(t,10)$, based on ten day steps between 1976 and 2006 were comparable to the development of the mean water temperature (Fig. 9). The fluctuations among periods were stronger, but, the increase in spring and summer as well as the decrease in November were constantly observed. Lower temperatures were also observed in June. The development of the mean number of sunshine hours of five year periods, $\overline{S}_h(t,10)$, from 1976 to 2006 were quite different (Fig. 10). A strong increase of $\overline{S}_h(t,10)$ has been observed in summer since 1981 – 1986 (not shown here). During spring, autumn and winter trends were not observed until 1990 – 1995. During the following periods $\overline{S}_h(t,10)$ started to increase in spring.

Significant autocorrelation was found for lags between 1 and 7 as well as between 11 and 25 based on time series model, suggesting that temperature values within about half a year and factors of one year were auto correlated as it is expected for strong seasonal developments. Partial autocorrelations were significant for lag one and two as well as between 4 and 15. This implies that it would take a rather complicated autoregressive model to describe the observed data, which is not surprising given its non-stationary (trending) nature. The period with the highest ordinate (expressed as $\frac{n}{2}(a_i^2 + b_i^2)$ where n is the number of observations and $a_i$ and $b_i$ are the coefficients of the i-th Fourier frequency) was period 36 with an ordinate of 51672. This period corresponds with a year based on results of 16 decades. In addition, three periods were found with ordinate > 100 (period of 85.8 which corresponds with ~2.4 years, ordinate = 138; period of 18 which corresponds with 0.5 years, ordinate of 161; period = 12 which corresponds with 0.33 years, ordinate of 110). Ordinates of all other periods were less than 100. Similar relations were found for the mean air temperature of 10 day periods. In addition, periods of 10 and 6 years had ordinates above 100 which suggest a minor low frequency effect.

*Relations between water surface temperature, air temperature and hour of sunshine*

Multiple linear regression models showed that about 92 % of the variability of mean water temperature within the period of 10 days, $\overline{T}_w(t,10)$, can be explained by mean air temperature, $\overline{T}_a(t,10)$, the change of the air temperature, $D[\overline{T}_a(t,10)]$ and the mean number of hours with sunshine, $\overline{S}_h(t,10)$ based on 1107 datasets.

$\overline{T}_w(t,10) = 0.857 + 0.955\ \overline{T}_a(t,10) - 0.074\ D[\overline{T}_a(t,10)] + 0.144\ \overline{S}_h(t,10)$

The p-values of all regression parameters were < 0.0001, but, the effects of $D[\overline{T}_a(t,10)]$ and $\overline{S}_h(t,10)$ are small because the coefficient of determination decreases only to a value of $R^2 = 0.91$ if the model is reduced to $\overline{T}_w(t,10) = 1.124 + 1.003\ \overline{T}_a(t,10)$.

The relation between $\overline{T}_a(t,10)$ and $\overline{T}_w(t,10)$ based on 10 day periods is presented in Figure 11. Relatively stable deviation of $\overline{T}_a(t,10)$ from the estimated mean was observed for $\overline{T}_a(t,10) > 9$ °C. The higher variability for $\overline{T}_a(t,10) < 9$ °C and especially for $\overline{T}_w(t,10) = 0$ °C can be explained by ice coverage. In these cases $\overline{T}_w(t,10)$ was estimated with 0 °C. Furthermore, the ice coverage reduced the direct relation between the air and water surface temperature.

### *Effects of North Atlantic Oscillation (NAO) and Baltic Sea Index (BSI)*

The North Atlantic oscillation index (NAO) and Baltic Sea Index (BSI) are significantly positively correlated between December and March based on monthly indices (Tab. 1, Fig. 12). Both indices are also significantly positively correlated with mean air temperature, $\overline{T}_a(t,30)$, and the mean water surface temperature, $\overline{T}_w(t,30)$, during the same period. Correlation coefficients of these parameters were lower and mostly not significant between spring and autumn. Neither NAO nor BSI are significantly correlated with the mean number of sunshine hours, $\overline{S}_h(t,30)$. On the other hand $\overline{T}_a(t,30)$ and $\overline{T}_w(t,30)$ are significantly correlated with $\overline{S}_h(t,30)$ between May and September (Fig. 13). Similar results were observed for 10 and 30 day periods used for estimating the means. Negative correlation coefficients were found from October to March (significantly different from zero in December). That means that increase of $\overline{S}_h(t,30)$ results in a decrease of $\overline{T}_a(t,30)$ during this period. Opposite relation was found between April and September with a maximum of 0.82 in July where an increase of $\overline{S}_h(t,30)$ results in an increase of $\overline{T}_a(t,30)$. The variability of $\overline{T}_a(t,30)$ and $\overline{T}_w(t,30)$ which are significantly correlated in all month, in April and October can't be explained by the variability of NAO, BSI and $\overline{S}_h(t,30)$ likely due to the high variability of $\overline{T}_a(t,30)$ and $\overline{T}_w(t,30)$ in combination with the used monthly period.

## Discussion

The study evidently demonstrated the strong relation between mean sea surface temperature of the Greifswalder Bodden and ambient air temperatures as well as the trend for increasing spring temperatures. Both, positive and negative trends of seasonal temperature change among ten day periods were observed which did not always significantly differ from zero.

Data of mean sea surface temperature were not available in the Greifswalder Bodden for each single day between 1/1/1976 and 31/12/2006. Therefore, missing data were estimated by interpolation between successive sampling dates. Results on seasonal development of the water temperature corresponded with estimates based on other sources, however, data do not reflect high day to day variability (see Fig. 2), particularly where the distance between sampling dates is more than 30 days. Mean values calculated based on ten day periods are particularly realistic in spring and autumn due to almost linear trends and high resolution of sampling dates during these seasons. Higher uncertainty of the estimated daily mean SST can be expected in winter, especially during periods with ice coverage as well as in summer because the maximum water temperatures were probably not included due to large distances between subsequent sampling dates.

A relatively constant increase of water temperatures of five year periods was observed from January to October with short period in June where negative trend occurred like in November – December. Maximum increase of the water temperature of 2.4 °C in summer between the periods 1976 - 1980 and 2001 – 2005 is higher than the observed increase of 1.5 °C of the mean water surface temperature in the Baltic Sea since the mid-1980s (MacKenzie & Schiedek, 2007). They stated that the probability of extremely warm winters, summers and years has increased by two- to fourfold in the 1990s and 2000s relative to the probability in nearly all previous decades. Similar developments were found in the Greifswalder Bodden where the mean water surface temperature in April and May was higher than the mean temperature of the total period in eight of ten years between 1997 and 2006. The stronger increase of the water tempeature in the Greifswalder Bodden can be explained by the lower capacity of temperature buffering due to the low depth of the Greifswalder Bodden and the limited exchange with the Baltic Sea. On the other hand the stronger decrease of the water temperature in winter is associated by the lower capacity to store energy expressed as temperature.

The temporal development of the mean water surface temperature of the Greifswalder Bodden is highly correlated with the air temperature. Both, the mean water surface temperature and the mean air temperature of ten day periods showed similar trends from 1976 to 2006 **(**Fig. 6 and Fig. 9). The stable relations of the trends of air and water temperature in spring, where the density of sampling points has been high at least since 1992, suggest that the interpolated water temperature values present realistic estimates. About 91 % of the variability of the water temperature can be explained by the variability of the air temperature. The increase of the air temperature and the mean number of hours with sunshine also affect the water temperature significantly, but, their proportion to explain the variability of the water temperature is low. This low effect is caused by the negative correlation between $\overline{T}_a(t,x)$ and $\overline{S}_h(t,30)$ between autumn and spring and the opposite correlation in summer (Fig. 13). That means that the transport of temperature by air due to the different weather conditions is more important that the intensity of sunshine. These results correspond with observations based on climate models which suggest that surface temperature is strongly coupled with the atmosphere above it, especially in mid-latitudes, where migrating cold fronts and warm fronts can cause relatively large swings in the surface temperature (IPCC, 2007). These effects seem to be dominant in estuary like the Greifswalder Bodden with shallow water and relative small connections with the Baltic Sea. Omstedt *et al*. (2004) showed that average air temperature from Stockholm has been increased since about 1960 and that increased frequencies of anti-cyclonic circulation and westerly winds have resulted in a slightly warmer climate with reduced seasonal amplitude and reduced ice cover. MacKenzie & Schiedek (2007) pointed out that the frequency of occurrence of extremely warm and cold years of the Baltic water has, respectively, increased and decreased which is consistent with changes in the frequency of extremes of European air temperatures. Luterbacher *et al*. (2004) showed that the late 20th and early 21st-centrury European climate is very likely warmer than that of any time during the past 500 years based on multi proxy reconstructions of monthly and seasonal surface temperature fields. Moberg *et al*. (2005) pointed out that no evidence for any earlier periods in the last two millennia with warmer conditions that the post-1990 period were found. North Hemisphere Temperature anomalies also showed a positive trend between 1976 and 2000 (Brunel & Boucher, 2007). The relations between NAO and mean air temperature as well as the mean water surface temperature in winter suggest that winter temperatures of the Greifswalder Bodden will slightly increase with oscillations according the NAO (Hurrell, 1995). Conclusions concerning the developments of temperatures between spring and autumn cannot be drawn from the NAO, but, it is likely that the mean water surface temperature before 1970 was cooler because the negative winter NAO was dominant between 1960 and 1972 and Northern Hemisphere Temperature anomalies were observed during the same period (Jones & Moberg, 2003). The more regional Baltic Sea index, BSI, is correlated with the NAO in winter (Tab. 1) but not in summer. However, the BSI which describes the difference of the normalized pressure system of the central Baltic Sea is also not suitable to explain the variability the mean air and water temperature in the area of the Greifswalder Bodden.

Further developments of the water temperature in the Greifswalder Bodden can be derived from forecasts of the development of the air temperature due to the high correlation between both parameters. Climate models estimate mean increase of air temperature between 1.1 °C to 6.4 °C during the twenty-first century (IPCC, 2007) with differences in the local development. A mean increase of ~ 3.5 °C was estimated for the period March to May in 2080 to 2099 against 1980 – 1999 by Christensen et al. (2007). Döschner & Meier (2004) forecasted an increase of the surface temperature of the Baltic Sea between 2 °C and 4 °C during the next 80–100 relative to the period 1961 to 1990 based on regional prognostic models. The low correlation of NAO and BSI concerning the seasonal development of $\overline{T}_a(t,x)$ and $\overline{T}_w(t,x)$ suggest that strong local variability of the atmospheric condition determines the development of the mean water surface temperature in the Greifswalder Bodden and that conclusions concerning the future developments must take into account that climate predictions on a regional scale are still of limited reliability (New & Hulme, 2000; Volz, 2004; Janßen, 2007). The study also revealed that the development of the air and water temperatures can differ seasonally as the increase of more than 2 °C in spring and summer and decrease in November have shown.

The outcome of the climate models suggest that the mean water surface temperature in the Greifswalder Bodden will further increase in at least spring and summer. Therefore, possible effects of the changing water temperature related to the reproduction success of the spring-spawning herring must be evaluated in the future because critical water temperature can be reached earlier during the reproduction period (Pörtner & Peck, 2010). Furthermore, the importance of the spawning areas outside of the current main spawning ground must be investigated because it is likely the stronger exchange with the open Baltic Sea results in a slower increase of the water temperature.

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# Tables

Table 1: Correlation coefficients of the linear regressions between monthly mean values of the independent and dependent variables North Atlantic Oscillation (NAO), Baltic Sea Index (BSI), Mean air temperature ($T_a$), mean water temperature ($T_w$) and mean number of hours with sunshine ($S_h$) between 1976 and 2006. Correlation coefficients larger 0.38 significantly differ from zero with error of first kind $\alpha = 0.05$.

| Independent | NAO | NAO | NAO | NAO | BSI | BSI | BSI | $S_h$ | $S_h$ | $T_a$ |
|---|---|---|---|---|---|---|---|---|---|---|
| dependent | BSI | $T_a$ | $T_w$ | $S_h$ | $T_a$ | $T_w$ | $S_h$ | $T_a$ | $T_w$ | $T_w$ |
| Jan | 0.55 | 0.75 | 0.58 | -0.06 | 0.74 | 0.64 | 0.07 | 0.22 | 0.19 | 0.83 |
| Feb | 0.73 | 0.66 | 0.59 | 0.15 | 0.74 | 0.65 | 0.10 | -0.08 | 0.12 | 0.85 |
| Mar | 0.66 | 0.45 | 0.27 | -0.15 | 0.68 | 0.52 | 0.09 | -0.11 | 0.14 | 0.79 |
| Apr | 0.13 | 0.28 | 0.26 | -0.03 | -0.14 | -0.10 | 0.26 | 0.29 | 0.21 | 0.57 |
| May | 0.17 | 0.21 | -0.08 | 0.04 | 0.47 | 0.15 | 0.36 | 0.49 | 0.49 | 0.73 |
| Jun | 0.28 | 0.19 | 0.08 | 0.13 | -0.23 | -0.14 | -0.09 | 0.74 | 0.57 | 0.77 |
| Jul | 0.25 | 0.03 | 0.02 | 0.03 | -0.20 | -0.25 | -0.10 | 0.86 | 0.82 | 0.93 |
| Aug | 0.41 | 0.23 | -0.04 | -0.01 | -0.33 | -0.46 | -0.23 | 0.63 | 0.40 | 0.83 |
| Sep | 0.30 | 0.22 | 0.13 | 0.25 | 0.10 | -0.08 | 0.45 | 0.61 | 0.46 | 0.69 |
| Oct | 0.35 | 0.22 | 0.10 | -0.16 | 0.42 | 0.15 | 0.12 | -0.01 | 0.18 | 0.75 |
| Nov | 0.32 | 0.38 | 0.20 | -0.30 | 0.59 | 0.56 | 0.30 | 0.22 | 0.42 | 0.79 |
| Dec | 0.61 | 0.53 | 0.46 | -0.22 | 0.61 | 0.39 | -0.04 | -0.62 | -0.47 | 0.66 |

# Figures

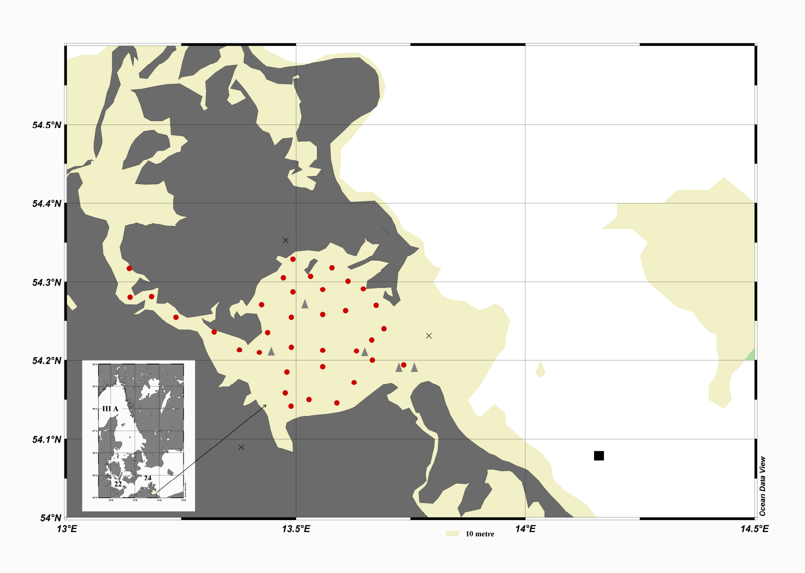

Figure 1. Map of the Strelasund and the Greifswalder Bodden with the sampling stations (▲: surface temperature, “Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommern”; ■ : temperature of different depth levels, pile close to the Oderbank, Federal Maritime and Hydrography Agency, Hamburg; ●: surface and bottom temperature, sampled weekly; X: air temperature and number of hours with sunshine, Deutscher Wetterdienst). Inset shows the area inhabited by western Baltic spring spawning herring and the ICES subdivisions.

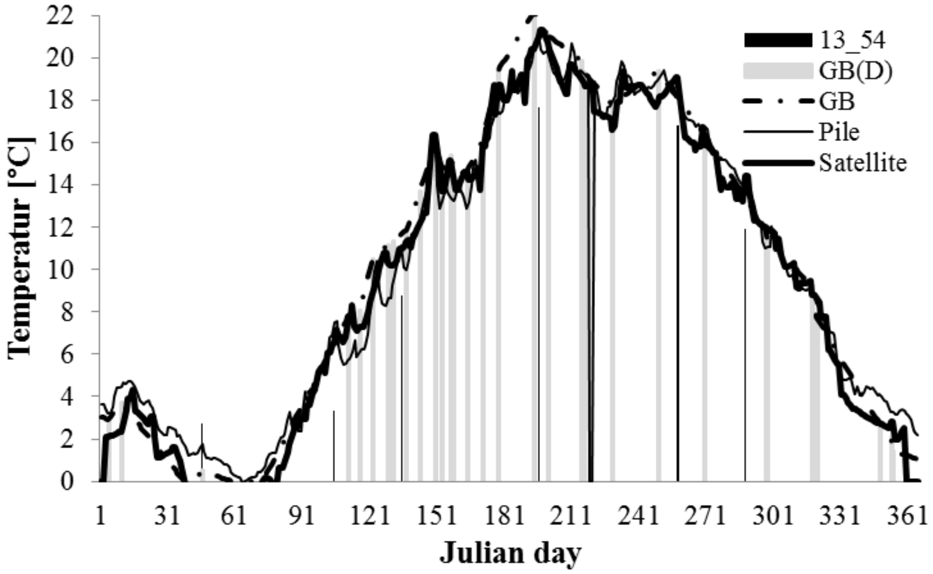

Figure 2: Daily mean water surface temperature (GB, blue line) calculated by linear interpolation between the available sampling points (GB(D), blue bars) and data of water temperature from other sources (date from the pile close to the Oderbank (Pile, red line), satellite data (Satellite, green line) and the Arkona Sea (13_54, black bars) in 2005

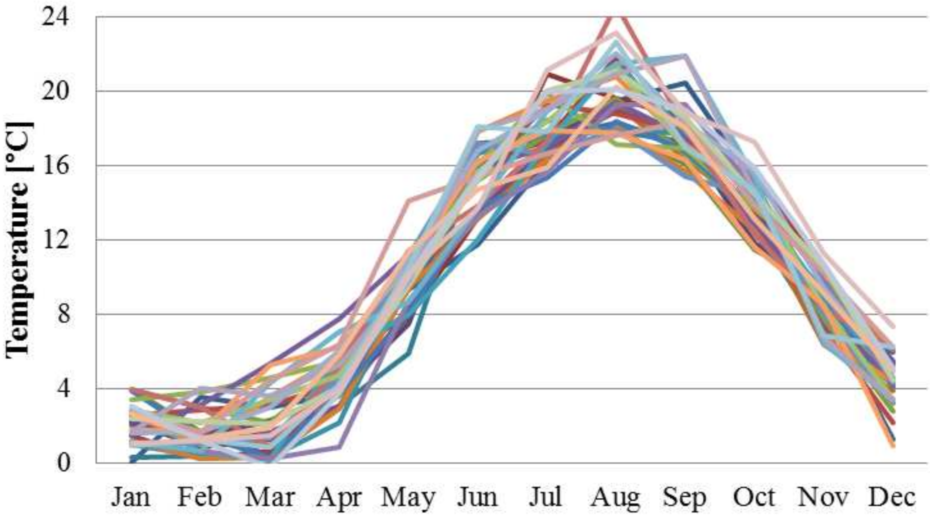

Figure 3: Changes of surface temperature in the Greifswalder Bodden between 1976 and 2006 (each color presents one year).

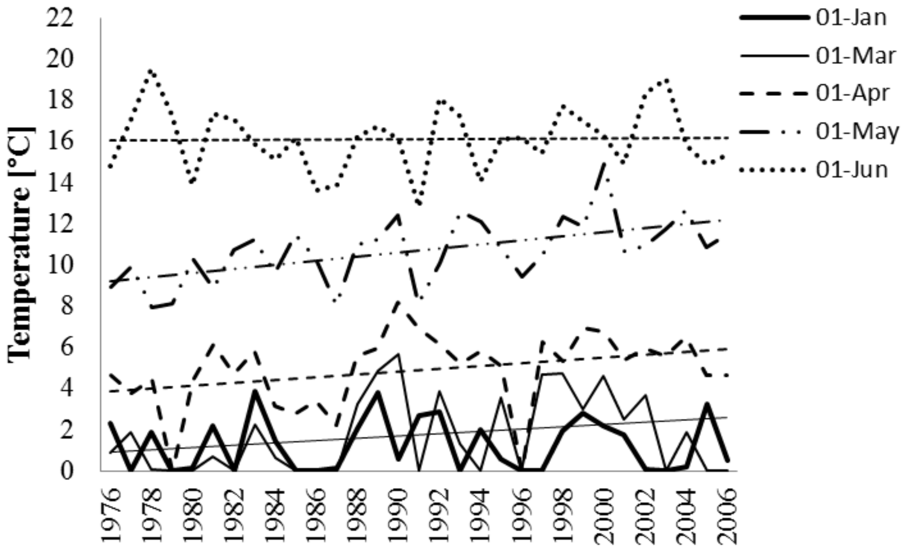

Figure 4: Mean water surface temperature at the beginning of the month (first to tenth day of the month) from January to June (February not presented) with linear trend.

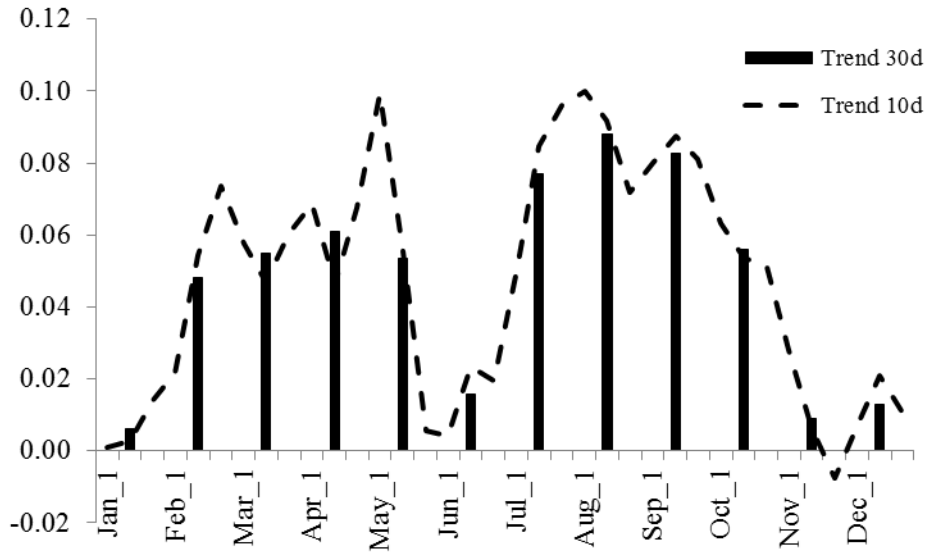

Figure 5: Trend of mean water surface temperature, $\overline{T}_w(t,x)$, between 1976 and 2006 based on 10 day periods and 30 day periods from January to December

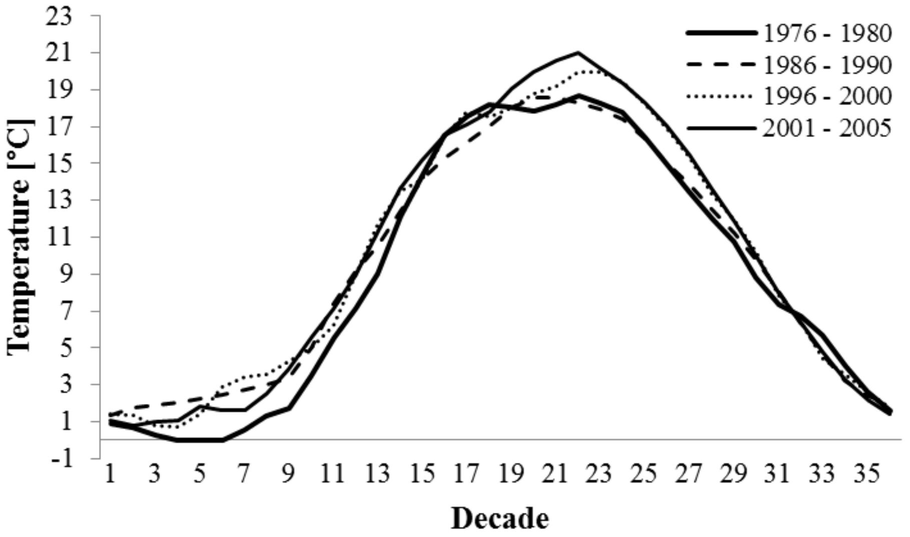

Figure 6: Seasonal development of the mean water temperature of ten day periods, $\overline{T}_w(t,10)$, based on the average of five years. Years from 1976 to 1981 were used as standard period. The different figures present the different five year periods.

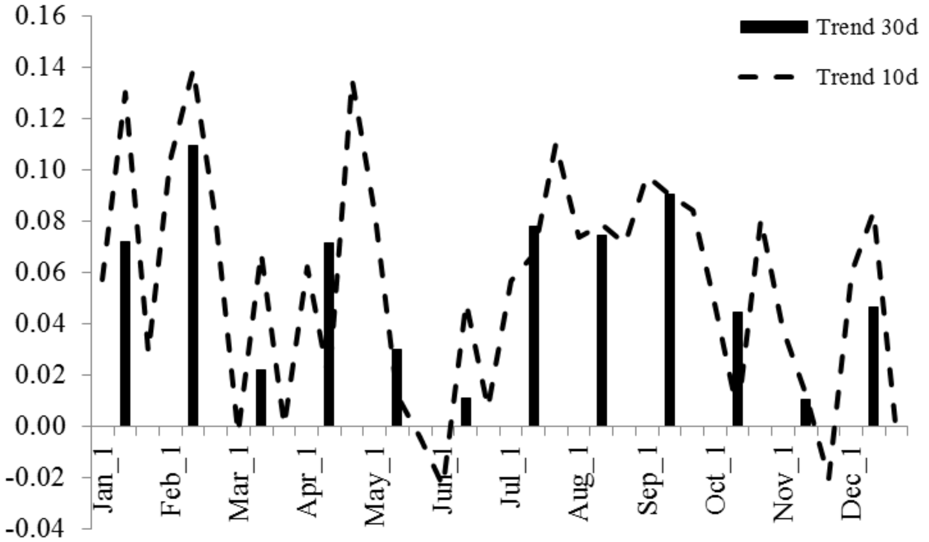

Figure 7: Trend of mean air temperature, $\overline{T}_a(t,x)$, between 1976 and 2006 based on 10 (Trend 10d) and 30 (Trend 30d) day periods from January to December

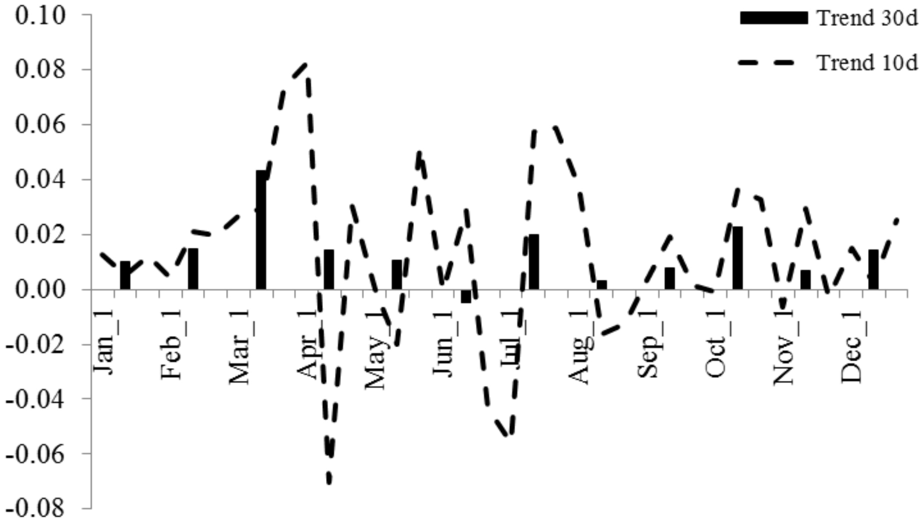

Figure 8: Trend of mean number of hours with sunshine, $\overline{S}_h(t,x)$, between 1976 and 2006 based on 10 (Trend 10d) and 30 (Trend 30d) day periods from January to December

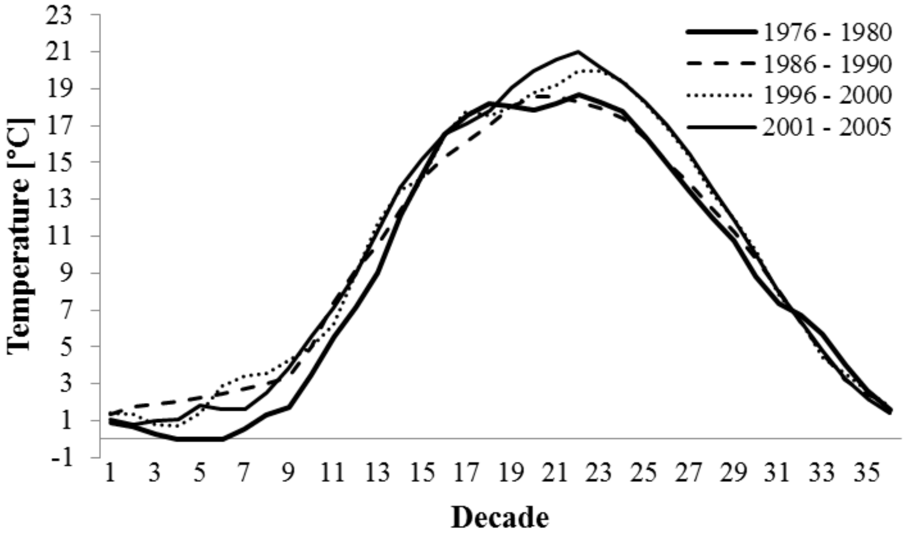

Figure 9: Seasonal development of the mean air temperature of ten day periods, $\overline{T}_a(t,10)$, based on the average of five years. Years from 1976 to 1981 were used as standard period. The different figures present the different five year periods.

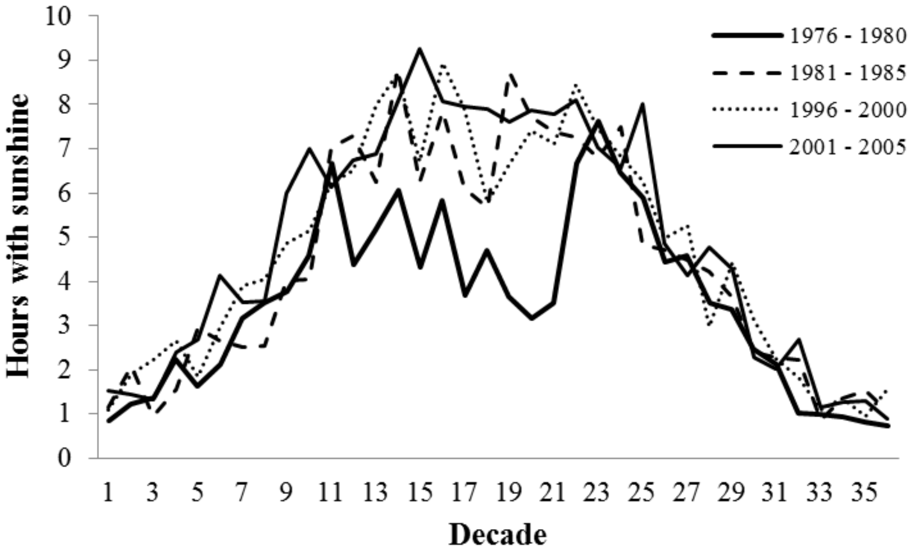

Figure 10: Seasonal development of the mean number of sunshine of ten day periods, $\overline{S}_h(t,10)$, based on the average of five years. Years from 1976 to 1981 were used as standard period. The different figures present the different five year periods.

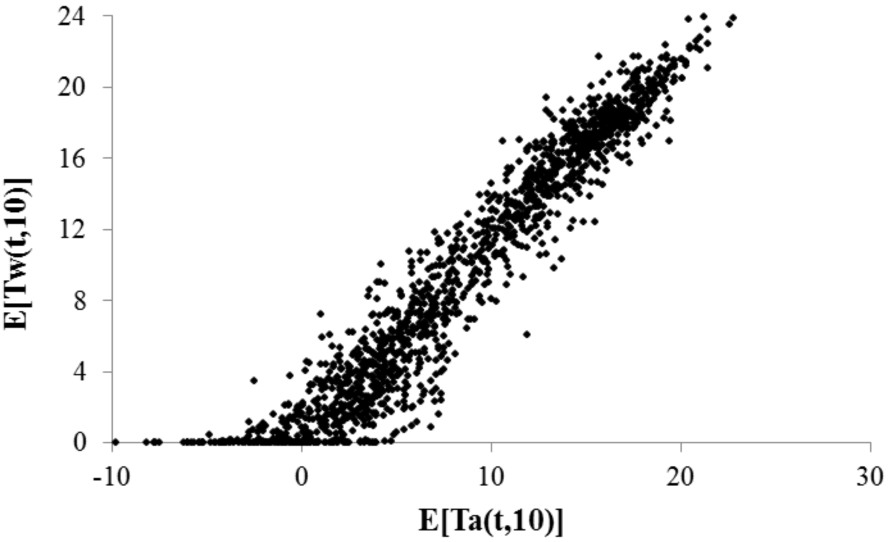

Figure 11: Relation between the mean air temperature and the mean water surface temperature between 1976 and 2006 based on means of 10 day periods

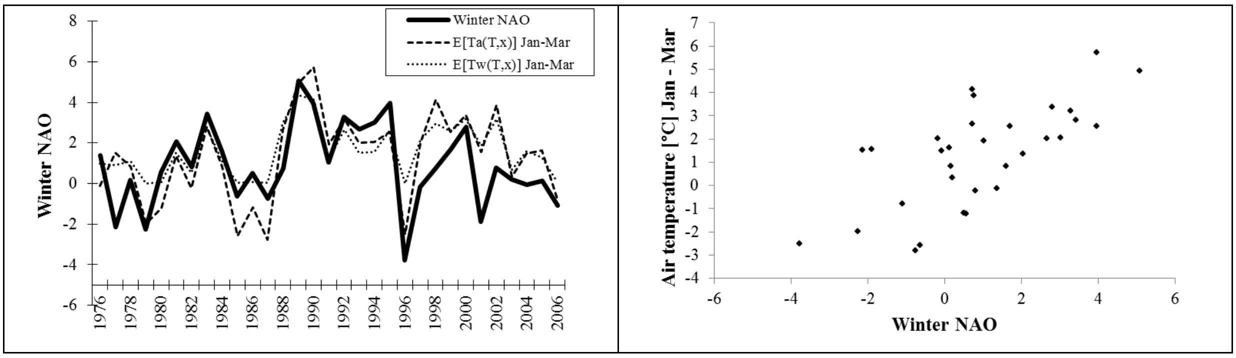

Figure 12: Development of the winter North Atlantic oscillation index, NAO, the mean air temperature, $\overline{T}_a(t,x)$, and the mean water surface temperature, $\overline{T}_w(t,x)$, between 1076 and 2006 (left panel) and the relation between winter NAO and $\overline{T}_a(t,x)$ of the same period (right panel).

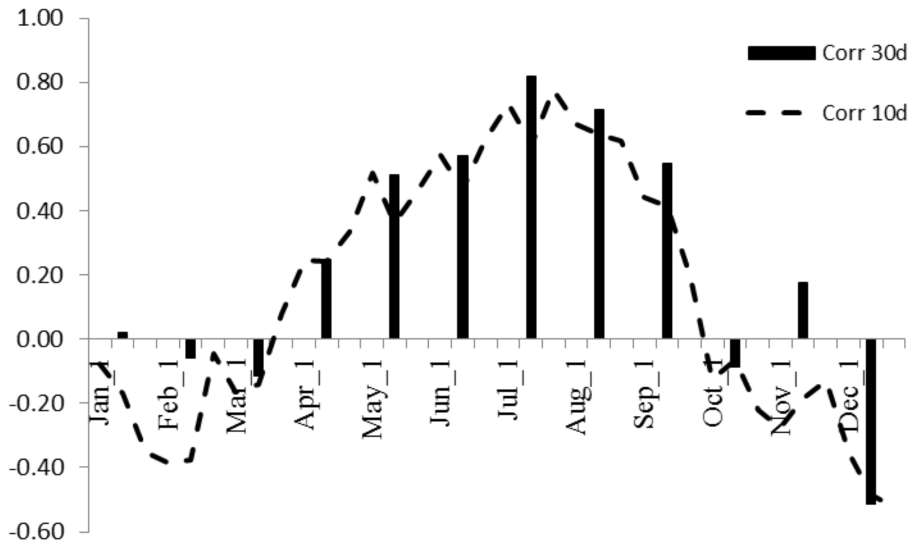

Figure 13: Correlation between mean number of hours with sunshine, $\overline{S}_h(t,x)$, and air temperature, $\overline{T}_a(t,x)$, based on 10 (Corr 10d) and 30 (Corr 30d) day periods between 1976 and 2006 from January to December