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Variability of the water temperature in the western Wadden Sea on tidal to centennial time scales

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ABSTRACT

Daily observations of the sea surface temperature in the Marsdiep tidal inlet, which connects the shallow Dutch western Wadden Sea with the deeper North Sea, already started in the summer of 1860, over 140 years ago. Since the year 2000 the sampling frequency has strongly increased because of the use of electronic sensors and data logging by computer. Analysis of these temperature data has revealed variations with time scales from tidal, daily, seasonal, inter-annual, to centennial. The tidal temperature variations are generated by advection of the seasonally varying temperature gradient between Wadden Sea and North Sea, while the daily variations are mainly caused by the daily variation of solar radiation. The seasonal variation in sea surface temperature only lags a few days behind the coastal surface air temperature, contrary to the sea surface temperature in the deeper nearby North Sea, which is delayed with about 1 month. The North Atlantic Oscillation index has been used as large-scale proxy for the atmospheric forcing of the Wadden Sea temperature. Only for the winter and spring a significant correlation is found between temperature and the winter index. However, this correlation is so strong that also the annual mean temperature is correlated significantly with the North Atlantic Oscillation. At longer time scales, from decadal to centennial, also large temperature variations are observed, of the order of 1.5 °C. However, these are not related to long-term changes of the North Atlantic oscillation. These long-term temperature changes involve a cooling of about 1.5 °C in the first 30 years of the record and a similar warming in the last 25 years. In between, these long-term changes were smaller and more irregular. Similar conclusions can also be applied to individual seasons as well as to the date of the onset of spring.

1. Introduction

The sea surface temperature (SST) is an important parameter describing the Northwest European coastal climate. It is also a very important factor in the coastal ecosystem of estuaries in this region like the western Wadden Sea (Fig. 1). Dyer (1995) lists a series of processes by which increase in temperature due to climate change may influence the silt budget of estuaries. Water temperature may also have strong effects on the physiology of marine organisms; e.g. bivalves show a lower metabolism during cold winters, resulting in a higher preservational biomass (Zwarts, 1971; Honkoop and Beukema, 1997) and consequently in the production of more eggs in early spring (Honkoop and Van Der Meer, 1997, 1998). The phase of the seasonal temperature cycle may trigger life cycle events of marine species; e.g. the shellfish *Macoma balthica* spawns (criterion: 50% spent) in spring when the gradual increase of the mean (monthly averaged) water temperature surpasses 8.3 °C (Philippart et al., 2003). Cold winters delay the onset of the crustacean reproduction in the North Sea and subsequent settlement of new-born shrimps onto the tidal flats of the Wadden Sea (Beukema, 1992). This delay enables the bivalve recruits to escape predation by outgrowing their predators (Beukema et al., 1998). Since climate change probably also will alter the seawater temperature in the coastal zone, it can be expected that the ecosystem will undergo temperature related changes due to climate change. Several publications have shown that present biological trends, i.e., phenological (timing) shifts, shifts in range boundaries, and changes in species abundances, are consistent with predicted effects of climate warming (Parmesan and Yohe, 2003; Root et al., 2003, Philippart et al., 2003). Increasing catches of the subtropical European sea bass (*Dicentrarchus labrax*) are attributed to the warming trend of the Dutch coastal waters in the last few decades (H. Witte, pers. comm.). Climate variability may induce variations in marine and estuarine ecosystems at all levels of the food chain, from primary productivity to the top predators including fisheries (Stenseth et al., 2004). Both the growth of prey species as well as predators can be temperature related in magnitude and timing. Variability and trends in climate therefore are expected to cause shifts in species distributions and predator–prey interactions (Freitas et al., 2007).

Climate variability in the past probably was (partially) responsible for observed ecosystem changes in the Dutch coastal waters. In this

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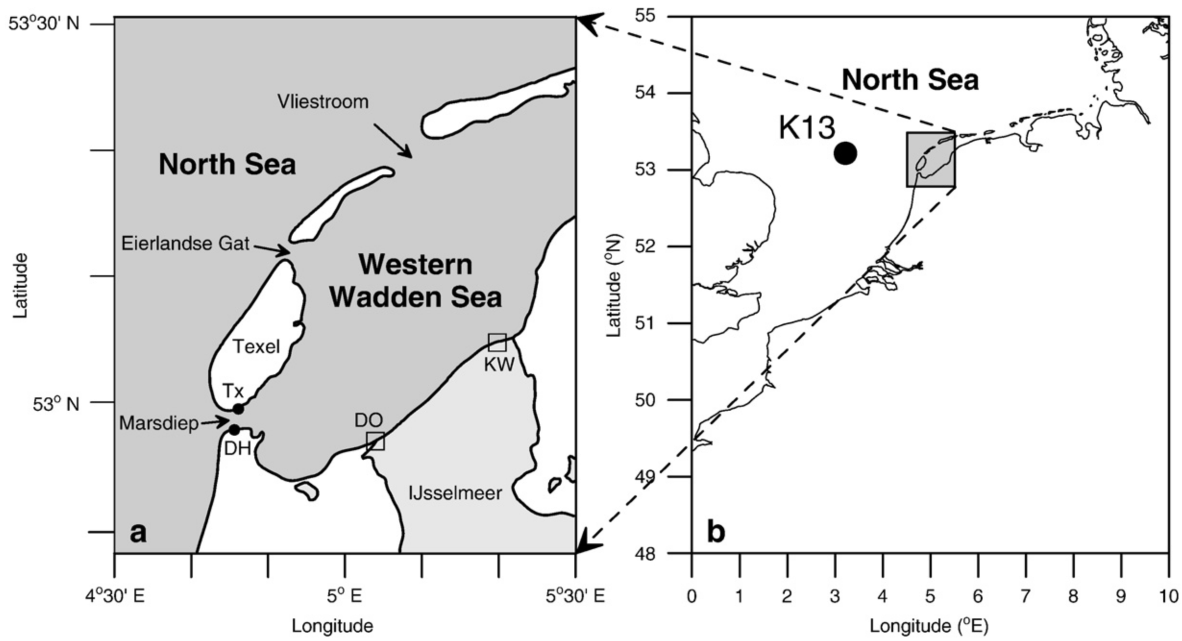

Fig. 1. Maps showing the western Wadden Sea (a) and the surrounding southern North Sea (b). The main connections of the Wadden Sea with the North Sea are the tidal inlets Marsdiep and Vliestroom. The inlet Eierlandse Gat only flushes a small sub-basin of the western Wadden Sea. Since 1932 the Wadden Sea has become separated from the former Zuiderzee, presently the freshwater lake IJsselmeer. The latter discharges surplus freshwater via outlet sluices near Den Oever (DO) and Kornwerd (KW). Since 1861 sea surface temperatures were daily measured from the sea dyke in Den Helder (DH), while since 1947 similar measurements were measured from the sea dyke of the Wadden Island Texel. The black symbol in (b) shows the position of the K13 oil platform.

paper we present over 145 years of daily observed seawater temperatures in the Marsdiep, the main tidal inlet of the Dutch western Wadden Sea, in order to describe the temperature regime in this Northwest European estuary at a range of time scales from tidal to centennial. The Marsdiep is a tidal inlet between the island Texel and Den Helder on the mainland of Holland (Fig. 1). It connects the western Wadden Sea with the North Sea. Up to 1932 the western Wadden Sea was part of the larger Zuiderzee, a shallow, brackish inland sea. Its main freshwater source was the river IJssel. In 1932 the “Afsluitdijk”, the enclosure dyke between Kornwerd (KW) and Den Oever (DO), was closed to prevent flooding of coastal regions around the Zuiderzee. Then the brackish inland sea became the freshwater lake IJsselmeer, thereby reducing the total surface of the brackish region to the remaining western Wadden Sea. The typical depth of the central channel in the Marsdiep, between Den Helder and Texel, amounts to 25 m. The depth of the tidal channels decrease eastwards, while over 30% of the western Wadden Sea consists of shallow tidal flats which are submerged during at least 50% of the tidal cycle. There the average depth (flats+channels) is only about 3.5 m (Zimmerman, 1976).

In 1861 daily measurements were started of sea surface temperature and salinity from the sea dyke in Den Helder (DH in Fig. 1), an initiative for scientific support of the fisheries in the Netherlands. Salinity measurements in Den Helder were discarded in 1962, but in 1947 the State Institute for Fisheries Research had already started daily measurements of sea surface temperature and salinity at the other side of the Marsdiep, from the sea dyke of the Island Texel (Tx in Fig. 1). After 1982 these observations were continued by the Netherlands Institute for Sea Research. The measurements were carried out each morning at 8 o'clock, local time. The monthly averages of these data until 1982 were described by Van Der Hoeven (1982). In 2000 the daily observations from a bucket with a mercury thermometer were replaced by continuous electronic temperature observations, located about 1 m below the low water spring level. This allowed us to monitor operationally the continuous variation of the sea water temperature over the tidal cycle. Salinity and thermal stratification between 5 and 15 m in the Marsdiep is only observed during the passage of the tidal front in the main channel of the Marsdiep. Near the sea dyke, where the local water depth at low water spring is only 2 m thermal stratification is quite rare, and it can be assumed that the electronic measured salinity is close to the sea surface temperature (J. Nauw-Van Der Vegt, pers. comm.). This assumption was confirmed from regular calibration samples from the sea surface with a bucket.

Contrary to the deeper North Sea, the shallow Wadden Sea contains a large area of tidal flats, which are submerged only part of the tidal cycle. This has probably strong effects on the heat balance of the Wadden Sea, e.g. strong heating of the dry tidal flats by the sun in daytime, releasing much of the stored heat from the sediment into the overlying water, when becoming submerged. The tidal flats thereby contribute to the heat balance, even when not submerged (Onken et al., 2007). This effect will reduce the thermal response time of the Wadden Sea, allowing a fast response to meteorological forcing.

This paper is a companion paper of a publication on the salinity variability in the Marsdiep, published earlier (Van Aken, 2008). A short description of the temperature and salinity data set was published by Van Aken (2003). That research has made clear that the long-term variability of the salinity in the Marsdiep and western Wadden Sea is mainly due to climatic variations of the precipitation over the catchment area of the river Rhine, as well as human induced changes of the transport of Rhine water via the river IJssel and the outlet sluices near Den Oever and Kornwerd (Fig. 1) towards the western Wadden Sea. The salinity field in the Wadden Sea is determined by advection of fresh water and mixing with North Sea water, while the influence of local climatic variations in precipitation can be ignored. For the temperature field in the Wadden Sea, it is expected that advection of water from the North Sea, and subsequent modification due to local air–sea interaction are dominant, while temperature effects of discharge of (fresh) water from lake IJsselmeer through the outlet sluices can be ignored. Existing estimates of the heat budget of the North Sea near Texel, based on the monthly mean temperature distributions and on bulk estimates of the air–sea heat flux, have indicated that in summer as well as in winter advection of heat by the mean circulation can be ignored (Becker, 1981).

Following the estimates by Becker (1981) the net downward surface heat flux in the North Sea near Texel has a maximum of ~95 W/m^2 in May, and a minimum of −65 W/m^2 in December. The short-wave solar radiation is the single dominant term in the local heat budget of the North Sea near Texel (O(140 W/m^2)), balancing the net infrared radiation and the storage term (both O(60 W/m^2)) and the latent heat flux (O(45 W/m^2)), while the sensible heat flux and the advective heat flux are relatively small (O(10 W/m^2)). The latter value, attributed by Becker (1981) to advection by the residual circulation, probably does not differ statistically from zero, given the limited accuracy of the flux estimates. Estimates of the heat budget of the western Wadden Sea proper have not been published. Unpublished estimates of the heat budget of the western Wadden Sea have confirmed that although advection of heat by the tides is significant, the heat advection by the mean flow through the Marsdiep can be ignored compared to the other terms in the heat budget (Ettema, 2001). A preliminary analysis of 8 years of ADCP measurements from the ferry between Den Helder and Texel suggest that the mean residual flow, and thereby the mean advective heat flux, through the Marsdiep is close to zero (J. Nauw-van der Vegt, pers. comm.).

2. The data

Halfway through the 19th century scientific interest in the application of the newly emerging meteorological and oceanographic sciences grew. In 1854 the Royal Netherlands Meteorological Institute (KNMI) was founded. Support of shipping activities was an important task of this young scientific institute. In order to support fisheries activities in the Wadden Sea and the nearby North Sea it was decided to monitor temperature and salinity at a series of coastal stations in the Netherlands. One of these stations was situated on the Den Helder sea dyke along the Marsdiep (Van der Hoeven, 1982). From 1860 until 1962 daily observations of the SST were carried out at the Den Helder side of the Marsdiep (DH in Fig. 1a). Surface water samples were initially taken with a bucket at 08:00 AM. The SST was determined with a calibrated sea water thermometer. Later these observations were replaced by measurements with an electronic temperature sensor. Since 1947 similar SST measurements were made by the State Institute for Fisheries Research (RIVO) on the opposite side of the Marsdiep, at the coast of the Island Texel (Tx in Fig. 1a), allowing the determination of a monthly mean offset to relate observations on both sides of the inlet. The data set with monthly mean temperatures from 1861 until 1981 has been quality controlled and described by Van der Hoeven (1982). Because of interference of daily observations at a fixed time with the tidal SST signal in the Marsdiep, resulting in a 14 day beat, it was necessary to use monthly mean values of the SST. In 1982 the Netherlands Institute for Sea Research took over the responsibility for the Marsdiep series collected from the Texel sea dyke. The daily observations of temperature and salinity are continued till present (Van Aken, 2003). Since March 2000, temperature and salinity are measured continuously by means of electronic sensors, mounted on a jetty that extends about 10 m from the Texel sea dyke. The SST observations are now archived as 30 min values, although the continuous measurements do allow an increase in temporal resolution to 1 min values.

Den Helder was one of the five locations, where the newly founded KNMI started its meteorological observations. Meteorological data from Den Helder since 1906, among which the daily mean surface air temperature (SAT), are available from the KNMI web site. Because of the lack of reliable meteorological data from the open Wadden Sea, which can be used for the calculation of the local air–sea heat exchange, we will use these daily mean SAT values as a proxy for the thermal forcing of the Wadden Sea. SST data from the open North Sea (platform K13 at 53°13′N, 3°13′E, depth 27 m) were downloaded from the DONAR data base of the Department of Roads and Waterways (Rijkswaterstaat).

With the long-term time series it is useful to discriminate between inter-annual thermal variability and variability with time scales of decades to over a century. We have used very simple filters to discriminate between the high-frequency variability connected with the year to year meteorological variability and the longer-term climatic variability. To describe the longer-term changes we use a 10 year running mean as a low-pass filter. Subtracting the low-pass filtered data from the original data produces a high-pass filtered data set, used to analyse the inter-annual changes with time scales less than a decade. This pragmatic choice of the low-pass filter width maintains about 22% of the variance of the annual mean SST in the low-pass filtered time series, ascribing 78% of the variance to the high-pass filtered data. Doubling the width of the low-pass filter to 20 years decreases the low-pass variance to 13% of the original annual mean SST data. The number of degrees of freedom in the time series has been estimated from the auto-correlation time scale to be 60 for the original time series, 7 for the low-pass filtered data, and 105 for the high-pass time series. These values have been used to determine the significance of correlations between time series.

3. High-frequency variations of the sea surface temperature

A plot of the annual SST cycle in 2005 (Fig. 2a) clearly shows that regularly high-frequency variability at tidal frequencies with a magnitude of several degrees is superimposed on the clear seasonal

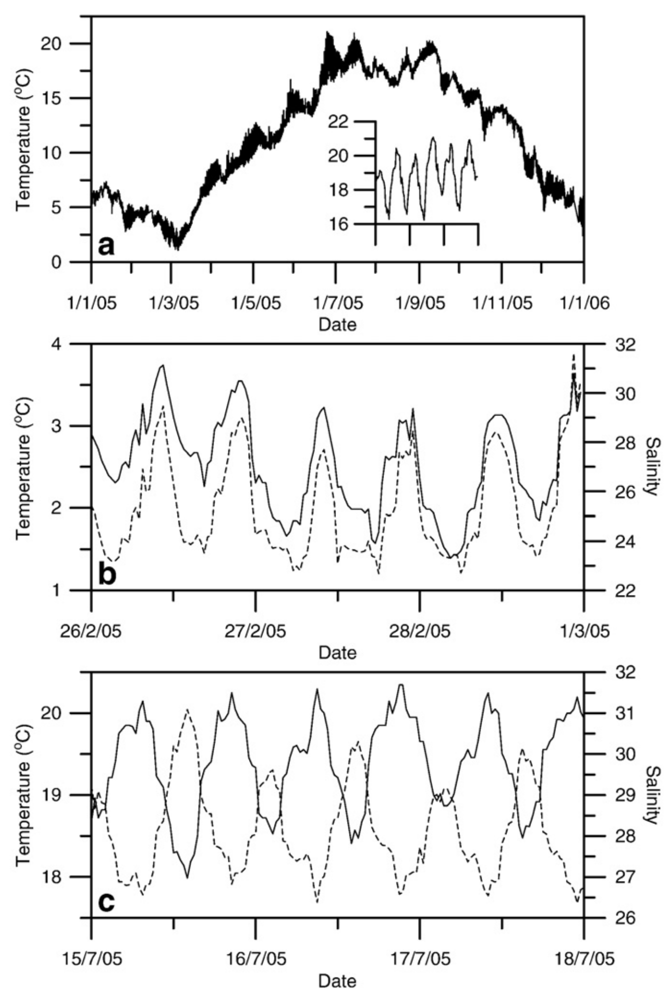

Fig. 2. A plot of the sea surface temperature in the Marsdiep recorded every 30 min throughout 2005 (a), a plot of temperature and salinity during 3 days in the winter of 2005 (b), and a similar plot for the summer of 2005 (c). The date labels follow the European date/month/year convention. The temperature records are shown as a full line, while the salinity is presented by the dashed line. The inset in (a) shows the large temperature variability from 23 to 25 June 2005.

signal. A detailed plot of temperature and salinity from the winter (Fig. 2b) and summer (Fig. 2c) season reveal that while in winter temperature and salinity are in phase, they are in counter-phase in summer. These data indicate that the water of the saline North Sea is warmer than the fresher Wadden Sea in winter, while this temperature contrast is reversed in summer. This seasonal difference can be attributed to the larger heat capacity per square meter of the deeper North Sea compared to the shallow Wadden Sea. In the latter seasonal temperature changes will occur faster, while more extreme temperatures can be reached. From the data it is clear that the tidal temperature and salinity variability is due to advection of the along-estuary gradients by the tidal current.

From the continuous temperature and salinity observations, carried out from 2002 until 2006, the monthly mean temperature difference between the ebb and flood current were determined (Fig. 3). The SST, coincident with the salinity maximum, was used as flood current temperature, while the SST coinciding with the salinity minimum was used for ebb current temperature. The flood current was colder than the ebb current in the warming season from April to August, while in the cooling season from September until March the ebb current was coldest. The largest mean differences, observed in June and December, are of the order of 1.5 °C. However, in individual days the flood minus ebb SST difference may surpass 3 °C (e.g. June 2005, see inset in Fig. 2a).

The daily inequality of the tidal current through the Marsdiep is the likely cause of a daily inequality in salinity (Van Aken, 2008). Also the temperature of the Marsdiep regularly shows a daily inequality (Fig. 4 shows 3 examples). In winter the warmest of the two semi-diurnal cycles may occur either in the first, or in the second half of the day (Fig. 4a shows a winter situation with the highest temperatures in the morning). However, in the warming period (spring and summer) the daily inequality systematically shows higher temperatures during the outgoing ebb tide in the late afternoon and early evening (Fig. 4b, c). This effect can be attributed to the release of heat from the tidal flats and shallow parts, derived from solar radiation stored earlier, during daytime. This systematic difference may cause a systematic bias in monthly and annually averaged SST values, based on observations made at a fixed time, in our case 08:00 AM.

We have analyzed the difference between the coinciding monthly mean SST values derived from 08:00 AM SST values (T_{8AM}) and from 5 years of continuous SST values, sub-sampled every 30 min (T_{cont}) (Fig. 5). Ten out of the twelve months show a negative bias (T_{8AM}−T_{cont}) in the monthly mean SST values, based on 08:00 AM SST observations. This shows that the release of solar heat from the tidal flats also takes place in winter, despite the net heat loss in that season. The largest negative bias of over −0.2 °C was found for the warming months May and June. In October the bias was near zero, and only in November the bias, although small, is well over zero. The difference between the monthly mean averages from the 08:00 AM and continuous observations also has a stochastic contribution with a mean standard deviation of 0.1 °C. Averaged over the 5 years, used to

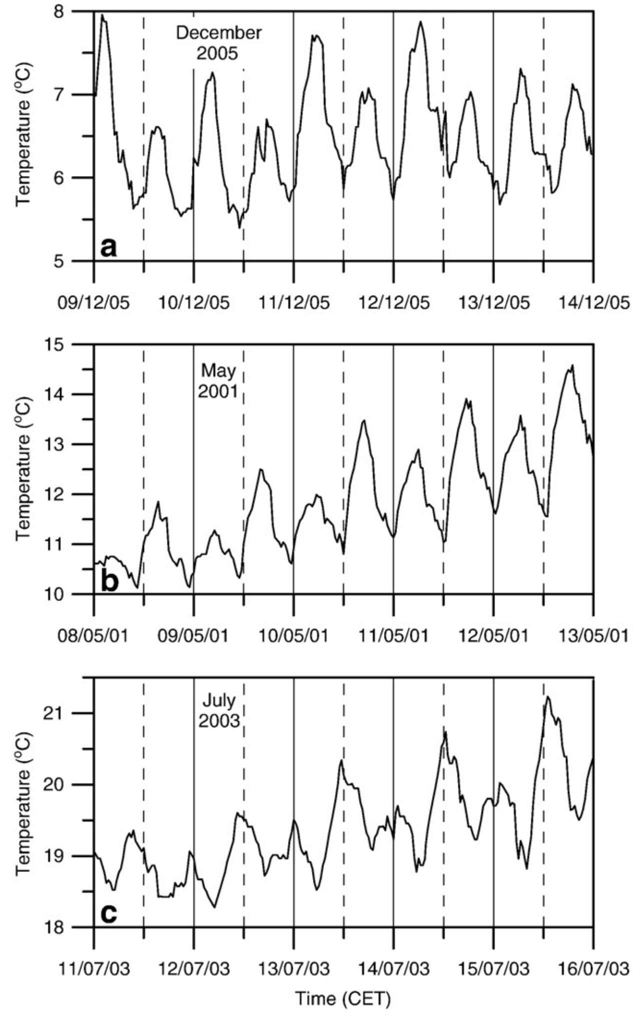

Fig. 4. Exemplary plots of the sea surface temperature in the Marsdiep, showing the daily inequality for December 2005 (a), May 2001 (b) and July 2003 (c). The vertical full lines indicate Midnight, Central European Time, the dashed line indicate noon. The time labels follow the European date/month/year convention.

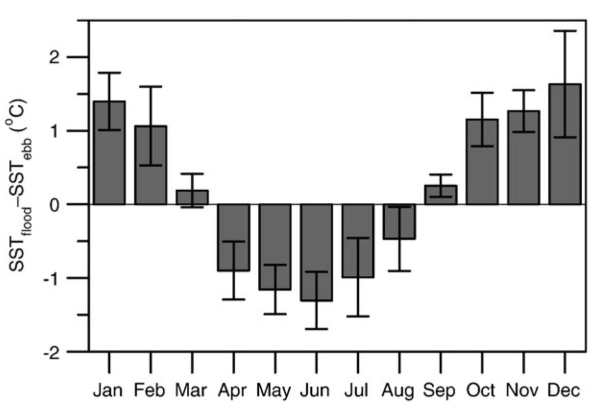

Fig. 3. Monthly mean sea surface temperature differences between flood and ebb, based on 5 years continuous observations from 2002 until 2006. The error bars show the standard deviations, derived from the single month averages of the difference.

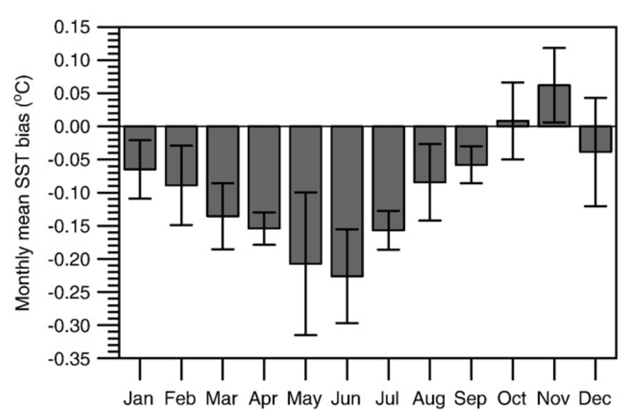

Fig. 5. Plot of the monthly SST bias (T_{8AM}–T_{cont}), constructed from monthly mean SSTs derived from 08:00 AM SST values, and from the continuous observations during the 5 years from 2002 until 2006. The error bars show the standard deviations, derived from the individual monthly mean SST values.

determine Fig. 5, the systematic bias in the annual mean SST due to early morning sampling amounts to −0.1 °C, with a stochastic contribution with a standard deviation of only 0.03 °C. Most of the years, reported in this paper, are based on 08:00 AM observations and contain that bias. In order to make the data set homogeneous and make comparisons possible, the long-term (1861–2006) time series presented in this paper are all based on 08:00 AM observations, despite the availability of continuous observations since 2002.

4. The annual SST cycle from 2002 until 2006

The heat budget of the western Wadden Sea depends on the heat exchange with the atmosphere as well with the North Sea. The detailed meteorological data, which would enable the calculation of the air–sea heat exchange according to bulk formula are lacking. Therefore we will use the SAT, measured in Den Helder, as a proxy for the meteorological heat forcing of the western Wadden Sea. The daily mean SST from 2002 to 2006 shows a clear annual cycle with a typical mean amplitude of 7.9 °C (Fig. 6, thick full line). The SAT in Den Helder (Fig. 6, thin grey full line) has a nearly similar annual cycle (amplitude 7.3 °C), but with more high-frequency variability due to the synoptic weather variations. From the monthly mean temperatures over these 5 years it appears that the Marsdiep SST is warmer than the Den Helder SAT in all months but March ($\Delta T_{\mathrm{march}}=-0.5(\pm 0.2$ std. error)°C), resulting in a 5 year mean temperature difference of 0.7(±0.1 std. error)°C. The phase lag between the Den Helder SAT and the Marsdiep SST is small, only 2 days according to a cross correlation analysis, 5 days according to a harmonic analysis of the 5 years of data. That implies a fast thermal response of the Marsdiep temperature on the local meteorological forcing. SST data from the K13 platform in the open North Sea (Fig. 6, thick dashed line) show an annual mean temperature within 0.1 °C from the Marsdiep SST. However, in the North Sea the amplitude is 1.5 °C smaller (6.4 °C), while the annual SST cycle near the K13 platform lags about 1 month behind the Marsdiep, as can be expected from the deeper North Sea. From this comparison it is confirmed that at annual time scales the local meteorological forcing of the of the SST in the Marsdiep is dominant over the advection of the delayed annual SST cycle from the deeper North Sea, as also has been observed for the shallow Dutch coastal waters of the North Sea (Becker, 1981).

The averaged monthly mean Marsdiep SST values for the whole 1861 to 2006 period are shown in Fig. 7. The warmest 3 months of the year are July to September, while the coldest 3 months are January to March. The monthly standard deviation, reflecting the inter-annual to centennial variability of the monthly mean temperature, also shows a seasonal variation with a typical value of 1.7 °C for the winter months December to March, while in the rest of the year (April to November) the monthly standard deviation amounts to 1.0 °C. In the following analysis we will consider the average SST for January to March and for July to September as representative respectively for the winter situation and the summer situation.

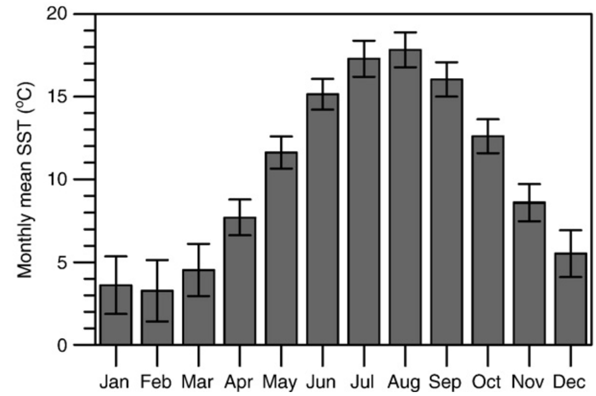

Fig. 7. Averaged monthly mean SST with standard deviation for the period 1861–2006. The error bars show the standard deviation, derived from the individual monthly averages.

5. Long-term SST variability

The annual time series of seasonally averaged SST values shows strong inter-annual variability (st. dev. O(0.9 °C)), while the 10 years running mean displays a smaller variability (st. dev. O(0.4 °C)) on decadal to centennial time scales (Fig. 8a). The largest standard deviation of the seasonally averaged temperature is observed in winter (1.5 °C), nearly double the averaged standard deviation for the other seasons (0.8 °C). This contrast is due to a large inter-annual variability, since such a difference was not found in the standard deviation of the low-pass filtered (10 year running mean) winter SST of 0.5 °C relative to 0.4±0.1 °C for the decadal to centennial SST variability in spring to fall. The reason for the exceptionally high inter-annual SST variability in winter has to be sought in an irregular occurrence of extremely cold winters (skewness=−0.7). In the 146 year long record two winters with a seasonal mean SST below 0.0 °C are found (−0.5 °C in both 1947 and 1963). Monthly mean

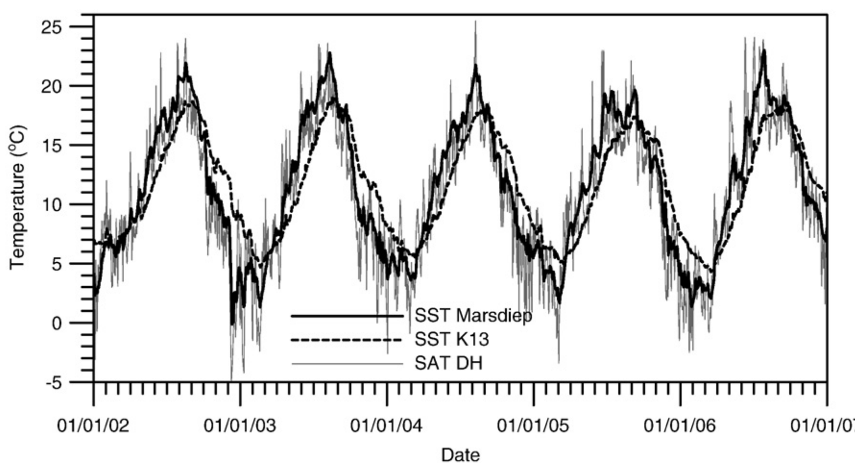

Fig. 6. Five years of daily mean sea surface temperature data from the Marsdiep (thick full line) platform K13 (53°13′N, 3°13′E, 27 m depth) in the North Sea (thick dashed line), and the daily mean surface air temperature from the meteorological station at the airport De Kooij near Den Helder (thin grey full line). The data labels follow the European date/month/year convention.

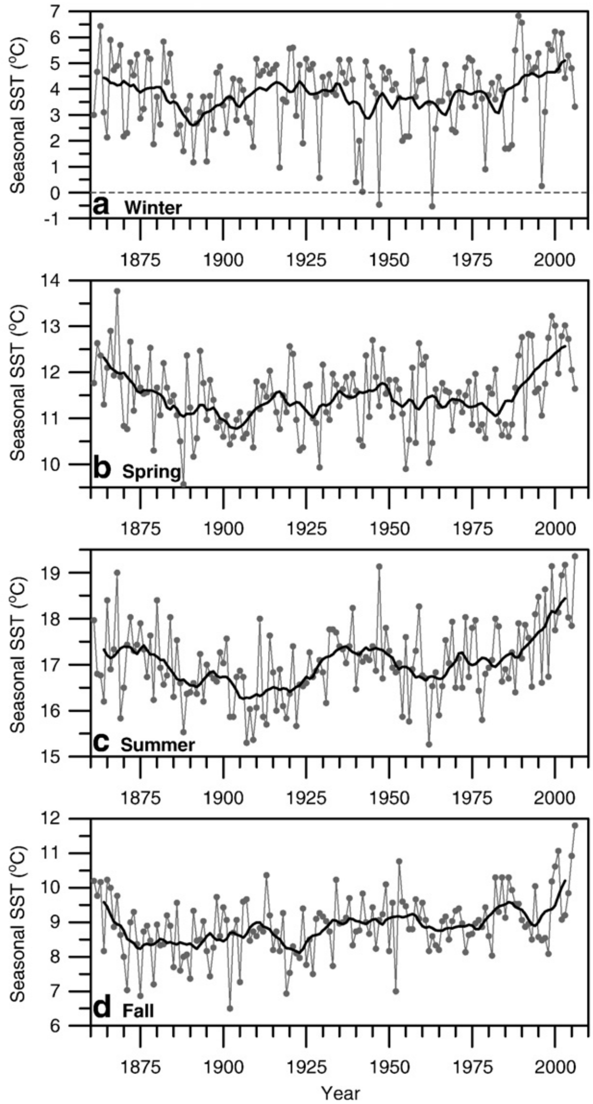

Fig. 8. Long-term time series of seasonally averaged SST (thin grey line with symbols) for the (a) Winter (January to March), (b) Spring (April to June), (c) Summer (July to September), and (d) Fall (October to December). The thick black line represents the 10 year running mean.

SST values below zero are also scarce (Fig. 7), 19 out of 438 winter months. Most of the coldest winters (SST<1.0 °C) occurred in the mid 1900s, (five out of the ten coldest winters fall in the 34 years from 1929 until 1963). The warmest 2 years are 1989 and 1990, both with a winter mean SST above 6.5 °C. The low-pass running mean SST in winter showed a decrease of 1.6 °C from 1864 to 1891. Then followed an increase of 0.6 °C until 1916, followed by an irregular decrease of 1.2 °C, lasting several decades until 1983. From then on the low-pass filtered winter SST increased monotonously with 1.9 °C.

In the other seasons (Fig. 8b to d) the seasonally averaged SST was distributed more symmetrically (mean skewness=0.2), and with a lower standard deviation (0.8 °C). The long-term development of the 10 year running mean seasonal SST differs from season to season. However, all seasons show a decrease in seasonal SST in the earliest decades of the long-term time series, and an increase since 1985. The linear correlation between the SST for successive seasons may be influenced strongly by this longer-term trend, if we use the original data (thin line with dots in Fig. 8). To remove this effect we have used the high-pass filtered SST data (original SST data minus the 10 year seasonal running mean SST) for further analysis. The correlation between the high-pass filtered data for successive seasons (Table 1) indicates that in the warming half-year (winter to summer) the quarterly mean SST values are significantly correlated at the 1% level, especially winter and spring (R=0.62). The correlation between spring and summer SSTs, although much weaker (R=0.29), is also significant at the 1% level with 105 degrees of freedom, contrary to the cooling half-year (summer to winter), where the season to season correlations do not significantly differ from zero. The mean seasonal SAT in Den Helder (1906–2005), which is well correlated with the Marsdiep seasonal SST (R=0.99), shows a similar correlation between successive seasons, with a significant correlation (p=1%) only in the winter to spring period (R=0.41). This implies that cold winters will lead to cold springs, but that hot summers don't induce warmer autumns or winters. The apparent influence of the thermal inertia of both the atmosphere and the western Wadden Sea probably is connected with the skewed SST distribution, due to the irregular occurrence of very cold winters and following cold springs. Removal of the 30 coldest winters form our 146 year record reduces the correlation between winter and spring SST from 0.62 to 0.37.

Table 1
Correlation between the SST in successive seasons, based on the analysis of the high-pass filtered seasonal SST data

Fall–winter	0.14
Winter–spring	**0.62**
Spring–summer	**0.29**
Summer–fall	0.17

The significant correlations (1% level, 105 degrees of freedom) are indicated by bold print.

As can be expected, the annual mean SST (Fig. 9a) is significantly correlated with all four seasonal mean SST values shown in Fig. 8. The highest correlation for the high-pass filtered data (difference between actual data and 10 years running mean) occurs in winter (R=0.83), probably because the variability of the seasonal mean SST variability is largest in winter. We have seen above, that the Marsdiep SST shows a fast response to the annual SAT cycle in Den Helder. That also applies to longer time scales. The annual mean SST is also significantly correlated with the annual mean SAT in Den Helder (R=0.95). This relation suggests that the SST in the western Wadden Sea also depends on the large-scale atmospheric circulation. For north-western Europe the North Atlantic Oscillation (NAO) index is used

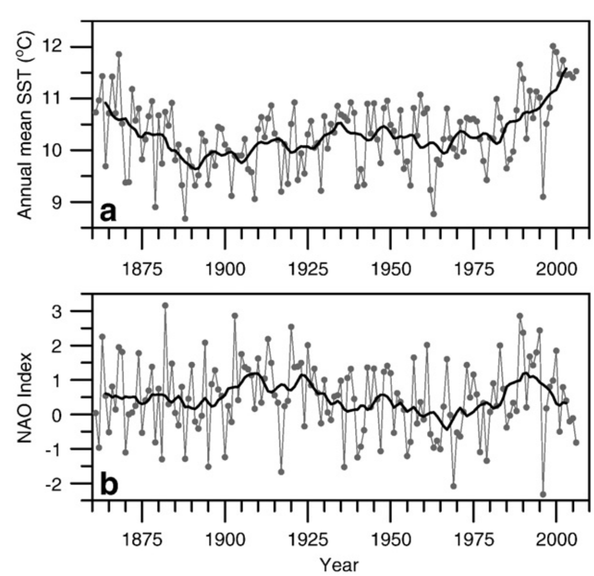

Fig. 9. Long-term time series of (a) the annually average SST and (b) the winter NAO index (December to March). The thin grey lines with symbols represent the annual data, the thick full black lines the 10 year running mean.

often as a shorthand proxy to represent the large-scale atmospheric forcing over the Atlantic Ocean (Hurrell, 1995). The NAO index is a normalized meridional air pressure difference between a station in the north Atlantic (generally on Iceland) and a station on the Iberian Peninsula or one of the subtropical Atlantic Islands. The value of the NAO index is related to the zonal atmospheric geostrophic transport of mass, heat, and moisture over the North Atlantic Ocean. The winter NAO index is shown to correlate well with climate parameters in north-western Europe (Hurrell and Van Loon, 1997). The linear correlation of the 3 month seasonal mean SSTs from Fig. 8 with the coincident 3 month seasonal mean NAO index from Fig. 9b appears not to be significant at the 1% level but for the winter season (R=0.66). Here we will use the more customary 4 month NAO index based on winter (DJFM) pressure data from SW Iceland (Reykjavik) and Gibraltar (Jones et al., 1997), which can be downloaded from internet (http://www.cru.uea.ac.uk/cru/data/nao.htm). Both the original values of the NAO index as well as the low-pass filtered time series are shown in Fig. 9b. The strongest linear correlation with the winter NAO index is found for the Marsdiep winter SST (R=0.68), while also the correlation with the annual mean SST is significant at the 1% level (R=0.48). This is mainly due to the fast inter-annual variations, represented by the high-pass filtered data. The correlation between the high-pass filtered winter NAO index and the high-pass filtered annual mean SST amounts to 0.67. As can be expected, that significant correlation (p=1%) is mainly due to the fast response of the winter SST to the winter NAO index, which have a mutual correlation of 0.75 (high-pass filtered data). Because of the significant positive correlation between the winter and spring SST, the high-pass filtered spring SST is also significantly (p=1%) correlated with the winter NAO (R=0.58). This correlation is probably not caused by a delayed direct interaction between the atmosphere and the shallow coastal sea, but by the apparent thermal inertia during the warming half-year.

6. The warming signal and thermal timing triggers

The winter mean SST variations, presented above, will have had their ecological consequences in the past, like influencing the winter metabolism of bivalves and the subsequent production of more bivalve eggs in early spring, or the predation of bivalve recruits by shrimps. In the Introduction it was mentioned that some organisms use the increasing temperature in spring as a trigger for live cycle events, e.g. spawning by the *M. balthica*. Here we will work out, as an example, the long-term variation of the date that the daily mean SST surpasses 8.3 °C, the boundary value for *M. balthica* spawning within the Wadden Sea. Similar to Philippart et al. (2003) who calculated that date for the 1972 to 2002 period, we have calculated the 8.3 °C trigger date from the long-term time series of the monthly mean SST values (Fig. 10).

Similar to the seasonal temperature, the trigger date shows a large variability, with a range of well over 1 month (31 March to 6 May), and a standard deviation of 8 days. Less than 20% of the total variance of

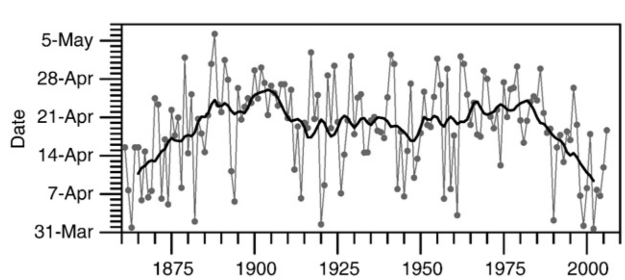

Fig. 10. Long-term time series of the trigger date for the spawning of *Macoma balthica* when the Marsdiep SST surpassed 8.3 °C, derived from the monthly mean SST values (thin grey line with symbols), and the low-pass version of these dates, obtained by applying a 10 year running mean (full thick black line).

the 8.3 °C trigger dates can be attributed to the decadal to centennial time scales (the 10 year running mean), while over 80% of the variance was connected with the inter-annual variability. Despite this relatively small contribution to the trigger date variability from the longer time scales, the low-pass filtered data show a persistent 16 day spring delay from 1861 to 1908, and a shift to a 15 day earlier trigger date from 1982 to present.

The thermal development in the Wadden Sea in winter and spring is closely related to the atmospheric forcing as expressed by e.g. the NAO index. However, the low-pass filtered trigger dates are not significantly correlated with the low-pass NAO index (R=−0.21). That can also be discerned from the 10 year running mean of the NAO index (Fig. 9b), which lacks large systematic trends in the above mentioned periods. In contrast, the inter-annual variability of the trigger date, derived from high-pass filtered data, is significantly correlated with the high-pass filtered winter NAO index (R=−0.66). Since the long-term average SST=8.3 °C trigger date is 19 April, it is no surprise that these trigger dates and the monthly mean SST for April are very well correlated (R=−0.96). There is also a significant correlation (p=1%) of the trigger date with the Den Helder SAT (R=−0.82), which can be expected, given the small delay between the annual cycle of SST relative to the SAT annual cycle. The low-pass filtered NAO index does not show the persistent trend after 1982, observed in SST and SAT. Probably the cause of the long-term trends in the trigger date is not caused by a strong change in the zonal winter winds over the North Atlantic Ocean, contrary to the shorter-term changes, but reflects a real large-scale warming trend.

7. Conclusions

The Marsdiep is a tidal inlet of the Wadden Sea, where the SST changes twice daily with the semi-diurnal ebb and flood currents. A daily inequality of the SST can be observed, partly connected with daily inequalities in the tidal current, but also partly connected with interference of the tides and the daily cycle of the surface heat budget, especially the short-wave solar radiation, in the Wadden Sea. The latter may lead to a systematic error in the long-term temperature time series, based on 08:00 AM observations. However, this error is small compared with the seasonal and inter-annual to decadal variability of monthly and annually averaged SST values.

The annual cycle of the Marsdiep SST is well correlated with the annual cycle of the SAT, observed in Den Helder, with a delay of only a few days. That also applies to the annual mean SAT and SST, which are also very well correlated. This indicates that the thermal variability in the western Wadden Sea reflects the regional climate variability in the Dutch coastal zone. At inter-annual time scales the annual mean SAT and SST are well correlated with the winter NAO index, mainly because of the strong correlation with the winter and spring temperatures. However, the long-term trends in SST and SAT are not significantly correlated with the low-pass filtered NAO index. This suggests that at decadal to centennial time scales this index, as a proxy for the zonal winds over the ocean, is too simple to explain most of the regional climate variability. The SST in summer and fall are not significantly correlated with the winter NAO index, or with the summer and fall indexes. It appears that in these seasons, the zonal winds over the Atlantic are less directly coupled to the coastal climate in the Netherlands.

For all seasons the high-pass inter-annual SST variability is dominant over the low-pass filtered decadal to centennial variations. In winter and spring these inter-annual variations are correlated with the winter NAO index variations, as are the SST=8.3 °C trigger dates in spring. Given the many ecological and physiological relations with water temperature in the Wadden Sea ecosystem, it can be expected that the atmospheric variability, reflected by the winter NAO index, will influence the ecology of the Wadden Sea. But given the many different feedback mechanisms between organisms which different responses to temperature forcing, the relation between the thermal regime and the success of specific species may be quite indirect (Stenseth et al., 2004; Freitas et al., 2007), although for all abiotic forcing factors generally the best correlations are found with winter or spring temperature (Philippart et al., 2003). The early life stages of the animals are probably involved in this link. The correlations between NAO index and ecological parameters (Stenseth et al., 2004) then can be explained from the correlation of winter NAO index and the SST in these seasons.

The long-term trends in the thermal regime of the western Wadden Sea, represented by the low-pass data, undoubtedly will have their effect on the Wadden Ecosystem. An invasion of southern species in the last 15 years is often intuitively attributed to the persistent warming of the North Sea and Wadden Sea (H. Witte, pers.com.). It may be interesting to collect or reconstruct ecological data from the cooling period in the last 40 years of the 19th century, in order to find out whether the changes in that period were related but opposite to the ecological changes from the last 20 years.

The temperature variance connected with inter-annual (high-pass filtered) variability appears to dominate over the decadal to centennial (low-pass filtered) variability. Therefore it can be expected that existing studies on the relation between the ecosystem and temperature forcing mainly will reveal the causes of inter-annual ecosystem variability. It is not clear yet whether similar relations can be applied to longer-term climate trends like those expected from global warming.

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