ROYAL BELGIAN INSTITUTE FOR NATURAL SCIENCES
OPERATIONAL DIRECTORATE NATURAL ENVIRONMENT

Section Ecosystem Data Analysis and Modelling
Suspended Matter and Sea Bottom Modelling and Monitoring Group

Climate change: analysis of time series of sea water temperature at the Belgian coast

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1. Introduction

In the framework of the CREST project, climate change scenarios are set up for the Belgian coastal waters. In separate reports, the analysis of climate change on waves and storm surges and on sea level rise is presented. In this report the changes of sea water temperature in the Belgian coastal waters are analysed. Sea water temperature is an important factor for the ecosystem. The effects on it were discussed in e.g., Ponsar et al. (2008). The changes in sea water temperature are amongst others of great importance for the fisheries. Changing temperature could cause changes in the distribution of the fishes, with implications for the food chain, etc.

The report is an update of the work, done in the framework of the CLIMAR project (Van den Eynde et al., 2008). As in that report, the NOWESP methodology (Visser et al., 1996) is applied to the observations. In the first section the measurements that were gathered are shortly discussed. The focus will be on the Belgian coastal waters. The analysis is presented in the next sections. Some conclusions are finally presented.

2. Measurements

For the present report, three data sets were analysed.

2.1. 4DEMON

The first dataset were data sets that were prepared in the framework of the Belspo project 4DEMON, where historical data sets were recovered to be used for today's needs. More information can be found in the website http://www.4demon.be. A total set of 7997 values in the Belgian coastal waters were provided, covering the period 1968-2014. The data coverage is shown in Figure 1. The original time series is shown in Figure 2. The data points with value above 32°C and exactly equal to -1°C were discarded as spurious values. Data within the range of 0°C to 28°C were selected in the region 2°E – 3.6°E, 51°N – 52°N. Finally, 7687 data were kept.

2.2. ODAS

A second data set that has been investigated is the ODAS data set. This is the automatic temperature measurements on board of the RV Belgica. Since the RV Belgica is only operational since 1984, the data are only starting then. Only the data in the box 51°N to 52°N and 2°E to 3.6°E are taken into account for this study. Since the automatic measurements are taken every 10 minutes, more data are available here. A total of 264767 data points is available. The distribution of the data in the area is plotted in Figure 3. The data do cover a wide part of the area. At some places more than 3000 measurements are available over the period. The original time series is shown in Figure 4. Some unrealistic values are noted, which are as high as 38°C. All values higher than 28°C were considered unrealistic and were removed. Although the data set contains more data, its main disadvantage is its shorter time span.

2.3. WODB

The third data set which is used has been downloaded from the World Ocean Data Base 2013 (https://www.nodc.noaa.gov/OC5/WOD/pr_wod.html). Different data sets can be downloaded which include temperature profiles over the depth. For the current application, only the near surface data are used. Again, only data in the box 51°N to 52°N and 2°E to 3.6°E were selected for the current application. The data coverage and the time series are presented in Figure 5 and Figure 6. Some suspicious data were removed from the data series, i.e. the measurements of exactly 0°C in the period between 1900 and 1950. Remark that sometimes even in the months July or August some measurements are equal to 0°C. The values above 28°C were removed as well. A total of 12106 data values were used in the analysis. Remark that this data set covers a very long period, with data already available from 1864.

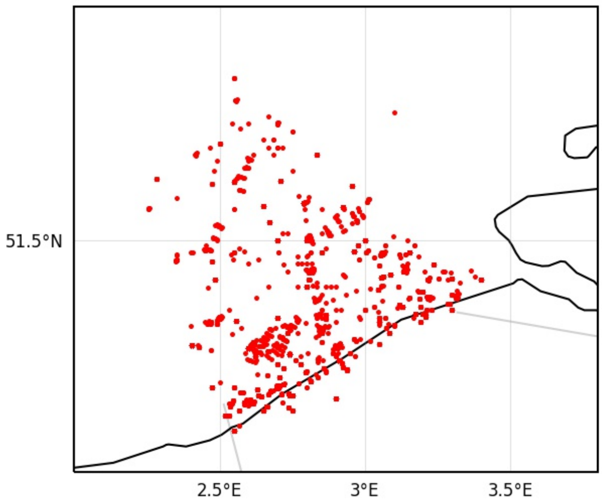

Figure 1: Data points of 4DEMON data set.

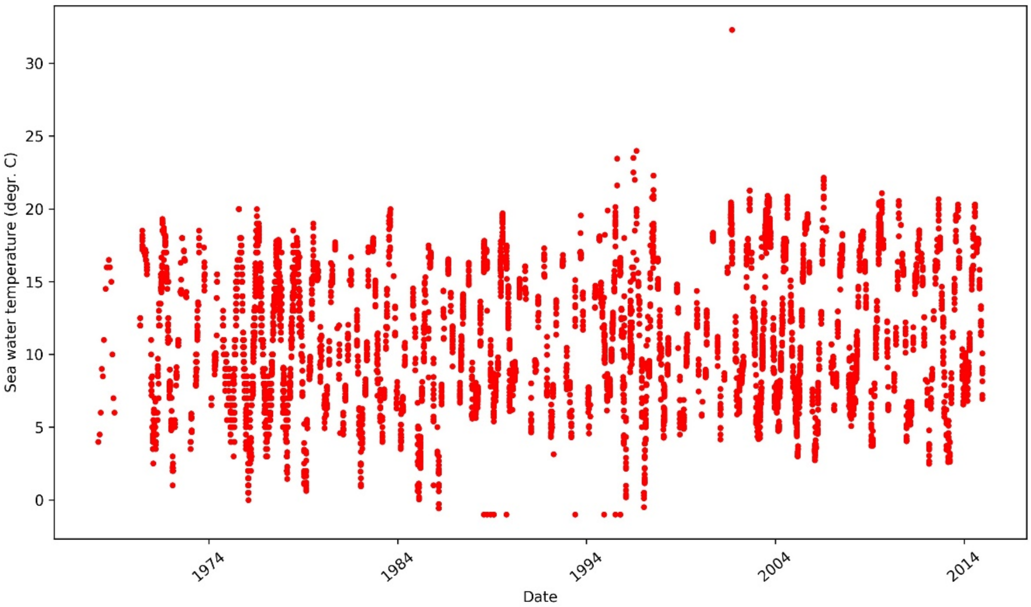

Figure 2: Time series of sea water temperature, 4DEMON data set.

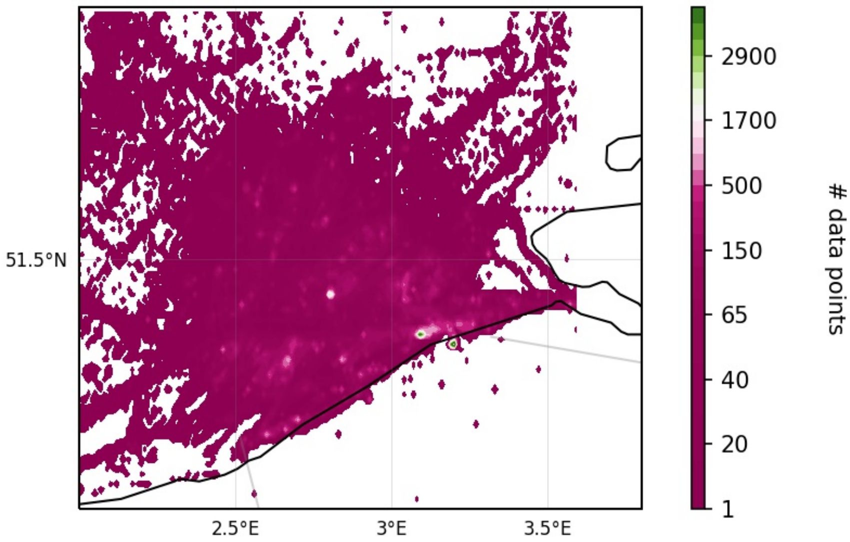

Figure 3: Data points of ODAS data set.

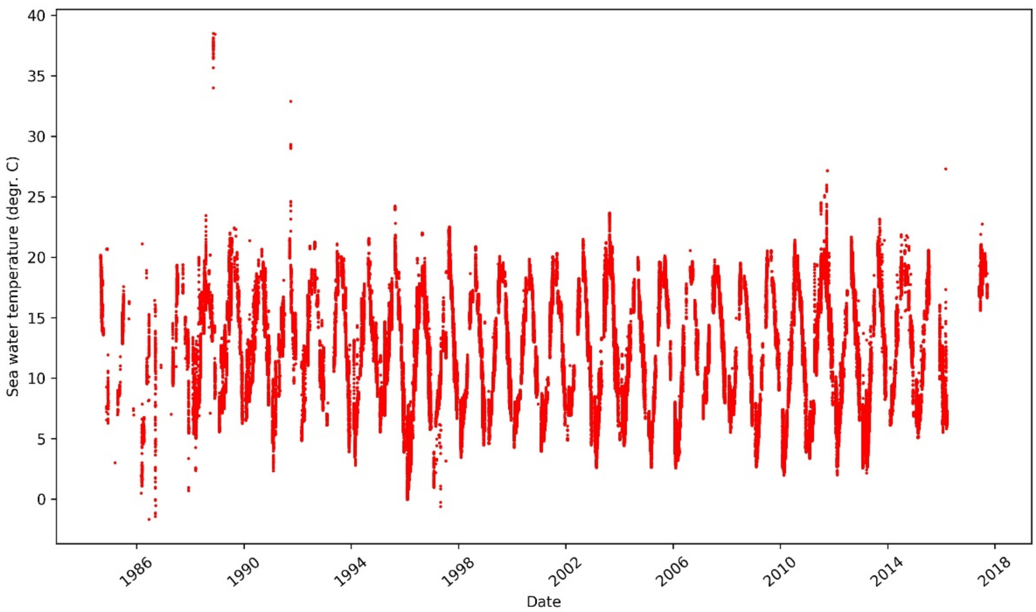

Figure 4: Time series of sea water temperature, ODAS data set.

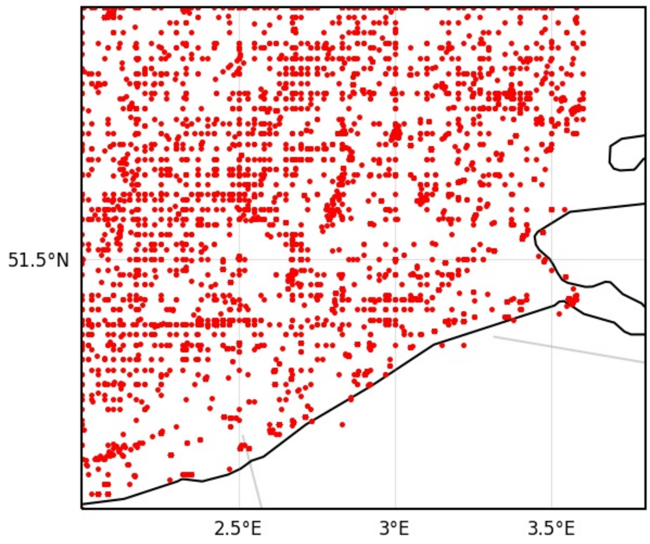

Figure 5: Data points of WODB data set.

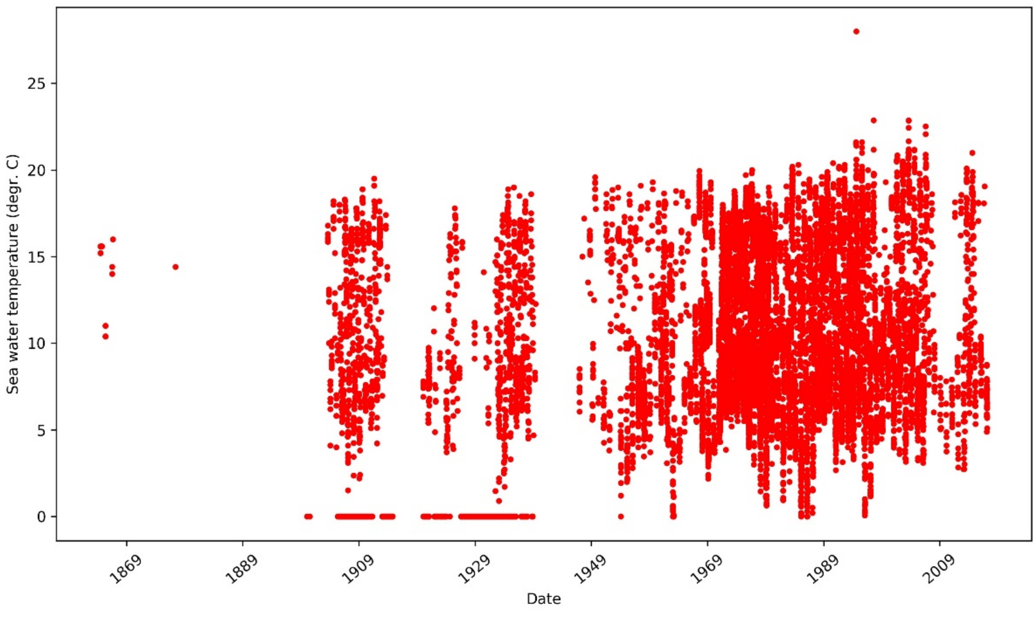

Figure 6: Time series of sea water temperature, WODB data set.

3. Methodology

3.1. Monthly means

Since the time series are not uniform and complete, and the temperature has a clear seasonal cycle, it is important to prepare a uniform time series, before analysing the long-term trends. Therefore, the monthly mean values were calculated first, to be further evaluated. This method was also used in Visser et al. (1996). The time series of the monthly means is then used to calculate the seasonal cycle and the long-term trend. When monthly mean data are not available, due to lack of data, the monthly mean is estimated from the seasonal cycle and the long-term trend (iteratively).

3.2. Long-term trend, seasonal cycle and residu

The time series of the monthly means will be divided in a long-term trend, a seasonal cycle and a residu (Visser et al., 1996). Since not for all months a value is available, this method is applied iteratively to fill in the gaps that coincide with the long-term trend and the seasonal cycle.

The seasonal cycle is calculated by averaging the monthly means for the different months. The long-term trend is calculated using a moving average:

$$R_N(Y(i)) = \frac{1}{N}\left[\frac{Y(i-N/2)+Y(i+N/2)}{2} + \sum_{j=I+1-N/2}^{i-1+N/2} Y(j)\right] \quad (1)$$

with R_N the moving average of time series $Y(i)$ over a period of N months. In Visser et al. (1996), it is proposed to use a moving average over 36 months for time series of 20 years or shorter, and over 60 months for longer time series. Using longer periods for the moving average clearly diminished the (short-term) variability. Using longer periods however also makes the resulting time series shorter. In this study, a moving average over 48 months, i.e., 4 years is used.

3.3. Linear regression

A different method to quantify a long-term trend is calculating the linear regression of the time series of the long-term trend of the monthly means (e.g., Press et al., 1989). The long-term trend of the monthly mean sea water temperature is then represented by a simple linear function:

$$H_i \approx a + b(t_i - t_{init}) = a + bT_i \quad (2)$$

with H_i monthly mean value (here sea water temperature), t_i time (in years) and t_{init} the reference year. The parameters a and b are the intercept and the slope of the linear regression, that can be calculated by minimizing the χ^2 function:

$$\chi^2(a,b) = \sum_{i=1}^{N}\left(\frac{H_i - a - bT_i}{\sigma_i}\right) \quad (3)$$

with σ_i the standard deviation on the measurement (H_i, T_i). Since these individual standard devations on the measurements are not know, it is supposed that these are constant and equal to a value σ . According to Press et al. (1989) following formulae can be derived for the intercept and the slope:

$$a = \frac{\sum_{i=1}^{N} T_i^2 \sum_{i=1}^{N} H_i - \sum_{i=1}^{N} T_i \sum_{i=1}^{N} T_i H_i}{N \sum_{i=1}^{N} T_i^2 - \left(\sum_{i=1}^{N} T_i \right)^2} \tag{4}$$

$$b = \frac{N \sum_{i=1}^{N} T_i H_i - \sum_{i=1}^{N} T_i \sum_{i=1}^{N} H_i}{N \sum_{i=1}^{N} T_i^2 - \left(\sum_{i=1}^{N} T_i \right)^2} \tag{5}$$

The variances on these results can be derived as (Press et al., 1989):

$$\sigma_a^{\ 2} = \sigma^2 \frac{\sum_{i=1}^{N} T_i^2}{N \sum_{i=1}^{N} T_i^2 - \left(\sum_{i=1}^{N} T_i \right)^2} \tag{6}$$

$$\sigma_b^{\ 2} = \sigma^2 \frac{N}{N \sum_{i=1}^{N} T_i^2 - \left(\sum_{i=1}^{N} T_i \right)^2} \tag{7}$$

Assuming the standard deviations σ are not known and assuming that the linear regression is a good approximation of the time series, the standard deviation on the measurements can be estimated as:

$$\sigma = \sqrt{\frac{\chi^2}{(N-2)}} \tag{8}$$

This allows to calculate the variances on the estimates for the intercept and the slope.

4. Results

4.1. 4DEMON

The 4Demon data set contains data between February 1968 and December 2014. In the original data set, monthly mean temperature can be calculated for 73.5% of the months. The result is shown in Figure 7.

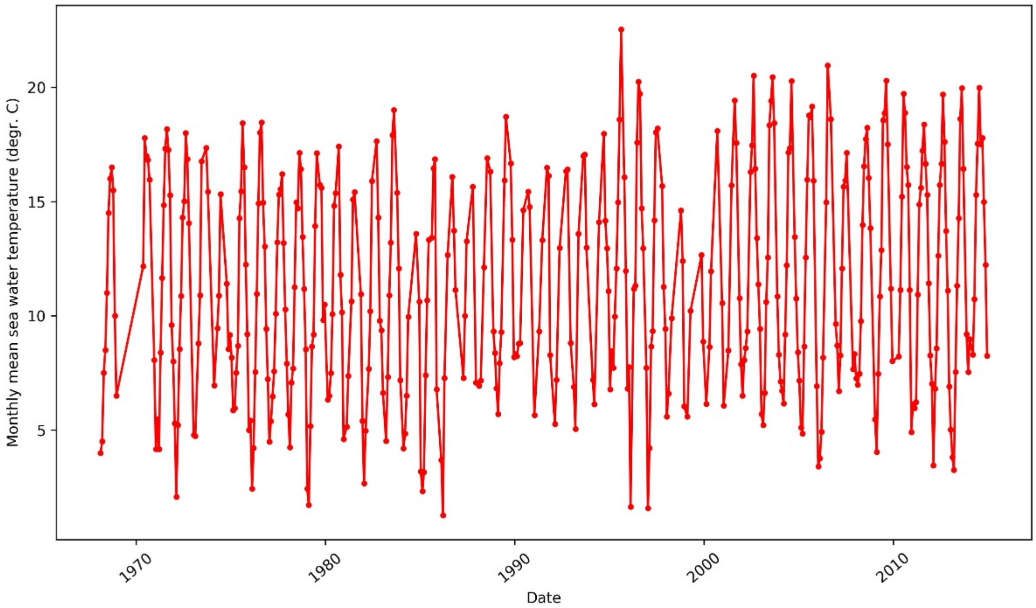

Figure 7: Monthly mean sea water temperature, derived from the 4Demon data set.

To fill in the gaps and to calculate the long-term trend and the seasonal cycle, the procedure of Visser et al. (1996) is applied. The gaps are filled iteratively, until no significant changes are found anymore in the calculation of the long-term trend and the seasonal cycle. The resulting time series is shown in Figure 8. Due to the moving average procedure, some data are lost in the beginning and the end of the time series. Gaps in the time series are however filled in, so that a consistent long-term trend and seasonal cycle can be calculated. The long-term trend, together with the final time series is shown in Figure 9, while the seasonal cycle is presented in Figure 10. In the long-term trend, a clear increase in sea water temperature is found between 1985 and 1990. The seasonal cycle is as expected with coldest sea water temperatures in January and February, and warmest sea water temperatures in August. The temperature over the year varies between almost -6°C to more than +6°C with respect to the long-term mean.

When a linear regression is calculated through the long-term trend, an increase of +0.046°C / year is found (see Table 1).

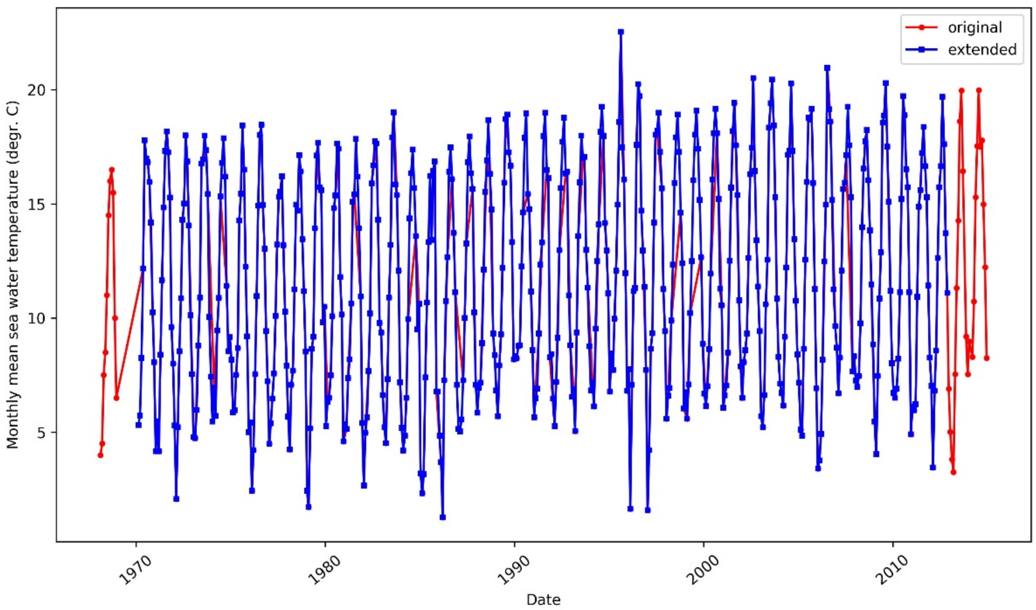

Figure 8: Extended time series of the monthly mean sea water temperature from the 4Demon data set.

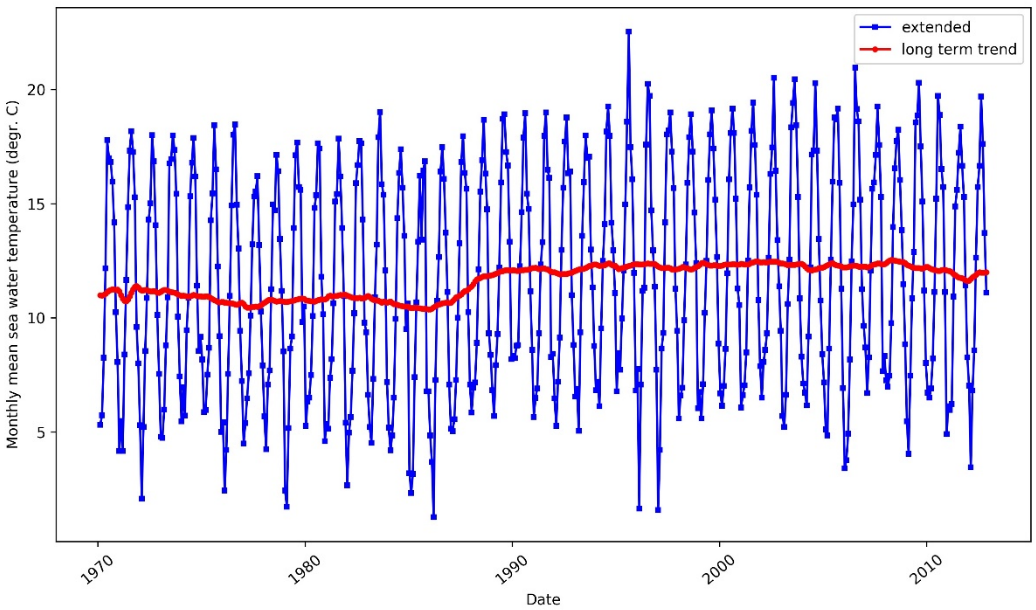

Figure 9: Extended time series of the monthly mean sea water temperature from the 4Demon data set, together with the (moving averaged) long-term trend.

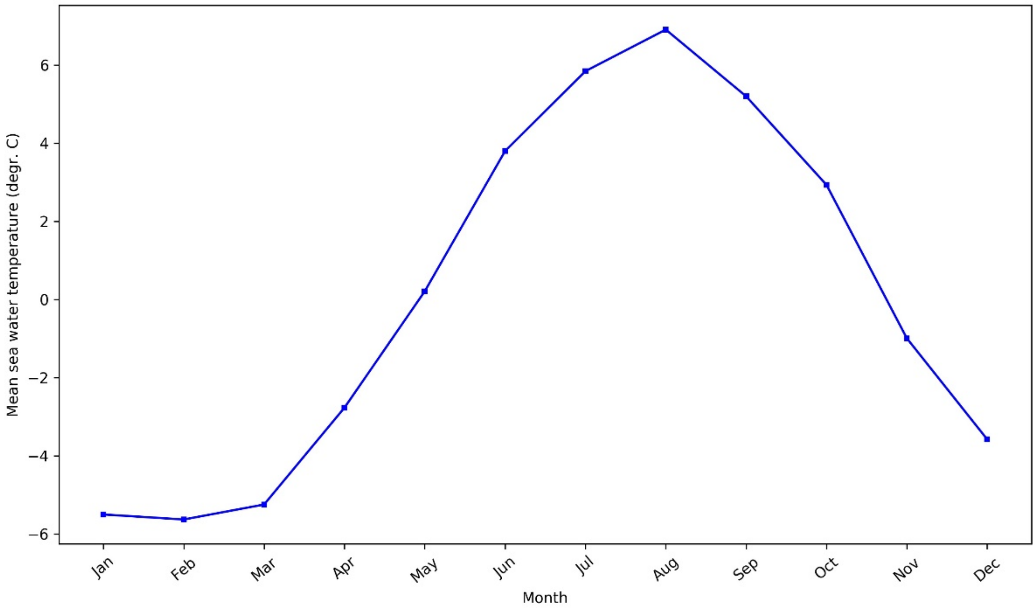

Figure 10: Seasonal cycle of the monthly mean sea water temperature from the 4Demon data set.

Table 1: Linear regression results of the long-term trend

Data set	Period	Mean temperature (°C)	Trend b (°C/year)	Standard deviation trend (°C/year)
4Demon	1970-2012	11.62	+0.0457	0.000008
ODAS	1986-2015	12.21	+0.0006	0.000048
WODB	1905-2015	11.42	+0.0072	0.000001
WODB	1949-2015	11.57	+0.0099	0.000001

4.2. ODAS

For the ODAS data set, the same procedure is followed. For 86.9 % of the months, data are available. In Figure 9 the monthly mean sea water temperatures, together with the long-term trend are shown. In this case the linear regression shows a smaller sea water temperature increase of only 0.0006 °C /year. The main reason for this could be the shorter time series, which only covers the period 1985 to 2017.

4.3. WODB

From the data set from the World Ocean Data Base, data are available from before 1900. However, since the data are too sparse in that period; the analysis is executed starting from 1903. A monthly mean temperature can be computed for only 62.8% of the months. For the remaining 37.2%, the monthly mean value is filled in by the analysis. The result is shown in Figure 12. The linear regression through the long-term trend shows an increase in sea water temperature of 0.007 °C/year (see Table 1).

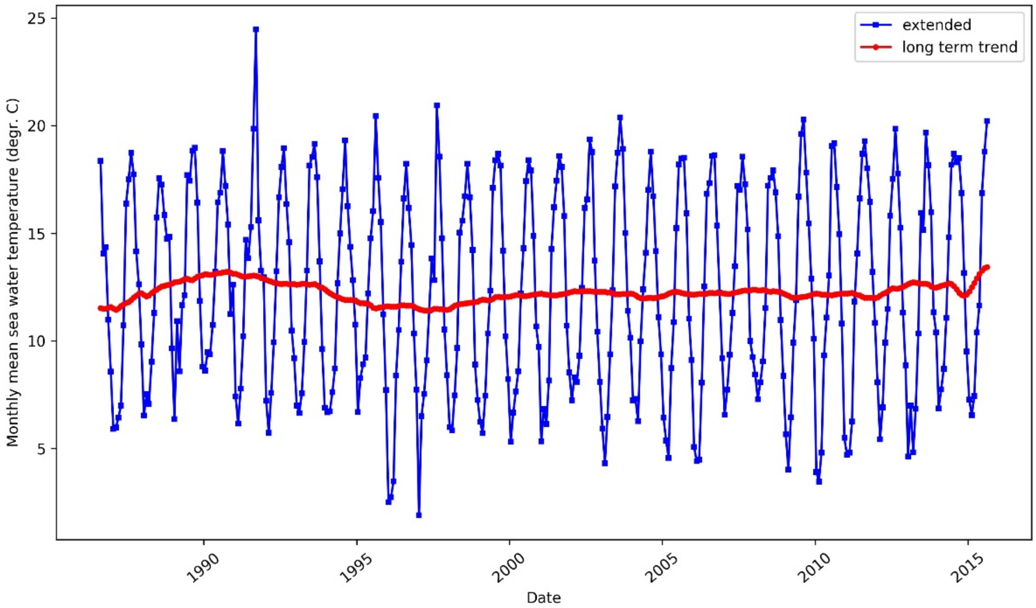

Figure 11: Extended time series of the monthly mean sea water temperature from the ODAS data set, together with the (moving averaged) long-term trend.

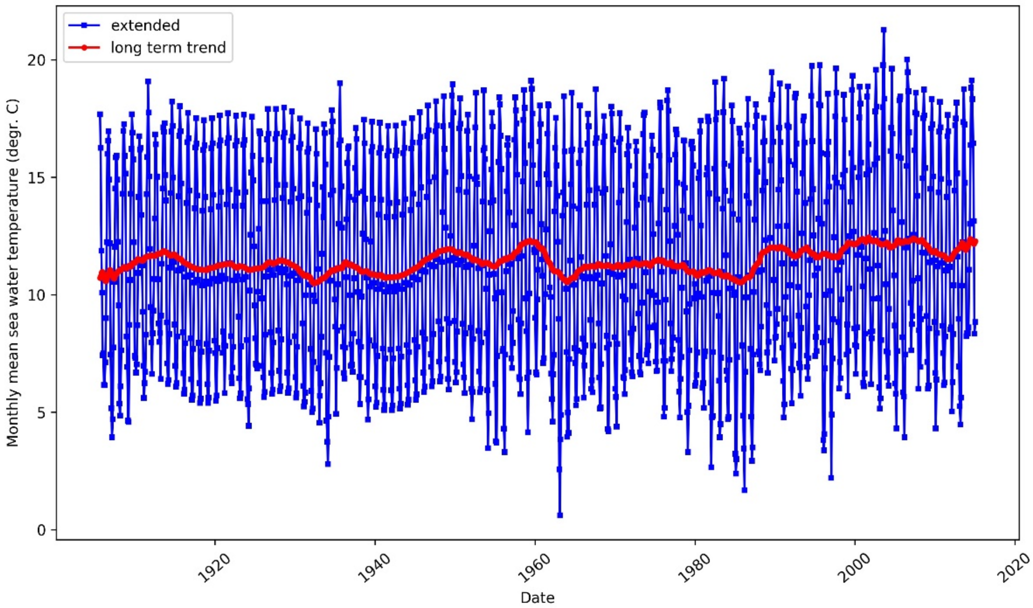

Figure 12: Extended time series of the monthly mean sea water temperature from the WODB data set, together with the (moving averaged) long-term trend.

Since in the time series, large data gaps for the periods 1913-1920 and 1939-1946 are present, a second analysis has been executed for the period 1947-2017. These results are shown in Figure 13. The linear regression shows an increase in sea water temperature of 0.0099 °C / year in this case.

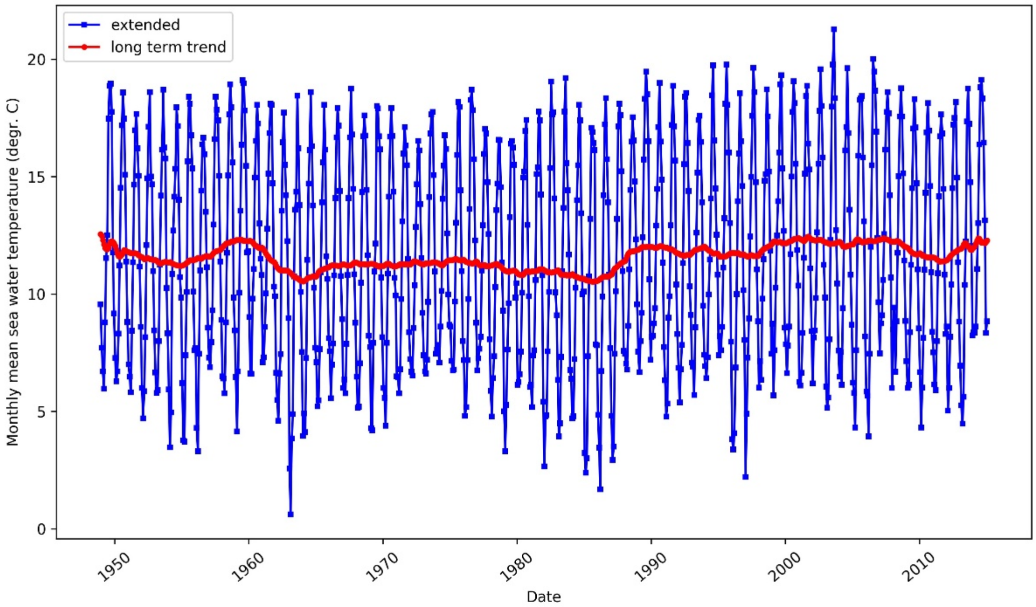

Figure 13: Extended time series of the monthly mean sea water temperature from the WODB data set, together with the (moving averaged) long-term trend.

5. Discussion

In the current report, three data sets were analysed. The long-term trends and the seasonal cycles were separated. In the Figure 14, the seasonal cycles are presented for the three data sets. As expected the results are quite similar, with the coldest sea water temperature in January to March and the warmest sea water temperature in August. One can see that the WODB data set, gives slightly warmer sea water temperature in January and slightly lower sea water temperature in Spring (April to June).

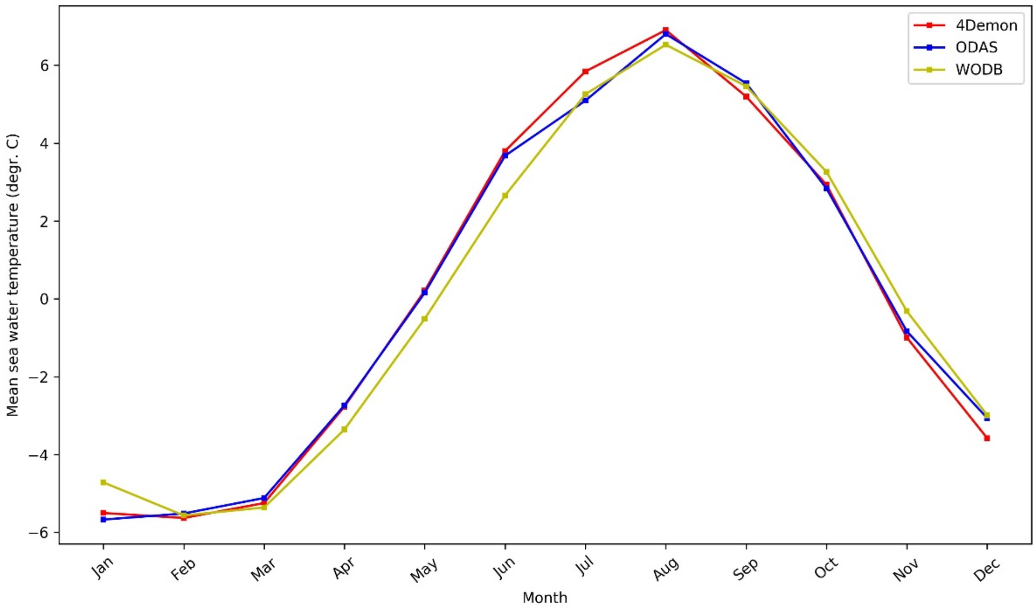

Figure 14: Seasonal cycles for the three data sets.

The long-term trends are shown in Figure 15. A natural variability with a period of 7 to 8 years could be noted. This could be related to the variability in the North Atlantic Ocillation Index (NAO), which was already noted by Sündermann et al. (1996). The clear increase in sea water temperature around 1990 to 1995 is visible in the three data sets. It can be noted that the 4Demon and the WODB data sets give similar results, except for the periods 1972 to 1979 where the 4Demon sea water temperature is lower, and the period 1995 to 1998, where the 4Demon sea water temperature is higher. The ODAS data set is much higher in the period 1985 to 1993, than the two other data sets. This could be due to the density of the data and possibly to the location of the data.

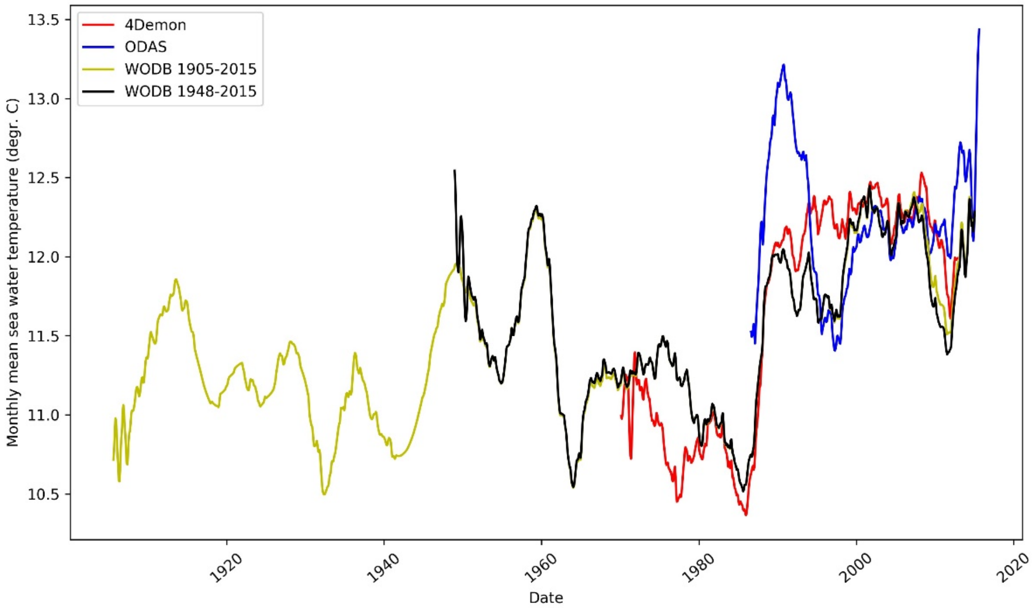

Figure 15: Long term trends cycles for the four data sets.

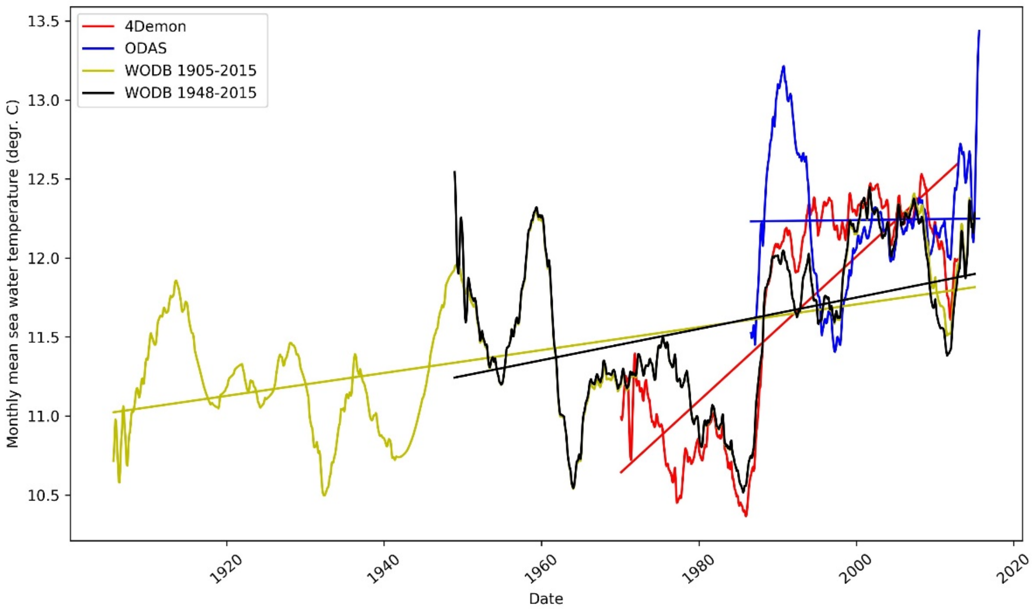

Figure 16: Linear regressions for the long term trends of the four data sets.

The linear regressions of the long term trend of the three data sets differ quite strongly. While the linear regression of the WODB is 0.008 °C /year for the long data set and 0.010°C / year for the data set 1948-2015, the 4Demon data set gives significantly higher increase of temperature, of 0.045°C / year, while the ODAS data sets gives much lower increase of temperature, of only 0.001°C / year. The fact that the 4Demon data set gives a higher increase in due to the lower temperature in the period 1972-1979 and higher temperature in the period 1995-1998, and due to the shorter time series. The value of 0.01°C /year of the WODB 1948-2015 data set, gives an increase of temperature of 1°C for 2100. This value is lower than the values found in literature, that expect an increase of 2°C to 4°C (Ponsar et al., 2007; Hulme et al., 2002). The values are also lower than the values found in Van den Eynde et al., 2008, where for the Southern Bight of the North Sea, a value of 0.034°C / year was found. In that report, only a period of 1972 to 2003 was used. The analysis stresses the importance of longer data sets to get reliable data and indicate the natural variability of the sea water temperature.

One of the possible explanations for the differences could be the fact that the positions of the measurements are not spatially uniform distributed over the time series. This was tested for the WODB 1948-1998 data set. The data were split in two time series with nearshore measurements and offshore measurements, see Figure 17. The long-term trend for the full data and for the offshore and nearshore data were calculated separately and are presented in Figure 18. The differences between the long-term trends are clear, but the differences are however limited and are not a good explanation of the differences between the long-term trend of the different data sets. Remark that at some moments, the offshore long-term temperature is higher than the nearshore long-term temperature, which is somewhat unexpected. Remark also that the high long-term temperature in the beginning of the time series is probably due to the scarcity of the data in the beginning, the single data points get too much value, during the filling of the gaps to get a uniform data set. Unfortunately, this cannot be avoided.

Three data sets were evaluated from different sources. Although there are clearly some similarities in the results the different (linear) increase in average sea water temperature is however remarkable. This is probably due to the fact that the data are not uniformly distributed, both spatially and in time, due to (unavoidable) measurement errors and due to the too short time series. The increase in sea water temperature is clearly shown, but much uncertainty still exists on the exact quantification of this increase.

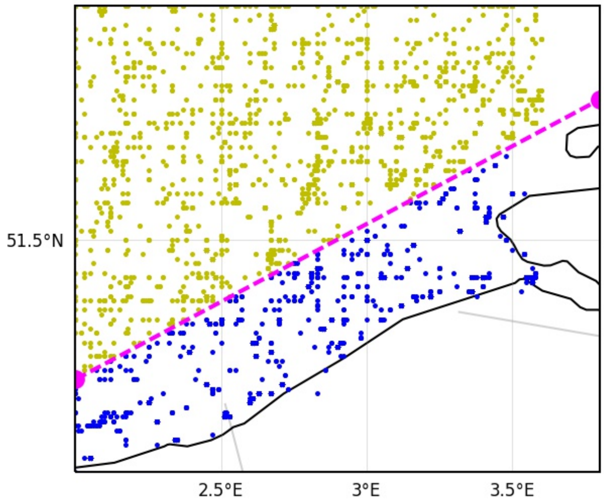

Figure 17: Split of the data between nearshore data (blue) and offshore data (yellow) for the WODB 1948-2015 data set.

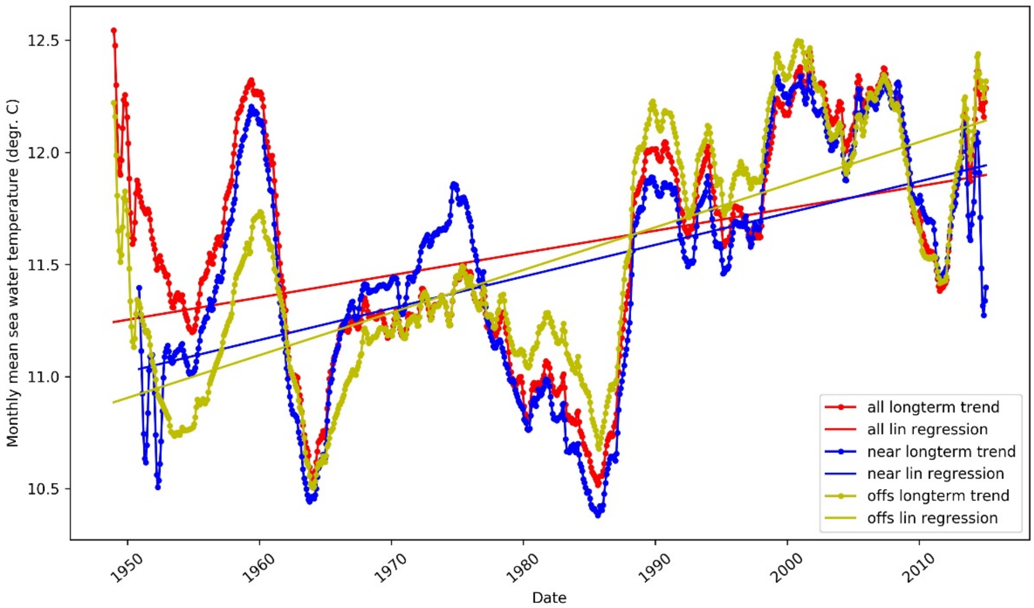

Figure 18: Long-term trend for the WODB 1948-2015 data set: full data set (red), nearshore data set (blue) and offshore data set (yellow).

6. Acknowledgements

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