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

Revisiting the trend analysis of relative mean sea level rise at Oostende (southern North Sea – Belgian coast)

José Ozer, Stéphanie Ponsar & Dries Van den Eynde

CREST/X/JO/201906/EN/TR02

Prepared for CREST project

RBINS-OD Nature
100 Gulledelle
B–1200 Brussels
Belgium

Table of Contents

1. Introduction

The purpose of this report is to present the work done at OD Nature within the framework of the CREST project, dealing with the investigation of trends in relative mean sea level at Oostende. Such an investigation has already been done in the framework of the CLIMAR project (Van den Eynde et al., 2011; Ozer et al., 2008), amongst others (Van Cauwenberghe, 1993; 1995; 1999). But this occurred more ten years ago, it appears therefore of interest to update the study using the most recent data.

The report is organized as follows. The data sets used within the current investigation are presented in the next section. For reasons given in that section, it was finally decided to work only with the data made available by the Permanent Service of Mean Sea Level (PSMSL). These data cover the period 1937-2016. Up to five models have been fitted to the data. They are presented and discussed in the third section. Section 4 is devoted to the presentation and discussion of the results of these models. A summary is given at the end.

2. Data

PSMSL offers two time series of monthly values of Mean Sea Level (MSL) at the station Oostende (Southern North Sea, Belgian coast). One time series is referred to as Revised Local Reference (RLR) data while the other is referred to as metric data. The second file corresponds to the data as they are transmitted by the local authorities (*i.e.*, the Flemish Hydrography in this case) while the first one has been reworked by PSMSL to get values referred to the same reference level. Indeed, for the metric data, two reference levels have been used: the so-call z-level was used prior to 1981 and the Tweede Algemene Waterpassing (TAW) is the national reference level in Belgium since 1981. Knowing that the z-level lies 0.108 m below TAW, it is a fairly easy task to get all metric data referred with respect to TAW. It is with these data that we decided to work.

Yearly mean values were derived from the monthly mean values. Twelve monthly mean data must be available to compute the yearly mean. Gaps in the time series in the monthly mean value were found, in particular during the period 1937- 1950. The period 1951 to 2016 is complete however. In Ozer et al. (2008), efforts were made to merge different data sets (PSMSL data set; hourly time series and HW-LW time series) to get the as long as possible time series of yearly MSL values. Thanks to those efforts, it was possible to go back in time up to 1927 (but still with gaps between 1927 and 1950). In the present study, only PSMSL data are used to ensure the homogeneity of the data set.

Data are presented on Figure 1. The long-term mean value is equal to 2.278 m. The presence of a trend in the data is quite evident. It is noticeable, for instance, that there is no value above 2.30 m up to 1980 while there is no more value below 2.30 m since 1998. For the period 1951-2016, the long-term mean is equal to 2.282 m (already 4 mm above the value for the whole period).

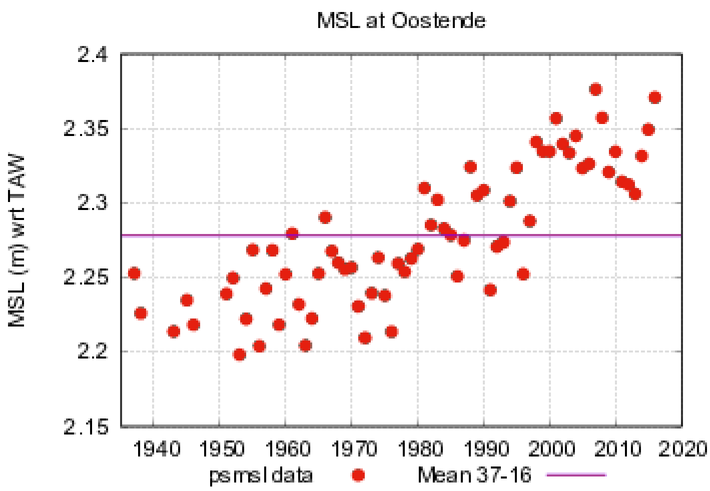

Figure 1: yearly mean sea level at Oostende for the period 1937 – 2016. All data are referred with respect to TAW. The horizontal line indicates the long term mean value which is equal to 2.278 m.

3. Models

Four models are fitted to the data. They are discussed hereafter.

3.1. *Model A: constant trend*

The first model is a simple linear model that reads:

$$\hat{y} = a + b(t - t_a)$$

where a is the intercept, b the slope of the regression line, t denotes time and t_a is the time start of the time series. The slope and the intercept are computed by a conventional least squared fit method that minimizes the sum of the squared errors *SSE*:

$$SSE = \sum_{i=1}^{N} (\hat{y}_i - y_i)^2$$

The goodness of fit of the model is computed according to

$$s = \sqrt{\frac{SSE}{n - m}}$$

where n is the number of data and m the number of estimated parameters (m=2 in this case).

3.2. *Model B: step trend without jump*

In model B, it is assumed that the slope of the regression line can change somewhere between t_a and t_b where t_b is the time end. If we denote by t_c the time at which the slope changes, the model reads:

$$\hat{y} = a_1 + b_1(t - t_a) \quad for\ t_a \leq t \leq t_c$$

$$\hat{y} = a_2 + b_2(t - t_c) \quad for\ t_c \leq t \leq t_b$$

$$a_2 = a_1 + b_1(t_c - t_a)$$

Where $t_c \in [t_a + 4, t_b - 4]$. For $t \in [t_a, t_c]$, a conventional least squared fit approach is used to determine the value of a_1 and b_1. For $t \in [t_c, t_b]$, only b_2 is used to minimize the sum of squared errors. The optimum is considered as being reached when the goodness of fit is minimum (computed with m=4).

Remark that this piecewise linear model, also referred to as the inflexion method, is also the approach followed by Metrevelli *et al.* (1980). In their investigation, these authors however decided to fix the inflexion point, *tc, a priori*. It was set at the middle of the time period covered by the data. Here, we decided to consider tc, as a model parameter and a least squared fit method is used to determine the various model parameters. The "optimal" model set up is reached when the Standard Error is minimum.

3.3. *Model C; step trend with jump*

As in model B, it is assumed that the slope of the regression line can change somewhere but, moreover, a jump between both regression lines may exists. The model reads:

$$\hat{y}_1 = a_1 + b_1(t - t_a)\ for\ t_a \leq t < t_c$$

$$\hat{y}_2 = a_2 + b_2(t - t_a)\ for\ t_c \leq t \leq t_b$$

For each value of $t_c \in [t_a + 1, t_b - 1]$, a regression line is fitted to the data between t_a and t_c as well as to the data between (t_c+1) and t_b. Note that on both sides of t_c a regression line is fitted to the data if and only if the test on the linear correlation coefficient r (also called the Pearson's r) indicates that the null hypothesis of zero correlation can be disproved (p value less than 0.01). Otherwise the data are simply fitted by a constant value equal to their arithmetical mean. The optimum model is reached when the goodness of fit is minimum. In this model, the number of fitted parameters, m, is varying between 3 and 5.

3.4. *Model D: 2nd order polynomial*

The fourth model fitted to the data is a second order polynomial. The model reads:

$$\hat{y} = a_0 + a_1(t - t_a) + a_2(t - t_a)^2$$

In this case, it is assumed that a constant acceleration of the trend occurred during the whole period of interest. The same model was applied by Woodworth (1990) to long records from European tide gauges. In this study, no evidence was found for MSL accelerations significantly different from zero over the period 1870-1986 although non-zero accelerations were observed at individual stations.

3.5. *Model E: 3rd order polynomial*

The model reads:

$$\hat{y} = a_0 + a_1(t - t_a) + a_2(t - t_a)^2 + a_3(t - t_a)^3$$

4. Results

The five models presented in the previous section have been applied to two time series. The first one contains all the data (see Figure 1). It starts in 1937 and stops in 2016. They are gaps in the data up to 1950. We will refer to this time series in what follows as TS-3716. The second time series starts in 1951 and ends in 2016. It has no gap. It will be referred to as TS-5116.

4.1. *Model A: constant trend*

For both time series, the statistical test on the linear regression coefficient *r* indicates that the null hypothesis of zero correlation between MSL and time can be disproved with a high level of confidence. For sure, MSL is increasing as time passes. The slope for TS-3716 is marginally greater than that obtained by Ozer et al. (2008) for the time series 1937-2006 (TS-3706) (1.69 mm/yr) and is close to the value of 1.7 mm/yr that was estimated by the IPCC (Bindoff et al., 2007) for the global average sea level rise during the 20th century. That obtained for TS-5116 is clearly greater indicating that the rate of change of MSL may have been greater in the last decades than it was in the past. The results of the fitting are shown in Figure 2.

Table 1: Results of Model A: straight line, for the two time series

	TS-3716	TS-5116
Intercept *a*	2.201 m	2.219 m
Slope *b*	1.76 ± 0.29 mm/yr	1.94 ± 0.34 mm/yr
Goodness of fit *s*	0.0264 m	0.0261 m
Correlation coefficient *r*	0.92	0.82
Numbers of freedom	69	64
p-value	$1.6\ 10^{-18}$	$2.8\ 10^{-17}$

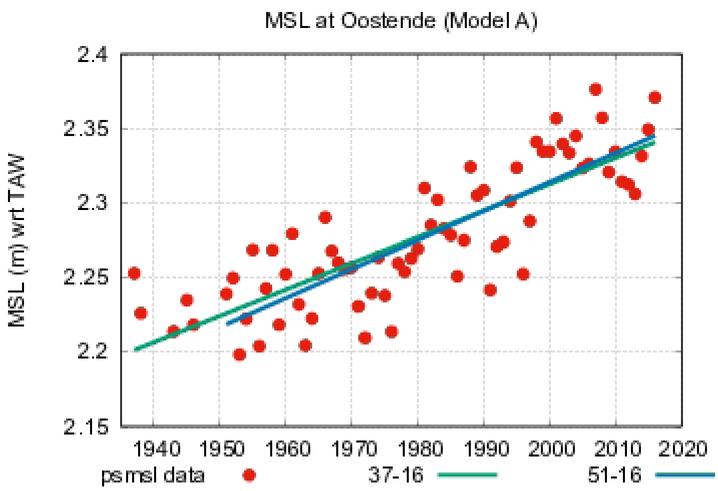

Figure 2: Model A, fitting a straight regression line.

Previous estimates of the trend of MLS at Oostende are listed in Table 2. Once again, our new estimates are above all the previous ones, as already shown in Ozer et al.

(2008). These seems to indicate that the trend at Oostende might increase during the last decades. This is in agreement as well with studies that evidence a recent enhancement of coastal sea level rise (e.g., Holgate and Woodworth, 2004; Church and White, 2006).

Table 2: Trends in MSL at Oostende in different studies. VC= Van Cauwenberghe.

# of years	Period	Slope (mm/yr[1])	Standard error (mm)	Studies
79	1835 - 1991	1.0	24.5	VC, 1993
65	1927 - 1991	1.4	25.3	VC, 1993
82	1835 - 1994	1.00	-	VC, 1993
68	1927 - 1994	1.42	-	VC, 1993
86	1835 - 1998	1.02	-	VC, 1993
72	1927 - 1998	1.44	-	VC, 1993
58	1937 - 2003	1.64 +/- 0.2	27.0	PSMSL, 2005
74	1927 - 2006	1.69		Ozer et al., 2008
65	1937 - 2006	1.72		Ozer et al., 2008

4.2. *Model B: step trend without jump*

For both time series, the time of change in the trend occurs in 1972 and the slope of the regression line for the period 1972-2016 is almost the same (~2.4 mm/yr). Moreover, in both cases, it seems that the null hypothesis of zero correlation between MSL and time can be disproved with a high level of confidence for that period of time. However, this is far from being the case for the first part of both time series. There, the linear regression coefficient is pretty low and its p value is rather large. Both render the choice of this model questionable. The fit is shown in Figure 3. The variation of the Goodness of Fit as a function of the change in trend in shown in Figure 4 with a minimum for both time series in 1972.

Table 3: Results of Model B: step trend (1), for the two time series

	TS-3716	TS-5116
Time t_c	1972	1972
Intercept a_1	2.227 m	2.235 m
Slope b_1	0.60 mm/yr	0,71 mm/yr
Correlation coefficient r_1	0.24	0.177
Numbers of freedom	25	20
p-value$_1$	0.23	0.43
Intercept a_2	2.248 m	2.250 m
Slope b_2	2.39 mm/yr	2.34 mm/yr
Correlation coefficient r_2	0.78	0.78
Numbers of freedom	42	42
p-value$_2$	$5\ 10^{-10}$	$5\ 10^{-10}$
Goodness of fit s	0.0249 m	0.0255 m

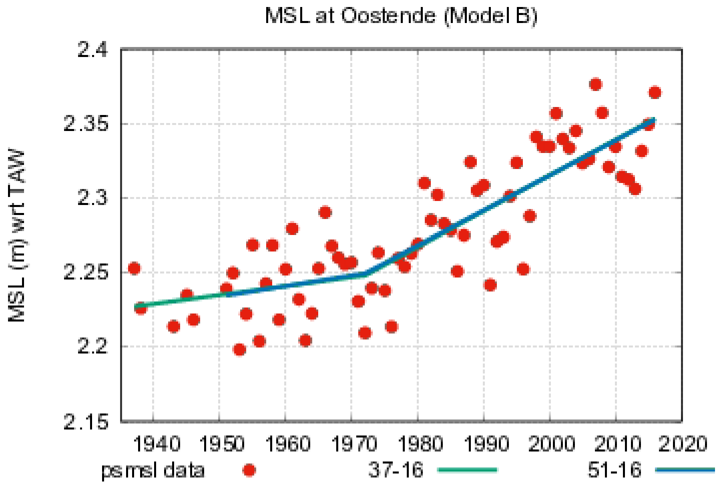

Figure 3: Model B, fitting a broken line.

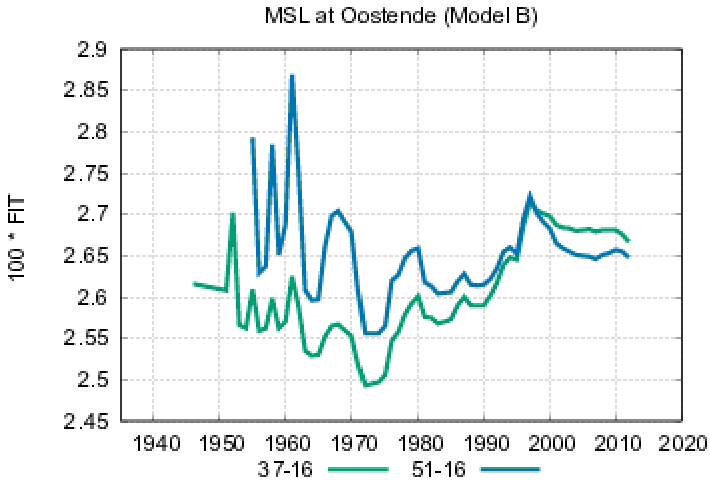

Figure 4: Goodness of fit for the model B, fitting a broken line to the data, as a function of the time of slope changing. Minimum at 1972.

To better understand results of model B, we can consider how the contributions to the total sum of squared errors evolve as a function of the position of t_c between t_a and t_b. Results for TS-3716 are presented on Figure 5. For the time interval $[t_a{:}t_c]$, increasing the length of the time series contributes to increase the value of r (not shown here) as well as the value of the sum of the squared errors which will be referred to as SSE_a in what follows. The inverse occurs for the time interval $[t_c{:}t_b]$. The sum of squared errors on that time interval will be referred to as SSE_b. In the beginning, SSE_b decreases more rapidly than SSE_a increases and in a less regular fashion. The total SSE tends to decrease as well. The particular behavior of SSE_b could be due to the fact that only the slope of the regression line is used to minimize it. The 1972 minimum in SSE occurs just after a relative "large" decrease in SSE_b not compensated by a comparable increase in SSE_a. After 1972, SSE_b remains constant or slightly increases during almost 10 years. During the same period of time, SSE_a

continues to increase.

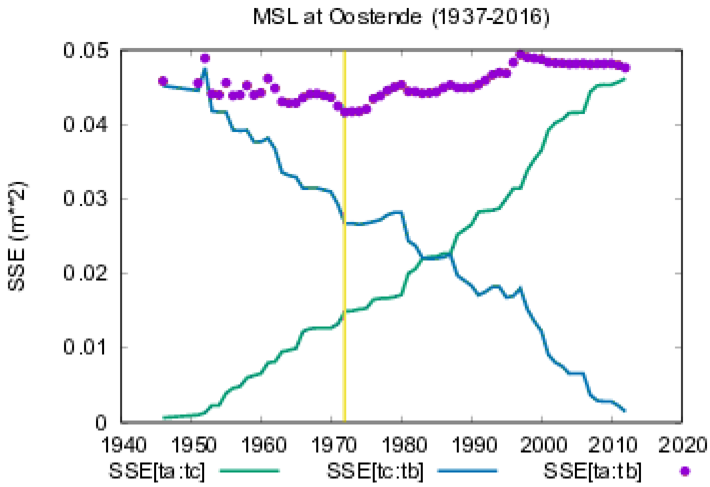

Figure 5: Model B, fitting a broken line to the data. The green line shows how the SSE on the time interval [t_a:t_c] evolves with t_c varying between t_a and t_b. The blue line does the same but now for the time interval [t_c:t_b]. The mauve circles show the total SSE. The vertical yellow line indicates the year 1972.

Remark that in Ozer et al. (2008) an optimal time of change was found in 1992, while also another local minimum was found in 1976. The adding of the new data and the removal of older data, see above, apparently made the time of change in the trend much earlier, resulting in a much lower sea level rise over the second period. Remark that due to the removal of older data, also the sea level rise in the first perid became higher. While in Ozer et al. (2008) a sea level rise for the period 1927-1992 was found of 1.41 mm/yr, and 1992-2006 of 4.41 mm/yr, these values are lower now. The latter value agreed well with the estimate of Holgate and Woodworth (2004) of 4.0 mm/yr for the global average rate over the period 1993-2002. Part of the explanation is certainly due to the fact the time of change in the trends was earlier in 1972 in this case. Overall, despite of the model being questionable, it seems to indicate again an increase in sea level rise over the last decades.

4.3. *Model C: step trend with jump*

Compared to model B, model C also searches for a modification in the trend but it does not impose the choice of the linear regression on both sides of the break if any. It converges, for both time series, towards a break in 1998 with a regression line for the first part of the times series and a constant value for the second part. The fit is shown in Figure 6.

Table 4: Results of Model B: step trend with jump for the two time series

	TS-3716	TS-5116
Time t_c	1998	1998
Intercept a_1	2.215 m	2.227 m
Slope b_1	1.22 ±0.43 mm/year	1.40 ± 0.55 mm/yr
Intercept a_2	2.337 m	2.337 m
Slope b_2	0 mm/yr	0 mm/yr
Correlation coefficient r_2	0.62	0.60
Numbers of freedom	50	45
p-value$_2$	8.0 10^{-7}	6.9 10^{-6}
Goodness of fit s	0.0237m	0.0240 m

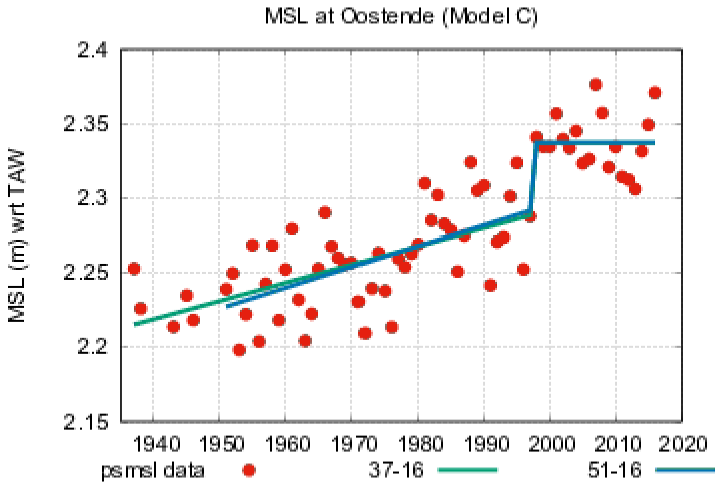

Figure 6: Model C, fitting a broken line with jump to the data.

The variation of the Goodness of Fit as a function of the change in trend in shown in Figure 7 with a minimum for both time series in 1998. The ay the model converges towards this minimum value for the goodness of fit is presented on Figure 7. The passage by the minimum is rather abrupt.

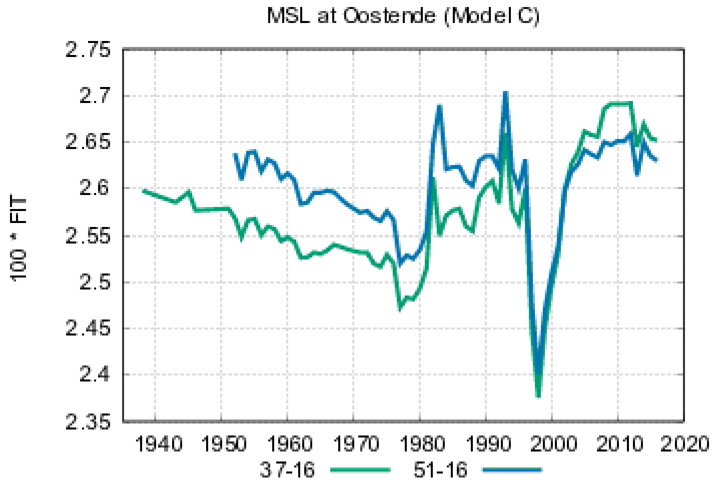

Figure 7: Goodness of fit for model C, fitting a broken with jump to the data, as a function of the time at which the line is broken.

As for model B, considering how the contributions to the total sum of squares errors evolve as a function of the position of t_c between t_a and t_b helps understanding the minimum in the goodness of fit. Once again, the latter occurs due to a large decrease in SSE_b not compensated by a similar increase in SSE_a. The former took place just when the model replaces the straight line for the interval $[t_c{:}t_b]$ by a constant value, which occurs in 1998.

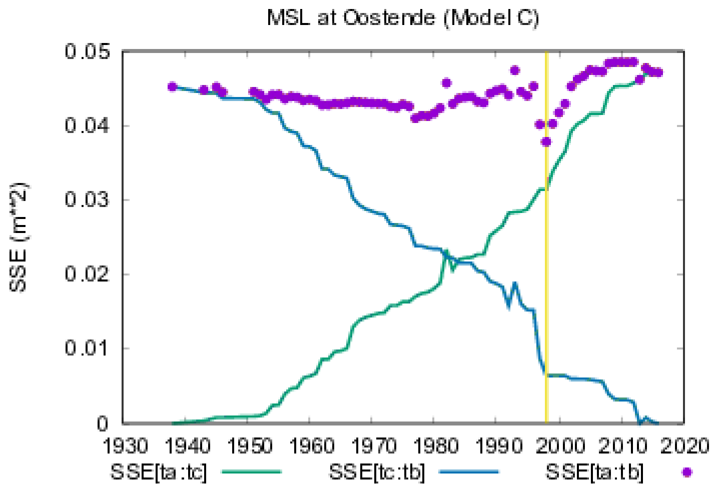

Figure 8: Model C, fitting a broken line with jump. The green line shows how the SSE on the time interval $[t_a{:}t_c]$ evolves with t_c varying between t_a and t_b. The blue line does the same but now for the time interval $[t_c{:}t_b]$. The mauve circles show the total SSE. The vertical yellow line indicates 1998.

Although this model gives the best Goodness of Fit, it is on the other hand quite unrealistic, due to the jump in sea level rise in 1998.

4.4. Model D: 2nd order polynomial

With model D, the slope of the polynomial is always positive (see Figure 9 and

Figure 10). For TS-3716, it starts at 0.2 mm/y in 1937 and ends at 3.12 mm/y in 2016. For TS-5116, it starts at 0.99 mm/y in 1951 and ends at 2.9 mm/y in 2016.

Remark that model D fits better with TS-3716 than with TS-5116 (see Table 5).

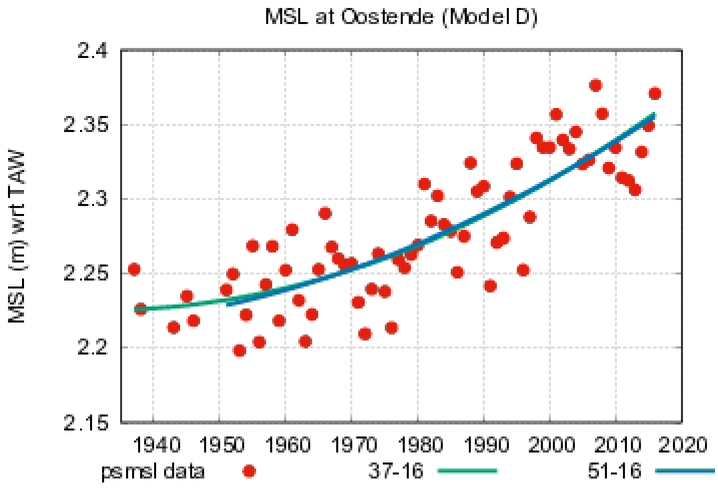

Figure 9: Model D, fitting a 2nd order polynomial to the data.

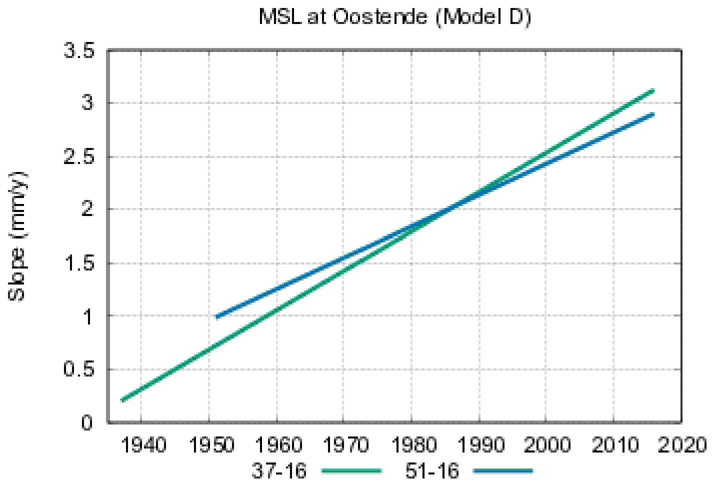

Figure 10: Variation of the slope for model D, fitting a 2nd order polynomial to the data.

Table 5: Results of Model D: 2nd order polynomial: straight line, for the two time series

	TS-3716	TS-5116
a_0	2.225 m	2.229 m
a_1	0.204 mm/yr	0.989 mm/yr
a_2	1.85 10^{-2} mm/yr^2	1.47 10^{-2} mm/yr^2
Goodness of fit	0.0252 m	0.0285 m

Remark that in this case the acceleration of the trend is higher than the value obtained by Church and White (2006), where they found an acceleration of 1.3 10^{-2} mm/yr^2.

4.5. *Model E: 3th order polynomial*

The results for model E, fitting the data with a 3th order polynomial are given in . The fit is shown in Figure 11. The variation of the slope is presented in Figure 12.In this case the sea level rise slope is negative in the years before 1950 or 1955 for the TS-3716 and TS-5116 time series and is decreasing again after a peak of around 2.5 mm/year around 1990.

Table 6: Results of Model D: 2nd order polynomial: straight line, for the two time series

	TS-3716	TS-5116
a_0	2.240 m	2.240 m
a_1	-1.61 mm/yr	-1.19 mm/yr
a_2	7.31 10^{-2} mm/yr^2	9.91 10^{-2} mm/yr^2
a_3	-4.48 10^{-4} mm/yr^3	-8.66 10^{-4} mm/yr^3
Goodness of fit	0.0250 m	0.0256 m

Remark that in Ozer et al. (2008) the variation of the slope was different that the results in this case, with a slope which was positive over the entire period and with higher slopes in the year between 1920 to 1940, lower slopes between 1940 and 1980 and increasing slops since then, with a slope higher than 5 mm/yr in 2006. The adding of the data from 2007-2016 and probably as important, removal of the reconstructed data before 1937, are clearly important for these results. The results could also be influenced by the nodal period of about 18 years.

Although this model might be interesting from a statistical point of view, the results are therefore not realistic. Remark also that the Goodness of Fit is becoming larger again than for the models A to C.

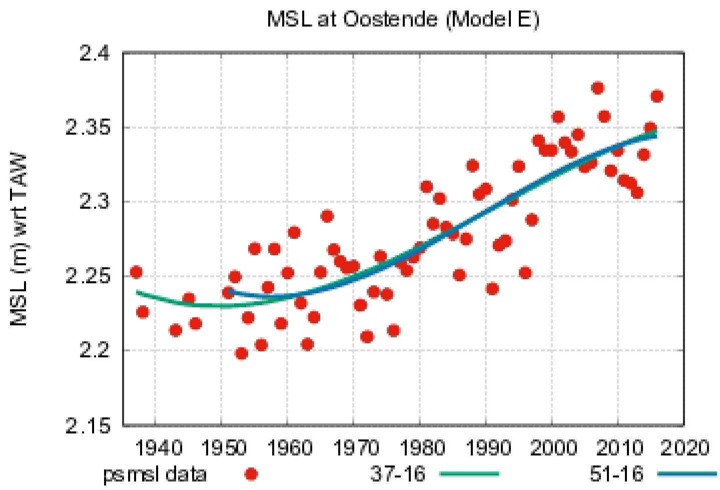

Figure 11: Model E, fitting a 3rd order polynomial to the data.

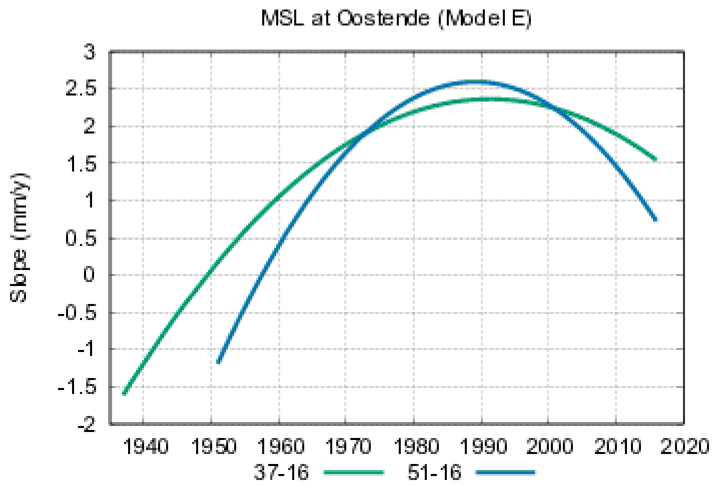

Figure 12: Variation of the slope for model E, fitting a 3rd order polynomial to the data.

5. Conclusions

To analyze how mean sea level has evolved during the last 80 years along the Belgian coast, a time series of yearly mean values covering the period 1936-2016 has been built with the data from the PSMSL, available at the station Oostende. Five different models have been fitted to these data.

The MSL level rise over the whole period is estimated at 1.72 mm/yr. This is the largest sea level rise ever reported for this station. This rise is in fairly good agreement with the global average sea level rise estimated for the 20th century.

Models in which the mean sea level rise is allowed to vary in time generally fit better with the data than the simple linear regression model. When the data are fitted with a broken line, the model indicates a change in the sea level rise around 1972, with a clear higher sea level rise during the second period, than during the first period. This also agrees with the rsults when the model is fitted with a 2^{nd} degree polynomial, where also an increase in sea level rise during the last decades is shown. This might agree with other results found in literature.

The model with two lines but with a shift in sea level might give statistically the best results, but are unrealistic due to this shift in sea level. Also the model with a 3th order polynomial doesn't give realistic results in this case.

Overall, one could conclude that over the period, a sea level rise of 1.72 mm/yr is observed and that there are some indications that the sea level rise is increasing. When taking the entire time series into account, the sea level rise over the period 1972-2016 seems to be around 2.39 mm/yr, which is a clear increase. The nodal cycle of about 18 years is however not included in the analysis and could influence the results. Therefore, the results still should be treated with caution.

6. Acknowledgements

Agency for Marine and Coastal Services (MDK – Maritieme Dienstverlening en Kust) are acknowledged for making tidal data available for this research.

7. References

Bindoff, N.L., J. Willebrand, V. Artale, A. Cazenave, J. Gregory, S. Gulev, K.Hanawa, C. Le Quéré, S. Levitu, Y. Nojiri, C.K. Shum, L.D. Talley and A. Unnikrishnan, 2007: Observations: Oceanic Climate Change and Sea Level. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, eds). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Church, J.A., and N.J. White, 2006. A 20th century acceleration in global sea-level rise. Geophysical Research Letters, 33, L01602, doi:10.1029/2005GL024826.

Holgate, S.J., and P.L. Woodworth, 2004. Evidence for enhanced coastal sea level rise during the 1990's. Geophysical Research Letters, 31, L07305, doi:10.1029/2004GL019626.

Metreveli, G.S., I.G. Plotk'na and N.K. Kuchuashvili, 1985. Calculating rates of secular fluctuations of sea level and land surface according to level series. Soviet Meteorolofy and Hydrology, 2, 68-72.

Ozer, J., D. Van den Eynde and S. Ponsar, 2008. Trend analysis of the relative mean sea level at Oostende (Southern North Sea – Belgian coast). Report CLIMAR/X/JO/200807/EN/TR3. Prepared for the Belgian Science Policy, Project CLIMAR, contract SD/NS/01A. Management Unit of the North Sea Mathamatical Models, Brussels, 14 pp.

Permanent Service for Mean Sea Level (PSMSL), 2005. Table of MSL Secular Trends derived from PSMSL RLR Data. Last update 3 August 2005. (http://www.pol.ac.uk/ psmsl/datainfo/rlr.trends).

Van Cauwenberghe, C., 1993. Synopis of the tidal observations along the Belgian Coast – Conclusions with respect to the high water, the mean sea and the low water levels. Report nr. 37 bis of the Hydrografische Dienst der Kust.

Van Cauwenberge, C., 1995. Relative sea level rise: further analyses and conclusions with respect to the high water, the mean sea and the low water levels along the Belgian coast. Report nr 37ter of the Hydrografische Dienst der Kust.

Van Cauwenberghe, C., 1999. Relative sea level rise along the Belgian coast: analyses and conclusions with respect to the high water, the mean sea and the low water levels. Report nr 46 of the Hydrografische Dients der Kust.

Van den Eynde, D., R. De Sutter, L. De Smet, F. Francken, J. Haelters, F. Maes, E. Malfait, J. Ozer, H. Polet, S. Ponsar, J. Reyns, K. Van der Biest, E. Vanderperren, T. Verwaest, A. Volckaert and M. Willekens, 2011. Evaluation of climate change impacts and adaptation responses for marine activities: CLIMAR. Final Report. Belgian Science Policy, Research Programme Science for a Sustainable Development, Brussels, 114 pp.

Woodworth, P.L., 1990. A search for accelerations in records of European mean sea level. International Journal of Climatology, 10, 129-143.

8. Appendix I

Yearly mean sea level values used in the present study.

1937	2.253
1938	2.226
1943	2.214
1945	2.235
1946	2.218
1951	2.239
1952	2.250
1953	2.198
1954	2.222
1955	2.269
1956	2.204
1957	2.243
1958	2.268
1959	2.218
1960	2.252
1961	2.279
1962	2.232
1963	2.204
1964	2.223
1965	2.253
1966	2.290
1967	2.268
1968	2.260
1969	2.256
1970	2.257
1971	2.231
1972	2.210
1973	2.240
1974	2.263
1975	2.238
1976	2.214
1977	2.260
1978	2.254
1979	2.263
1980	2.269
1981	2.310

1982	2.285
1983	2.302
1984	2.283
1985	2.278
1986	2.251
1987	2.275
1988	2.324
1989	2.305
1990	2.308
1991	2.242
1992	2.271
1993	2.274
1994	2.301
1995	2.324
1996	2.252
1997	2.288
1998	2.341
1999	2.335
2000	2.335
2001	2.357
2002	2.340
2003	2.333
2004	2.345
2005	2.323
2006	2.326
2007	2.376
2008	2.357
2009	2.321
2010	2.334
2011	2.314
2012	2.312
2013	2.306
2014	2.332
2015	2.349
2016	2.371

COLOPHON

This report was issued by Operational Directorate Natural Environment in June 2019.

The reference code is CREST/X/JO/201906/EN/TR2.

Status	☐ draft
	☒ final version
	☐ revised version of document
	☐ confidential
Available in	☒ English
	☐ Dutch
	☐ French

If you have any questions or wish to receive additional copies of this document, please send an e-mail to *Dries.VandenEynde@mumm.ac.be*, quoting the reference, or write to:

Royal Belgian Institute of Natural Sciences
Operational Directorate Natural Environment
100 Gulledelle
B–1200 Brussels
Belgium
Phone: +32 2 773 2111
Fax: +32 2 770 6972
http://www.mumm.ac.be/

Royal Belgian Institute of Natural Sciences
Operational Directorate Natural Environment
Suspended Matter and Seabed Monitoring and Modelling Group

The typefaces used in this document are Gudrun Zapf-von Hesse's *Carmina Medium* at 10/14 for body text, and Frederic Goudy's *Goudy Sans Medium* for headings and captions.