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Analyses of Variations in Water Level Time-Series at the Southern Baltic Sea Coastline

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Abstract

The results of an investigation intended to provide information about the trends of the Mean Water Levels along the German Southern Baltic Sea coastline in comparison to the German North Sea coastline are presented. Four gauging stations at the German Southern Baltic Sea coastline were combined to so called mean normalized gauges to be able to make more general statements about the variations in the Baltic Sea water levels.

The time series were examined with linear and non-linear adaptation functions. A special emphasis lies on the detailed description of the water level time-series considering the influences of the nodaltide. With several analysis methods an estimation of the water level development up to the year 2020 was carried out.

As well as the Mean Water Level (MW), the annual High Water (HW) and annual Low Water (LW) for the Southern Baltic Sea were examined. The results show that the MW is increasing up to now and a further rise can be expected. All results of the investigations lead to the assumption that the tidal dynamics in the North Sea, and thus also the water levels in the Baltic Sea, have changed or are still changing.

1 Introduction

Changes in the global sea level have far reaching consequences for both humans and the natural environment. The entire German North Sea and Baltic Sea coastlines are protected against storm surges mostly by dykes in order to protect the partially lower lying hinterland. Particularly in highly industrialized countries, as, for example, Germany, space requirements for population and industry are increasing. The existing space is used intensively and, in the case of flooding, high significant monetary and ecological damage will result. The population and the economy must be protected against flooding. To achieve this, knowledge of long, medium and short-term trends of the water levels is important.

2 Data

Annual water level data from 4 Baltic Sea gauges are the basis for the current investigations. The four gauging stations are Travemünde, Warnemünde, Wismar and Sassnitz (Figure 1). In this Paper, the investigations and results of the changes of the Mean Water Levels (MW), Low Water Levels (LW) and High Water Levels (LW) at the Southern Baltic Sea will be discussed. The Mean Water (MW) in the Baltic Sea is defined by the arithmetic mean of the daily measurements at 12 o'clock. The data of the Baltic Sea gauges Warnemünde, Wismar and Sassnitz are normally referred the gauge datum "Höhen Null". The data were transformed to the gauge datum "Normal Null (normal zero)" by the formula:

W [cmNN] = W [cmHN] – 514 cm + Δ [cm]

with: W [cmNN]: water level [cm “Normal Null”]
W [cmHN]: water level [cm “Höhen Null”]
Δ: local system differences between HN and NN; Warnemünde (12.1 cm), Wismar (9.8 cm), Sassnitz (11.0 cm) (Stigge 1989)

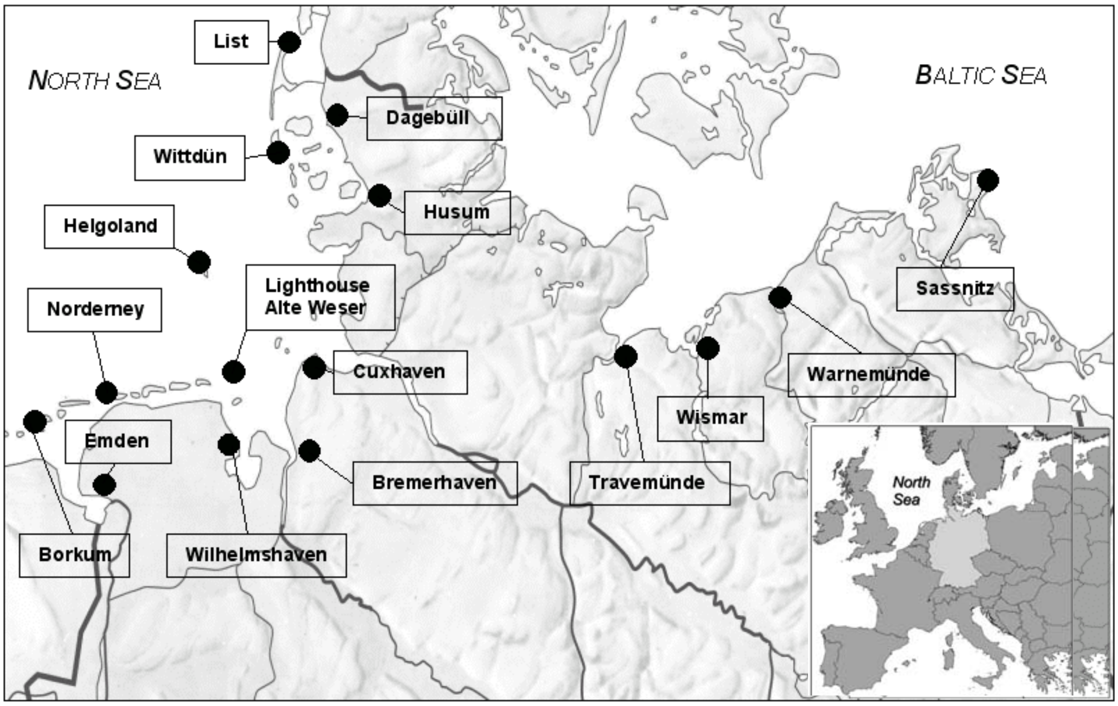

Figure 1: Gauging sites at the German North Sea and Baltic Sea

The aim of the investigation was to derive generalised statements about the trends of the water levels at the German Baltic Sea. Consequently, not all time series were analysed separately, but rather normalized and combined to one group, called mean normalized time series. It was determined a normalized gauge Baltic Sea for MW, LW and HW. The mean normalized time series are created using the original time series normalized by the mean of each and then calculating the arithmetic mean of the four time series. By creating a group of 4 time series, the following topics must be considered: Due to the fact, that not all time series have the same span of time, some effects are important. In the range where e.g. not all time series have data except one, the created normalized time series is determined by one time series only. By means of this the linear trend of the normalized time series can have a deviation in comparison to the arithmetic mean of the single trends of the time series. This effect is not so strong, so that the advantage of analysing only one times series for a parameter is more important. But for all interpretations of the results this effect must be considered.

These time series are shown in Figure 2. It can be recognized, that the gauge Travemünde has the longest time series from 1826 up to 2001. The shortest time series is Sassnitz with a span from 1936 up to 2001. In this figure only the original MW-time series are represented, but also the LW and HW time series were analysed. For the interpretation of the results of the analyses of water level time series at the Baltic Sea it must be considered, that the Baltic Sea is still influenced by e.g. tectonic movements. Along the Southern Baltic Sea coastline these relative movements between land and seasurface are smaller than the sea level rise.

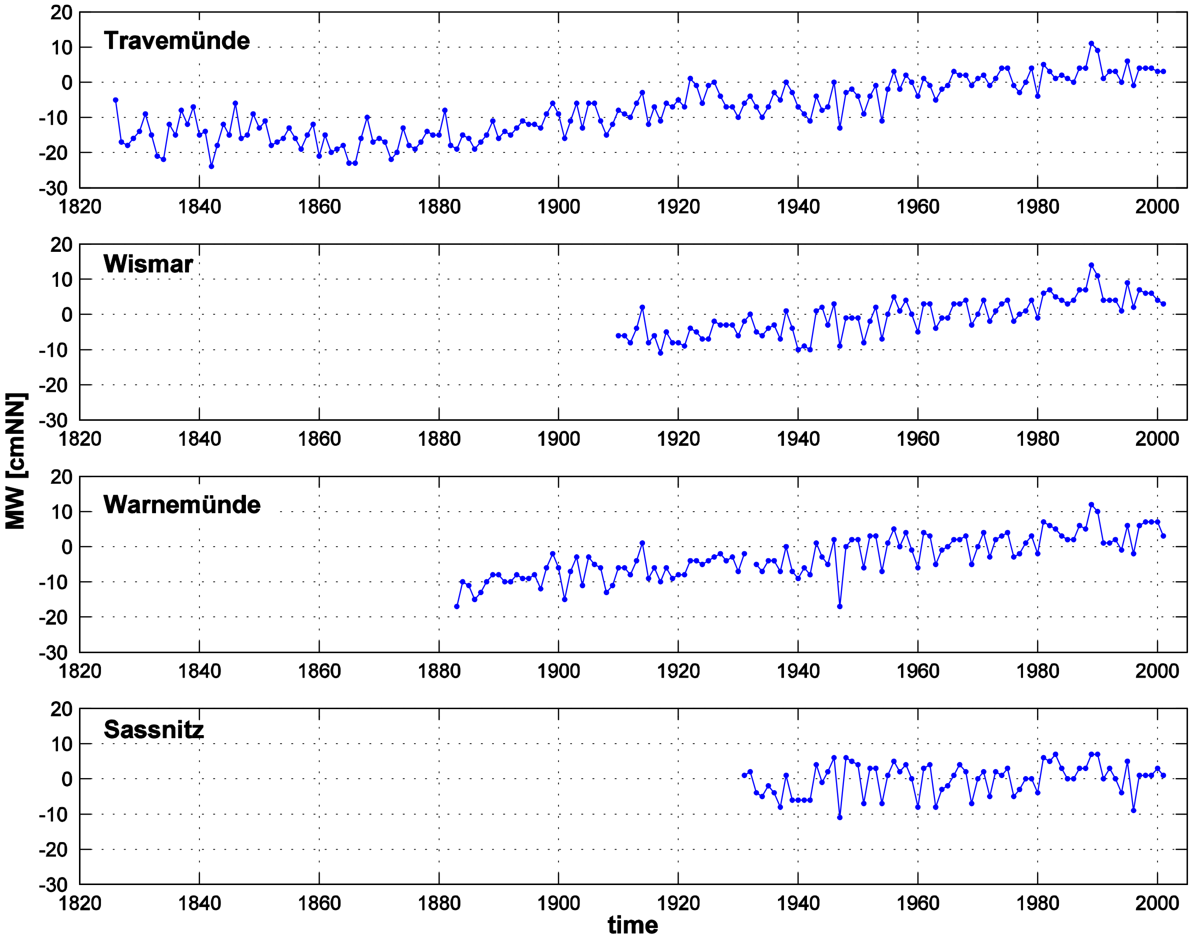

Figure 2: observed MW time series of the investigated gauges

3 Analyses and Results

In the present investigation, a statistical analysis of the time series was carried out. Basic statistical parameters, such as, for example, mean values, standard deviations and linear trends, were calculated for all time series. Further analyses, such as adaptation functions, were carried out only for the normalized time series. In Table 1, the mean values of the four Baltic Sea gauges are shown with the standard deviations.

gauges	time series	HW [cmNN]	± σ	LW [cmNN]	± σ	MW [cmNN]	± σ
Travemünde	1826 - 2001	112	38	-125	25	-8	8
Wismar	1910 - 2001	126	30	-121	26	-1	5
Warnemünde	1883 - 2001	107	25	-105	22	-3	6
Sassnitz	1931 - 2001	92	22	-85	19	0	4

Table 1: Mean values with standard deviations of the investigated gauges

With the aid of different adaptation functions, statements about the trends of the Mean Water Levels at the Baltic Sea coastline can be made up to the year 2020.

In Figure 3, the time series of the MW of the mean normalized gauge Baltic Sea is shown. First of all, a low-pass filter was calculated to generate a smoothed run of the time series. This low-pass filter is calculated using the moving average of the time series with a span of 19 years. The calculated mean value is used as the middle of the span in each case. The span of 19 years is chosen in order to consider the influence of the nodaltide (t = 18.61 years) (Jensen and Schönfeld 1990). The first and the last 9 values of the smoothed curve are calculated with a smaller span. The smoothed curve shows a linearly increasing trend starting from approximately 1900. To obtain a better description of the linear trend, two different linear regression lines were fitted to partial time series (Jensen 1984, Jensen, Bender and Blasi 2001). One regression line was fitted to the entire time series. A further regression line was fitted for the years 1965 to 2001, which corresponds to the cycle of two nodaltides. By interpretating the results it must be considered, that only the second regression line includes the influence of the nodaltide exactly. The other regression line were fitted from the beginning of the time series, in order to take into account the large quantity of data.

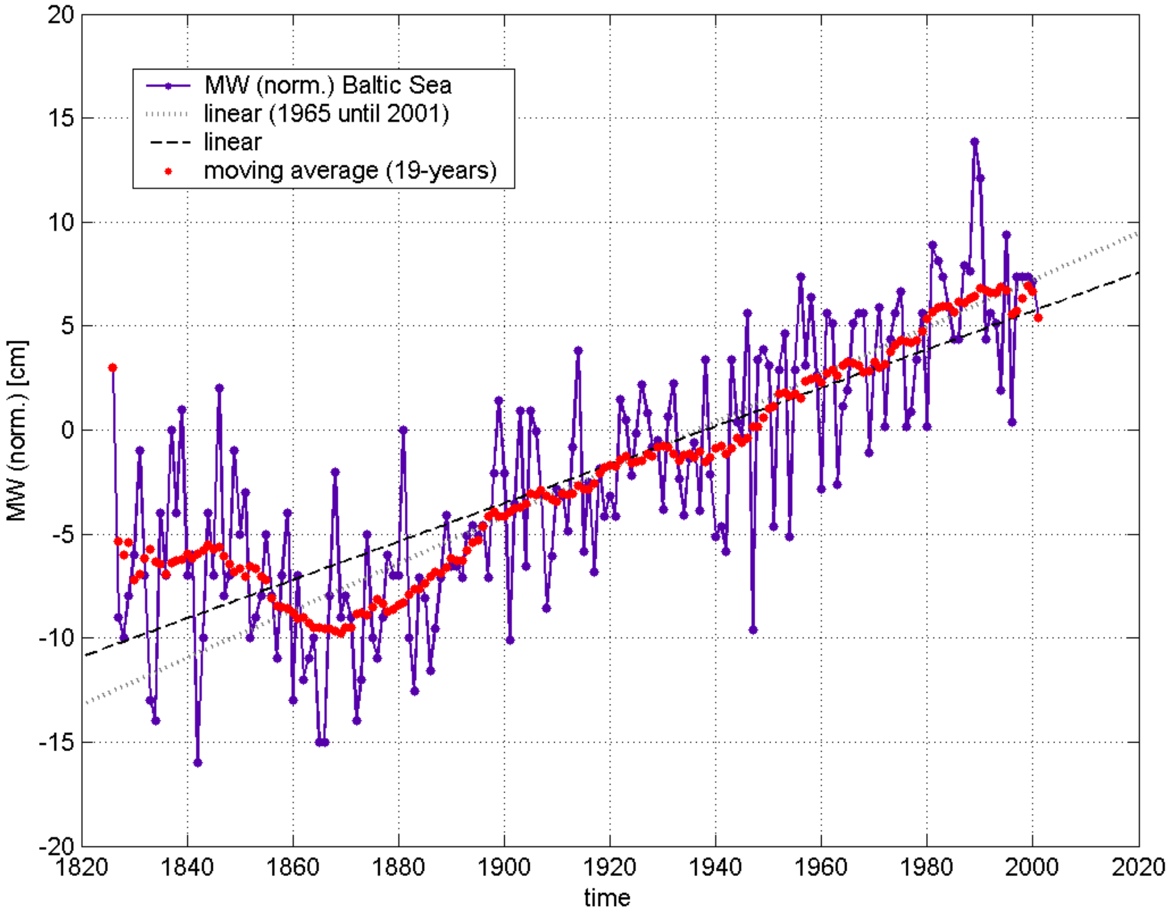

Figure 3: Time series plot of mean normalized gauge Southern Baltic Sea with moving average (19 years) and linear regression lines

The results show that the slopes of all regression lines quite greatly differ from each other at low and high water. Considering only the Mean Water the differences are not so strong; the secular trends (sT) vary between 10 and 16 cm/100 years, except of Sassnitz, where the trends are much smaller. In all figures it is important to know, that the zero line is not equal to the 0 cmNN. The zero line is just the mean value of the normalized time series. In Table 2, all trends of the original and normalized time series are shown.

Gauges	$s_{T(\text{whole time series})}$ [cm/100 years]	$s_{T(1965\text{ to }2001)}$ [cm/100 years]
	HW	
Travemünde	21 (1826 – 2001)	18
Wismar	22 (1910 – 2001)	43
Warnemünde	18 (1883 – 2001)	27
Sassnitz	12 (1931 – 2001)	21
HW (norm.) Southern Baltic Sea	15	28
	LW	
Travemünde	3 (1826 – 2001)	-18
Wismar	28 (1910 – 2001)	1
Warnemünde	23 (1883 –2001)	20
Sassnitz	-10 (1931 – 2001)	-15
LW (norm.) Southern Baltic Sea	1	-3
	MW	
Travemünde	13 (1826 – 2001)	10
Wismar	15 (1910 – 2001)	16
Warnemünde	14 (1883 – 2001)	15
Sassnitz	6 (1931 – 2001)	5
MW (norm.) Southern Baltic Sea	9	11

Table 2: Secular trends s_T of the investigated time series for different parameters

A more detailed description of the trend can be achieved by considering the influence of the nodaltide with a nonlinear adaptation function, which contains a linear portion with the trend and the portion of a sinus oscillation of the nodaltide with the amplitude H_N, period T=18.61 years, time t and phase shift φ (Jensen and Mudersbach 2002a) (1):

$$f(x) = a + s_T \cdot t + \frac{H_N}{2} \cdot \sin\left[2 \cdot \frac{\pi}{T} \cdot (t + \varphi)\right] \qquad (1)$$

The results are shown in Figure 4. For the time series, two adaptation functions for different time periods are determined: One from the beginning of the time series up to 2001, and the other from 1965 up to 2001. The results show that the adaptation function for the time span 1965 to 2001 shows a stronger rise and the amplitude is larger. In total, the result does not show any significant differences projected onto the year 2020. The nodaltide is considered only mathematically and not physically.

To describe the set of the **whole** time-series with **one** function, non-linear adaptation functions are needed. Due to the variations in the time-series it is not possible to do so with only **one linear** function (Jensen and Mudersbach 2003).

From this basis, further non-linear adaptation functions were examined which can describe the given time series better. The disadvantage of these adaptation functions lies in the fact, that they cannot be used so well for extrapolation. Therefore, particular care must be taken while using nonlinear adaptation functions at the point when the functions are ”running away”.

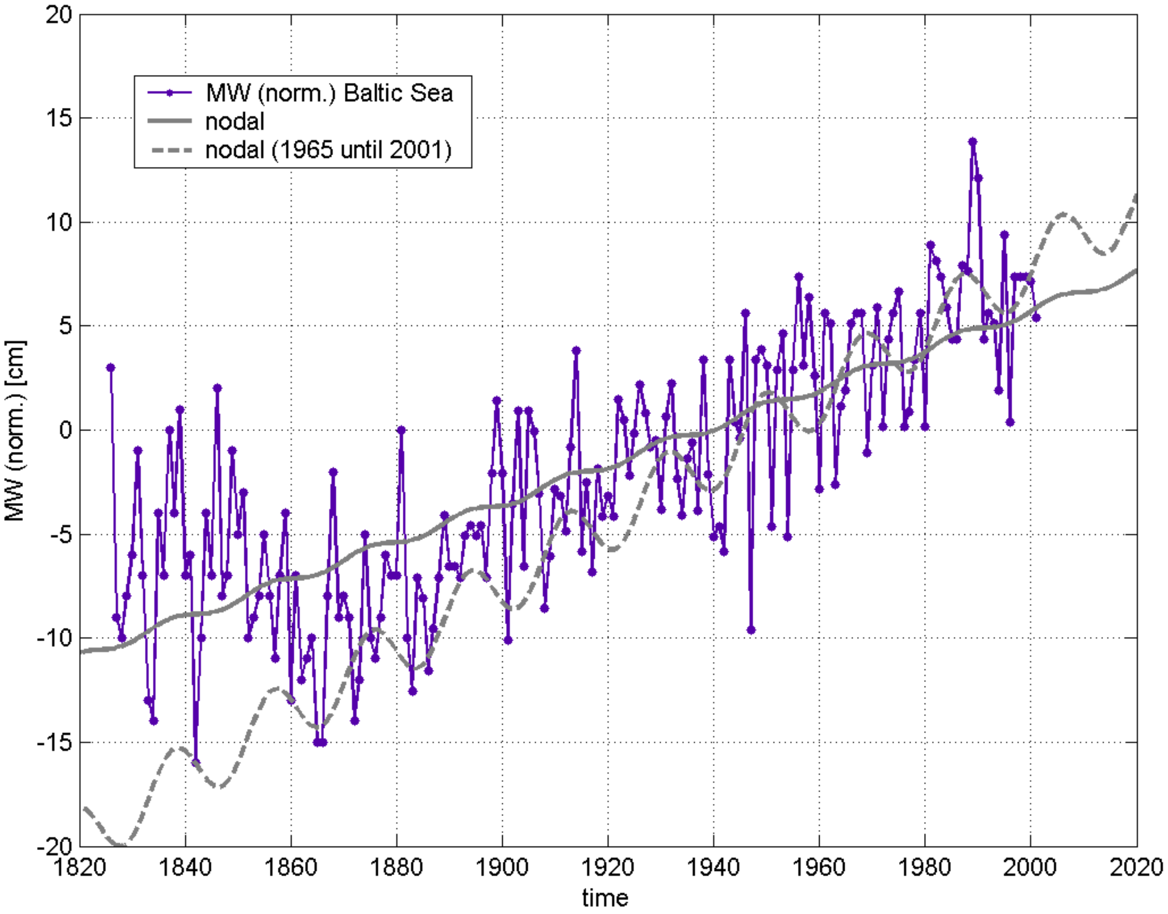

Figure 4: Time series plot of mean normalized gauge Southern Baltic Sea with fitted curve linear plus nodaltide

The investigations show that a polynomial adaptation function of the 3rd degree is a useful description of the behaviour of most of the time series (2).

$$f(x) = ax^3 + bx^2 + cx + d \qquad (2)$$

A further adaptation can be achieved if the polynomial function is overlaid with the nodaltide (3).

$$f(x) = ax^3 + bx^2 + cx + d + \frac{H_N}{2} \cdot \sin\left[2 \cdot \frac{\pi}{T} \cdot (t + \varphi)\right] \qquad (3)$$

The results are shown in Figure 5. The polynomial function describes the time series quite well (in the range of observed data) and clearly flattens between 2000 and 2020. The combined function (polynomial plus nodaltide) does not flatten between 2000 and 2020 and indicates a value of approximately 8 cm greater for 2020.

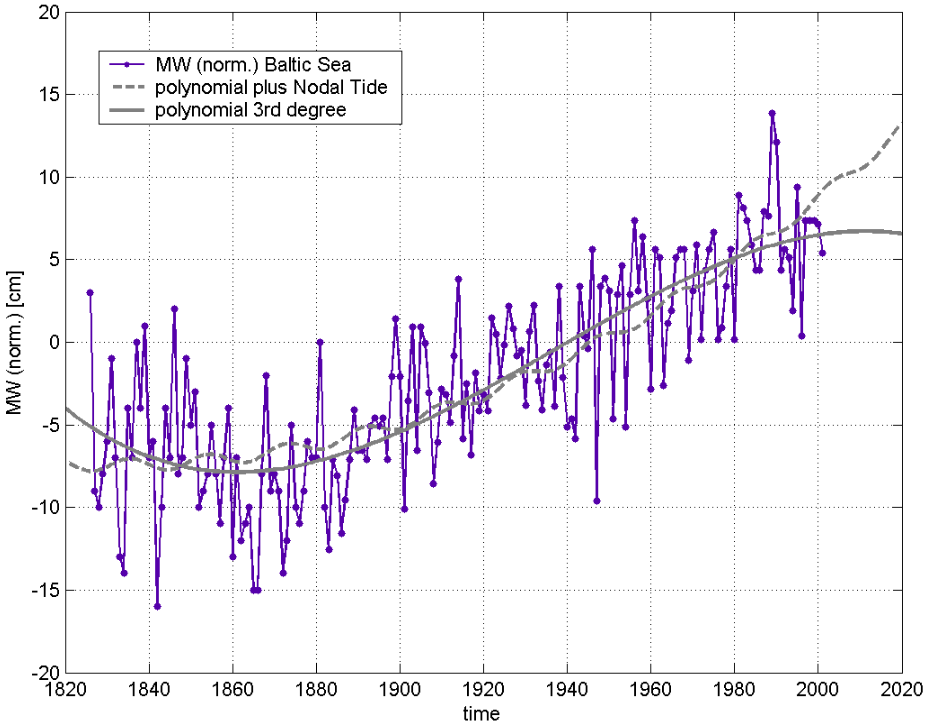

Figure 5: Time series plot of mean normalized gauge Southern Baltic Sea with fitted curve polynomial plus nodaltide and polynomial 3rd degree

For the year 2020, a value of the mean normalized MW (Baltic Sea) between 7 and 14 cm is indicated. If this value is added to the mean value of a corresponding MW time series, the approximate value of the water level can be derived up to 2020.

Using the root mean squared error (RMSE) as a parameter for the goodness of the fit for the adaptation functions above (a value closer to zero indicates a better fit), the best fit is the polynomial function 3rd degree (Table 3). But due to the problem of the instable behaviour in the range of non-observed data, as mentioned before, the combined fit with a polynomial part and the oscillation of the nodaltide shows also good results.

function	**Root Mean Squared Error**
linear	3.99 (Figure 3)
polynomial 3rd degree	3.66 (Figure 5)
polynomial plus nodaltide	3.82 (Figure 5)

Table 3: Goodness of fit of adaptation functions

The normalized HW time series (Figure 6) is especially marked by the extreme event in the year 1872 at the gauge Travemünde. It seems that the amplitude of the yearly High Water Levels becomes smaller, but there is an increasing trend of s_T = 15 cm/100years for the whole time series. Of special interest is the trend from 1965 up to 2001 which reaches a value of s_T = 28 cm/100 years.

For the normalized LW time series (Figure 7) there is no significant trend. The trend for the whole time series is about s_T = 1cm/100 years and the trends for the partial time series is about s_T = -3cm/100 years.

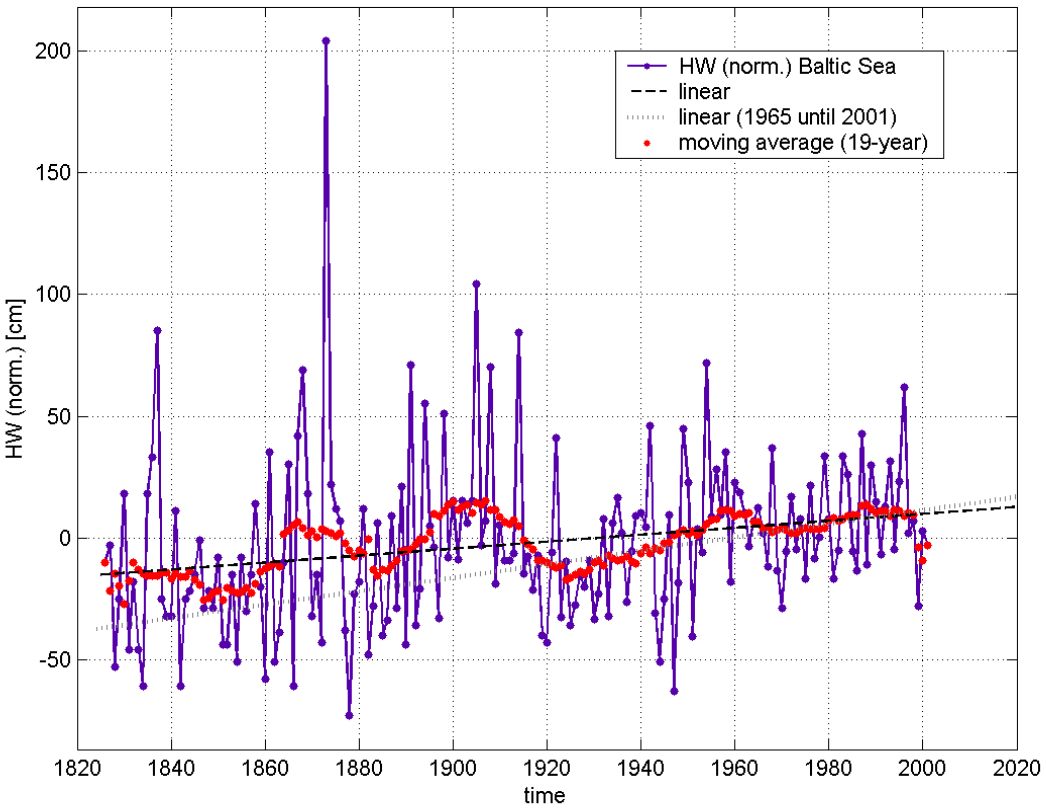

Figure 6: Time series plot of mean normalized gauge Southern Baltic Sea (HW) with moving average and linear trends

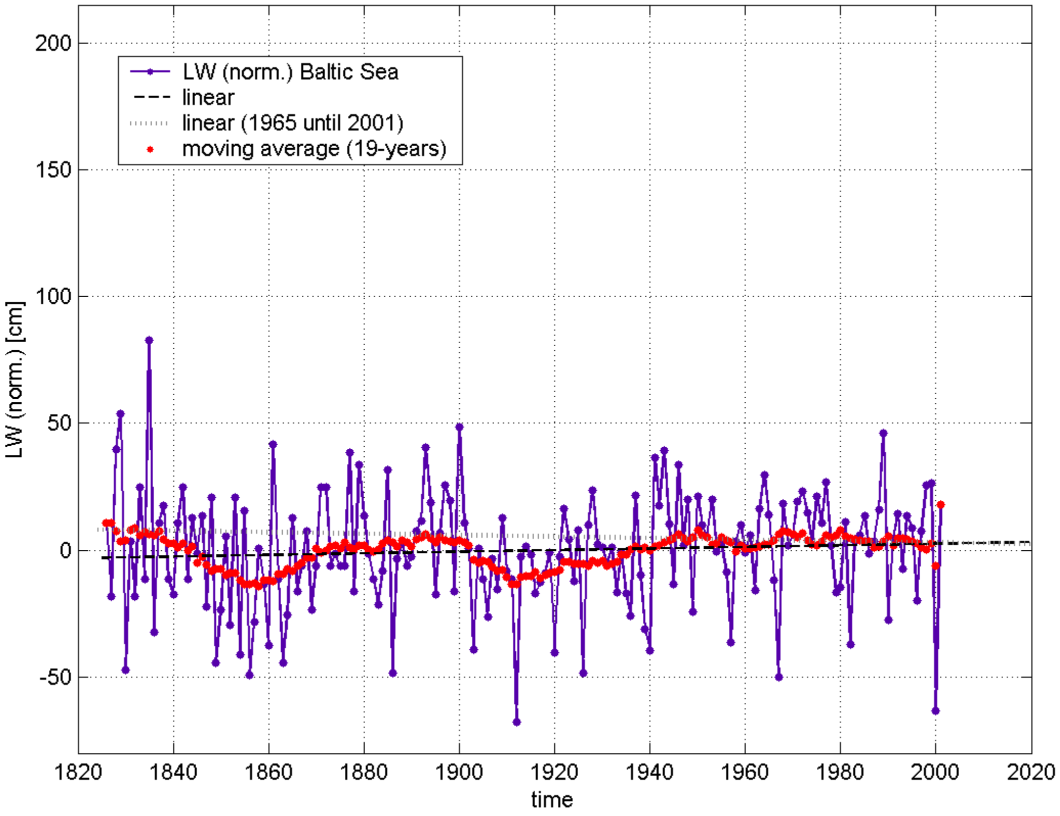

Figure 7: Time series plot of mean normalized gauge Southern Baltic Sea (LW) with moving average and linear trends

Another interesting question is, how the MW of the North Sea and the MW of the Baltic Sea are related to each other. Due to the small tidal range in the Baltic Sea, the Baltic Sea can be considered as a damped gauge of the North Sea. A correlation between the Southern Baltic Sea MW and the MW of the island-gauge North Sea shows these relationships (Figure 8). Within these correlation two spans of time are considered. The correlation from 1891 up to 1964 has approximately the same slope, than the correlation from 1965 until 2001. But it can be seen, that a parallel deviation of the correlation lines took place and so an indication for the rising water levels is given. Due to the slopes of the correlation lines it can be seen, that a buffering of the North Sea water levels in the Baltic Sea take place. More detailed statements about the correlation between North and Baltic Sea with annual values are not possible. For this questions further analysis with monthly or daily values are necessary.

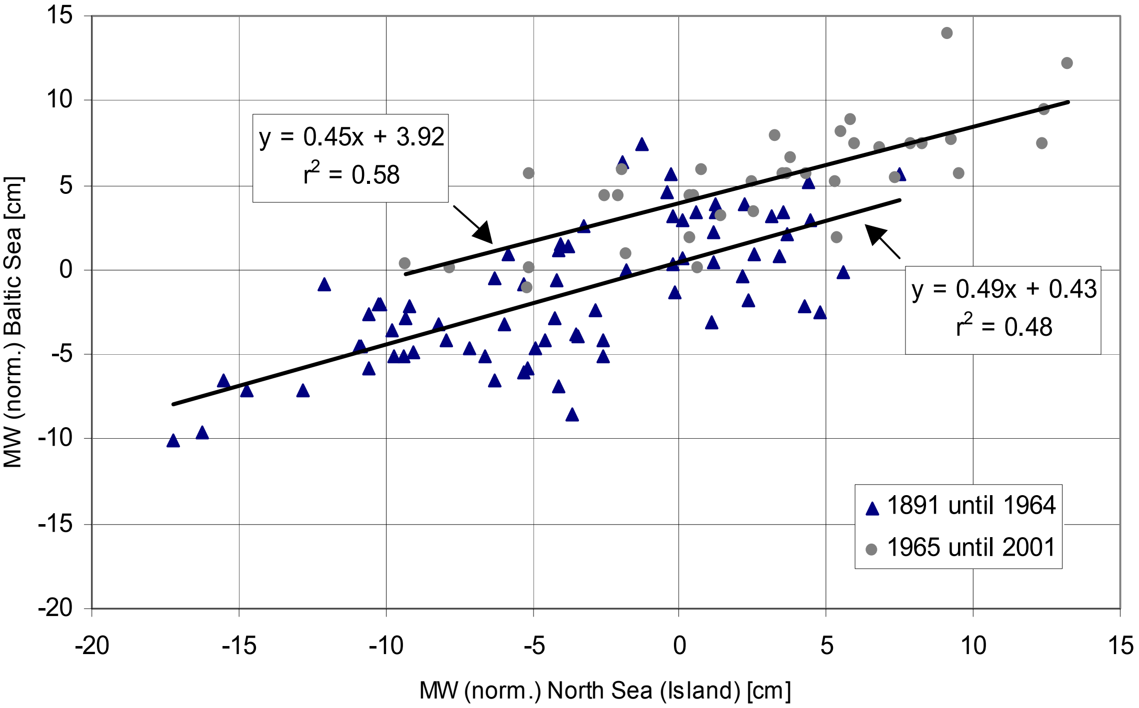

Figure 8: Correlation of MW (norm.) Baltic Sea and MW (norm.) North Sea (Island)

A comparison of the secular trends (1965 up to 2001) of the German North Sea (Island and Coastline) and the Southern Baltic Sea shows (Table 4), that the trends in the North Sea nearby equal (approx. 19cm /100 years) and the trend of the Baltic Sea is much smaller (11.4 cm/100 years). By the interpretation of this results must be considered, that the MW of the Baltic Sea and the North Sea namely are comparable, but not equal in detail because of the different definitions of the Mean Water Level. Nevertheless the results are important and expressive.

Linear trends	**linear trend (1965 – 2001)**
MW (norm.) North Sea Island	19.5 cm/100 years
MW (norm.) North Sea Coastline	18.8 cm/100 years
MW (norm.) Southern Baltic Sea	11.4 cm/100 years

Table 4: Comparison of secular trends of the German North Sea and Southern Baltic Sea coastlines

4 Conclusions

The results of the present investigation basically confirm the investigations of the IPCC 2001 concerning the rise of the mean water levels. For practical questions, the knowledge of specific trends of the water levels at the different gauging sites is of special importance. With the aid of this investigation, such questions can be answered better.

The results show, that the Mean Sea Level of the Southern Baltic Sea is increasing. The intensity of the rise in the Baltic Sea and the rise of the North Sea is different, but it can be recognized that the Mean Sea Level is increasing more strongly in the last 40 years. These analysis show, that a further rise of the MW and HW in future can also be expected All results lead to the assumption, that the tidal dynamics in the North Sea, and thus also the water levels in the Baltic Sea, have changed or are still changing.

The trends of the water levels have to be observed and analysed exactly in future. Further investigations are needed.

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