Long Term Water Level Observations and Variations

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Abstract

Numerous tide gauges have been recording data along the coastlines of the southern North Sea for more than a century, at Amsterdam even since 1700. Every tide gauge locality has its own unique sea level history; the data are more or less influenced by several factors. Some examples of how these factors affect the trend analysis of water levels (high, low, mean) are presented.

Statistical aspects with relation to predictions of the future water level trend are addressed. The evaluation of the Mean Sea Level (MSL) has become important with respect to the expected global climate change. Its relative trends are not constant, neither with regard to locality nor with regard to time. The MSL rise in the southern North Sea varies between 10 and 20 cm/100 years with an overall mean of about 15 cm/100 years. A rise of the relative Mean High Water (MHW), which has accelerated over the past decades, is found at all of the stations. The MLW sank slightly during the beginning of the second half of this century but subsequently has stabilised or shows a light positive trend. This results in a MTR increase for the tide gauges along the Dutch and German coast since 1950.

Introduction

The eustatic variations of the global sea level are strongly influenced by worldwide changes in climate. There is no longer any doubt that the "greenhouse effect" and other human activities have a definite impact on our climate. In the North Sea, bounded by Norway (N), Denmark (DK), Germany (D), The Netherlands (NL) and Great Britain (GB), and especially in the German Bight, an enhanced rise of the sea level will also lead to far-reaching alterations.

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In this context, not only changes in MSL are important, especially alterations in annual values of the mean tidal high water (MHW), mean tidal low water (MLW) and mean tidal range (MTR) will play a decisive role (all references to trends in the MSL, MHW etc. are considered to be *relative* changes between the land and sea level). Changes in tidal dynamics of the flat coastal regions affect erosion, degree of storm surge risk, ground water level and shipping. The evaluation of time series of annual data (MHW and MLW) and semi-diurnal tidal high water (THW) and tidal low water (TLW) shows an increase of the THW along the German and Dutch coastline, whereas the TLW decreases or stays constant (e.g. Jensen, 1984). This leads to the assumption, that during the last three decades a change in the tidal dynamics in the North Sea may have taken place. If this is a long term trend needs to be proven because of the influence of long term periodic changes (Jensen *et al.*, 1990).

Sea level rise between AD 1000 and 1850

Sea level curves covering the Holocene epoch are mostly based upon geological data and reach back to the last ice age about 18,000 years ago. Curves, which are based upon tidal gauge data, only cover the period from about AD 1850. Hardly any curve exists, which links the Holocene to the modern curves. For this reason, a probable MHW-curve for the southern North Sea covering the period from about AD 1000 onwards was established (fig. 1).

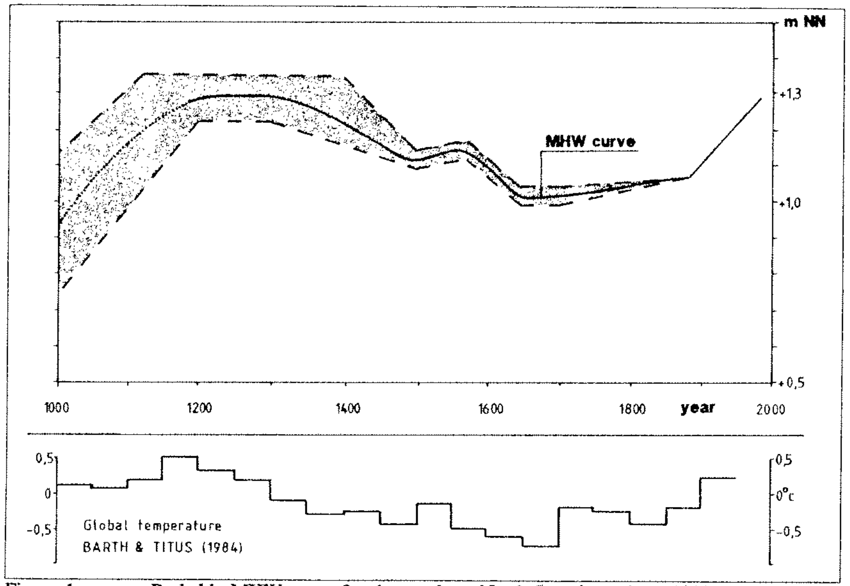

Figure 1: Probable MHW-curve for the southern North Sea since about 1000 (adapted from Hofstede, 1991)

Based upon dated organic samples from the East-Frisian barrier islands ,Streif (1989) suggested that the local MHW-level might have been between NN +1.22 and 1.35 m for a certain time interval between 1125 and 1395. This would mean that the modern MHW-level in this area was already reached about 500 to 800 years ago. According to Barth and Titus (1984), the 50-year global mean temperature for the time span 1200/1250 (Medieval Climate Optimum) was a little higher than the 1900/1950-mean (fig. 1). The MHW-maximum between 1125 and 1395 according to Streif (1989) correlates well with these climatological data.

The Medieval Climate Optimum was followed by a severe deterioration. According to the temperature curve of Barth & Titus (1984) the period between 1600 and 1700 was the coldest since 900 at the latest. The temperature difference between 1200/1250 and 1650/1700 was about 1.5 °C. Also, the first great expansion of glaciers in the Alps during the Little Ice Age occurred between 1600 and 1640 (Maisch, 1989). So it seems realistic to suggest that the MHW-minimum of the Little Ice Age was reached around 1650 (Gornitz *et al.*, 1982; Wigley & Raper, 1987; Oerlemans, 1989).

From 1700 on, sea level has been recorded at the tide gauge of Amsterdam (Netherlands). So from this time on more or less accurate data on relative sea level are available. Continuous German tide gauge records reach back to 1826 (Travemünde, Baltic Sea) and 1843 (or fixed to tidal datum 1855) (Cuxhaven, North Sea). The Baltic Sea is connected to the North Sea by three small entrances only. The consequence is a sea with a tidal range that can be neglected. The MSL-curves for these three gauges are presented in fig. 2.

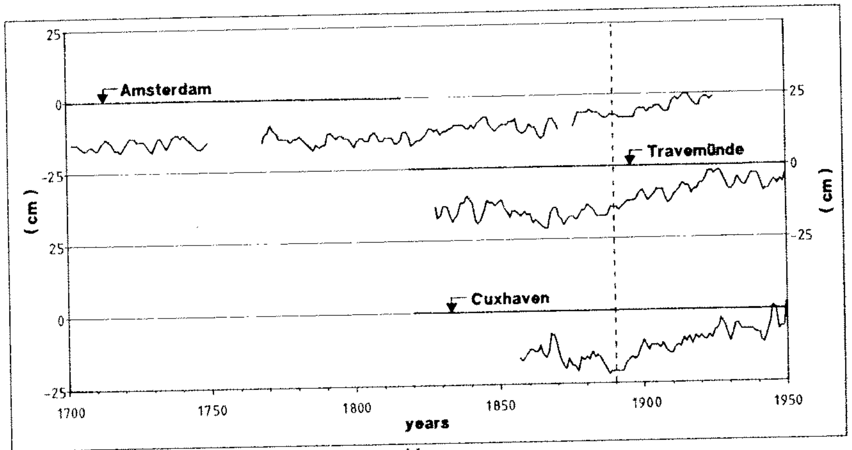

Figure 2: MSL-rise at three long-term tide gauges

According to these curves no significant fluctuations occurred between 1700 and about 1890. However, a stable MSL does not necessarily mean that the MHW remained constant. Independent changes in the tidal range might induce a MHW change as well. However, first results of Dutch investigations on tidal range fluctuations along the Dutch North Sea coast since 1700 seem to suggest that no significant change took place during this period.

According to Flohn (1985) a small temperature rise occurred between 1700 and 1850. During this period glacier variations appear to have been within a limited range, while after 1850 a world-wide retreat began (Oerlemans, 1989). So once again, the climatological data correspond well with the reconstructed MHW-curve of figure 3.

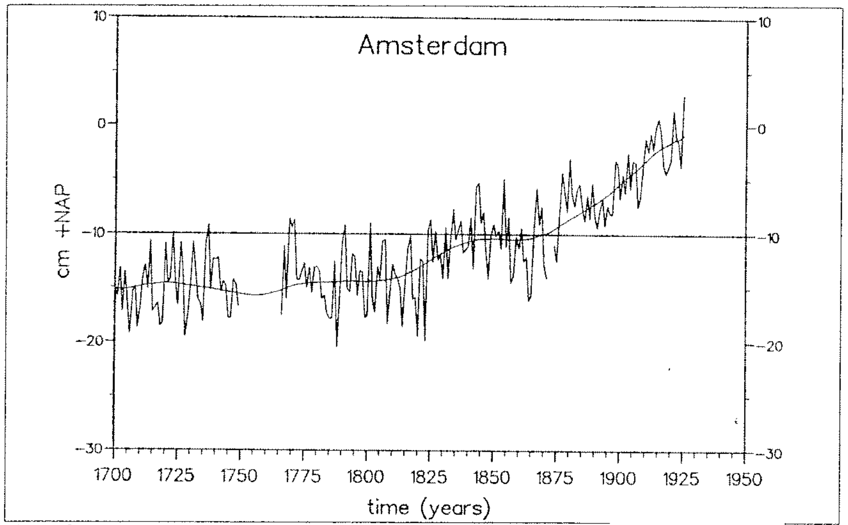

Figure 3: Record of mean sea level at the tide gauge of Amsterdam, 1700 - 1925

Based upon 21 long-term tide gauges Gornitz & Solow (1991) found weak statistical evidence for a common turning point around 1895 in the European MSL records which also can be seen in figure 4. It corresponds with the world-wide glacier retreat and temperature rise since about 1870. According to Oerlemans (1989), these processes might have contributed about 9.5 cm to the MSL rise since 1890.

It appears that, at least since AD 1100, sea level changes along the southern North Sea coast were controlled mainly by thermal eustatic processes.

Tide gauge records along the Dutch coast

The Netherlands have a dense network of tide gauges along their coastline, most of them have a record length of more than 100 years. The oldest tide gauge record of the world is that of Amsterdam which started in 1700 and lasted until 1930 (van Veen, 1954) at which time unfortunately (for the Amsterdam record) the former "Zuider Zee" was closed and Amsterdam was disconnected from the sea.

The record of Amsterdam is given in figure 3, including a filtered signal calculated with SSA (Singular Spectrum Analysis) (Heinen, 1992 and Vautard *et al.*, 1989). The record of Amsterdam shows quite clearly a change in relative sea level rise. Before about 1850, the measurements indicate no sea level rise, after about 1800 there is a distinct rise of the sea level. From 1800 to 1930 the rise has been 17 cm.

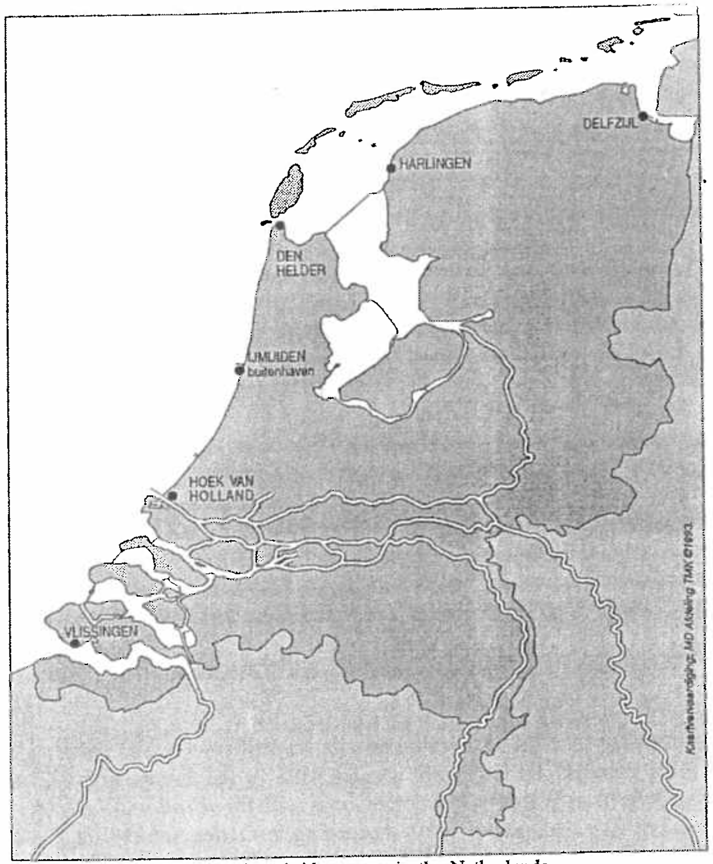

Figure 4: Location of mentioned tide gauges in the Netherlands

To explain this change in the rate of sea level rise one can look at the link with the sudden decline of most glaciers around the same time. This change is probably due to relatively lower levels of volcanic dust in the atmosphere (Oerlemans, 1988). One could also say that these changes are evidence of the end of the Little Ice Age. One thing at least is clear, it is not due to the greenhouse effect.

All tide gauge records along the the Dutch coast show a clear trend of relative sea level rise, which is shown in figure 5. A map of the Netherlands with the location of the tide gauges is given in figure 4.

The term *relative* sea level rise has been used here because the changes measured are due to two phenomena, namely sea level rise and subsidence. The Dutch benchmarks have their foundation in the Pleistocene layer several tens of meters deep. The Pleistocene under the Netherlands is subsiding at a rate of 2 - 8 cm per 100 years.

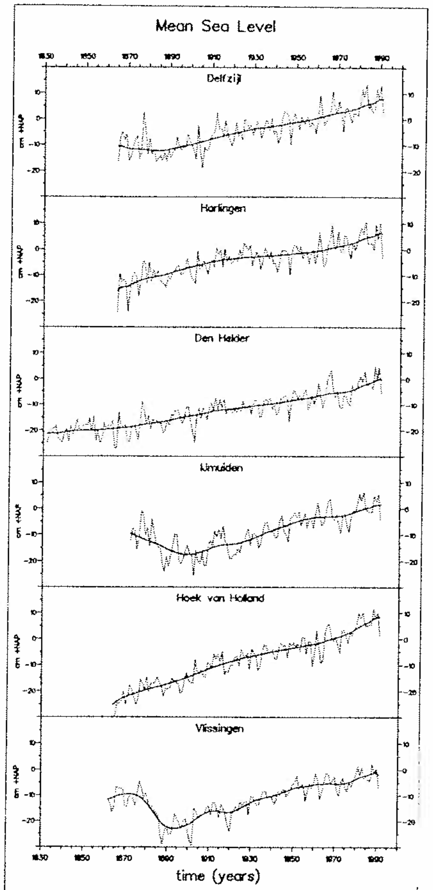

Figure 5: Records of 6 Dutch tide gauges up to 1991; the smooth lines have been derived with SSA.

From 1900 onwards the records in figure 5 show more or less the same trend; before 1900 some of the records have a more fluctuating behaviour due to unknown causes. The rate of relative sea level rise is given in Table 1 for the periods 1900-1990 and 1940-1990.

	1900 - 1990	1940 - 1990
Vlissingen	23	19
Hoek van Holland	26	28
IJmuiden	21	20
Den Helder	17	20
Harlingen	16	19
Delfzijl	21	23
Mean value	21	22

Table 1: Mean relative sea level rise in cm per 100 years.

The fluctuations between the rates of relative sea level rise of the different tide gauges cannot be neglected. These differences can be partly explained by different rates of subsidence of the Pleistocene and partly by local changes near the gauges (dredging and harbour works). The local changes also can greatly influence the tidal range and the MSL.

In figure 5 the filtered signal calculated with SSA for every tide gauge has been plotted as well. This method has also been used for a combined time series of the six tide gauges (fig. 6). During the last 15 years a small increase in relative sea level rise can be noted at several gauges as well as in the combined signal.

In order to investigate this, first it has been tried to reduce the noise level of the signals. A part of the signals can be explained by the changes in air pressure and by the nodal tide. With a multiple linear regression technique using the nodal signal and air pressure data of six stations (Edinburgh, Bergen, De Bilt, Stykkhisholmur, Charlotte Town and Lisbon) it was possible to reduce the noise level. E.g. for the combined signal of the six Dutch tide gauges the noise level was reduced by 40%.

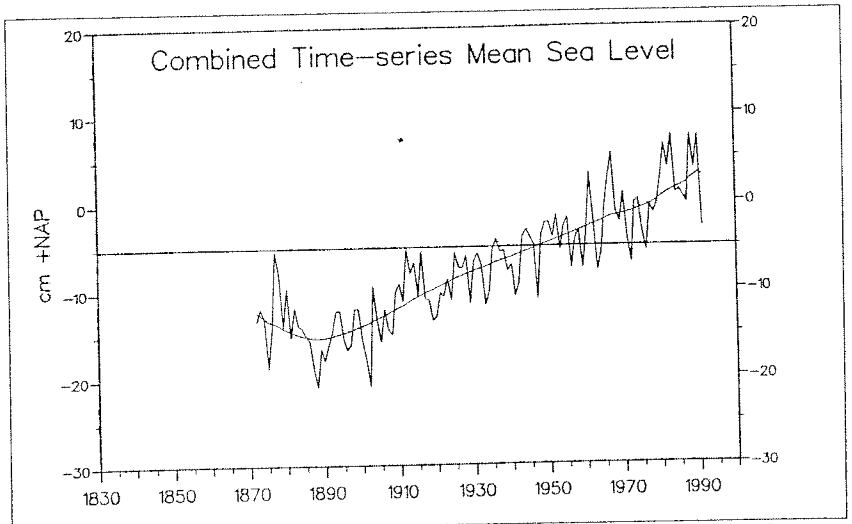

Figure 6: Combined record of six Dutch tide gauges up to 1991; the smooth lines have been derived with SSA

Of the total variance 75% could be explained by the trend, 11% by air pressure and 0.06% by the nodal tide, leaving 14% for the noise. The time series for this case are shown in fig. 7.

When SSA is used after reduction of the noise level by using air pressure data, one finds that the resulting filtered signal show remarkable differences compared with the earlier ones (fig. 8 and 9). The small increase in relative sea level rise at the end of the records has disappeared and the SSA-lines shown are smoother than before. Along the Dutch coast not only relative sea level is increasing but also the tidal range is showing an increase. Increasing tidal ranges are also found along the Belgium and German coasts, but not along the British coast.

In Table 2 the rates of rise of MHW, MLW and MTR for the six tide gauges are given for the period 1940-1990.

Period 1940-1990			
Station	Mean High Water	Mean Low Water	Mean Tidal Water
Vlissingen	29	15	14
Hoek van Holland	(44)	22	(22)
IJmuiden	32	16	16
Den Helder	22	12	10
Harlingen	31	14	17
Delfzijl	(49)	(-10)	(60)
Mean value without ()	29	16	14

Table 2: Mean rise in cm per 100 years of mean high water, mean low water and mean tidal range during the period 1940-1990
( )=there is no uniform trend

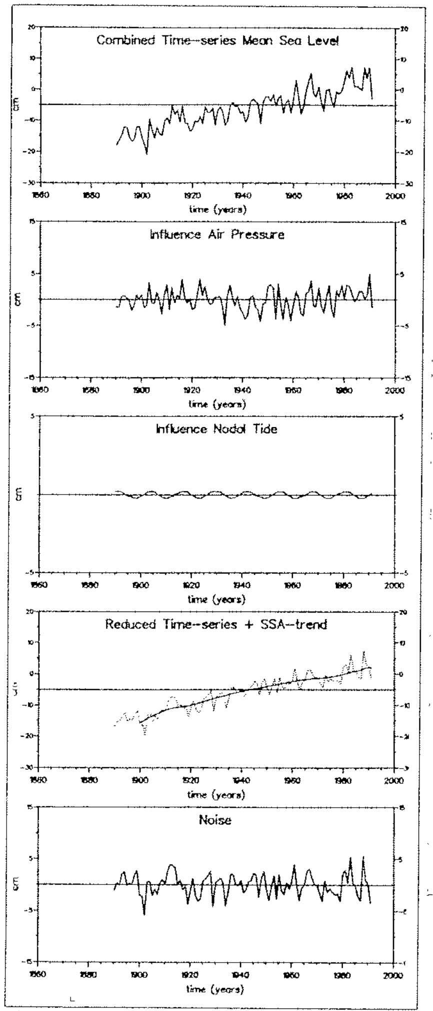

Figure 7: Separation of the combined record of Dutch mean sea level in the parts induced by air pressure, nodal tide, SSA-trend and noise

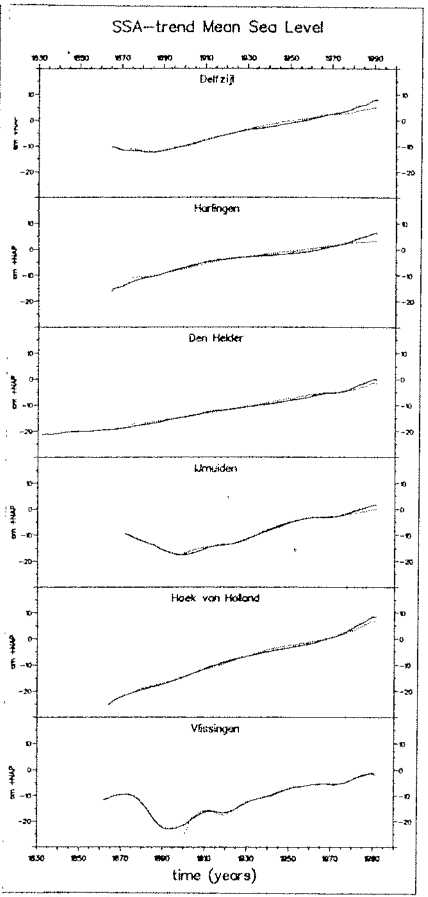

Figure 8: Comparison of the SSA-trendlines before and after noise reduction for the combined time series

All gauges show an increase of the MTR. The greatest increase can be seen in Delfzijl and can be explained largely by dredging in the Ems estuary. In spite of sea level rise, MLW is decreasing. The second largest increase is in Hoek van Holland. The MTR of this station shows large fluctuations and there is no uniform trend. The other stations show a more or less uniform trend in the MTR.

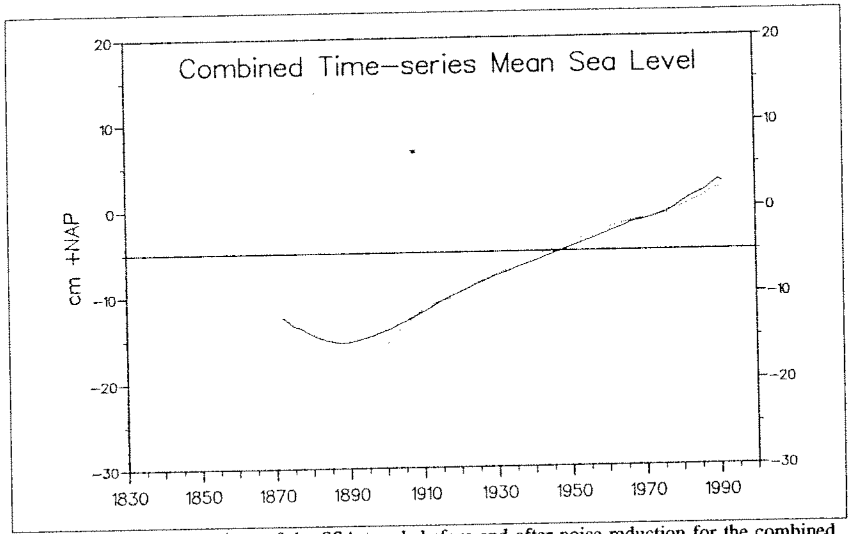

Figure 9: Comparison of the SSA-trends before and after noise reduction for the combined time series

The causes of these changes must be partly due to dredging, harbour works and delta works (the closing of several major tidal inlets in the southern part of the Netherlands) and partly due to some up to now unknown external sources which seem to change the tidal amphidromic system in the North Sea.

As an example, fig. 10 shows the changes in relative MSL, MHW and MTR of the tide gauge Vlissingen.

Tide gauge records along the German coast

Figure 11 gives a general view of the German Bight, the southeastern part of the North Sea, and the sites of the main gauges along and in front of the German coast from the Dutch border in the west to the Danish border in the north. Most of these gauges were established during the second half of the last century. The oldest gauge on the German coast is the one in Cuxhaven that started recording in 1788, with continuous records since 1843 and with a reliable data connection to the German datum (NN = Normal Null, fixed to the Amsterdam gauge and the Dutch datum [NAP]) since 1855 (e.g. Gaye, 1951, Rhode, 1977). The rate of subsidence/uplift for the tide gauge locations is not well known. For the western part (East-Frisia) the subsidence is likely in a range of about 5 cm/100 years.

A first idea of the regional changes in the southeastern North Sea is given by the comparison of mean tidal ranges and propagation velocities for a period around 1925 and 1980 by Lassen and Siefert (1991). The first survey of the MSL conditions of the German North Sea coast was made by Lassen (1989).

For the evaluation of long term trends on relative sea levels, gauge locations are necessary which can be expected to be free of any influence by human activities such as dredging, training works etc.; furthermore continuous series of records from as long ago as possible must be available. 12 such stations have been selected in the German Bight; these are located on the islands (Borkum, Norderney, Helgoland, List on Sylt, Wittdün on Amrum), at the mouths of large estuaries (Emden, Wilhelmshaven, Bremerhaven and Cuxhaven) or in small harbours (Büsum, Husum, Dagebüll) (fig. 11).

Additional data from seasonally operating and intermediate gauges in the North Sea were included and connected to the German datum, which led to the result that the southeastern North Sea was almost completely covered with more than 230 gauges.

Special correlations between data of seasonal and of main gauges provide reliable information on annual means, even for discontinuous records (Siefert and Lassen, 1985).

From these gauges, the MHW and MLW are used as the arithmetic averages of all tides of each individual hydrological year (the German hydrological year starts on Nov. 1st). The sequences of these values describe the time history of these annual water levels.

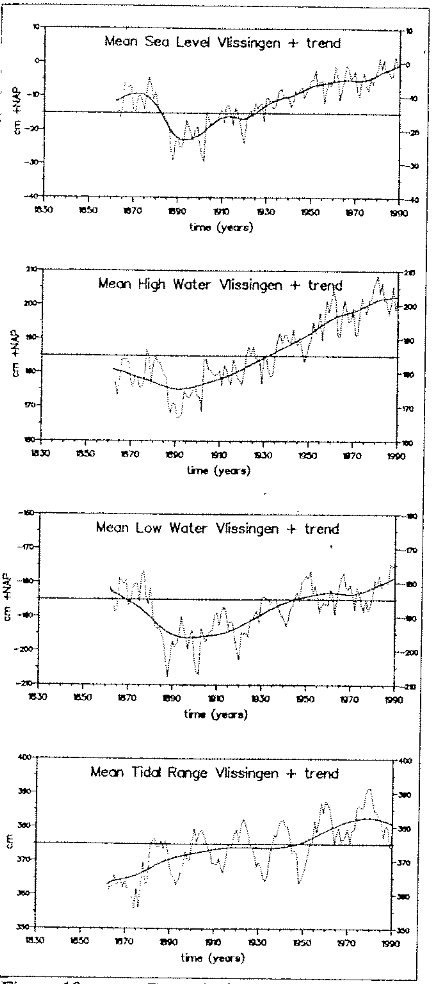

Figure 10: Record of the tide gauge at Vlissingen for MSL, MHW, MLW and tide range. Smooth lines with SSA

The German Bight as part of the North Sea is governed by semi-diurnal tides with nearly sinusoidal curves in front of the coast. MTR varies between 2.0 m and 3.5 m for the locations indicated in figure 12.

MTR is decreasing to the northwest, where amphidromic points for the M2 and S2 tides are situated (fig. 12). Spring and neap tides do not show remarkable dif-ferences from mean tides. Their tidal ranges are usually within 10 to 20 % of the mean.

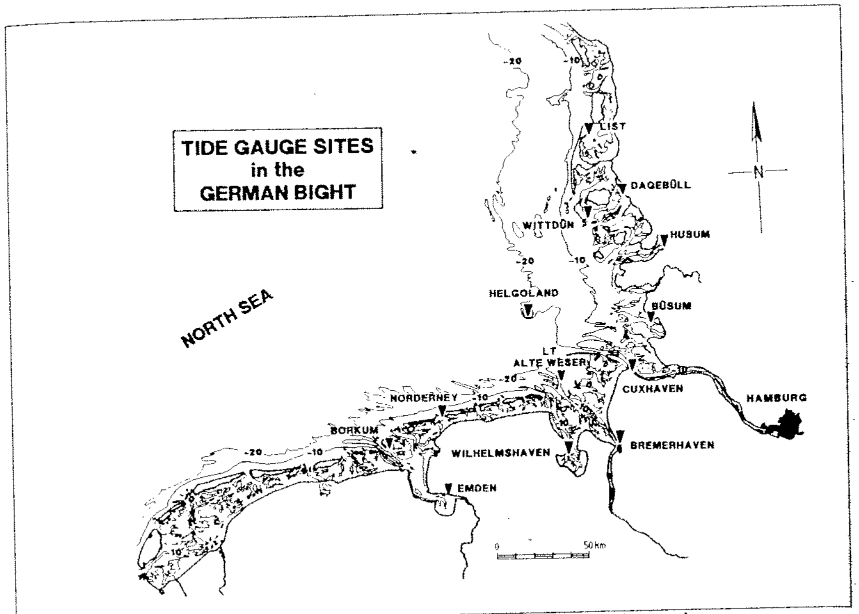

Figure 11: General view of the German Bight with the main gauging stations

Mean time differences between the occurrence of THW and TLW at different stations and the reference time (transition of the moon through the Greenwich meridian) become smaller in the last decades. The evaluations of THW and TLW occurrence times lead to the assumption that in the last decades the propagation velocity of the tide has increased in the southern North Sea (Jensen *et al.*, 1990).

In these very simple tidal conditions it is convenient to use a substitute parameter for MSL, that usually lies some centimetres below MSL:

$$T½w = ½ * (THW + TLW)$$

Nevertheless MSL-changes and T½w-changes are more or less identical, so that it is quite easy to evaluate MSL changes by simply analyzing annual THW and TLW developments.
A long term trend s_T can be described by a linear function:

$$H = H(t) = H_o + s_T * t$$

With respect to an evaluation after the method of least squares, s_T represents the mean slope of the function related to a period of 100 years (the effect of the nodal tide with a period of T = 18.6 years must be reduced).

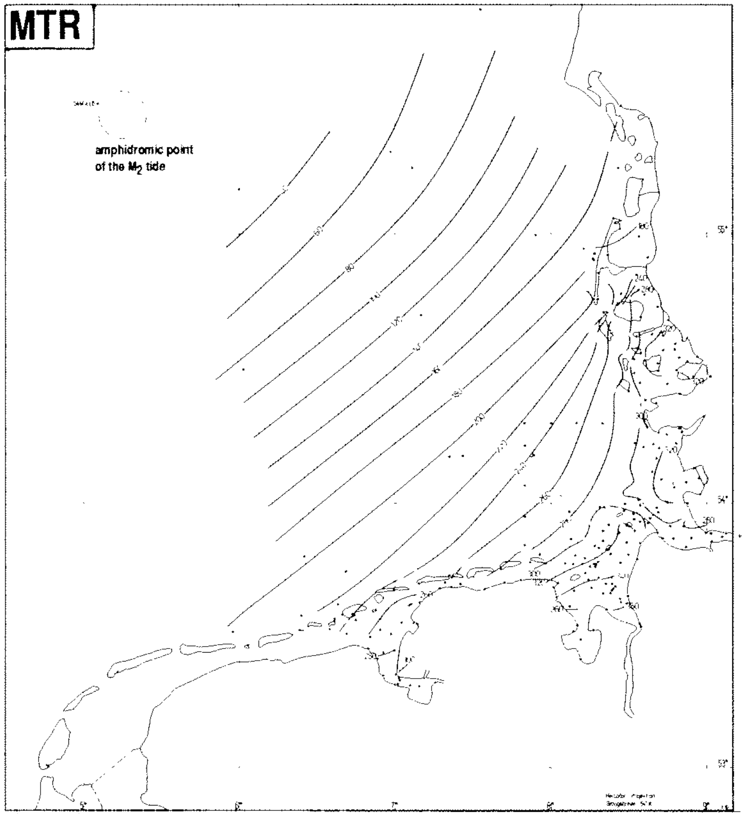

Figure 12: MTR 1975-1985 in the southeastern North Sea

As a summary of the time series of annual tidal high and low water presented in fig. 13, table 3 shows, related to the base of 1991, the changes in cm/100 years for MHW, MLW, MTR and ≈MSL from the time series N = 100 years and the extrapolation of N = 37 years (2 cycles of the nodal tide) (stations from table 3 as well as Helgoland and Wittdün).
For the 10 gauges, the time series of the annual values for the MHW show an increasing trend superimposed by annual fluctuations. These are mostly due to large scale meteorological effects and occur simultaneously (e.g. 1947) in the time functions of all gauges. In the time series for the MLW the same annual fluctuations as in the MHW can be detected (e.g. 1947). The long term trend, however, is not as clear as that for the MHW (Töppe, 1992).

Taking the equally weighted values of all 12 stations, mean values for the complete area of the German Bight can be computed (table 3; Jensen, 1984; Führböter and Jensen, 1985).

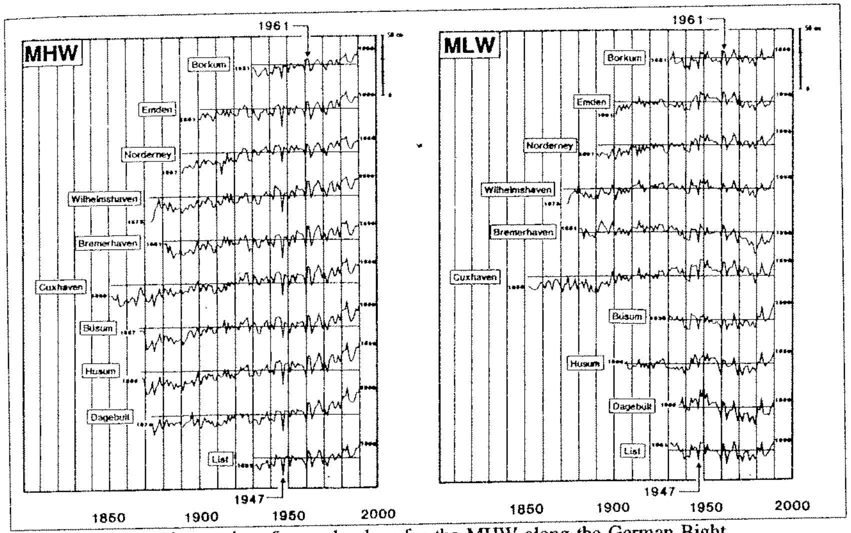

Figure 13: Time series of annual values for the MHW along the German Bight

	Secular Trends in cm/100 years calculated from N=37 and N=100 years							
	Mean High Water		Mean Low Water		Mean Tidal Range		Mean Sea Level	
Locations	1955 1991 (37a)	1892 1991 (100a)	1955 1991 (37a)	1892 1991 (100a)	1955 1991 (37a)	1892 1991 (100a)	1955 1991 (37a)	1892 1991 (100a)
Borkum	31	-	15	-	15	-	23	-
Emden	43	-	-22	-	65	-	10	-
Norderney	27	-	5	-	22	-	16	-
Wilhelmshaven	27	27	-1	1	28	26	13	14
Bremerhaven	24	24	-39	-18	65	42	-7	3
Cuxhaven	34	25	-9	13	43	12	13	19
Helgoland	24	-	2	-	21	-	13	-
Büsum	27	19	35	-	11	-	41	-
Husum	56	31	6	-	49	-	31	-
Wittdün	44	-	1	-	43	-	23	-
Dagebüll	60	29	-17	-	77	-	21	-
List	32	-	4	-	28	-	19	-
Mean value Stand.deviation	36 +/-12	26 +/-4	0	0	39 +/-21	27 +/-12	18 +/-11	12 +/-7

Table 3: Secular Trends s_T of MLW, MHW, MTR and ≈MSL for different stations

Whereas the standard deviations for the MHW are much lower than the absolute values (which clearly show an increasing tendency within the last 37 years), the mean deviations for the MLW are higher than the absolute values themselves.

These numbers indicate a trend of:

+12 to +18 cm/100 years

for MT½w (and roughly for MSL as well) on the basis of the last 100 or the last 37 years respectively.

The different developments of MHW and MLW seem to be the result of a nonlinear reflection process in the shallow water areas of the tidal flats surrounding the German North Sea coast.

In order to gain a better insight into the temporal changes of the trend, the trend s_T is computed only for a period of N = 37 (100) years starting at the beginning of the data, this results in a time dependent function $s_{T\,(N\,=\,37\,(100)\,\text{years})}$ as $s_{T(t)}$.

Figure 14 shows this time-function (trend of a linear regression model over 37 years (2 cycles of the nodal tide)) for Cuxhaven. The first period of 37 years at Cuxhaven starts in 1843 (from 1855 reliable data). The secular trends (in cm/100 years, as running means over 37 years) in Cuxhaven vary between 0 and + 35 cm/100 years, with a mean value of about + 20 cm/100 years. Trend investigations should be based on time windows with a length of cycles of the nodal tide (T = 18.6 years) for the calculation of running means.

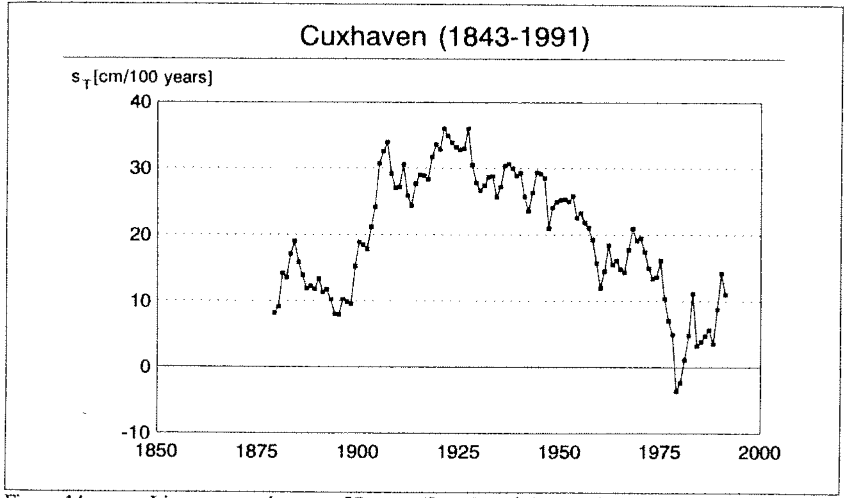

Figure 14: Linear regression over 37 years (2 cycles of the nodal tide) for Cuxhaven

The increase of the trend in MHW can clearly be seen, the trends of MLW are much smaller, at some tide gauges MLW is even decreasing. Due to this development the trends of MTR increase faster and those of MSL rise much slower than the trends of MHW. Conspicuous alterations have taken place in the last decades.

Evaluations made by Jensen, Mügge and Schönfeld (1990 and 1992) reveal that there is no uniform trend in the tidal regime of the German Bight. The secular rise strongly depends on the location of the tidal gauge and on the period of time considered. One obtains different results depending upon whether MSL (predominantly used parameter) or THW and TLW are computed. Based on the historical development of MSL in the German Bight, no extraordinary rise can be detected when time periods of more than 30 years are taken into account. Only computations of trends over shorter periods reveal an enhanced increase of the MSL in the German Bight. More interesting developments have occurred with respect to the extreme values of the tidal regime. The rise of MHW compared with constant or decreasing MLW leads to an enhanced increase of the MTR. The rise of MTR is of great importance for tidal dynamics. Enhancement of tidal energy will lead to increased current velocities and sediment transports. This has great impact on the morphological structure of the coastal regions and is of high importance for coastal engineering purposes.

In order to gain a better insight into the development of the extreme high (e.g. storm surges) and low water levels the following quantiles: $THW_{99\%}$, $THW_{95\%}$ and $THW_{50\%}$ (≈MHW), $TLW_{50\%}$ (≈MLW), $TLW_{5\%}$ and $TLW_{1\%}$ were investigated (Table 4).

	THW-trend [cm/100a]			TLW-trend [cm/100a]		
	THW 99%	THW 95%	THW 50%	TLW 50%	TLW 5%	TLW 1%
Borkum	43	36	14	15	3	18
Emden	81	63	39	-21	-43	-37
Norderney	48	45	24	2	-11	4
Wilhelmshaven	51	47	30	-5	-11	-5
Lt. Alte Weser	51	58	20	5	-11	-8
Cuxhaven	52	69	33	-14	-29	-19
Helgoland	45	52	20	-2	-13	-4
Büsum	64	74	46	28	24	34
Husum	78	91	51	-3	-15	-31
Wittdün	86	80	43	-8	-13	-7
Dagebüll	103	88	54	-24	-54	-76
List	77	57	27	-4	-6	-5

Tabel 4: Trends in the time series (TLW- and THW-Quantiles) from 1954 to 1991 of selected tide gauges along the German Bight

The trend of extreme high water levels (e.g. $THW_{99\%}$) is much steeper than the trend of the mean high water levels (e.g. $THW_{50\%}$). The same can be seen for the most low water levels and extreme low water levels ($TLW_{1\%}$).

Depending on the period, its length and the treatment of the available data slightly different results for MSL variations can be found, given for three representative gauges (fig. 13) in Table 5.

Location	Period	Treatment	Secular Trend cm/100 years
Cuxhaven	1925-1974	hourly values	20+/-6
	1855-1987	yearly means	14+/-6
	1945-1987	yearly means	-1+/-3
	1906-1986	mean tide curves	12+/-3
	1955-1991	yearly means, (MT½w)	13+/-6
	1892-1991	yearly means, (MT½w)	19+/-8
Borkum	1933-1988	mean tide curves	15+/-3
	1955-1991	yearly means, (MT½w)	23+/-5
Helgoland	1953-1986	hourly values	1+/-4
	1916-1986	mean tide curve	4+/-1
	1955-1991	yearly means, (MT½w)	13+/-6

Table 5: Different estimations (data basis, length of the time series and method) for MSL changes for three representative gauges

The almost tide-free Baltic Sea may be regarded as a damped gauge of the North Sea (Jensen and Töppe, 1986). The centennial change of the MSL in the Baltic Sea (Travemünde gauge) amounts to 16 cm/100 years during the period 1826 to 1990 (N = 165 years). The trend increases when shorter periods are investigated (last decades). In comparison to the behaviour of the North Sea, the mean water levels at the Travemünde gauge show a behaviour similar to the MSL of the North Sea.

Time series and trend-corrected time series of annual extreme water levels (storm-tide water levels) allow us to make assessments concerning storm surge intensity based upon probability theory of the frequency of occurrences of storm tides (Jensen, 1985).

Selection of data sets and its impact on results

Many investigations apply statistical tools and data selection criteria that deal with tide gauge data. This will be addressed by examples.

Trend investigations can be based on different time windows for the calculation of running means. An example showing the impact of the window length is given in figure 15. Displayed are MHW as well as MLW registered by the tide gauge Bremerhaven. The large differences are obvious, although the length of the windows only differs from 20 to 30 years. Similar results have been published by Lohrberg (1989; see also Jensen, 1984; Führböter and Jensen, 1985). A part of the curves could be explained by dredging, training works etc. in the Weser estuary and the influence of the nodal tide. The trend curves can be described by a superpositioning of periodic parts (Jensen *et al.* 1991).

Extreme events may be neglected to get more significant information on trends of mean high or low water levels. With regard to MHW, a result is shown in figure 16.

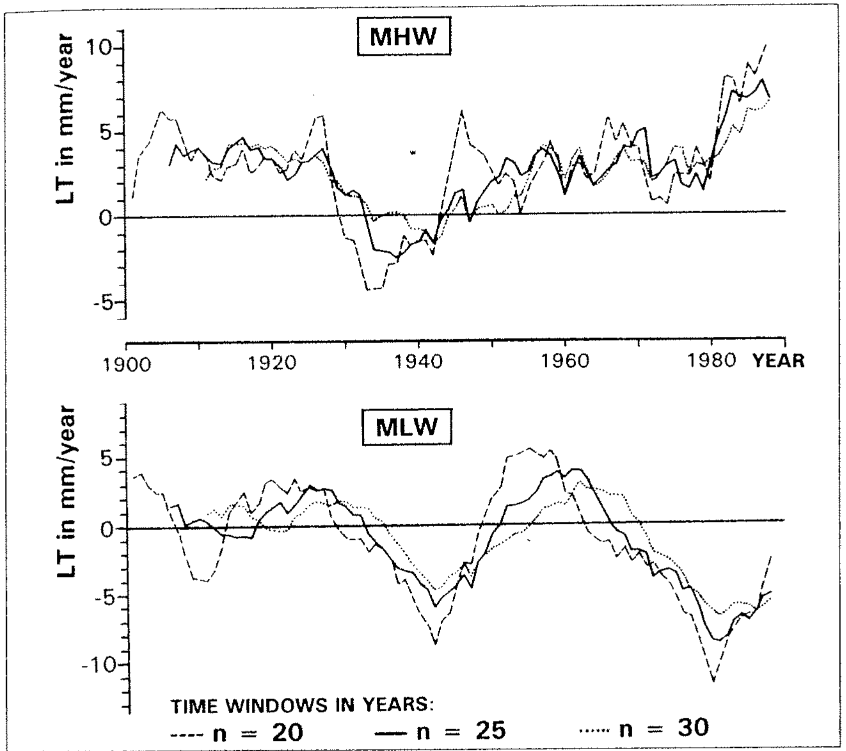

Figure 15: Linear trends for MHW and MLW calculated with different time windows; tide gauge Bremerhaven (Kunz & Niemeyer, 1993)

The upper graph compares linear trends of the tide gauge Wilhelmshaven (time window of 20 years) gained by investigations which were based on all tides (solid line) and on tides below the level of storm surges (dashed line; see also tables 4 and 5).
The probability method (DNA, 1979; Rohde 1979) used defined specific frequencies of occurrence differentiated by three grades of severeness (f < 10; 0.5; 0.05 with f = occurrences per year). The differences between the two graphs can be seen in the figure lower: they reach from about +3 to -4 cm; a kind of periodic pattern can be recognised. Investigations concerning MLW lead to comparable results.

It is also essential to consider the long term trend of the MHW (secular rise). Data have to be corrected with respect to a non-horizontal reference level, neglecting the secular rise will lead to falsified results; an artificial trend of increasing storm surge frequency is created which does not exist in reality. An example is plotted in figure 17 for the tide gauge Norderney.

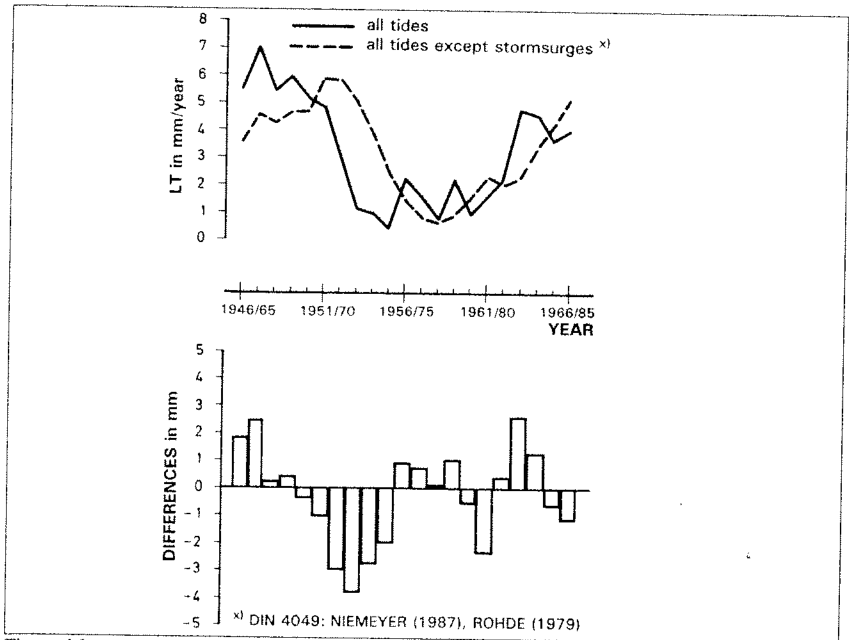

Figure 16: Linear trends of MHW-level rise for different data sets; tide gauge Wilhelmshaven (Niemeyer, 1987)

To get valid information on trends of storm surge climate, it is recommended to base investigations on time series with a length of at least two return periods. Reported frequencies differ quite a bit: 7 years (Siefert, 1989) to 60 years (Lüders, 1936).

There is no definite proof for a long term tendency of increasing storm surge frequency; extraordinary storm surges occurred in former times as well (Niemeyer, 1987, Halcrow/NRA ,1991), but some authors claim that such tendency exists (e.g. Lamb, 1982).

Conclusions

A rise in the MHW (≈25 cm/100 years), which has accelerated over the past decades, is found at all of the stations (all references to trends in the MSL, MHW etc. are considered to be *relative* changes between the land and sea level). The MLW sank slightly during the beginning of the second half of this century but subsequently has stabilised or shows a light positive trend. This results in a MTR increase (≈20 cm/100 years) for the tide gauges along the Dutch and German coasts since 1950. In spite of this, the MTR along the British coast seems to decrease. The MT½w, as an approximation for MSL, has therefore not risen as fast as the MHW.

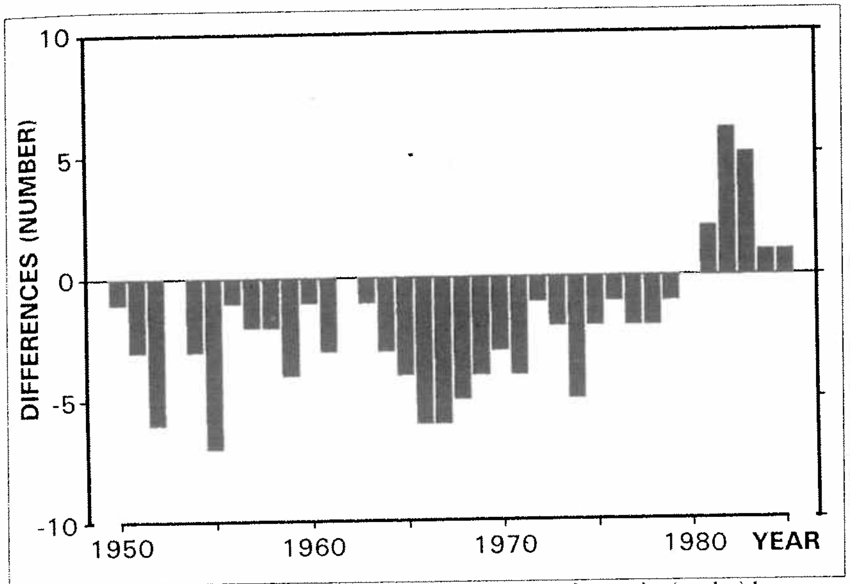

Figure 17: Over- and underestimation of yearly storm surge frequencies (number) by neglecting the linear trend of the MHW; tide gauge Norderney (Niemeyer, 1987)

The rise of MHW compared with constant or decreasing MLW leads to an enhanced increase of the MTR. The rise of MTR is of great importance for tidal dynamics. Enhancement of tidal energy will lead to increased current velocities and sediment transports. This has great impact on the morphological structure of the coastal regions and is of great importance for coastal engineering purposes. The causes for this development must be partly due to dredging, harbour works and delta works (e.g. the closing of several major tidal inlets in the southern part of the Netherlands) and partly due to some up to now unknown external sources which seem to change the tidal amphidromic system in the North Sea.

MSL in a coastal region forms a relatively complicated sphere. The trends of the MHW, MLW, MTR and MSL are not constant, neither with regard to locality nor with regard to time. Depending on data set, evaluation, period and length of period, MSL rise in the southern North Sea varies between 10 and 20 cm/100 years with an overall mean of about 15 cm/100 years. The MSL rise shows a higher tendency in last years, which should not be misunderstood as a significant change in the long term rend. For the interpretation of these results a subsiding in a range from 2 to 8 cm per century must be taken into account.

References

Barth, M.C., Titus, J.G., (eds), 1984: Greenhouse effect and sea level rise, Van Nostrand Reinhold, New York

DNA 1979: DIN 4049 - Begriffe der quantitativen Hydrologie; Deutscher Normen ausschuß (DNA)

Flohn, H., 1985: Das Problem der Klimaänderungen in Vergangenheit und Zukunft, Erträge der Forschung 220

Führböter, A., Jensen, J., 1985: Longterm Changes of Tidal Regime in the German Bight (North Sea). *Proc. 4th Symp. on Coastal and Ocean Management,* Baltimore

Gaye, J., 1951: Wasserstandsänderungen in der Ostsee und der Nordsee in den letzten 100 Jahren, *Die Wasserwirtschaft, Sonderheft:* Vorträge der gewässerkundlichen Tagung 1951 in Hamburg

Görnitz, V., Lebedeff, S. and Hansen, J., 1982: Global sea level trend in the past century, *Science* 215, 1611-1614

Görnitz, V, Solow, A., 1991: Observations of long-term tide-gauge records for indications of accelerated sea-level rise

Halcrow/NRA, 1991: Shoreline Management: The Anglian Perspective, *in*: The future of shoreline management - conference papers: report of the National River Authority and Sir William Halcrow Partners, GB

Heinen, P.H., 1992: Singuliere Spectrum Analyse toegepast op tijdreeksen (in Dutch), Rapport DGW-92.031

Hofstede, J.L.A., 1991: Sea Level Rise in the Inner German Bight Since AD 600 and its Implications upon Tidal Flats Geomorphology, *in* Brückner and Radtke (*Ed.*): Von der Nordsee bis zum Indischen Ozean. Franz Steiner Publ., Stuttgart

Jensen, J., 1984: Änderungen der mittleren Tidewasserstände an der Nordseeküste. *Mitt. des Leichtweiß-Inst.*, Vol. 83, Braunschweig

Jensen, J., 1985: Über instationäre Entwicklungen der Wasserstände an der Nordseeküste, *Mitt. Leichtweiß-Institut der TU Braunschweig,* Vol. 88

Jensen, J., Töppe, A., 1986: Zusammenstellung und Auswertung von Original-aufzeichnungen des Pegels Travemünde, *DGM,* Vol. 4

Jensen, J., Mügge, H.-E., Schönfeld,W., 1990: Development of Water Level Changes in the German Bight, an Analysis based on Single Value Time Series. *Proc. 22nd ICCE,* Delft, ASCE, New York

Jensen, J., Mügge, H.-E., Schönfeld,W., 1992: Wasserstandsentwicklung in der Deutschen Bucht, *Die Küste,* Vol. 54

Kunz, H., Niemeyer, H.D., 1993: Der Einfluß des Datenkollektivs sowie gewählter Bezugshorizonte auf Ergebniss statistischer Untersuchungen zum Wasserspiegelanstieg an der niedersächsischen Küste, *Jahresbericht Forschungsstelle Küste,* Norderney

Lamb, H. H., 1982: Climate, History and the Modern World, S. Methuen & Co. Ltd., London and New York

Lassen, H., 1989: Örtliche und zeitliche Variationen des Meeresspiegels in der südlichen Nordsee. *Die Küste,* Vol. 50

Lassen, H.,Sieffert, W., 1991: Mittlere Tidewasserstände in der südöstlichen Nordsee - säkularer Trend und Verhältnisse um 1980. *Die Küste,* Vol. 52

Lohrberg, W., 1989: Änderungen der mittleren Tidewasserstände an der Nordseeküste, *DGM,* Jahrg. 33, Vol. 5/6

Maisch, M., 1989: Der Gletscherschwund in den Bündner-Alpen seit dem Hochstand von 1850, *Geographische Rundschau* 41(9), 474-485

Niemeyer, H.D., 1987: Zur Klassifikation und Häufigkeit von Sturmtiden; *Jahresbericht 1986, Forschungsstelle Küste,* Vol 38, Norderney

Oerlemans, J., 1988: Simulation of historic glacier variations with a simple climate-glacier Model, *Journal of Glaciology,* Vol. 34, No. 118, 333-41

Oerlemans, J., 1989: A projection of future sea level, *Climatic Change* 15, 151-174

Rohde, H., 1977: Sturmfluthöhen und säkularer Wasserstandsanstieg an der deutschen Nordseeküste, *Die Küste,* H.30

Rohde, H. 1979: Die neue DIN 4049 - Teil 1 - Hydrologie, Begriffe, quantitativ, *Wasser und Boden,* 31, Vol. 12

Schönfeld, W., Jensen, J., 1991: Anwendung der Hauptkomponentenanalyse auf Wasserstandszeitreihen von Deutschen Nordseepegeln, *Die Küste,* Vol. 52

Siefert, W.,Lassen, H., 1985: Gesamtdarstellung der Wasserstandsverhältnisse im Küstenvorfeld der Deutschen Bucht nach neuen Pegelauswertungen. *Die Küste,* Vol. 42

Siefert, W., 1989: Mean Sea Level changes and storm surge probability, *Proc. XXIII IAHR/AIHR-Congress,* Ottawa

Streif, H., 1989: Barrier islands, tidal flats and coastal marshes resulting from a relative rise of sea level in East-Frisia on the German North Sea coast, *Proc. KNGMG Symp. "Coastal lowlands, Geol. and Geotechn.",* 1987

Töppe, A., 1992: Zur Analyse des Meeresspiegelanstiegs aus langjährigen Wasserstandsaufzeichnungen an der Deutschen Nordseeküste, Promotion, *Mitt. Leichtweiß-Institut der TU Braunschweig.*

Vautard, R. and Ghil, M., 1989: Singular Spectrum Analysis in nonlinear dynamics, with application to paleoclimatic time series, *Physica* D35 (1989)

Veen, J. van, 1954: Tide gauges, subsidence gauges and flood-stones in the Netherlands, *Geologie Mijn.* NS 16

Wigley, T.M.L. and Raper, S.C.B., 1987: Thermal expansion of sea water associated with global warming, *Nature* 330

Long Term Wave Statistics

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Abstract

Long term wave statistics are needed for many applications in coastal engineering and oceanography in the southern North Sea. Three sources of wave data are available: visual observations, wave measurements and hindcast data from numerical wave models. The availability of these sources and their reliability are discussed. A review is made of applications of long term wave statistics to coastal problems in the southern North Sea.

Introduction

Long term wave statistics are important in many research and engineering studies. We may define long term wave statistics as the distribution of wave characteristics over periods of years rather than hours. In the short term of about 1 hour, waves are characterised by a spectrum giving the energy of the waves as a function of frequency. The area under the spectrum is m_0 which provides the definition of significant wave height, H_s, given by $H_s = 4m_0^{1/2}$. A corresponding wave period can be associated with this wave height and this is often chosen to be the mean zero-crossing period, T_z, or the spectral peak period, T_p. Finally, a wave direction, θ_p, associated with the direction at the spectral peak, is often used to characterise the direction of the wave system. A sea state can thus be defined in the short term by its height, period and direction.

In contrast, long term wave statistics are associated with the probability distribution of wave height, period and direction taken over many years.

Three types of information on long term wave statistics are available in the southern North Sea. These are derived from visual observations, wave measurements and hindcast data synthesised from numerical wave models. The largest data base consists of visual observations from ships and from offshore platforms in the southern North Sea.

Visual observations have been made for many years and various compilations of these statistics have been produced by different countries in the form of atlases.

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