SEA LEVEL RISE IN THE INNER GERMAN BIGHT (GERMANY) SINCE AD 600 AND ITS IMPLICATIONS UPON TIDAL FLATS GEOMORPHOLOGY

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ABSTRACT

Using all currently available relevant climatological and sea level data, a probable mean high-water (MHW) curve for the Inner German Bight covering the period from about AD 600 onwards was established.

A MHW rise of about 0.23 ± 0.9 cm/yr between AD 600/700 and AD 1200/1300 culminated in the medieval Climatic Optimum peak level which lasted till 1400 at the latest. During this period MHW was about as high as today. Subsequently it fell about 15 to 20 cm. From 1520 till about 1590 the MHW level remained more or less stable. From 1590 on it fell again, this time culminating in the Little Ice Age lowstand which lasted from 1650 till 1700. During this period MHW was about 25 to 30 cm lower than today. Between 1700 and 1890 a small MHW rise of about 3 to 8 cm occurred. Since 1890 MHW is rising 0.22 cm/yr at the tide gauge of Cuxhaven.

The morphological development of the supratidal sands in the Inner German Bight seems to reflect these changes in sea level. Aeolian processes, vegetation, agriculture and/or settlement took place in a concentrated manner during regressive phases, whereas transgressive periods were characterized by flooding and, since the last century, by protective measures. Until 1850 the supratidal sands probably remained more or less in the same position; since 1850, however, they are drifting coastward with increasing velocity.

1. INTRODUCTION

The German North Sea coast is part of the Wadden Sea which ranges from Den Helder in the Netherlands to Esbjerg in Denmark. The German sector can be subdivided into three regions; the East Frisian Islands, the Inner German Bight (Fig. 1) and the North Frisian Islands. This tripartition can be seen as a result of variation in tidal range (STREIF 1978). Along the East and North Frisian Islands tidal range varies between 1.5 m and 2.9 m (SIEFERT & LASSEN 1985), which promotes the formation of barrier islands. In the Inner German Bight tidal range exceeds 3.0 m, which means that barrier islands cannot develop. In their position large mostly unvegetated supratidal sands exist. These sands can be characterized as barrier islands which persist in their „embryo"-stage of development (HOFSTEDE, in press).

H. Brückner & U. Radtke:
Von der Nordsee bis zum Indischen Ozean.

During the past 10 years extensive investigations concerning the impact of increasing levels of carbon dioxide and other „greenhouse" gases in the atmosphere upon the world's climate and mean sea level, respectively, have been carried out. It is now generally accepted that one consequence of the human-induced climatological changes will be an acceleration in mean sea level rise. However, the magnitude and character of this speeding up are still subject to discussion (Fig. 2).

Compared to the barrier islands, the supratidal sands in the Inner German Bight are more sensitive to changes of the hydrological regime. However, both function as a major natural defense line for the tidal flats as well as the mainland against the incoming deep-water waves from the North Sea. Therefore, in the context of German coastal protection it is of high interest how these sands will react upon the expected acceleration in sea level rise.

The following developments seem to be possible. Firstly, sea level rise could reach such dimensions that the sands will submerge. This would mean that the tidal flats as well as the mainland coast in the Inner German Bight will be exposed to the large deep-water waves. As a result the tidal flats would probably become subjected to severe erosion and the mainland would have to be „fortified" at immense costs to prevent landlosses. Secondly, the sands could be able to balance sea level rise. However, for this scenario large quantities of sediment are necessary. As longshore drift will probably not intensify under the influence of an acceleration in sea level rise, other sources would have to be found. One such source area could be the broad subtidal shoreface and the intertidal foreshore. At Scharhörn (Fig. 1) for instance, these two zones reach about 8 km west of the Scharhörn sand. However, this would mean that the beach-profile becomes steeper. As a consequence larger waves could reach the sands and induce erosion. A coastward retreat of the entire tidal flats could also release large quantities of sediment. This is what most probably occurred during the strong early and middle Holocene sea level rise. This progressive „thinning" of the Wadden Sea area would have serious effects upon the present coastline.

One way to evaluate which of the above mentioned scenarios is most likely to happen is a reconstruction of the former interaction between hydrological and morphological changes. This reconstruction is the main topic of this article.

Although the sands probably already existed more or less in their modern position about 4500 years ago (Hofstede, in press), the oldest reliable historic data on the sands reach back to about AD 1300 (Lang 1970; 1975). This means that a reliable reconstruction of the interaction between hydrological and morphological changes can only be made for the last 700 years. Additional data upon the drifting of the sands since about 1800 come from Göhren (1975) and Ehlers (1988).

The modern behaviour of the sands seems to be controlled mainly by the MHW level and storm surge intensity and frequency (Hofstede, in press). Therefore, „hydrological" attention was focussed upon these two aspects.

In literature two MHW curves exist for the German Bight covering the past 2000 years (Linke 1982; Rohde 1985; Fig. 7). According to these curves sea level was rising constantly by about 0.25 cm/yr since 1500 (Rohde 1985) or by about 0.16 cm/yr since about 700 (Linke 1982). However, more recent sea level studies (Görnitz & Solow 1989, Hanisch 1980, Streif 1989) do not seem to support these curves.

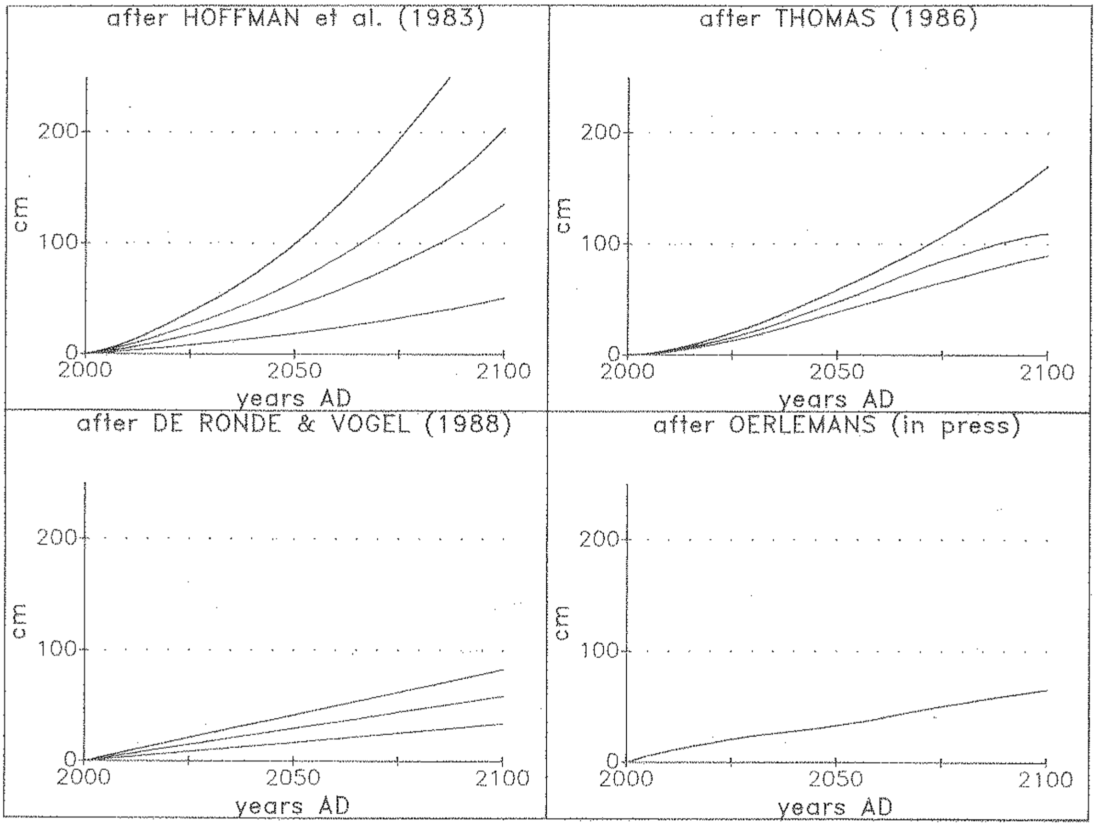

Fig. 2: Estimates of total sea level rise during the next century according to different authors.

The author thought it therefore necessary to re-evaluate the existing sea level data from the German North Sea coast and to reconstruct a new MHW curve (Fig. 3). This curve is based on all currently available sedimentological, morphological, botanical, archaeological and historical sea level data. It should be stressed that future investigations will allmost certainly make it necessary to improve the suggested curve.

Storm surge investigations in the German Bight have been carried out by Linke (1982) for the last 6000 years, by Rohde (1977) for the last 300 years, and by Siefert (1984) for the last 50 years. Additionally the results of Lamb's storm surge investigations for Northwest Europe since about 1000 were taken into consideration (Lamb 1982; 1984).

2. SEA LEVEL RISE IN THE INNER GERMAN BIGHT SINCE AD 600

2.1 The MHW curve from about AD 600 till 1890

Based upon dated *Scrobicularia plana* shells and salt-marsh samples from the East Frisian barrier islands Wangerooge and Juist Streif (1989) concluded that the MHW level along the East Frisian Islands was between 0.0 and 0.4 m NN (Normal Null = German Ordinance Date) between 600 and 800.

Furthermore he was able to establish a MHW level of about 1.22 to 1.35 m NN for a certain time interval between 1125 and 1395 along the East Frisian Islands. This would mean that the modern MHW level in this area was already reached about 500 to 800 years ago. So for the first time since the last glacial period sea level fluctuated around the same level for a period of 500 to 800 years. Furthermore, as MHW is rising about 0.22 cm/yr since about 1890 at Cuxhaven a MHW fall of at least 22 cm must have occurred sometime between 1400 and 1890. As for the period 1400–1700 no dated sea level markers from the North Sea coast are available, we have to rely on (climatic) sea level indicators.

The longest temperature record for Northwest Europe has been established for England by LAMB (1977). It reaches back to about AD 900. Based upon this record and other climate indicators, BARTH & TITUS (1984) reconstructed a global temperature curve since about 900 (Fig. 3). This curve shows that the period between AD 900 and 1200 was characterized by increasing temperatures. According to GÖRNITZ et al. (1982) a mean global temperature rise of 1 °C will result in a sea level rise of about 16 cm, caused by thermal expansion of the upper layers of the oceans. Other authors, however, mention a rise of 4 to 10 cm per degree warming (WIGLEY & RAPER 1987; OERLEMANS, in press). So at least part of the MHW rise between 600 and 1100/1200 was caused by increasing temperatures. However, since MHW level must have risen 0.9 to 1.3 m between AD 600 and 1100/1200 this factor was insignificant. The greatest part of the MHW rise must therefore have been caused by glacio-isostatic rebound and/or halokinetic subsidence.

The time span from about AD 1000 to 1350 is generally called the medieval Climatic Optimum. According to BARTH & TITUS (1984), the 50-year global mean temperature for the time span 1200/1250 was a little higher than the 1900/1950-mean. Based upon dendroclimatological investigations in the Alps and Lapland (Scandinavia), SCHWEINGRUBER et al. (1988) showed that the period from about 1070 till 1220 was characterized by above average summer temperatures in the Alps (Fig. 3). The MHW highstand between 1125 and 1395 according to HANISCH (1980) and STREIF (1989) correlates well with the above mentioned climatological data.

The MHW peak level was accompanied by a peak in storm surge activity in the 14th century (LAMB 1984; Fig. 3). The combination of these two factors caused severe losses in land and human lives along the German North Sea coast during the Climatic Optimum, for instance during the so-called „Große Mandränke" (Second Marcellus Flood) of 16 January 1362.

The medieval Climatic Optimum was followed by a severe deterioration. Between AD 1250 and 1500 global temperature dropped by about 0.9 °C. Using the calculations of GÖRNITZ et al. (1982), this might have resulted in a thermally induced sea level lowering up to about 14 cm. The falling temperatures most probably induced expansion of glaciers which might have resulted in an extra fall in sea level. According to MÖRNER (1984) the medieval sea level maximum around 1250 was followed by the first Little Ice Age lowstand around 1525 in the area of Stockholm (Sweden). Accordingly, the MHW level in the Inner German Bight might have dropped by about 15 to 20 cm between 1400 and 1520.

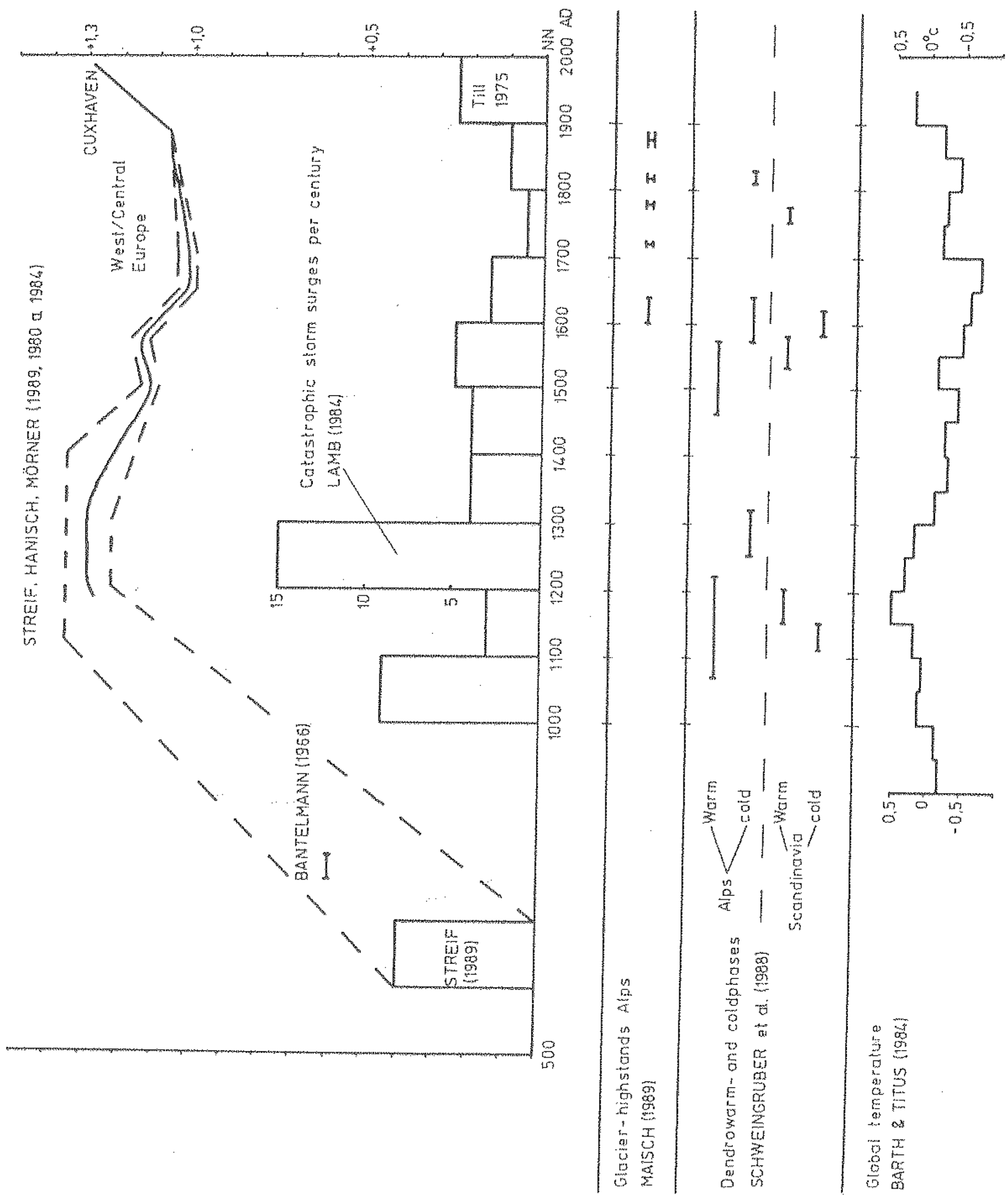

Fig. 3: Probable MHW curve for the Inner German Bight since about AD 600. The proposed curve is compared with the number of catastrophic storm surges per century in north-west Europe (LAMB 1984), with highstands of glaciers in the Alps (MAISCH 1989), with dendro-warm and dendro-cold phases (SCHWEINGRUBER et al. 1988) and with a global temperature curve (BARTH & TITUS 1984).

According to SCHWEINGRUBER et al. (1988) summer temperatures were above average in the Alps between 1460 and 1570, and in Lapland between 1530 and 1570. This rise in temperature can be recognized in the global temperature curve of BARTH & TITUS (1984) as well. These data suggest that the time interval from 1500 till about 1570 was characterized by a small climatic amelioration. This might have induced a small MHW rise between 1520 and 1590. It is noteworthy that the most catastrophic storm flood along the German North Sea coast between about 1500 and 1800 took place in 1570.

According to the temperature curve of BARTH & TITUS (1984) and the dendro-climatological data of SCHWEINGRUBER et al. (1988) 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. Besides that, in the Alps the first great expansion of glaciers during the Little Ice Age occurred between 1600 and 1640 (MAISCH 1989). So it seems realistic to suggest that the MHW lowstand of the Little Ice Age was reached around 1650, at which time MHW might have been about 25 to 30 cm lower than the Climatic Optimum highstand. According to LAMB (1982) the difference between the medieval highstand and the Little Ice Age lowstand along the British North Sea coast might have amounted to 50 cm. MÖRNER (1984) determined a second Little Ice Age lowstand around 1640 at Stockholm.

During the Little Ice Age, storm flood activity reached a lowstand (LAMB 1984; Fig. 3).

From 1700 on, sea level has been recorded at the tide gauge of Amsterdam (Netherlands). So from this time on more or less accurate sea level data are available. GÖRNITZ & SOLOW (in press) have examined 21 long-term tide gauges on fluctuations in sea level rise. Based on ten west European tide gauges they were able to establish a normalized mean sea level curve for west-central Europe reaching back to 1700 (Fig. 4). The following ten tide gauges were used: Amsterdam (1700–1940), Brest (1807–1970), Den Helder (1832–1985), Aberdeen (1862–1965), Vlissingen (1862–1985), Hoek van Holland (1864–1985), Delfzijl (1865–1985), Harlingen (1865–1985), Ijmuiden (1872–1985) and West Terschelling (1887–1985). From this curve it can be seen that between 1700 and 1895 no significant mean sea level fluctuations occurred. However, a stable mean sea level does not necessarily mean that MHW remained constant. Independent changes in tidal range might induce a MHW change as well. Momentarily investigations on tidal range fluctuations along the Dutch North Sea coast since 1700 are being carried out. The first results seem to suggest that no significant changes took place between 1700 and 1850. So probably MHW did not change significantly between 1700 and 1895 as well.

For the west-central European curve no German tide gauges have been used. Therefore, the author established a normalized mean sea level curve for Cuxhaven (the only tide gauge along the German North Sea coast which has been recording sea level data long enough before 1895) since 1855 (Fig. 4). The conformity of both curves since 1855 seems to suggest that the west-central European curve is valid for the German North Sea coast as well.

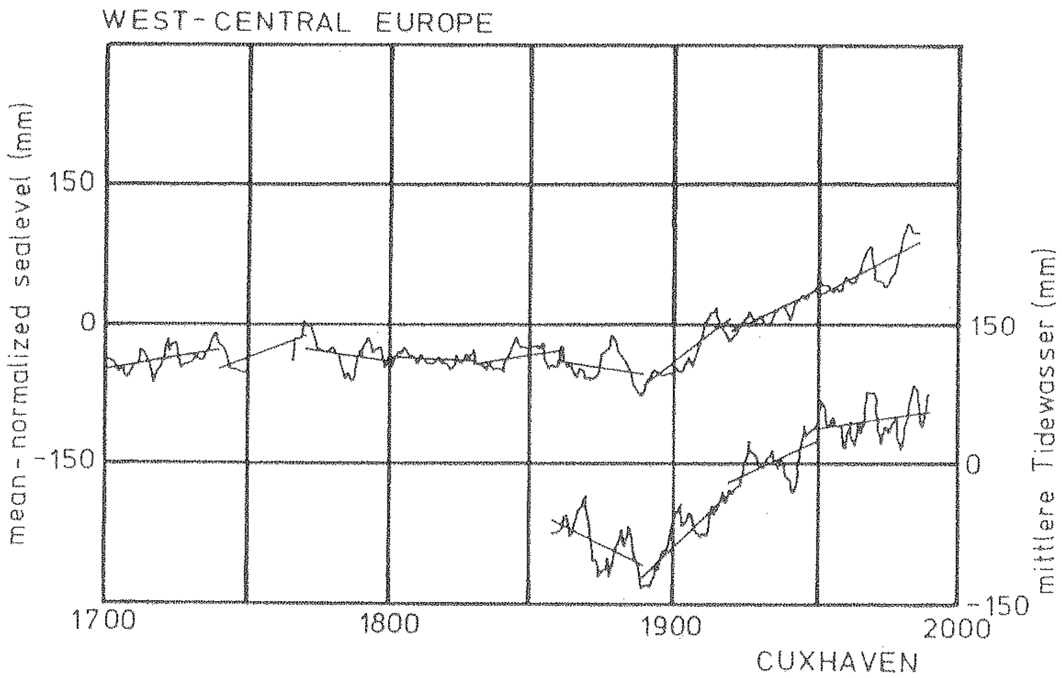

Fig. 4: Mean sea level curves for west-central Europe (GÖRNITZ & SOLOW, in press) and for Cuxhaven. The data are smoothed, using the 5-year running mean. The least squares linear trends for successive 30-year intervals are shown.

EKMAN (1988) has investigated the glacio-isostatic upheaval in the area of Stockholm since 1774. He calculated two linear regressions for two succeeding centuries:

$$\Delta H_{(1774-1874)} = 4.93 \pm 0.23 \text{ mm/yr}$$
$$\Delta H_{(1874-1984)} = 3.92 \pm 0.19 \text{ mm/yr.}$$

EKMAN (1988) explains the difference of 1.01 ± 0.3 mm/yr between both regressions by the post Little Ice Age sea level rise of about 1 mm/yr. This would mean that in the area of Stockholm no thermal-eustatic sea level rise occurred from 1774 till 1874.

According to FLOHN (1985) the period from 1700 till about 1850 was characterized by a very unstable climate. Alltogether, a small temperature rise seems to have happened. Between 1640 and 1850 glacier variations seem to have been within a limited range, while after 1850 a world-wide retreat began (OERLEMANS, in press). So once again, the climatological data correspond well with the reconstructed MHW curve.

As stated above, storm flood intensity remained low till about 1800 to 1850.

As already stated in the introduction, two MHW curves from the German Bight, covering the last 2000 years, have been published (LINKE 1982, ROHDE 1985; Fig. 7).

Both curves, however, do not seem to be up-to-date anymore. In ROHDE's (1985) curve the medieval MHW highstand (HANISCH 1980; STREIF 1989) is situated about 300 to 500 years too early, and in LINKE's (1982) curve it fails altogether. Furthermore, the regression of about 80 cm between 900 and 1500 in the MHW curve from ROHDE (1985) would ‚heave' large parts of the tidal flats above MHW level, which should have resulted in extensive aeolian activity upon the tidal flats. Up till now no aeolian sediments have been found here, which could be dated into this period. Besides, no documents dealing with aeolian activity on the tidal flats exist. Finally, according to new sea level data (GÖRNITZ & SOLOW, in press) as well as climatological data (FLOHN 1985; BARTH & TITUS 1984), a constant MHW rise since 1550 of about 20–30 cm per century seems to be very unlikely.

2.2 The MHW rise since 1890 and its causes

From Fig. 4 it is evident that mean sea level started to rise about 1890. This „knickpoint" can be found in the MHW curves as well. However, different tide gauges show different rates. In the Netherlands, MHW rise varies between 0.19 and 0.33 cm/yr (DE RONDE & VOGEL 1988), along the German North Sea coast between 0.19 and 0.32 cm/yr and in Cuxhaven finally it amounts to 0.22 cm/yr (Fig. 5a).

In the Netherlands mean sea level rose about 11 to 15 cm between 1890 and 1960. According to VAN MALDE (1984) no significant mean sea level rise occurred along the Dutch coast after 1960. As can be seen in Fig. 5 the same development took place in Cuxhaven. Between 1890 and 1960 mean sea level rose by about 17 cm and stabilized subsequently.

Fig. 5 shows also that about 5 cm of the MHW rise of 22 cm since 1890 has been caused by an increase in tidal range since about 1960. So 17 cm of sea level rise since 1890 remain to be explained.

Almost certainly thermal expansion of the upper layers of the ocean will have contributed to this rise. However, different authors mention different values for this component, ranging between 2 and 8 cm (GÖRNITZ et al. 1982, WIGLEY & RAPER 1987, OERLEMANS, in press).

Another factor that certainly contributed to the MHW rise since 1890 is the globally observed glacier retreat since about 1850 to 1890. Here the estimates range from 1.5 to 4 cm (MEIER 1984) or 3.5 cm according to OERLEMANS (in press).

Thermal expansion combined with glacier retreat might have contributed 10 to 15 cm to the MHW rise since 1890 according to THOMAS (1986) and 9.5 cm according to OERLEMANS (in press).

This means that at the tide gauge Cuxhaven 2 to 7.5 cm of the recorded MHW rise since 1890 must have been induced by other non-global mechanisms. As the Inner German Bight lies in the vicinity of Scandinavia it seems reasonable to suggest regional glacio-isostatic subsidence as one of the causing factors. However, based upon geodetic surveys carried out between Hamburg and Cuxhaven since 1855, LASSEN et al. (1984) were able to exclude this possibility: between 1855 and 1980 a significant (i.e. > 2 cm) tectonic or glacio-isostatic subsidence did not take place in the area of Cuxhaven.

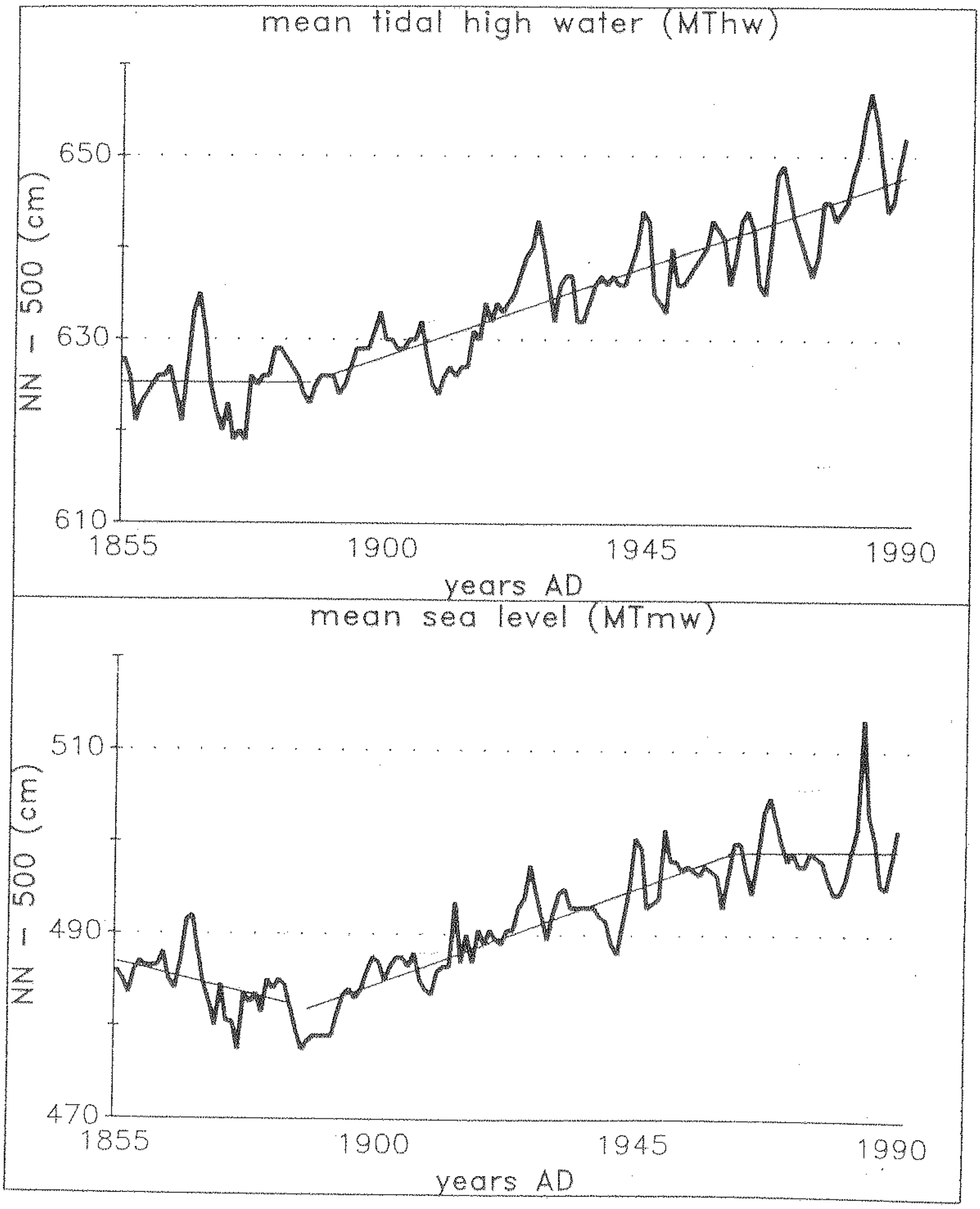

Fig. 5: Sea level rise at the tide gauge Cuxhaven since 1855. The data are smoothed, using the 3-year running mean.

Another regional mechanism that might have had some influence are geoidal changes. Along the Dutch shoreface for instance, the geoidal sea level shows an absolute height difference of about 100 to 150 cm (VAN WILLIGEN 1986). According to NEWMAN et al. (1980) the shifting of the geoid caused a sea level rise of about 100 cm between 4000 and 2000 BP in north-western Europe. This value is still subject to controverse discussion. According to MÖRNER (1976) local geoidal changes can induce short-term sea level fluctuations. However, he is unable to support this hypothesis by examples.

Subsequent to global and/or regional mechanisms, local processes can induce significant sea level changes as well. Along the Danish west coast, height differences between spring and autumn sea level amounting up to 20 cm have been recorded (CHRISTIANSEN et al. 1985). These differences are caused by seasonal meteorologic and oceanographic circumstances as for instance changes in wind set-up or air pressure.

More long-term fluctuations, as for instance spatial changes in cyclonic activity, can influence local sea level, too (LAMB 1980). Changes of the wind component of the climate can induce changes in wind set-up. At the tide gauge of Esbjerg (Denmark) the influence of wind set-up upon local sea level varied between 11 and 13 cm during the period 1900–1940 (DIETRICH 1954). According to ROHDE (1977), the impact of wind set-up in Cuxhaven has been fluctuating periodically since 1840. Maxima were reached around 1840 and 1920/25, minima around 1875/80 and 1950/55. So the influence of wind set-up upon local sea level in Cuxhaven has been decreasing from about 1840 to 1876 and from 1923 to 1953. The periods of 1876–1923 and 1953–1988 on the other hand are characterized by an increasing wind set-up. The effect of wind set-up upon the MHW curve at the tide gauge Cuxhaven is illustrated in Figure 6. Although this comparison suggests that there is a strong correlation, the results have to be used with care. A hypothetical extrapolation of these periodic fluctuations would predict the next wind set-up maximum in the Inner German Bight around 2000.

SIEFERT (1984) has investigated the storm surge development since 1940 along the German North Sea coast. According to this study, storm surge heights as well as frequency has been increasing since about 1960, which correlates well with the MHW curve. This increase is explained by changes in meteorological conditions as for instance wind directions.

2.3 Synthesis

After a critical evaluation of all presently available sea level and climatological data the MHW development in the Inner German Bight since about AD 600 might have occurred as follows (Fig. 3).

A MHW rise of about 0.23 cm/yr between AD 600/700 and 1100/1200 culminated in the Climatic Optimum peak level sometime between 1200 and 1400 which was comparable with today's MHW level. Between 1400 and 1520, a regression in the order of 15 to 20 cm took place. Until 1590, MHW remained more or less stable. Subsequently another regression until 1650 of about 5 to 15 cm resulted

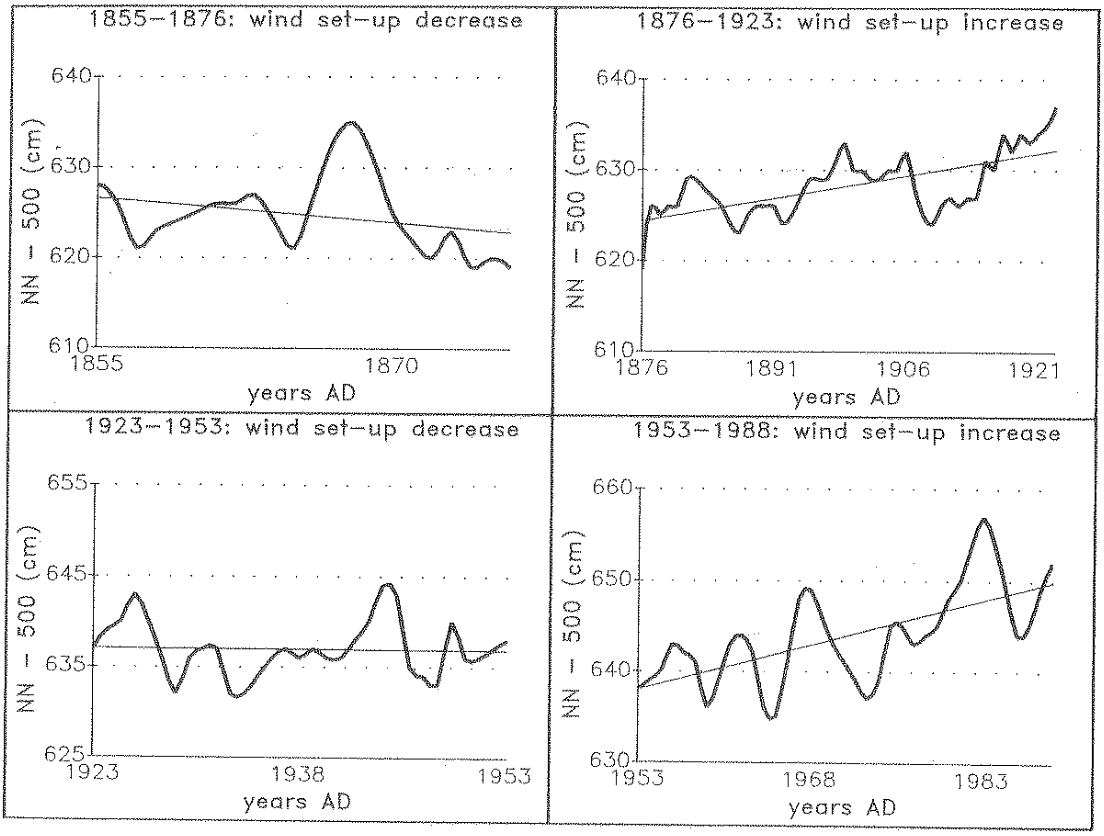

Fig. 6: MHW rise at the tide gauge Cuxhaven (3-year running mean), compared with cyclic fluctuations in wind set-up according to ROHDE (1977). The least squares linear trends for the different time intervals are shown.

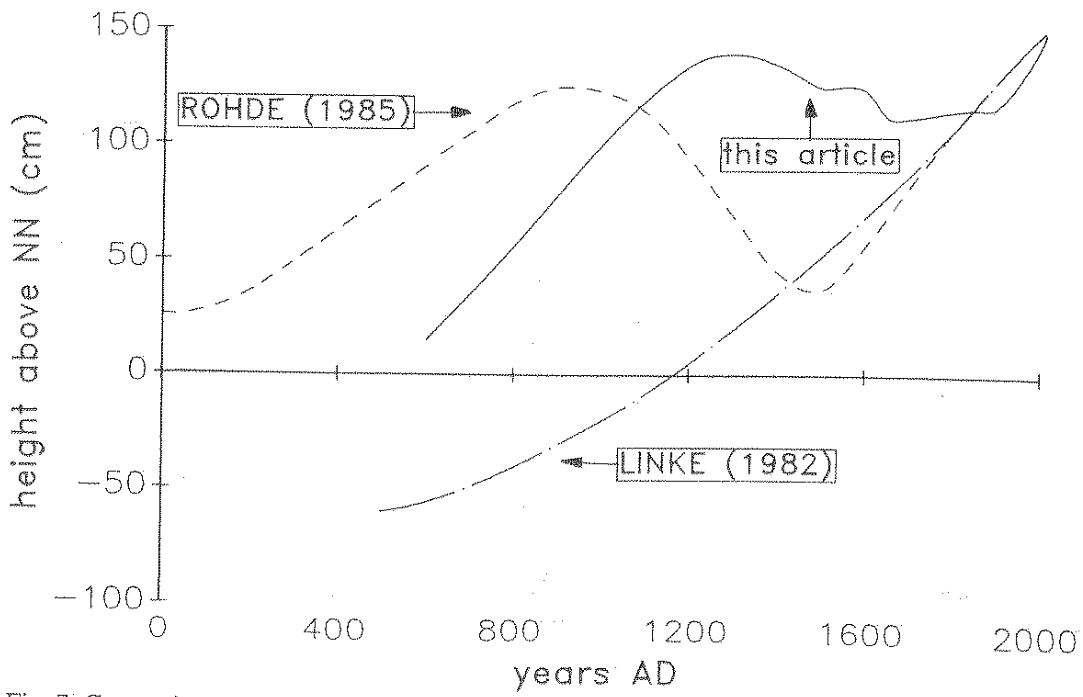

Fig. 7: Comparison of three MHW curves for the German Bight.

in the Little Ice Age lowstand. During this period MHW was about 25 to 30 cm lower than today. Between 1700 and 1890, probably a small MHW rise in the order of 3 to 8 cm occurred in the Inner German Bight. Since 1890, MHW is rising 0.22 cm/yr at the tide gauge Cuxhaven.

This means that the postglacial sea level rise in the German Bight can be divided into three phases. The first period was dominated by the melting of the large Laurentian and Scandinavian ice shields. It ended about 5000 BP. The second phase was characterized by glacio-isostatic rebound. In the Inner German Bight this period ended around AD 1200. The third phase still lasts on and is caused by thermal-eustatic sea level changes.

It is interesting to note that the sea level curve for the German Baltic coast shows a similar course for the last thousand years (Klug 1980). Here a transgressive period culminated in a medieval highstand around 1400. Subsequently, a sea level lowering took place, which lasted till the 17th century. This regression was followed by a slight sea level rise, and since 1850 the modern transgression takes place.

3. HISTORICAL DEVELOPMENT OF THE SUPRATIDAL SANDS

Based upon historical documents, Lang (1970; 1975) carried out extensive investigations with respect to the morphological development of the supratidal sands in the Inner German Bight (Fig. 1). Later, more data became available, especially upon the drifting of the sands (Ehlers 1988, a.o.). The following description is based primarily on Lang's results.

Some of the sands were firstly mentioned during the medieval Climatic Optimum (Scharhörn: 1299, Mellum: 1410). This means that shortly after MHW had reached its medieval highstand at least some of the sands (re)emerged. Consequently, they must have been able to balance a MHW rise of about 0.23 ± 0.09 cm/yr for four to six centuries. Whether this process was accompanied by a shoreward drifting of the sands cannot be reconstructed.

The Blauort sand was first documented in 1551. At least until 1623 it only emerged during low-tide. In 1752, however, a dune has developed, which existed till 1784 at the latest. Accordingly, Blauort exists as a supratidal sand since the 18th century.

Trischen was first mentioned in 1610 and had a vegetation cover around 1721. This cover disappeared around 1735. During the first half of the 19th century three supratidal sands developed. Two of these sands were submerged before 1866. The remaining sand showed a vegetation cover and some primary dune forms by 1854. This sand was influenced superficially between 1868 and 1943. From 1872 till 1899 and, after a period of drownings, from 1907 till 1943 Trischen was inhabited and cultivated. Despite of massive coastal protection measures the sand had to be abandoned in 1943.

Scharhörn was first mentioned in 1299 as a dangerous obstacle for navigation. It is not documented since when exactly a supratidal sand exists in this position; but on a map from 1594 two oval forms can be recognized, suggesting that by this time the sand had emerged above MHW level. A document from 1585 underlines this statement. The sand submerged at least two times (1784 and 1886). Since about 1927 an artificial dune exists on the Scharhörn sand.

The Knechtsand sand was first mentioned in 1683 (Meithorn as probable predecessor in 1575). Like Mellum, it currently experiences erosion (EHLERS 1988).

Mellum was already mentioned in 1410 (GÖHREN 1975). Between 1870 and 1903 a vegetation cover developed, which was probably favoured by the convergence of an old marsh island and a sand bank (HOMEIER 1974).

Table 1 shows the drifting velocity of the supratidal sands during the last centuries. Only a few data exist covering the period before 1850. These few data suggest that the sands probably did not drift significantly before 1850. Since then, however, and especially during the last decades, the sands are drifting with increasing velocity in a coastward direction.

Tab. 1: Mean yearly drifting velocity of the supratidal sands in the Inner German Bight for different periods.

period	Blauort	Trischen	Scharhörn	Knechtsand	Mellum
1551–1846	0				
1560–1860			0		
1789–1859				14	
1876–1904	7				
1868–1968			14		
1885–1967		29			
1859–1969				30	
1939–1967	39				
currently	35	30	33	30	30

4. DISCUSSION AND CONCLUSION

A comparison of the proposed MHW curve for the Inner German Bight with the development of the supratidal sands since the medieval Climatic Optimum shows some striking similarities. Aeolian processes, vegetation cover, agriculture and/or habitation primarily took place during the Little Ice Age. This is reasonable since this period was characterized by a MHW lowstand as well as a low storm surge intensity.

Since the middle of the last century storm surge intensity is rising. Combined with a rising sea level since 1890 this induced flooding and, after a period of protective measures, abandonment. At the same time the sands start drifting in a coastward direction, which occurs in the form of (storm)erosion at their seaward sides and sedimentation at their landward sides. Parallel with an acceleration in storm surge intensity since about 1960 the drifting velocity of the sands is increasing.

Since 1868, the supratidal sand Scharhörn drifted almost 3 km to the east (HOFSTEDE, in press), while the low water line remained in the same position. Consequently, the intertidal zone was increased by about 3 km and the beach angle was lowered correspondingly. According to CHRISTIANSEN (1976), this can be seen as an adjustment to increasing storm surge intensity. However, it means that the drifting of the supratidal sand did not release a significant amount of sediment, needed to rise the height of the tidal flats.

SIEFERT & LASSEN (1987) investigated the development of the hights of the tidal flats between the Isle of Neuwerk and Cuxhaven (Fig. 1) since 1864. They showed that although MHW rose by about 22 cm and the mean storm surge by twice that amount, there was no rise of the mean height of the tidal flats. This means that only the sand Scharhörn was able to balance the MHW rise since 1890, thereby diminishing in area.

Likewise, a MHW rise of about 0.23 ± 0.09 cm/yr for four to six centuries seems to have been balanced by the supratidal sands before 1300. It is not certain, whether this rise was accompanied by a „thinning out" of the tidal flats or not. However, the MHW rise combined with an increase in storm surge intensity, resulted in huge land-losses during the 14th to 16th centuries. So it seems that the rising sea level could only be balanced until a certain internal threshold was exceeded. It should be stressed that this threshold had decreased by human interference, as for instance (insufficient) dike-building and salt-winning in the marshes (BANTELMANN 1966).

Until now the modern MHW rise is balanced by the supratidal sands. The tidal flats on the other hand, seem to have been unable to balance the rise. So it seems to be a matter of time before the natural internal threshold will surpass the critical maximum and massive coastal protection measures will become necessary.

One area, where the natural treshold has surpassed the critical maximum for some time is the Isle of Sylt. Here, the internal threshold had to be reinforced by massive coastal protection measures. In 1990 alone, some 20 million DM had to be invested to restore the damages from the stormy winter of 1989/90. This raises the question how much a country is prepared to invest in coastal protection.

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