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Storm surge development in the Southern North Sea and the Elbe river in Europe during the last century and its practical application

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सार — इस शोध पत्र में पिछली शताब्दी के दौरान यूरोप के उत्तरी सागर तथा एलबे नदी में तूफानी लहरों के उत्पन्न होने के बारे में जानकारी प्रस्तुत की गयी है । परिणामों से पता चलता है कि इस अवधि में तूफानी तरंगों, तूफानी लहरों तथा किनारों पर उठने वाली लहरों की संख्या में तो वृद्धि हुई है, किन्तु इनके स्तर में कोई वृद्धि नहीं हुई है । तूफानी लहरों तथा विशेषकर किनारों पर एक से अधिक भंवर वाली लहरों में वृद्धि पवनों की अवधि बढ़ने के कारण हुई है ।

किनारों पर उठने वाली तथा ऊँची उठने वाली तूफानी लहरों के विश्लेषण से प्राकृतिक जलप्रवाह का अभिकल्पन संभव है ।

ABSTRACT. The development of storm surges during the last century in the European North Sea and the Elbe River is presented. The results show an increase in the number of the storm tides and the storm surge curves, but no increase in the level. The reason for the increase of the storm surge curves - especially those with more than one storm tide crest - must be an increase of the wind duration.

With the analyses of the storm surge curve and the storm surge peak, it is possible to calculate the design dike level.

Key words — Greenhouse, Storm Surges, North Sea, Elbe, Design Level, Frequency.

1. Introduction

In the last decades of this century, climate change, greenhouse effect and sea level rise have increasingly been discussed and, with this, the research and the public interest in the development of storm surges has grown. The discussion is focussed on the question, whether the storm surge climate changes and how the level, number and the duration of the storm surges develop. This knowledge is necessary, for example, for the calculation of the level of the dikes. These questions will be answered in a research project called, 'Storm surge analysis of the North Sea and the Baltic Sea' financed by the German Federal Research Minister.

The aims of the research project are:

(*i*) The registration of storm surge climate changes (level, number and duration) during the 20th century.

(*ii*) The analysis of anthropogenic or natural reasons for possible changes in the storm tide climate.

2. Research area

Research in the European North Sea region is concentrated in the German Bight, especially on the national gauge places Norderney, Cuxhaven, Amrum (Wittdun) and Helgoland (Fig. 1). These four gauges represent the coastline of the German Bight.

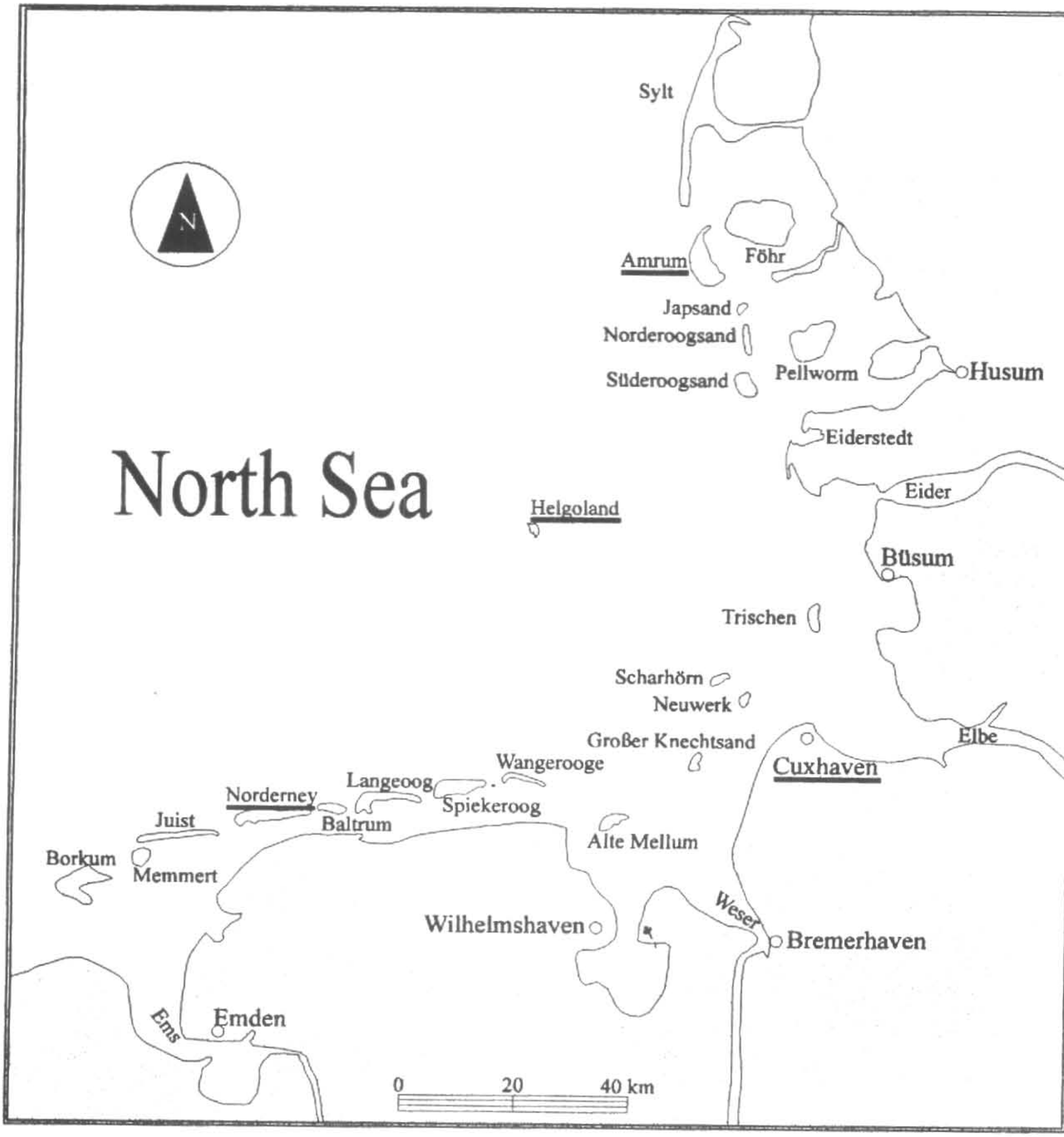

Fig. 1. Research area : The German Bight with main gauges

3. Definition of storm surge for the Southern North Sea

For the research of storm tides and their alteration, storm tides have to be defined exactly. For example, Murty (1984) defines storm tides as "(...) oscillations of the water level in a coastal or inland water body in the period range of a few minutes to a few days, resulting from forcing from the atmospheric weather system". This definition already includes the two necessary points of storm tides: (*i*) the change of the water level and (*ii*) the cause of its change. To integrate the cause of the change of water level in the definition, it is not sufficient to define storm tides only by means

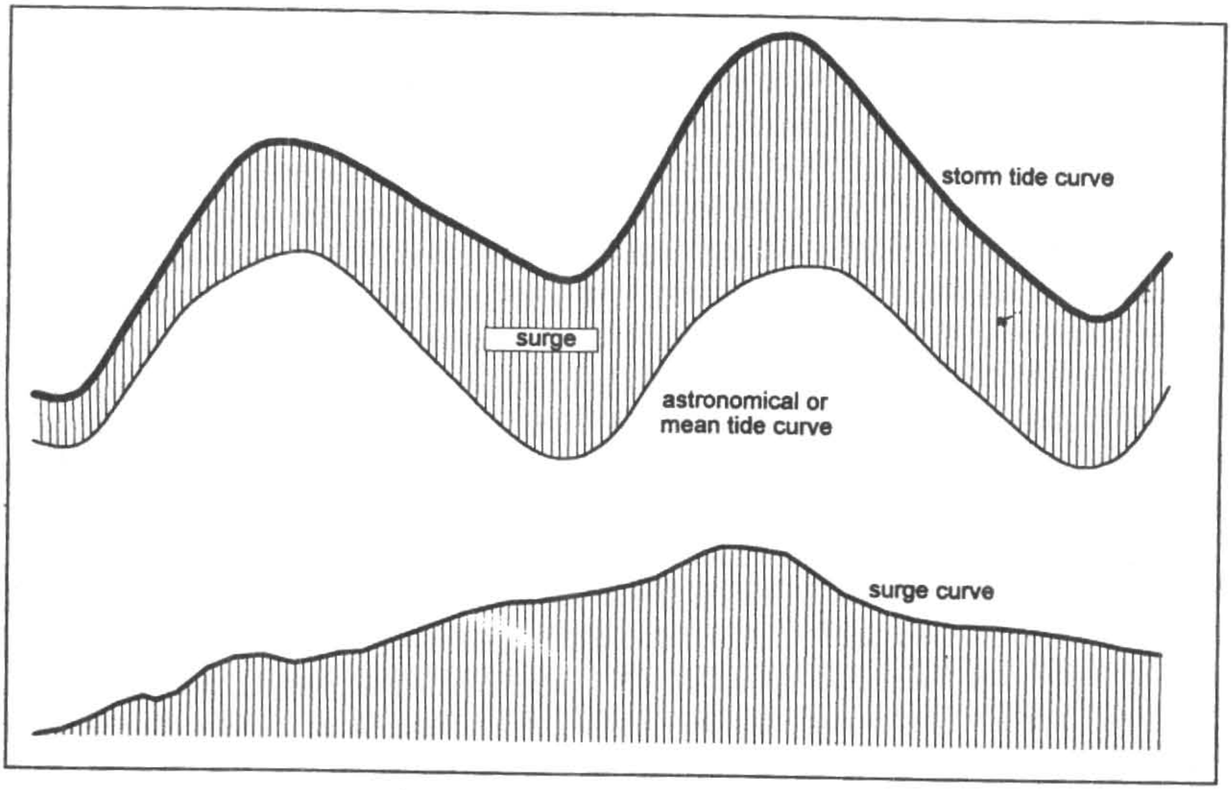

Fig. 2. Definition of the surge

of peak or height in dependence of the yearly frequency. On the basis of such a definition research about the change of storm surge climate is impossible. The reason is that the crests of the storm tides only represent the wind influence on the water body during high tide. To analyse the change of the storm surge climate in detail, it is necessary to take into account the influence of the wind on the whole event, which is more than the peak. A definition which considers the whole event and the physical value of a storm tide is possible with a definition including the rising water level resulting from the effect of wind the surge (Siefert 1968). The surge is described by the surge curve. The storm surge curve shows directly the influence of wind duration, wind direction and wind speed during the tide. Therefore the analysis of the surge curve is the only method which can be used to investigate storm surge climate change in certain detail.

The surge curve can be calculated as Fig. 2.

(a) the difference curve between the actual tide and the astronomical tide predicted for the same time. In this case, the surge curve includes all deviations from this tide, including the astronomical and topographical influences;

(b) the difference curve between the actual tide and the mean tide predicted for the same time. The curve also includes the astronomical part, basically the semidiurnal. It should be used only in areas with relatively small astronomical variations.

Because of the minimal alteration of the astronomical part of the tide in the southeastern North Sea, it is possible to treat wind surge as the difference between mean tide curve and actual tide.

The term "wind surge curve" is not completely correct, because it comprises in addition to the wind, the static air pressure, the temporal change of the air pressure, water temperature and the difference of temperature between air and water but the wind is the most influential parameter (about 90% in the North Sea). To analyse the change of the storm tide, the surge is the best phenomenon, because it includes the meteorological factors. Therefore storm tides are defined for the southern North Sea as events with surge height in Cuxhaven of 2m or more (Siefert 1985) between low water time and four hours after high water time (Ferk 1993). During low tide the surge, generated by a certain wind field, reaches a higher level than during

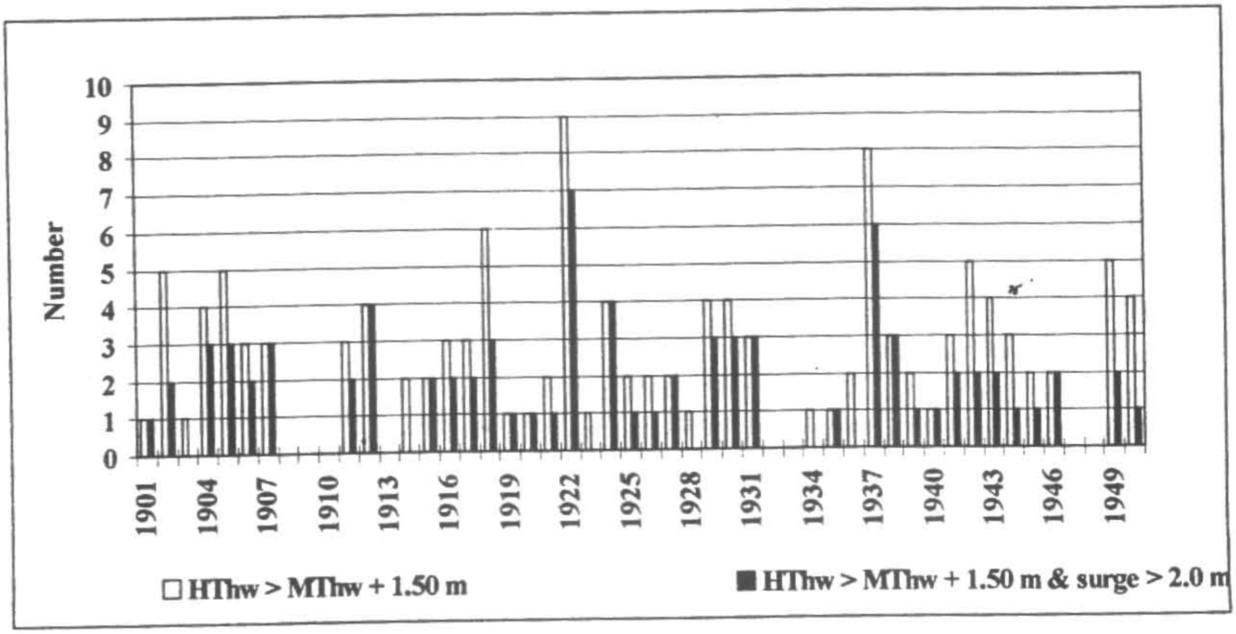

Fig. 3. Number of storm tides with HThw ≥ MThw + 1.50 m and of storm surges with HThw ≥ MThw + 1.50 m & surge > 2.0 m for the period 1901-50

high tide. Therefore the collective is restricted to all storm tides with a surge level higher than 1.50 m at high tide. With this restriction the collective encloses 193 storm tides and 154 storm surges since 1901. For this research only the terminus storm surge is used. Because of the fact that one storm surge can enclose more than one storm tide crest the terminus storm tide is only used for the description of one tide crest but not for the whole phenomenon.

The type of definition is necessary for understanding the results of the research. This may be explained by a comparison between two definitions: The first definition is a statistical method, which defines storm tides with 1.50 m above mean high water level. The second is the above described definition of the research presented here.

Fig. 3 shows the frequency of storm tides with HThw ≥ MThw + 1.50 m and of storm surges with HThw ≥ MThw + 1.50 m & Surge > 2.0 m for the period 1901-50. It can be seen that only more or less 80 percent of the tides with 1.50 m above high tide reach is surge of 2m without restriction to the tidal phase. That means that the collective based on the statistical definition HThw ≥ MThw + 1.50 m includes storm surges with an influence of the wind which is not able to lift the water body 2m and more. Therefore the statistical definition compared different kinds of tides with different minimal wind influence and there must be different results.

4. Astronomy

In this research the surge curve is calculated with the mean tide curve. Research on the astronomical influence shows that out of 192 storm tides of the presented collective only 32 occurred during spring tide and 16 during neap tide. But the tides in the North Sea show that there is a longer influence of the astronomy which produce spring and neap tide (Dietrich *et al.* 1975). That was the reason to define a longer period of neap and spring tide time. If you enlarge spring and neap tide intervals to high water time at Cuxhaven from 0 to 4 O'clock and 12 to 16 O' clock for spring tide and from 6 to 10 O' clock and 18 to 22 O' clock for neap tide, there are 93 storm surges at spring tide and 31 storm surges at neap tide. That shows that nearly half the storm surges happened at spring tide.

The analysis of the level difference between astronomical tide and mean high and low levels of the mean tide curve shows that all storm tides are covered by both definitions of storm tide. The biggest

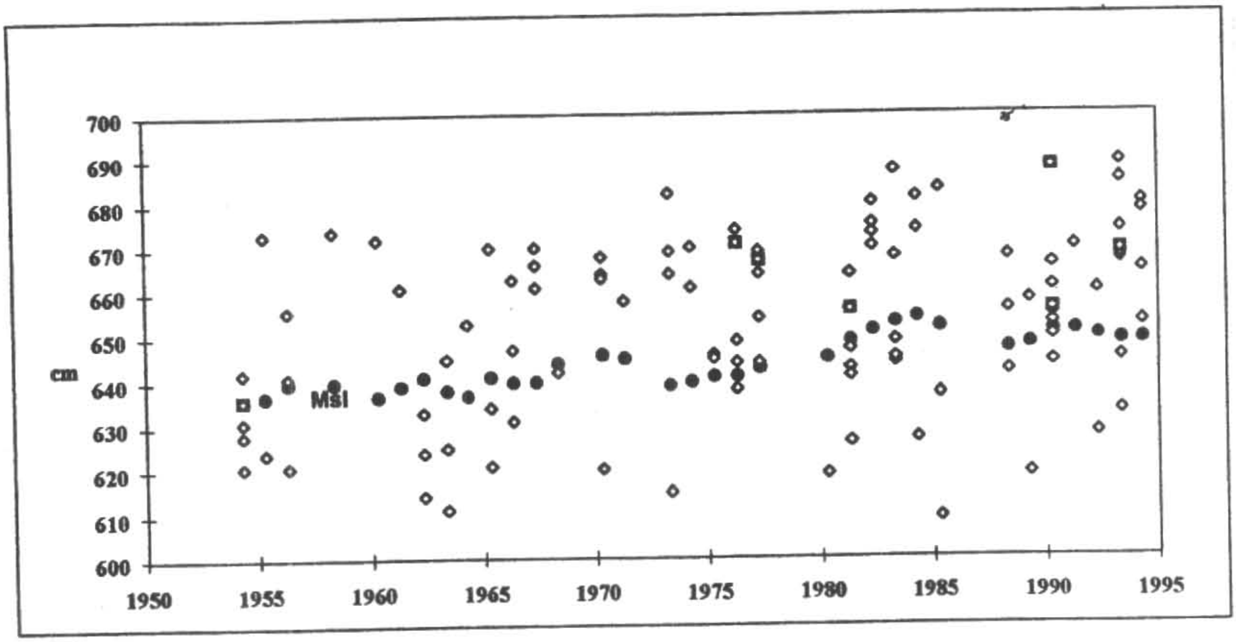

Fig. 4. Difference between MThw (5-year means) and the astronomical tide at Cuxhaven (1950-95)

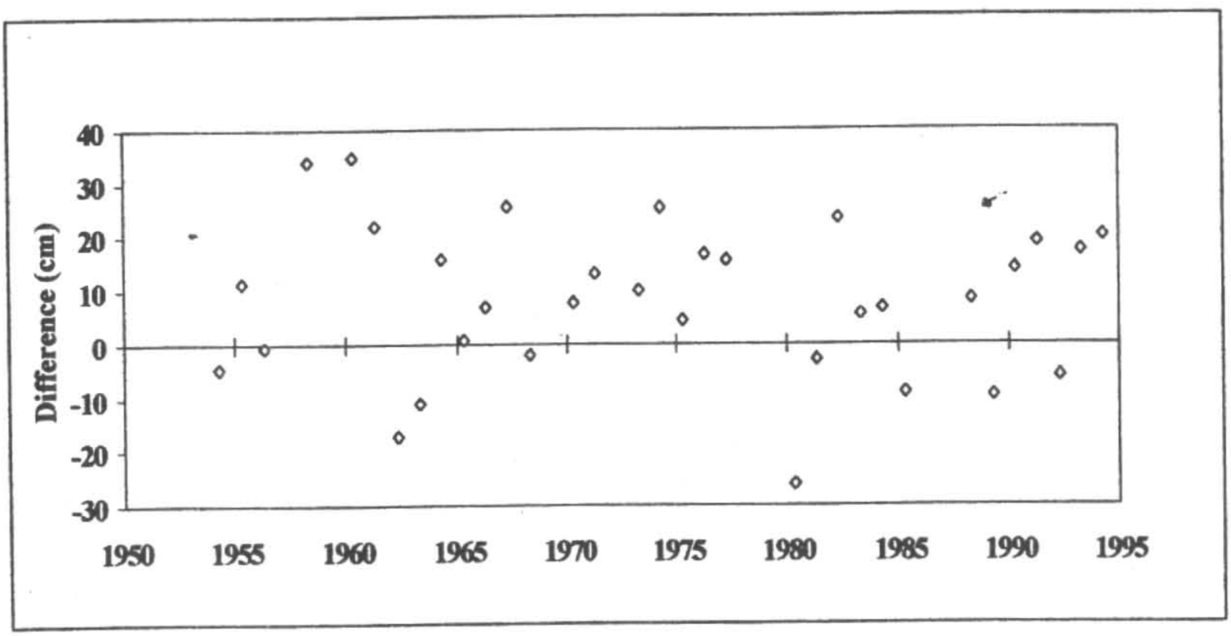

Fig. 5. Difference between astronomical tide (1-year mean) and MThw (5-year means)

difference between mean tide curve and astronomical curve amounts to 50 cm.

This is too much to ignore the astronomical influence. That is the reason that we have to take into

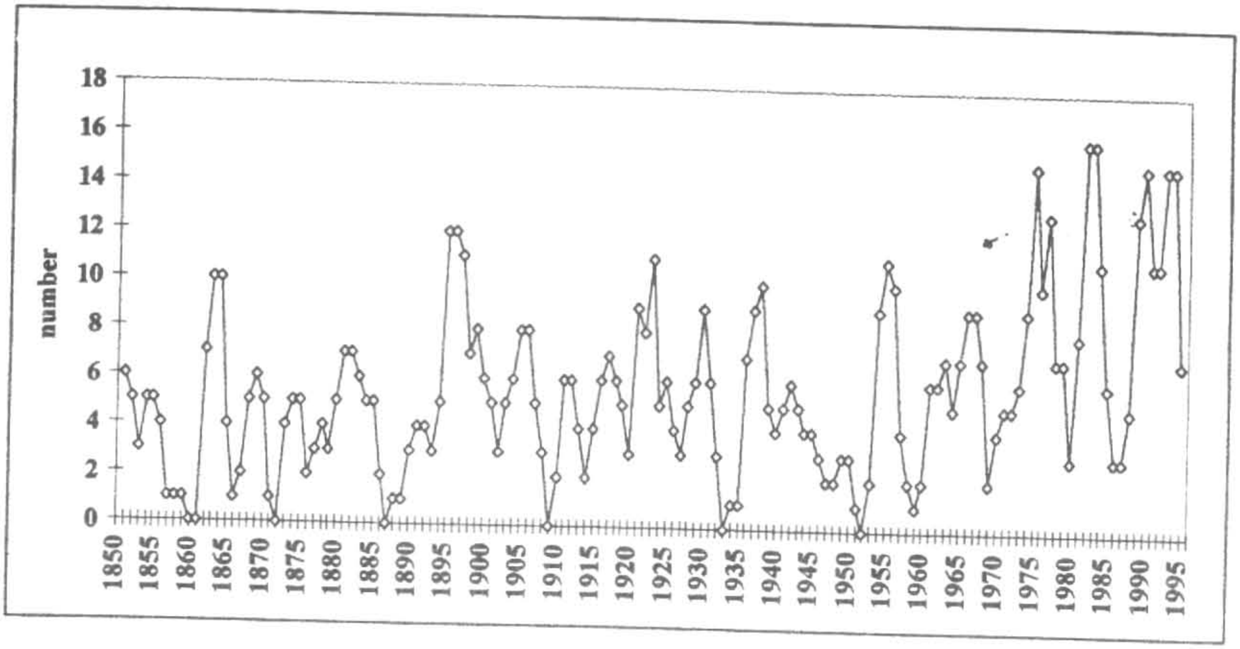

Fig. 6. Number of storm tides per year at Cuxhaven during 1850-1995 (3-year means)

account all astronomical tides for the interpretation too.

The calculation of a mean value per year shows, firstly, that the difference between the middle and the five year mean tide changed every year and the mean value of all years gives a deviation of plus 7 cm. For this research, which looks at the climate change and the energy change, these 7 cm are not relevant. Secondly, there is an equalisation between high tide level and low tide level at spring tide, because the low tide level at spring tide is lower than the mean tide. Thirdly, it cannot be seen that there has been any trend to a higher influence of the astronomical tide during the last 50 years.

Nevertheless the presented research considers the astronomical HW height for the definition and the interpretation. The reason why we do not take the complete astronomical tide is, firstly, the described equalisation and, secondly, that there is no exact calculation for the tide curve itself, but only for the peaks. The calculation of the mean tide curve, however, is calculated according to the method of the Department of Port and River Engineering Hamburg and includes both the flood and ebb phases of the tide.

5. Development of storm tides in the Southern North Sea

5.1. *The frequency*

In view of the discussion about climatic change, it is necessary to look at first at the development of the number of storm tides. As Fig. 6 shows, the number of storm tides in the southern North Sea has increased continuously after 1950.

But with the distinction between storm tides, heavy storm tides and very heavy storm tides it becomes obvious that the increase concentrates on the storm tides, while heavy storm tides and very heavy storm tides show no increase in number (Fig. 7).

The number of the surge curves increased as well (Fig. 8) but not as remarkably as the number of storm tides. The reason must be that surges with more than one crest become more frequent, *i.e.*, surges become longer.

As Fig. 9 shows, there is a small increase for surge curves with two crests over the last 100 years.

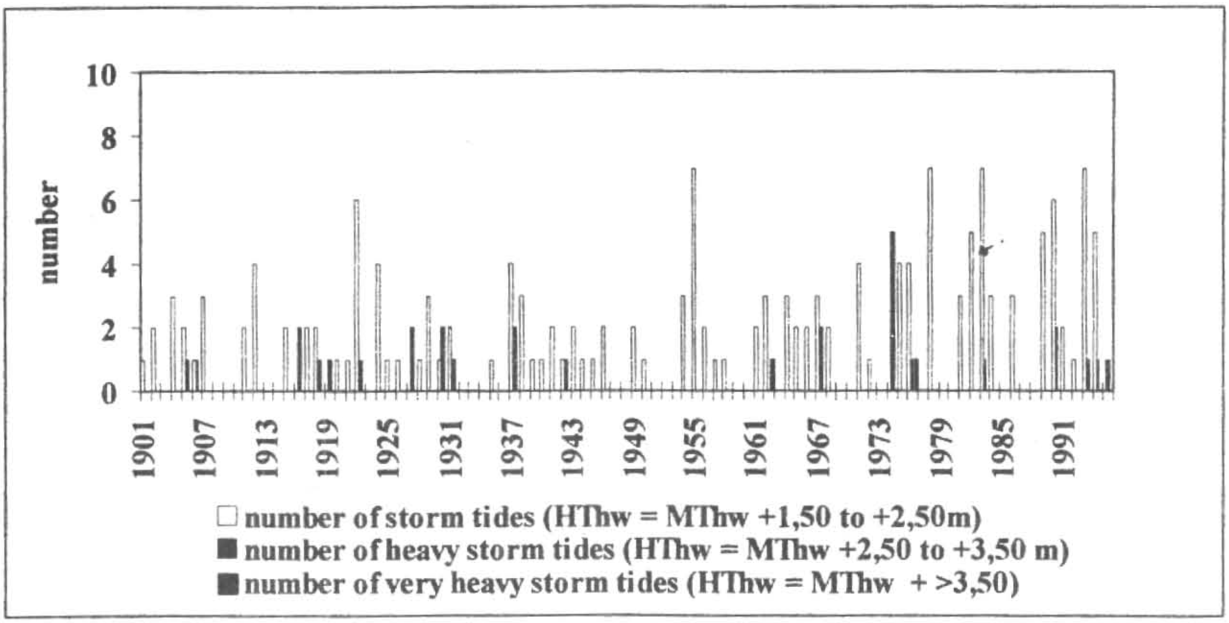

Fig. 7. Frequency of storm tides, heavy storm tides and very heavy storm tides at Cuxhaven during 1901-1995

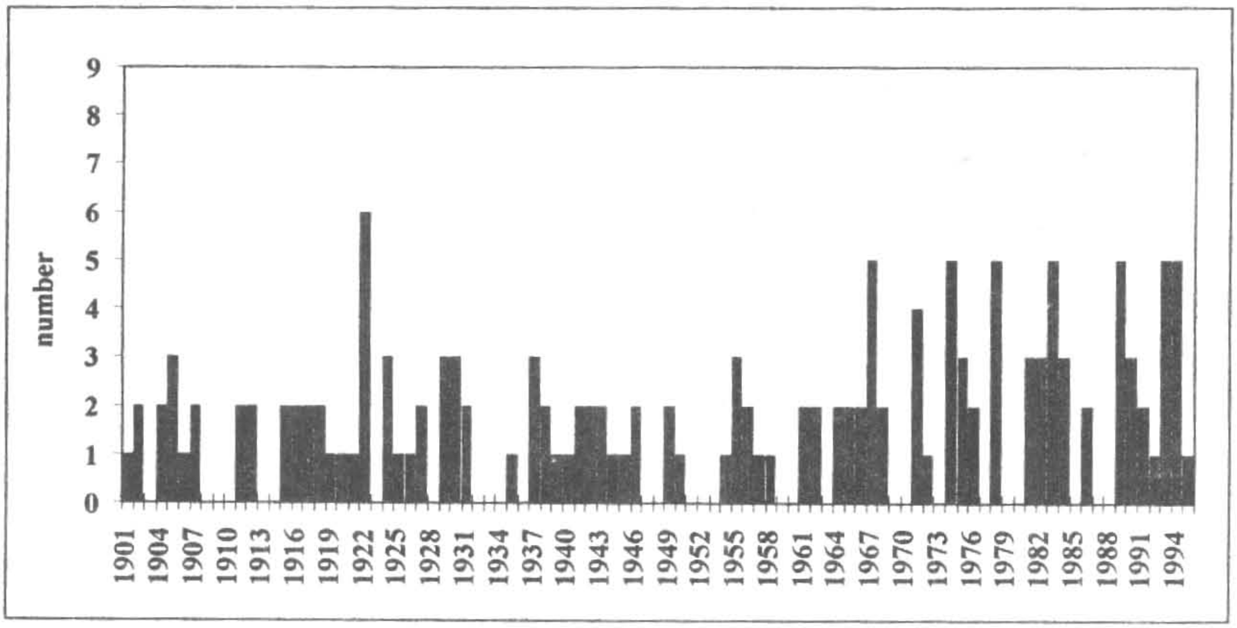

Fig. 8. Number of storm surges at Cuxhaven since 1901

That means that, in addition to and within the increase of the ordinary storm tides, the winds with low velocity and long duration must have increased. This can be shown more clearly by the surges with three, four and five crests. These kinds of surge do not occur within the first 50 years of this century. But this must be considered with care, because there was a surge with 6 crests in both 1790 and 1897 and those were heavy storm surges. The surge with 3 and 4 crests also produced heavy storm surges.

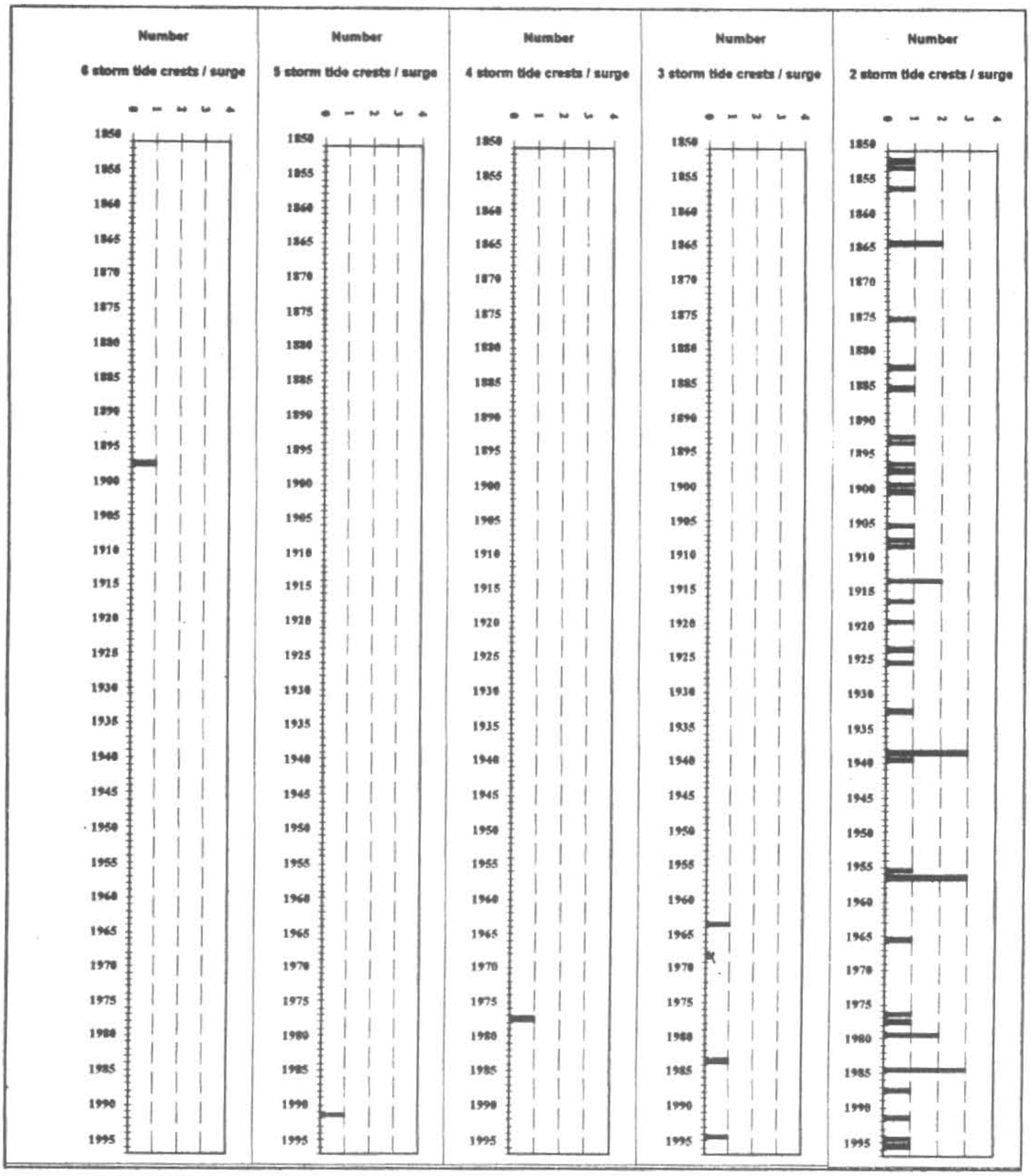

Fig. 9. Number of storm surges with more than one storm tide crest at Cuxhaven

5.1.1. *Reasons for the development: Wind change*

The reason for such a development of storm surge occurrence in the southern North Sea can be simply stochastic or climatic change. On account of the fact that the wind has the influential impact for the formation of a storm tide, the development of the duration of the wind was analysed. In this context we have to accept the fact that only a very small number of reliable wind records exist for this area, good data usually starting in the fifties. As Fig. 10 shows, the duration of wind with a minimum speed of 17 m/s has increased for the duration of 5 h to 9 h from 1950 to 1995. This correlates directly with the increase of number of storm surges with more than one storm tide crest. An increase of the duration is also perceptible for winds with a minimum speed of 14 m/s, but not with the same intensity. As a preliminary result of this it is possible to interpret that the increase of the number of storm tides is caused by the increase of the wind duration.

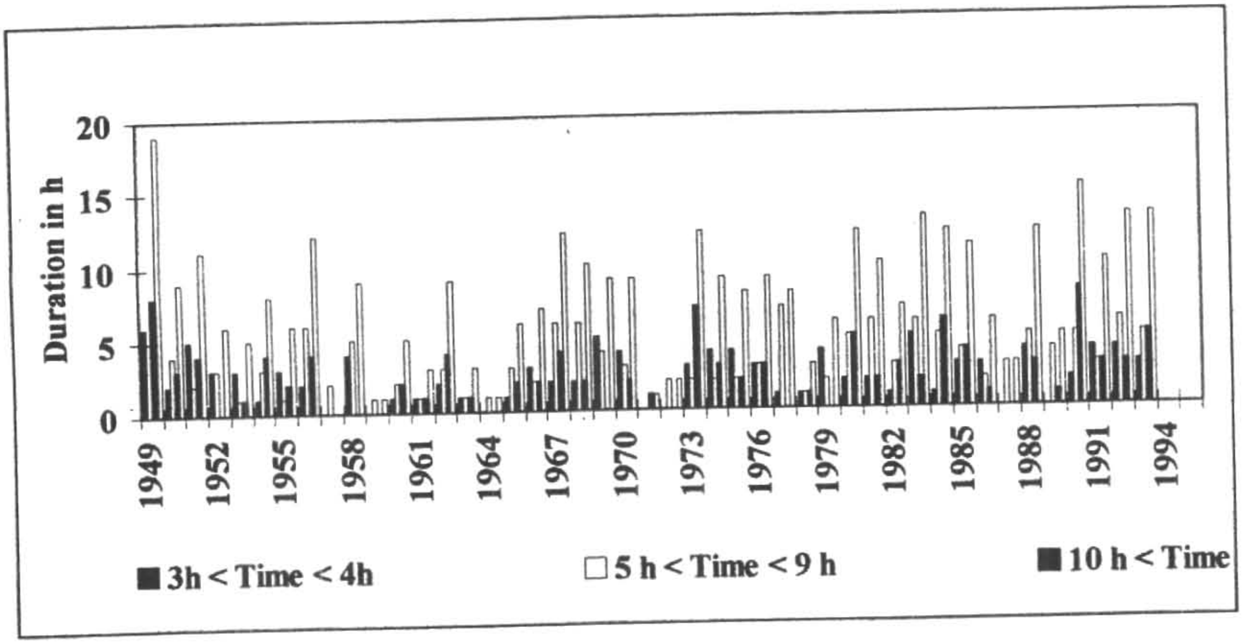

Fig. 10. Development of the duration of wind with a minimum speed of 17 m/s from direction of 240° to 330° over the North Sea

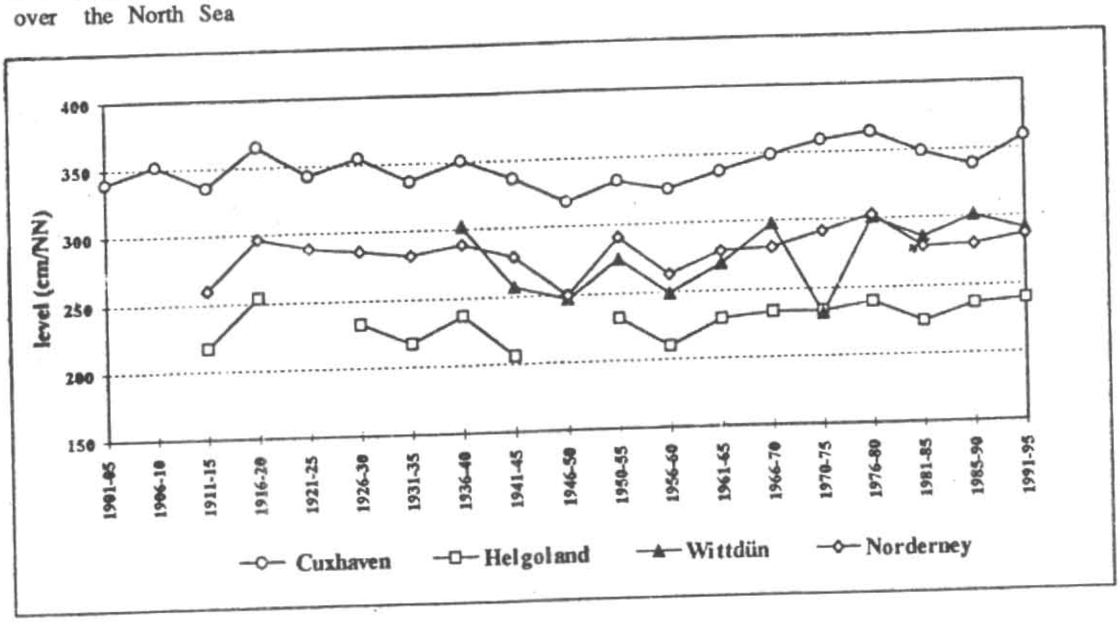

Fig. 11. Development of storm tide water level at Cuxhaven, Helgoland, Wittdün and Norderney (5-year means; surge $\geq$ 2.0 m)

5.2. *The level*

The best way to get a first impression of the development of the level during the last 100 years is to calculate the 5-year means of the level at Helgoland, Norderney, Cuxhaven and Wittdun. As Fig. 11 shows, the height is kept constant at all gauges.

To specify these results it is necessary to take into account all crests of storm tides at Cuxhaven for the period 1788 to 1995 (Fig. 12). It is obvious that most storm tides reach a level between 1.50 m and 2.50 m above mean high tide. More interesting than the low storm tides are those storm tides which reach 2.50 m to 3.50 m above mean high tide and more than 3.50m

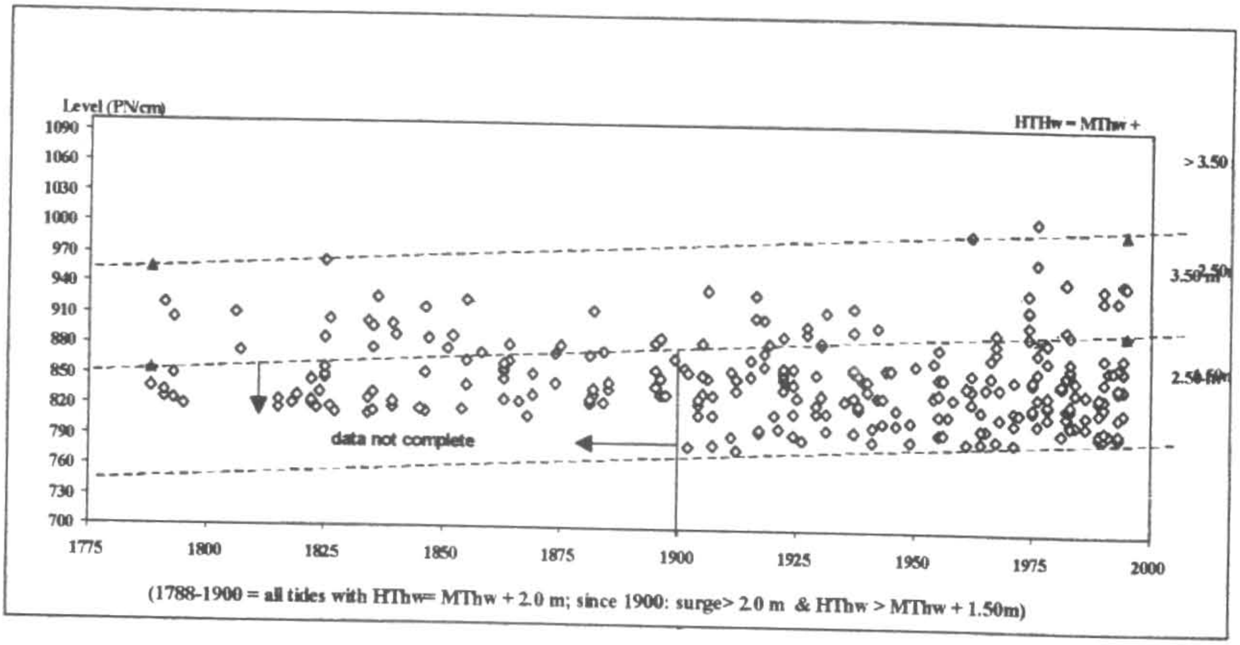

Fig. 12. Crests of storm tides at Cuxhaven during 1788-1995

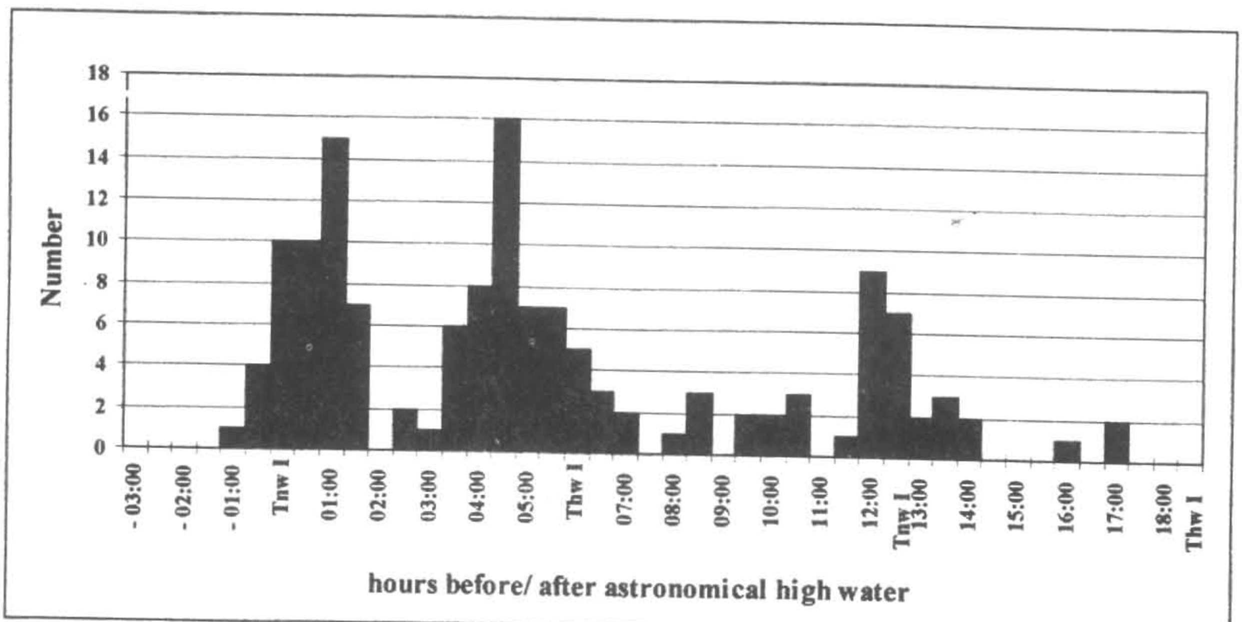

Fig. 13. Number of surge maxima over tidal phase at Cuxhaven during 1901-97

above mean high tide. The lines show the increase of the mean high water level in Cuxhaven. This line was chosen because the trend of the mean sea level was less significant within the last decades. A comparison of the storm tide water level with the mean sea level trend would lead to wrong results.

Fig. 12 indicates that the height of the heavy storm tides has not increased by more than the mean high tide level. But if we look separately at the very heavy storm tides above 3.50 m for the period 1990-95 it seems that the levels of the crests have increased, simply by omitting older events. The analysis of the

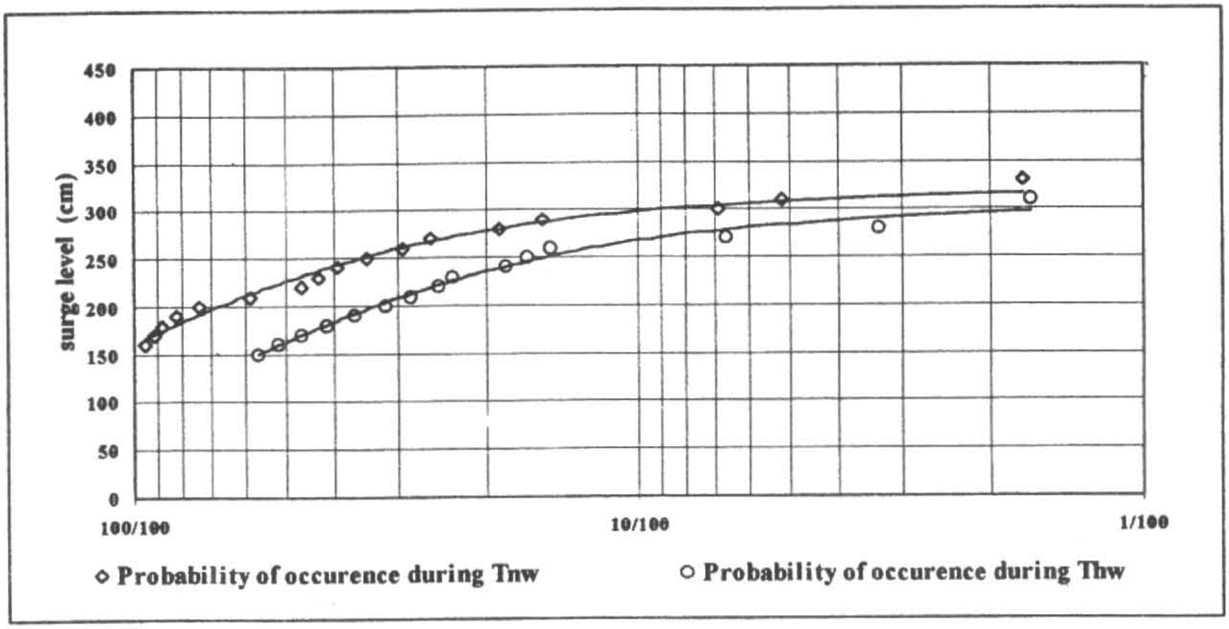

Fig. 14. Probability of occurrence at Norderney during 1938-97

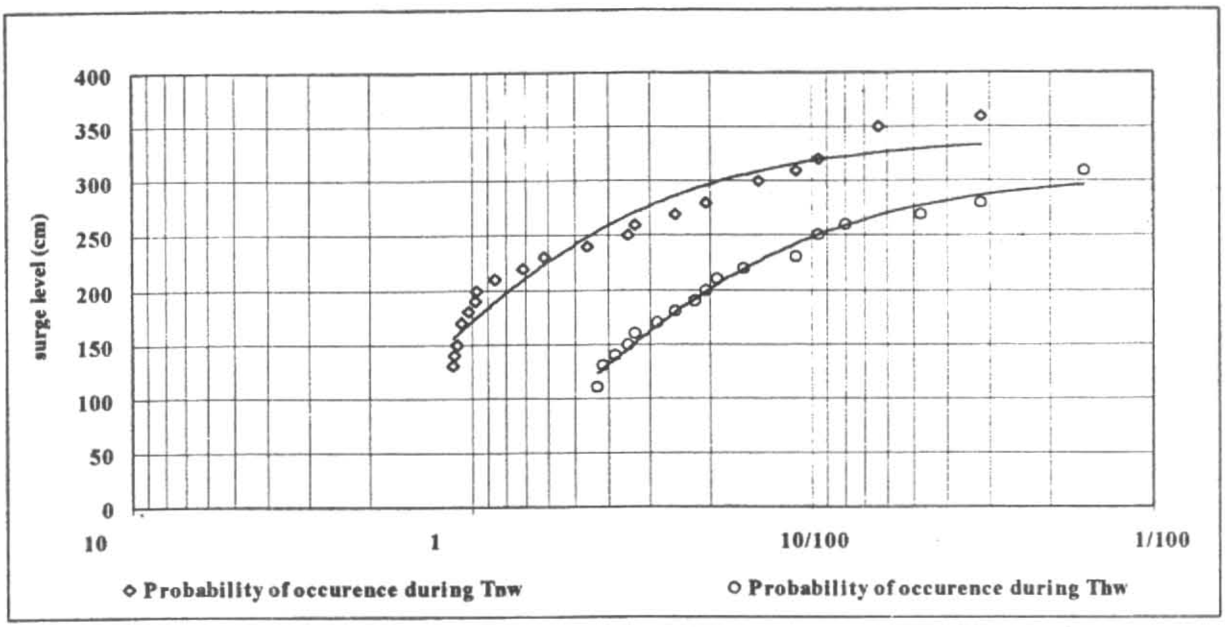

Fig. 15. Probability of occurrence at Wittdün during 1935-97

last 200 years shows that a 3.50 m storm tide level had already reached in 1825, and if the rise of the mean high tide level is separated, it is possible to calculate a probability of occurrence of 1:100 years.

In Fig. 12 only the storm tides with a level of 2m and more above the mean high tide height were considered for the period 1778-1900, as data is not complete.

If we look at the storm tides with levels between 2.50 m and 3.50 m, the results of the period 1900-95 can be transferred to the period 1778-1900. The crests did not increase more than the mean high tide.

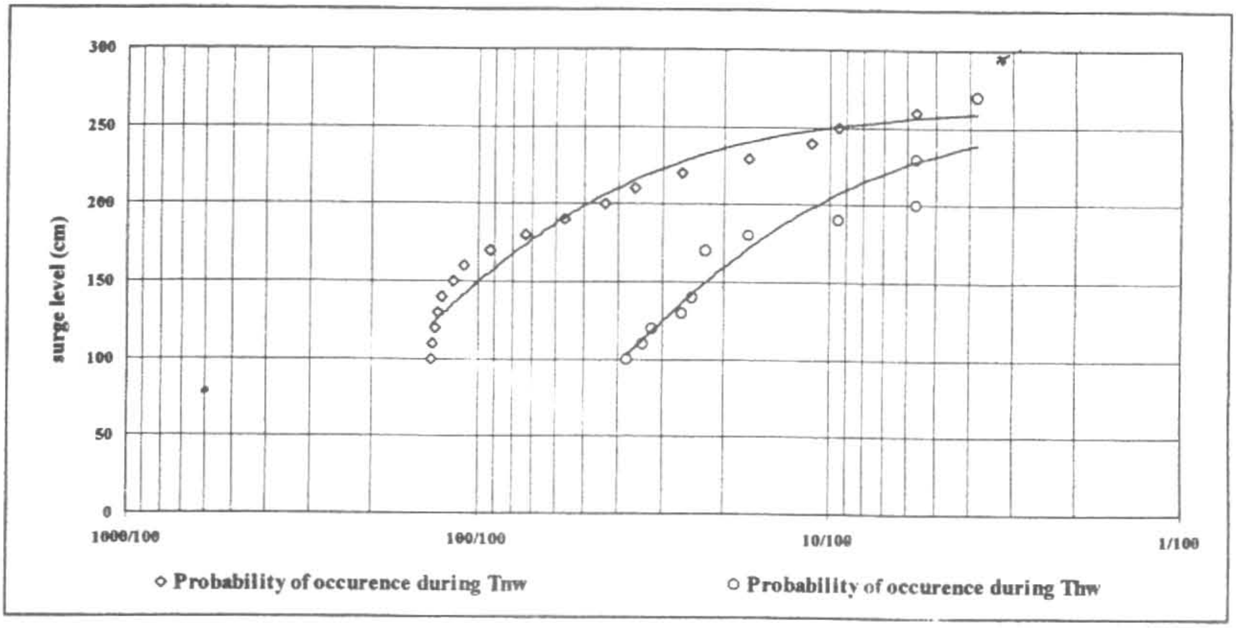

Fig. 16. Probability of occurrence at Helgoland during 1940-97

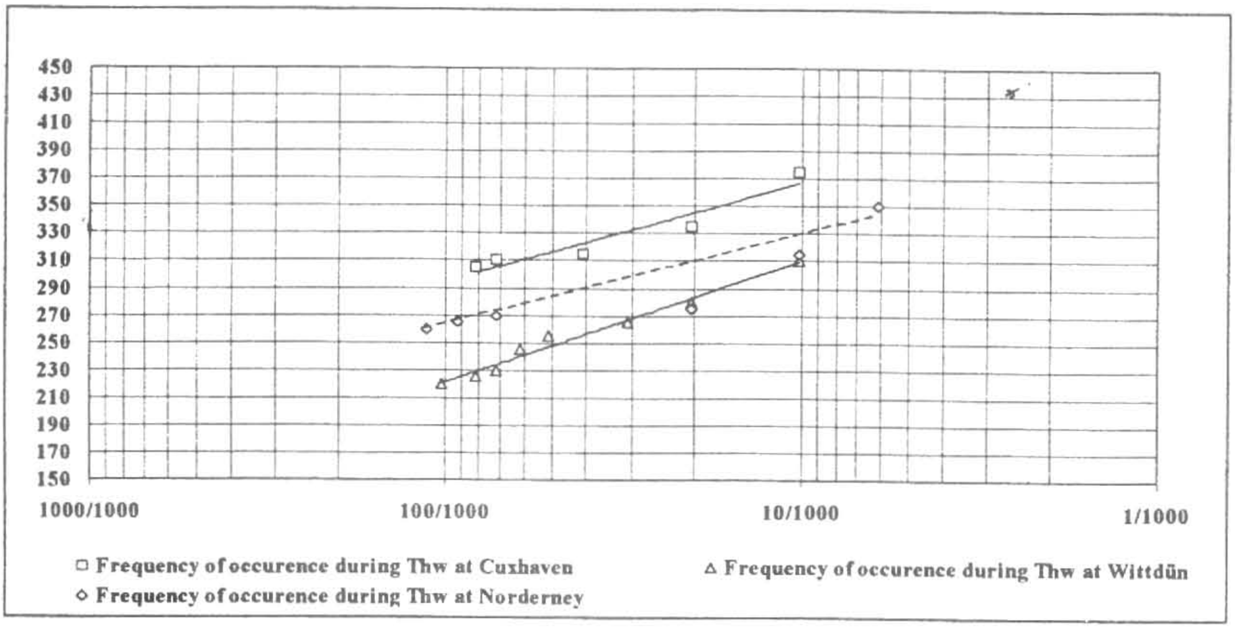

Fig. 17. Frequency of occurrence of the 10 highest surge peaks during Thw at Cuxhaven, Norderney and Wittdün during 1901-97

6. Practical application: The calculation of design levels

For the calculation of design levels in the German Bight and the Elbe River, a group from three German federal states defined the design levels of the dikes. They calculated a design storm tide curve, which includes the addition of the mean tide curve and an extreme surge curve with the following components (Länder-Arbeitsgruppe 1988):

(*i*) The actual situation of the tide at the coast

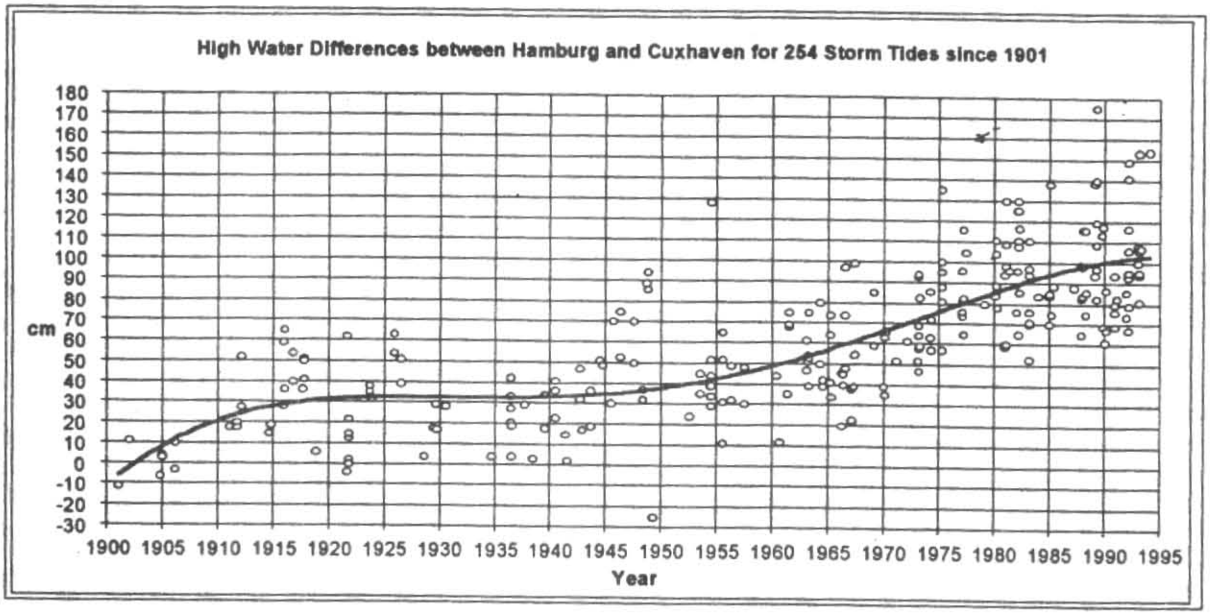

Fig. 18. High water difference between Hamburg and Cuxhaven (100 km apart) for 254 storm tides since 1901

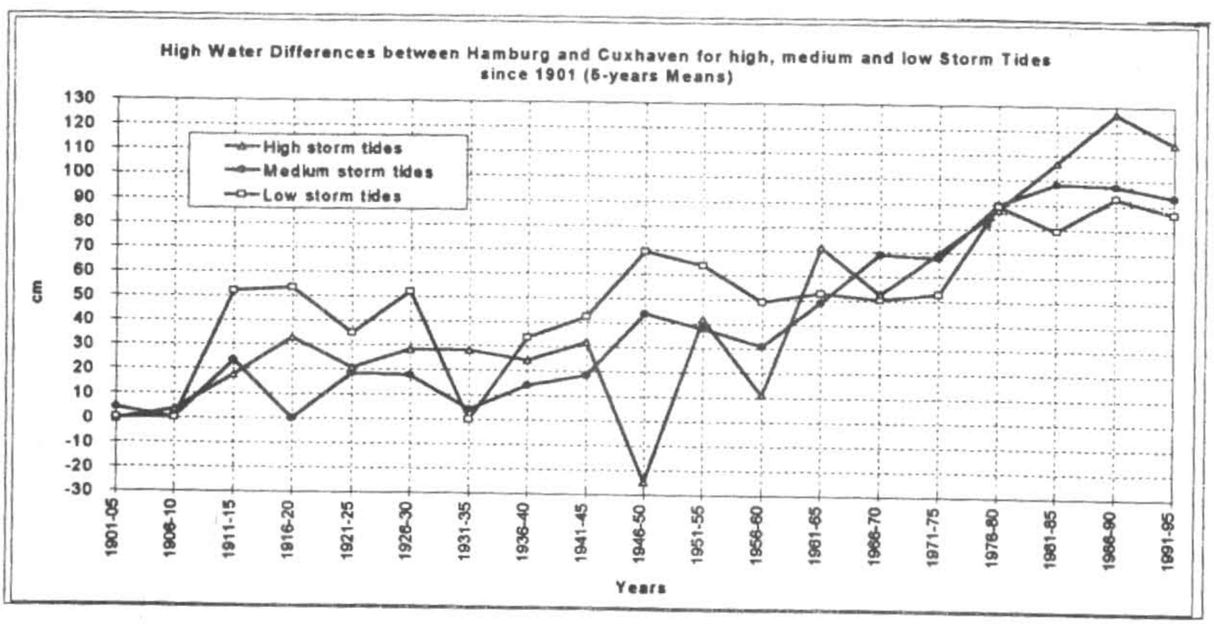

Fig. 19. High water differences between Hamburg and Cuxhaven for high, medium and low storm tides since 1901 (5-year means)

(*ii*) astronomical influences

(*iii*) storm surge and, with this, the meteorological aspects (wind velocity and direction)

(*iv*) influences from the North Sea and external surges

(*v*) mean sea level rise.

In section 4, the astronomical influence was described. For the calculation of the surge curve, it is necessary to consider the maximum of the surge curve at all tidal phases and not only during high tide,

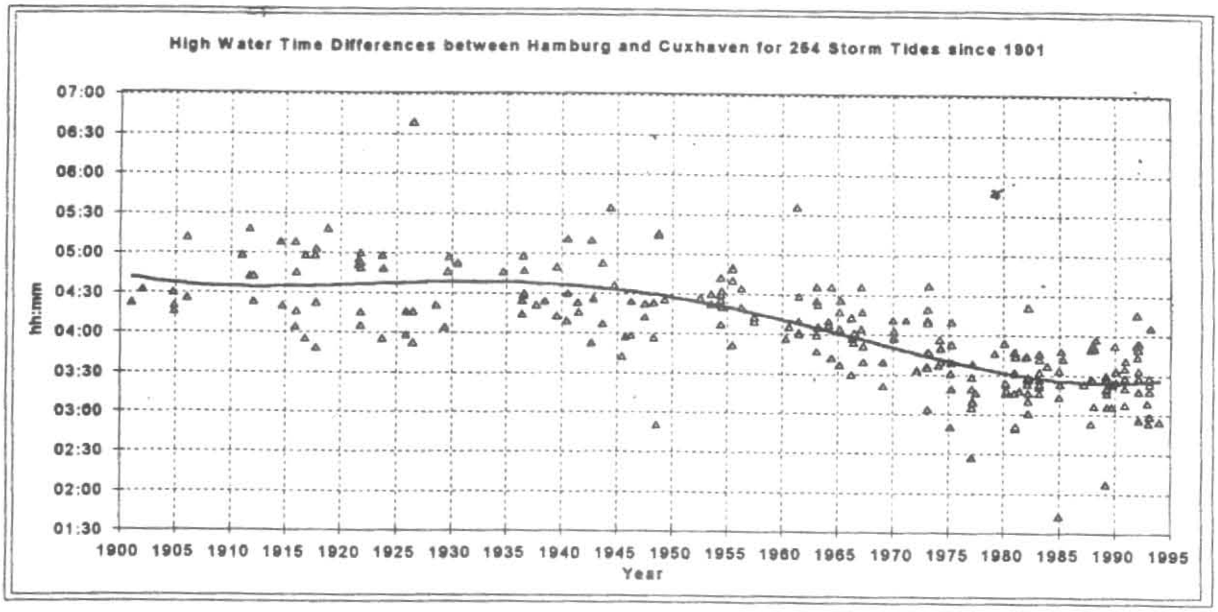

Fig. 20. High water time differences between Hamburg and Cuxhaven for 254 storm tides since 1901

because the surge peak mostly happened during low tide (Fig. 13) and the interaction of tide and surge during their propagation into the estuary is of importance.

It might be considered that the highest surge peak during low tide could happen during high tide. But as the Lander- Arbeitsgruppe (1988) found out, the relation between the surge level during low tide and the surge during high tide is around 10 : 7, at its maximum about 10 : 9. Consequently they chose 90% of the surge peak levels during low tide.

The results of Fig. 13 demand that the frequency of occurrence is calculated for the surge maxima during low tide (3.5 h before Tnw to 3h after Tnw) and during high tide (3 h before Thw to 3h after Thw) separately. As Figs. 14 to 16 show it is possible to calculate an asymptotic surge level for high tide and for low tide. For this, the frequency of occurrence has been calculated in steps of 10 cm and presented in a logarithmic scale.

For Norderney it is possible to calculate a frequency of occurrence of 1: 100 years of less than 3.50 m for Tnw and Thw. This is a safe level, which has not been reached in the last 60 years, but it could be reached if the calculation included the surge of the storm tide of 1825 with 3.50 m.

With the same method, it is possible to calculate a surge maximum of 3.60 m during low tide and 3.10m during high tide at Wittdün.

For the gauge Helgoland 50 km off the coast the surge maximum during low tide and during high tide reaches 2.70 m

As Figs. 14 to 16 show, the logarithmic function is normally very good for the lower level and shows a bad adaptation for the higher levels. Therefore it is better to calculate a function only for the 10 highest surge peaks during high tide.

Fig. 17 indicates that for Cuxhaven it is possible to calculate for the frequency of occurrence of 1: 100 a level of 3.70 m, for Norderney of 3.30 m and, for the frequency of occurrence of 1 : 185, a level of 3.50m and for Wittdün a level of 3.10 m. For the security surcharge it is better to compare this level with 90% of the highest level during low tide.

7. Storm surges in the Elbe estuary

Four estuaries empty into the German Bight. Besides the Eider estuary, which is provided with a flood protection barrier, there are the estuaries of the Ems, Weser and Elbe rivers. The Elbe estuary is the largest of these; the tidal influence from the North Sea reaches some 150 km upstream to the weir of Geesthacht, which constitutes an artificial tidal boundary. The entire tidal stretch of the river is provided with dikes and other flood protection works. The city of Hamburg, which is situated about 100 km upstream from the mouth of the Elbe estuary, is economically the most important area in this region and is home to one of the biggest container ports in the world. Some facts about the development of storm tides in the lower Elbe river in the last 95 years are presented in Figs. 18, 19 and 20.

Fig. 18 shows the high water differences for all storm tides since 1901 between the tidal gauges of Cuxhaven (at the mouth of the estuary) and Hamburg-St. Pauli (100 km upstream). It can clearly be detected that at the beginning of this century, there was no difference in height during storm tides between Cuxhaven and Hamburg, *i.e.*, every storm tide had approximately the same maximum height both in Hamburg and Cuxhaven. During the period up to mid-fifties, the high water difference between the two gauges amounted to roughly 30 to 40 cm. Especially the sixties and seventies are characterised by a remarkably strong increase of this difference by some 60 cm, and nowadays, the peak of an "average" storm tide in Hamburg is almost 100 cm higher than at Cuxhaven. Though it should be noticed that the range of these high water differences is considerably large: the greatest difference ever observed amounted to 175 cm on 26 February 1990 and the lowest was 25 cm on 24 October 1949.

This development of the high water differences between Hamburg and the North sea is almost entirely the result of human activities carried out during the sixties and seventies. The main factors that contributed to this development were the several deepenings of the fairway of the Elbe river (altogether by roughly 4 m) and above all the endikements of vast low-lying areas along the estuary. As various model results proved (*i.e.* Siefert and Havno 1989), for high storm tides the influence of the fairway improvements on the increase of high water levels at Hamburg only amounts to roughly 10 to 15 cm (= 1/4 of the total value of 60cm), whereas 45 to 50 cm have their origin in the new dikelines. (It goes without saying that these artificial influences have also affected the mean tidal conditions in the lower Elbe. Particularly, they led to an increase in mean high water level and a decrease in mean low water level. These changes have, in contrast to the modification of high water conditions, mostly been affected by the artificial deepenings of the fairway of the Elbe river). Even though it should be added, that due to certain circumstances, some local endikements also led to a decrease of storm flood heights further upstream.

Fig. 19, which shows the high water differences between Hamburg and Cuxhaven for 5-year means of low, medium and high storm tides (Low storm tides : High water (Cuxhaven) < 3,00 m above NN, Medium storm tides : High water (Cuxhaven) 3,01 to 3,50 m above NN, High storm tides : High water (Cuxhaven) > 3,51 m above NN) indicates that the anthropogenic measures in and along the Elbe river specifically increased the height of the high storm tides in Hamburg, whereas the influence on comparatively lower storm tides was clearly weaker. During the first sixty years of this century, lower storm tides even had a greater high water difference (roughly 20 cm) than the higher ones. But since the early eighties, after the period of massive human interference in the hydrological system of the lower Elbe river, this relation has become completely converse. Today, high storm tides in Hamburg are in average almost 130 cm higher than at the mouth of the estuary, whereas low and medium storm tides only have a high water difference of less than 100 cm. The reason for these facts is clear: the higher the storm tide, the greater the cross- sectional area of the river and consequently the influence of the new dike lines.

In fact the above mentioned human activities along the Elbe estuary have not only affected the height of water level, but also the velocity of storm tides in the river. This is demonstrated in Fig. 20, which indicates the high water time differences between the tidal gauges of Hamburg and Cuxhaven from 1901 until today.

Again the influence of the new dikes along the lower river and the deepenings of the fairway mainly during the sixties and seventies on the tidal course of the Elbe estuary is clearly detectable, although the range of values extends from 6 hours, 39 minutes (10 October 1926) to 1 hour, 43 minutes (6 November 1985). Until the early to mid-fifties, it took a high water peak in average roughly 4 : 30 to 4 : 45 hours to get the 100 km from Cuxhaven to Hamburg. Nowadays the high water time difference between the gauges is only slightly over 3 : 30 hours for an "average" storm tide. This means that today a storm tide reaches the city of Hamburg over 1 hour earlier than it did about 40 years ago. This is an important fact which is taken into account at the storm surge forecast service for the city of Hamburg.

8. Conclusions

It can be seen that there is an increase of the wind duration in the last 50 years, which can explain the increase in number, especially the increase of storm surges lasting longer than one tide. But this must be considered with care and cannot be interpreted as a storm surge climate change, because a period of 50 years is too short. Therefore research gives a more reliable result, with the last one or two centuries taken into account. Furthermore it is necessary to calculate the duration of the storm surges to interpret storm surge climate changes more exactly. But data is not always reliable.

For design purposes of the coast, the calculation of the level by evaluating the last 100 years is a good procedure. It can be shown that the surge peak during low tide is higher than during high tide, which must be considered. Furthermore it could be shown that a maximum surge level for all gauges can be calculated much more satisfactory than a maximum tide level.

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