FREQUENCIES AND PROBABILITIES OF EXTREME STORM SURGES

(On the Time-Dependent Changes of the Probability of Extreme Storm Floods at the German North Sea Coast)

by

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Abstract

The North Sea as a very shallow sea with high wind set-up effects is acting highly as extremely sensitive measuring equipment for climatic changes, especially for surge producing weather conditions. The flood disaster in the Netherlands 1953, in Germany 1962, the Adolph-Bermpohl-Orkan (1967), with mean wind speed of 37 m/sec. over 5 hours, the strong continental storm with high damages in the forests from France till Poland in November 1972, a series of 6 heavy floods in November/ December 1973 and two extreme floods in January 1976 with the highest water levels ever registrated in the German bight are indications for some changes in meteorological conditions.

In this paper some hypothetical models shall be introduced which are able to show how extreme storm surge frequencies and probabilities are changing with time.

It is well known, that, on behalf of the high variability and possibilities of superpositions from meteorological parameters (wind velocity, direction, duration a.s.o.) with tidal regimes nobody can give an exact prediction about the highest possible storm surge. As early as in 1939, WEMELSFELDER therefore introduced a method to predict the probability of a storm surge level using the observed frequencies of storm flood levels from long-time series of observations from tidal gauges. In semilogarithmic coordinates, he found for high water levels (= low frequencies) a nearly linear relation between water levels and frequencies; by extrapolation, water levels can be computed which are to be expected - in the average, according to the laws of probability theory! - once, in 100 years, 500 years a.s.o. The basis for this method, however, is, that the stochastic process producing storm surges is a stationary one, i. e. not a time-dependent process.

For these calculations long time series are necessary. They are available on the German North Sea coast at the tidal stations of Cuxhaven (1813 - 1976, n = 164 values), at Wilhelmshaven (1854 - 1976, n = 123 values) and at Husum (1867 - 1971, n = 110 values) as collections of the highest annual storm surge levels.

For Cuxhaven, Fig. 1 shows the logarithmic plotting of this collection for the original values and for the same values adjusted to the year 1975 due to the centennial rise of the water level which was found for

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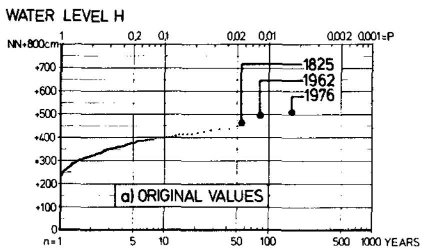
Cuxhaven to nearly 23 cm/100 years. For all stations, these corrections are necessary in order to eliminate longterm trends which are not connected directly with the actual meteorological conditions. For Cuxhaven, for example, it can be seen that by this correction the storm flood of 1825 was ranked from the third to the second place (fig. 1) in the collection.



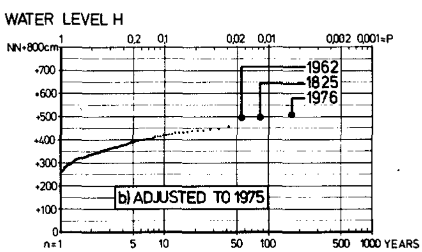


Fig. 1: Frequency curves of annual HW (Harbour diagram) for the station CUXHAVEN from 1813 till 1976 (n = 164 values)

a) original values

b) adjusted to 1975 due to centennial rise of water level

Fig. 1 shows observed frequencies; the question is to compute the abstract probability (after POISSON) from these frequencies. It can be seen, that for low frequencies (i. e. extreme surges) the linear approximation by WEMELSFELDER is quite satisfactory.

From the exact theory of probability, always an "event" is defined for instance by a game with dices; also for such a game here the "abstract probability" is exactly known as 1 to 6 when the dice is not "prepared". But for instance in 1973, 6 heavy storm surges occurred inside the German bight during 2 months; it is evident that this, seen from theory of probability, only was one event according to the meteorological conditions. Moreover, it can be assummed that even the meteorological behaviour of sequences of years may not be independent in the light of probability theory.

Contrary to the classical applications of the probability computations (v. MISES 1972) namely in the game of chance e. g. in the game of dice, where every throw represents an

"Event" and the sum of the throw represents the "Collection of Events", in the case of extreme storm floods, the expression "Events" and the connected expression "Collection of Events" have to be defined first, as they do not correspond to discrete events. The chain of storm floods as in 1962, 1973 and 1976 cannot possibly be viewed as independent events in the realm of probability computations.

As the equipments to register storm weather (meteorologically conditioned accidental events) are coupled with other similar equipments in large space and over long years of at least the North Atlantic region, if not globally, it can only be taken as an assumption, and not as a confirmation, to observe for example that an yearly HW is an independent event.

The approach of "Extreme Storm Flood Levels" of WEMELSFELDER results in a simple logarithmic representation of an approximately linear relationship between the water levels and their corresponding frequencies. From the observed frequencies the abstract probabilities for the period of investigation (time series) are interpolated and for the future extrapolated. The abstract probability according to POISSON (1841) is then known already deductively, as for e. g. in a game of dice with W = 1/6, for each number it is known; but in the case of storm flood events it must first be calculated from the observed frequencies.
An estimate of abstract probabilities from the observed frequencies demands an exact and reproducible definition of "Events" and "Collection of Events" (v. MISES 1972). Irrespective of arbitrary definitions of the expression "Storm Flood", it can be shown through a proof of convergence (FÜHRBÖTER 1976) that the values H_{100}, which represent the abstract probabilities according to POISSON and assign by stationary probability the water levels - in the mean! - occurring once in 100 years, in the form of a function $H_{100}(N)$ for $N > 5$ years, converge to nearly constant values, when the water level HW is assigned as the "Event" in a series of N = 1, 2, 3, ... up to 20 years in the case of a long series of gauges as in CUXHAVEN, as also till N = 30 years. This holds good for the linear approach of WEMELSFELDER. For non-linear fitting functions (GUMBEL, FRECHET, JENKINSON etc.) the convergence can be expected to be already by $N < 5$ years. This proof of convergence which leads from the observed frequencies to abstract probabilities (POISSON) delivers for the three North Sea gauges uniformly asymptotically reaching constant values for H_{100} with $N > 5$ years. As "Event" in the sense of independence an extreme water level HW is to be assigned which occurs in the series of N = 5 years.

Fig. 2 shows the convergence test (FÜHRBÖTER 1976) with the behaviour of the functions H(N) with their constant pattern for $N > 5$ years for all 3 stations; on fig. 3 (Cuxhaven), fig. 4 (Wilhelmshaven) and fig. 5 (Husum) is to be seen that the linear fitting for N = 5, 10, 15 and 20 years is nearly the same independently from N (FÜHRBÖTER 1976).

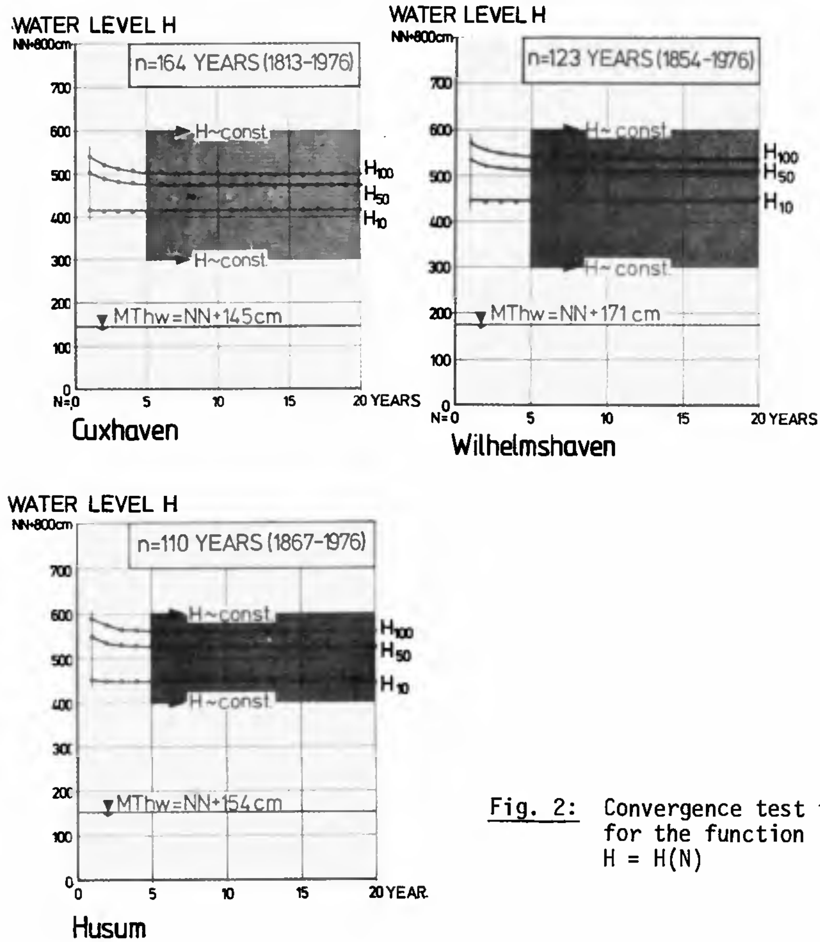


Fig. 2: Convergence test for for the function $H = H(N)$

With this the possibility is open for the investigation of the time-dependent changes of the abstract probabilities with a reproducible method which are calculated from the observed frequencies as per WEMELSFELDER method. For the non-stationary applications of WEMELSFELDER method the value H_{100}, the storm flood level - in the mean! - which is reached or exceeded once in 100 years, will be used as the representative value of the corresponding best fit straight line (fig. 2 - 5).

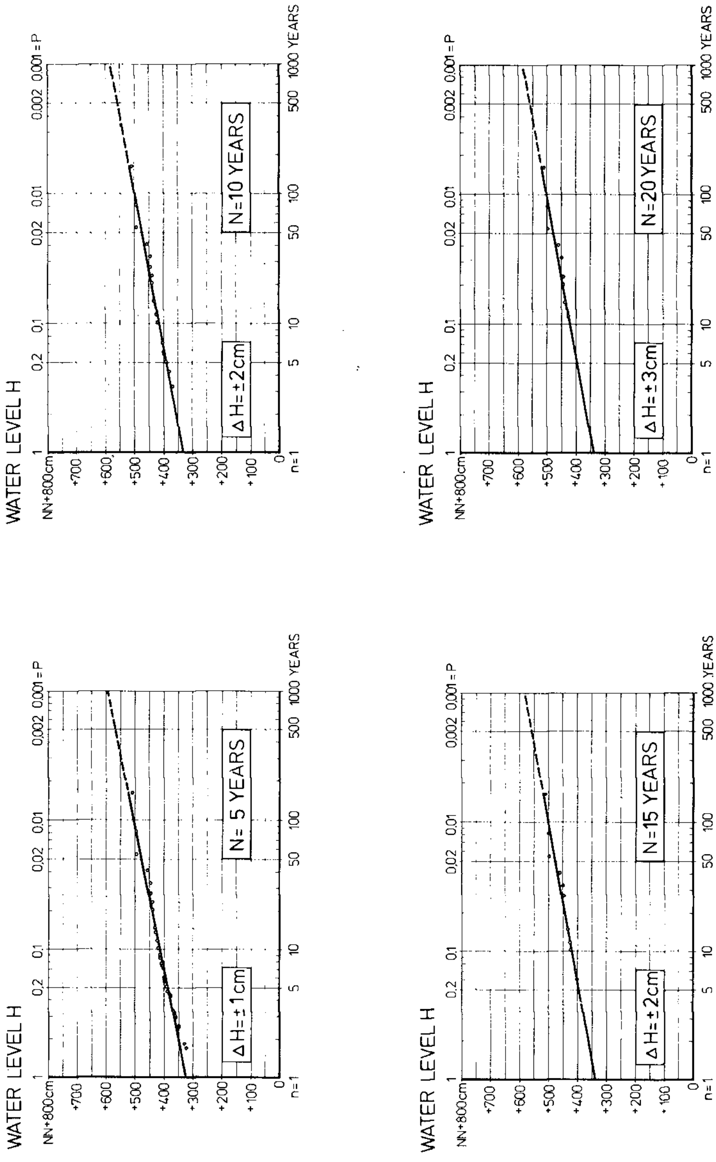


Fig. 3: Convergence test Station CUXHAVEN 1813 - 1976 (n = 164 years)

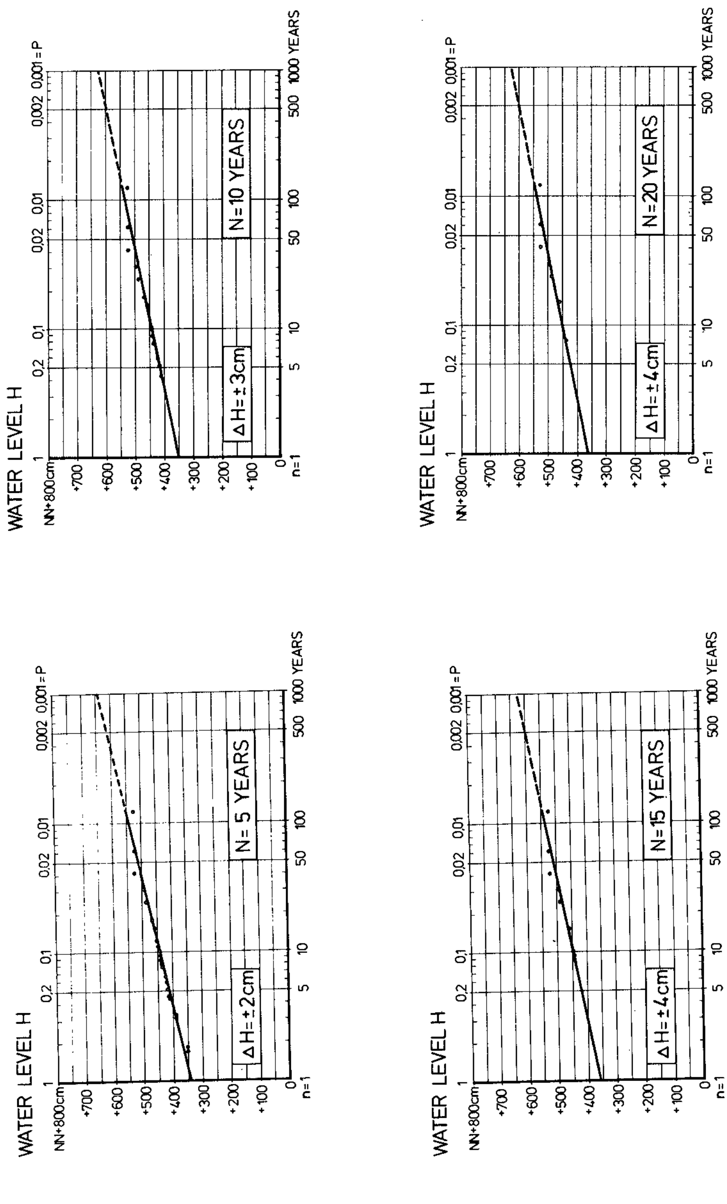


Fig. 4: Convergence test Station WILHELMSHAVEN 1854 - 1976 (n = 123 years)

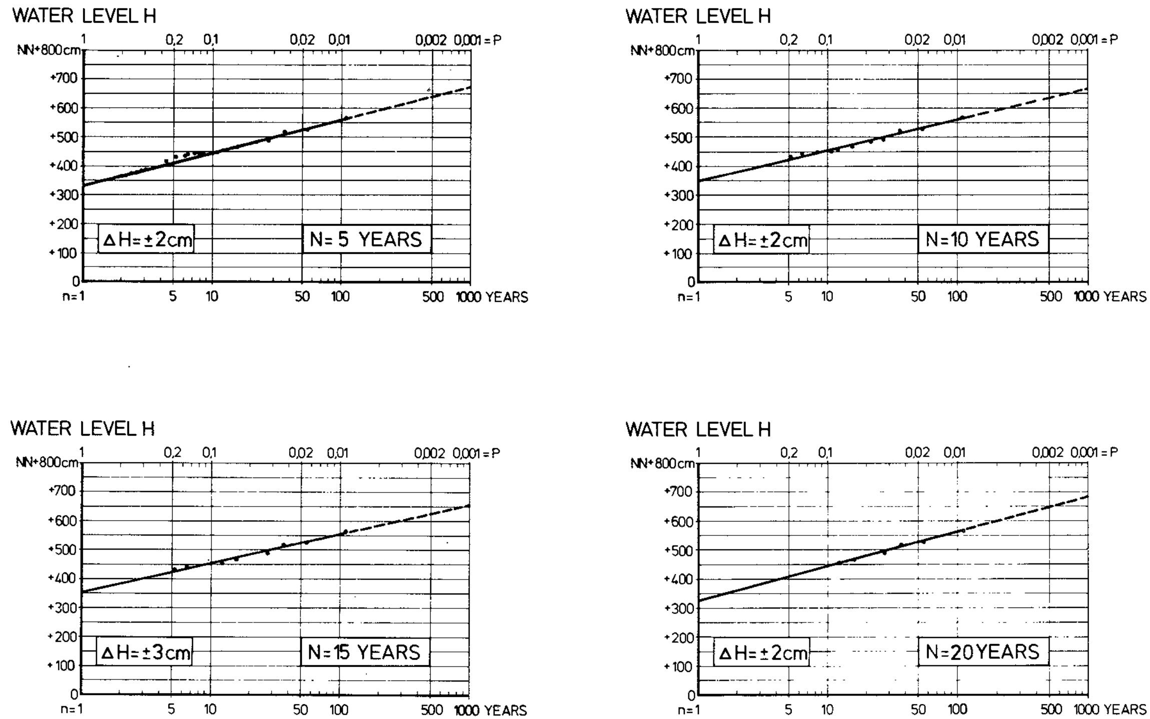


Fig. 5: Convergence test Station HUSUM 1867 - 1976 (n = 110 years)

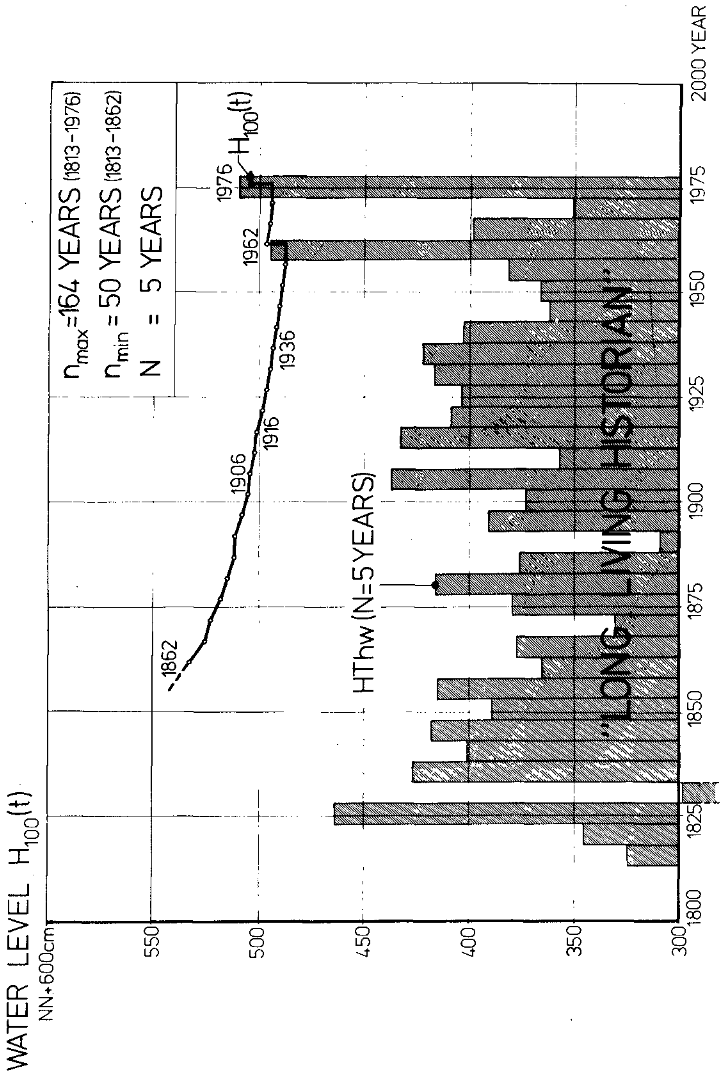


Fig. 6: Hypothetical model: "Long living Historian" (Station Cuxhaven)

One of the methods of investigation in non-stationary cases is the hypothetical model named "Long living Historian". He begins his work after supplying a 50 years series at the given gauge and examines after every following 5 year period its predictions for the value H_{100} vis-a-vis the new HW of these 5 years. This gives rise to a function $H_{100}(t)$ which can give information about the time-dependent changes of the probability of extreme water levels (FÜHRBÖTER 1976).

Fig. 6 shows the results from the model "Long living Historian" for Cuxhaven; the curve $H_{100}(t)$ ("abstract probability") is combined with the presentation of the HW for each N = 5 years ("observed frequency").

It is to be seen here that the function $H_{100}(t)$ has an always falling trend till 1962. Here and 1976 firstly discontinuities occur in form of jumps towards higher levels.

The comparison of the function $H_{100}(t)$ on fig. 6 with this on fig. 7 shows that there is no stationary pattern in the function $H_{100}(t)$ from the "Long living Historian".

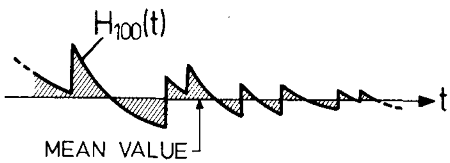


Fig. 7: Example for a function $H_{100}(t)$ from a stationary process

A model opposite to the "Long living Historian" is the "Remembering Historian" who begins his work in 1976 with a 50 year series from 1927 - 1976 and goes than back into the past with his memory. For Cuxhaven, fig. 8 shows the function $H_{100}(t)$ for this model; here a general rising tendendy with some small discontinuities is to be seen.

Another method of investigation is represented by the hypothetical model "Forgetting Historian" (FÜHRBÖTER 1976). He begins with the first 50 year series of the given gauge, similar to the "Long living Historian", but forgets as the time function $H_{100}(t)$ develops all the values that lie behind 50 years, but applies uniformly a 50 year series as moving investigation period. Corresponding to the greater weightage of the events in that period of 50 years in this hypothetical model, the discontinuities since 1962 occur somewhat stronger than in the previous model; at the CUXHAVEN gauge the jumps in 1962 and 1976 result in an increase in the value of H_{100} by about one meter (fig. 9).

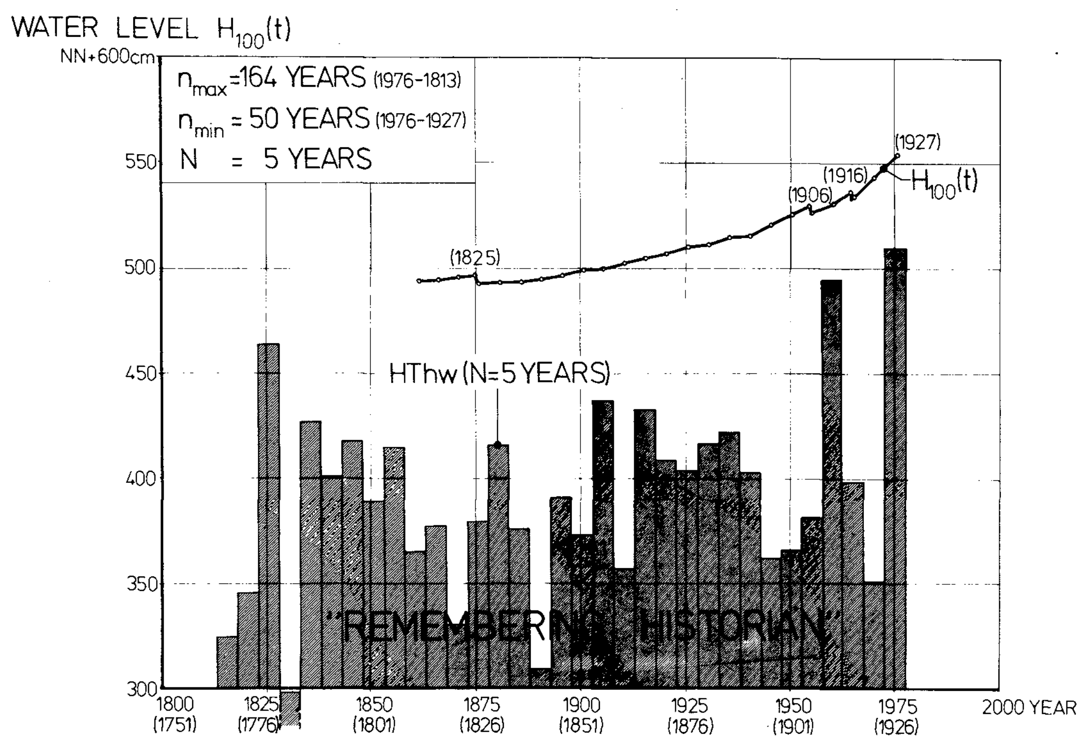


Fig. 8: Hypothetical model: "Remembering Historian" (Station Cuxhaven)

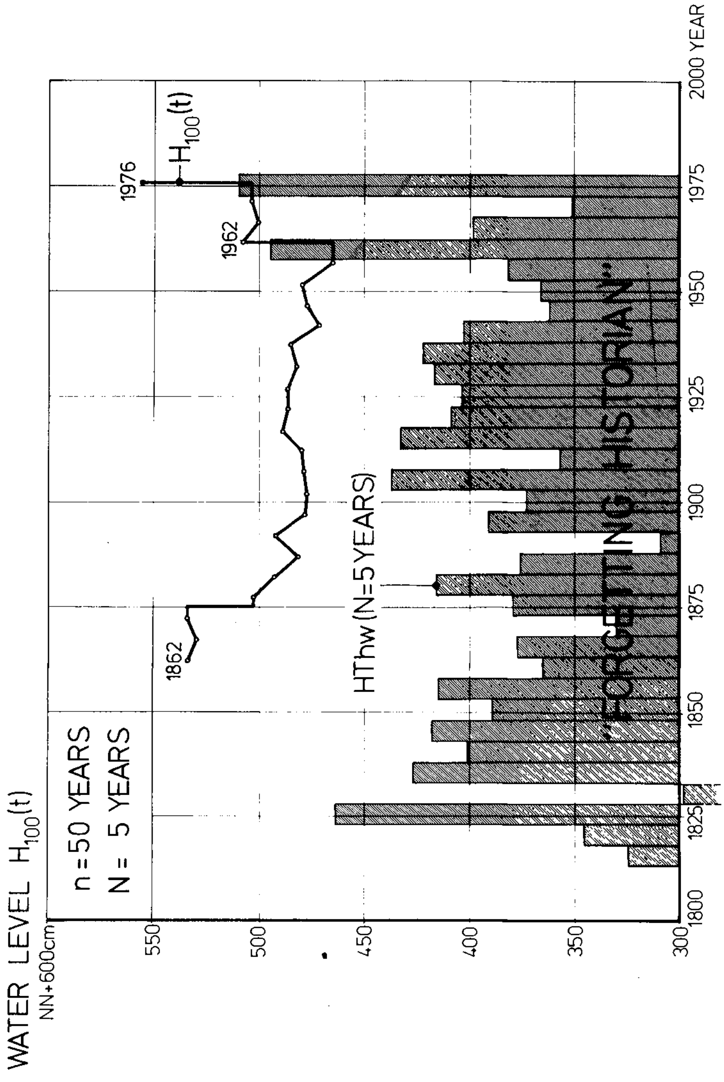


Fig. 9: Hypothetical model: "Forgetting Historian" (n = 50 years) (Station Cuxhaven)

Whereas in the "Long living Historian" it is assumed that the meteorological parameters, whose eventual superimposition determines the occurrence of the storm flood, are remaining the same in the mean value, in the model "Forgetting Historian" the meteorological events of the previous 50 years alone are considered as determining the storm flood, also for the period of 100 years, to which the value H_{100} will be extrapolated.

The stations of Wilhelmshaven and Husum show similar trends. It may be of high interest that also on the east coast of England for the harbour of Immingham GRAFF (to be published 1979) found comparable results with time series from 1920 - 1978 (fig. 10).

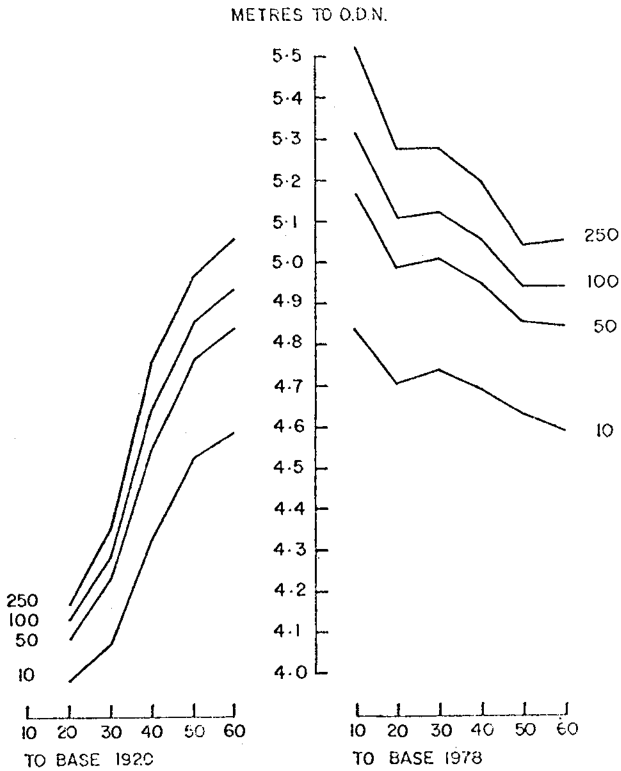
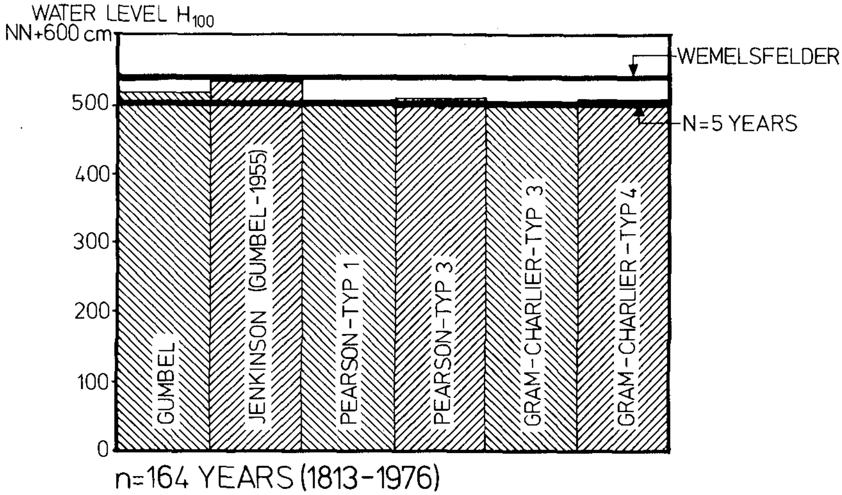


Fig. 10: Sea levels from $H_{250}(t)$ till $H_{10}(t)$ for the harbour of Immingham (from GRAFF, to be published 1979)

The curves "to base 1920" can be compared with the hypothetical model "Long living Historian" (fig. 6), those "to base 1978" with the "Remembering Historian" (fig. 8).



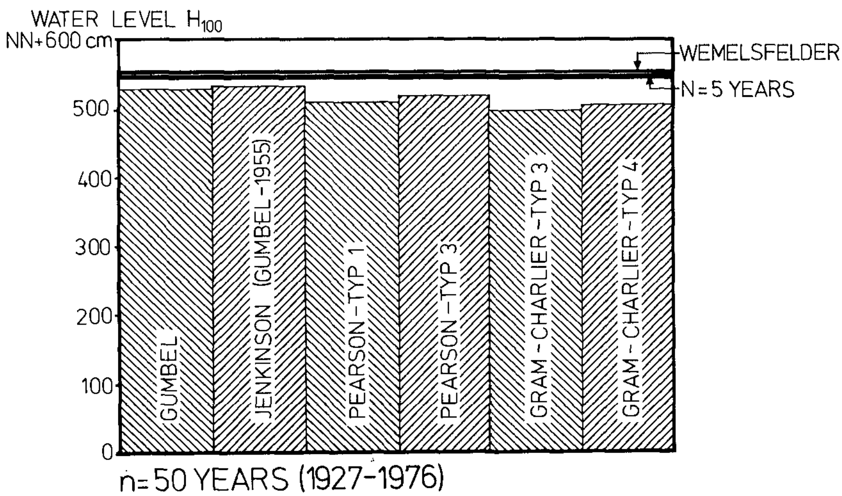


Fig. 11: Comparison of different approximation functions with the value H_{100} for the station of CUXHAVEN (values adjusted to 1975) (from WOLPERS, to be published 1979)

GRAFF used for his computations the distribution function of JENKINSON (1955). On fig. 11, for different probability distributions the values computed after WEMELSFELDER (1939) and with N = 5 years (FÜHRBÖTER 1976) are compared for Cuxhaven. It is to be seen that the question which time series are taken for the computation is much more predominat than the question which distribution was used (fig. 11).

The same effect is illustrated for Cuxhaven on fig. 12. The water level H_{100} computed with n = 50 years is for the series 1927 - 1976 nearly one meter higher than for the series 1912 - 1961 (FÜHRBÖTER 1976).

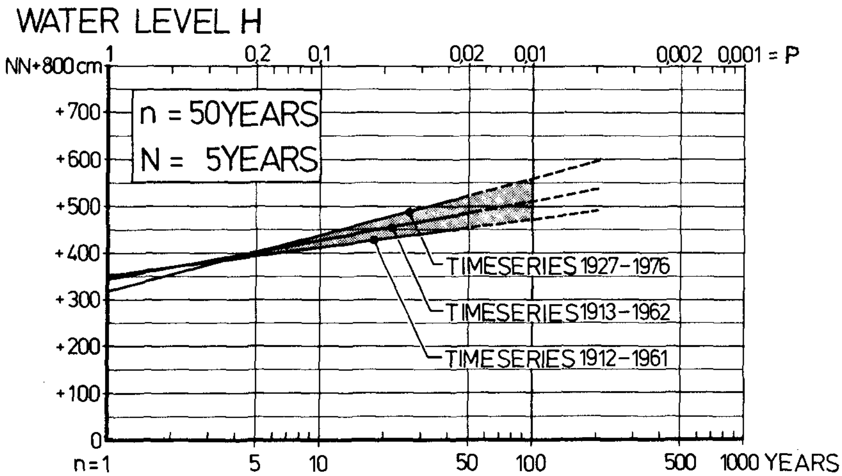
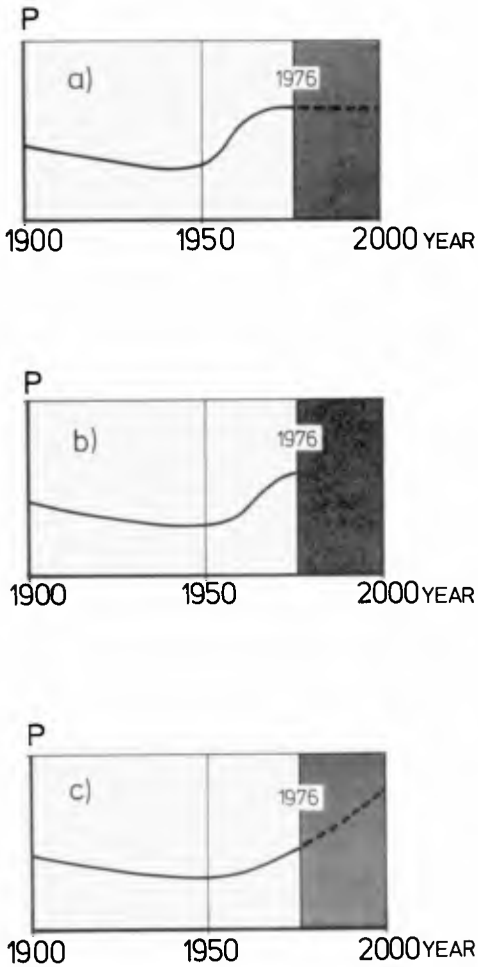


Fig. 12: Changes of $H_{100}(t)$ with different time series for Cuxhaven

The North Sea as a very shallow sea with high wind set-up effects is acting highly as extremely sensitive measuring equipment for climatic changes, especially for surge producing weather conditions. The flood disaster in the Netherlands 1953, in Germany 1962, the Adolph-Bermpohl-Orkan (1967), with mean wind speed of 37 m/sec. over 5 hours, the strong continental storm with high damages in the forests from France till Poland in November 1972, a series of 6 heavy floods in November/December 1973 and two extreme floods in January 1976 with the highest water levels ever registrated in the German bight are indications for some changes in meteorological conditions.

Three possibilities must be taken into consideration for the future (fig. 13):



a) There is a sort of flip-flop mechanism in climate with higher but constant probabilities P for extreme surges for the next future (fig. 13a)

b) Like some periods during the Middle Ages, there is a temporary maximum with a trend of reduction in future (fig. 13b) or

c) the worst development: the probability P shows a furtherly increasing trend (fig. 13c).

Fig. 13: Possibilities of futural development of storm surge probability P

From meteorology, no exact prediction can be given for the next future (see FLOHN 1967, LAMB 1976). Also how far human impacts on the climate may be responsible for the events, cannot be answered at time, but meteorologists and engineers should observe very carefully this development for the future (FÜHRBÖTER 1976).

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