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Storm Surges on the German Coast

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Storm Surges on the German Coast

By JÜRGEN JENSEN and SYLVIN H. MÜLLER-NAVARRA

Contents

1. Introduction

Storm surges are natural events that have always threatened life at the coast, and which may cause heavy damage due to an increasing use of the coastal regions nowadays. Both coastal protection and natural disaster defence measures are based on analyses of extreme flood levels. One of the oldest accounts of storm surges at the North Sea coast dates from the year 340 or 120 B.C. when, according to historical records, storm surges forced the Cimber people to leave the area of Holstein and Jutland. A reliable early record of a Baltic Sea storm surge dates back to the year 1044 (cf. JENSEN and TÖPPE, 1990).

Frequency and occurrence of historical extreme storm-surge events have to be considered in the context of the climate or weather conditions prevailing at the time. After early settlers had begun colonising Greenland around the year 1,000, when the climate was warming (Greenland ice-free, long and warm summers, route to America ice-free), a colder period set in around 1300 (the ice returned). Around the year 1400 the last Viking settlement on Greenland had to be abandoned. During this period, many disastrous storm surges occurred along the North Sea coast (cf. Tab. 2). It should be considered though, that chroniclers describing such catastrophic events focused primarily on the effects and damage caused by the surges. In bad times (poverty, epidemics, wars), even smaller storm surges may have had catastrophic consequences (e.g. due to poor condition of dikes). Over the past decades, the economic damage caused by natural disasters has multiplied, which is attributable to increasing urbanisation, industrialisation and population growth in exposed coastal regions (KRON, 2005).

Fig. 1: Development of the island of Sylt; top left: Sylt before the severe storm surge of 1362; top right: Sylt before a strong storm surge in 1634 (from DANCKWERTH, 1652); bottom left: Sylt in 1793 (from BUGGE and WILSTER, 1805); bottom right: Sylt today (sylt.citysam.de/landkarte-foehr-amrum.htm)

In the following, the history of coastal development and surge events will be briefly outlined, followed by a discussion of present storm surge forecast methods and future trends to be expected against the background of climate change. Rising sea levels caused by climate change would lead to dramatic morphological changes at shallow coastlines and in tidal estuaries.

2. Development of the German North and Baltic Sea Coasts

Extreme storm surge events causing major losses of land have shaped the North Sea coastline and islands over the centuries. An example is shown in Fig. 1, which depicts the development of the largest German North Sea island of Sylt since the 14th century. The Figure illustrates the enormous losses of land suffered during several surge events. First studies on the frequency of surge events were conducted by BRAHMS (1754) and WOEBECKEN (1924) (cf. e.g. SCHELLING, 1952). Although storm surges have hit the North Sea coasts again and again during the past centuries, surges in the recent past, beginning with the disastrous flooding of the Netherlands in 1953, have given rise to the question whether there has been a change in the pattern of storm surge occurrences in the North Sea region (cf. e.g. FÜHRBÖTER, 1976 and 1979; SIEFERT, 1978; FÜHRBÖTER, JENSEN and TÖPPE, 1988).

The development of North Sea water levels since the end of the last glacial period has been characterised by alternating transgression (rising water level) and regression (falling water level) phases. Sea level development directly affects the morphology of the coastal foreshore and coastal erosion processes.

Tab. 1 provides a hydrographical and hydrological comparison between the North Sea and the Baltic Sea, which refers not only to the German waters but to the complete body of water in each case.

Table 1: Hydrographical and hydrological comparison of the North Sea and Baltic Sea

	North Sea	**Baltic Sea**
Area	580,000 km²	415,000 km²
Mean depth (largest depth)	93 m (Norwegian Deep 725 m)	52 m (north of Gotland 459 m)
Mean salinity	≈ 35 ‰	3–5 ‰
Tides	Mean tidal range = 3.5 m	Almost free of tides (< 10 cm)
Hydrographical classification	Shallow marginal sea of the Atlantic Ocean	Enclosed sea, connection with North Sea (Kattegat)
Chart datum	NN = „Normal Null" (approx. MSL Amsterdam)	HN = „Höhen Null" (MW Kronstadt) HN = NN + 14 cm
Coastal properties	Tidal flats, long coastline including tidal estuaries, sandy and dune coasts and barrier islands	Graded shoreline, coastal lagoons and cliffs
Coastal defence structures	Dikes, some sea walls, revetments and groynes on the islands, storm surge barriers	Groynes, breakwaters dikes and dams at parts of the coastline
Extreme event	Storm surge	Storm high water
Historical extreme events	Storm surges in 1953, 1962, 1976	1872
Storm surge levels	NN + 5.1 m (Cuxhaven 1976)	HN + 3.3 m (Travemünde 1872)
Development of storm surges	"Wind surge" – meteorological influences: gale-force winds from N–NW; repetitive weather patterns (wind force, direction and duration) – impact on tides (spring tide) – external surges from the Atlantic	"Seiches" – meteorological influences: gale-force winds from E–NE; large water volume of the Baltic Sea; very rare weather patterns (wind force, direction, change in direction from W to E and duration of wind)

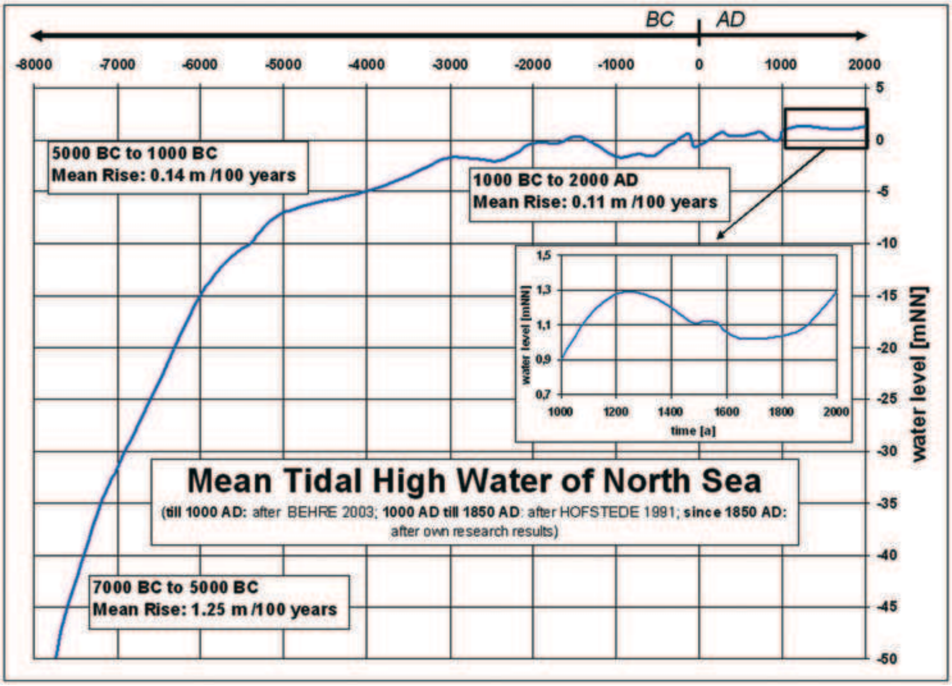


Fig. 2: Post-glacial sea level changes on the German North Sea coast (after BEHRE, 2003; HOFSTEDE, 1991 and own research results)

Fig. 2 shows probable post-glacial sea level changes on the German North Sea coast. On the whole, the transgression process has not been continuous but interrupted by short regression phases.

To be able to classify historical storm surges, i.e. storm surges up to the early 19th century, it is necessary to know the temporal development of mean (tidal) levels because the sea level data are referred to mean water level (MW) in the Baltic Sea, and mean high water (MHW) or mean sea level (MSL) in the North Sea. Since not only the impacts of glaciation but also of coastal movements (tectonics) have to be taken into account, an exact assessment of the temporal development of the mean sea level is hardly possible. Detailed data on water level developments at the North and Baltic Sea coasts are available from about 1850. Since the end of the last glacial period, both the Baltic Sea and North Sea coasts have been shaped by melting ice masses; the maximum of the Weichselian glaciation has been dated at 25,000 to 18,000 years B.P. After a rapid initial sea level rise, the rate of increase slowed down about 5,000 years B.C. and has been as low as a few decimetres during the last thousand years. Apart from eustatic processes, which affect the world-wide water regime, also movements of the Earth's crust and load reductions due to melting inland ice masses have an impact on relative movements between land and sea levels in the Baltic region. It may be assumed that 4,000 years ago the water level of the south-western Baltic Sea was about 1 m below the current mean level. Around the time of Christ's Birth, it was about 50 cm higher than in the Middle Ages, likewise in the North Sea coastal area (JENSEN and TÖPPE, 1990).

3. Storm Surge Generation

PETERSEN and ROHDE (1977) defined a storm surge as a "period of time during which water levels on the coasts and in estuaries are high, due primarily to strong winds". Accordingly, high water levels at the coast and in the estuaries which have not been caused by storm should not be termed storm surges. In studying the generation of storm surges, a clear distinction has to be made between the North Sea and the Baltic Sea, which have different hydrological regimes. The factors leading to storm surges in the two bodies of water are summed up in the following.

3.1 Generation of North Sea Storm Surges

Storm surges at the German North Sea coast result mainly from a build-up of water masses along the coasts (e.g. wind set-up), i.e. they are caused by stochastic (stochastic: science of random processes, i.e. of time variable processes) impacts of meteorological origin which are superimposed on the astronomical tides. Wind set-up at the North Sea coast may reach more than 5.00 m. For example, at the Husum gauge station, a wind set-up of 5.70 m was observed on February 10, 1949, though at the time of tidal low water. As a rule, extreme storm surges at the German North Sea coast occur when heavy storms from north-westerly directions reach wind speeds in excess of 25 m/s. Basically, two types of North Sea storm surges can be distinguished. The wind set-up type is characterised by winds blowing for a long time from a north-westerly direction, driving water masses into the south-eastern North Sea. Storm surges of the wind set-up type can be reliably forecasted, and warnings can be issued up to 18 hours and more in advance. In contrast, the circulation type is clearly more difficult to forecast, because here a small intense low-pressure system tracks across the British Isles at high speed, gaining strength over the North Sea. Consequently, there may be situations in which no exact forecasts can be made until a few hours before peak level. (MÜLLER-NAVARRA, 2005). The ratio of stochastic influences in relation to deterministic influences (e.g. astronomical tide) in water levels at the German North Sea coast is very high. This has to be taken into account when computing storm surge levels based on probability calculations.

3.2 Generation of Baltic Sea storm surges

Whilst by definition the North Sea is a semi-enclosed sea, the Baltic Sea constitutes a (nearly) closed system. The differences between the systems (cf. Table 1) account for the different mechanisms of storm surge generation. Unlike the North Sea, the Baltic Sea is hardly subject to tidal influence, which explains why the term "storm surge", which is normally used to describe high water levels, is usually replaced by the term "storm high water" in context with the Baltic Sea. The Baltic Sea is connected to the North Sea through narrow Belts and the Sound which, far from simplifying the system, lead to an even more complex system behaviour.

In the Baltic Sea, different weather patterns may be involved in the generation of a storm high water; the Baltic Sea, unlike the German Bight, does not have a certain predominant weather pattern creating particularly high water levels. The principal difference among storm surge events in the Baltic Sea is their classification either as a wind set-up event, where wind is the only cause, or a storm surge where seiches involving the whole water body of the Baltic Sea can influence the water level in the western Baltic by a few decimetres. Moreover, the actual water volume in the Baltic Sea also affects the development and peaks of extreme water levels in this region.

Thus, leaving aside flood events caused exclusively by wind set-up, there are several wind directions that may cause high water levels and will lead to a storm surge if they occur in a certain sequence. The maximum water level reached in a particular storm surge event thus depends not only on local winds but is decisively influenced by the temporal sequence of particular wind directions and on wind forces acting in the different regions of the Baltic Sea – including regions that are quite distant from the western Baltic. These specific scenarios are linked closely to the tracks of storm surge relevant cyclones and to the speed at which they travel. Studies have shown that the weather situations leading to the different types of storm surge are fundamentally different (MEINKE 1998 and 1999; HUPFER et al. 2003). The water level records of storm surges since April 1952 have been evaluated and classified according to their generation mechanism (MEINKE 1998).

3.3 History of North and Baltic Sea Storm Surges

Available studies of storm surge events and extreme water levels on the North and Baltic Sea coasts either deal with individual extreme events, e.g. the catastrophic Baltic Sea storm surge of November 1872 (BAENSCH, 1875), or are based on extreme values, e.g. annual maxima (e.g. BRAHMS, 1754; WOEBCKEN, 1924; SCHELLING, 1952; HUNDT, 1955; LIESE, 1963; LÜDERS, 1971; FÜHRBÖTER, 1976 u. 1979; SIEFERT, 1978; JENSEN, 1985; BAERENS et al., 1995); there also exist current studies of the contribution of wind set-up to storm surges (GÖNNERT, 1999) on the North and Baltic Sea coasts. From a statistical point of view, storm surges are subdivided into three categories: small, severe, and very severe:

- small storm surge (wind surge): mean frequency of occurrence (n) of maximum water level: n = 10 to 0.5 annually (North Sea), 2 to 0.2 annually (Baltic Sea)
- severe storm surge (storm surge): n = 0.5 to 0.05 annually (North Sea), 0.2 to 0.05 annually (Baltic Sea)
- very severe storm surge (hurricane surge): n = <0.05 annually (North and Baltic Seas); the frequency of such surges on the North and Baltic Sea coasts is less than once in twenty years

In practice, for operational warnings, distinct deviations from mean high water (North Sea: MHW) and mean water level (Baltic Sea: MW) are given (Tab. 3).

Tab. 2 is a compilation of historical storm surges events on the German North and Baltic Sea coast (southwestern Baltic Sea coast). The total number of storm surges with extreme water levels is substantially higher on the North Sea coast than on the Baltic Sea coast. The main cause is the meteorological situations triggering such events: weather situations causing extreme water levels on the Baltic coasts are relatively rare.

Table 2: History of storm surges/high-water events on the German North and Baltic Sea coasts after KRAMER, 1989; JENSEN und TÖPPE, 1990; PETERSEN und ROHDE, 1991

North Sea		Baltic Sea	
Date	Comments / heights	Date	Comments / heights
340 B. C.	So-called "Cimbrian Flood" (possibly 120 B. C.)	1044	? (details unkown)
17.2.1164	First St. Juliana's Flood, entire North Sea coast		
16.1.1219	First St. Marcellus Flood (Netherlands)		
14.12.1287	Lucia's Flood, entire North Sea coast	1304 (1307, 1309)	New deep created between Rügen and Ruden
		30.11.1320	Lübeck: MW + 3.10 to 3.20 m
23.11.1334	St. Clemens Flood, Flanders to East Friesland		
16.1.1362	Second St. Marcellus Flood, East Friesland to North Friesland		
9.10.1374	First St. Dionysius Flood, East Friesland	1374	?
9.10.1377	Second St. Dionysius Flood, Flanders, Zeeland, Holland, East Friesland	1396	
1400	Frisian Flood	1412	?
18.11.1421	St. Elizabeth's Flood, East England and Netherlands		
1434–1501	Six "Gallic Floods"		
11.1.1436	All Saints' Flood, German North Sea coast	1449, 1467	?
6.1.1470	Three Kings' Flood, German North Sea coast	30.11.1497	?
26.9.1509	Kosmas and Damian Floods, Netherlands, East Friesland		
16.1.1511	St. Antonius Flood, German North Sea coast	1519	?
31.10.1532	Third All Saints' Flood, North Sea coast: Canal to Eiderstedt	1552, 1558	
1.11.1570	Fourth All Saints' Flood, Flanders to Eiderstedt	Summer of 1570	Lebamünde destroyed?
1572	Grain Flood	1573/96, 1609	?
26.2.1625	Carnival Flood, South Holland to Jutland	10.2.1625	Lübeck: up to MW + 2.84 m
11.10.1634	Second "Mandränke" (Great Drowning), Schleswig-Holstein	1645	?
22.2.1651	St. Petri Flood, Friesland	1663, 1690	?
12.11.1686	St. Martin's Flood, Groningen to Land Wursten	10./11.1. 1694	Lübeck: MW + 2.86 m Travemünde: MW + 2.65 m

continued on the next page

continuation of Table 2

24.12.1717	Christmas Flood, North Sea coast	1709	
31.12.1720 1.1.1721	New Year‘s Flood, Zeeland to North Friesland	1736, 1741, 1784	
3./4.2.1825	February Flood, East to North Friesland (highest tidal high water)	19.12.1835	Flensburg: MW + 2.54 m
		26.12.1836	Lübeck: up to MW + 2.20 m Schleswig: up to MW + 2.75 m
1./2./4.1.1855	January Flood, East Friesland	30.12.1867	Lübeck: MW + 2.04 m
		12./13.11. 1872	Highest storm surge so far in Lübeck / Travemünde: up to MW + 3.40 m
		25.11.1890	Travemünde: MW + 2.10 m
		30./31.12. 1904	Travemünde: bis MW + 2.22 m Flensburg: MW + 2.33 m
13.3.1906	March Flood, East Friesland (highest tidal high water)	29./31.12. 1913	Travemünde: MW + 2,00 m
31.1./1.2.1953	Holland Flood, Netherlands and England	4.1.1954	Travemünde: MW + 2.07 m
16./17.2. 1962	Catastrophic storm surge, East Friesland to North Friesland (highest tidal high water)	14.1.1960	?
23.2.1967	Adolph Bermpohl hurricane with the highest wind speeds measured so far		
19./20.11 1973	November Flood, Lower Saxony and Schleswig-Holstein		
3./4.1. 1976	January Flood, Lower Saxony and Schleswig-Holstein (highest tidal high water north of the Elbe)	31.12.1978 15.2.1979	
24.11.1981	November Flood, Schleswig-Holstein (highest tidal high water in North Friesland)	13.1.1987 27./28.8. 1989	Summer flood causing considerable damage
Jan./Feb. 1990	5 hurricanes in 3 days, Schleswig-Holstein		
21./22.1. 1993	Several storm surges, sand losses on Sylt, Schleswig-Holstein		
28.1.1994	Hamburg, Schleswig-Holstein	6.11.1995	Baltic Sea to Mediterranean Sea
6.2.1999	Entire North Sea coast		
3./4.12. 1999	Elbe (Hamburg), Schleswig-Holstein to Denmark		
29./30.1. 2000	Denmark, substantial sand losses on Sylt (cliff)		
9.11.2007	Storm surge caused by low-pressure system “Tilo” affects almost the entire North Sea coast		

3.4 Recent Storm Surges

Whilst Tab. 2 lists all recorded historical storm surges in the North and Baltic Seas, including available information on their severity and areas affected, recent storm surges which have occurred since the beginning of continuous gauge data recording (about 1820) will be discussed in more detail in the following, as part of the systematic study of storm surges.

3.4.1 Storm Surge Levels at the North Sea Coast

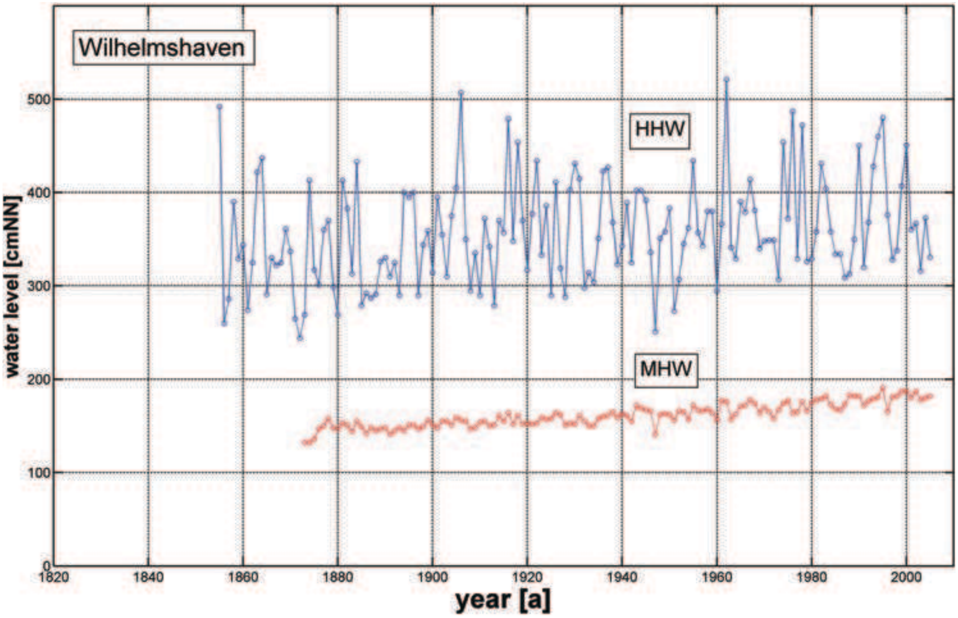
A comparison of maximum wind set-up data for the coast of Lower Saxony shows that storm surges vary considerably in their characteristics depending on local wind conditions and the shape of the coastline. The highest water levels in East Friesland were produced by the storm surge of 1906, in the Jade-Weser area by the storm surge of 1962, and in the Elbe area by that of 1976.

The extreme storm surges of the past 30 years produced maximum water levels especially in the inner German Bight and in North Friesland; this is evident from the fact that the highest tidal high water level at the Borkum and Emden gauge stations was recorded during the 1906 storm surge, whereas in the area between the Weser and Elbe estuaries the highest storm surge level ever recorded occurred on 16 February 1962. In Cuxhaven and on the west coast of Schleswig-Holstein, the historically highest storm surge level was measured on 3 January 1976; this in turn was exceeded by the levels recorded at the Dagebüll and List/Sylt stations which are located farthest north.

In January and February 1990, 5 hurricanes caused storm surges on the coasts of Schleswig-Holstein; several storm surges on 21/22 January 1993 reached particularly high levels on the North Sea coast of Schleswig-Holstein and caused substantial losses of sand on the island of Sylt. Also the storm surge of 28 January 1994 led to the highest water levels ever observed on the northern coasts of Schleswig-Holstein. The storm surge event of 6 February 1999 affected the entire German North Sea coast. The storm surges of 3/4 December 1999 and 29/30 January 2000 which again caused very high water levels on the North Sea coasts of Schleswig-Holstein and Denmark also constitute extreme events because of the tracks of the depressions and of the wind speeds involved. The most recent storm surge in this series, caused by the low-pressure system "Tilo", is that of 9 November 2007 which led to relatively minor damage because flood protection measures were taken at an early stage.

Fig. 3 shows the time series of mean tidal high water (MHW) and high tidal high (HHW) water for the gauge stations at Wilhelmshaven and Bremerhaven, and Fig. 4 those of Büsum and Cuxhaven. The individual time series will not be analysed in detail here (e.g. with respect to trends). The gauge stations (island and mainland stations) have been selected on the basis of their time-series length and location, which should be distributed along the whole North Sea coastline.

On the whole, it has been found that during the past three decades the north-to-south coastline of Schleswig-Holstein and the Elbe estuary were affected more often by extreme water levels than the west-to-east coast of Lower Saxony.



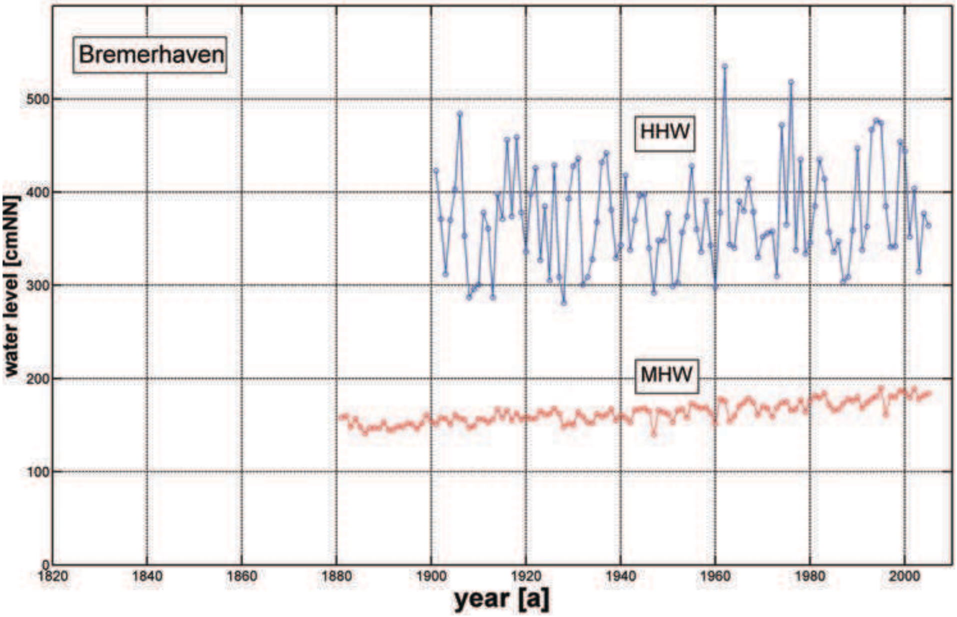
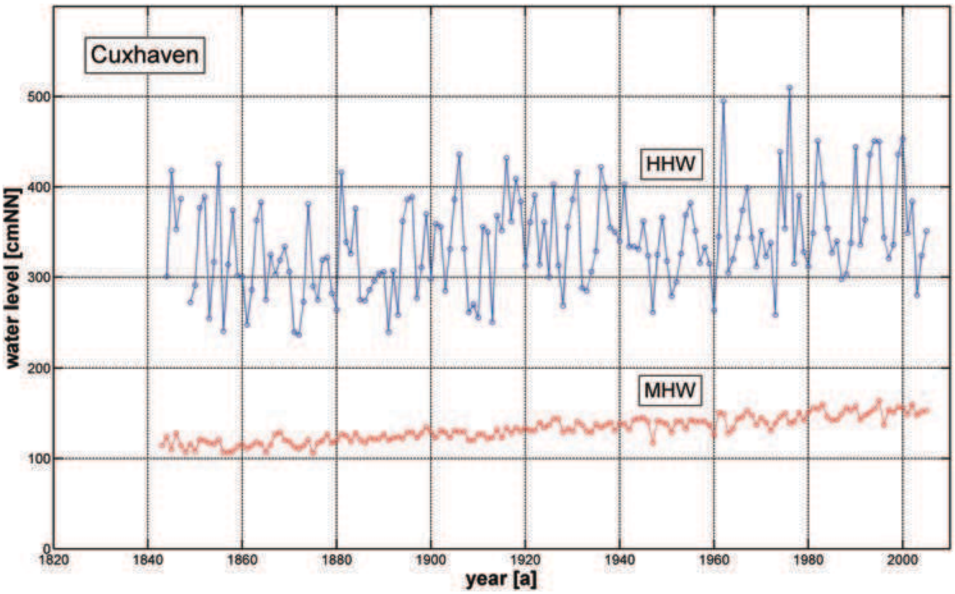


Fig. 3: Time series of mean tidal high water and high tidal high water at the Wilhelmshaven and Bremerhaven gauge stations



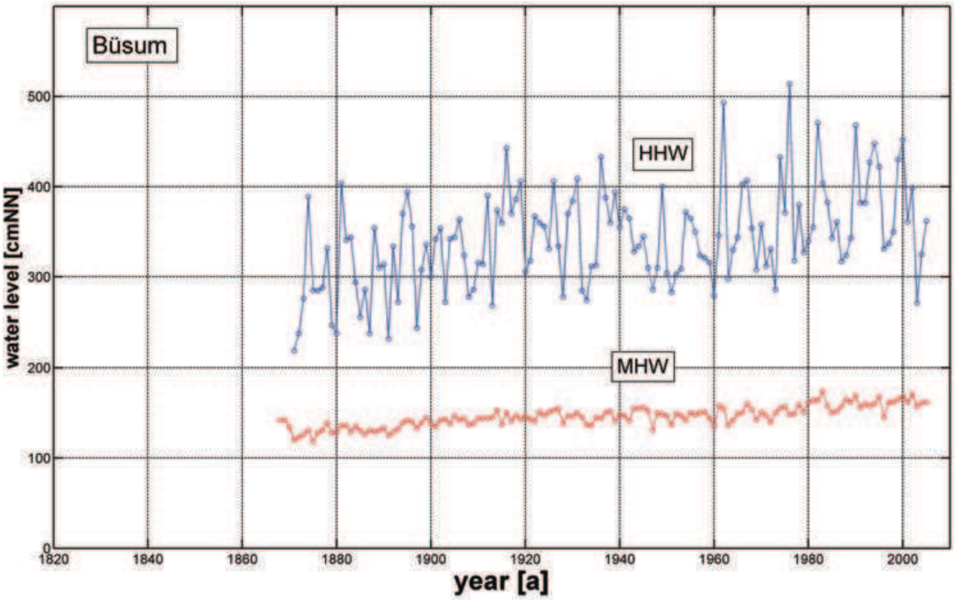


Fig. 4: Time series of mean tidal high water and high tidal high water at the Cuxhaven and Büsum gauge stations

3.4.2 Storm Surge Levels at the German Baltic Sea Coast

The first records of storm surge events at the Baltic Sea coasts, including the maximum water levels measured, date back to the 14th century. The first precise measurement showed an elevation of 3.2 m above the Baltic Sea mean water level, measured at Lübeck during the storm surge of 1320 (JENSEN and TÖPPE, 1990). In November 1872, a storm surge of unprecedented severity hit the Baltic coasts, with a maximum of up to 3.5 m above mean water level. Many authors have described this catastrophic storm surge event at the Baltic Sea coasts (e.g. BAENSCH, 1875).

Fig. 5 shows the available time series of mean water level (MW) and high water level (HW) at the Travemünde and Warnemünde gauge stations, representative of the Baltic Sea coast; an analysis of the time series (e.g. with respect to trends) is not provided here (JENSEN and BLASI, 1998). The gauge station at Travemünde has the longest uninterrupted time series of measurements in this area.

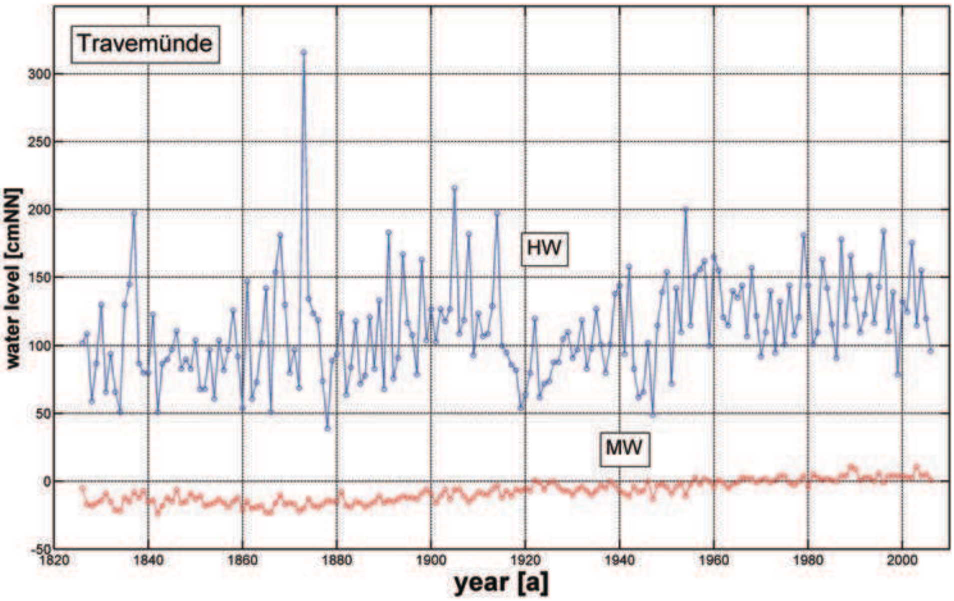
In the 20th century, peak values of more than 2 m above mean water level were measured during the storm surge events of 30/31 December 1904, 30/31 December 1913, 4 January 1954, and 6 November 1995. Flood events on the Baltic Sea coasts, like those on the North Sea coasts, normally occur in the winter months from October to March. The flood event of 27/28 August 1989 came unexpected because it occurred during summer, and caused heavy damage. The extreme flood of November 12/13, 1872, has to be considered a singular event with regard to its maximum water level, and thus will continue to serve as design flood in the future.

4. Future Developments

As has been pointed out above, life at the coast has always been strongly influenced by recurring storm surges. In order to be able to assess future risks and take early action to strengthen coastal defences, some detailed studies still have to be made. In particular, questions concerning the probability of occurrence of extreme storm surges and the impact of climate change on storm surge events at the German coasts still have not been answered satisfactorily.

4.1 Probabilities of Occurrence of Extreme Storm Surges

Storm surges at the coast are natural phenomena which occur at irregular intervals and differ in severity. To be able to carry out long-term coastal risk management, it is essential to determine the probability of occurrence of certain storm surge levels. Within the framework of the German Coastal Engineering Research Council GCERC (Kuratorium für Forschung im Küsteningenieurwesen KFKI) funded research project 'MUSE – Model-based studies of storm surges with very low probabilities of occurrence' (Modellgestützte Untersuchungen zu Sturmfluten mit sehr geringen Eintrittswahrscheinlichkeiten), observed and simulated extreme water levels were analysed statistically. The model simulations had been carried out using modelling chains of the German Meteorological Service (Deutscher Wetterdienst DWD) and the Federal Maritime and Hydrographic Agency of Germany (Bundesamt für Seeschifffahrt und Hydrographie BSH). DWD computed physically possible wind and weather situations capable of causing exceptionally high storm



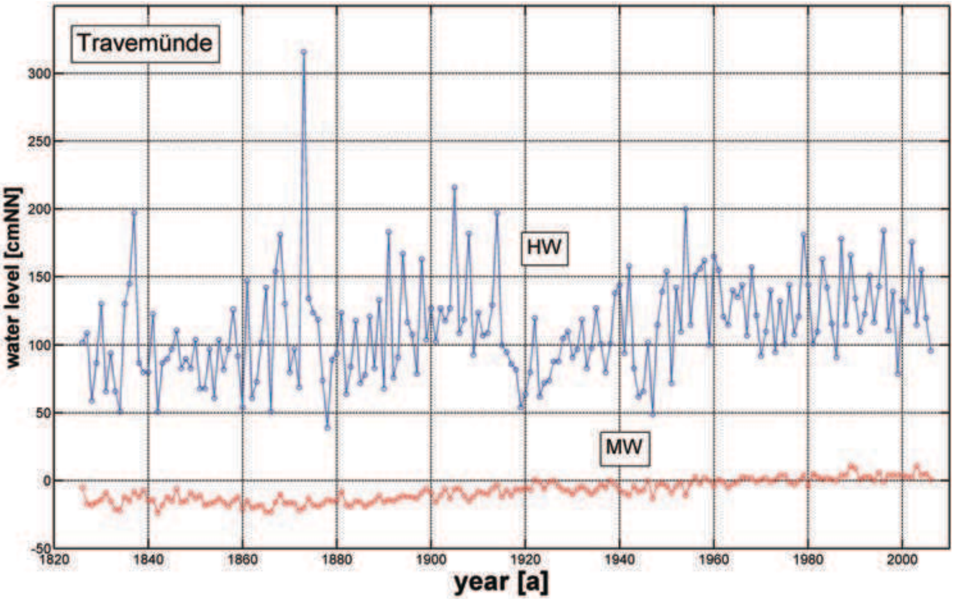


Fig. 5: Time series of mean water and high water levels at the Travemünde and Warnemünde gauge stations

surges in the German Bight, using numerical forecast models in a hindcast mode. Its results were transferred to the BSH, which computed the resultant water levels and wind set-up data for several coastal locations, using physically consistent numerical 2D and 3D water level forecast models which are in routine operational use at the BSH to forecast storm surges. The statistical evaluation of modelled and measured water levels was made at Siegen University's Research. It used a statistical method based on the Gumbel type III distribution (GUMBEL, 1958) which allowed the modelled extreme values to be correlated with the observed data with a view to improving the statistical evaluation of very rare storm surges.

The results show that, in the German North Sea region, storm surge producing weather conditions are possible that may lead to water levels exceeding historical maximum levels by up to 1.4 m. On the basis of the modelled water levels, it will be possible to better assess the probability of occurrence of extreme storm surge peak water levels.

Detailed information on the MUSE research project and its results was published by JENSEN et al. in 2006.

4.2 Storm Surges and Climate Change

An important research issue in the field of coastal engineering is the question how climate change will influence storm surge occurrences. As storms are a characteristic element of the regional climate in Northern Germany, any change in the storm regime will have significant effects on the coastal areas. Research carried out by the coastal research institute of GKSS (Geesthacht research centre) and the Coastal Research Station Norderney (Forschungsstelle Küste) has shown that despite the temperature increase that has taken place in the winter months (about 1 degree Celsius during the past 150 years) no major changes in the storm surge regime (VON STORCH and NIEMEYER, 2008) can be detected. However, future scenarios show an increase in wind speeds (especially westerly gale-force winds) by up to 10 % in the North Sea by the end of this century, which will of course have an impact on the storm surge regime and, consequently, on coastal protection measures. In addition to sea level rise and the resultant higher static load, there would also be a higher set-up during storm surges. Moreover, due to increased water depths, more extreme sea states and strong dynamic loads on the coastal flood defences structures can be expected. Studies of WOTH, VON STORCH and WEISSE (2005) have shown a possible increase in storm surge levels by 20–30 cm along the 10 m bathymetric contour. Adding this increase to the 40 cm sea level rise which IPCC considers possible by the end of the 21st century, assuming certain emission scenarios, there is a risk that climate change alone might lead to 60–70 cm higher water levels in the German Bight. Taking into account the results of the MUSE research project as well, the conclusion is that by the end of this century there is a possibility for the occurrence of water levels during extreme storm surge events which may exceed historical maximum levels by 2.0 to 2.1 m. There are uncertainties in these computations regarding the emission scenarios used such as the behaviour of ice covers and glaciers and possible combinations of the above effects (increasing storm surge levels, rising sea level, more severe wave regimes). These may have to be taken into account. Further research should be aimed at defining and minimising these uncertainties.

5. Storm Surge Forecasting

5.1 Organisation

Storm surge forecasts for the German coasts are issued by Bundesamt für Seeschifffahrt und Hydrographie (BSH, Federal Maritime and Hydrographic Agency of Germany) in Hamburg (MÜLLER-NAVARRA, 2006), in conformity with the "Seeaufgabengesetz" (Federal Maritime Responsibilities Act) (ANON., 2006). The forecasting service, which provides information to the public, was started by the BSH's predecessor "Deutsche Seewarte" in 1924 and is the longest standing public warning service in any of the North Sea states (TOMCZAK, 1955).

According to available records, storm surge warnings for the Baltic Sea coast of Schleswig-Holstein have been issued sporadically by Deutsche Seewarte since 1940 (archives of the BSH's water level forecasting service). Warnings for the Baltic coast of Mecklenburg-Vorpommern have been issued since 1952. Until 1990, different institutions of the German Democratic Republic (GDR), located in Warnemünde, were in charge of the water level forecasting service. The first of these institutions was the "Ostseeobservatorium des Seehydrographischen Dienstes" (Baltic Sea observatory of the hydrographic service). The last one prior to the reunion of Germany was the hydrographical department of the coastal waterways directorate (O. MIEHLKE, pers. comm.). After the reunion, this service was integrated into the BSH at its Rostock headquarters.

The BSH's tidal service has an even longer tradition. The first tide table for the German North Sea coast and other European coasts was issued for the year 1879 (ANON., 1878). This time series has been continued uninterrupted to the present day. Tidal predictions are in fact the prerequisite to any storm surge forecast for tidal waters.

Because of the considerable effort and expense involved in maintaining a storm surge warning service (Fig. 6), centralised operation is the preferable approach, as will become apparent from the following description. Nevertheless, local warning services for the German North Sea coast exist in the German federal states (NLWKN in Lower Saxony, LKN-SH in Schleswig-Holstein, and HPA in Hamburg) which use the BSH's forecasts and supplement them in adaptation to local conditions or additionally use own empirical methods (WADI Hamburg, SIEFERT, 1968; SIEFERT et al., 1983).

The terms used at BSH to characterise the severity of storm surges and deviations of (Δh) from mean high water (MHW) and mean water level (MW) are listed in Tab. 3. While the classification for the German Bight has been generally accepted, different categories exist in the western Baltic Sea (HUPFER et al., 2003, from p. 116). For example, it might be reasonable to introduce an additional category "very severe storm surge" for water levels exceeding 2.0 m.

Table 3: Classification of storm surges according to the BSH

German Bight		Western Baltic Sea	
Term used	**Deviation from MHW**	**Term used**	**Deviation from MW**
Storm surge	$1.5\ m \leq \Delta h < 2.5\ m$	Small storm surge	$1.0\ m \leq \Delta h < 1.25\ m$
Severe storm surge	$2.5\ m \leq \Delta h < 3.5\ m$	Moderate storm surge	$1.25\ m \leq \Delta h < 1.5\ m$
Very severe storm surge	$\Delta h \geq 3.5\ m$	Severe storm surge	$\Delta h \geq 1.5\ m$

5.2 Problems Involved

In mathematical terms, the problem of water level forecasting is closely related to that of weather forecasting. Both are initial-boundary-value problems. The atmosphere and ocean are dynamically coupled at the water surface. Wind forces currents and causes wave action, and the wind profile depends on the roughness of the wave-dominated water surface and on the air/water temperature difference. Current operational forecasts are still made in two steps: the weather forecast is made first; the water level forecast follows as a second step, as a partial problem of ocean forecasting.

For about 25 years, a chain of numerical forecast models has been used at BSH to deal with these problems (DICK et al., 2001; MÜLLER-NAVARRA, 2003). So far, numerical forecast methods have not yet been able to fully replace empirical methods using latest measurement data, especially in forecasting extreme events. In the field of weather forecasting, synoptic methods have a long tradition (SCHERHAG, 1948; KURZ, 1990); the term used correspondingly in water level forecasting is empirical statistical methods (SAGER et al., 1956; SCHMAGER, 1984; MÜLLER-NAVARRA et. al., 1999).

Under hydrological aspects, storm surges at the German North Sea coast and in the western Baltic Sea have identical causes. However, their development takes place in different types of ocean basin, which are connected in different ways with the open ocean (see Tab. 1). The latter fact leads to a fundamental difference in operational storm surge forecasting. In large areas of the North Sea, the tides are the essential factor which determines the time of the storm surge maximum. In contrast, the weak tides in the Baltic Sea are virtually unnoticeable during a storm surge, and the surge maximum is determined primarily by hydrological and meteorological factors. To arrive at a deeper understanding of storm surges in the Baltic Sea, especially in its western part, the existence of a combined North and Baltic Sea system has to be assumed. During the passage of low pressure systems and storms across the transition area between the North Sea and Baltic Sea, enormous water masses of alternating directions are passing through the Belts and Sound and have a strong impact on local water levels (WEIDEMANN, 1950; MÜLLER-NAVARRA, 1983). This has often been described by the poorly defined term of "pre-filling", which is not suitable for operational forecasting. Particular storm tracks with hurricane-force winds may first cause a storm surge in the German Bight and one day later a surge in the western Baltic Sea (e.g. "All Saints Flood", November 1/2, 2006, MÜLLER-NAVARRA, 2006).

5.3 Weather Forecasting

Without the occurrence of intense low-pressure systems, there would be no storm surges in the North Sea or Baltic Sea. In the German Bight, only wind directions from the sector WSW to NNW can produce storm surges. In the western Baltic Sea, by contrast, surges are caused by winds from the sector N to E. The tracks of low-pressure systems causing such storms may vary considerably (KOHLMETZ, 1967). In most cases, the low-pressure systems are generated in the North Atlantic Ocean and travel eastward across Great Britain. However, storm surges in the Baltic Sea may also be caused by low-pressure systems tracking both from the Mediterranean area across Central Europe or southward from the Polar Seas (MIEHLKE, 1962).

All these weather situations have in common that they involve special problems of maritime meteorology. Three questions are at the centre of the forecasting problem:

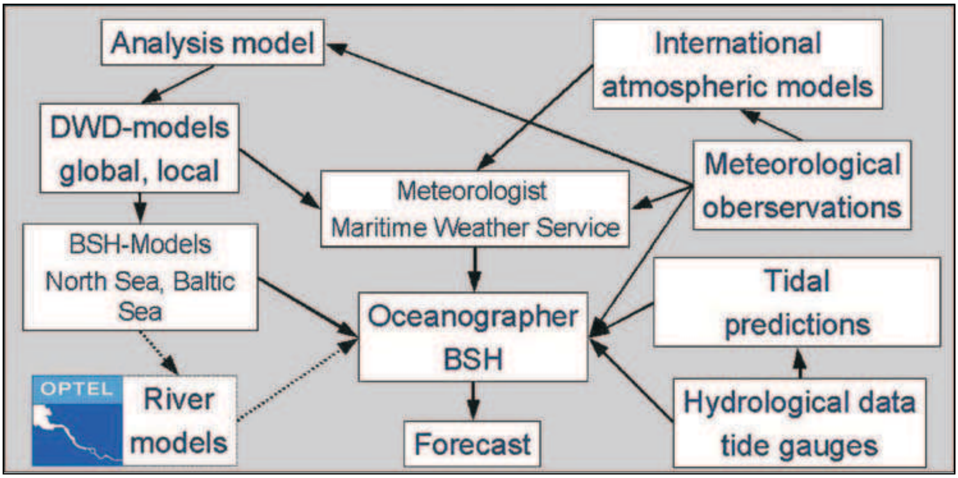


Fig. 6: Information sources used by the oceanographer in storm surge forecasting

1. How fast does the low pressure system move, and on what track?
2. Will the cyclone increase in intensity?
3. How will the near-bottom wind profile, depending on stratification, develop?

The first question concerning track and speed is of special relevance with regard to small, high-intensity cyclones, because the time of wind maximum must be related in a particular way to the computed time of astronomical high water on the German North Sea coast. It is not helpful to state that maximum wind will occur sometime in the next 18 to 24 hours, because the only effect might be an extremely high low water. This happened, for example, in the early morning of February 10, 1949 (TOMCZAK, 1950). The tidal phase problem does not exist in storm surges in the western Baltic Sea. But the track of such small cyclones is equally important to the North and Baltic Sea coast because wind direction and the area of maximum wind fetch depend on it (storm "Anatol" on December 3, 1999, MÜLLER-NAVARRA, 2002). Without this data, no reliable regional storm surge forecasts can be made.

The relevance of the second point "increase in intensity" to short-term forecasts is often underestimated. Particularly over the sea, there is no sufficient number of observation stations which would allow an estimate of whether the hurricane has already lost its force or is still increasing in intensity. This also gives rise to the problem that insufficient data availability makes it impossible to compute satisfactory analyses, and that the initial distributions of model runs are missing important features (frontal zones, cold air troughs). This problem resulting from poor data availability over the oceans is not new but was already encountered when Deutscher Wetterdienst (DWD, German Weather Service) ran the very first baroclinic models (BUSCHNER et al., 1973). Thus, in the individual case, it is still the experienced synoptic meteorologist at the maritime weather service who has to compile and evaluate the model results and incoming station data in order to make a reliable forecast.

The third point "stratification and wind profile" is a problem often overlooked. Although it has been a research topic in meteorology for many years (HASSE, 1968), gaps of knowledge concerning the atmosphere/ocean impulse transfer at very high wind speeds still exist. Because of this, parameterisation of the impulse transfer in numerical modelling chains still involves major uncertainties (JENSEN et al., 2006). Two examples may illustrate this point. In a situation of unstable stratification, wind gustiness can increase wind stress and water set-up on the coasts; such conditions probably prevailed during the storm surge caused by the Hamburg hurricane (RODEWALD, 1962; KOOPMANN, 1962). An inflow of cold air on November 12/13, 1872, probably contributed to the extreme peak levels reached during the storm surge of November 13, 1872 (ROSENHAGEN et al., 2008).

5.4 Storm Surge Forecasts for the North Sea

The water level forecasting process is closely linked to the availability of operational data and information. Today, first preparatory work can be done and information provided much earlier than, e.g., 20 years ago. Moreover, the tides establish a certain time frame, and extreme storm surge levels can only occur within a narrow time window of ± 2 hours around the time of astronomical high water. This requires different warning strategies depending on the individual case. Neither should warnings be issued too early, nor should the public be confused by contradictory information or by too much detail. Warnings, once issued, are never cancelled because two successive storm surges are not so uncommon events. Looking at past experience, storm surge warning routines for the German North Sea coast can be broken down into five phases:

Phase 1: 72–24 hours before high water

First information about the existence of intense low-pressure systems in the Northeast Atlantic with a storm surge potential, whose track is governed by high altitude flow, is provided by global models of the national weather services several days before their approach (MAJEWSKI et al., 2002b). This poses the first problems, because, in the past few years, radio and TV stations have increasingly focused on natural disasters. Each station wants to be the first to issue a concrete forecast. As has been pointed out above, model forecasts of track and speed over the sea are still very uncertain. Therefore, the following cannot be overemphasised:

Public warnings of storm surges should not be issued too early, because this would confuse the coastal population and cause them to lose trust in the longer term due to frequent forecasting errors.

Nevertheless, BSH's storm warning service does not stay inactive during this phase. Over a three-day period, the modelling chain of DWD and BSH provides updated high-water forecasts every six hours. The modelling chain comprises five models. Data are provided by DWD's two atmospheric models, a global model termed GME (MAJEWSKI et al., 2002b) and a local model, COSMO-EU (formerly called LM, STEPPELER et al., 2003), and by BSH's three interactively coupled ocean models which are based on the BSHcmod method: the Northeast Atlantic model, the North and Baltic Seas model and the coastal model (DICK et al., 2001). A wind set-up model with limited model physics is run parallel to these models.

First discussions, mainly regarding the quality of these early model forecasts, are held with the meteorologists of the maritime weather service during this phase (Fig. 6). Experience in storm surge forecasting has shown that currently used atmospheric models generally overestimate the severity of storms which are a longer time ahead. Another important issue in these discussions is whether the weather situation under review is comparable to past storm surge situations. Here, the expertise and experience of the meteorologist on duty is of crucial importance.

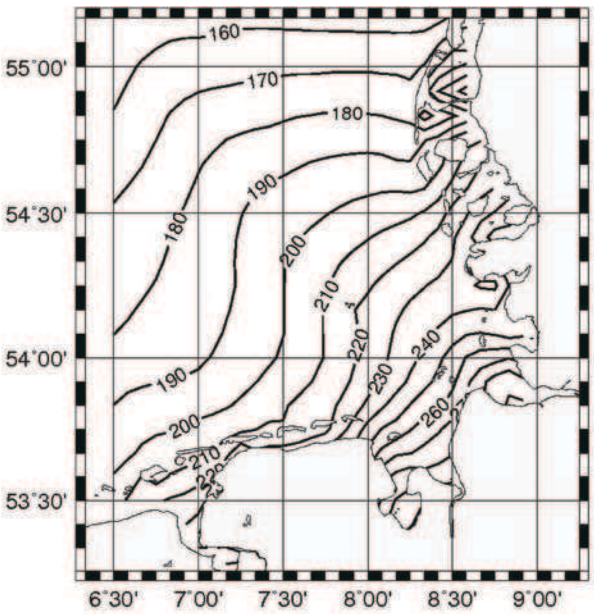


Fig. 7: Forecast of wind set-up of BSH's operational model system for the storm surge of November 9, 2007

The maximum water levels computed by means of this system (Fig. 7) form the basis for consultations held with the emergency control committees of the German coastal states. For example, when a storm surge has been predicted for the weekend, emergency personnel have to be alerted as early as Friday.

Phase 2 "Consolidation": 24–18 hours before high water

Almost 24 hours before the predicted high water, the runs of the various global and local models begin to resemble each other more and more, and variations in the temporal development are becoming less from one forecast run to the next. There are normally four model runs per day, starting with the analyses at 0, 6, 12, and 18 hours UTC. In this phase preceding the storm surge, a consolidation of results is taking place. The modelling data now reach a period of time that is accessible to synoptic treatment of such weather situations (SCHERHAG, 1948). This means that the model runs are supported by meteorological observations and synoptic forecasts made on that basis. When both of these components form a harmonic, convincing picture, the oceanographers and meteorologists on duty know that there will be a storm surge.

When a homogeneous, quasi-stationary wind field is expected over the North Sea, satisfactory results can be obtained for the German North Sea coast using historic methods which take into account the atmospheric pressure gradient over the entire North Sea (LEVERKINCK, 1915; RAUSCHELBACH, 1925). Better results can be obtained using empirical/statistical methods if data from wind monitoring stations in the German Bight are available (MÜLLER-NAVARRA et al., 1999). In that case, so-called wind set-up diagrams for individual locations are particularly easy to use (Fig. 8). In the consolidation phase, they provide a first rough idea of the maximum water levels to be expected. The required input is wind data – areal mean values in the southern German Bight, 3 hours before the time of high water at Cuxhaven. The thick, nearly vertical line in the diagram indicates the wind direction most likely to produce a set-up at Cuxhaven at certain wind speeds; at 50 knots the attached direction is 295° (WNW).

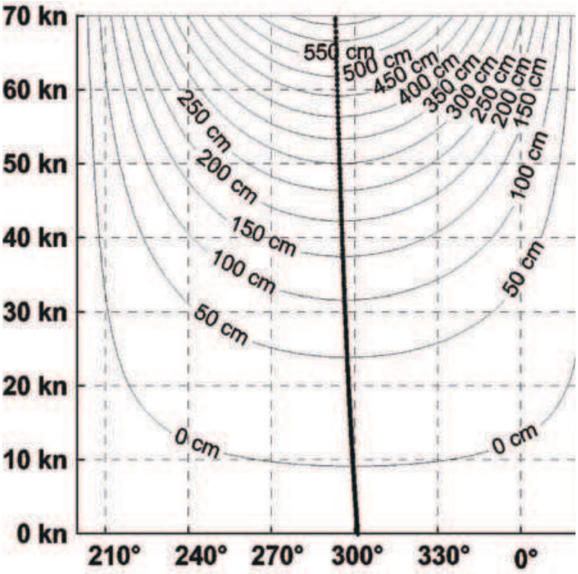


Fig. 8: Wind set-up diagram for Cuxhaven (MÜLLER-NAVARRA et al., 1997)

Cuxhaven, the central location on the German North Sea coast, serves as a reference point for the other coastal locations. Depending on wind direction and speed, deviations are added or substracted to the set-up value computed for Cuxhaven to obtain the values for the individual coastal locations (TOMCZAK, 1952a, 1952b). In this way, empirically calculated storm surge maximum levels are obtained for the different coastal regions. This method, which may seem outdated at first sight, provides fairly good results in the presence of homogeneous, stationary wind fields in the German Bight. However, the empirical method has weaknesses in non-stationary weather situations. It presupposes that a dynamic equilibrium develops between wind and water level gradient, and between surface currents and near-bottom compensating flow (Fig. 9), which is not always the case.

In non-stationary weather situations, the above-mentioned modelling chain of DWD and BSH is indispensable. Wind set-up is determined by parallel computation using two different model variants, one variant with all boundary conditions and another one without meteorological forcing. The computed difference is the wind set-up, although only wind set-up at the time of the low and high water maximums (skew surge) is computed. Another advantage of the model is an spatial representation of the set-up (Fig. 7). The occurrence of storm surge levels is sometimes limited to certain coasts. During SSW winds, for example, storm surge levels occur only along the North Frisian coast.

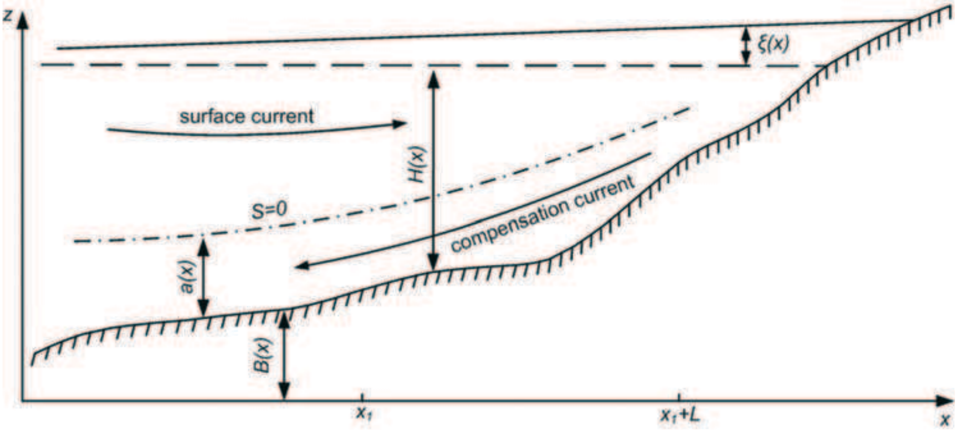


Fig. 9: Vertical current profile and wind set-up on shallow coasts (ERTEL, 1972)

Phase 3 "Warnings": 18–9 h before high water

Once the set-up has been computed using the method described above, the set-up value is added to the values of the computed astronomical high water, and the total value is referred to the local mean high water (MHW) value. If it is more than 1.5 m above MHW at any location, this is by definition a storm surge; above 2.5 m it is a severe storm surge, and more than 3.5 m above MHW is defined as a very severe storm surge (Tab. 3).

The BSH updates its water level forecasts four times a day, at 8 h, 14 h, 20 h, and 24 h, in case of storm surges even more often. Then, the water level forecast becomes a storm surge warning. The warning has to be worded unambiguously in such a way that it cannot be misunderstood, particularly when broadcast on the radio. On November 8, 2007, at 20:30 h, the following warning was issued for noon on the next day, i.e. about 16 hours earlier:

"There is a risk of a severe storm surge at the German North Sea coast. On Friday, high water levels at noon and in the afternoon are expected to be 3–3.5 m above MHW at the East Frisian coast and in the Weser and Elbe estuaries, and about 2.5 m above MHW at the North Frisian coast."

Detailed forecasts for places at the German North Sea coast are published on the Internet, and special warnings are sent to about 320 recipients by telegram (FACT24 Alarm Service, F24 Communication Services) (Fig. 10). The recipients are mostly organisations or agencies forwarding the warnings (e.g. emergency services, fire brigades, operators of barrages and container terminals, dike administrations, city utilities, nuclear power stations, pilot stations, navy, police and port authorities, local warnings services). Besides, there are numerous other communication channels with a major problem being the promulgation of identical information on all channels.

Phase 4 "Concretisation and updates": 9–4 hours before high water

In phase 4, the oceanographer of BSH is busy updating the forecasts of maximum water levels for the entire German North Sea coast. Concretisation and updates are supported, on the one hand, by new model runs as required and, on the other hand, by meteorological

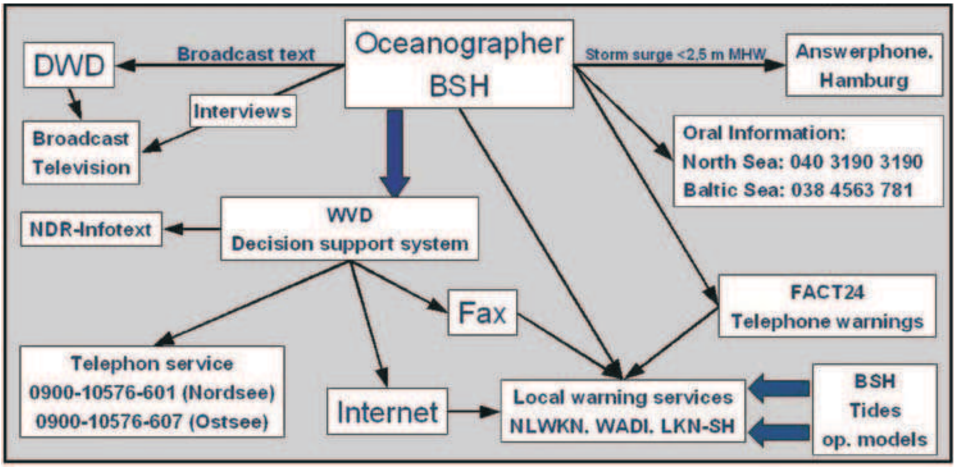


Fig. 10: Promulgation of warnings and information following the issue of a storm surge forecast by BSH's oceanographer

advice provided continuously by the synoptic meteorologist at the maritime weather service. Depending on the situation, BSH's oceanographer may contact the meteorologist every hour to obtain the latest data on storm development in the North Sea region. Another purpose of the continual updates is to provide forecasts for smaller areas. Radio broadcast messages and FACT24 warnings, as described above, only refer to the general situation and provide water level data for larger coastal areas.

If the situation becomes more threatening, different warning levels are used. Now, recipients of warnings have to prepare for higher peak levels. If, however, the present situation is considered less serious than expected, warning levels will not be lowered since the risk of the storm regaining strength is too high.

The continually updated peak levels are also communicated to people living in risk areas. During storm surges, lots of people will call pre-defined telephone numbers in order to obtain personal advice (Fig. 10).

Nine hours before the computed astronomical high water in Hamburg is also the earliest point of time that expected peak levels for Hamburg can be determined using the empirical method of WADI, the Hamburg warning service, at Hamburg Port Authority (HPA) (SIEFERT et al., 1983). This is the theoretical point of low water at Borkum. Moreover, the wind set-up computed for Borkum is available to be used – among other input parameters – for the WADI forecast. However, in case of pronounced non-stationary weather situations, this method is lacking accuracy, and the results have to be checked and revised by the responsible official at HPA. The forecasts for Hamburg are co-ordinated orally between HPA and BSH in order to be able to promulgate consistent forecasts.

Phase 5 "Tidal rivers": 4–0 hours before high water

It takes about 3.5 hours for a storm tide to travel from the mouth of the river Elbe to Hamburg. This time span and available data on storm surge peak levels in the Elbe estuary allow a precise forecast of peak levels to be expected in Hamburg. A similar method is used for the city of Bremen at the Weser estuary.

It is worth noting that the first warning systems in Hamburg, which date back to the 19th century, were based on water level data that had been transmitted by telegraph from the Cuxhaven gauge station (Official order, ANON., 1855).

In the last four hours before peak level is reached, some difficult work remains to be done. The exact large-area water level situation in the Elbe estuary and local wind conditions cannot be recorded precisely by the small number of operational measuring stations. But it is exactly in this area that the shape of the surge wave undergoes characteristic deformations which determine its progress and shape. The time series of water levels at Cuxhaven, supplemented perhaps by one recorded in the inner German Bight at "Beacon A", does not provide sufficient data for an estimate of the upstream evolution of the surge wave. Other factors to be considered in forecasts of peak water levels in Hamburg are wind conditions along the estuary (RUDOLPH, 1997) and the freshwater discharge, even though periods of high freshwater discharge (spring and autumn) do not usually coincide with the storm surge season.

Unfortunately, the "Elbe lightship" monitoring station, which used to provide important data for empirical computations of wind set-up in the inner German Bight, does not exist any more. As storm "Anatol" tracked across the area on December 3, 1999, the vessel capsized in heavy seas and suffered heavy damage. Unlike the aftermath of the "Elbe 1 hurricane" on 27 Oct 1936 (SCHERHAG, 1938), the unmanned lightship "Elbe" was considered unnecessary as an aid to navigation and was taken out of service. This meant the loss of an important oceanographic and meteorological monitoring station with a long tradition, whose data have been sorely missed in several storm surge forecasts since then.

Today, we try to compensate for the loss of this monitoring station by closely observing developments upstream, at the next important gauge station at Brunsbüttel (Fig. 11). There is no problem extrapolating the increase in wind set-up at Brunsbüttel, in comparison with the Cuxhaven station, to Hamburg. It has been found that, as good rule-of-thumb, wind

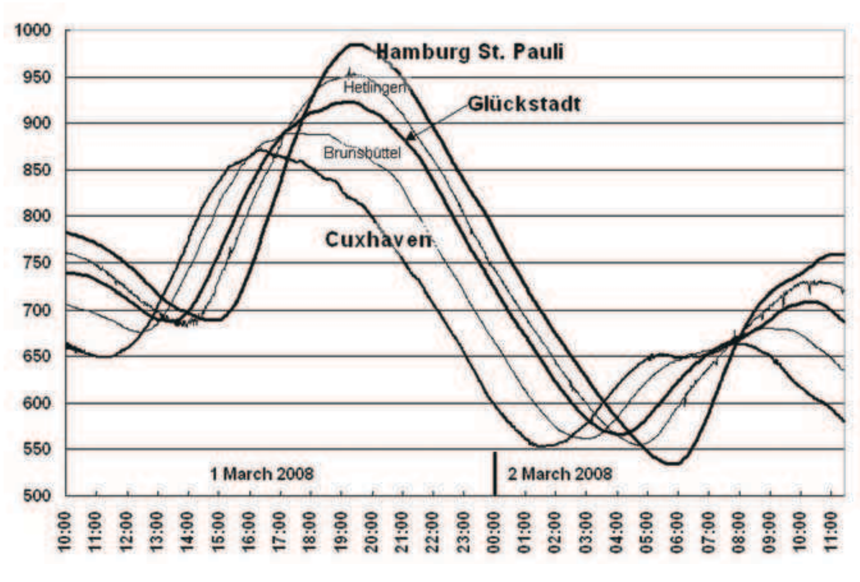


Fig. 11: Time series of water levels on March 1, 2008

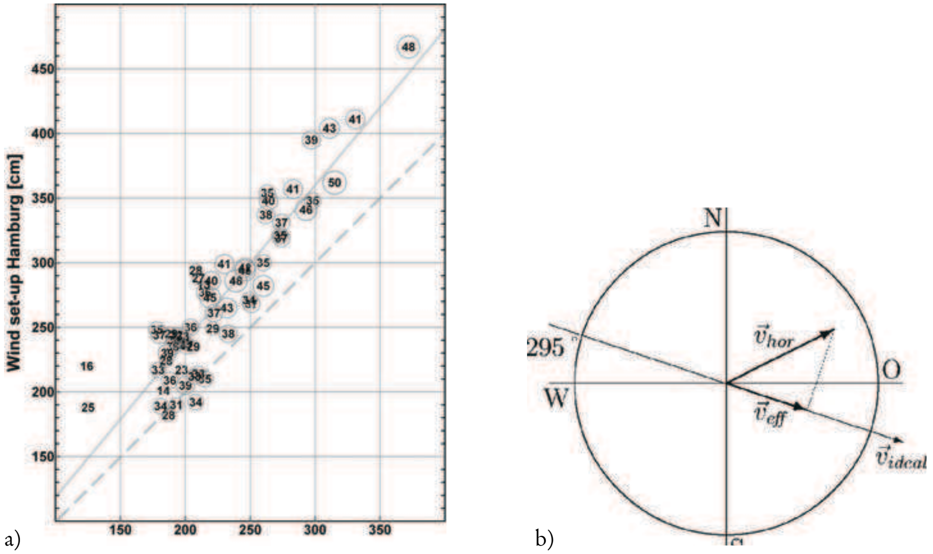


Fig. 12a): Wind set-up at Hamburg plotted against wind set-up at Cuxhaven (February 1965 to March 2008, cases with peak levels of 2 m above MHW in Hamburg). The figures in circles indicate the effective wind speed (knots) in the German Bight. b) Definition of effective wind speed: projection of wind vector onto the abscissa of a co-ordinate system which has been rotated 25°

set-up increases by 20 % on its way from Cuxhaven to Hamburg (Fig. 12a). There is a considerable scatter of data, though.

In historical storm surges of the late 19th and early 20th century, wind set-up in Hamburg was lower than in Cuxhaven. Additional harbour basins built in Hamburg during these years dampened the storm tide (HENSEN, 1955). The coastal defence measures taken after the severe storm surge of February 1962 (MÜLLER-NAVARRA et al., 2006) had a decisive impact on the situation. The frequency of storm surges in Hamburg as compared to Cuxhaven has increased markedly since early 1970, after the completion of barrages and straightening of dikes (DÜKER et al., 2006). In the period from 1950 to 1972, the same number of storm surges was recorded in Hamburg and Cuxhaven, on average; between 1972 and 2007, however, Hamburg experienced about 3–4 storm surges more per year (Fig. 13). Today, the deepened riverbed poses little resistance to the incoming tidal wave. Recent hydraulic engineering works and training measures carried out in the riverbed – mainly close to the navigation channel – have hardly changed anything about this situation.

5.5 Storm Surge Forecasts for the Baltic Sea

The Baltic Sea water level forecasting service was integrated organisationally into BSH's ice warning service in 2006. On workdays, it is operational at least from 6:30 h to 15:00 h; outside this period it is on standby. Water level forecasts for the western Baltic are issued twice a day, at 8 and 14 h. When water levels are expected to exceed 1 m above normal, the water level forecasting service becomes the Baltic Sea storm surge warning service, which is on duty for 24 h/day.

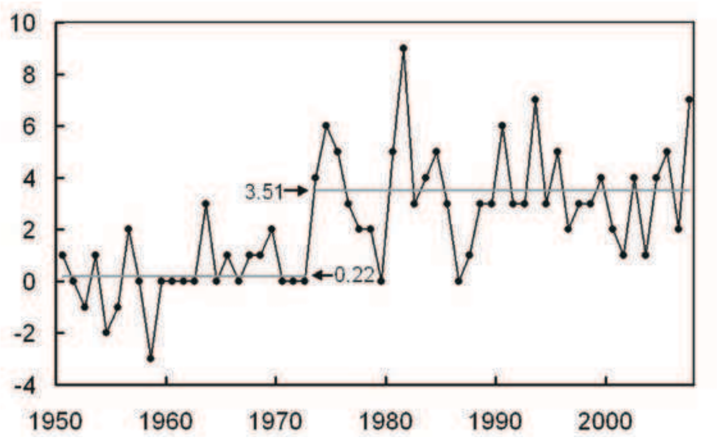


Fig. 13: Difference in the number of storm surge peaks of Δh ≥ 1.5 m above MHW at Hamburg and Cuxhaven 1950 to 2007

BSH's operational model system is the most important tool for these forecasts. In addition, current water level data from about 50 gauge stations along the western Baltic Sea coast are included in the computations. Another forecast is based on statistics in empirical methods, which establish a connection between wind data measured in certain parts of the Baltic Sea and local water levels (SCHMAGER, 1984; SAGER et al., 1956; ENDERLE, 1989). The empirical-method wind set-up of SCHMAGER (1984, Fig. 14) is based on wind data from the Arkona monitoring station, measured 6 hours before the expected peak high water. The thick line from the top to the bottom left corner in the diagram indicates the wind direction most

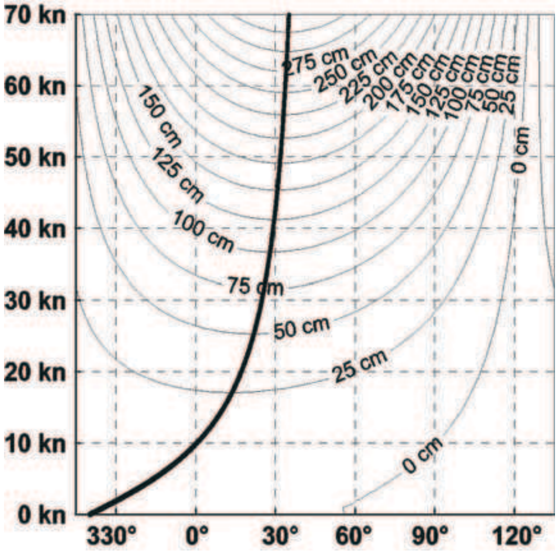


Fig. 14: Wind set-up diagram for Warnemünde (SCHMAGER, 1984)

likely to produce a set-up at Warnemünde for certain wind speeds; at 50 knots, it is 32° (NNE).

Because of the small tidal range in the Baltic Sea, storm surges in this region lack the typical tidal pattern that makes forecasts for the German Bight so difficult. Therefore, the speed at which low-pressure systems travel across the Baltic Sea area is less important than in the North Sea, and it may be quite appropriate to issue warnings early (e.g. on Friday for the following weekend). Consequently, it is not necessary to distinguish between different forecast phases. Forecasts are made rather continuously, and water levels rise more or less steadily until they reach peak level, depending on the weather situation. There are no interruptions due to low-tide phases. Storm surge warnings for the Baltic, therefore, can be issued for longer periods. They go to more than 80 recipients including many information multipliers, as is done in the North Sea region.

5.6 Accuracy of Storm surge forecasts

In assessing the accuracy of storm surge forecasts, the above-mentioned uncertainty of wind forecasts should be taken into account. The statistics include data on a logical linkage of forecasts with warnings. The main purpose of issuing warnings is to protect people and their property and to keep damage to a minimum. To this end, sometimes worst-case scenarios have to be assumed. This can happen when wind forecasts indicate possible wind set-ups of 4–5 metres but the corresponding temporal evolution cannot be forecasted some 18 hours earlier with an accuracy of 3 hours. Then the worst-case assumption could read that the storm will reach its highest intensity just before the computed astronomical peak level is reached. That was the situation as storm „Kyrill“ approached in January 2007, accompanied by radio and TV broadcasts which were describing a disaster scenario for days preceding the arrival of the storm. Although the weather services later evaluated the forecasts positively (DMG, 2007), it is evident that the low-pressure centre crossed Jutland about 3 hours earlier than forecasted, and thus did not have the maximum impact on water levels. Warnings nevertheless had to be issued, but the forecasted very severe storm surge did not occur (MÜLLER-NAVARRA, 2008), and the peak level forecasted 14 hours earlier was 1.75 m too high (Fig. 15, triangle top right).

The quality of forecasts can be assessed in different ways. Especially in extreme events, a number of parameters are suitable for this purpose. It is, for example, important to know whether or not a forecasted event (exceeding of a limit value) occurs at all. Another important question is how often forecasted water levels deviate by more than a fixed amount from measured water levels. This has been investigated for the North and Baltic Sea coast by perusing the examples of Cuxhaven and Warnemünde, respectively. The database used included all events during which the water level at the Cuxhaven gauge station differed more than 1 m from MHW (Fig. 15). At the Warnemünde gauge station this was more than 1 m from MW (Fig. 16). The forecasts for Cuxhaven, marked by triangles, cover periods of 6 to max. 18 hours, those for Warnemünde 6 to max. 39 hours.

Fig. 15 shows that the forecast error has decreased markedly from the mid-1990s. With the exception of storm “Kyrill”, the error has never exceeded ± 75 cm.

Probably even more important is the fact that not a single extreme event has been overlooked since then, which still happened sporadically in the early 1990s. This is attributable to several reasons. Firstly, the frequency of storms in the German Bight was higher in the early 1990s; secondly, substantially more personnel has been employed in the water fore-

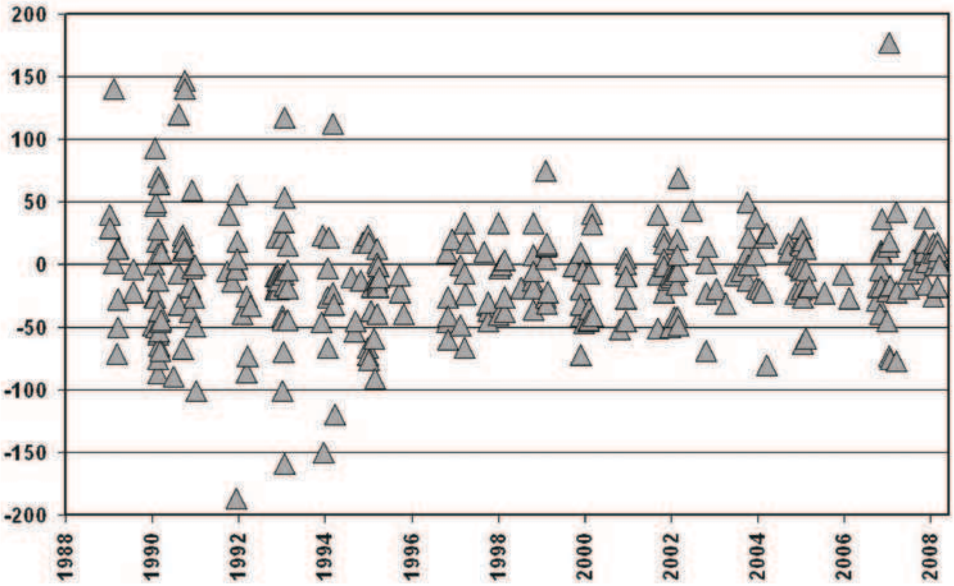


Fig. 15: Forecast error in cm (forecasted deviation from MHW at Cuxhaven minus measured deviation from MHW), all cases from January 1989 to March 2008 with observed deviations from MHW greater than 100 cm

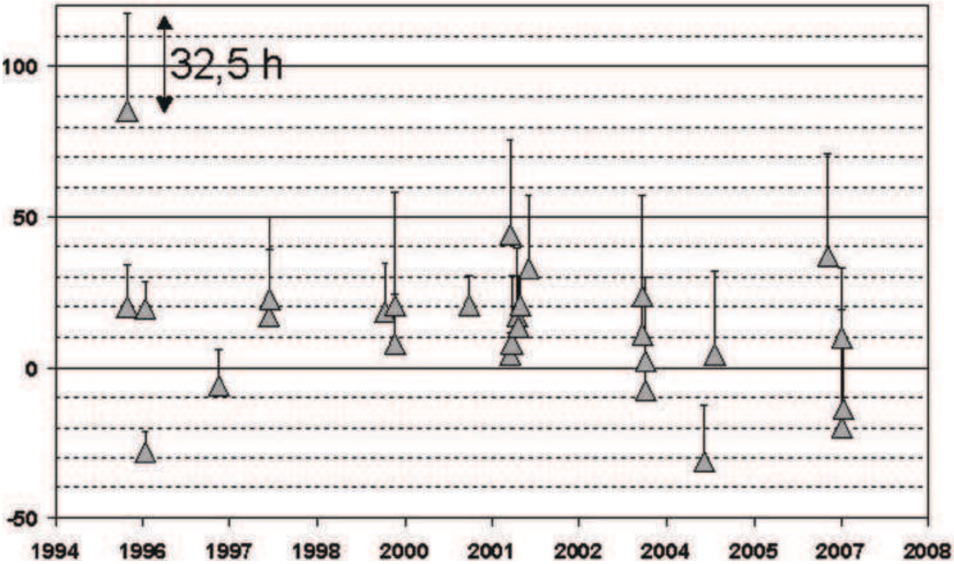


Fig. 16: Forecast error in cm (deviation from MW forecasted for the coast of Mecklenburg-Vorpommern less deviation from MW at Warnemünde) and forecast period in hours (line above triangles), all cases from 1995 to 2007 in which observed deviations from MW exceeded 100 cm

casting services since the mid-1990s; and thirdly, considerable improvements have been achieved in numerical weather and water level forecasts in the past 15 years. Nevertheless, there has been no significant reduction of the error interval in the past 10 years. Here, nature obviously is showing us current limits of predictability. Probably the meteorological observation network at sea, i.e. in the North Sea, Baltic Sea, and Northeast Atlantic Ocean, is simply too thin. In the individual case, the forecast of a storm surge peak probably has to be considered a success if it can be predicted with an error of ± 50 cm half a day in advance.

Statistics for the German Baltic coast, covering the period since 1995, only allow the conclusion that the error has been within the narrow range of ± 50 cm – with one exception. But only very few cases are documented, and forecasted values generally were not archived prior to 1995. The GDR's water level forecasting service did not routinely review and criticise forecasts made for the Baltic coastlines of Mecklenburg-Vorpommern in order not to impair the good co-operation between hydrologists and meteorologists at the Warnemünde sea weather service (O. MIEHLKE, pers. comm.).

Forecasts for the Baltic coast of Schleswig-Holstein were not routinely subjected to critical review, either. There only exist two hindcasts of KOOPMANN (1961) from 1960/61 which cast some light on forecasting problems encountered at the time.

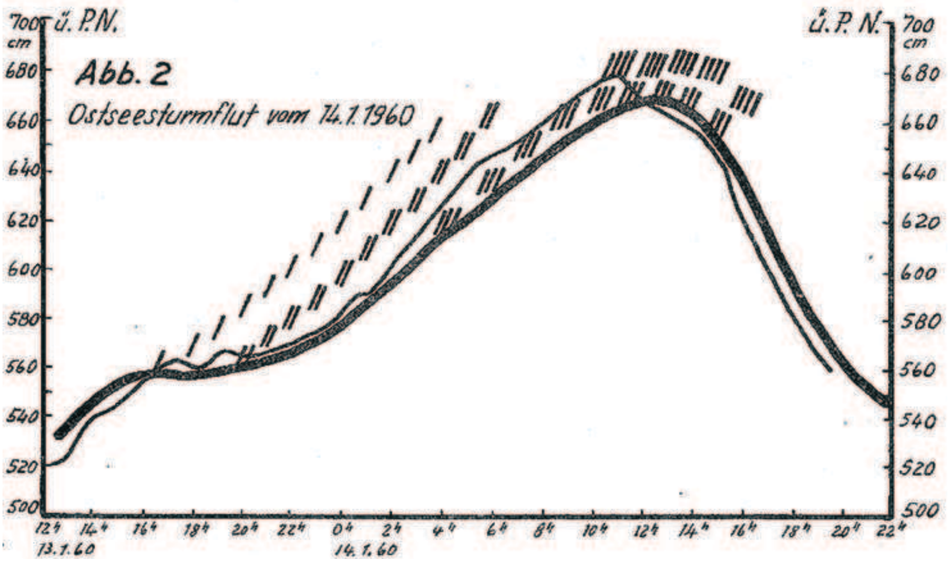


Fig. 17: Baltic Sea storm surge of 14 January 1960, water level above zero gauge (thin line: measurements; thick line: hindcast based on observed weather data. The short lines indicate water levels derived from 4 meteorological forecasts (KOOPMANN, 1961)

The example of the storm surge of January 14, 1960, shows quite nicely how the scientist on duty, taking into account latest meteorological forecasts, successively closed in on the peak water level that was eventually measured at the Kiel gauge station (about 1¾ above MW) on January 14, 1960, towards 11:00 h. The first forecast made in the late afternoon of the preceding day still was ¼ m too low and predicted the time of the peak water level 8 hours too early. It was only the third forecast (symbol "///" in Fig. 17) in the morning of January 14, 1960, which produced satisfactory results. But even the hindcast based on observed meteorological data, using an empirical method (unpublished), was not entirely convincing after all. Since the autumn of 1990, BSH has been operating a coupled model of the North and Baltic Sea, which also predicts water levels at the coasts of Mecklenburg-Vorpommern. It was instantly found to be a useful supplement to existing empirical methods. Since that time, forecasts for the German Baltic Sea coast have been based "at least at 80 % on the hydrodynamic numerical model (HN model) of the BSH" (STIGGE in: HUPFER et al., 2003, p. 54). This may also account for the fact that over-predictions have been more frequent than under-predictions (Fig. 16), because current numerical atmospheric models usually overestimate the maximum wind speeds of events that are farther ahead in the future. As the forecasted event approaches, the severity of forecasted storms in the model runs tends to decrease.

5.7 Open Issues and Outlook

One major future problem will be the increasing automation of the meteorological and oceanographic forecasting services in order to save costs. Automation in this context means that the human factor, i.e. the personal contact and interaction between meteorologist and oceanographer, will ultimately be eliminated from the operational forecasting process. Although acceptable results may be obtained in this way for moderate wind situations (BALZER, 2002), this method is not likely to work for storm surge forecasts because of an insufficient data availability at sea, as has been pointed out in more detail above.

Another, as yet largely unsolved, problem is the parameterisation of the atmosphere/ocean impulse transfer during extreme storm surges. While parameterisation at wind speeds of up to approx. 25 m/s is considered to be well supported by measured data (SMITH et al., 1975), that is not the case at higher values. Both computation of the wind profile (10-m wind) in atmospheric models and of the wind stress coefficient, which depends on wind speed, are still subject to research.

It remains to be seen whether 'ensemble prediction systems' (EPS) will be capable of significantly improving the quality of storm surge forecasts. Although it will be possible using this method to allocate a probability to forecasted events (MOLTENI et al., 1996), experience has shown that the end-users of forecasts do not appreciate such information. By contrast, the forecasters consider it essential to know whether or not a high percentage of model runs have the same tracks and tracking speed. This information may help them to bring forward the decision whether or not an extreme event is about to occur.

Depending on the coastal sector affected, it may be useful for emergency response services to obtain information not only about maximum water levels but also about sea states, because dike stability may also be threatened by wave overtopping (MAI, 2004). To be able to predict wave action at shallow coasts in storm surge situations, simulation tools for wave breaking require a high resolution grid. Because of the enormous computer time needed for such simulations, operational wave forecasts of adequate quality are not yet available for the German coast. However, over the past few years, theories and a hindcast model with a horizontal resolution of just under 2 km have been developed, at BSH (MURAWSKI, 2007). The latter will be operational for wave forecasts in coastal waters in the near future. Hindcasts of extreme storm surges using this model have shown that waves breaking on the foreshore have caused a set-up of a few decimetres between and behind barrier islands.

Any uncertainties concerning wind set-up development in the Elbe estuary are to be eliminated in the coming years by the development of an operational model for the tidal Elbe estuary. The "OPTEL" project (Wind Set-up Studies and Development of an Operational Tidal Elbe Estuary Model) was started in April 2008 as a joint project of the Federal Waterways Engineering and Research Institute (BAW), the German Meteorological Service (DWD), Hamburg Port Authority (HPA), and the Federal Maritime and Hydrographic Agency (BSH). The Elbe model will complement the range of BSH's models and will include the option of an application to the other German North Sea estuaries at a later date. As soon as the Elbe model becomes operational, its data will be available to all Federal and State administrations.

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