Storm Surge Case Studies

Hans von Storch[1], Wensheng Jiang[2] and Kazimierz K. Furmanczyk[3]

[1]Institute of Coastal Research, Helmholtz Zentrum Geesthacht, Germany

[2]Ocean University of China, Qingdao, China

[3]University of Szczecin, Poland

Abstract

This chapter presents details on a number storms surge cases: along the Southern Baltic sea coast, the estuary of the Elbe in Germany and the East China Sea coast at Qingdao. These case studies feature storm surge characteristics, specifically, losses of life and property, erosion extent, and relationship to extra-tropical and tropical storm intensity. These cases demonstrate the severity of the issue and the need of precautionary measures, not only for limiting the possible damages, but also for being able to manage for a possible failure of the coastal defense measures.

1. Introduction

Storm surges are the major geophysical risk in coastal regions (von Storch and Woth, 2008; Gönnert et al., 2001); they are often associated with significant losses of life and property (Fig 1). Along the Bangladesh coast, tropical storms and their surges in 1876, 1891, 1970 and 1991 went along with a toll of a hundred thousand and more lives, and it was only in 2008 that the tropical storm Nargis killed more than 100,000 people in Myanmar (Fritz et al., 2009). In mid latitudes, the number of losses is usually several orders of magnitude smaller, namely up to a few hundred, which is, of course, bad enough.

All coastal of the world where strong storms occasionally or regularly pass are affected by storm surges, which comprise most of the world's coasts (Figure 2). There are two major types of storms, tropical and extra-tropical storms. In principle there are more, such as polar lows, cold surges and medicanes, which regionally play a role with storm surges, but this chapter is limited to the two main types. The different characteristics of these storms and the associated surges are listed in Table 1.

The hazard of storm surges is related to high water levels, which may flood low-lying areas with strong near-shore currents and waves. The former threatens life and property; in historical times, large stretches of land were never recovered (such as the Dollart at the German/Dutch border). The latter is associated with enhanced erosion and loss of dunes, beaches and cliffs.

A storm surge are a phenomenon that has always affected coastal inhabitants (e.g., Lu, 1984; Petzelberger, 2000). When assessing the intensity of historical storm surges, the simplest method determine the maximum water level is to measure markings on buildings (Figure 3a shows a marking at a house in Schleswig at the German Baltic Sea coast; Figure 3b shows a modern tide gauge station in Swinoujście, Poland). The measures for protecting people and property against these extreme and dangerous events have a long history, as explained by Niemeyer, et al. (1996)

This chapter introduces case studies from three regions on the globe: the East China Sea coast at Qingdao the estuary of the Elbe and Hamburg, and the southern Baltic Sea coast. These examples are not representative of all possible issues and problems associated with storm surges; however, the cases we selected highlight some of the major issues and problems related to the global hazard of storm surges.

2. The case of Qingdao, China

China faces the west Pacific Ocean and has more than 18000 km of coastline. Storm surges are the major marine disaster to China and are mainly caused by typhoons. According to Hou et al. (2011), the Shanghai to Quanzhou and the Zhujiang Estuary to northeast-Hainan coastal areas are the two regions of China most affected by storm surge disasters. There are fourteen tide gauge stations along the Chinese coast. From 1949-2009, storm surge heights exceeded 2.00 m 43 times, with most of them impacting the two aforementioned regions. Hou et al. (2011) also found that the severity of these disasters, which are predominately in September, has increased in last two decades.

China has 4000-year history, which includes written documentation of storm surges. Lu (1984) derived records of storm surges from Chinese historical literature and determined that the first storm surge ever recorded in China, and likely in the world, is in a Chinese history book titled the "Book of Han" that was completed in the first century. A storm surge in the Bohai Sea was described in this book: "*It rained for a long time. The northeast wind blew and the sea water was overflowed to southwest. The water intruded into the land for more than 100 kilometers and the land of Nine-River area was inundated.*" (Lu, 1984). Unfortunately, the time of the surge was not mentioned.

This chapter focuses on the storm surge record from Qingdao. Qingdao is an important harbor city in China that faces the Yellow Sea and is located on the west coast of the Jiaozhou Bay (Figure 3). The city of Qingdao was a small village that was established in 1891. In the last approximately 125 years, it has grown to a city comprising more than 8 million people. The major cause for storm surges in this area is typhoons, even though extra-tropical storms can cause surges and damages.

Zhang et al. (2006) examined the tide gauge data in Qingdao from 1949 until 2003, and found fourteen cases of high water levels related to typhoons. Nine of these events were associated with sea levels exceeding +5.10 m.[1] The highest absolute water level was +5.48 m in 1997 - including tide and storm effect. The highest surge height, related only to the wind effect above the tidal component, was 1.47 m in 1952.

Peak surge heights in the Qingdao depend on which one of the four typical typhoon paths is followed. The first type is typhoons that first make landfall on the Jiangsu coast before continuing north to Qingdao. The second one represents typhoons that make landfall in Fujian Province and then move north until turning east to Qingdao. The third moves north from the

---

[1] Here, and elsewhere in this article, sea level heights are given relative to some local reference

East China Sea to Qingdao. And the fourth one stands for the typhoons that move northwest to Qingdao.

The following describes two severe storm surge disasters in Qingdao. The first storm was a (still nameless) typhoon that formed on 22 August 1939 in the Pacific Ocean. On the evening of 30 August the typhoon approached Qingdao and was accompanied by severe precipitation. At 6 AM on 31 August, the typhoon center was about 120 km south of Qingdao and the wind speed in Qingdao likely exceeded 150 km/hr. At 9 AM the typhoon made landfall on the west coast of Jiaozhou Bay, which is the location of the city of Qingdao. In Qingdao City, seventeen people were killed by storm surge. More than 1000 houses were destroyed and an additional 3000 houses were damaged. About 460 hectares of farmland near the coast was inundated. The loss of grain harvest was estimated at approximately 11 thousand tons. The total economic loss was equivalent to USD 4 million (ca. 1939). The disaster is still remembered by the local people through oral transmission from the community elders (Cai et al., 2010).

More recently, in August 1985, a storm surge disaster happened when Typhoon *Mamie* hit Qingdao (Figure 4). Twenty-nine people were killed in this disaster and 368 people were wounded. More than 8000 meters of sea dykes and other coastal defense measures were destroyed. The economic loss was equivalent to around 200 million US$.

Along this coast, extratropical meteorological storms can also cause storm surges. In May 2013 a storm surge hit Qingdao. The famous Zhanqiao Pier was damaged for the fourth time in 100 years (Figure 5).

Qingdao is an important city to the economy of China, therefore the ability to adapt to the risk of storm surges is crucial. The well-established storm surge forecasting service in China is a prerequisite for managing the storm surge hazard. While an intensification of storm surges due to the general rise in sea level is almost certain, possible changes of storm intensities due to anthropogenic climate change are still under investigation.

3. The case of Hamburg and the Elbe estuary[2]

Hamburg, Germany is a harbor in the estuary approximately 140 km upstream along the river Elbe. The estuary opens to the North West into the German Bight, which is prone to storm surges (Figure 6). The history of storm surges in Hamburg since 1750 is characterized by three phases: 1) a frequent damage-period (prior to 1850); 2) a calm period (1855 – 1962); and 3) a period of elevated but well-managed storm surge-levels (1962 to present) (Figure 7). In 1962, a storm surge disaster killed more than 300 people in Hamburg. This event served as warning the city and its residents, and coastal defense was massively improved in the following years.

---

[2] See von Storch and Woth (2008), von Storch et al. (2008)

In the 18th century, storm surges and breaking dikes were relative frequent in Hamburg. The dike failures took place at water levels of approximately +5.20m. Interestingly, these storm surges occurred in clusters. After the severe storm surge in 1825, dike heights were raised to +5,70m. After beginning to raise the dikes, and until 1962, only one severe storm surge happened (in 1855). After this storm flood, for more than 100 years until 1962, the improved dike levels were not really challenged; all gauge readings were well below +5.00 m.

The 1962 event proved to be a major event in the perceptions of storms surges in Hamburg. After the catastrophe of WWII, which left large parts of Hamburg in ruins, people were focusing on economic progress and had little sense for the risk of natural disasters. The more than 300 drowning victims were from poorer quarters of the city, many of whom resettled after having fled form the east at the end of WW II and were unaware of the risk (Figure 8). It became obvious that the coastal defense was insufficient; the badly maintained dikes broke in several locations (Figure 9), and the civil defense for the case of a dike failure turned out to be inefficient. After the 1962 catastrophe massive investments into the coastal defense were made; dikes were raised to +7.20 m.

The next substantial flood following the dike improvements occurred in 1976 and it exceed the 1962 surge level reaching +6.45 m. The newly enforced coastal defense held and damages were insignificant in Hamburg. Nevertheless, dikes were raised again to a level between +8.00m and +9.30m. Since 1962 several very high storm surges took place with heights between +5.50 m and +6.00 m, but only minor damage was reported.

It has been speculated that the increase of storm surge occurrence in Hamburg since 1962 is related to anthropogenic climate change. This speculation is very likely false, the main part of the increase is likely due to the improvement of coastal defense and the dredging of the shipping channel. The intensification of the North-Atlantic Oscillation during the period between 1960 and 1995 may have contributed a minor increase (Weisse and Plüß, 2005). A measure of the effect of the former two causes accounts for the difference of storm surge heights in Cuxhaven, at the mouth of the Elbe estuary, and in Hamburg (for locations, see Figure 6). Prior to 1962, storm surges in Hamburg were on average about 30 cm higher than in Cuxhaven. After 1962 this difference rose to about 1 m (Grossmann et al., 2007). Experts estimate that about three quarters of this increase is related to coastal defense measures and one quarter to the deepening of the shipping channel from less than 11 m to 14.50 m. Thus, modifications of the river Elbe has significantly increased the storm surge height in Hamburg, while climatic effects being rather minor (cf. Weisse and Plüß, 2005; WASA, 1998; Alexandersson, et al., 2000)

4. The case of the Southern Baltic Sea cast

The Baltic Sea is a semi-closed basin with limited connection to the North Sea via the Danish Straits. The tidal range in the Baltic Sea does not exceed a couple of centimeters and are practically negligible. Every couple of years, or so, the “filled basin” phenomena occurs, when a very strong wind blowing from W-NW moves water from the western to the eastern parts of the Southern Baltic Sea, pumping water from the North Sea to the Baltic Sea via Danish Straits at the same time. This causes more water to accumulate in the South Baltic and the level subsequently rises. When the strong wind changes direction to N-NE in a filled-basin situation, even more water accumulates at the western part of the South Baltic, and the water level increases significantly, reaching levels of +1.5m to 2.0m (Furmańczyk, 2013). Such situation leads to catastrophic effects on the coast. Low dunes are eroded and water overflows thus creating coastal flooding. Cities located at the river mouths are usually affected by this event.

A filled-basin scenario has occurred many times in the history of southern and western part of the Baltic Sea. In historical reports we can find that in the past many strong storms at the Southern Baltic took place, which were associated with significant coastal and complete villages destroyed. For example, a storm at the beginning of 13th century separated Ruden Island from Rugia Island. A storm in 1497 created a new connection between Wisła Lagoon and the Baltic Sea. A storm in 1558 and the years following destroyed Łeba village and the barriers on Rugia Island, Usedom Island and Hel Peninsula were broken in many locations.

The greatest documented storm event in this region took place on 13-14 November 1872 (Figure 10). Many people lost their lives by the storm. Two years later in 1874 another great storm took place with high storm surges in Kołobrzeg (+2.20 m) and in Świnoujście (+1.96 m). Another strong event took place on 30-31 December 1904 at the Pomeranian Bay. Water levels near Rugia Island were about +2.5 m to +2.8 m, in Świnoujście +1.8 m, and in Warnemünde and Flensburg about +1.9 m to +2.2 m (Majewski et al., 1983). The highest water levels observed at the tide gauges located along the Polish part of the coast are presented in Table 2 (after Wiśniewski and Wolski, 2009).

The storm event on 13-14 November 1872 was successfully reconstructed from pressure maps and surge heights, scattered air pressure data, and numerical modeling by Rosenhagen and Bork (2009). The intensity of 1872 event is put into perspective when plotting annual maximum storm surges from 1926 to 2006 (Figure 11). The maximum surge height in 1872 was about +3.30 m, while in all other years the level of +2 m was almost never passed. Indeed the 1872 event was an outlier. If it had not been documented so well at multiple locations, one may be misled to suspect the recoding as an error. It is suggested that this event was due to the concurrent effect of a basin-filling, the wind-induced surge and a contribution of the major eigen-oscillation in the Baltic Sea.

At the end of the 19th century along the southern coast of the Baltic Sea, coastal dunes were perceived as a dam to protect against flooding (Furmańczyk, 2013). People began to protect them by constructing fences to increase the deposition and accumulation of sand. These dune restoration strategies took place in Dziwnów, Poland, for example.

Dziwnów is a small town comprising approximately 3,000 residents located at Dziwna Strait that connects the Kamieński Lagoon with the Pomeranian Bay. Dziwna Strait is one of the conduits transporting water from the Szczecin Lagoon, via the Kamieński Lagoon, into the Baltic Sea. At the end of the first half of the 19th century, Dziwnów was initially a small fishing village. Since then, it has gained importance as a holiday and spa resort, and began growing vigorously. Hotels and health centers, a beach hall, a promenade on the dune, beach baths (on piles over the beach), and a pier were constructed in 1890 and later (Figure 12). In a short period of time starting after 1890, Dziwnów became the most popular holiday destination on the Baltic coast, and was designated as the “Pearl of the Baltic” (Gerlach-Jósewicz et al., 1996).

Unfortunately, on 30 December 1913, a substantial storm devastated the “Pearl of the Baltic” and the community has not since been rebuilt. The devastation started on 27 December with strong N-NW winds (Beaufort 8-9). On 30 December the winds shifted to N-NE and formed a strong storm surge. Elevated water levels in the region were observed, for example: Kołobrzeg (+1.59 m), Świnoujście (+1.98 m), Travemünde (+1.95 m) and Kiel (+1.82 m) (Majewski et al., 1983). In the afternoon of 30 December water overflowed the low dunes and flooded the low-lying hinterland. Part of the town was affected and several buildings and tourist infrastructure were partly destroyed or filled with water (Figure 13).

The first hydrodynamic reconstruction of the 1913 event was completed using the XBeach model (Bugajny et al., 2013). The modern day coastal profile was adopted and the dune morphology was approximated from old postcards: the dune top and width were estimated at +4m and +16m, respectively. A water level of +1.0m at the beginning of the storm was used with a maximum level of +1.14m (maximum water level in Dziwnów was noted +1.15m in 1874). Significant wave height was at 4.5 m (0.5 m higher than was noted at the time of storm “Xavier” that took place at the same place in December 2013).

The XBeach simulation demonstrated an overflow effect after a couple of hours from storm initiation (Taranowicz, 2013). The model results corresponded well with descriptions provided by local witnesses shortly after the storm. This same storm impacted other communities along the southern Baltic coast. In Gdańsk, located along the eastern shore of Gdańsk Bay, a water level of +1.56 was measured. There was a lot of damage to the port and tourist infrastructure. In Sopot, a famous resort in the Gdańsk Bay, water overflowed low dunes and caused flooding in the city.

The 30 December 1913 event was one of the greatest (biggest) storm surges in the southern part of the Baltic Sea coast. After the storm five tons of amber was deposited. Since then many protection measures have been implemented, including beach nourishment and dune restoration to make this area less vulnerable to future storm surge events.

5. Concluding remarks

The risk emanating from storm surges is a global, albeit regionalized phenomenon, affecting a large percentage of the world population, many urban conglomerates and centers of commerce and trade (Mc Granahan et al., 2007; Hoozeman et al., 1993; Nicholls and Hoozemans, 2000). The scientific community, interested in the dynamics, prediction and management of the hazard of storm, surges, comprises oceanographers, meteorologists, hydrologists, coastal engineers, geographers, planners, historians and other earth and social scientists. Because of the breadth and the regionally limited impact of storm surges, this scientific community is highly fragmented, and is separated by regional languages, cultures and management concepts. More efforts are needed to bring this community together.

The specific case studies presented in this chapter demonstrate the multiple processes that result in storm surge and the various associated results. Changing coastal morphology, pumping ground water and compacting deltas are some examples of the results. While climate change, in particular via changing “the degree of filling” (sea level), is of great importance, storm surges deserve attention because of the challenge they represent today even without the predicted effects climate change.

References

Alexandersson, H., T. Schmith, K. Iden and H. Tuomenvirta, 1998: Long-term trend variations of the storm climate over NW Europe. *The Global Atmos. Oc. System* 6, 97-120

Bugajny, N., Furmańczyk, K., Dudzińska-Nowak, J., Paplińska-Swerpel, B., 2013. Modelling morphological changes of beach and dune induced by storm on the Southern Baltic coast using XBeach (case study: Dziwnow Spit) *In:* Conley, D.C., Masselink, G., Russell, P.E. and O'Hare, T.J. (eds.), *Journal of Coastal Research*, Special Issue No. 65, pp. 672-677.

Cai Q., Liu S.-S. and Sun, H., 2010: A Study of the Storm Tide Disaster and the Relief Work in 1939 in Qingdao. *Oriental Forum* 5:12-16

De Kraker, A.M.J., 2009: Stormweer in de Nederlanden tijdens de 15^e en 16^e eeuw. In Essink, K. (ed.): *Verdronken Geschiedenis*. Mededelingen van de Vereniging voor Terpenonderzoek, Nr. 12 (juni 2009). http://www.verdronkengeschiedenis.nl/nl/stormvloed/docs/3-Adriaan%20de%20Kraker-2-NL-opmaak-def-def-3.pdf

Fritz, H.M., C.D. Blount, S. Thwin, M.K. Thu, and N. Chan, 2009: Cyclone Nargis storm surge in Myanmar, *Nature Geoscience* 2:448-449, doi:10.1038/ngeo558.

Furmańczyk, K., 2013. Poland, In: Pranzini, E. and Williams, A. (eds.) *Coastal Erosion and Protection in Europe*. Routledge, pp. 81-95

Gerlach-Jósewicz, A., Walasek, L. and Wójcik K., 1996. Studium ruralistyczne (skrócone) gminy Dziwnów. *Biuro Dokumentacji Zabytków*, Szczecin.

Gönnert G., S.K. Dube, T. Murty T,and W. Siefert, 2001: Global Storm Surges, *Die Küste* - 63, ISBN 3-8042-1054-6, 623 pp.

Grossmann, I., K. Woth and H. von Storch, 2007: Localization of global climate change: Storm surge scenarios for Hamburg in 2030 and 2085. *Die Küste* 71, 169-182

Hoozemans FMJ, M. Marchand, and H.A. Pennekamp, 1993: *A Global Vulnerability Analysis, Vulnerability assessments for population, coastal wetlands and rice production on a global scale*, 2nd Edition, Delft Hydraulics and Rijkswaterstaat, Delft and the Hague.

Hou J.M., F.J. Yu, Y. Yuan, and X. Fu, 2011: Spatial and temporal distribution of red tropical storm surge disasters in China. *Marine Science Bulletin*, 30(5): 535-539

Kremer, H., R. Nicholls, B. Ratter and R. Weisse, R., 2013: Interdisciplinary Research and Perspectives on Current and Future Storm Surges. *Natural Hazards*, 66, 1293-1294

Lu, R.J., 1984: *Historical records of disastrous tide in China*. Beijing: Ocean Press, 295pp.

Majewski, A., Dziadziuszko, Z. and Wiśniewska, A., 1983. *Monografia powodzi sztormowych 1957–1975*. Wydawnictwo Komunikacji i Łączności, Warszawa.

McGranahan G., D. Balk and B. Anderson, 2007: The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment and Urbanisation*: 19, 17-37.

Nicholls RJ and FMJ Hoozemann, 2000: Global vulnerability analysis. In. Schwartz M (ed.) *Encycopledia of Coastal Science*, Kluwer Academic Publishers.

Niemeyer, H.D., H. Eiben, and H. Rohde, 1996: History and Heritage of German Coastal Engineering, in N.C. Kraus (ed): *History and Heritage of Coastal Engineering*, American Society of Civil Engineers, 45pp

Petzelberger, B.E.M., 2000: Coastal development and human activities in NW Germany. In Pye, K. and J.R.L. Allen (eds): *Coastal and Estuarine environments: sedimentology, geomorphology and geoarchaeology*, Geological Society, London, Special publication, 175, 365-376

Rosenhagen, G., and I. Bork, 2009: Rekonstruktion der Sturmflutwetterlage vom 13. November 1872, *Küste* 75: 51-70

Taranowicz, W., 2013. Upadek Perły Bałtyku, In: *www.echo kamienia.pl*

von Storch, H. and K. Woth, 2008: Storm surges, perspectives and options. *Sustainability Science* 3, 33-44; DOI 10.1007/s11625-008-0044-2

von Storch, H., G. Gönnert, and M. Meine, 2008: Storm surges – an option for Hamburg, Germany, to mitigate expected future aggravation of risk. *Env. Sci. Pol.* 11: 735-742

WASA, 1998: Changing waves and storms in the Northeast Atlantic? - *Bull. Amer. Met. Soc.* 79, 741-760

Weisse, R. and A. Plüß, 2005: Storm related sea level variations along the North Sea Coast as simulated by a high-resolution model 1958-2002, Ocean Dynamics, 56(1), 16-25, DOI: 10.1007/s10236-005-0037-y

Wiśniewski, B. and Wolski, T., 2009. *Katalog wezbrań i obniżeń sztormowych poziomów morza orz ekstremalne poziomy wód na polskim wybrzeżu*. Wydawnictwo Naukowe Akademii Morskiej, 156 pp.

Zhang X.-H.,Sheng C.-Y and Shao, Z.-H., 2006: Analysis of storm surge at coastal area of Qingdao. *Marine forecasts*, S1:42-46

Figure 1: Historical engraving of a storm surge with dyke failure in The Netherlands in 1673 (von Storch and Woth, 2008)

Figure 2: Coasts endangered by storm surges (with permission by Munich Re)

Figure 3: Recording storm surge heights – historical marks of high water (a) in 1872, 1694 and 1836 in Schleswig, Germany, and a modernized tide gauge in Swinoujście, Poland (b), which is with short interruptions operating since 1811.

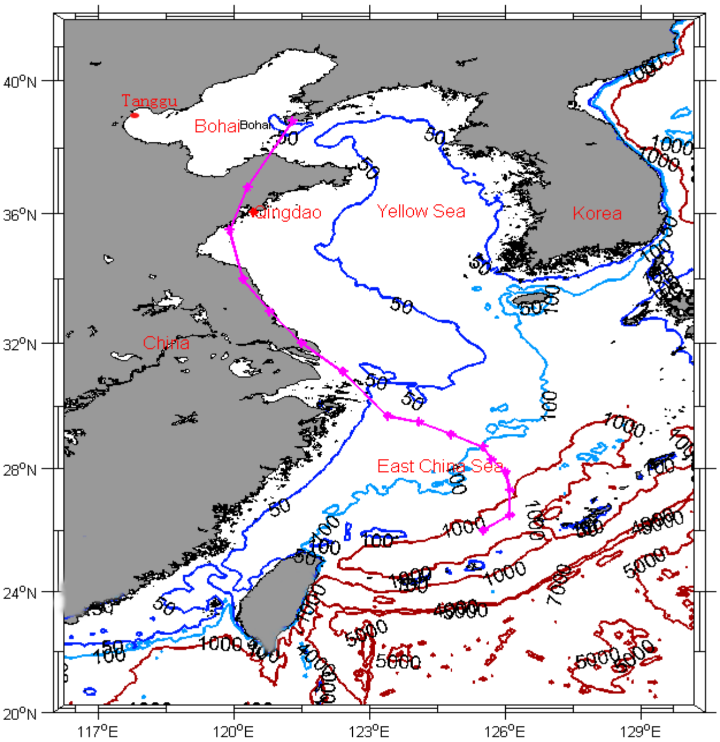

Figure 4: Bathymetry (in meters) of the East China Sea, with Qingdao at the southern coast of the Shandong peninsula. The pink line denotes the path of the Typhoon Mamie in August 1985.

2013年5月
28
星期二

今日32版

青島晚報

百姓情怀　有家有爱

买家具
购建材
首选富尔玛

晚报24小时新闻热线
82860085

岛城普降大到暴雨局部特大暴雨，为同期52年来第一次

巨浪逞凶
栈桥险成“断桥”

桥体约50米坍塌，已封闭待修，历史上曾3次被冲断 [3-8版]

纪检监察人员
限期清退会员卡

中纪委要求限6月20日前“退卡”，做到“零持有、零报告” [2版]

女骑警花费受质疑

大连退休警察质疑骑警乱花钱，申请公开信息 [22版]

长春盗车杀婴凶手判死刑

[20版]

2013首届
苏沪杭新品丝绸服装服饰

Figure 5: The local newspaper reporting the damage of the Zhanqiao Pier in Qinngdao in 2013.

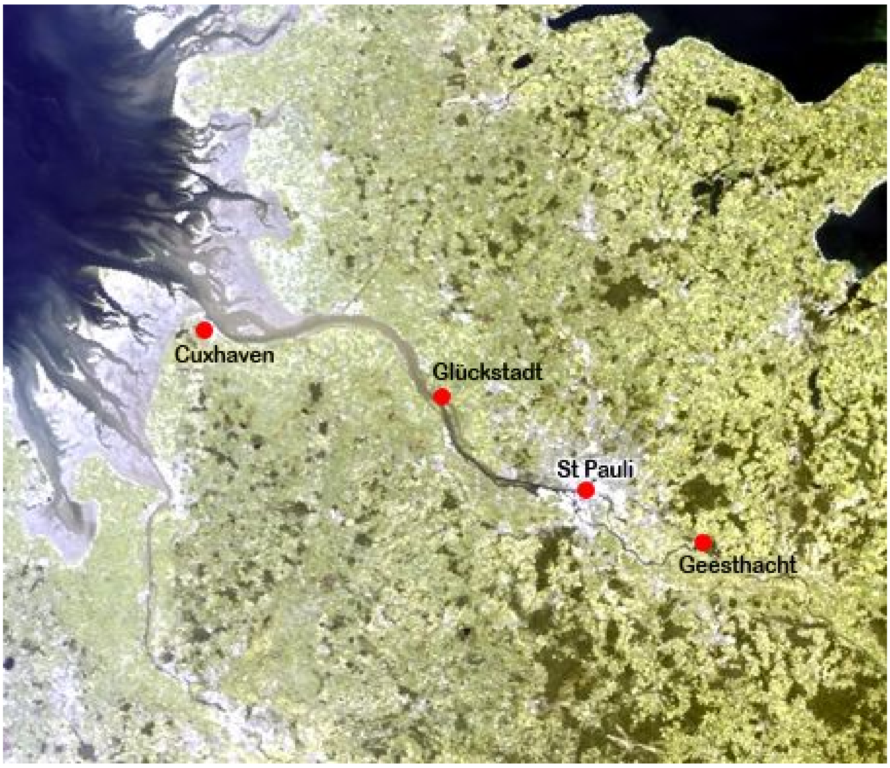

Figure 6: Satellite image of the Elbe estuary, with Cuxhaven Glückstadt, Hamburg-St.Pauli and Geesthacht. With permission of Schönfeld, GKSS. The distance between Hamburg-St. Pauli and Cuxhaven is about 140 km. (von Storch et al., 2009)

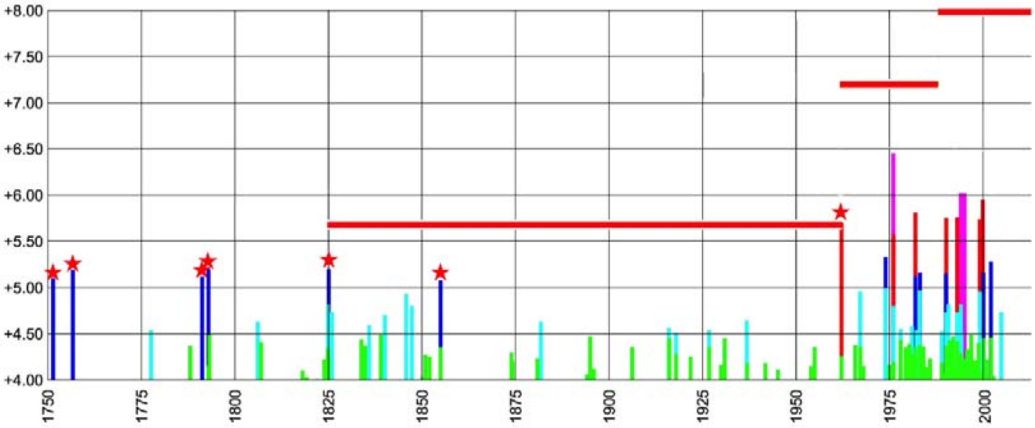

Figure 7: Storm surge heights (vertical bars) and dike heights (red horizontal lines) as recorded at the tide gauge St Pauli in Hamburg from 1750 to 2004. The color coding represents different surge heights. The red stars indicate dyke failures. (von Storch et al., 2009)

Hamburger Abendblatt

Berichte und Bilder von der Flutkatastrophe auf den Seiten 3, 5, 9, 10, 11, 12, 13, 18

Hamburger, bitte helft!
Nehmt Obdachlose auf!

Bisher 119 Tote geborgen

Hamburg, 19. Februar

Hamburger, helft! 40000 Menschen sind immer noch obdachlos! Der Senat hat heute mittag die Besitzer größerer Wohnungen aufgerufen, Obdachlose aufzunehmen.

Die Sturmflutkatastrophe hat nach den bisherigen Ermittlungen 119 Todesopfer gefordert. Mindestens 150 Männer, Frauen und Kinder werden noch vermißt. Rund 12000 Hamburger sind immer noch vom Wasser eingeschlossen.

Wasser und Nahrung für die Eingeschlossenen

Die Flut geht zurück

Die Türen auf!

Straßen im Freihafen heute morgen blockiert

Landestrauer für drei Tage

Figure 8: Reporting in the local press about the 1962 storm surge disaster. The main headline reads: “People of Hamburg, please help. !”

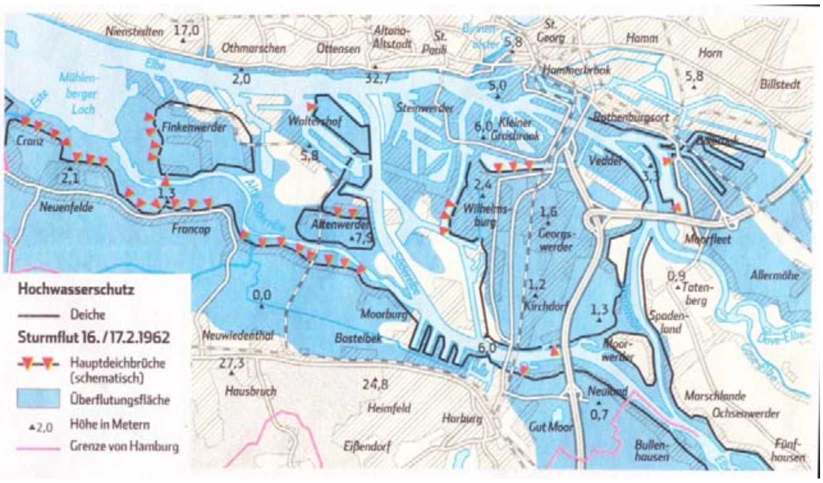

Figure 9: Flooded areas (blue) during the storm surge of 16 february 1962 in Hamburg. The black line describes the coastal defense line; the red triangles dike failures. (Unknown source)

Figure 10: Southern Baltic Sea Storm surge on 13/14 November 1872, as depicted by Illustrirte Zeitung, Leipzig, 21.12.1872.

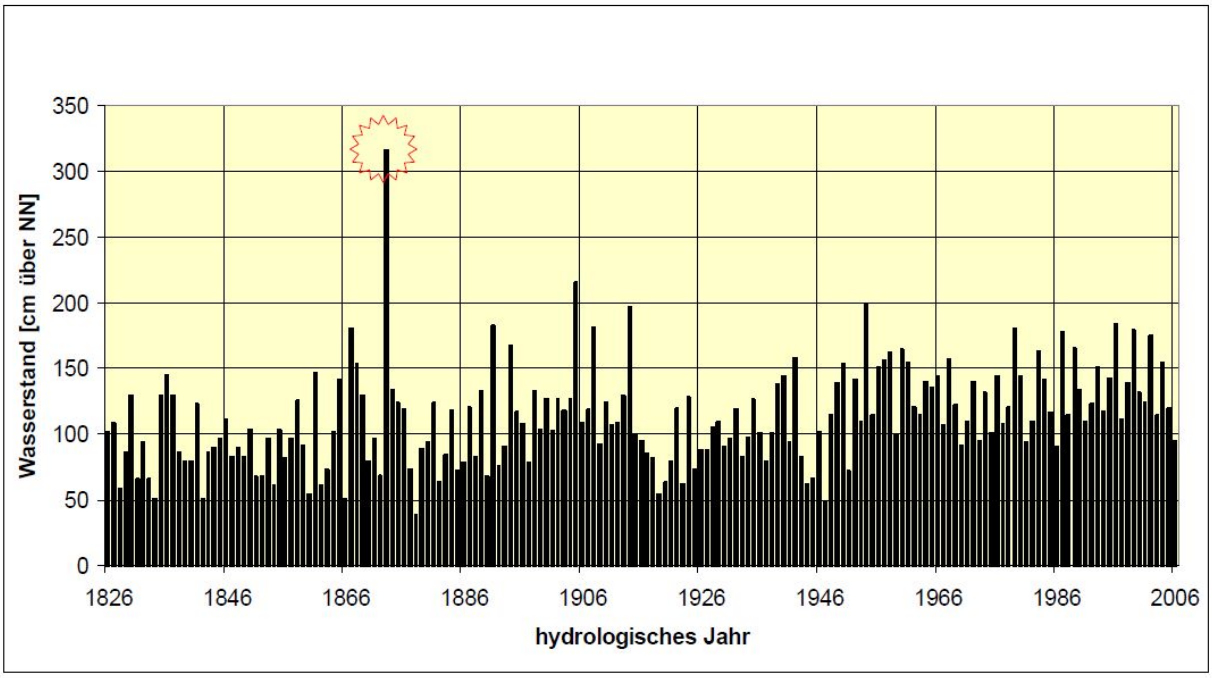

Figure 11: Annual maximum surge heights in the years 1826-2006 in Travemnde, Germany. Notice the peak for 1872. From Rosenhagen and Bork (2009)

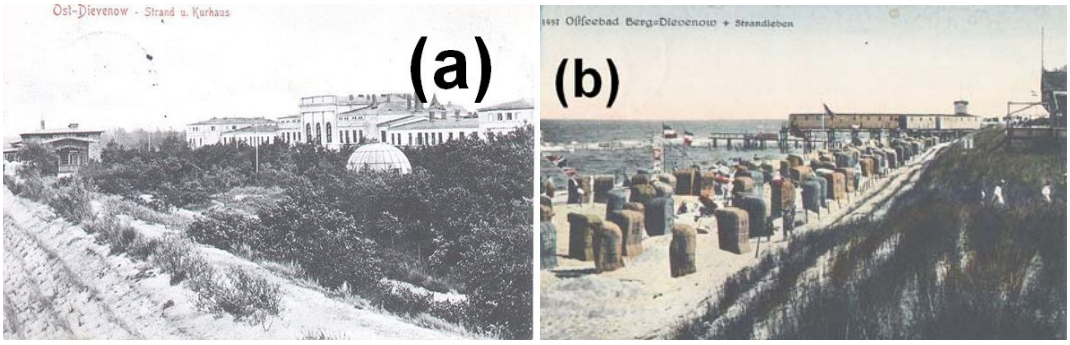

Figure 12. Postcards from Dziwnów, Poland, before the storm surge on 30 December 1913.(a): The “Kurhaus”, beach hall and promenade; (b): Beach activity and vegetated foredune.

Figure 13. Postcards showing damages in in Dziwnów, Poland, caused by the storm surge on 30 December 1913.

(a): Beach hall; (b): Schoolhouse

Table 1: Characteristics of storm surges causes by tropical storms (hurricanes, typhoons) and extra-tropical storms (von Storch and Woth, 2008; Gönnert et al., 2001)

Parameter	Tropical cyclone	Extra-tropical cyclone
Spatial scale of storm	500 ± 200 km	1000 ± 500 km
Representation in weather re-analyses of past decades (since 1960)	In earlier decades underrepresented; sometimes cyclones are missed	Mostly well described, in particular in well-monitored Northern Hemisphere regions; some inhomogeneities remain.
Amplitude of surges	Larger – hurricane Camille caused a surge of 7.5 m in Gulfport, MS (USA), in August 1969	Smaller – surges of 5m are infrequent events.
Duration of surge	Several hours, up to half a day	2- 5 days
Length of coastline affected by the surge	Less, usually < 200 km	Several hundred kilometers
Geometry of the storm	Compact and nearly symmetrical	Ill defined and sprawling geometry

Table 2. The highest water levels observed at the tide gauges located along the Polish coast, from west to east (Wiśniewski and Wolski, 2009). Note that the dates vary across the entire time.

Station	Max. water level above NN (m)	Date
Świnoujście	1.96	10.02.1874
Dziwnów	1.15	10.02.1874
Kołobrzeg	2.22	13.11.1872
Darłowo	1.59	9.01.1914
Ustka	1.58	15.12.1898
Łeba	1.68	15.12.1898
Władysławowo	1.44	23.11.2004
Hel	1.22	14.01.1993
Gdynia	1.32	23.11.2004
Gdańsk	1.64	16.12.1843