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Conference Title

Storm Surges: Phenomena, Forecasting and Scenarios of Change

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Abstract

Storm surges are behind the geophysical risk of short term and abrupt inundating low-lying coastal regions known along most coasts of the world. They are related to meteorological phenomena, mostly wind storms. Storm surges represent a challenge for science and risk management with respect to short term forecasts of specific events but also with long-term changes of the statistics of storm surges due to anthropogenic global climate change, sinking coasts and estuarine water works. Storm surges are expected to become more severe in the coming decades and centuries because of ongoing and expected accelerated mean sea level, and much less so because of more energetic wind storms.

Keywords: Storm surges, Modelling, Scenario, Risks

1. Storm surges[a]

Storm surges are the major geophysical risk in coastal regions; they are often associated with significant losses of life and property (for a general overview refer to [2]; for specific historical accounts of the German and Dutch North Sea coasts, refer to [3,4]). 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 [2], which is comparable to the disaster created by the 2004 tsunami. In mid latitudes, the number of

[a] This section follows largely [1]

losses is usually several orders of magnitude smaller, namely up to a few hundred, which is, of course, bad enough.

Most coasts of the world are affected by storms surges – all coasts where strong storms pass by occasionally or regularly. There are two major types of storms, tropical and extra-tropical storms. In principle there are more types, such as polar lows, which regionally play a role with storm surges, but for the sake of simplicity we limit our discussion here to the two main types. The differing characteristics of these types and the associated surges are listed in Table 1.

Table 1. Characteristics of storm surges causes by tropical storms (hurricanes, typhoons) and extratropical storms (after [2])

Parameter	**Tropical cyclone**	**Extratropical cyclone**
Spatial scale of storm	500 ± 200 km	1,000 ± 500 km
Representation in weather re-analyses of recent 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
Surge amplitude	Larger: hurricane Camille caused a surge of 7.5 m in Gulfport, MS, USA, in August 1969	Smaller: surges of 5 m are infrequent events
Surge duration	Several hours, up to half a day	2–5 days
Length of coastline affected by the surge	Less: usually < 200 km	Several hundred kilometers
Storm geometry	Compact and nearly symmetrical	Ill-defined and sprawling geometry

Tropical storms cause storm surges along the East coast of North America, the Gulf of Mexico, Hawai’i, Mexico, the Caribbean Sea, the Bay of Bengal, the Arabian Sea, the South West and East Indian Ocean, the western tropical Pacific, the coasts of Australia, Japan, China, Korea, Philippines, Myanmar, Vietnam and Thailand. Surges related to extra-tropical storm activity are common along the East coast of Canada, in the Great Lakes, in Argentina, and in Europe in the North Sea, the Baltic Sea, the Irish Sea, the Mediterranean Sea, the Adriatic and Aegean and also the Black Sea (cf. [2]). Obviously 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 (cf. [5,6,7]).

Since the statistics, and thus the risks of certain surge heights, depend on the storms, any change in storminess will lead to a change in storm surge heights. Of course, the statistics depend also on the mean sea level; both the mean sea level and the activity of storms likely will change in the course of the expected man-made climate change in the next and following centuries to come [8]. While mean sea level is expected to rise, storms may become in some regions more frequent and violent, while in others less so.

Tropical cyclones (the terms hurricanes and typhoons are alternative names used in different regions) are big thermodynamic machines that transform heat, mainly sucked from a very warm sea surface, into kinetic energy, i.e., wind. The extra-tropical storms, on the other hand, gain their energy from the horizontal temperature gradient (baroclinicity). Extratropical and tropical storms differ with respect to size and intensity; their associated storm surges show characteristics consistent with these differences (cf. Table 1). The different characteristics of these types of storms, in particular concerning wind speeds and spatial scale of the storm, cause the differences listed in Table 1. In tropical regions, storm surges are much less frequent at a given position than at mid-latitudes; they are also considerable more limited in extent. But if they hit, then the effect is usually stronger than in mid-latitudes.

In general, the research about storm surges is suffering from multiple fragmentations so that not all knowledge is as widely available as one would hope. One fragmentation comes from the different disciplines involved, chiefly coastal engineering (e.g. [9]) and oceanography. The other is related to the relatively small scale of storm surges, so that the problem is perceived as a regional problem – and scientific insights and methods developed for one part in the world do not necessarily find their way into other parts affected by storm surges.

2. Challenges

Obviously, storm surges represent a major societal risk, which forces people to adapt their way of living and working to this threat. In early historic times, the dangers related to storm surges were relatively easily dealt with, when the defense was limited to the immediate housing area and population was sparse [10]. Large areas were flooded, but the elevated water levels were minor. This changed when dikes were built to protect from flooding, to allow for more effective agriculture and higher population densities (for the Dutch rivers, this development was analyzed by [11]). Ever since, keeping dikes in order was a challenge, and keeping the dangers of storm surges at bay was an important community task, the activity of which can nowadays partly be reconstructed by studying costs to repair dikes in historical times [12]. A more modern account of the history of managing the risk of storm surges along the North Sea coast is provided by [9].

Conventional challenges related to storm surge risk management relate to

1. Preparing of short term forecast
2. Preparing for measures in case of failure of coastal protection
3. Monitoring of changing storm surge heights and statistics

2.1. Forecasting

Forecasting storm surges can be done in different ways – with the main approaches of exploiting past statistical evidence about precursors (that is statistical forecasting), and of using dynamical models, which simulate in detail currents and water levels in a regional set-up.

The statistical systems have the advantage that they may be very fast and very simple, such as a delayed regression equation, or a set of simple “rules”. They have the disadvantage that they may suffer from either over-specification – too many details are employed, and the underlying statistical model may lack of robustness, or from under-specification – too few details are used, and the system may be unable to take important specifics of “the next case” into account. Also, such systems are based on the statistics of past events, which is becoming a problem, when the geophysical conditioning of the storm surge is changing, for instance because of changing sea level associated with global climate change or vertical land movement, because of local modification of estuaries or near shore topography related to engineering works.

Dynamical systems make use of an analysis of the ongoing hydrodynamic and meteorological state (normally, the latter being forecast by an operational weather forecast system), and feed these as initial conditions and as boundary conditions into numerical models based on discretized equations of motion and mass conservation. In principle these equations are just the vertically averaged shallow water equations, featuring two horizontal current components plus the horizontal water level displacement (cf., [13,14]). Key sub-grid scale processes, which need paramterization, are the bottom friction and the surface wind stress. The hydrodynamic boundary conditions may include the discharge of rivers. Such systems are much more challenging in logistic terms, and may suffer from errors in the initial or boundary conditions (if the prediction of a storm is not good, the prediction of a following storm surge cannot be either), as well as errors in the dynamical model.

A variant of the dynamical model approach is to frame the forecast problem not as a initial-boundary value problem with a set of differential equations, but as a state space problem, which is solved by assimilating incoming local observation into the numerically determined trajectory of expected future developments. This method is regularly used in weather forecasting, and is getting more popular in oceanographic contexts – it goes with the technical term "*data assimilation*".

In principle storm surge forecast systems have reached mature levels of development and are in wide operational use by governmental agencies and other institutions. Such models often use variable mesh formulations for covering near-coastal and estuarine regions better than the open coastal sea.

2.2. Risk Management

Since it is hardly possible to determine the largest possible flood along a coastal segment, and the risk of failure of certain coastal defense structures can never be excluded, there is always a – hopefully – small but nonzero risk for coastal inundation. Thus, it is an important task for planers to prepare for such disasters. In many parts of the world, such preparations are implemented, and exercises are done to train governmental services as well as the public for this case. But, as one could observe during the disastrous Nargis storm in Myanmar, there are also cases when the forecast was good [15] but no significant preventive measures were in place, not even proper warnings were voiced.

2.3. Changing Risk: Scenarios of possible futures

The specter of man-made climate change, caused by elevated concentrations of atmospheric greenhouse gas concentrations, is also causing changing expectations about the risk of storm surges, and thus coastal inundations. There are three major mechanisms for changing the regional sea level, which may result in such changes:

a. Changing mass of sea water due to a net increase in mass through depletion of glaciers and ice sheets (not mention the most significant ones).
b. Changing density of sea water due to warming, or regionally changing freshwater fluxes
c. Changing ocean circulation, and changing self attraction of sea water (related to changing masses of the ice sheets)

There is broad consensus that there is presently a sea level rise going on, and that it will continue also beyond the 21st century, even if an efficient "climate policy" (such as the "2 degree goal") is successfully implemented. There relative importance of the different causal factors is presently under a lively scientific discussion, and the range of suggestions of a possible rise of sea level until the end of the 20th century extends to 2 m by some, while a group of experts gathered by the Dutch Delta Kommissie thought that 1.20 m would be an plausible high-end scenario for 2100, with "more than three times these values by 2200" [16].

The scientific arguments used to assess and estimate future changes of sea level range from scenarios with dynamical models – this refers to thermal expansion of sea water and changing ocean circulation – to paleo-climatic analogs and back-of-the-envelope estimates – concerning changing ice sheet volumes. These approaches leave room for many different consistent expectations

The other component of storm surge risk, namely the effect of changing storm statistics, be it duration of events, frequency or intensity, may also change. The effect may be significant in the tropics, where mighty tropical cyclones rage, while the expected effect in extra-tropics, such as the North Sea is minor, when compared to the sea level rise. In the latter case, the scenarios are constructed by using scenarios of changing wind and air-pressure statistics and using regional ocean models to evaluate what these changes in forcing may imply for coastal water level variations [17,18,19,20].

The models used are essentially the same as those used for forecasting, with the main difference that they need to be integrated for much longer times (multiple runs over many tens of years) than forecast models (multiple runs of a few days), Therefore the former may be formulated with very high grid resolution (up to 100 m), in particular in the near-coastal range including estuaries, while the latter run with grid resolutions of a few kilometers.

A review of the present knowledge about expected future sea level rise as well as about changing storm surge conditions is presently prepared by the IPCC for the nest assessment report, which is to be published in 2014. Thus, we are mentioning here only a few methodical issues, which are relevant for determining ongoing and plausible future change.

When assessing ongoing change of sea level and storm surge statistics two challenges must be met:

- The data must be homogeneous, that is: changing statistics must be unrelated to changes in local environment, measurement technology and reporting practice [21].
- Data series must cover a period of sufficient lengths, for instance sixty and more years, so that two separate 30 year segments are available to derive statistics – which may then be different in the earlier time than in the later time.
- When empirical models are built, care must be taken that such models have a sound statistical basis. For a while, so called “semi-empirical models”, which relate changes in temperature to changes in sea level, have been popular. It was later shown, however, that such a linkage is physically unsound [22], and statistically flawed, because it amounted essentially to comparing two trends [23].

A relevant question is whether there is a recent acceleration of the rise in sea level. This has become a contested issue, and for the North Sea, the recent rise is faster than a few decades before, but not faster than what people believe to have happened in the 1930s [21].

When deriving expectation for possible future development, it would be beneficial if the present increase would be shown of being consistent with what models, or other sources of knowledge, describe as plausible future developments. This is an open question, which is receiving increased attention in recent years.

3. Epilogue

Storm surges are a major geophysical risk, which have over the years and centuries caused massive catastrophes, with losses of live of the order of 100,000 people and more. Most of these events take place in the tropics, while in extra-tropics the numbers are considerable smaller, namely 10,000 and less. Since these phenomena are well known, coastal communities in many countries are well prepared and know how to deal with threat and intermittent disasters. A major step forward was the development of reliable weather forecasts, which went along with forecasts of water movement. For instance, the 1953 storm surge hit the southern coast of The Netherlands almost unwarned. Nowadays the warning lead time of 24 hours and more is common.

Predicting storm surges and managing storm surge risk is a challenge of planning and governmental efficiency. But, of course, all tools, also good ones, can be further improved. What can be done in principle on a regular grid with a vertically averaged shallow water equations, can be done much better with 3d model run on an adaptive grid, where wave-set-up is included.

A topical issue is the perspective of man-made climate change, be it regional changes of shipping lanes in estuaries or the release of greenhouse gases onto the atmosphere. In this case a number of major scientific challenges prevail, first of all the issue of mean sea level rise. The effect of changing storms, in particular in extratropical regions, seems less important. The IPCC will come up with a new assessment of the state of scientific knowledge in 2014.

Another major challenge with climate change and sea level and changing storminess is the ubiquitous politicization of the issue. All too often scientific results and perspectives are presented to a wider public with a purpose unrelated to the issue itself, namely to either heighten public attention to the problem and public willingness to support efficient climate policies, or to raise the perception that the issue of man-made climate change is of minor importance. If this is something, the scientific community and the public just have to live with, or if the agitation will calm down, will remain to be seen.

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