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INFLUENCE OF CLIMATE CHANGE ON STORM SURGE CONDITIONS IN THE GERMAN ESTUARIES AND TESTING OF PROBABLE ADAPTATION STRATEGIES

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As climate will change in the next century and beyond, politics and stakeholders need to know the effect of climate change on German estuaries on, e.g, shipping, economy and nature. In order to find a strategy for adaptation to climate change it is important to understand today's situation and to analyse the future situation under the influence of climate change. The aim of this study is to investigate storm surges in a changing climate in the three most important German estuaries Ems, Jade-Weser and Elbe, and the effectiveness of probable adaptation measures by means of hydrodynamic modelling. A 3D hydrodynamical numerical model is used to calculate water levels and currents while the local wind fields over the estuaries are provided by a meteorological model of DWD. The investigation is carried out in a sensitivity study. Here, scenarios are developed where the key parameters (mean sea level, river runoff, wind field) are systematically varied according to the knowledge about an expected future climate. Then, the modelling approach is used to investigate the impact on water levels. Finally, the effect of potential adaptation measures on storm surge conditions is shown.

INTRODUCTION

In the light of climate change in this century and beyond, politics and stakeholders need to know the potential consequences of climate change for shipping, waterways and ecosystem functioning. To enable the appropriate options for adapting to climate change to be developed, it is not only necessary to understand the current situation but also to analyse potential future conditions. The actual impact of climate change on sea levels, for example, or on wind conditions in the German Bight in 2050 or 2100 are unknown. Nevertheless, the SRES scenarios (IPCC [1]) for a number of parameters that determine the height of storm surges provide an indication of how those parameters might change. It is therefore possible to investigate the significance of changes in such parameters for storm surges on federal waterways in Germany. The results of a sensitivity study on storm surges on the Elbe, Jade-Weser and Ems are presented by way of illustration. The aim of the study is to achieve a better understanding of the range within which the peak water levels during storm surges vary under current conditions and may vary in future. The results are a contribution towards identifying the conditions along waterways in the estuaries of the Elbe, Jade-Weser and Ems, analysing features that the estuaries have in common as well as their differences and developing appropriate adaptation measures in collaboration with stakeholders, such as the Federal Waterways and Shipping Administration (WSV), Hamburg Port Authority (HPA) or research institutions.

STORM SURGE SCENARIOS

Storm surges in the estuaries of the Elbe, Jade-Weser and Ems are influenced not only by the tidal dynamics and the wind set-up in the German Bight but also by processes taking place in the estuaries themselves which can extend up to 100 km into the North German Plain. For example, the development of the water level in the German Bight, local wind effects over the estuaries, the fresh water discharge into the estuaries and their topography all affect the highest water level occurring during storm surge (HW) along the estuaries concerned. A sensitivity study on storm surges is investigating scenarios that are intended to highlight central elements of a possible future [Kosow and Gassner [2]]. One of those central elements has been identified, for example by Becker [3], as an increase in precipitation in winter and the resultant higher fresh water discharges in the storm surge season [von Storch *et al.* [4], Horsten [5]]. Heinrich [6] has identified the rise in sea level in the German Bight as a central element of climate change. The results for the following scenarios are presented by way of illustration:

- An increase in the fresh water discharge Q: Storm surge scenarios are combined with the actual discharge and three increased discharge levels (2000 m^3/s, 3000 m^3/s and 4000 m^3/s for the Elbe and Weser and 350 m^3/s, 700 m^3/s and 1200 m^3/s for the Ems). The highest values in the study correspond to the present-day highest known value HHQ for each estuary.
- A rise in the sea level of the North Sea slr: Storm surge scenarios are combined with rises in the sea level of 25 cm, 80 cm and 115 cm (see Gönnert *et al.* [7] for assignment of the values).

The sensitivity study is based on very high historical storm surges (those occurring on the Elbe and Jade-Weser on 3 January 1976 (SF76) and on the Ems on 1 November 2006 (SF06)). By applying hydrodynamic numerical (HN) models (UnTRIM, Casulli and Walters [8] and BAW [9]), the effect of the processes referred to above on the development of the water level during a storm surge can be investigated individually. The wind fields were provided by the German Meteorological Agency (DWD).

MODEL SETUP

The hydrodynamic numerical model UnTRIM (Casulli and Walters [8] and BAW [9]) is used to simulate flow and transport processes with free-surface flow for each estuary under investigation. This semi-implicit finite difference model is based on the three-dimensional shallow water equations and uses unstructured orthogonal grids with wetting-and-drying algorithm. Table 1 gives an overview of the main model properties for each estuary while Figure 1 (see next page) depicts the model areas and the topography, respectively.

Table 1: Main properties of the estuary models of Elbe, Jade-Weser and Ems

Estuary	Number of polygons	Size of polygons (min – max) (m^2)	Total area (km^2)	Simulation time step (s)
Ems	241,627	32 – 510,000	2,431	30
Jade-Weser	402,051	44 – 193,000	2,134	100
Elbe	146,783	47 – 627,000	1,711	100

RESULTS OF THE SENSITIVITY STUDY

The effect of a rise in sea levels on the development of water levels during storm surges is shown in Figure 2, taking the storm surge scenario SF76 for Brake on the Lower Weser as an example. The increase in the sea level alters the water level at high water Thw and low water Tnw and the times at which the high and low tides occur on the day before the storm

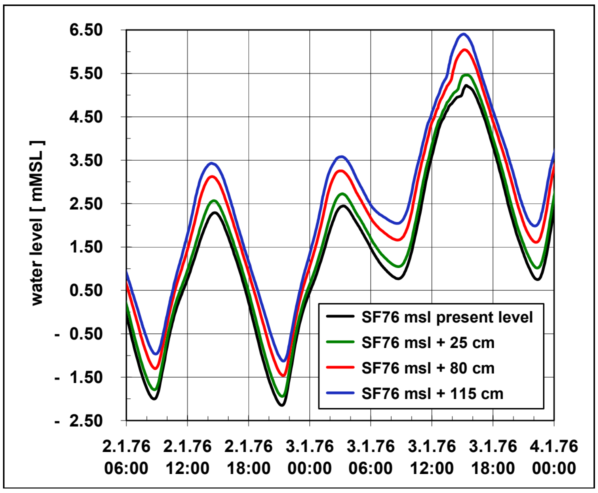

Figure 2: Development in the water levels at Brake (Weser km 40) for the storm surge scenarios with a rise in mean sea level

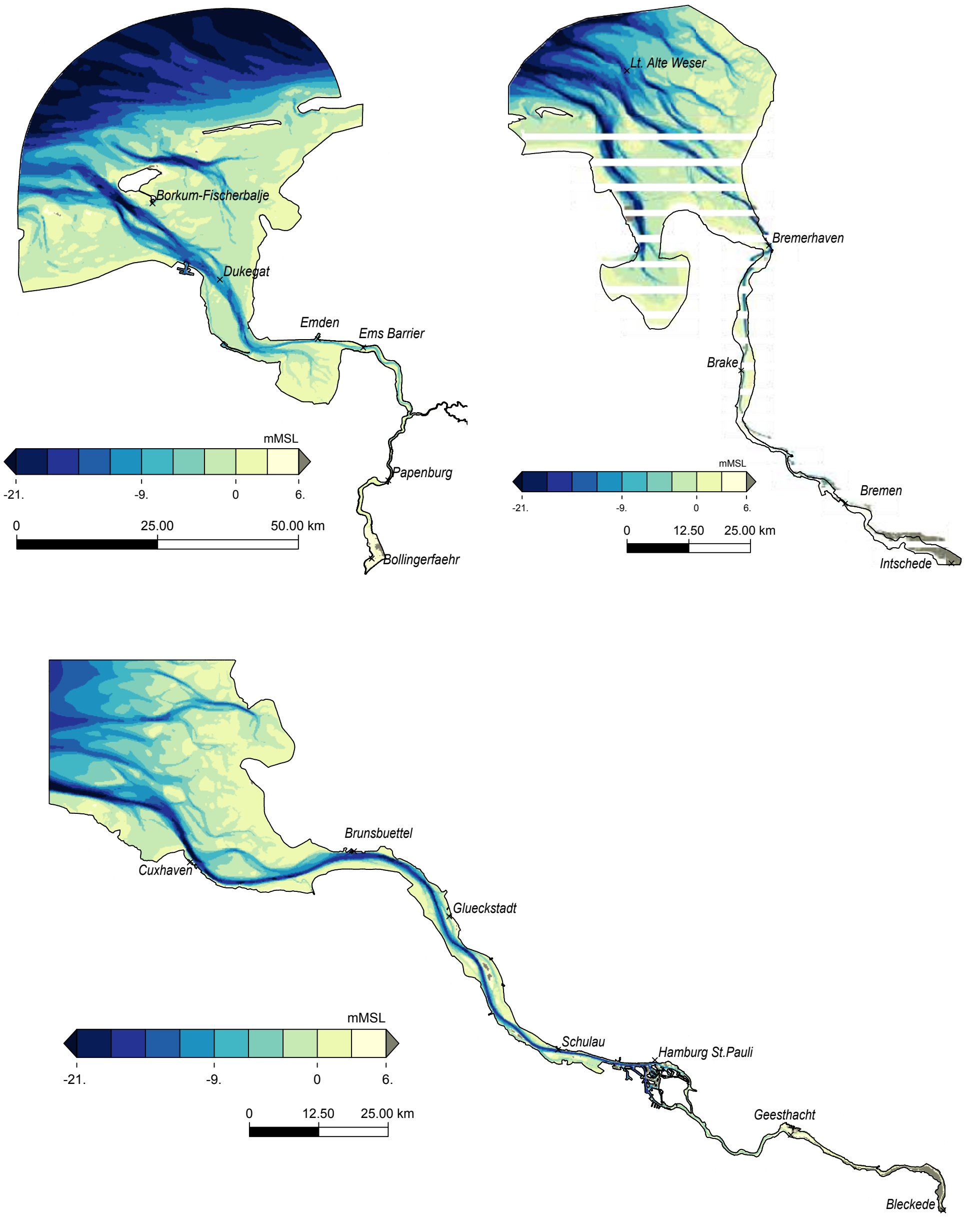

Figure 1: Topography of the estuary models of Ems (upper left), Jade-Weser (upper right) and Elbe (lower figure) used in this investigation

surge. The storm surge peak HW increases owing to the rise in sea level and also occurs earlier. The duration of the high water level also increases.

Storm surge peak time

Considering one particular town on the Ems estuary, it is shown that, in the case of Emden for example, the HW in the reference scenario SF76 is reached after 100 minutes. Sea level rises of 25 cm, 80 cm and 115 cm mean that the storm surge peak HW occurs around 5 minutes, 20 minutes and 25 minutes earlier respectively. A rise in sea levels means that there is less time for preparing the defence of the dykes, evacuating harbour areas in danger of flooding and warning the inhabitants in the event of a storm surge.

Duration of high water

Drainage systems and sluices without pumps rely on a gradient in the water level. Furthermore, harbour facilities cannot operate when water levels are very high. Locks and flood barriers are closed during storm surges, thus restricting shipping. If a 24-hour period of reference scenario SF76 in Hamburg is considered, water levels higher than 3.00 m above mean sea level occur for a total of 11.5 hours. This period increases by around 30 minutes if the sea level rises by 25 cm, by 5 hours if the sea level rises by 80 cm and by around 6 hours if the sea level rises by 115 cm.

Storm surge peaks HW

Changes in the sea level or in the fresh water discharge affect the storm surge peaks along the estuaries in different ways. An increase in the discharge does not alter the high water at the mouth of an estuary. HW rises by several centimeters in the middle reaches of the estuary and by several decimeters in its upper reaches. However, higher sea levels mean that the storm surge peaks extend further up in the estuaries.

A combination of a rise in sea level and an increase in the fresh water discharge, see Figure 3, shows that the rise in sea level alters the height of the storm surge peaks at the mouths of the estuaries. Both the rise in sea level and the altered discharge affect the storm surge peaks in the middle reaches of the estuaries. In the upper reaches of the estuaries, the height of the storm surge peaks is mainly determined by the fresh water discharge. The results of the sensitivity study enable those areas along the estuaries where the altered parameters cause marked changes in the storm surge peaks to be identified.

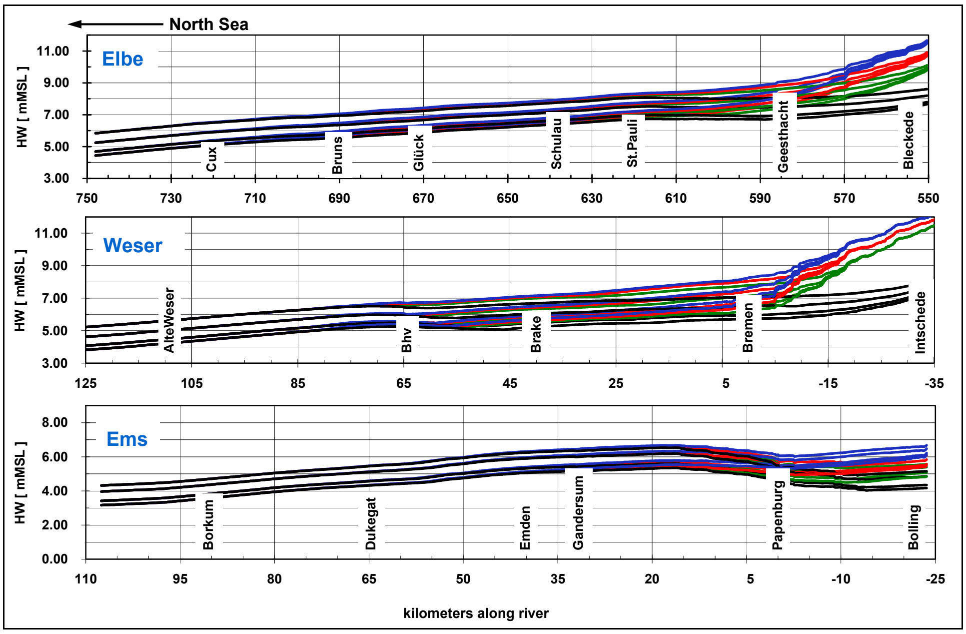

Figure 3: Effect of a rise in sea level (present-day mean sea level msl, msl + 25 cm, msl + 80 cm, msl + 115 cm) and an increase in the fresh water discharge (measured discharge shown in black, 2000 m³/s or 350 m³/s (green), 3000 m³/s or 700 m³/s (red) and 4000 m³/s or 1200 m³/s (blue)) on storm surge peaks along the Elbe, Weser and Ems estuaries

ADAPTATION MEASURES

Estuaries can be protected against storm surges by constructing storm surge barriers. The Ems is already protected against storm surges by the Ems barrier at Gandersum (see Figure 1). The four sea level scenarios referred to above are considered in conjunction with the scenarios for the fresh water discharge. Figure 4 shows, by contrast to Figure 3, the storm surge peaks on the Ems when the Ems barrier is closed. The present-day nominal height of the dyke (left and right banks) is also shown. The area upstream of Gandersum is protected when the storm surge barrier is closed. The storm surge peaks there are relatively low and depend on the fresh water discharge and on how long the Ems barrier is closed. The storm surge peaks on the seaward side of the Ems barrier are not affected by the discharge but only by the rise in sea level. A comparison of the nominal heights of the dykes and the storm surge peaks in the sensitivity study shows that the storm surge barrier is an appropriate adaptation measure for nearly all of the scenarios considered. However, it is also possible to identify certain areas on the Ems where the storm surge barrier does not prevent the problems caused by storm surges during certain scenarios as the dykes are not high enough, for example.

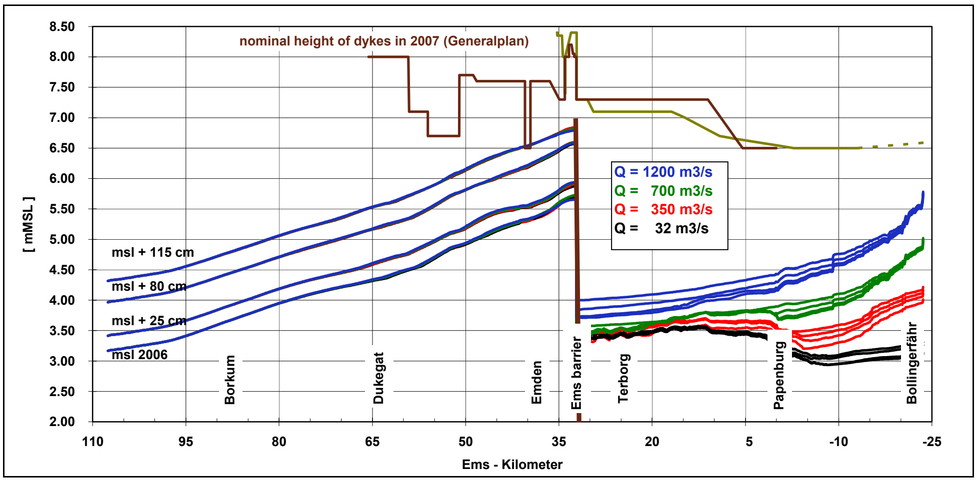

Figure 4: Effect of the rise in mean sea level and the increase in the fresh water discharge Q on the highest water level during storm surge HW along the Ems when the Ems barrier is closed

SUMMARY

In a sensitivity study of storm surges on the Elbe, Jade-Weser and Ems, the parameters that may alter as a result of climate change were systematically varied. The changes in the storm surge peaks are summarized in Table 2. The storm surge peak at the mouth of an estuary is determined by events in the North Sea, i.e. by the storm surge and the rise in sea level. The storm surge peaks in an estuary are affected by events both in the North Sea and inland (fresh water discharge).The scenarios considered result in an increase in the height of storm surge peaks, cause the storm surge peaks to begin earlier and lead to an increase in their duration. It may be assumed that the well-known problems occurring during storm surges will be aggravated by climate change. By taking the example of the Ems barrier, it can be shown how the results of a sensitivity study can be used to identify problems on federal waterways and develop appropriate adaptation measures in collaboration with the Federal Waterways and Shipping Administration.

Table 2: Changes in storm surge peaks on the Elbe, Jade-Weser and Ems estuaries for the scenarios under consideration

Scenarios	Mouth of estuary	Middle reach of estuary	Upper reach of estuary
Fresh water discharge Q	+/- 0.01 m	0.05 to 0.3 m	0.1 to 1 m
Sea level rise slr	+ slr	+ (slr +/- 0.1 m)	+ (slr +/- 0.1 m)
Combination Q & slr	+ slr	≤ (slr + Q)	≤ (slr + Q)

ACKNOWLEDGMENTS

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