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Climate change and hydrodynamic impact in the Jade-Weser area: a case study

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Abstract

Estimates of hydrodynamic stress patterns in coastal forelands and alterations caused by estimated climate change are important for planning of medium and long-term coastal defence measures, for sustainable use of coastal areas and for the investigation of ecological trends in these forelands. The impact of a climate change scenario (sea level rise, increased tidal range and stronger winds) on the hydrodynamic conditions in the Jade-Weser area is estimated from changes compared to the status quo. The variability of water levels, inundation characteristics and flow patterns is obtained from numerical simulations. In the climate scenario with status quo-topography the rise in water levels at the seaward boundaries propagates with slight deviations throughout the Jade-Weser area. During storms from the north-west the wind set-up increases towards the Jade Bay proper and the Weser estuary. Storm surge barriers in the Jade Bay and the Weser estuary as coastal protection measures in the climate scenario would increase the high water levels in the outer Weser estuary and at the eastern coast significantly. The implied decrease of eulittoral and supralittoral is of relevance not only for the ecological situation but also for coastal defence planning. Parts of the tidal flats are exposed longer to increased currents and waves, and therefore to increased bottom shear stresses. This investigation is part of the joint interdisciplinary project KRIM funded by the Bundesministerium für Bildung und Forschung.

1 Introduction

1.1 Objectives

The coastal zone of the German Bight (southern North Sea) has been inhabited by man since historical times, and coastal defence activities can be traced back to the middle ages. Growing and new settlements close to the coast and intensive agricultural, industrial and touristic use of the coastal zone gave rise to the development of sophisticated coastal defence technology. A future climate change together with rising water levels, changing currents, waves and shear stresses acting on the bottom and changing morphological structures can endanger the safety of coastal defence systems leading to an increased risk of flooding of the low-lying hinterlands and can influence the ecology in the coastal areas. Estimates of possible present and future changes of the hydrodynamic stress in the forelands are useful and important information for planning of medium and long-term coastal defence measures, for sustainable use of coastal areas, and for the analysis of ecological trends in the forelands.

The Jade-Weser area (Figure 1) covers part of the central German Bight. Its hinterland is protected by a system of dike lines. This area showing various disparate morphological structures includes the eastern part of the East Frisian Wadden Sea with the barrier island Wangerooge and its backbarrier tidal flats and channel systems, the Jade Bay and the Weser estuary with deep tidal channels and the exposed Hohe-Weg Watt and Wurster Watt with the islands Mellum to the left and Knechtsand to the right of the Weser estuary. As only a few small rivers discharge into the Jade Bay the water exchange with the open sea is little restricted and the hydrography of the bay is controlled by the water entering from the German Bight. The Weser estuary is subdivided into the channel-like inner estuary upstream of Bremerhaven and the funnel-shaped outer estuary which consists of two main channels with cross connections amidst large tidal flats. The hydrography is controlled both by the intruding water from the German Bight and by the Weser river discharge having a long-term mean of about 325 m^3/s. In the course of time, various parts of the Jade-Weser area have been affected by engineering measures of different impact (Wangerooge: e.g. Ehlers 1988; Jade Bay: e.g. Garrelts et al. 1973; Irion 1994; Weser estuary: e.g. Barthel 1977; Dieckmann & Pohl 1991; Wetzel 1987). Today large areas of this region belong to the national park "Niedersächsisches Wattenmeer".

The hydrodynamic response in the Jade-Weser area to climate change and coastal protection scenarios is estimated. This investigation is part of the interdisciplinary joint project "Klimawandel und präventives Risiko- und Küstenschutzmanagement an der deutschen Nordseeküste" (KRIM, Climate Change and Preventive Risk and Coastal Protection Management on the German North Sea Coast; Schuchardt und Schirmer 2003; http://www.krim.uni-bremen.de) funded within the German Climate Research Program (DEKLIM) by the Bundesministerium für Bildung und Forschung. Within the project KRIM the investigation of the hydrodynamic changes contributes to the analysis of the risk-of-failure of today's and future coastal defences and to the investigation of ecological trends in the forelands.

First, the hydrodynamic conditions of the Jade-Weser area were analysed for the status quo. Then, the impact of the anticipated climate scenario on the hydrodynamics was estimated from changes compared to the status quo. The climate scenario includes a rise in sea level, a tidal range increase and an increase in wind forcing in winter. The analysis of the different scenarios was based on numerical simulations. As the possible impact of climate change on the hydrodynamics of the inner Weser estuary had been investigated previously (Grabemann et al. 2001) only the outer Weser estuary downstream of Bremerhaven was taken into account.

In this paper changes of water levels, inundation and flow fields between the status quo and the anticipated climate scenario are quantified and discussed with respect to coastal protection and ecological trends in the forelands. Simulations for the climate scenario were carried out with the status quo-topography left unchanged. This implies that the heights of the tidal flats do not increase with mean sea level rise. Simulations are in preparation using an adapted topography in which the heights of the tidal flats are adjusted to the rising water levels while the tidal channels are made deeper.

A climate change causing a sea level rise is expected to have implications for today's coastal defences (e.g. Elsner et al. 2004). The analysis of the risk-of-failure of coastal defences together with adaptation measures is the object of the Franzius Institut für Wasserbau und Küsteningenieurwesen (Universität Hannover) who is partner in the project KRIM. Effects of storm surge polders in the inner Weser estuary are presented in von Lieberman et al. (2004). In this paper the impact of two storm surge barriers on water levels is discussed.

1.2 Method

The water levels and currents were calculated using a circulation model based on the three-dimensional model TRIM (Casulli and Stelling 1998). The model can treat temporarily dry falling and inundated solution domains. For the status quo, the forcing data were taken from weather and tidal prediction models comprising larger areas (Deutscher Wetterdienst (DWD) and Bundesamt für Seeschiffahrt und Hydrographie (BSH)). In order to minimize scale inconsistencies due to the large scale differences between the BSH model data (resolution: about 1 nautical mile) and the grid of the Jade-Weser area (resolution: 100 m), four nested grids were used in the simulations (800 m → 400 m → 200 m → 100 m). Some grid point saving was possible by neglecting the already investigated lower Weser estuary between Brake and Bremen which is only a small portion of the total domain considered. For the Weser estuary the daily river discharge (from Deutsche Gewässerkundliche Jahrbücher, Weser-/Emsgebiet) was prescribed at the southern landward boundary Brake. Soundings from the respective coastal authorities were used to construct the course-grid topographies. The topography of the finest grid was supplied by the Franzius Institut für Wasserbau und Küsten-ingenieurwesen.

Based on the projection of the Intergovernmental Panel on Climate Change (IPCC) for the next 50 years, the scenario of a changed climate was constructed by superimposing to the status quo forcing data the anticipated sea level rise of 0.55 m, tidal range change of 0.25 m (increase of high water + 0.55 m + 0.1 m, increase of low water + 0.55 m - 0.15 m) and stronger winds (+ 7 %, December to February).

For the simulations of calm weather to moderate winds, two spring-neap cycles in September 1999 were chosen. Shorter periods of several days were included to examine the effects of strong offshore and onshore winds.

Hypothetical storm surge barriers were introduced in the Jade near Wilhelmshaven and in the Weser near Bremerhaven as possible coastal defence adaptation measures to climate change. Additional simulations were carried out.

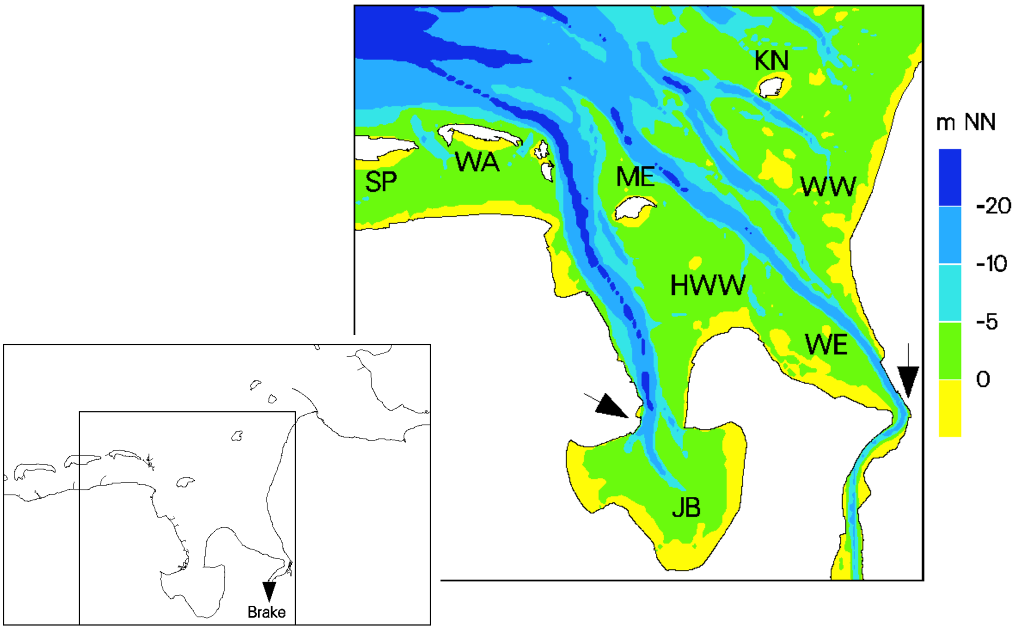

Fig. 1: Topography of the Jade-Weser area (100 m * 100 m grid). The insert shows the extent of the 800 m * 800 m grid. SP: Spiekeroog, WA: Wangerooge, ME: Mellum, HWW: Hohe-Weg Watt, JB: Jade Bay, WE: Weser estuary, WW: Wurster Watt, KN: Knechtsand. The arrows point to the cities of Wilhelmshaven (Jade Bay) and Bremerhaven (Weser estuary).

2 Results

The impact of the climate scenario was obtained by analysing the differences between the simulations done for the status quo and for the climate scenario with unchanged topography.

For the status quo, the quality of the simulations of the water levels has been assessed against water level measurements showing an average deviation of about + 0.1 m for high water and of about + 0.2 m for low water; for individual tides these deviations can be of the order of 0.5 m. Possible explanations for these discrepancies can be differences between the topography used in the model and the "real" topography existing at the time of the measurements. The water level data used as boundary values for the 800 m * 800 m grid stem from tidal forecast simulations obtained with predicted wind fields, and are therefore likely to contain deviations to measured water levels. The water levels near Bremerhaven may also be slightly in error because the small area of the lower Weser estuary upstream of Brake was not included in the solution domain.

2.1 Water levels

The Jade-Weser area can be classified as meso- to macrotidal; the tidal wave propagates from the west to the east.

In the status quo the mean tidal range increases from about 2.8 m north-west of Wangerooge to about 3.7 m in the Jade Bay near Wilhelmshaven and to about 3.5 m in the Weser estuary near Bremerhaven. The mean high water level rises from about 1.4 m NN to about 1.8 m in the Jade Bay near Wilhelmshaven and in the Weser estuary near Bremerhaven. The mean low water decreases from about –1.4 m NN to about –1.8 m NN and –1.6 m NN, respectively (mean values for September 1999). Coincident values can be found in Niemeyer and Kaiser (1999).

The wind influence on the water levels is most pronounced towards the south-east of the area (Figure 2 left). Storms over the German Bight with wind directions from the north-west cause an increase of high water towards the south-east coast of 2 m and higher. During severe offshore winds the high water levels decrease at the south-east coast (≈ -1.5 m).

In the climate scenario the rise in water levels at the seaward boundaries (high water + 0.65 m, low water + 0.4 m) propagates with only slight local deviations throughout the Jade-Weser area. These deviations vary from tide to tide but are generally less than ± 5 cm; in the Jade Bay, they can differ up to 8 cm.

Such deviations occur also during storms without changing the wind forcing. If in the climate scenario, the assumed wind increase of 7 % is taken into account, the high water levels show an additional increase of about 5 cm towards the south-east and east coast (Figure 2 right, Figure 3).

The difference in the mean tidal range between the status quo and the climate scenario varies around the assumed tidal range change of 25 cm. In the Jade Bay, for example, it can be about 30 cm.

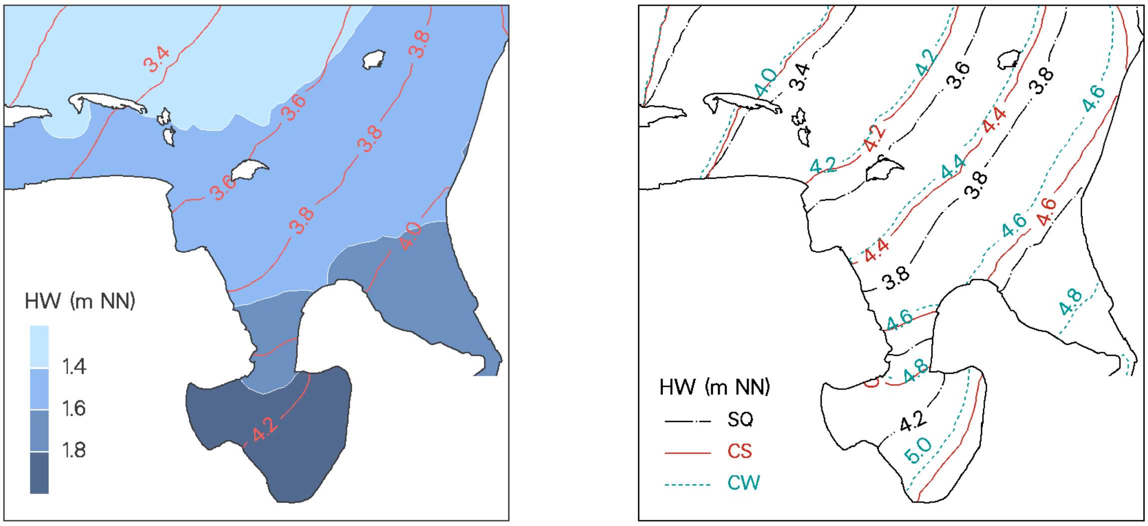

Fig. 2: Spatial distribution of simulated high water levels (HW) for different scenarios. Left: Effects of different wind speeds and directions in the status quo; blue shadings: mean tide and moderate wind in September 1999, red lines: storm in February 1999. Right: Comparison of high water during the storm in 1999 between the status quo (SQ) and the climate scenario without (CS) and with increase of the wind speed (CW).

In order to possibly reduce the impact of the climate scenario on the coastal defences in the inner Jade Bay and the inner Weser estuary, artificial storm surge barriers have been introduced in the Jade near Wilhelmshaven and in the Weser near Bremerhaven in the model domain. If both barriers are closed in the climate scenario around low water at Wilhelmshaven and Bremerhaven the water levels for the subsequent high water during the storm increase significantly in the outer Weser estuary (Figure 3). The water which is stopped seaward of the barrier in the Jade, flows over the Hohe-Weg-Watt towards the outer Weser estuary. Together with the water stopped at the barrier in the Weser it increases the water levels in the outer Weser estuary and at the adjacent eastern coast.

When closing the barriers two hours later, the water levels in the outer Weser estuary and at the eastern coast are increased (by about 10 to 20 cm for the storm in February 1999). The water level in the eastern part of the area remains low for a longer time because the water masses can enter the inner Weser estuary. Due to the higher inertia of the incoming water from the western part the tide runs up higher when the barriers are finally closed.

Whereas the water levels in the Jade Bay proper essentially depend on the intruding North Sea water, those in the Weser estuary are also influenced by the freshwater runoff behind the storm surge barrier. The runoff was about 530 m^3/s during the storm in February 1999 (shown in Figures 2 and 3) but was twice that value during a storm in January 1994 (Deutsche Gewässerkundliche Jahrbücher, Weser-/Emsgebiet, Abflußjahre 1994 und 1999). In the latter case the runoff would increase the water level upstream of the barrier in the Weser by about 0.4 m within 6 hours.

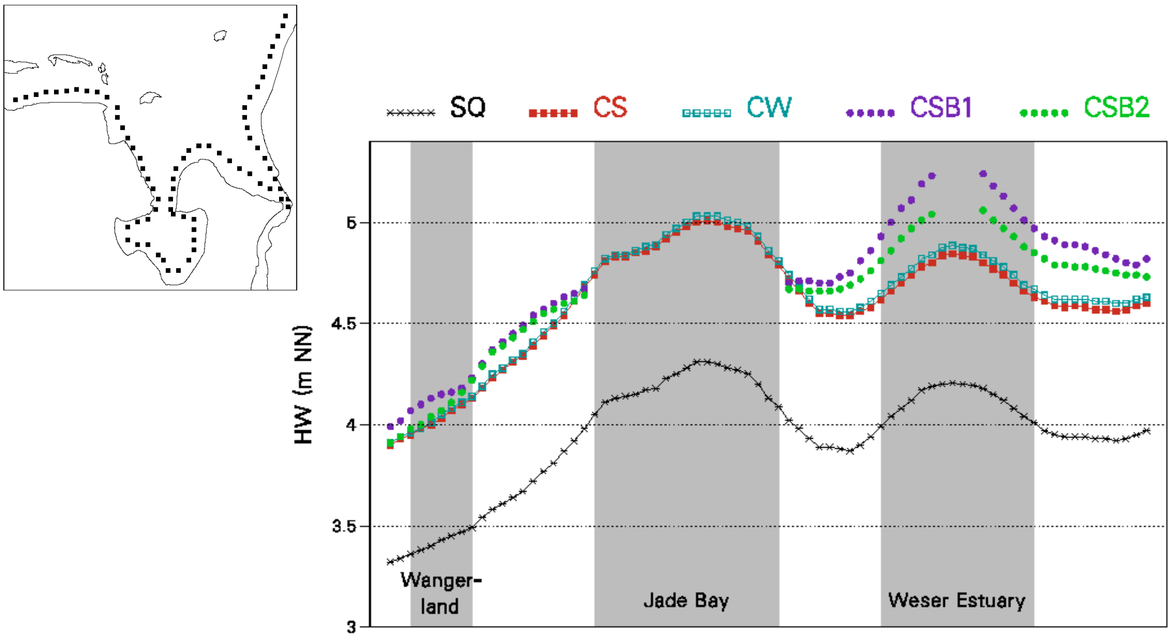

Fig. 3: High water levels near the coast of the Jade-Weser area for different scenarios. SQ: status quo, CS: climate scenario, CW: climate scenario with wind speed increase, CSB1 and CSB2: climate scenario with storm surge barriers in the Jade near Wilhelmshaven and in the Weser near Bremerhaven closed at about low water and at about low water plus two hours, respectively. The small map presents the locations for which high water is shown.

2.2 Inundation and tidal prism

Changes in water levels and tidal range correspond to changes in water volumes and to the expansion of temporarily or permanently flooded areas. On the tidal flats with heights between -2 m and 2 m NN a small change in water levels causes a large change in the percentages of flooded and dry areas. Therefore the numbers below for inundation, eulittoral, supralittoral and tidal prisms are most sensitive for deviations in water levels as well as to errors in the model topography and give more qualitative estimates.

In the status quo, the rear areas are less than 10 % inundated during the tides in September 1999. These areas are only flooded during high spring tides or during storms. About 69 % of the tidal flats are flooded for half the time (Figure 4 left).

About 66 % of the Jade-Weser area (shown in Figure 1 except the Weser estuary upstream of Bremerhaven) belong to the sublittoral, about 32 % to the eulittoral and only less than 2 % to the supralittoral. If the mean water level deviations between measurements and simulations are taken into account, these percentages change to 2 %, 39 % and 59 %, respectively. In the Jade Bay, for example, the eulittoral occupies about 100 km^2. This value is close to the one given in Irion (1994).

In the climate scenario the flooding duration of the tidal flats is prolonged. About 78 % are flooded for half the time. Most of the tidal flats which are flooded in the status quo are inundated longer in the climate scenario by about 10 % (Figure 4 right). Futhermore, the temporarily flooded areas extend closer towards the coast. Eulittoral and supralittoral of the area decrease by about 7 and more than 90 %, respectively, whereas the sublittoral increases by about 7 %.

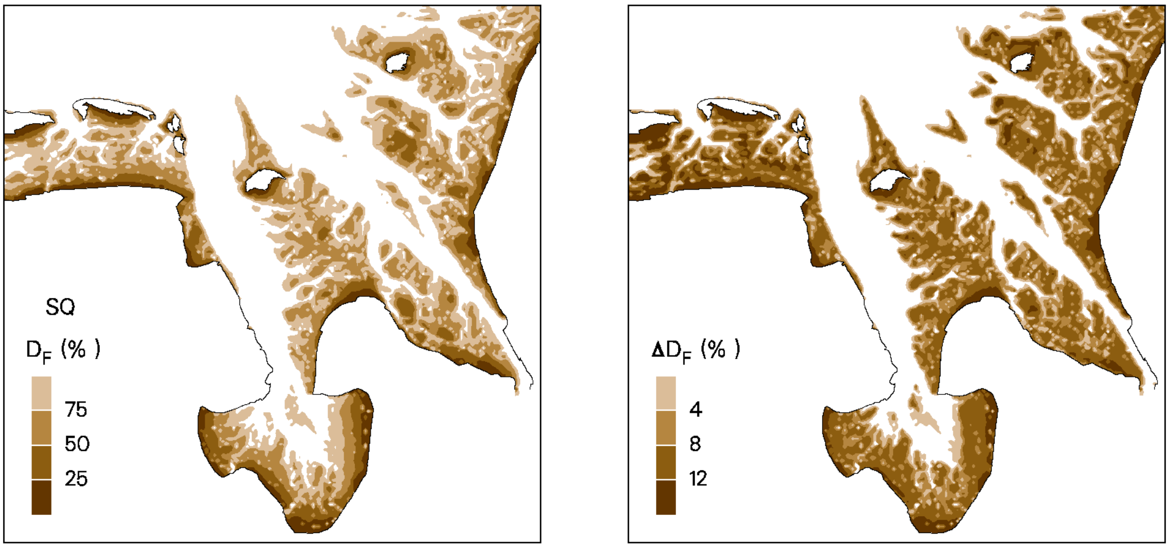

Fig. 4: Spatial distribution of the flooding duration (D_F) in the status quo (SQ, left) and of the difference (ΔD_F, right) between the status quo and the climate scenario (in % of the total time of 53 tidal cycles in September 1999).

The tidal prisms of the tidal basins of the Harle (between Spiekeroog and Wangerooge), Blaue Balje (east of Wangerooge) and Robinsbalje (south of the island Knechtsand) are 146, 89 and 257 Mio. m^3 in case of the status quo. These values are slightly higher than those in Ferk (1994) which may be due to somewhat different dimensions and topographies of the basins and water levels. In the climate scenario the tidal prisms of these three basins increase by about 26 % due to water level rise and tidal range change.

2.3 Currents

Strong tidal currents occur in the deeper tidal inlets and channels. In the status quo, surface tidal currents can exceed 1.5 m/s in the fairways of the Jade and the Weser. On the tidal flats the currents are smaller and range up to about 0.5 m/s (Figure 5).

In the climate scenario the maximum tidal currents show an increase which can locally differ from tide to tide. On the average the increase of the maximum surface currents is less than 0.2 m/s. Locally it can exceed 0.3 m/s in the deep shipping channels and in the tidal inlets. As in these areas the maximum surface currents are already high, this increase is generally less than 20 % of the respective status quo velocities. On the tidal flats the increase of the surface currents is generally less than 0.1 m/s but can be higher locally. On high-lying tidal flats changes of about 0.2 m/s can result in changes of 100 %.

Changes in the directions of the surface currents between status quo and climate scenario are generally small. The wind distortion of the tidal ellipes for the surface currents are generally larger than the differences between the status quo and the climate scenario.

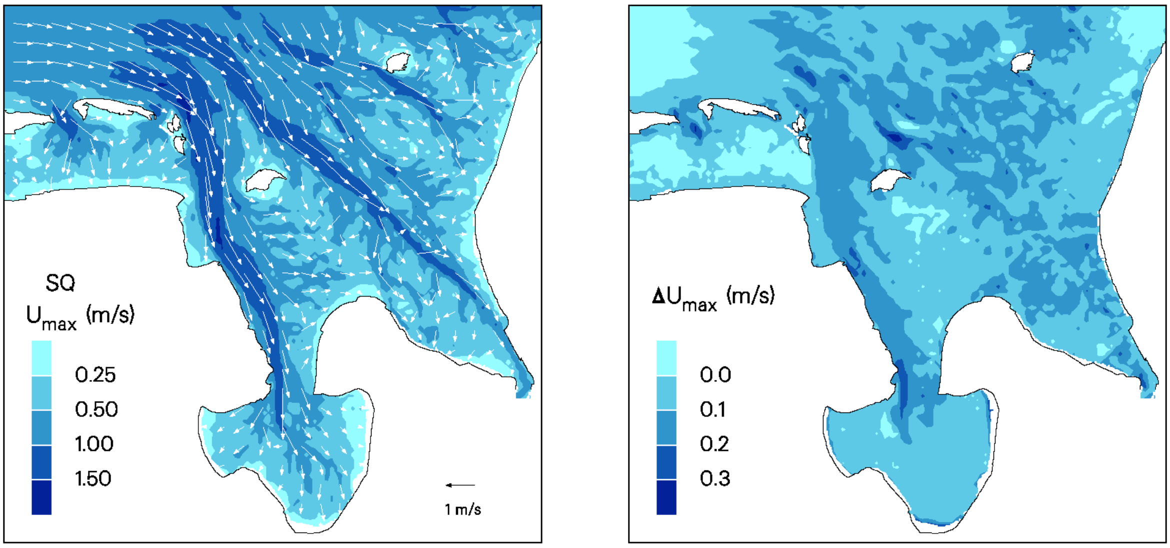

Fig. 5: Spatial distribution of maximum flood surface currents (U_{max}) for a mean tide and moderate wind in the status quo (SQ, left) and differences of velocity magnitudes (ΔU_{max}) between the status quo and the climate scenario (right).

3 Discussion

The anticipated climate scenario (with status quo-topography) causes higher water levels, changes in the location of flooded areas and in their inundation and increased currents. The possible impact of these changes and their effects on the resulting bottom shear stresses and possible erosions on the tidal flats and dike forelands can be important for future coastal protection as well as for future ecological trends. Wave action which is not considered here is the dominant factor for morphological changes in the areas lying above mean sea level (e.g. Niemeyer et al. 1995). It is to be expected that higher water levels above the tidal flats in the climate scenario allow higher waves to destabilize the sediment which in turn can then be transported away by not necessarily strong circulation. To address this problem, bottom shear stresses have also been calculated together with estimates of likely area changes of erosion and sedimentation (to identify possible morphological trends). These results will be published elsewhere.

The impact of storms on water levels and coastal defences increase in the status quo and the climate scenario towards the south-east in the Jade Bay and the Weser estuary and to the adjacent eastern coast. The rise of about 0.65 m in the climate scenario is likely to increase the risk-of-failure of the coastal defences especially at these coastal strips. In the Wangerland, for example, the today's probability of failure of less than 1/2500 would increase to about 1/500 for a mean sea level rise of 0.55 m (Elsner et al. 2004). Storm surge barriers in the Jade Bay and the Weser estuary would lower the impact of storms in the bay proper having about 50 km dikes and the inner estuary having about 120 km dikes, but they would increase the storm water levels significantly in the outer Weser estuary and at the eastern coast and less significantly at the coast south of Wangerooge. The impact on these coasts would increase and would imply the need for additional coastal defence measures.

For three selected tidal basins the tidal prisms have been calculated using the status quo-topography. In the climate scenario an increase for all of them has been found. Changes in the tidal prism of tidal basins together with changes of their tidal inlet gorge are used as indicators for morphological stability (e.g. Misdorp 1990, Ferk 1995, Hofstede 1999). If tidal prism and tidal inlet gorge of a tidal basin are not in equilibrium two possible reactions can lead to a new equilibrium. Either the tidal prism will become larger by deepening of the tidal flats and the inlet gorge will become smaller or the tidal prism will become smaller due to accruing of the tidal flats and the inlet gorge will become larger. Ferk (1995) concluded for the east Friesian tidal basins and for those between the mouths of the rivers Weser and Elbe that the heights of their tidal flats will increase and that their inlet gorges will become larger in case of an accelerated mean sea level rise of 0.6 m until the end of the 21. century. But the growth of the tidal flats will not make up for the mean sea level rise and the differences between the heights of the tidal flats and mean high water will be greater than today. This aspect will be considered in the climate scenario simulations for the Jade-Weser area with an adapted topography in which the heights of the tidal flats are increased with the rising water levels and the tidal channels are made deeper.

The decrease in eulittoral and supralittoral in the climate scenario may have consequences for the zoning of the biotopes. The ecological relevance of such changes as well as its importance for coastal protection is discussed by Wittig et al. (2004). The increase of currents is likely to also affect the fauna and flora.

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References

Barthel, V. (1977): Die Stabilität von Tiderinnen und ihre Abhängigkeit von Strombaumaßnahmen. Die Küste 31, 144-154.

Casulli, V. & G. S. Stelling (1998): Numerical simulation of 3D quasi-hydrostatic, free surface flows. J. Hydraulic Engineering 124, 678-686.

Dieckmann, R., & H.-J. Pohl (1991): Strombau im Weserästuar. Zwischen Weser und Ems 25 (Hrsg. Wasser- und Schiffahrtsdirektion Nordwest), 14-42.

Ehlers, J. (1988): The Morphodynamics of the Wadden Sea. Balkema, Rotterdam.

Ferk, U. (1995): Folgen eines beschleunigten Meeresspiegelanstiegs für die Wattgebiete der niedersächsischen Nordseeküste. Die Küste 57, 135-156.

Deutsches Gewässerkundliches Jahrbuch, Weser- und Emsgebiet, Abflußjahre 1994 (1995). Niedersächsiches Landesamt für Wasserwirtschaft (Hrsg.), Hildesheim.

Deutsches Gewässerkundliches Jahrbuch, Weser- und Emsgebiet, Abflußjahre 1999 (2001). Niedersächsiches Landesamt für Ökologie (Hrsg.), Hildesheim.

Elsner, A., S. Mai & C. Zimmermann (2004): Risikoanalyse - ein Element des Küstenzonenmanagements. This issue.

Garrelts, E., H. Harten, G. Hovers, F. Lucht, H. Oebius, F. Ohlmeyer, H. Rohde, J. Sindern, H.-J. Vollmers & V. Wigand (1973): Die Ausbauten der Mündungsstrecken der deutschen Tideströme und deren Einfluß auf die Sandbewegung. Internationaler Schiffahrtskongreß, 197-228.

Grabemann, H.-J., I. Grabemann, D. Herbers & A. Müller (2001): Effects of a specific climate scenario on the hydrography and transport of conservative substances in the Weser estuary, Germany: a case study. Climate Research 18, 77-87.

Hofstede, J. L. A. (1999): Das Wattenmeer- Struktur, Funktion und künftige Stabilität. Jahrbuch der Marburger Geographischen Gesellschaft e.V., 246-253.

Irion, G. (1994): Morphological, sedimentological and historical evolution of Jade Bay, Southern North Sea. Senckenbergiana maritima 24, 171-186.

Misdorp, R., F. Steyaert, F. Hallie & J. de Ronde (1990): Climate change, sea level rise and morphological developments in the Dutch Wadden Sea, a marine wetland. In: Beukema, J.J., et al. (eds): Expected Effects of Climatic Change on Marine Coastal Ecosystems. Kluwer Academic Publishers, 123-131.

Niemeyer, H. D., R. Goldenbogen, E. Schroeder & H. Kunz (1995): Untersuchungen zur Morphodynamik des Wattenmeeres im Forschungsvorhaben WADE. Die Küste 57, 65-94.

Niemeyer H. D. & R. Kaiser (1999): Mittlere Tidewasserstände. In: Nationalpark Niedersächsisches Wattenmeer & Umweltbundesamt (Hrsg.), Umweltatlas Wattenmeer, Band 2 - Wattenmeer zwischen Elb- und Emsmündung. Verlag Eugen Ulmer GmbH & Co, 24-25.

Schuchardt, B. & M. Schirmer (2003): Ansatz und Ziel des interdisziplinären Forschungsvorhabens "Klimawandel und präventives Risiko- und Küstenschutzmanagement an der deutschen Nordseeküste" (KRIM). In: Daschkeit, A. & H. Sterr (Hrsg.): Aktuelle Ergebnisse der Küsten-forschung. 20. AMK-Tagung Kiel, Berichte Forschungs- und Technologiezentrum Westküste d. Univ. Kiel 28, Büsum, 31-42.

von Lieberman, N., I. Grabemann, A. Müller & S. Osterkamp (2004): Vergleichende Abschätzung von Effektivität und Nebenwirkungen verschiedener Reaktionsvarianten des Küstenschutzes an der Unterweser gegenüber einer Klimaänderung. In: Schuchardt, B & M. Schirmer (Hrsg.): Klimaänderung und Küste. Die Zukunft der Unterweserregion. Springer Verlag, in press.

Wetzel, V. (1987): Der Ausbau des Weserfahrwassers von 1921 bis heute. Jb. Hafenbautechn. Gesellschaft 42, 83-105.

Wittig, S., D. Kraft, J. Meyerdirks & M. Schirmer (2004): Risikobewertung ökologischer Systeme an der deutschen Nordseeküste im Klimawandel. This issue.

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