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Localization of global climate change:
Storm surge scenarios for Hamburg
in 2030 and 2085

By Iris Grossmann[1], Katja Woth[1] and Hans von Storch[1,2]

Zusammenfassung

Auf der Grundlage eines regionalen Szenarios, das unter Verwendung eines hydrodynamischen Modells der Nordsee erstellt wurde, wird ein lokales Szenario für zukünftige Höchstwasserstände des Pegels von Hamburg, St. Pauli entwickelt. Zwei unterschiedliche Emissionsszenarien, A2 und B2 (charakterisiert im IPCC Special Report on Emission Scenarios, SRES), die mit Hilfe unterschiedlicher globaler und regionaler Klimamodelle auf Europäisches Klima projiziert wurden, werden betrachtet. Bis zum Zeithorizont 2030 erscheint ein Anstieg der jährlichen Höchstwasserstände in St. Pauli von 20 cm möglich und plausibel. Bis 2085 erhöht sich der projizierte Anstieg auf im Mittel 64 cm. Bei diesen Berechnungen wird ein Anstieg des mittleren Meeresspiegels von 9 cm (2030), bzw. von 29 und 33 cm (2085) zugrunde gelegt. Die Ergebnisse sind mit Unsicherheiten behaftet, insbesondere für den Zeithorizont 2085. Die Unsicherheiten entstehen nicht nur durch die verwendeten Emissionsszenarien, sondern auch infolge mehrerer Regionalisierungsschritte, die die Prozesse ausgehend von den globalen Emissionsanstiegen bis hin zu den lokalen Auswirkungen spezifizieren. Durch die Verwendung unterschiedlicher Szenarien und Modelle summieren sich die Unsicherheiten bis auf ± 20 cm um 2030 und auf ± 50 cm um 2085. Diese Werte berücksichtigen auch Unsicherheiten in den Abschätzungen des mittleren Anstiegs des Meeresspiegels sowie in den Abschätzungen des Abschmelzens von Inlandeismassen in einem wärmeren Klima.

Summary

A local scenario for future high water levels for the tide gauge of Hamburg, St. Pauli is constructed on the basis of a regional scenario prepared with a hydrodynamical model of the North Sea. Two different emission scenarios, A2 and B2 (characterized in the IPCC Special Report on Emission Scenarios, SRES), which were projected onto European climate conditions by different global and regional climate models, are considered. An increase of the annual maximum water level in St. Pauli of about 20 cm appears possible and plausible for the time horizon of 2030. In 2085, the mean scenario for St. Pauli amounts to an increase of 64 cm. These calculations employ a mean sea level rise of 9 cm (2030) and of 29 and 33 cm (2085), respectively. These values are uncertain, in particular for the time horizon 2085, not only because of the employed emission scenarios but also because of a series of downscaling steps, which describe the sequence of processes from increased emissions to local changes. When using different scenarios and models, we find uncertainties of up to ± 20 cm in 2030 and up to ± 50 cm in 2085. These numbers also account for the uncertainty in mean sea level rise and the unknown response of land-ice to a warmer climate.

Keywords

North Sea, Climate change, High water levels

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<div align="center">C o n t e n t s</div>

1. I n t r o d u c t i o n

Since both the disastrous flood of 1962 and the well-managed 1976 flood, flood protection in the city of Hamburg and the area downstream between Hamburg and the Elbe mouth has been constantly adapted to changes in high water levels. Such changes may be due to river engineering measures (Freie und Hansestadt Hamburg, 2005, Arbeitsgemeinschaft für die Reinhaltung der Elbe, 1984, SIEFERT et al., 1988) or to changes in the global and regional climate (Freie und Hansestadt Hamburg, 2005).

Fig. 1 shows, among others, the temporal development of the depth of the Elbe waterway and of the mean high water (MHW, red curve) in the Port of Hamburg since 1950. Deepening measures have been carried out since approximately 1850 (Arbeitsgemeinschaft
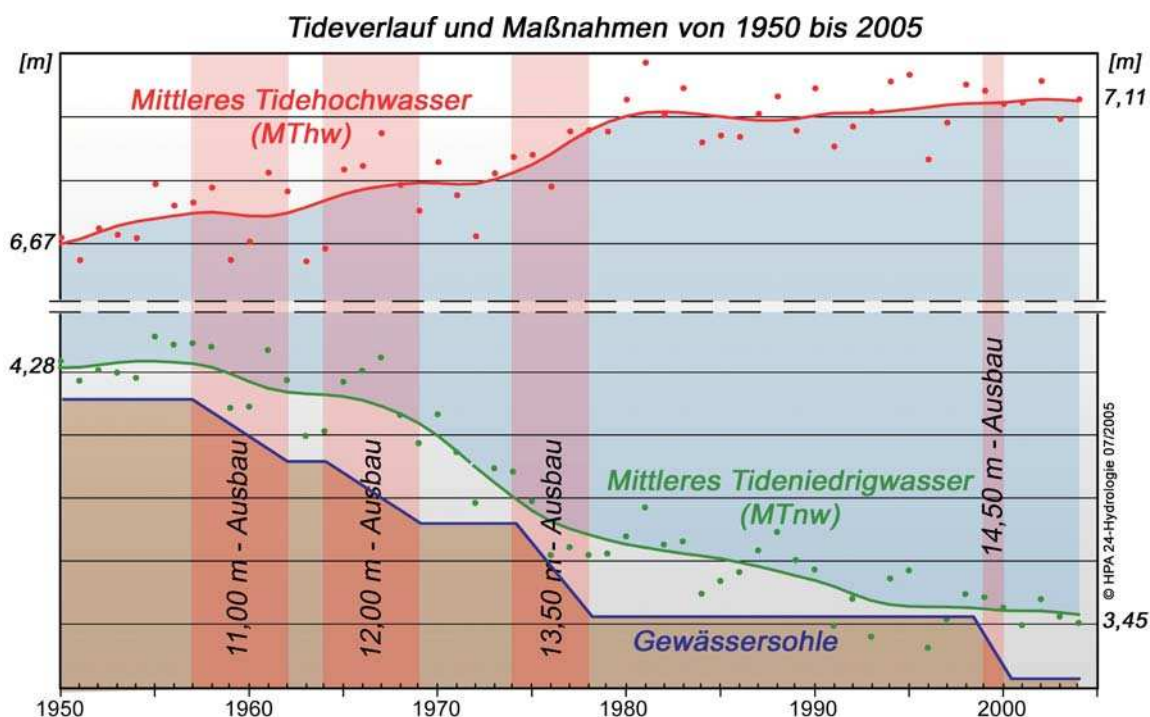
Fig. 1: Mean depth of the waterway, mean low water (MLW, green line) and mean high water (MHW, red line) at Hamburg St. Pauli 1950–2004. The depth of the waterway is given in chart datum (SKN) while MLW and MHW are indicated in m above the tide gage (Pegelnull) of 5 m. The MLW is not stable during the interval of interest (1980–1990) but the MHW is stable. The horizontal lines delineate 20 cm differences. Courtesy of Hamburg Port Authority, Hydrology

für die Reinhaltung der Elbe, 1984). A depth of 8 m was reached in 1910 and a depth of 10 m in 1950. In the late 1950s the waterway was deepened to 11 m. At the same time, the MHW in St. Pauli rose by 10 cm. A depth of 13.50 m was achieved in the mid 1970s; then the MHW had increased by about 40 cm since 1950. The tidal change displayed in the figure is due to coastal protection measures, barrages and modifications of the tributaries, and to the deepening of the waterway (GÖNNERT, pers. comm.). These measures also had an effect on the heights of extreme high waters. It is estimated that measures of coastal defense led to an increase of 45 cm and the deepening the shipping channel to an increase of 15 cm (HAAKE, 2004).

Since the 1980s the MHW has remained relatively constant. Another indication that the hydrodynamical regime of the Elbe estuary has not changed significantly since the 1980s is provided by Fig. 2 – the difference between extreme high waters in St. Pauli and in Cuxhaven has remained stationary since about 1980. That shows that the influence of human impact on the Elbe River on extreme high waters has stabilized since the 1980s.

In the present study, the influence of the possible future climate change on high water levels in Hamburg St. Pauli is investigated. This possible future climate change is described by "scenarios" of future climate change. These scenarios present possible, consistent, plausible but not necessarily probable futures (e.g., SCHWARTZ, 1991). They have been prepared by first envisaging emissions of climatically relevant substances into the atmosphere, and by then simulating the effect of these emissions on the climate system with numerical models.

Towards this end, results from "A2" and "B2"-scenarios (HOUGHTON et al., 2001) of extreme high waters at the North Sea coast between 2071 and 2100 are projected for Hamburg St. Pauli for the time horizons 2030 and 2085. These scenarios are part of a series of scenarios which have been considered in the EU project PRUDENCE (CHRISTENSEN et al., 2002). They are all derived from global climate change simulations with either the General Circulation Model HadAM3H of the Hadley Center (HUDSON and JONES, 2002; HULME
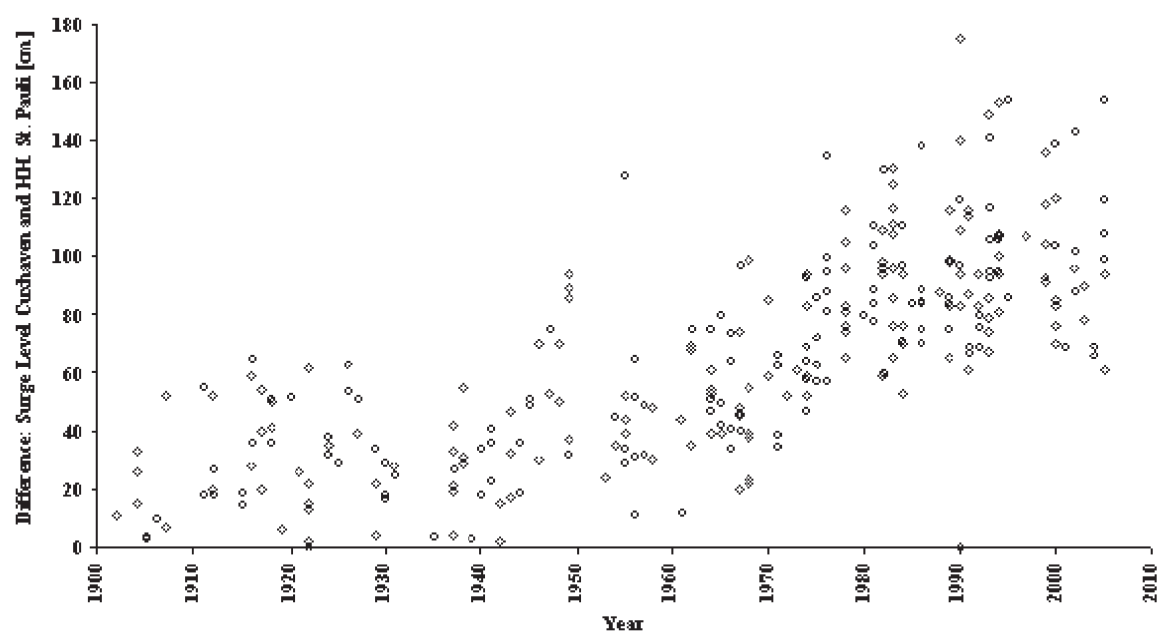

Fig. 2: Differences between extreme high waters in St. Pauli and Cuxhaven (in cm). Due to dredging of the waterway and coastal defense measures the difference has grown during the 1960s and 70s, but since about 1980 conditions are stationary. Courtesy of Hamburg Port Authority, Hydrology
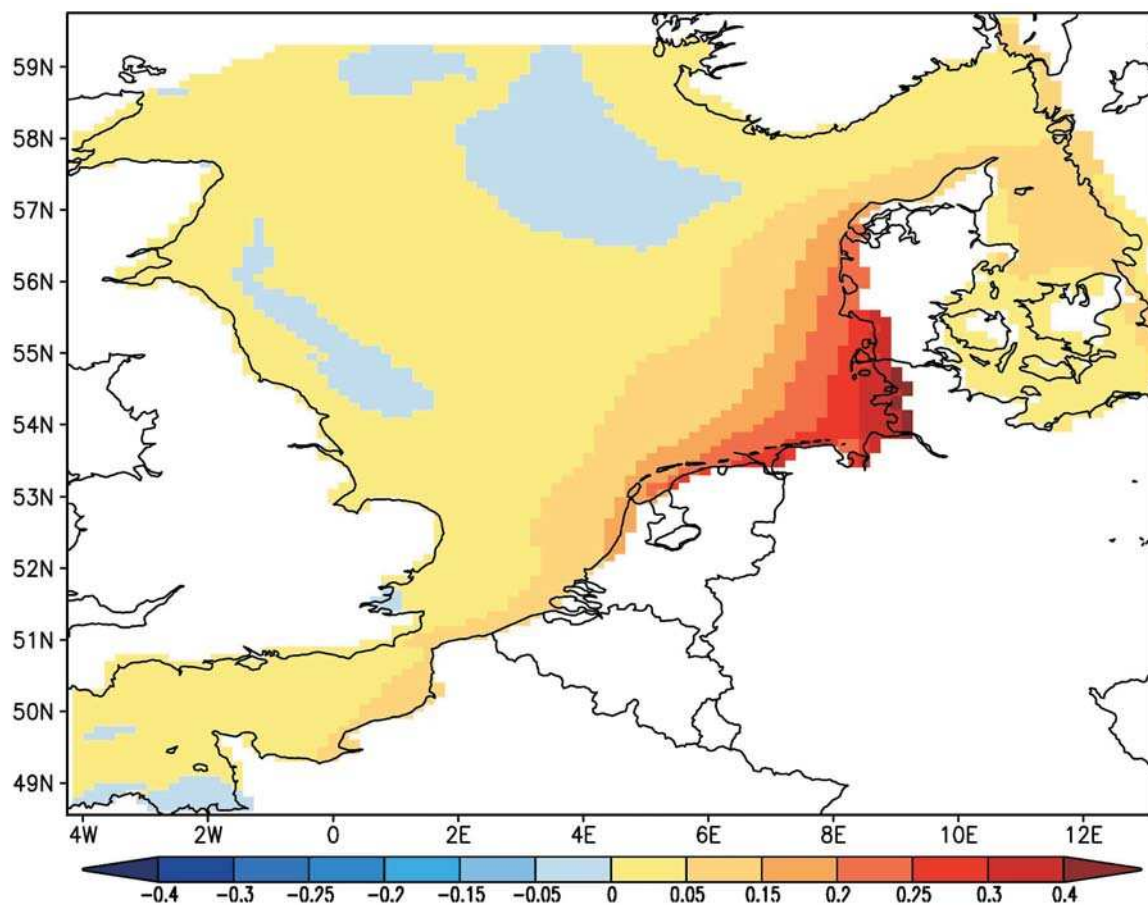
Fig. 3: Changes of the 30 winter mean of the annual maximum of high waters [m] in the A2-scenario projected for 2071–2100, as simulated by TRIMGEO in response to RCAO winds

et al., 2002) or the Max-Planck-Institute for Meteorology model ECHAM4/OPYC3 (ROECKNER et al., 1999). The two emission scenarios A2 and B2 envisage an increase of atmospheric greenhouse gas concentrations at the end of the 21st century which correspond to more than a tripling of pre-industrial levels (A2) and more than a doubling (B2). A2 is a relatively pessimistic scenario, whereas B2 expects considerably lower emissions (see also http://www.grida.no/climate/ipcc/emission).

A series of scenarios of high waters and storm surges[3] in the North Sea (WOTH et al., 2006) is constructed in two steps. First, the HadAM3H global atmospheric scenarios given on a 300 × 400 km² grid are dynamically downscaled[4] to a 50 km grid covering Northern Europe. Then, based on the downscaled wind and air pressure fields, the barotropic hydrodynamic model TRIMGEO (CASULLI and CATTANI, 1994; CASULLI and STELLING, 1998) simulates water levels and currents for the North Sea on a grid of about 10 × 10 km² (e.g.,

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[3] High water levels are understood as the actual highest water level within a tidal cycle. These do not necessarily coincide with the astronomical high tide. Storm surges are understood to describe the water level that is obtained by subtracting the tide. Both have been simulated with TRIMGEO (WOTH et al., 2006).

[4] Dynamic downscaling: regionalization with a regional climate model.

ASPELIEN and WEISSE, 2005) for decades of years. If future conditions are simulated then the expected rise in mean sea level is not considered. Instead, following KAUKER (1998) and LOWE et al. (2001) it can be assumed that surge levels are unaffected by the mean sea level, at least in the North Sea itself, and according to PLUESS (2004) this can be extended to overall high water levels[5]. Therefore, we consider changes in mean sea level height and high water levels as independent developments. This may not apply to the Elbe estuary, i.e., for the St. Pauli tide gauge, but is expected to provide an upper boundary for changes in the high water levels.

The dynamical downscaling is achieved using four different regional models (WOTH et al., 2006). However, the resulting scenarios of storm surges and high water levels depend only weakly on the regional climate model used. Fig. 3 shows one of these scenarios, which was obtained by running the TRIMGEO model with winds simulated with the regional climate model RCAO of the Rossby Center in Norrköping, Sweden. RCAO (DÖSCHER et al., 2002) is a coupled atmosphere-ocean model, which incorporates the Rossby Centers regional atmosphere model RCA (RUMMUKAINEN et al., 2001) and their ocean model RCO (MEIER et al., 2003).

The downscaling sequence described above leads to an estimate of the expected changes from 1961–90 to the time horizon 2071–2100 given the emission scenario A2 or B2. It is not possible to use the simulation for the 2071–2100 directly as a possible future for this time. This is because of the systematic errors in the simulations – when simulating the 1961–90 time horizon, the simulated high water levels are underestimated, which is mainly due to the global climate change simulation. Therefore it is common in climate research to consider only the change, assuming that the relatively small systematic errors cancel out.

An interesting detail is the similarity between A2 and B2 changes in storm surge levels (WOTH, 2005). The differences between the surge levels in the two scenarios are statistically not significant, and numerically small. Therefore, we do not distinguish between the two scenarios.

As a result of the downscaling sequence, scenarios of possible and plausible changes in the height of extreme high waters in grid boxes covering the North Sea are available. We relate changes in boxes in the mouth of the river Elbe to the water level in St. Pauli located some 140 km upstream of the Elbe estuary in Hamburg. One of the boxes on the outside margin, which later emerges as the best suited box, contains the tide gauge of Cuxhaven[6]. Case studies have shown that in a storm surge situation the water levels increase from the deeper North Sea to the German Bight and to the shoreline gauges (LASSEN et al., 2001), so that differences between the grid box values and the local values in Cuxhaven have to be expected. In fact, the simulated surge levels in the box compare well with those observed (WOTH et al., 2006), but the tidal signal is too strong in the simulations.

In the following we present a simple statistical method to derive estimates for the site St. Pauli in Hamburg for the foreseeable future of 2030, and for the more remote time of 2085 from the extreme high waters in the North Sea as simulated for grid boxes in the Elbe mouth.

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[5] Pluess found an increase of high water levels by less than 10 % of the assumed rise of the mean sea level (40 cm) – an order of magnitude that is negligible for our purposes.

[6] Cuxhaven is located at the Elbe mouth. The runoff is discharged east of the grid box in which Cuxhaven is situated.

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2. Methodology

We need to introduce two empirically based approximations:

- A link relating historic water levels at St. Pauli in the port of Hamburg with water levels at coastal grid boxes near the Elbe mouth simulated by the TRIMGEO model for the same time period. This approach has been suggested by LANGENBERG et al. (1999). See also LASSEN et al. (2001).

- An estimation of the situation at the midterm 2030 from the two available time horizons 1961–90 and 2071–2100. For the horizon 2085 no such approximation is needed, because this is simulated directly by the hydrodynamical model.

2.1 Linking high waters in the North Sea and in St. Pauli

A statistical function (Fig. 4) is derived which describes common variations of high water levels at the coastal grid box and at Hamburg St. Pauli. The function allows estimating the water level in Hamburg St. Pauli given the water level in the coastal box.

For this purpose, historical data on high water levels in Hamburg St. Pauli between 1980 and 1990 is used. This particular interval has been chosen because river deepening measures
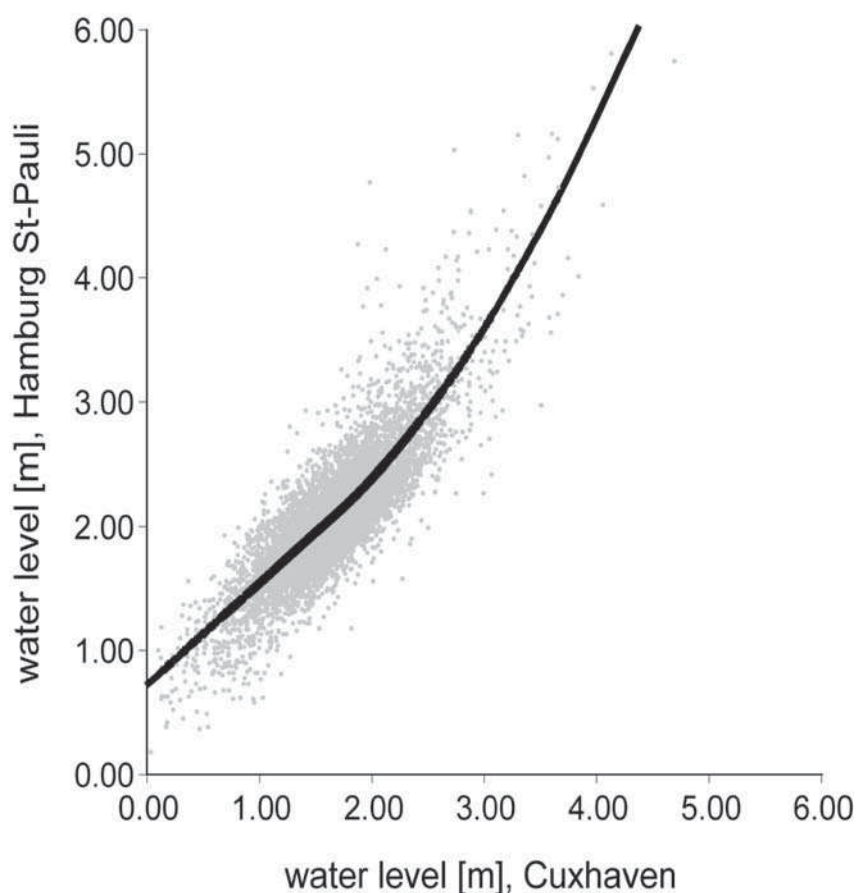

Fig. 4: Linear-quadratic fit for the observed high water levels at Hamburg St. Pauli (vertical axis) and those modeled for the coastal grid box 53.8°N / 8.8°E (Cuxhaven; horizontal axis). Units: m

which might influence water levels have not been carried out during this time (Fig. 1).[7] Also, future dredging of the shipping channel in the Elbe river is not expected to go along with further significant changes of the hydrodynamic regime (HEINZELMANN and HEYER, 2004). The St. Pauli-data are related to the high tide water levels in a grid box of a "hindcast" run (WOTH et al., 2006) during the same time period. This hindcast run was made with the TRIM-GEO model, forced with high-resolution "analyzed" wind and air pressure. "Analyzed" means a best guess of the synoptic situation derived from observations (FESER et al., 2001).
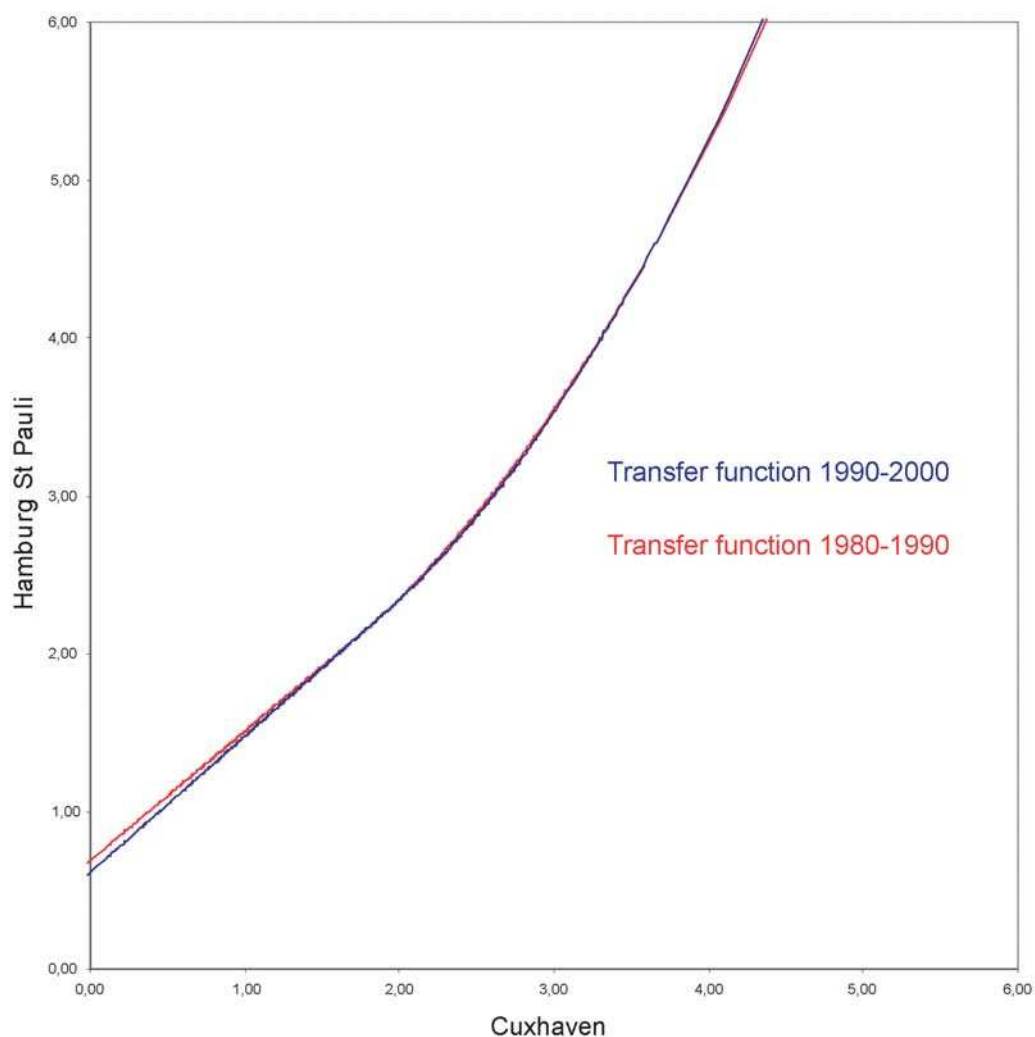
Fig. 5: The transfer functions describing the relationship between historic high water levels in Hamburg St. Pauli and high water levels in a model hindcast at Cuxhaven for the two time periods 1980–1990 and 1990–2000

When the exercise is repeated for the period 1990–2000 a virtually identical empirical model is found to be the best fit (compare Fig. 5). The maximum norm of the differences between the two functions is $\delta = 8$ cm.

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[7] Other measures such as the filling up of port basins did take place but did not (or only insignificantly) influence the mean high water (Fig. 1).

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High tide water levels for 3 different grid boxes located at the coast close to the Elbe mouth and for 2 grid boxes located on the 10 m bathymetry-line close to the Elbe mouth are considered.

A preliminary comparison of the two data sets on the basis of scatter diagrams suggested that a curve, which changes at a point x_k from a linear function to a quadratic function, would provide a good fit (Figure 4). Thus, $f(x)$ is a linear function $f_1(x)$ for $x < x_k$ and a quadratic function $f_2(x)$ for $x \geq x_k$:

$$f(x) = \begin{cases} f_1(x) = ax + b, \; x < x_k \\ f_2(x) = cx^2 + dx + e, \; x \geq x_k \end{cases} \quad \text{with } f_1(x_k) = f_2(x_k) \text{ and}$$

$$f_1'(x_k) = f_2'(x_k)$$

We want to describe the change in extreme high waters in terms of the multiyear mean of annual maxima. Therefore, we add the constraint $f_2(\mu_{H,s}) = \mu_{O,SP}$. Here $\mu_{O,SP} = 4.56$ m represents the multiyear annual maximum in observations O at St. Pauli recorded during the time period of interest (1980 and 1990) and $\mu_{H,s}$ the multiyear annual maximum at the grid box s close to the Elbe mouth of the hindcast H for the same time period.

We determine the coefficients a, b, c, d, e, λ_1, λ_2, λ_3 which minimize for the site s and given x_k the error

$$\varepsilon(s, x_k) = \sum_{i=1}^{k-1} (f_1(x_i) - y_i)^2 + \sum_{i=k}^{n} (f_2(x_i) - y_i)^2 + \lambda_1 \gamma_1 (f_1(x_k) - f_2(x_k))$$

$$+ \lambda_2 \gamma_2 (f_1'(x_k) - f_2'(x_k)) + \lambda_3 \gamma_3 (f_2(\mu_{H,s}) - \mu_{O,SP}).$$

The last three terms, featuring the Lagrangian multipliers $\lambda_1, \lambda_2, \lambda_3$, have been introduced to enforce the constraints mentioned above. The numbers γ_i are weights given to the constraints. In our case, we have $\gamma_1 = 500$, $\gamma_2 = 1$ and $\gamma_3 = 1$. Thus, maximum weight is given to the continuity of the fit[8]. Minimum weight is given to the equivalence of the multiyear annual maximum heights at St. Pauli and at the grid box at the mouth of the Elbe, and to the continuity of the derivative of the fit. We calculate the error $\varepsilon(s, x_k)$ for a range of possible x_k values and for a total of five coastal grid boxes.

The smallest value for $\varepsilon(s, x_k)$ is reached for the coastal grid box s centered at 53.8°N 8.8°E and for $x_k = 1.714$. This grid box contains Cuxhaven. The optimal constants are a = 0.8197, b = 0.6882, c = 0.2428, d = –0.0128, and e = 1.402. Figure 4 shows the linear/quadratic fit for this set of parameters and the scatter cloud of pairs of high tide values at St. Pauli and at the selected grid box containing Cuxhaven. The constraints of continuity of the function and of its derivative are satisfactorily fulfilled, also the condition is met that the simulated mean maximum $\mu_{H,s} = 3.63$ m at s is mapped on the observed mean maximum of $\mu_{O,SP} = 4.56$ m at St. Pauli.

For low high water levels, say 2 m, the observed water levels in St. Pauli are about 30 cm higher than the simulated water levels in Cuxhaven; for 3 m the difference is on average 50 cm, but for 4 m the difference is about 1.20 m – which is similar to the observed differences between the two tide gauges.

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[8] Continuity is lost if γ_1 is not significantly larger than γ_2 and γ_3.

The root mean square error of the fit, i.e.,

$$\sqrt{\frac{1}{k-1} \sum_{i=1}^{k-1} (f_1(x_i) - y_i)^2 + \frac{1}{n-k+1} \sum_{i=k}^{n} (f_2(x_i) - y_i)^2},$$

mounts to 37 cm for the selected optimal set of parameters. This reflects factors such as differences in the runoff contribution.

2.2 Temporal interpolation

As outlined in the introduction, the simulations provide at this time only a projection of the expected change from the "control" period 1961–90 to 2071–2100, given scenario A2 or B2 and the global HadAM3H simulation.

To establish a projection of the results onto the time horizon 2030, we assume a development of extreme high waters parallel to the increase of temperature in the global scenario (HOUGHTON et al., 2001). The expected increase in A2 from 1990 to 2030 is 0.7 K which is about 20 % of the increase from the interval 1961–1990 to the interval 2071–2100 (3.25 K). For the B2 scenario the temperature rise after 2030 is slower than in A2. The B2 temperature increase of 0.9 K from 1990 to 2030 is about 40 % of the increase from the interval 1961–1990 to the interval 2071–2100 (2.45 K). As already mentioned the changes in the simulated extreme high waters in A2 and B2 are not significantly different (WOTH, 2005) even though the temperature changes are markedly different. Therefore we assume that the mean maximum water levels at the location at the mouth of the Elbe in both the A2 and B2 scenarios are raised by $\varphi = 30$ % of the increase derived from the various TRIMGEO scenarios for the 2071–2100 time horizon.

For the mean sea level rise D, which we add to the meteorologically caused change, we use the projections provided by the IPCC (HOUGHTON et al., 2001) for 2030, and for 2085. These are 9 cm and 33 cm for A2, and 9 cm and 29 cm for B2, respectively. The uncertainty of these numbers is given by the IPCC to be about ± 5 cm and ± 20 cm, which accounts for different global climate models and emission scenarios. If the possible response of land-ice is factored in, the uncertainties rise to about ± 10 cm and ±30 cm (HOUGHTON et al., 2001). We assume that mean sea level rise and changing storm surge height are independent and may simply be added[9]. This assumption may not fully apply in the case of an estuary like the Elbe but is expected to provide upper bounds of plausible changes.

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[9] See section 1.

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3. R e s u l t s

We consider the multiyear mean of the annual maximum M, specifically for the hindcast simulation $H_{1961-90}$, the "control" simulation $C_{1961-90}$ and the A2/B2 Scenarios $S_{2071-2100}$. In the following we drop the indices. We begin with using the control and the A2-scenario-si-mulation generated with the RCAO/HadAM3H winds and air pressure (see above). The heights obtained with this model are somewhat in the middle of the range of changes obtained with the different regional climate models. This range is later used to estimate a range of uncertainty.

The RCAO/HadAM3H projected mean annual maximum high tide water level P at St. Pauli is estimated as

$$P = f \left(\mu_{H,s} + \varphi \left[M\left(S\right) - M\left(C\right) \right] \right) + D.$$

The difference of the mean annual maximum high tide at the Cuxhaven coastal grid box $s = (53.8°N\ 8.8°E)$ in the Scenario $S = A2$ and Control-Run C, M(S)-M(C), amounts to 0.21 m. The present mean annual maximum $\mu_{H,s}$ is 3.63 m. The expected global mean sea level rise in 2030 is D = 0.09 m. For the Cuxhaven grid box, the increase would be 0.09 m plus 30 % of 21 cm, i.e., about 0.15 cm. For the projected mean annual maximum high tide at St. Pauli in 2030 we have P = NN + 4.73 m, which represents an increase of 0.17 m. If the mean sea level did not simply add, the increase would be smaller, namely 0.08 m.

For the time horizon 2085 the expected increase in mean sea level is 0.33 m, so that the total increase in Cuxhaven would be 0.54 m. For St. Pauli, the mean annual maximum is expected to be P = NN + 5.25 m, which is 0.69 m higher than the present μ_{SP} = 4.56 m.

As pointed out in the introduction, more scenarios of extreme high waters have been produced for the Cuxhaven grid box (WOTH et al., 2006; WOTH, 2005) mostly for the A2 but also for the B2 IPCC scenario. These scenarios have been obtained with different re-gional and global models. The mean value and the range of the expected changes in extreme high waters for St. Pauli for 2030 and 2085 are depicted in Fig. 6. Detailed data is given in Table 1.

The storm related change of the mean maximum high waters at the Cuxhaven grid box for the end of the 21st century varies between 42 cm to 61 cm with a mean value of 50 cm across all models and scenarios. Using our formula above, we find a mean possible and plau-sible rise at St. Pauli of 18 cm for 2030 and 64 cm for 2085. The range of minimum and ma-ximum values is 13 cm to 23 cm in 2030 (about ± 5 cm) and 48 cm to 84 cm in 2085 (about ± 20 cm).

If we factor in the uncertainty of mean sea level rise, then these ranges widen to ± 10 cm in 2030 and to ± 40 cm in 2085 when only the model and scenario uncertainty is accounted for. If the unknown response of land-ice is added, the numbers increase to ± 20 cm and ± 50 cm, respectively.
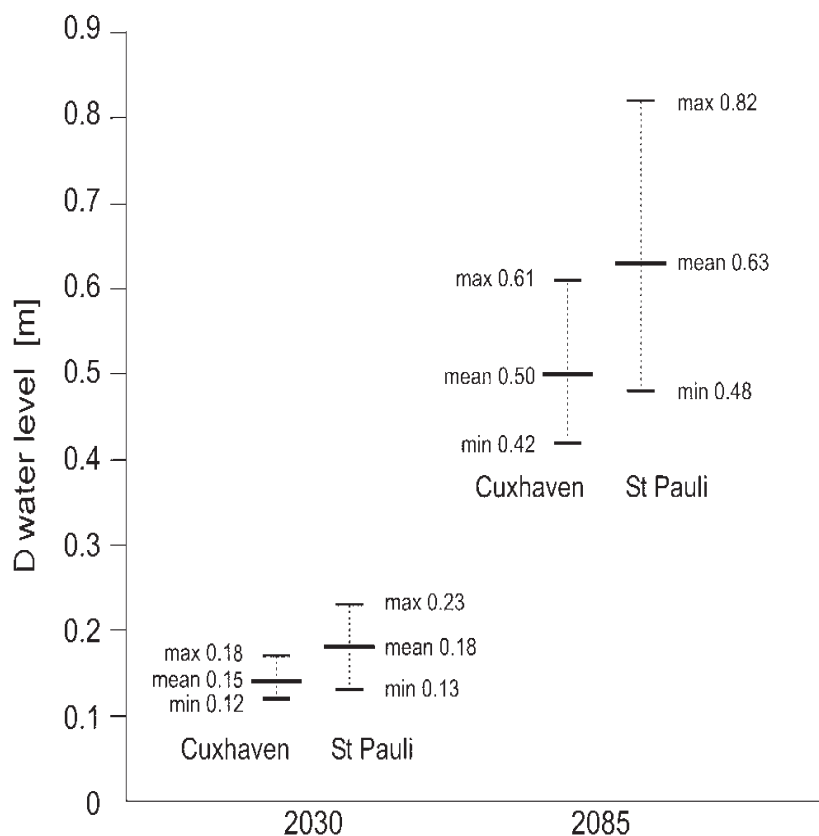
Fig. 6: Scenarios of changes in extreme high waters (incl. sea level rise) in Cuxhaven and St. Pauli, 2030 and 2085, based on TRIMGEO simulations forced with winds and air pressure from different regional models and emissions scenarios. Since the A2 and B2 scenarios do not differ significantly we indicate the mean value across all models and scenarios and the minimum maximum range

Table 1: Scenarios of changes in extreme high waters including mean sea level rise in Cuxhaven and in Hamburg St. Pauli in 2030 and 2085, based on simulations with TRIMGEO forced with winds and air pressure from the regional models HIRHAM, REMO, CLM, RCAO (forced respectively with the global model HadAM3H and ECHAM4/OPYC3), and the emissions scenarios A2 and B2.

	Model and Scenario	Cuxhaven	St. Pauli
2030	HIRHAM-E-A2	0.12	0.13
	REMO-E-A2	0.13	0.18
	CLM-E-A2	0.15	0.23
	RCAO-H-A2	0.13	0.2
	RCAO-H-B2	0.17	0.19
	RCAO-E-A2	0.16	0.18
	RCAO-E-B2	0.15	0.16
2085	HIRHAM-E-A2	0.42	0.48
	REMO-E-A2	0.51	0.65
	CLM-E-A2	0.61	0.82
	RCAO-H-A2	0.54	0.7
	RCAO-H-B2	0.47	0.63
	RCAO-E-A2	0.51	0.65
	RCAO-E-B2	0.43	0.55

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4. Discussion and caveats

We have presented a simple approach to estimate changes in extreme water levels at the tide gauge of Hamburg St. Pauli. This method relates scenarios for North Sea near-coastal conditions to the highly location-specific conditions far inside the Elbe estuary. This link takes the form of a transfer function, which maps coastal high water levels simulated in a hindcast with a hydrodynamical model, on observations taken at the tide gauge. This transfer function is valid only for the specific hydrodynamical model TRIMGEO, which has been employed in the hindcast and in the scenario simulations. The transfer function is also only valid for a a runoff situation and a morphodynamical configuration of the Elbe estuary which are close to the present ones.

The resulting values suffer from significant uncertainty, not only because of the employed emission scenarios but also because of a series of downscaling steps, which describe the cascade of processes linking increased emissions and local climate change impact.

In a further step, we have examined the projected increases in storm surge heights in a series of A2 and B2 scenarios. The A2 scenarios range from 9 cm to 28 cm and the B2 scenarios from 15 cm to 19 cm. Different combinations of global and regional climate models were employed. The uncertainty amounts to ± 20 cm in 2030 and to ± 50 cm in 2085.

Scenarios are not meant to be forecasts but storylines which permit decisions makers to assess which threats may develop in which time, and which countermeasures should be considered and possibly prepared (SCHWARTZ, 1991). The scenarios all point to extreme high waters that are higher than at present both in Cuxhaven and in Hamburg St. Pauli. Until 2030 the possible increases seem less dramatic and to be manageable within presently available tools and strategies. For the later time horizon 2085, however, the possible and plausible changes may require not only much more costly but possibly different adaptations measures.

Altogether these results show that Hamburg's safety level of NN + 7.30 m has been well chosen in view of present and possible future surge risks. The highest storm surge in Cuxhaven and Hamburg was in February, 1976 with NN + 6.45 m in Hamburg St. Pauli. Adding 0.20 m in 2030, the storm surge level would be about 6.65 m. This number is well below the safety level in Hamburg (NN + 7.30 m) even if the uncertainty of ±0.20 m is taken into account. Also for 2085, our estimate of 6.45 + 0.63 m = 7.08 is below that critical value, but the uncertainty at that time is rather large (± 0.5 m). However, because of the time lag until then for the foreseeable future it is sufficient to carefully monitor the future development and to implement no-regret measures to reduce the risk of the already today unabatedly dangerous storm surges in the Elbe estuary. Hopefully, the worst scenarios for 2085 can be avoided by efficient reductions of greenhouse gas emissions into the atmosphere.

5. Acknowledgements

6. References

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