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Storm-related sea level variations along the North Sea coast as simulated by a high-resolution model 1958–2002

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Abstract Storm-related sea level variations 1958–2002 along the North Sea coast from a high-resolution numerical hindcast are investigated and compared to the results of earlier studies. Considerable variations were found from year to year and over the entire period. The large-scale pattern of these variations is consistent with that derived from previous studies, while the magnitudes of the long-term trends differ. The latter is attributed to different analysis periods, improvements in the atmospheric forcing, and the enhanced spatial resolution of the numerical simulation. It is shown that the different analysis periods, in particular, represent an issue as the increase in storm-related sea levels was found to be weaker over the last few years that have not been included in earlier studies. These changes are consistent with observed changes of the storm climate over the North Sea. It is also shown that observed and hindcast trends may differ significantly. While the latter are in agreement with observed changes in the storm climate, it may be concluded that observed sea level changes along the North Sea coast comprise a considerable fraction that cannot be attributed to changes in the large-scale atmospheric circulation.

Keywords North Sea · Storm surge variability · Long-term trends · Storm surge hindcast · Tide-modeling

Introduction

Storm surges represent a particular threat for low-lying coastal areas. Along the North Sea coast, much of the hinterland (especially in the Netherlands, Denmark, and Germany) is below or only slightly above mean sea level and has to be protected from the effects of storm surges. For example, the west coast of Schleswig-Holstein in Germany comprises about 553 km of coastline, which are protected by 408 km of dikes (Ministerium fur ländliche Räume, Landesplanung, Landwirtschaft und Tourismus des Landes Schleswig-Holstein 2001).

Accordingly, in these countries there has always been a great interest in the possible extremes of the storm-related sea level variations (storm surges) and their long-term changes. Many studies have concentrated on the analysis of time series form tide gauges. For example, Woodworth and Blackman (2002) analyzed changes in extreme high waters in Liverpool since 1768. Considering the entire period, they found considerable interannual variability but no clear long-term trend. Bijl et al. (1999) considered sea level variations from a number of stations in the coastal zones of Northwest Europe over the past 100 years. Similar to the findings of Woodworth and Blackman (2002) they concluded that there is strong natural variability present in the data but no sign of a significant increase in storm-related water levels.

Without distinguishing between storm-related and non-storm-related sea level fluctuations, Jensen and Mudersbach (2004) analyzed long-term changes in mean high and low waters at 12 tide gauges along the German North Sea coast. Averaging over several combinations of the tide gauges, they found pronounced increases in the mean high water levels that have amplified since about 1955–1960 and smaller changes in the mean low water levels. They concluded that significant changes in the tidal regime were observed in the German North Sea.

While the analysis of tide gauge records may reveal the long-term variations observed at the site of the observations, there are many places where no measurements have been taken or where observational records are too short to allow for the assessment of extremes or long-term changes. In these cases, hindcasts performed with numerical models may represent an alternative that complements the analysis of observational records. Flather et al. (1998) performed

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one of the first 40-year (1955–1994) hindcast simulations for North Sea storm surges and compared extreme values derived from observations with those obtained from the model simulation. This way, they demonstrated that realistic estimations of storm surge extremes can be derived directly from model simulations for areas (e.g., offshore) or situations (e.g., climate change) where no observational data exist, provided that the atmospheric forcing yields sufficient quality. Wakelin et al. (2003) performed a tide-surge hindcast from1955–2000 for the Northwest European Shelf and investigated the relationship of sea level variations and the North Atlantic Oscillation (NAO). They concluded that the NAO sensitivity of sea level is strongest in the Southern North Sea. Langenberg et al. (1999) analyzed trends in storm-related sea level variations along the North Sea coast obtained from both, a hindcast study 1955–1993 and a statistical analysis of observational data. Although, caused by the resolution of the hindcast study, the model failed to reproduce the most severe water levels at coastal locations, they found that the results of both analyses are in a qualitative agreement. Langenberg et al. (1999) in particular concluded that during the hindcast period, winter means of high water levels along the North Sea coast have increased in the order of 1–2 mm yr^{-1} on account of only the atmospheric forcing, while considering much longer periods, observed storm-related fluctuations show no clear trend.

While the study of Langenberg et al. (1999) provided one of the first comprehensive analyses of observed and model-based changes of the storm surge climate in the North Sea, it suffered from a decisive drawback in the homogeneity of the atmospheric forcing and the relative coarse spatial resolution near the coasts, which prevented the model from reasonably simulating the highest water levels. In the meantime, an improved storm surge hindcast has been produced in which these drawbacks have been reduced and which additionally covers a somewhat longer period compared to that of Langenberg et al. (1999). It thus appears timely to provide an update of the analyses of Langenberg et al. (1999) and to investigate the long-term storm surge variability in comparison to that earlier hindcast. The latter is the purpose of this study. In Section 2, we briefly describe our storm surge model and the hindcast that was performed. In addition, some validation of the hindcast is provided, and the differences between Langenberg's et al. (1999) and our hindcast are elaborated. In Section 3, our results are described. We particularly analyze long-term changes in winter mean high waters and storm surges along the North Sea coast and compare our findings to earlier results. We eventually elaborate on differences between observed and modeled long-term trends. In Section 4, our results are summarized and discussed.

The North Sea storm surge hindcast 1958–2002

Model and model set-up

Since summer 1998, the Federal Waterways Research Institute, Coastal Division (BAW-AK) has been setting up a hydrodynamical model to simulate the tidal and storm surge dynamics in the North Sea and particularly in the German Bight. This model was developed for the simulation of tide and tidal currents to provide the spacious estuary models of the BAW-AK with respectively needed boundary conditions. In addition, this model was approved for investigations about the tidal characteristic values, the residual currents, and the salinity/sediment transport in the entire coastal area of the German Bight. For this reason and under long-term modeling aspects, the whole North Sea has to be coupled because of the interaction between coast/estuary and the open sea. The model set-up and the generation of the steering forces at the open boundaries were made in cooperation with the Bundesamt für Seeschifffahrt und Hydrographie (BSH). The boundary conditions, time series of the water level, were calculated by reanalyzing the tidal harmonic constants for each boundary location. This procedure includes the variation of the tidal amplitudes due to the variation of the nodal tidal cycle. For hindcast simulations during a period that is much longer than the nodal cycle of 18.6 years, these effects had to be included.

The complex coastline, islands, and bathymetric structures in the coastal zone and the mouths of the estuaries coupled with the whole North Sea region demand for the use of an unstructured mesh (triangles). The calculation mesh consists of approximately 50,000 triangular elements and 27,000 nodes the distance of which varies between about 75 m near the coast and in the estuaries and 27 km in open sea regions. The depth distribution and dimension of the hydrodynamic model domain are shown in Fig. 1. For details see Plüβ (2004).

The calculations were made using the TELEMAC2D-code from Electricité de France (EDF) (Hervouet and Haren 1996). Over the whole domain, this model applies time and space variable wind fields as an external force at the interface between water and air. Several storm surge

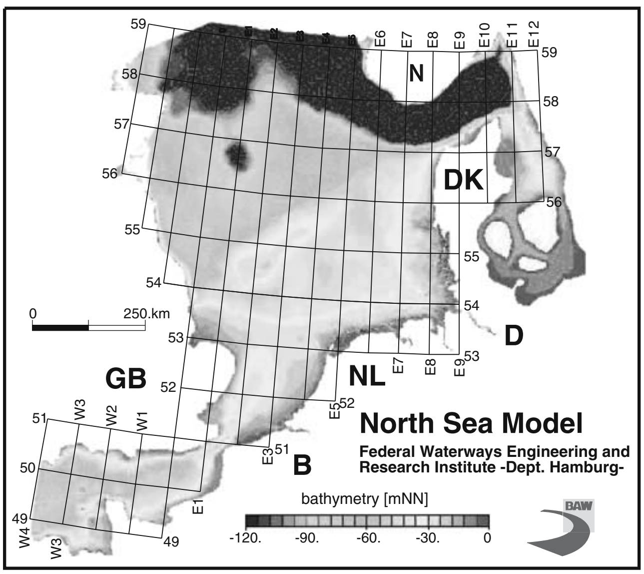

Fig. 1 Model domain and bathymetry used for the simulation

calculations for German estuaries were performed successfully in the past (e.g., Plüβ et al. 2001).

Atmospheric forcing and lateral boundary conditions

Earlier hindcast studies were often hampered by inhomogeneities in the atmospheric forcing fields (e.g., The WASA-Group 1998; Langenberg et al. 1999; Günther et al. 1998). Recently so-called weather reanalyses (e.g., Kalnay et al. 1996; Kistler et al. 2001; Gibson et al. 1996) have become available. These reanalyses were performed with state-of-the-art numerical weather models and data assimilation systems so that some of the inhomogeneities present in earlier products (such as those caused by changes in the analysis technique or data assimilation) have been removed. Furthermore, observational data, which were not available in real time, were additionally considered. While the reanalyses products still may contain inhomogeneities such as those caused by increasing data availability from formerly data sparse regions, it may be expected that they are much more homogeneous than earlier products.

Despite the improved homogeneity of the reanalyses, owing to their global coverage, their spatial and temporal resolution (typically in the order of about 200 km and 6 h) remains too coarse to directly drive a North Sea storm surge model with. In our study, we therefore use atmospheric wind and pressure fields that were obtained from a dynamical downscaling (Feser et al. 2001) of the National Centers for Environmental Prediction (NCEP) reanalysis (Kistler et al. 2001). In this downscaling, the regional atmosphere model SN-REMO (Meinke et al. 2004), covering Northern Europe and adjacent seas, was driven by the NCEP reanalysis data for the period 1958–2002. From this simulation, wind and pressure fields were available every hour at a spatial resolution of about 50 km and have been used to drive our storm surge model. Information on the quality of these forcing fields can be found for instance in Weisse et al. (2005), García-Sotillo et al. (2005), García-Sotillo (2003), or Weisse and Feser (2003).

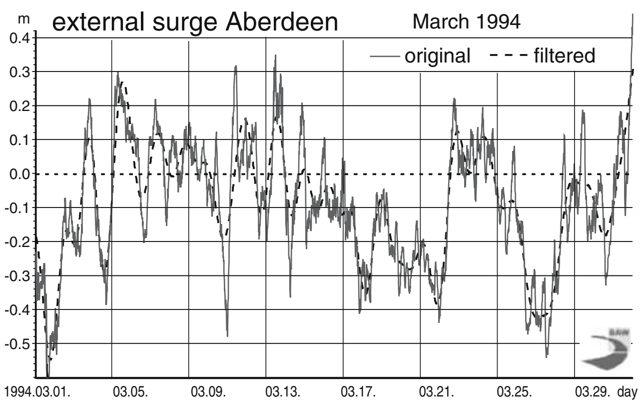

Fig. 2 Calculated external surge at gauge Aberdeen in March 1962 and the filtered time series to avoid artificial peaks due to a phase shift between reanalysis out of tidal harmonic constants and measurements

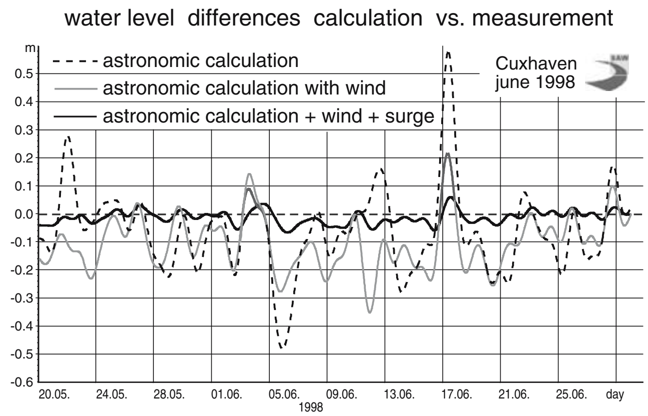

Fig. 3 Water level differences at gauge Cuxhaven between measurements and several model calculations taking tide-only (*dashed*), tide and wind (*light gray*), and tide, wind, and external surge (*black*) into account

The prediction of the steering forces at the lateral boundaries using the harmonic tide analysis of the tidal constants lack of longer periodic/aperiodic water level changes. These effects are known as external surges. The subtraction between the water level, reanalyzed out of tidal harmonic constants and measurements, generates the surge water level. An example is given in Fig. 2 for the gauge Aberdeen near the northern open boundary of the North Sea. For time-periods of several days, the mean aperiodic water level varies for decimeters. Some peaks are generated due to a time shift between the measurements and the reanalysed time series out of tidal harmonic constants. For further use, these artificial bumps were filtered out of the time series.

To enhance the model results, these filtered surge levels at Aberdeen were included in the steering forces of the model. With a time shift of about 1/2 h between the gauge Aberdeen and the northern boundary (Wick-Stavanger), these external surges were added to the astronomic time series homogeneously along the open boundary. At the gauge Cuxhaven, the differences between measurements and several calculations show the advantage of this procedure (Fig. 3). In the first case, the steering forces are generated only out of astronomic constants. In the second step, the wind fields have been included, and finally in the third experiment the external surge from Aberdeen was added to the boundary values at the northern open boundary. The latter approach clearly yields the smallest differences between observations and model results. As data from Aberdeen have been available for the entire 1958–2002 period apart from some minor gaps, they have therefore been assimilated into our simulation.

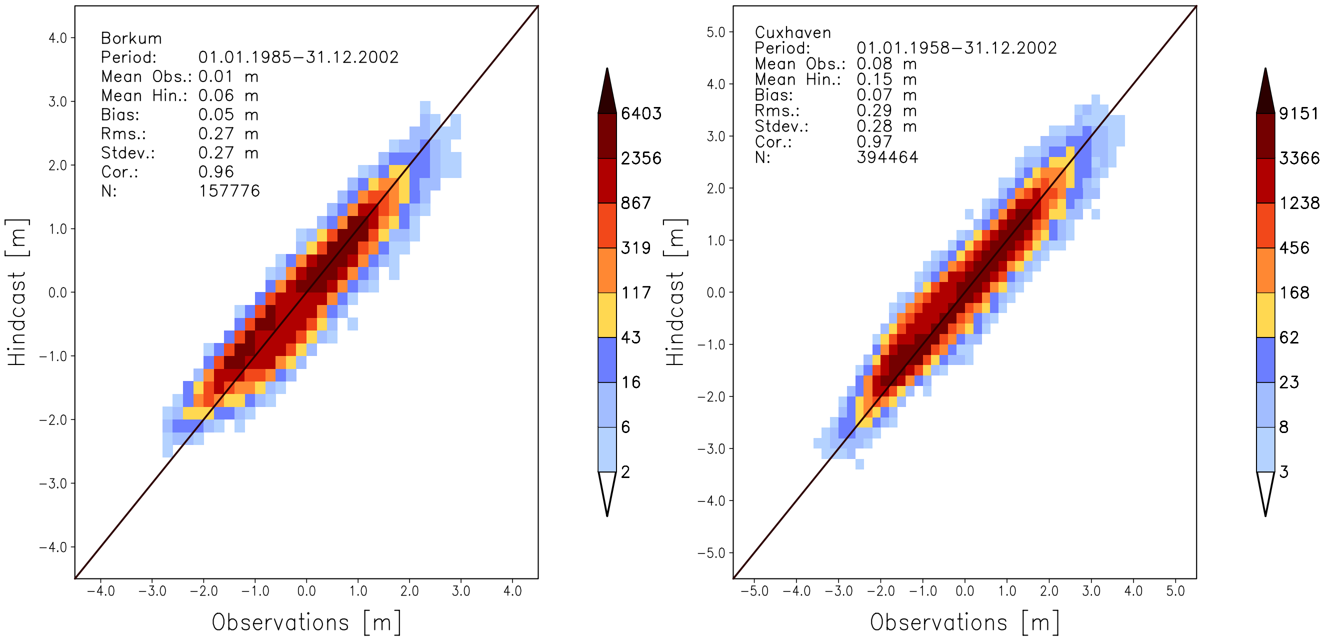

Fig. 4 Scatterplot between observed (*x-axis*) and hindcast (*y-axis*) hourly water levels at Borkum (*left*) and Cuxhaven (*right*). *Colors* indicate the number of cases in each 0.2 m×0.2 m box. In addition, the following statistics are presented (*from top*): analysis period, observation mean, hindcast mean, bias and root-mean-square error between observations and hindcast, standard deviation of the differences between hindcast and observations, correlation, and number of observed/hindcast data values that have been used in the analysis

Validation

Figure 4 shows a comparison between observed and hindcast water levels[1] for Borkum and Cuxhaven. For both stations, the comparison was made between hourly data. Because of the limited data available, the comparison for Borkum is restricted to the period 1985–2002, while for Cuxhaven the entire hindcast period 1958–2002 is considered. A good agreement between observed and hindcast water levels is obtained at both locations in general. There is a tendency to overestimate the lowest water levels at both stations while no such tendency can be inferred for the highest water levels. In particular for high waters, the hindcast appears to be calibrated, i.e., there is no systematic bias between observations and model values, and the probability of the hindcast to over- or underestimate observed water levels appears to be similar. Long-term root-mean-square-errors are smaller than 30 cm and the correlation between observed and hindcast hourly water levels is above 0.95 for both stations.

Figure 5 shows a similar plot for the storm surge component of the water level fluctuations. For Cuxhaven, there is again a small tendency to overestimate the lowest surges. The largest surges appear to be reasonably simulated at both stations. Root-mean-square errors between observed and hindcast storm surges are in the order of about 15 cm and the correlations are 0.92 for both stations. A rather good agreement between observed and modeled values can again be inferred in general.

The model also reasonably simulates the observed interannual variations. This is demonstrated by a comparison between observed and hindcast annual winter mean and winter 90-percentile[2] high waters (Fig. 6). While the year to year fluctuations show a reasonable agreement, there appears to be a difference between the observed and the hindcast long-term trends in winter mean and 90-percentile high waters. This difference is elaborated later in detail in Section 3.3.

The storm surges in February 1962 are surveyed in detail where two storm periods around 13 and 17 February 1962 generated relatively extreme top surge water levels in the German Bight to demonstrate the calculation accuracy of the water levels during periods of high storm surges. It was found by comparing observed and hindcast water levels at the gauge Helgoland that the hindcast run corresponds to the observations in good agreement even for the most severe events (Fig. 7).

In summary, we conclude that the model hindcast reasonably simulates the observed coastal sea level variations, both on short and long (year-to-year) time scales.

[1] Throughout the paper, water levels are referenced relative to the German vertical geodetic datum (NN).

[2] The value that is exceeded by 10% of the data only

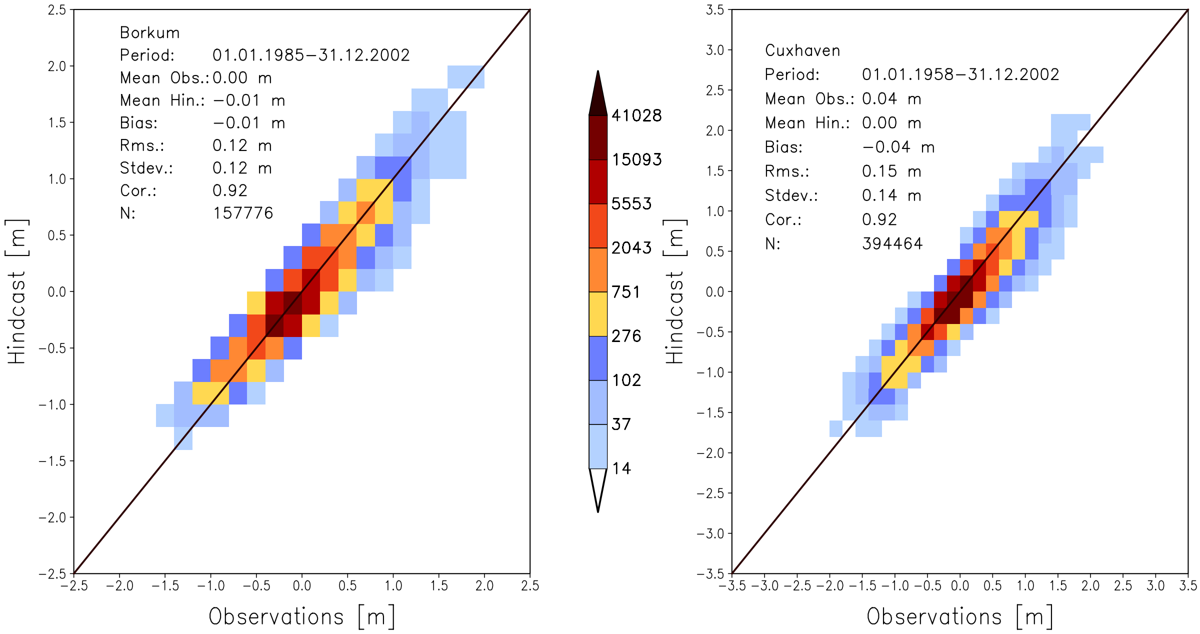

Fig. 5 Scatterplot between observed (*x-axis*) and hindcast (*y-axis*) hourly storm surge levels at Borkum (*left*) and Cuxhaven (*right*). Storm surges were computed by subtracting the result of a harmonic analysis that takes the 30 major tidal constituents into account. *Colors* indicate the number of cases in each 0.2 m×0.2 m box. In addition, the following statistics are presented (*from top*): analysis period, observation mean, hindcast mean, bias and root-mean-square error between observations and hindcast, standard deviation of the differences between hindcast and observations, correlation, and number of observed/hindcast data values that have been used in the analysis

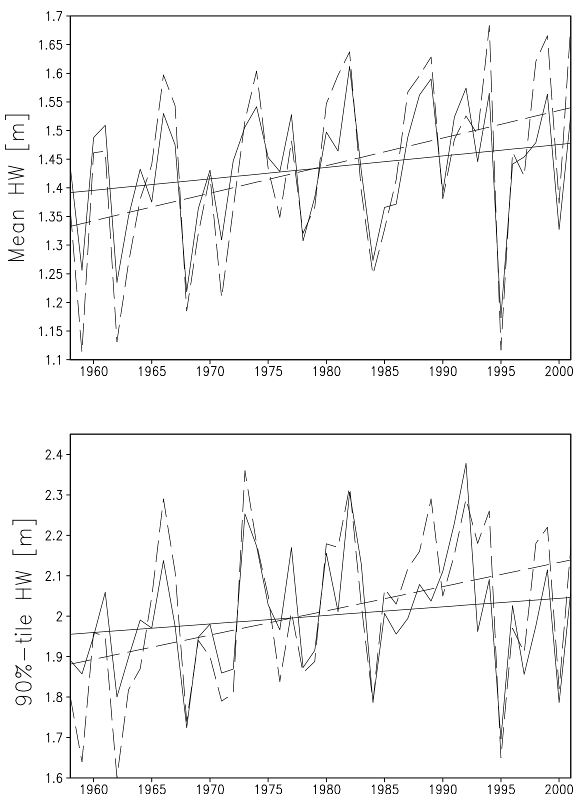

Fig. 6 Time series and linear trends of observed (*dashed*) and hindcast (*solid*), winter (November–March) mean (*top*), and winter 90-percentile high water (*bottom*) at Cuxhaven in meters

Major differences to earlier hindcast studies for the North Sea

The main motivation of the present study was to provide an update of the earlier hindcast of Langenberg et al. (1999) (hereafter referred to as LPSS) as, in the meantime, improved models, forcing fields, and increased computa-

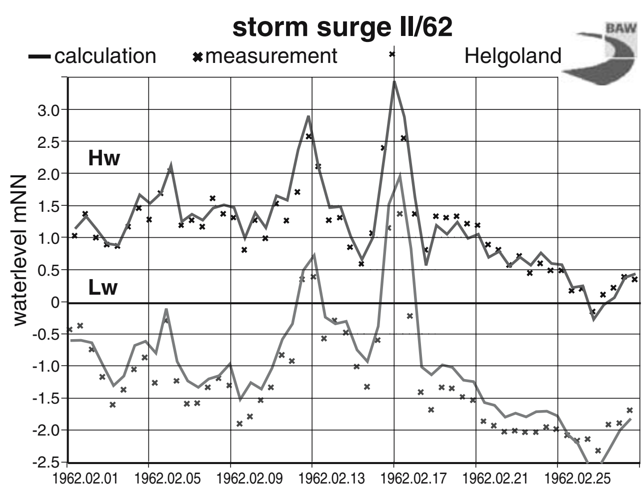

Fig. 7 Observed (*crosses*), hindcast high (*upper curve*), and low (*lower curve*) water levels at gauge Helgoland for February 1962

tional power have become available. We briefly summarize in this section the main differences between the LPSS hindcast and our simulation.

In LPSS, surface pressure fields from the weather analysis of the Norwegian Meteorological Institute (DNMI) were used to calculate wind stresses following an approach by Luthardt and Hasse (1981) to drive the ocean model with. The pressure fields were available every 12 h for the period 1955–1993 at a spatial resolution of about 100 km. According to LPSS, their atmospheric data suffered from a decisive drawback because after 1982, the method of analysis changed from manual to numerical and simultaneously the area covered by the analysis was altered. In our study, we used hourly wind fields for the period 1958–2002 obtained from a high-resolution atmospheric hindcast (Feser et al. 2001) at about 50-km resolution that was driven by the NCEP weather reanalysis (Kistler et al. 2001). The period covered by our hindcast is somewhat longer: 45 compared to 39 years.

LPSS used a dynamical vertically integrated (barotropic) storm surge model set-up for the Northwest European Shelf and the North Sea with a grid size of approximately 10 km. In our case, we used the barotropic TELEMAC-2D model set-up for the North Sea with a variable resolution of the grid spacing (see Section 2.1).

While LPSS extended their model domain covering the Northwest European Shelf to account for the effect of external surges, we chose a somewhat smaller domain and assimilated observed water levels from Aberdeen to take external surges into account. Thermal expansion, which is not accounted for in the simulation of LPSS, is allowed to some extent in our experiment through the assimilation of Aberdeen data.

As near-shore water levels are far from uniform the simulation of LPSS required, owing to its relatively coarse spatial resolution, an empirical correction function to reasonably represent observed coastal sea level variations. With the recent advances in available computing power and modeling technique (unstructured meshes in coastal regions), we were able to increase the spatial resolution considerably in our hindcast. Consequently, no such correction is needed (Figs. 4, 5, 6).

Results

Long-term trends in winter water levels

Following the analyses of LPSS, we analysed long-term changes in winter (November–March) mean and 90-percentile high waters along a section following the North Sea coastline (Figs. 8 and 9). It can be inferred that the changes in winter mean high water are close to zero for much of the UK and The Netherlands coast. An increase in winter mean high waters is obtained for the German and the Danish coasts. However, this increase was found to be statistically different from zero only for a small part mainly along the North Frisian coast. The increase here is in the order of about 2 mm year^{-1}. A similar pattern was obtained for the change in the winter 90-percentile high waters with a

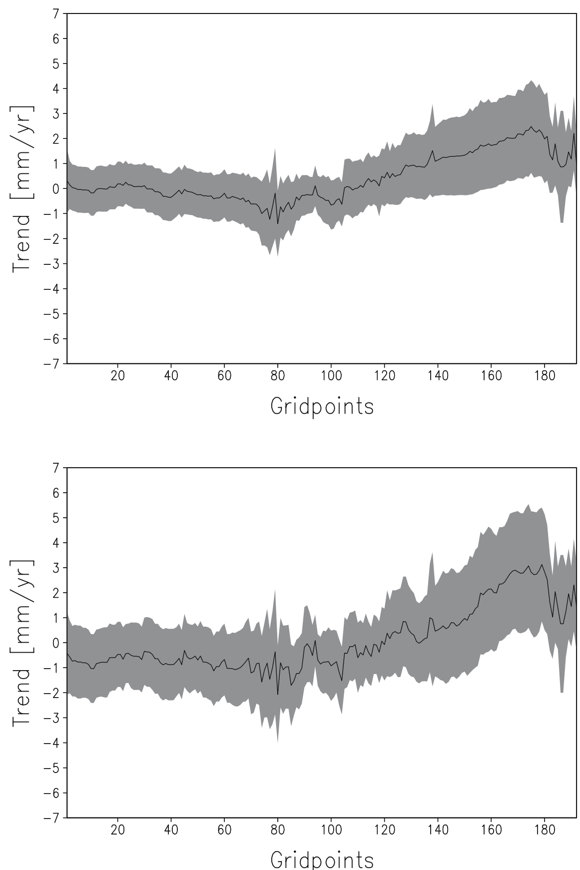

Fig. 8 Linear trend for 1958–2002 in mm year^{-1} (*solid*) of winter (November–March) mean (*upper*), and 90-percentile (*lower*) high water. The 95% confidence interval based on a local *t*-test is indicated in *grey*. The *x-axis* represents grid points along a section, the locations of which are given in Fig. 9

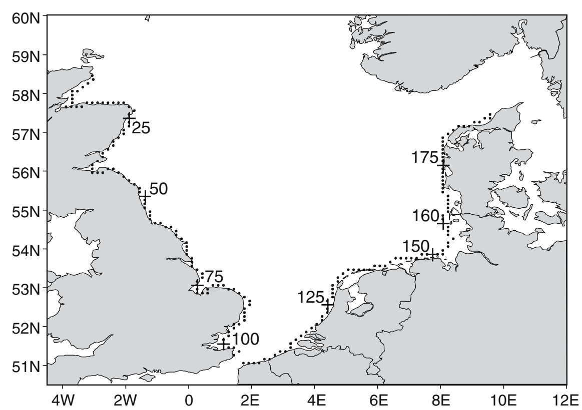

Fig. 9 Section used for analysis of linear trends. The section starts in the western North Sea following the east coast of Great Britain, The Netherlands, Germany, and finally Denmark. Grid points were selected such that the section basically follows the 10 m depth contour line. Every *25th* grid point is numbered and marked with a *cross*. In addition, grid point *160*, for which time series is shown, is also marked

maximum increase of about 3 mm year^{-1}. The spatial pattern is largely consistent with that described by LPSS although the amplitudes of the trends differ.

We recomputed the trends in winter high waters for the period 1958–1993 to elaborate whether the differences may be caused by the different analysis periods. This period is as close as possible to that of LPSS as we have no data available before 1958. In general, we found the same spatial signal with small and insignificant changes along the UK and parts of The Netherlands coastline and increases along the German and Danish coasts. However, the largest increases found were about 3 and 6 mm year^{-1} for the winter mean and 90-percentile high water levels respectively. Compared to our earlier figure and that of LPSS, two conclusions can be drawn: First, the trends for the period 1958–2002 appear to be smaller than those for 1958–1993, indicating a decrease in winter high waters in recent years. This conclusion is confirmed by a visual inspection of the November–March 90-percentile high water level time series at grid point 160 located in the German Bight (Fig. 10). Second, although the spatial pattern of the trends is similar to that of LPSS, the absolute numbers deviate considerably. The latter may have several reasons: The data for 1955–1957 that were not available for our analysis, differences in the meteorological forcing, or differences in the magnitude of sea level variability caused by the different resolution of the models may have had an influence on the estimated trends.

We also analysed trends 1958–2002 in the summer (April–October) mean and 90-percentile high waters (not shown). Here the pattern was found to be rather uniform near all coasts with a small decrease in the order of 1–2 mm year^{-1}. For most of the grid points, this change was found to be significantly different from zero, although visual inspection of the time series reveals considerable variability on interannual and decadal time scales (not shown).

To investigate whether the winter mean and winter 90-pecentile high waters reasonably reflect the metrologically driven sea level fluctuations, we performed a harmonic analysis of the hindcast water levels along the section, taking into account the 30 most important tidal constituents and removed the tidal signal from our data. For the remaining meteorological residual (surge), the trend analysis was repeated for the November–March mean and 90-percentile. No significant difference was found compared to the analysis of winter mean and 90-percentile high waters, indicating that the latter may be considered as a reasonably proxy for the storm induced sea level fluctuations.

The background against which the changes have to be considered is illustrated in Fig. 11. It can be inferred that surges are most pronounced in the German Bight and are generally smaller along the UK coastline. Noticeable year to year variability, in particular along the Frisian coast, can also be deduced.

Coastal sea levels

So far all analyses have been performed for a section following the 10 m depth contour line along the North Sea coast. As our validation revealed no tendency to underestimate coastal sea level fluctuations, we also analyzed long-term changes for a number of tide gauges along the German coastline (Fig. 12). For the period of 1958–1993, a significant increase in both winter (November–March) mean and 90-percentile surge levels can be inferred for all analyzed stations. Trends are generally somewhat larger along the North Frisian coast and smaller along the East Frisian coastline. The figure changes when the entire hindcast period from 1958 to 2002 is considered (Fig. 12). The trends are considerably smaller for all stations and are statistically different from zero only for part of the stations situated mostly in the eastern part of the analysed domain. This indicates that considerable low frequency variability is present in the data.

Comparing the trends with those obtained along the 10 m depth contour line reveals the same large-scale structure. Increases are smaller in the western part and largest around the Elbe estuary and the North Frisian coast.

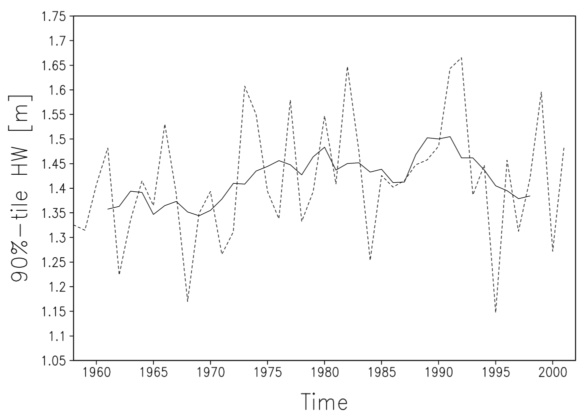

Fig. 10 Time series (*dashed*) and the 7-year running mean (*solid*) of annual November–March 90-percentile high waters in meters at grid point 160. For the exact location of the grid point, see Fig. 9

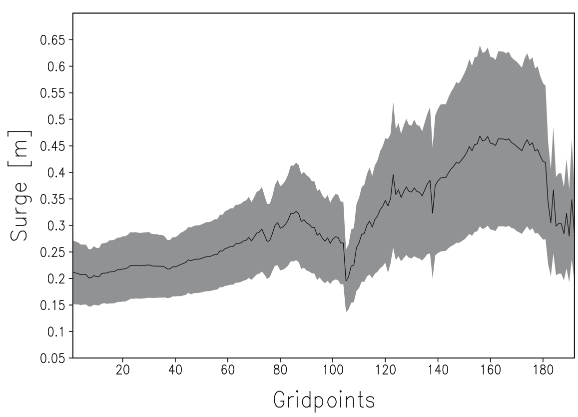

Fig. 11 Long-term (1958–2002) winter (November–March) mean 90-percentile (*solid*) surge in meters. The *grey shaded area* indicates ±1 standard deviation of annual winter 90 percentiles. The *x-axis* represents grid points along a section, the locations of which are given in Fig. 9

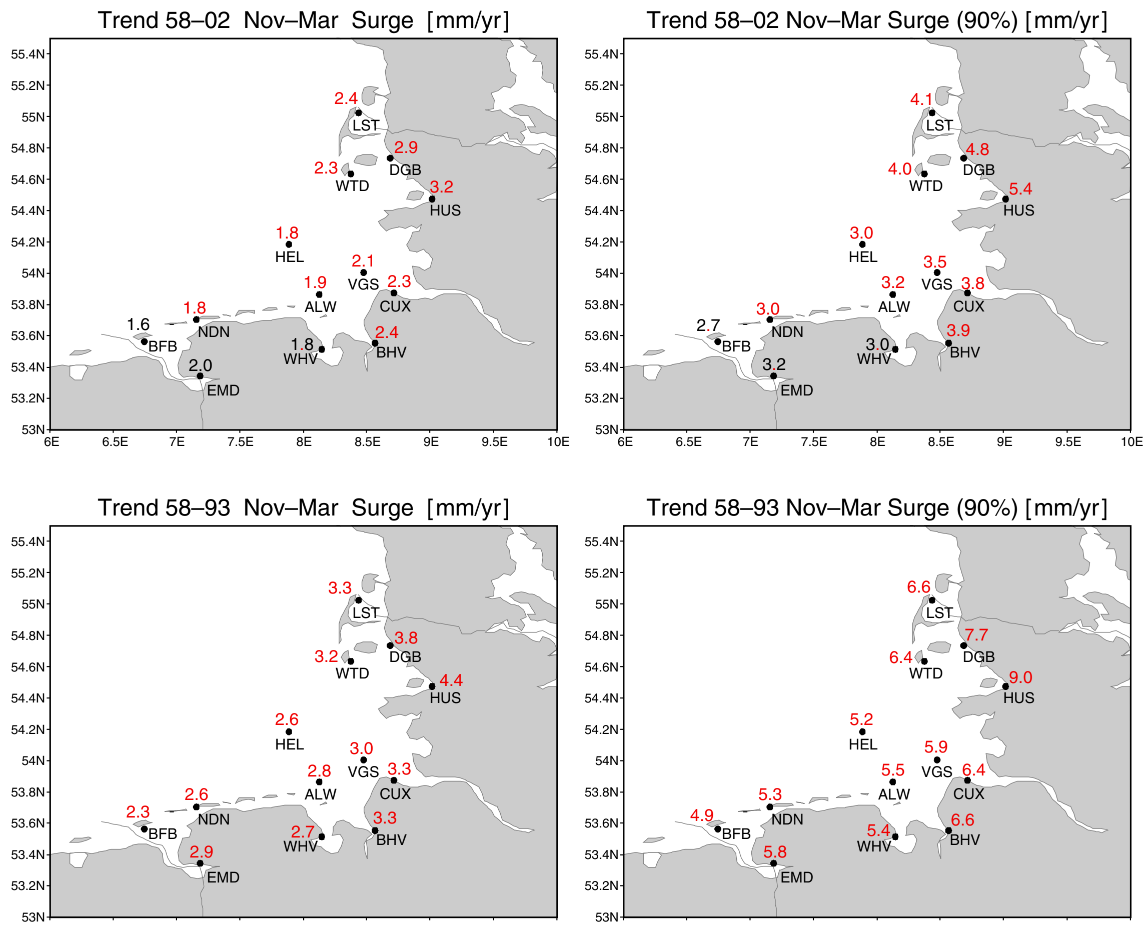

Fig. 12 Linear trend 1958–2002 (*upper*) and 1958–1993 (*lower*) of winter (Nov–Mar) mean (*left*) and 90-percentile (*right*) storm surge in mm yr^{-1} for a number of tide gauges along the German coast. Numbers in red indicate that the trend is statistically different from zero at the 95% confidence limit. *BFB* Borkum Fischerbalje, *EMD* Emden, *NDN* Norderney, *WHV* Wilhelmshaven, *BHV* Bremerhaven, *ALW* Alte Weser, *HEL* Helgoland, *VGS* Grosser Vogelsand, *CUX* Cuxhaven, *HUS* Husum, *WTD* Wittdün, *DGB* Dagebüll, *LST* List

Compared to the increase along the 10 m depth contour line, coastal sea level variations and trends, however, are considerably stronger.

Differences in observed and hindcast trends at Cuxhaven

The inspection of Fig. 6 indicates that although there is a reasonable agreement between observed and hindcast year-to-year fluctuations of winter mean and 90-percentile high waters at Cuxhaven, differences in the long-term trends may exist. Hindcast values particularly appear to be systematically above/below observed values at the beginning/end of the analysis period. To test whether there are significant differences in the 1958–2002 trends, we computed the differences between hindcast and observed winter mean and 90-percentile high waters and tested these differences for the presence of a linear trend. The result of this exercise is shown in Fig. 13. Both time series show clear downward trends that are significantly different from zero at the 95% confidence limit, indicating that hindcast and observed trends differ significantly.

This result is not surprising. The hindcast trends only comprise that part of the observed changes that are caused by long-term changes in the atmospheric conditions. Changes in bathymetry, either by construction work or natural processes, are not taken into account. Our result therefore suggests that observed sea level variability cannot

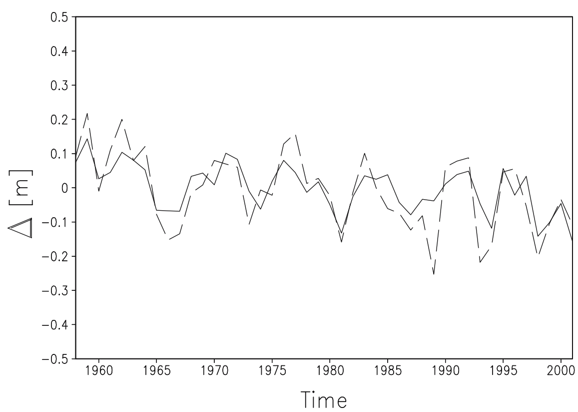

Fig. 13 Differences in meters between winter mean (*solid*) and 90-percentile (*dashed*) hindcast and observed high waters at Cuxhaven

solely be interpreted as a result of changing atmospheric conditions and that other coastal processes have to be taken into account to account for the full range of observed long-term sea level variability.

Summary and discussion

Storm-related sea level fluctuations from a high-resolution numerical hindcast for 1958–2002 have been analysed along the North Sea coast. It was found that they have undergone considerable variations, but apart from a small section along the German and Danish coastline, no significant increase was found.

The result is mainly consistent with that reported by LPSS although no confidence limits have been estimated by these authors. In particular the large-scale patterns of the analysed linear trends are in broad agreement, while the magnitudes may differ for some areas. When we removed the last 9 years from our data set and repeated the analyses for a period as close as possible to that hindcast by LPSS, even larger differences were found. Several conclusions can be drawn from these findings: First, the results appear to be rather sensitive to the analysis period. Particularly over the last few years, increases in storm-related sea levels appeared to be smaller, leading to smaller trends for the period 1958–2002 compared to 1958–1993. This is confirmed also from an analysis of changes in North Sea storminess from observations (e.g., Alexandersson et al. 2000) and model results (Weisse et al. 2005), both of which show a decrease or weakened increase for the periods later than 1990–1995. The years 1955–1957, which were included in the analysis of LPSS but not simulated in our study, may also account for some of the differences. Second and probably the most likely reason, differences can be attributed to differences in the atmospheric forcing, the ocean model, and its spatial resolution, which differ between the two studies. In our study, we used dynamically downscaled atmospheric forcing fields derived from a regional atmosphere model simulation driven by the NCEP reanalysis (Feser et al. 2001). While this forcing presently represents one of the most homogeneously gridded atmospheric data sets, it was not available when the simulation of LPSS was performed, and their forcing suffered from some inhomogeneities such as changes in the analysis technique.

The spatial resolution of the LPSS hindcast was about 10 km. In our simulation, the spatial resolution was largely enhanced, and we consequently obtained a better representation of coastal sea levels. As we found trends to be generally larger in the immediate vicinity of the coasts (cf. Section 3.2) these differences may also account for a considerable fraction of the differences between LPSS and our analyses.

While there was a very good agreement between observed and hindcast interannual sea level variability, the analysis of observed and hindcast sea level trends revealed significant differences. Hindcast trends near Cuxhaven were found to be smaller and significantly different from observed ones. There are two principal explanations: First, hindcast trends comprise only changes caused by long-term changes in the atmospheric forcing, while observed trends may contain also contributions from construction work or natural and other anthropogenic changes in the surrounding of the station and the sea bed. Second, the hindcast trends do not completely reflect the observed atmospheric changes. The latter appears to be rather unlikely. The analyzed changes compare well with observed (Alexandersson et al. 2000) and modeled Weisse et al. (2005) changes of the North Sea storm climate. From both, a strong increase in storm activity since about 1960 or so with high levels around 1990–1995 and a decrease or only moderate increases for some points afterwards can be inferred. These findings are consistent with the changes in storm-related sea levels obtained from our analyses. As a result, it may be concluded that observed sea level trends along the North Sea coast comprise a considerable fraction that cannot be attributed to changes in the storm climate.

Summarising, we found a good agreement between observed and hindcast coastal sea level variations. While a significant increase in storm-related sea levels was found for some points along the coast, there is considerable variability within the time series that follows that of atmospheric storminess. The latter has undergone considerable variations on the time scales of years and decades but has no significant trend since the beginning of the 20th century.

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