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LETTER

The exceptional influence of storm 'Xaver' on design water levels in the German Bight

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Abstract

Design water levels for coastal structures are usually estimated based on extreme value statistics. Since their robustness depends heavily on the sample size of observations, regular statistical updates are needed, especially after extreme events. Here, we demonstrate the exceptional influence of such an event based on storm 'Xaver', which caused record breaking water levels for large parts of the southwestern German North Sea coastline on 6 December 2013. We show that the water level estimates for a 1 in 200 years event increased by up to 40 cm due to the update after 'Xaver', a value twice as large as the estimated regional sea level rise for the entire 20th century. However, a thorough analysis of different independent meteorological (winds and pressure) and oceanographic components (tides, surges, mean sea level (MSL) anomalies) driving the event reveals that their observed combination does not yet represent the physically possible worst case scenario. Neither tides, nor surges nor MSL anomalies were at their observational maximum, suggesting that there is a realistic risk of a storm like 'Xaver' to cause even higher extreme water levels by a few decimetres under current climate conditions. Our results question purely statistical design approaches of coastal structures, which neglect the physical boundary conditions of individual extreme events.

Introduction

Coastal regions are increasingly exposed to flood damages due to growing population assets, rising sea levels and possibly more frequent and intense storms (Hallegatte *et al* 2013, Dangendorf *et al* 2015, Hinkel *et al* 2015). To provide safety standards against flooding, coastal defenses are usually designed to withstand extreme water levels of a given return period. Typically, this corresponds to water levels with an average return period of 100–10000 years (depending on the nationally set standards) (Arns *et al* 2013). Such return water levels are usually derived from extreme value statistics applied to observational records at specific locations (Coles 2001, Arns *et al* 2013). A frequently asked question both in research and practical applications is how these extreme water levels might be redefined over the lifetime of coastal defenses (Mudersbach and Jensen 2011, Lin *et al* 2012, Dangendorf *et al* 2013, 2014b, Arns *et al* 2015a, Marcos *et al* 2015) due to the combined effect of shorter return periods of intense windstorms (Della-Marta and Pinto 2009) and global and regional sea level rise (Church *et al* 2013) in the upcoming decades. However, a topic rarely discussed is how robust the extreme value statistics are under current climate conditions, as the observations are often limited to a few decades. Thus, the available records represent only a very narrow window of the Earth's history and it is questionable whether this window is long enough to capture the natural variability on multi-decadal to centennial scales. Henceforth, we cannot assume per se that the input information for our statistics can be considered representative for the full range of physically possible extreme water level conditions, leaving us with the realistic risk of both over- and under-estimating required design levels. It is thus indispensable to regularly update extreme value statistics, especially after the occurrence of record high extreme events (Coles 2001).

In this study we present and discuss the exceptional influence of an extreme event for the entire German Bight located in the southeastern North Sea. On 6 December 2013, the study area was hit by storm ‘Xaver’ which brought record breaking sea levels for several coastal stretches (e.g. Spencer *et al* 2015, Jensen *et al* 2015, Wadey *et al* 2015). Recent assessments have provided detailed information regarding the temporal development of the corresponding extreme sea levels along the coast, their geomorphological impacts, their influence on crustal deformations, and their classification in terms of existing extreme value statistics (Fenoglio-Marc *et al* 2015, Jensen *et al* 2015, Spencer *et al* 2015, Wadey *et al* 2015). Here, we go one step further and investigate whether the magnitude of the event has changed the extreme value statistics themselves and their corresponding return levels at specific locations along the coastline of the German Bight. It has recently been shown (Arns *et al* 2013) that an assessment based on using the Peak Over Threshold (POT) sampling linked to the generalized pareto distribution (GPD) provides the most robust estimates of return periods of extreme sea levels in the German Bight, under the premise that the last record corresponding to storm ‘Capella’ (3 January 1976) is included. Since ‘Xaver’ has displaced ‘Capella’ as an observational maximum record at many locations (Jensen *et al* 2015), it is intuitive to ask whether the robustness of existing statistics is affected by ‘Xaver’ or not.

Additionally, we investigate whether the observations of storm ‘Xaver’ provide helpful information on the upper limit of regional extreme water levels under current climate conditions. Extreme water levels are a combination of high astronomical tides (driven by gravitational forces between the Earth, the Moon and the Sun), surges driven by deep lows in combination with strong onshore winds, and more slowly changing mean sea level (MSL) anomalies, which act as a base level upon which high tides and surges built (Woodworth and Pugh 2014). Therefore, the maximum possible extreme water level event under observed conditions can be viewed as the in-phase superposition of their observational maxima under the consideration of their physical dependencies (e.g. the interaction of tide and surges; Horsburgh and Wilson 2007). Here, we investigate the genesis of storm ‘Xaver’ in more detail and examine whether the different components were indeed occurring in phase and, if not, how the worst case could look like. This is achieved using oceanic and meteorological observations in combination with numerical and statistical model simulations.

The paper is organized as follows. In section 2 we describe the data used for our assessment. Methods are introduced in section 3. In section 4 results are presented and discussed, while the article closes with some concluding remarks in section 5.

Data

We use 15 tide gauge records of tidal peaks from stations in the German Bight, whose locations are listed in supplementary table 1. The tide gauge records, provided by the German Federal Institute of Hydrology (BfG), are the same as in Arns *et al* (2015a), but updated for the most recent years to include storm ‘Xaver’, thus covering 1970–2013. Arns *et al* (2013) demonstrated that the use of the 1970–2012 period yields stable and similar return water levels in comparison to centennial records in the region.

We also analyse the hourly record from the tide gauge at Norderney, an island located in front of the Lower Saxony North Sea coastline, to investigate the individual components (water levels, tides, surges, MSL) of extreme events over the observational period from 1999 to 2014. To separate MSL from the hourly records, a 14 d LOWESS filter (Cleveland 1979) is applied to the raw data. The cut-off period of 14 d is used as a trade-off between short-term tidal and atmospherically induced sea level variations and slower components related to MSL changes. The filtering retains the most dominant tidal fluctuations, including the spring-neap cycle in the residuals. Longer-term tidal variations such as the gravitational component of the seasonal cycle (Woodworth and Pugh 2014), the nodal cycle, or the 8.85 year cycle of lunar perigee (Haigh *et al* 2011) have only minor influences on MSL and are therefore neglected at this stage. Comparisons of the MSL component estimated with the 14 d LOWESS filter and daily nearby satellite altimetry from AVISO have shown a generally good correspondence (not shown). Residuals between the observed hourly sea levels and the MSL component are further separated into tides and surges by applying a classical harmonic analysis (with 67 constituents) using the MATLAB software T-Tide (Pawlowicz *et al* 2002).

Moreover, a bias corrected water level hindcast from a two dimensional, depth-averaged barotropic ‘tide & surge’ model of the North Sea based on MIKE21 FM is used to evaluate water level extremes at 1478 grid points along the entire German North Sea coastline. The model is forced with tides from the MIKE21 internal global tide model at the model boundaries and 10 m surface wind and pressure fields from the 20th century reanalysis (Compo *et al* 2011). A flexible mesh is used providing the highest spatial resolution in the German Bight (~1 km; see Arns *et al* 2015a). The model outputs have recently been used to transfer extreme value statistics from individual tide gauge locations to the entire coastline (Arns *et al* 2015a). To reduce the effects of inaccuracies in the forcing or the model itself, the model output was bias corrected to match observations. Further details on the model set up and the bias correction can be found in Arns *et al* (2015a, 2015b).

The ERA-Interim reanalysis dataset (Dee *et al* 2011) is used to characterize the large-scale atmospheric conditions associated with the occurrence of storm 'Xaver'. ERA-Interim is an atmospheric reanalysis dataset from the European Centre for Medium-Range Weather Forecasts, has a spatial resolution of about 80 km, and is available six-hourly.

To produce high resolution atmospheric fields for the storm event over the North Sea, the Consortium for Small-Scale Modeling (COSMO) model; http://cosmo-model.org) is used in its climate version COSMO-Climate Limited-area Model (CCLM), hereafter; Rockel *et al* 2008) forced with ERA-Interim boundary conditions. The CCLM has been successfully used in the past to model historical storms (e.g. Born *et al* 2012, Ludwig *et al* 2015). The CCLM-simulation is performed on a 0.22° × 0.22° rotated grid with 35 layers in the vertical for the area defined in figure 3(a). The CCLM simulation starts on 04 December 18 UTC and is integrated for 66 h until 07 December 2013 12 UTC. Spectral nudging (von Storch *et al* 2000) is applied to the horizontal wind components in the upper atmosphere down to 850 hPa to keep the large-scale atmospheric flow close to the driving reanalysis data. The model simulations are validated against station data (mean wind speed, wind direction, wind gust and MSLP) from Norderney (WMO Station 10113).

Methods

Following the recommendations from Arns *et al* (2013), a direct method is chosen to evaluate the extreme value statistics in the German Bight. The method assesses extreme water levels without any further distinction of deterministic (tides) and non-deterministic (surge, MSL) components, and generally yields most stable results in comparison to other common extreme value statistics approaches in the German Bight (Arns *et al* 2013). The method consists of the following steps:

1. Selection of high water peaks, including the 1976 'Capella' event (here 1970–2013).
2. Creation of a stationary dataset by removing a 1 year moving average from the high water peaks.
3. Creating an extreme value sample using the POT approach with the 99.7th percentile as a threshold u.
4. Declustering of the sample using the extremal index (see e.g. Coles 2001).
5. Fitting the GPD to the declustered and detrended sample.

The GPD is defined as:

$$\mathrm{GPD} = 1 - \left[1 + \frac{\varepsilon y}{\sigma^{\sim}}\right], \text{ with } \sigma^{\sim} = \sigma + \varepsilon(u - \mu),$$

where μ, σ, ε are defined as the location, scale and shape parameter, respectively, which are fitted to the observation using the common maximum likelihood estimator (e.g. Smith 1986, Hosking and Wallis 1987). This approach is applied to obtain return water levels for specific return periods at all tide gauge locations, as well as for all coastal grid points from the numerical model output in the German Bight.

To evaluate whether storm 'Xaver' had an exceptional influence on the return water levels in the German Bight, sensitivity experiments are carried out, in which the year of storm Xaver (2013) was either excluded or included in the analysis of extremes: at each location, the return levels are calculated once for the periods 1970–2012 and 1970–2013, respectively, and the differences for individual return periods are assessed. The significance of the differences are assessed using a Monte-Carlo-Simulation (MCS) approach. At each of the 1478 coastal grid points, the parameters μ, σ, and ε (estimated over the period 1970–2012) are used to generate 10.000 random GPD samples of similar length as the sample from the period 1970–2013. For each sample, a similar sensitivity assessment is performed as for the observations, i.e. each sample is divided in two sub-samples of 43 and 44 years and differences between return levels are calculated. This results in 10.000 values for the differences in individual return periods per location, from which the 95% confidence intervals (CI) are used to evaluate the statistical significance of the differences. The results are calculated for 10, 20, 50, 100, 200, 500, and 1000 year return levels, whereby a special focus is given to the once in 200 years events (for presentation purposes).

Results and discussion

Extreme value statistics

The update of the extreme value statistics with the inclusion of the year 2013 results in significantly higher 200 year return water level estimates for six tide gauge records (out of 15; figure 1). Five of these records are located in the southwestern part of the German Bight, i.e. along the Lower Saxony coastline and only one record (Büsum) is located in the northeastern coastline of Schleswig-Holstein. In the remaining nine records, slightly negative but non-significant changes in the 200 year return water levels are obtained. The positive changes in water levels range from roughly 10 to more than 40 cm, which is in a similar order or even twice of the totally observed 20th century sea level rise in the region (~20 cm since 1900; Wahl *et al* 2013, Dangendorf *et al* 2014a).

Return water levels based on the two dimensional 'tide & surge' model are in close agreement to the findings from tide gauge records, but enable a clearer view

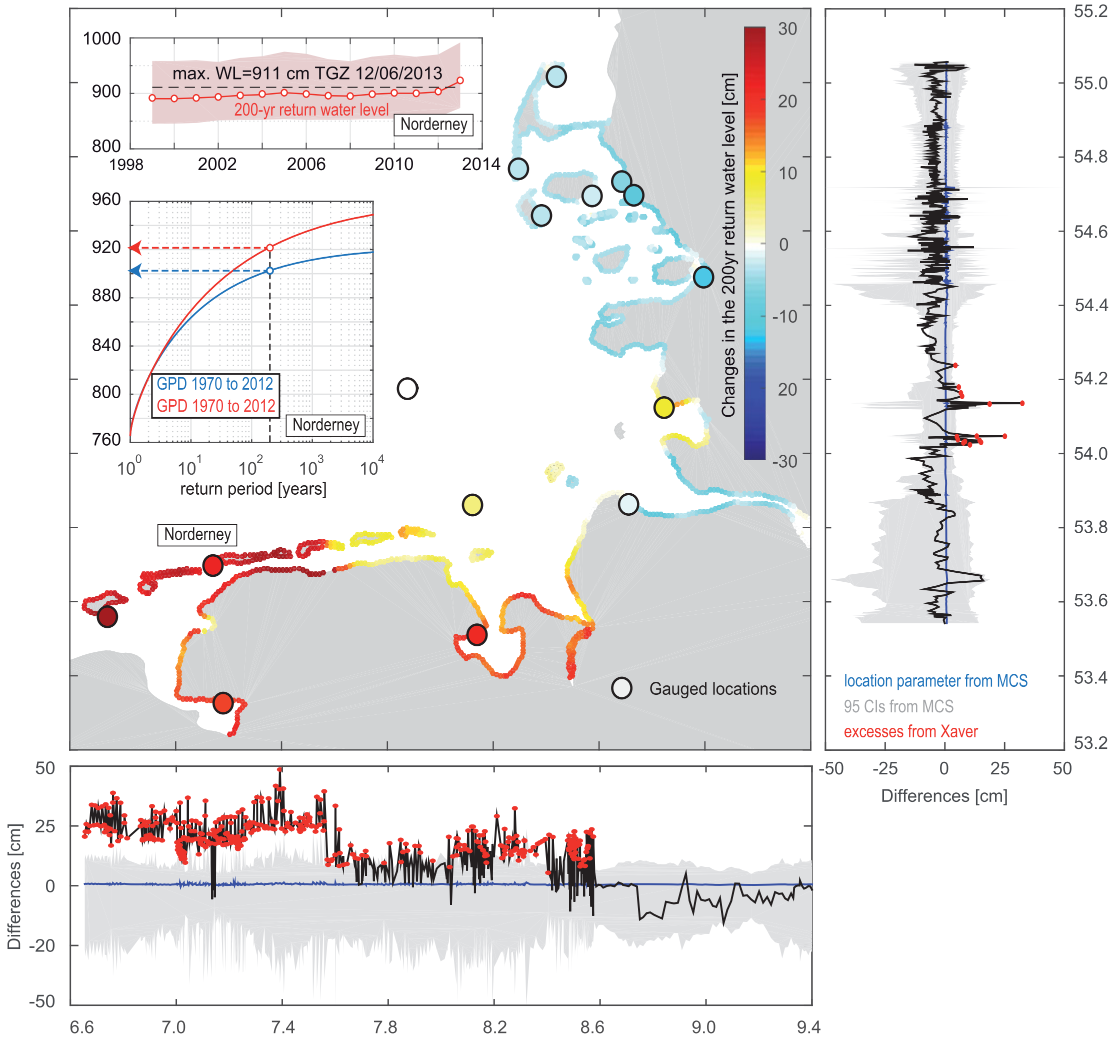

Figure 1. Results of the extreme value statistics update (in terms of a once in 200 years event) by one additional year (2013) including storm 'Xaver' using the GPD. The large circles in the map show the differences derived at individual tide gauges, while model results are shown as small circles along the coast. The significance of the derived differences is tested in 10 000 Monte-Carlo simulations and shown below and right to the map ($P = 0.95$). Significant changes are marked with red circles. The large inset shows the return levels before and after the 2013 update for the station Norderney. The small inset shows the stability of the extreme value statistics for the 200 year event over time.

of the spatial footprint of the impact of storm 'Xaver' along the German Bight coastline (figure 1). The largest changes induced by 'Xaver' are found for the southeastern end of the German Bight, with maximum values of roughly 40 cm or more around the small offshore islands of Borkum, Juist, Norderney and Langeoog as well as the nearby Lower Saxony coastline. Changes in the order of 20 cm are obtained in the embayments (Dollard and Jadebusen), where the tide gauges of Emden and Wilhelmshaven are located. Towards the central part of the German Bight and further northeastwards, there are zero to slightly negative changes in the 200 year return water levels. An exception is the Meldorf Bight in the Schleswig-Holstein coastline, where positive changes of approximately 10 cm are found.

The larger inset in figure 1 highlights the impact of including the year 2013 for all return periods between 1 and 10 000 years, demonstrated here for the station of Norderney. There is an increase in uncertainties related to the very low return periods, especially in the domain of extrapolation (not shown). While the return water levels using both sub-samples roughly agree for shorter return periods, the curves increasingly diverge above the 10 years return period, with differences between 20 and 30 cm. Further results for individual return periods and sites are presented in figure 2. Along the Lower Saxony coastline, the surge associated with 'Xaver' shifted the return levels to a higher level, particularly for the lower return levels. The opposite is true for the Schleswig-Holstein coast, although with much smaller magnitude. At some locations along the Lower Saxony coastline, differences in the once in 500/1000 year events exceed 50/70 cm. To estimate whether similar changes have been observed in former years, the stability of return levels was tested for the once in 200 year return period affecting Norderney by iteratively adding one year of data to the

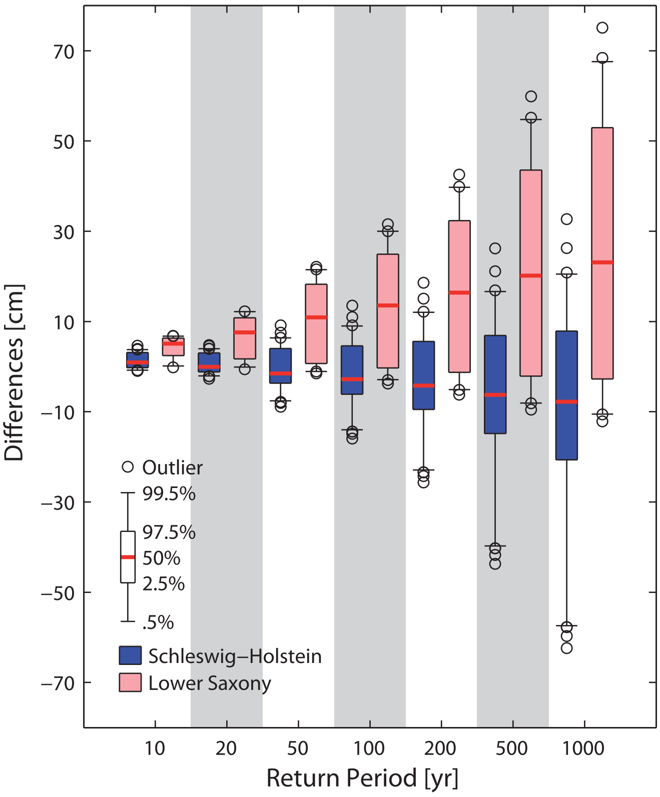

Figure 2. Differences between selected return water levels from the 1970–2013 minus 1970–2012 assessment from each grid point time series from the two-dimensional 'tide & surge' model separated into the two geographical areas of Schleswig-Holstein (blue) and Lower Saxony (red).

sample starting 1970 and ending from 1999 up to 2013 (small inset in figure 1). In agreement with Arns *et al* (2013), the 200 year return water levels remained stable from 1999 to 2012, but an unprecedented increase is detected when including 2013. This underpins the exceptional influence of storm 'Xaver' on the return water levels along the southwestern coastline of the German Bight.

The MCS is conducted separately for each tide gauge record and numerical model grid point time series, as shown in the outer sub-panels of figure 1. Results indicate that the obtained positive changes are statistically significant almost everywhere along the Lower-Saxony coastline (red dots). i.e., the differences in the observational or reanalyzed time series with and without 2013 exceed the 95% CIs simulated from 10.000 MCS (grey shaded areas). In the MCS, the differences generally do not exceed 10–15 cm (depending on the location). On the other hand, the observed differences sometimes exceed 30 cm for once in 200 year events. In the northwestern part of the German Bight along the Schleswig-Holstein coastline, the obtained negative differences (i.e. a slight decrease in the 200 year return water levels) are non-significant, except of the area in the Meldorf Bight, where the differences are positive and significant. This strongly suggests that storm 'Xaver' significantly changed the shape of the extreme value distribution of extreme water levels for the southwestern part of the German Bight. This further motivates to analyse the physical genesis of this particular event in more detail to examine whether the individual components generating this event were indeed that exceptional as the results of the extreme value analyses suggest.

Meteorological and oceanographic conditions

It is important to explain in detail the meteorological and oceanographic conditions which caused these record breaking water levels and their spatial variability along the coast. Figure 3 shows the meteorological boundary conditions for storm 'Xaver'. The storm approached Europe on the December 5th 2013 on a zonally orientated path around 60°N (figure 3(a)). The core pressure of the storm decreased from 999 to 961 hPa (CCLM modelled values) in 24 h between December 4th 18 UTC and December 5th 18 UTC (figure 3(b)), while the storm moved from 23.0°W to 12.6°E (see figure 3(a)). This pressure drop by more than 24 hPa/24 h corresponds to a development of explosive characteristics (Sanders and Gyakum 1980). The tracks based on ERA-interim and CCLM are quite consistent (figure 3(a)). On December 5th 12 UTC, the storm was located over Southern Norway (figure 3(d)), with a simulated core pressure of 967 hPa (same as for ERA-Interim, figure 3(b)). At this time, the cold front of 'Xaver' extended from Southern Norway over the North Sea towards the English Channel, following a

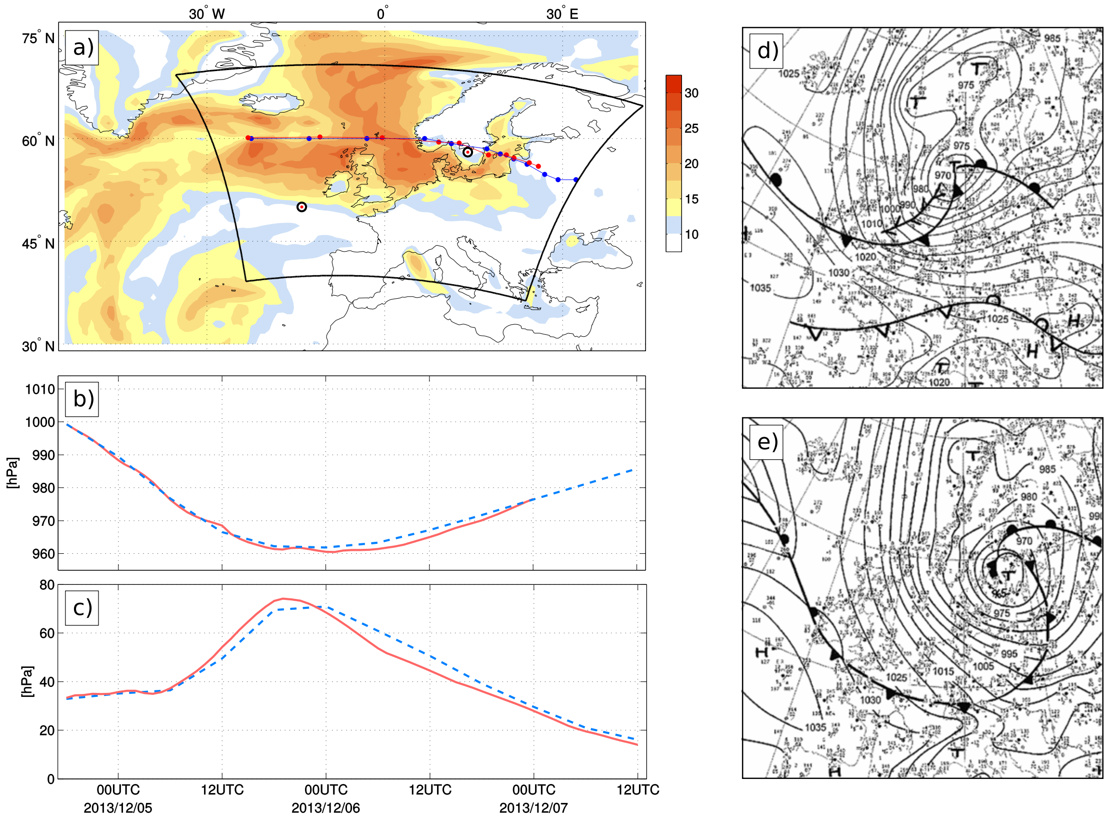

Figure 3. (a) Mean 10 m wind (in m s^{-1}) averaged over the simulation period 04/12 18 UTC–07/12 12 UTC. Xaver track as modelled by CCLM (red) and from ERA-Interim (blue) with six-hourly time steps (dots). (b) Change of pressure gradient between the two marked points (black circles with the red point in the middle) in (a). (c) Changes of core pressure over time. (d) Weather chart German weather service 05/12 12 UTC (e) same as d for 06/12 00 UTC.

convergence line (figure 3(d)). Isobars were very close to each other over the North Sea, indicating a strong pressure gradient and thus strong geostrophic winds from NW to SE. In fact, the large scale WSW–ENE pressure gradient over this area (quantified as the pressure difference between points A and B in figure 3(a)) significantly increased at this stage (figure 3(c)). Twelve hours later, Xaver has moved towards the Baltic Sea, and the cold front was then located over Eastern and Central Europe (figure 3(e)). The isobars remained very close together over the North Sea area, and the large-scale WSW–ENE pressure gradient peaked around this time (21 UTC, figure 3(c)). The resulting wind signature (peak wind speeds over 3 d) from CCLM simulation are shown in figure 4(a), revealing that the storm lead to wind speeds over 25 m s^{-1} over a most of the North Sea. Wind gusts exceeded 35 m s^{-1} over the area (not shown).

The strong winds from northwesterly directions (figure 4(a)) trapped the water against the coast, especially in the southwestern part of the domain. Partitioning the sea level signal at Norderney into its individual components shows that extreme water levels peaked on 6 December around 2 UTC during high tide (884 cm) as a result of strong and exceptionally persistent northwesterly winds in combination with low atmospheric pressure (figures 4(b), (d) and (e)). The resulting surges were characterized by two main peaks, one occurring a few hours before the tidal peak (02 UTC) and one six hours afterwards (08 UTC). For the first peak before 02 UTC, the increasing surge exceeded 182 cm and was mainly forced by northwesterly winds over the shallow shelf. The second peak was additionally driven by an external wave entering the North Sea north of Scotland, so that the total surge component further increase to above 267 cm during the early morning hours of 6 December (Fenoglio-Marc *et al* 2015). Note that external waves and locally driven storm surges are not necessarily forced by the same atmospheric storm event. This suggests that the tidal peak, the locally driven surge, and the external wave were slightly out of phase during ‘Xaver’ (neglecting nonlinear ‘tide & surge’ interactions). The concurrent MSL anomaly was positive with a magnitude of roughly 50 cm (figure 4(c)).

Even though this event corresponds to the highest ever recorded extreme water levels in parts of the German Bight, the above results suggest that not all different oceanographic components were in phase, and thus the physically possible ‘worst case’ scenario could be higher than the recorded levels for ‘Xaver’. Therefore, we analyse each individual component in the observational record as well as possible combinations

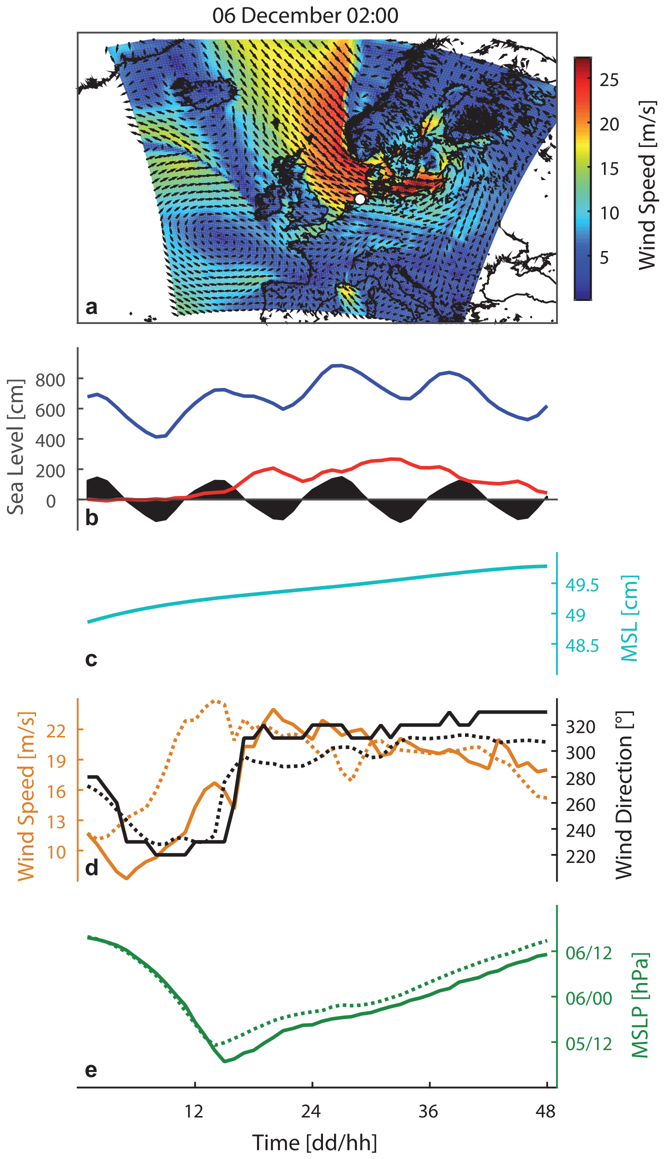

Figure 4. Oceanic and meteorological situation (observed and modelled) during storm Xaver. (a) Wind speeds as modelled by CCLM. The white dot marks the station of Norderney. (b) Water levels (dark blue), surges (red), and tides (black) at Norderney. The MSL component is shown in (c). Also shown are, in (d), the wind speeds and directions observed in 10 m height at Norderney (lines) and as modelled at the closest grid point to the station by CCLM (dotted). (e) as (d) but for observed and modelled MSLP curves.

in more detail. Figure 5 shows the empirical frequency distribution of the total water levels, MSL, surges as well as tides as estimated from the high resolution time series for Norderney (1999–2013). In spite of the record breaking total water levels, results clearly show that neither tides, surges nor MSL were at their respective peak values. For instance, the MSL component fluctuated around roughly 50 cm, which is more than 25 cm below the highest recorded anomalies during this 15 year period (note the comparatively short record length). Moreover, the tides were roughly 21 cm below their absolute maximum. The surges were the highest ever recorded when taking the 'Xaver' event as a whole, but the out of phase occurrence of the external wave and the surges triggered over the shelf actually lowered the total water level during the absolute peak by several centimeters or even decimetres (note the nonlinear interactions). This demonstrates that although 'Xaver' resulted in record high extremes, it still does not represent the physically possible worst case combination under present day climate conditions.

Nonlinear interactions

It is important to notice that the considered components are not completely independent but interact in a nonlinear way. The probably largest nonlinear interaction is found between tides and surges. It has long been recognized that the largest surges tend to accumulate during rising tides (Doodsen 1929, Horsburgh and Wilson 2007) due to a combination of depths effects on wave propagation and depth dependent frictional terms in the equations of motion. This 'tide & surge' interaction becomes clearly evident during 'Xaver',

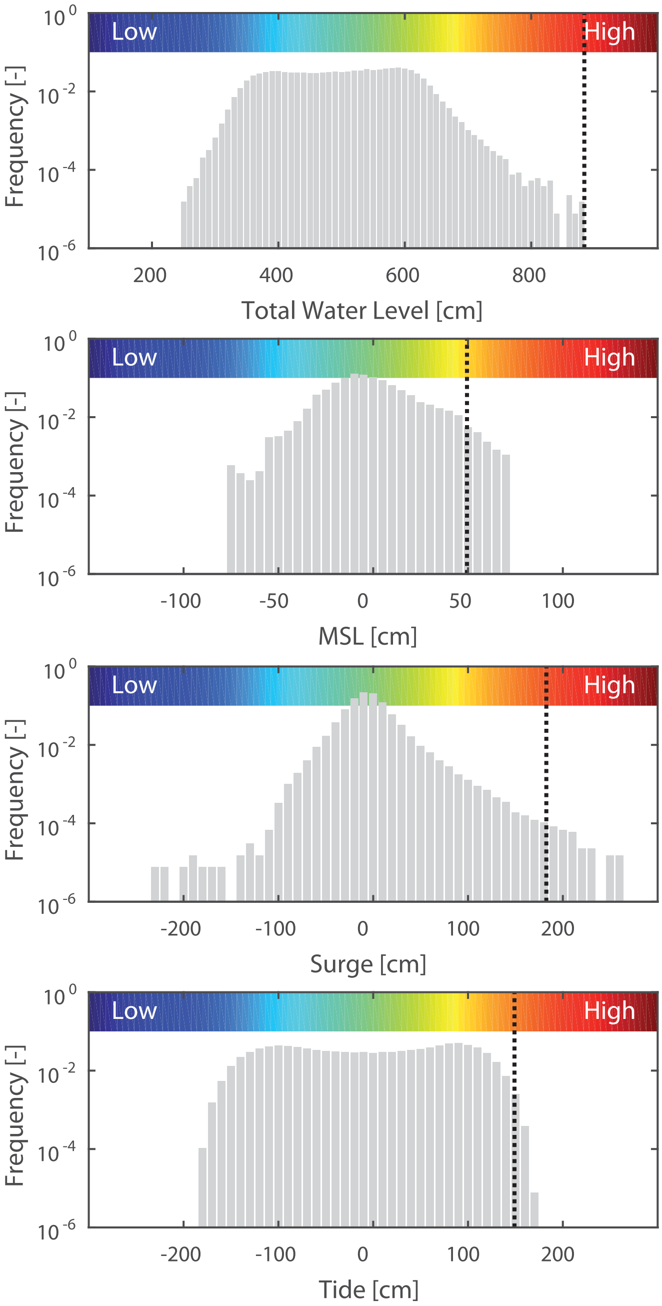

Figure 5. Histograms of each sea level component at Norderney over the observational record from 1999 to 2008. The black dotted line marks the magnitude during the high water peak of Xaver.

when persistently strong northwesterly winds led to two maximum surges, the first in the rising tide (20 UTC on 5 December) and the second 6 h after the high water peak (8 UTC, figures 4(b) and (d)). It is hard to judge how much of the second surge peak is the result of 'tide & surge' interaction or the delayed response to wind forcing over the open ocean and/or an external surge (Fenoglio-Marc *et al* 2015). A visual inspection of the propagation of the external surge explained in figure 4 and movie S1 of Fenoglio-Marc *et al* (2015) suggests that it might also contribute to the delayed increase in the surges. This means that there is some potential for higher surges, but a final quantification is not straightforward without extensive numerical simulations.

The MSL component is mostly independent from the other terms and its response to oceanographic and meteorological forcing happens on longer timescales than those relevant for the storm generation. However, the MSL increases/decreases the total water depths and might therefore increase/decrease the amplitude of tides due to changes in phase lags and change in tidal modulation, potentially overcompensating possible decreases in the surges due to 'tide & surge'-interaction at the same time (Arns *et al* 2015b). Hence, we suggest that the interaction between MSL and tides rather tends to counteract the lowering effects of the 'tide & surge'-interaction. Summarizing, there is a realistic risk for even higher extreme water level, under the assumption that the individual oceanographic components occur in phase during a 'Xaver' like storm. Simply summing the independent components of tides (21 cm) and MSL (25 cm) at the tide gauge of Norderney already results in a scenario for a potentially 46 cm higher extreme water level than occured during storm 'Xaver'. Further including the effects of an external wave occurring in phase with the maximum surge produced by local winds over the shelf and tendentially positive interactions between tides and MSL could potentially further increase this number, but the mostly unknown effects of the 'tide & surge' interaction do not allow for a final quantification of this component.

Conclusions

In this study we have investigated the influence of storm 'Xaver' on extreme sea levels in the southeastern North Sea under the consideration of both the meteorological and oceanographic components associated with the record breaking event. We have found that storm 'Xaver' brought record high water levels for many parts of the study area, which shifted the updated extreme value statistics to a significantly higher level. For the reference return period of an once in 200 years event the differences reached up to 40 cm at specific locations along the coast, while for the longer (more uncertain) return periods (1.000 years) increases of even up to 70 cm were obtained. These significant changes fall within the range of MSL projections for the second half of this century (23–98 cm, Slangen *et al* 2014) and highlight an intrinsic uncertainty of state-of-the-art extreme value statistics. Therefore, our first conclusion is that the temporally limited extent of the observational record requires regular updates of the extreme value statistics used for design purposes of costal structures, efforts in data archaeology (e.g. Dangendorf *et al* 2014b, Bradshaw *et al* 2015), and the consideration of historical events from alternative archives (Bulteau *et al* 2015). Recent examples comprise, for instance, morphological records from storm deposits (Brandon *et al* 2014)

Although Xaver brought record high total water levels, we have demonstrated that the observed combination of individual components (MSL, tides, surges) does not represent the 'worst case' scenario since none of the components reached their observational maximum. A hypothetical in-phase occurrence of the individual components might thus trigger higher total sea levels by a few decimetres without any consideration of future climate change effects. The magnitude of such a combined high water level might be as large as the projected MSL change in the region during the second half of the ongoing century (46 cm plus an unknown part from nonlinear interactions). Hence our second conclusion is that thorough analyses of observed extreme events and the different physical components associated with their genesis are required to obtain more robust estimates of extreme water levels in the southeastern North Sea and elsewhere.

Acknowledgments

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