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The impact of sea level rise on storm surge water levels in the northern part of the German Bight

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ABSTRACT

The impact of mean sea level rise (SLR) on extreme water levels is investigated using a numerical model that covers the entire North Sea, but has its highest spatial resolution in the northern part of the German Bight. A 40-year hindcast covering the period 1970 to 2009 is conducted using observed mean sea level (MSL) changes, tides and atmospheric forcing as boundary conditions. The model reproduces the observed water levels well for this control period. A second 40-year run is then conducted considering the same atmospheric forcing but adding +0.54 m to the MSL to explore the effects of sea level rise on storm surges in the investigation area. At most locations, the second model run leads to changes in the storm surge water levels that are significantly different from the changes in MSL alone. The largest increases of the order of 15 cm (in addition to the MSL changes) occur in the shallow water areas of the Wadden Sea. These increases in storm surge water levels are caused by nonlinear changes in the tidal constituents which are spatially not coherent. The response of the tidal propagation to SLR is investigated based on the results from a tidal analysis of each individual event. These analyses point to an increase in the M_2 amplitude and decrease in the amplitudes of frictional and overtides accompanied by less tidal wave energy dissipation. Attributed effects are changes in phase lags of individual constituents leading to a different tidal modulation, thus additionally increasing tidal water levels. Finally, we estimate how SLR affects return water levels in the northern part of the German Bight, with the result that relevant design water levels increase due to the non-linear relationship between SLR and changes in extremes.

1. Introduction

Mean sea level rise (SLR) is one of the most discussed aspects of climate change (Woodworth et al., 2011). It has been estimated that global mean sea level (MSL) might rise by up to +2.0 m in the 21st century alone (Nicholls et al., 2011). As MSL rises, the risk of beach erosion and salt water intrusion into groundwater systems increases. It also directly affects extreme water level events by shifting the frequency distributions of storm surges to higher base levels (i.e. events of a given height occur more frequently) (Hunter, 2010). In IPCC (2012) it was highlighted that the societal impacts from sea level change primarily occur via the extreme levels rather than as a direct consequence of mean sea level change. In order to plan adequate adaptation strategies to cope with climate change challenges it is therefore essential that reliable projections of extreme water level changes become available. This in turn requires a profound understanding of the physical processes driving these changes, i.e. all relevant driving factors for potential changes in water level extremes need to be thoroughly investigated.

The assessment of extreme water levels normally includes some form of statistical analyses (Dixon and Tawn, 1994). These models are usually based on the extreme value theory, which requires stationary data sets (see e.g. Jensen, 1984; Rao and Hamed, 2000). For many sites, however, extreme water level samples appear to have non-stationary features such as trends or cycles (Dixon and Tawn, 1994). This is why e.g. Coles (2001), Méndez et al. (2007), Menéndez and Woodworth (2010) and Mudersbach and Jensen (2010) introduced non-stationary approaches to estimate possible future extremes by including temporal changes and fluctuations into the extreme value models. Aiming at a description of possible changes in the exceedance probabilities of future extremes, Hunter (2010) combined observations of present-day sea level extremes with sea level rise projections. This simple approach was based on the assumption that changes in extreme water levels during the 21st century will be dominated by changes in MSL. Most coastal protection strategies adapted this methodology by raising design water levels according to the projected SLR for a particular region (Smith et al., 2010). Hence, the results are based on the assumption that mean and extreme water levels will rise by exactly the same amount. However, recent analyses of observational data indicate trend differences between mean and extreme water levels (see Jensen et al., 1992; Dangendorf et al., 2013b; Mudersbach et al.,

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2013). In such cases, the assumption of linear dependency may either under- or overestimate the impact of SLR on extreme water levels.

Some previous studies assessed future changes in extreme water levels due to both changes in the meteorological forcing and SLR, whereas the uncertainties accompanied with the former are still very large (see Section 2.2 for a review). In this paper we therefore focus on the impact of SLR alone. The overall aim is to examine the impact of SLR on extreme water levels in the German Bight. In this context we explore how SLR affects (i) peak high water levels (hereafter referred to as high water levels), (ii) high water occurrence times, (iii) high water level distributions, (iv) individual tidal constituents, and (v) we identify the spatial distribution of the observed changes. Finally, we also assess how these changes affect the results from extreme value analysis, which plays an important role in the design process of coastal defenses in the study area.

The paper is organized as follows. Section 2 provides a brief review of papers dealing with changes in extreme water levels and its components. This section is intended to justify our model assumptions and to review the current knowledge. In Section 3, the study area is introduced. In Section 4, the applied methodologies are described. The results are presented and discussed in Section 5, followed by the conclusions provided in Section 6.

2. Background

2.1. Changes in storm surge water levels

Many previous studies concluded that changes in extreme water levels broadly followed MSL changes (on a global scale e.g. by Woodworth and Blackman, 2004; Menéndez and Woodworth, 2010; for the English Channel e.g. by Haigh, 2009). Some authors also identified areas where extreme water levels changed at rates faster than those observed in MSL (e.g. for Oostende in Belgium by Ullmann et al., 2007). In the German Bight, Mudersbach et al. (2013) showed that trends in extreme high water levels differed significantly from those in MSL from the mid-1950s to approximately 1990. At six tide gauges, they performed trend analyses of different high percentile time series which have been reduced to MSL showing residual trends between +0.6 and +6.4 mm/year. They argued that this was mainly a result of changes in the amplitudes of some of the main tidal constituents.

Extreme water levels arise as a combination of the MSL, astronomical tides (hereafter referred to as tide), the dynamic response of the sea surface to atmospheric forces (hereafter referred to as surge), and the nonlinear interactions between them. Long term changes, e.g. due to climate change/variability, in any of those components may substantially alter the risk associated with extreme water levels (Weisse et al., 2011). Quantifying the individual contribution of each component to extreme water levels, however, is difficult using observational data. This is why numerous studies focus on model based investigations, considering one or more components to be changed.

Model based investigations on changes in extreme water levels from SLR are usually conducted by comparing a control run (i.e. a simulation of the observed period) to possible future scenarios. Based on such a comparison, Kauker and Langenberg (2000) concluded that North Sea storm surge heights do not increase faster than SLR in general. For the German Bight, similar investigations point to a different behavior showing extreme water level changes that are significantly different from the considered SLR at most of the investigated sites (Stengel and Zielke, 1994) and changes in total water levels of up to ±0.25 m relative to the considered SLR (Bruss et al., 2010).

Some studies have also investigated the impact of changes in atmospheric forcing on extreme water levels. By assuming a linear relationship between MSL and extreme storm surges, Woth et al. (2006) compared a storm surge model control run of the entire North Sea to scenario runs (the output from different climate models was considered) each covering a 30-year period. Overall, they identified large changes along the continental coast. In the German Bight up to Denmark, both intensity and duration of extreme water levels (e.g. the 99.5th storm surge percentile) showed significant increases in all scenarios ranging from +0.2 to +0.3 m. Comparing North Sea extremes under present-day and possible future climate conditions in combination with changes in MSL, Lowe et al. (2001) found statistically significant changes induced by future meteorological forcing but could not detect significant indirect changes from SLR. Similar findings were reported for the UK (Lowe and Gregory, 2005) and Dutch coastlines (Sterl et al., 2009).

2.2. Changes in atmospheric forcing

A number of recent publications have analyzed trends in mean and extreme wind conditions in the North Sea region. Using geostrophic winds in the southern North Sea from 1876 to 1989 (Schmidt and von Storch, 1993) and pressure records from two Swedish stations from 1780 and 1823 to 2002 (Bärring and von Storch, 2004), considerable inter-annual and decadal variability was noticed but no evidence for significant long-term trends was found. Using 13 Dutch records of near-surface winds, Smits et al. (2005) found extreme wind speeds to have declined by up to 10% per decade. Contradictory, they found extreme wind speeds to have increased by up to 20% per decade using reanalysis data covering the same period and region. They attribute these inconsistencies to inhomogeneities in the reanalysis data although overestimations from station data cannot be excluded. There are also other studies reporting opposite trends between station and reanalysis data for some areas (see Seneviratne et al., 2012 and references therein).

Fewer studies report shifts in the North Atlantic storm track (see Weisse et al., 2011 and references therein), with decreased storm frequencies and nearly constant storm intensities in mid-latitudes, superimposed by inter-annual and decadal variability during the second half of the 20th century. Based on reanalysis data, Siegismund and Schrum (2001) detected strong winds from south westerly directions to shift from the late autumn into early spring, a finding consistent with the occurrence times of the seasonal MSL peaks detected by Dangendorf et al. (2012).

With respect to future projections, an assessment of possible changes in the North Sea climate (WASA project) points towards a moderate increase of North Sea winds (WASA Group, 1998). From analyzing the outputs of the newest generation of atmosphere ocean global coupled climate models (AOGCMs; CMIP5), De Winter et al. (2013) found a possible shift towards more westerly winds in the southern North Sea region. These changes were, however, within the range of previously observed variations.

2.3. Mean sea level changes

SLR is one of the most important aspects of climate change (Wahl et al., 2013; Woodworth et al., 2011) and there is concern about the impact this could have on growing coastal communities (Nicholls and Cazenave, 2010). There have been numerous studies on the observed global and regional (North Sea) sea level changes (e.g. Church and White, 2006; Wahl et al., 2010, 2011, 2013; Woodworth et al., 2009; Wöppelmann et al., 2008, 2009), pointing to a considerable temporal and spatial variability (e.g. Church et al., 2004, 2008; Dangendorf et al., 2012, 2013a). These differences are mainly caused by regional meteorological, oceanographic and gravitational effects, vertical land movements as well as anthropogenic interventions (see e.g. Wahl et al., 2013 for a review for the North Sea). From a coastal management and planning perspective, regional or local relative sea level changes are most important (Nicholls et al., 2011) and it seems reasonable to assume that future changes in sea level will also exhibit a strong spatial variability (Wahl et al., 2011, 2013). The 5th assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) (Church

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