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Changing extreme sea levels along European coasts

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ABSTRACT

Extreme sea levels at European coasts and their changes over the twentieth and twenty-first centuries are considered, including a method to analyze extreme sea levels and to assess their changes in a consistent way at different sites. The approach is based on using a combination of statistical tools and dynamical modelling as well as observational data and scenarios for potential future developments. The analysis is made for both time series of extreme sea levels and individually for the different components contributing to the extremes comprising (i) mean sea level changes, (ii) wind waves and storm surges and (iii), for relevant places, river flows. It is found that while regionally results vary in detail, some general inferences can be obtained. In particular it is found, that extreme sea levels show pronounced short-term and long-term variability partly associated with seasonal and nodal tidal cycles. Long-term trends are mostly associated with corresponding mean sea level changes while changes in wave and storm surge climate mostly contribute to inter-annual and decadal variability, but do not show substantial long-term trends. It is expected that this situation will continue for the upcoming decades and that long-term variability dominates over long-term trends at least for the coming decades.

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1. Introduction

Extreme sea levels pose a significant threat to low-lying coastal areas which is expected to grow due to climate change. Coastal engineers need to address this issue by taking present and future extreme sea levels into account during planning, design and maintenance of coastal defences and related risk management strategies. Generally, extreme sea levels are caused by the combination of different factors acting over a wide range of spatial and time scales (Lowe et al., 2010; Weisse et al., 2012). These factors comprise the generally regular and predictable patterns of the ocean tides, the meteorological contributions from severe wind storms; that is, storm surges and wind generated waves at the sea surface (hereafter referred to as wind waves or sea state), and contributions from changing mean sea levels that shift the baseline upon which the other factors act (e.g., Menéndez and Woodworth, 2010; Weisse et al., 2012). Where major rivers enter the sea, in particular in the upstream parts of large estuaries, the situation may be further complicated by river floods that may coincide with extreme coastal sea levels.

Generally, contributions from these factors may not add linearly or contribute to the same amount to extreme sea levels, but there is considerable interaction and the magnitudes of the different factors may vary regionally. For example, for the UK North Sea coast a number of studies report a tendency for the most severe storm surges to occur most frequently on the rising tide (e.g., Doodson, 1929; Prandle and Wolf, 1978). Horsburgh and Wilson (2007) explain this phenomenon known as tide–surge interaction by a phase shift of the tidal signal in combination with a modulation in surge production and propagation due to water depth. Another example is the effect of rising mean sea levels on the range of the principal lunar semi diurnal tide (e.g., Kauker, 1999; Pickering et al., 2012; Pluess, 2006). Although the estimated magnitude of the effect varies considerably from a 1–4 cm increase per metre sea level rise in Kauker (1999) to almost 15 cm per metre sea level rise in Pickering et al. (2012), there is general agreement that the effect increases with higher values of mean sea level rise and towards the coasts; that is, in shallower waters (e.g., Pluess, 2006). Long tidal variations, such as the nodal tide with a period of 18.6 years, may also modulate the amplitudes of shorter period constituents and increase the risk of flooding at specific times (Pugh, 1987). For example, for the Gulf of Maine Ray (2006) reports variations in M2 tidal amplitudes in the order of about 20 cm associated with the nodal cycle. Menéndez and Woodworth

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(2010) evaluated the role of tidal fluctuations in extreme water return levels from a quasi-global tide-gauge dataset and found substantial influences in the Northeast Atlantic and the South China Sea. Haigh et al. (2011) examined the contribution of the 18.6 year lunar nodal cycle from a tidal model in conjunction with satellite observations and found the largest influences of the nodal cycle in diurnal regions with tidal ranges higher than 4 m.

Generally, most European coasts are well adapted and protected against present day risks. However, long-term changes in any of the factors contributing to extreme sea levels may substantially alter the risk and may generate a need to revisit coastal defence strategies and/or to develop and implement alternative and/or innovative measures. Causes for such changes are manifold and may include local subsidence (e.g., Venice, Italy), local water engineering (e.g., the Elbe, Germany) or large scale climatic changes. While there is extensive analysis of global and broad regional changes as discussed in this paper, there is a significant gap between this material and its application to strategic planning at more local scales and the knowledge is often fragmented and varies regionally. This paper addresses this gap for coastal flood management and protection in a European context. Within the European project, THESEUS[1] a number of study sites was selected for which common approaches were developed and applied making results comparable. The purpose of this paper is to review the approaches applied to estimate and to assess potential future changes in extreme sea levels providing the baseline for subsequent analysis. We start with a brief description on the current knowledge of recent and potential future changes in extreme sea levels in Europe (Section 2). We then describe the approach that has been taken within THESEUS to add to this knowledge (Section 3). In more detail, we describe results from analysing extreme sea level time series together with analyses of all the relevant individual components contributing to extreme sea level variability and change. In Section 4 our results are summarized and discussed.

2. Changing extreme sea levels in Europe: reviewing the present knowledge

The most prominent type of atmospheric disturbances that may produce wind fields severe enough to cause extreme sea levels around Europe are mid-latitude or extra-tropical cyclones. They tend to occur and to propagate within regionally confined areas, the so-called storm tracks (see e.g., Weisse and von Storch, 2009). For most of Europe, the influences from the North Atlantic storm track are most important; while for some areas such as the Mediterranean Sea secondary storm tracks may be relevant. Moreover, for some regions additionally smaller scale storms may be important, such as polar lows in the northern most parts of Europe (e.g., Zahn and von Storch, 2010) or Medicanes over the Mediterranean Sea (e.g., Cavicchia and von Storch, 2012). Extra-tropical cyclones play a major role in generating extreme sea levels and changes in their climatology such as their frequency, duration, or preferred path may have implications and consequences for coastal protection.

Direct wind speed observations are seldom used to assess changes in extreme wind speed climatologies because observational records are often short and compromised by in-homogeneities; that is, by e.g., changes in observing techniques that may cause spurious signals in particular when trends are considered (e.g., Weisse and von Storch, 2009). Instead past changes in extra-tropical storm activity are usually analyzed using either reanalysis or proxy data. Reanalysed data are obtained from state-of-the-art numerical models projecting the state of the atmosphere as known from a finite set of imperfect, irregularly distributed observations onto a regular grid (Glickman, 2000) while proxy data exploit existing physical relations between wind speed and a proxy variable such as air pressure gradients (e.g., Schmidt and von Storch, 1993).

For the Northern Hemisphere and based on reanalysis data, a number of studies report a noticeable poleward shift of the major storm tracks, increased storm activity, and/or a decrease in the number of extra-tropical cyclones during the second half of the twentieth century (e.g., Geng and Sugi, 2003; McCabe et al., 2001; Paciorek et al., 2002). Proxy data analysis confirms this result but, by covering longer time spans, demonstrates that such changes basically reflect inter-annual and decadal variability rather than systematic long-term changes. As a consequence, storm surges and extreme sea states also varied considerably on inter-annual and decadal time scales, but do not exhibit long-term systematic trends (see e.g., Gulev and Grigorieva (2004), Caires and Sterl (2005), or Izaguirre et al. (2011) for the global figure or Weisse and Günther (2007), Musić and Nicković (2008), Cieslikiewicz and Paplinska-Swerpel (2008), or Izaguirre et al. (2010) for regional studies in European coastal waters).

While for most areas, the storm-related contributions to extreme sea levels did not show any significant trend over periods longer than a few decades of years, extreme sea levels have nevertheless increased substantially at most places. This is illustrated, e.g., in studies of Woodworth and Blackman (2004) and Menéndez and Woodworth (2010) who analyzed extreme sea level changes in a global tide gauge data set. They showed that a substantial number of gauges showed significant increases in extreme sea levels over the analysed periods. By removing the contributions from mean sea level changes and from long (nodal) tidal cycles they demonstrated that most trends disappeared, indicating that observed trends in extreme sea levels are primarily a result of coherent changes in the mean sea level and of artefacts related to short-term trends in long-term astronomical tides. For the North Sea and the English Channel a similar result is described in von Storch and Reichardt (1997), Weisse et al. (2012) and in Haigh et al. (2010), respectively.

Future changes in storm surge and wind wave climate depend on corresponding changes in atmospheric wind and pressure fields that are highly uncertain (Christensen et al., 2007). Existing studies present a rather mixed picture with the confidence in future changes in wind climate in Europe remaining relatively low (Christensen et al., 2007). Following the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), a consistent result emerging among more recent studies appears to be a tendency for a poleward shift in storm activity of several degrees latitude in both hemispheres (Meehl et al., 2007), a tendency also visible in corresponding global wave climate projections (Mori et al., 2010; Semedo et al., 2013). Possible explanations have been discussed in, for example, Yin (2005) and Bengtsson et al. (2006, 2009) and are related to differential changes of the meridional atmospheric temperature gradient with height and associated changes in vertical stability. Regionally, large deviations from this large scale picture are possible and correspondingly, changes in wind wave and storm surge climate are needed on a local and a regional scale (e.g., Gaslikova et al., 2013; Grabemann and Weisse, 2008; Woth et al., 2006). The approach taken in the following text aims at providing such information consistently for a number of European coastal areas.

3. Recent advances: the THESEUS approach

The term 'extreme sea level' usually refers to the largest values in a particular record; that is, to events during which the sea level exceeds some site specified fixed level. The knowledge about and the methods to determine and to assess regional and local extreme sea level changes remains fragmented and varies regionally even at a European level. However, any long-term change in the statistics of extreme sea levels whether climatically induced or caused by other factors provide a challenge to coastal engineers because such changes may significantly modify present day risks. Climatically induced changes, in particular those associated with future changes in mean sea levels and/or wind wave and storm surge climate provide a particular challenge as they remain highly uncertain.

[1] See http://www.theseusproject.eu.

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