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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

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trends at least for the coming decades.

Keywords: extreme sea levels, mean sea level, wind waves, storm surges, climate change, European coasts

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; Pluess, 2006; Pickering et al., 2012). 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 (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 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.

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

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., McCabe et al., 2001; Geng and Sugi, 2003; 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 ofWoodworth 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., Woth et al., 2006; Grabemann and Weisse, 2008; Gaslikova et al., 2013). 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.

The European project THESEUS aims at developing innovative technologies for safer European coasts in a changing climate. Here we describe the approach that has been taken to provide the baseline information on changing extreme sea level statistics. 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 for the three different components contributing to the extremes: (i) mean sea level changes, (ii) wind waves and storm surges, and (iii), for relevant places, river floods. We start with a description of the analysis of extreme sea levels from total water level measurements (section 3.1). Subsequently contributions from different processes are discussed individually. Changes in mean sea level are discussed in section 3.2. Future atmospheric conditions that may drive corresponding changes in wind wave and storm surge climate or river floods are discussed in section 3.3. The latter are discussed by means of examples from the Emilia Romagna coast in Italy (section 3.4) and the Scheldt estuary in Belgium (section 3.5).

3.1. Extreme sea levels from total water level records

Time dependent extreme sea levels are analysed from total water level records at five tide gauges in different parts of Europe for which at least hourly data were available (Table 1). The analysis was made using monthly maxima and the statistical model proposed by Méndez et al. (2007) and Menéndez et al. (2009) for predicting the time-varying probability of occurrence for specific extreme sea level values. For details of this approach see

Appendix A.

The results of this exercise are summarized in Table 1 and Figure 1. Significant correlations of the magnitude and the variance of extreme sea levels with the nodal cycle were detected. Apart from Wladyslawowo which has a relatively short record for analysing nodal variations, the estimated nodal modulation in 50 year return levels is in the order of about 3 cm. Moreover, the records from Southern Europe, Santander and Venice, additionally show a statistically significant perigean modulation.

Apart from astronomical influences, the algorithm also reveals positive (upward) trends and strong seasonal (intra-annual) variability of extreme sea levels for all records. The latter is reflected by corresponding annual and semiannual cycles in the magnitude (location parameter) and the dispersion (scale parameter) of extreme sea levels, likely associated with the effect of higher storminess during winter season. The estimated linear trend is around 2-3 mm/year for all records, statistically significant at the 95% confidence level. Based on our analysis, a short-term extrapolation into the near-future (2025) is provided additionally, assuming a constant linear trend as estimated from the statistical model (Figure 1). Alternatively, other models accounting for a potential acceleration in the long-term trends could have been adopted (Church and White, 2011).

Summarizing, the results show that the strongest variations in extreme sea levels are associated with intra-annual variability (annual and semiannual), nodal variations and a long-term trend. By considering these factors and the different time scales of sea level variability, improved short-term forecasts of exceedance probabilities for extreme sea levels can be derived. The latter is essential for providing improved (time-varying) boundary conditions for coastal flood analysis.

3.2. Local mean sea level: Recent and future short term trends

Mean sea level is not expected to change uniformly over the globe and there is considerable variability in both the estimated rates of twentieth century sea level rise and the projected rates towards the end of the twenty first century. Moreover, comprehensive and reliable estimates of future regional and local mean sea level changes are lacking and there is considerable decadal variability in the observational records. This will continue and, at least over the next few decades, may be considerably stronger than the expected changes due to anthropogenic climate change.

To meet these challenges, a two-way approach was adopted. We rely on the extrapolation of observed decadal trends for short and medium time scales (2020s, 2050s); that is, as long as the decadal variability in the observed records is larger than the global mean changes projected by the IPCC (Meehl et al., 2007). For the long time scales, that is towards the end of the century, changes projected by the IPCC become more and more dominant and it is recommended to use the projections based on IPCC scenarios provided that no other information are available.

The most simple model for extrapolating observed decadal trends is persistence; that is, the next decadal (10, 20, 30-year and so forth) trend is the same as that of the previous period

$$z_{t+H} = a_t^H H + noise \tag{1}$$

where z denotes sea level, a denotes the decadal trend, t is time, and H denotes the decadal period for which the forecast is made. If we replace a_t^H by a_{t-H}^H a persistence estimate can be provided and a_{t-H}^H can be obtained by a regression onto the last H years of data. For short forecast intervals the skill of this simple model can be tested using historical data. Figure 2 shows an example for the Elbe estuary for the case of 15-year trends. When the latter are fitted to the period 1959-1974 and are used to provide a forecast for 1989 a good agreement can be inferred. When the same exercise is repeated in 1990, the forecast is less successful and the value observed 15 years later is outside the prediction interval. The skill of this simple model is shown in Figure 3. In the case of the Elbe estuary, using the simple model for 15-year trends would have produced a successful forecast in about 78% of all cases.

Based on available data, this simple model was used to provide estimates of local mean sea level changes at the same study sites as in section 3.1. Additionally, data for Devonport and Varna were considered. Venice was replaced with Trieste because of the strong subsidence in Venice (Table 2). For the short-term (2020s), there is considerable uncertainty in estimated rates of change because of the large inherent variability on these time scales. However, at the upper limit expected changes are generally up to about 10-20 cm within the next ten years, while at the lower limit even negative values cannot be excluded for all sites. For the past, the skill of these estimates generally varies between about 70 and 80%. For the 2050s, changes up to about 30 cm can be inferred. For this time scale the skill of the model cannot be tested because time series are generally too short to provide reliable estimates. With the exception of the Elbe estuary, time series are generally too short to provide estimates for the 2080s.

Figure 4 shows the local mean sea level changes obtained from extrapolating decadal trends at the various study sites together with those obtained from the IPCC projections. Note, that the comparison is somewhat inconsistent as we compare global with local changes and absolute with relative mean sea levels. However, some general conclusions can be inferred. In particular, for short and medium time scales uncertainty in projecting local mean sea level changes is considerably larger than the ranges provided by the IPCC for global mean sea level and for most cases higher or lower values are to be expected reflecting local processes not included in the IPCC projections. Such deviations from the global average include internal (decadal) variability, weather effects or local subsidence. We suggest that scenarios from extrapolating decadal trends should be used when shorter periods up to 2050 are of interest, while for longer periods more comprehensive regional and local mean sea level projections are required.

3.3. Atmospheric data for driving extreme sea level changes

Changes in wind speed, direction, and/or frequency and intensity of severe storms are of crucial importance for extreme sea level changes. Wind fields from a number of different climate change simulations were used in various ways to provide estimates on recent and potential future changes. For most study sites, wind fields from an ensemble of regionally downscaled IPCC scenario runs available at the World Data Centre for Climate, Hamburg, Germany were used. In these simulations, the regional climate model COSMO-CLM (see http://www.clm-community.eu/) was used in non-hydrostatic mode at a spatial resolution of 0.165 degrees (approx. 18 km) to downscale 6 hourly outputs from a global climate model (ECHAM5/MPIOM). The climate of the 20th century was simulated by three 20th century realization runs, set up at different initialization times. The climate of the 21st century was modelled with respect to two IPCC emission scenarios (A1B and B1) with different assumptions regarding the development of global greenhouse gas concentrations. From these simulations, hourly wind fields were available for all study sites.

Figure 5 shows the projected changes in mean wind speed around 2030 and 2085. While regional details and magnitudes of the projected changes vary considerably among the different simulations, some large scale consistency can be inferred. In particular in all simulations increases in mean wind speed appear to occur over and around the Baltic Sea as well as over the Aegean Sea while decreases are found over most of the Mediterranean and the Bay of Biscay. The pattern is generally noisier for the near future and appears to be more pronounced towards the end of the century. However, the projected changes are generally small and hardly exceed 5% in any of the simulations. Projected changes in extreme wind speeds towards the end of the century (not shown) broadly correspond to that obtained for mean wind speeds (Figure 5). The changes over the Mediterranean and the Bay of Biscay are, however, somewhat less pronounced and consistent (not shown).

3.4. Wind wave and storm surge simulations

To study possible changes in wind wave and storm surge climate hydrodynamical wind wave and tide-surge models were applied. Generally, these models were set-up for different study sites at European coasts and changes in wind wave and storm surge climate were analysed from comparing an ensemble of simulations in which these models were driven by atmospheric forcing representative for atmospheric conditions projected towards the end of the 21st century with an ensemble driven by present day atmospheric conditions. Here the approach is described in detail exemplarily for the coastal zone reaching from the coast of Emilia Romagna up to Venice in the North Adriatic Sea.

For this study, the Shallow Water Hydrodynamic Finite Element Model (SHYFEM) was used comprising a hydrodynamic core module coupled with a wind wave, a sediment transport, a bed load, and a dispersion module. Details and references for validation can be found in Umgiesser et al. (2004) and Bellafiore and Umgiesser (2010).

The model system was implemented covering the entire Adriatic Sea using an unstructured grid with the highest resolution in the study region; that is, close to the Northwestern end of the Adriatic Sea. The model was driven by the atmospheric forcing described in section 3.3. A comparison between the modelled and the observed wind climate in the 20th century was provided by Bellafiore et al. (2012). For the study region they found that the modelled data generally overestimate mean wind speed, except for Ravenna. Extreme wind speed in terms of 99 percentiles showed a reasonable agreement with observations suggesting a reasonable reproduction of extreme sea level events.

Climate change signals in wind climate over the study region were found to be small or moderate. Generally a small increase in mean atmospheric pressure and a decrease in mean wind speed were observed. Extremes in terms of 99 percentiles of near-surface marine wind speed and atmospheric pressure show a slight increase for the pressure values and a corresponding decrease in wind speed along the Italian coasts of the Adriatic Sea. Wind directions did not show substantial changes towards the end of the 21st century (Bellafiore et al., 2012).

From the SHYFEM model output significant wave height, total water level and surge residuals were extracted at four points along the Emilia Romagna coast. As an example, Figure 6 shows annual surge and significant wave height maxima, both for one realization of the 20th century climate and for one realization of the IPCC A1B scenario. There is considerable inter-annual and decadal variability in the meteorological induced parts of sea level extremes, but no clear trend. Similar results are obtained from the model simulations using forcing from the other climate change realizations described in section 3.3.

A similar analysis was performed for the 100-year return values. Generally for present day climate, the 100-year surge return values are about 10 cm higher at the northern stations (Bellocchio) where they reach values around 1.1 m. For the future, these values are not expected to change significantly according to our model simulations. A similar figure is obtained for the total water level. For significant wave height the figure appears to be more variable. Stronger effects are found for the southern stations (Cesenatico) where an increase in the 100-year return level from 4 m in 1960-1990 to 4.6 m during 2010-2039 was detected. Towards the end of the 21st century a decrease in 100-year return values of significant wave height was found over the entire study region. The latter suggests, that the projected increase during 2010-2039 reflects climate variability rather than a systematic trend in response to anthropogenic climate change.

To provide an indication on changes related to the severity of surge events we analyzed annual occurrences of events where surge height changes more than 20 cm within 1 h. Similarly to the results described above, there is substantial inter-annual and decadal variability, but no clear long-term trend. Summarizing, changes in wind and atmospheric pressure fields can be linked to corresponding changes in wave and surge regimes: the mean wind speed decrease and the mean atmospheric pressure increase partially explain some changes in wave and surge statistics. However, no significant trends are apparent and all observed values are consistent with present levels of variability.

3.5. River floods: inland-coastal climate scenario correlations

For coastal areas the river input to flood events can be significant, particularly if the coastal flood plain is located within the upstream parts of an estuarine environment. Here extreme water levels from the sea or rivers can occur individually or in combination. In the following, an approach to analyze joint occurrences is illustrated for the Scheldt estuary. In this estuary, three regions can be identified (Figure 7): the lower estuary, the upper estuary and the fresh tidal rivers region (de Brye et al., 2010). In the latter region, the water levels along the Scheldt river and the tributaries are influenced by coastal effects, upstream rainfall-runoff, and surface wind along the estuary. The climatic control of the upstream rainfall-runoff is caused by both, rainfall and potential evapotranspiration over the upstream catchment while coastal effects are mostly due to surges and changing mean sea levels.

Climatic changes of these estuarine forcings were investigated using statistical analysis of climate model projections provided by global climate model (GCM) runs of the IPCC's 4th Assessment Report Archive and the 31 and 18 regional climate model (RCM) runs from the EU-projects PRUDENCE (Räisänen et al., 2004) and ENSEMBLES (van der Linden and Mitchell, 2009) respectively. Additionally the regional simulations described in section 3.3 were utilized. From all climate model runs results were derived for the historical reference period 1961-1990 and the future period 2071-2100 (2080s). The results for the 2020s and 2050s were obtained by interpolation. Rainfall, potential evapotranspiration, wind speed and wind direction were obtained directly from the climate model outputs, while storm surges and changes in their statistics were estimated using a regression between coastal surge levels and mean sea level pressures over the Baltic Sea. For mean sea level rise, an increase of 60 cm (moderate scenario) to 200 cm (worst case scenario) by 2100 was chosen. This falls within the range of sea level rise projections from studies in neighbouring countries (Jensen and Soerensen, 2010; Lowe et al., 2009).

The highest surge changes were found to be around 21% while daily rainfall extremes were found to change by up to 30% towards the end of the 21st century. Near-surface wind climate did not change significantly. In the following, future wind climate was therefore assumed to be the same as for the recent past.

The climatic changes in coastal surges and inland rainfall together with their correlations (Ntegeka et al., 2012) were transferred to changes in historical time series providing the boundary conditions for a hydrodynamic model of the river Scheldt and one of its tributaries, the river Dender. This tributary river connects with the Scheldt at the city of Dendermonde, a flood prone area where the flood hazard is controlled by both, coastal and inland boundary conditions. The full hydrodynamic river model involves a 1D implementation of the rivers, and schematization of the floodplains along the river using a quasi-2D approach. This means that each floodplain was implemented by a network of 1D flood branches and spills (Willems et al., 2002) where the flood branches represent the topographical depressions and the spills the topographical elevations between these depressions.

Using the model, flood hazard maps were generated for return periods in the range between 1 year and 10,000 years. To do so, synthetic events were created as boundary conditions. These synthetic events were derived from an extreme value analysis of "nearly independent" extreme events extracted from historical time series of upstream river flow and coastal sea levels. This analysis was done for a range of aggregation levels (time scales over which the peak flows or coastal sea level maxima are averaged), to obtain composite river hydrographs (for the upstream boundaries) and coastal limnigraphs (for the downstream boundary) (Ntegeka et al., 2012).

Climatic changes to the model boundaries were introduced as perturbations derived from a quantile perturbation method accounting for seasonal effects (Willems and Vrac, 2011; Ntegeka et al., 2013). In the case of rainfall, the quantile perturbation method also accounts for changes in the number of wet/dry days next to the changes in rainfall intensities. The method also allows statistical downscaling from the relatively coarse time and space scale of the climate models to the hourly time scale and the spatial sub-catchment scale required for flood studies along rivers taking correlations between surges and rainfall into account.

In a first step, perturbed time series were produced for each RCM/GCM run available. In a second step, a limited set of "tailored scenarios" was derived (Figure 8) allowing the obtainment of impacts for the same range as provided by the full set of RCM/GCM scenarios. The tailored scenarios were subsequently applied to the time series of up- and downstream boundary conditions. The perturbed rainfall and potential evapotranspiration series were then processed by the rainfall-runoff models of the upstream catchments and transferred into perturbed time series for the upstream inflow into the Scheldt model. Coastal effects were treated similarly and, together with the modified upstream inflow, were used to derive the quantile perturbation factors. These factors were subsequently applied to the composite river hydrographs and coastal limnigraphs.

The impact of the tailored climate scenarios was studied on water levels along the Scheldt from Vlissingen on the Dutch coast to the city of Ghent in Belgium (2020s, 2050s, 2080s) for return periods up to 10,000 years. Particular focus was given to the water levels at Dendermonde. For that location, the impact on the flood maps was also studied. The results for a high impact scenario are shown in Figure 9. It can be inferred that the flooded areas increase from the short-term to the long-term and with increasing return periods.

To analyse the relative contributions from the different sources, changes in mean sea level, surge and upstream flow were considered individually. It was found that for the 100-year flood in the high impact scenario, changes in upstream river flow was the least important factor controlling the flood volume (factor change in flood volume of 1.03). Mean sea level rise was associated with a change factor of 1.71 while changes in surge climate provided the largest effect (change factor 5.19). This implies that the sea level rise and surges are by far the most important factors when evaluating the flood risk in the Dendermonde region. In combination the change factor was about 8 for the high impact scenario, meaning that the 100-year flood volume for the future 2080s is about eight times the current 100-year return volume for the Dendermonde area. For the mean scenario, the combined change factor was still about 3.78.

4. Summary

Extreme sea levels, their past and potential future changes were assessed for various places around Europe using a common approach. The approach consists of a combination of statistical tools, data analysis, and dynamical modelling. Extreme sea level changes were analysed from observations and a statistical model was developed to account for seasonal and nodal variations and to provide extrapolations into the near-future. Subsequently, the various potential contributions to extreme sea level changes were analyzed separately. For mean sea level changes, a statistical approach was adopted while for the meteorologically induced contributions from storm surges and wind waves dynamical model projections were used. For river floods, a combination of dynamical modelling and statistical downscaling was applied.

While the results vary in detail for the various places, some general inferences can be obtained. In particular, extreme sea levels show pronounced seasonal to decadal variability associated with seasonal variations and the nodal tidal cycle. On decadal scales variations in the storm climate also play a role. Extreme sea levels have generally increased over the past 100 years or so which is primarily a result from corresponding increases in mean sea levels. The latter may arise from climatic changes and/or land movements, water works etc.

For the near future it is expected that decadal variability will remain to provide substantial contributions to the expected changes in extreme sea levels. On the longer run, mean sea level changes will probably remain the largest contributor to the expected changes. These results have important consequences for coastal flooding and coastal engineering, long-term planning and possible adaption responses. They have provided the basis for the subsequent studies in the THESEUS project discussed in this issue.

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Appendix A. Time dependent extreme value analysis

The approach allows the identification and estimation of the effects of seasonality, inter-decadal variability, and secular trends on the magnitude, dispersion and shape parameters of the probability distribution of extreme sea levels. These factors are parameterized as functions of time. The approach starts from the Generalized Extreme Value (GEV) distribution for block maxima (monthly maxima) given by

$$F(z,\Theta) = \exp\{-[1+\zeta(1-\mu)/\Psi]_+^{-1/\zeta}\} \tag{A.1}$$

where $\Theta = \Theta(\mu, \Psi, \zeta)$ is a vector parameter, $[\ldots]_+ = max(0, \ldots)$, and μ, $\Psi > 0$ and ζ are the location parameter, the scale and the shape parameter respectively. The approach requires that block maxima of successive months are independent and identically distributed (iid) random variables; a condition, often not given in observational data as they are serially correlated. To address this issue, we make use of an extension of the standard models of extreme value theory for non-stationary variables. We assume that the monthly maximum sea levels z_t observed in month t follows a GEV distribution with time-dependent location parameter $\mu(t)$, scale parameter $\Psi(t) > 0$, and shape parameter $\zeta(t)$. We propose the following aggregation of factors for the location, scale and shape parameters, respectively

$$\begin{aligned} \mu(t) &= \mu(t)_{seasonal} + \mu(t)_{nodal} + \mu(t)_{perigean} + \mu(t)_{LT} \\ \Psi(t) &= \Psi(t)_{season} + \Psi(t)_{LT} \\ \zeta(t) &= \zeta(t)_{season} \end{aligned} \tag{A.2}$$

This allows the time-dependent statistical model to be influenced by different time scales: seasonality, perigean and nodal influences, and long-term trends. As an example, a model including in the location parameter an annual and a semi-annual cycle for the seasonality and a linear long-term trend is parameterized as:

$$\begin{aligned} \mu(t) &= \mu(t)_{seasonal} + \mu(t)_{LT} \qquad \text{(A.3)} \\ &= \beta_0 + \beta_1\cos(2\pi t) + \beta_2\sin(2\pi t) + \beta_3\cos(4\pi t) + \beta_4\sin(4\pi t) + \beta_{LT} t \end{aligned}$$

where t is given in years and the long-term trend is represented by β_{LT}.

The estimate of the return sea level value $\overline{z_R}$ for a certain year t_i is obtained by iteratively solving

$$1 - 1/R = \exp\left\{ \int_{t_i}^{t_i+T} [1+\zeta(t)(\overline{z_R} - \mu(t))/\Psi(t)]_+^{-1/\zeta(t)} dt \right\} \tag{A.4}$$

where T is one year. Confidence intervals can be obtained by the delta method, assuming approximate normality for the maximum likelihood estimators.

The modulation of the nodal cycle is introduced in the location and scale parameters proposing $\mu_N(t) = \beta_{N_1} \cos(\omega_N t) + \beta_{N_2} \sin(\omega_N t)$ and $\Psi_N(t) = \alpha_{N_1} \cos(\omega_N t) + \alpha_{N_2} \sin(\omega_N t)$ where $\omega_N = 2\pi/T_N$ and T_N =18.6 years. A similar parameterization for the perigean cycle with T_P =4.4 years is proposed.

We use standard likelihood theory to obtain the model parameter estimates $\hat{\Theta}$ and the confidence intervals (Méndez et al., 2007). An automatic selection algorithm, based on the likelihood ratio test, is carried out to achieve the best model following the principle of parsimony (see details in Menéndez et al., 2009).

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	Wladyslawowo, Poland	Cuxhaven, Germany	Ostend, Belgium	Santander, Spain	Venice, Italy
Period	1970-2000	1918-2005	1925-2001	1943-2009	1940-2010
β_0	5.291	7.065	4.844	4.785	0.695
α_0	0.197	0.361	0.163	0.162	0.132
γ_0	-0.204	0.006	-0.011	-0.334	-0.131
β_1	0.146(1)	0.226(2)	0.132(1)	0.069(2)	0.096(3)
β_2	$-0.124(1)$	$-0.118(2)$	0.002(1)	$-0.018(2)$	0.014(3)
β_3	0.040(5)	0.037(4)	$-0.028(4)$	$-0.098(1)$	0.060(4)
β_4	0.013(5)	0.018(4)	$-0.056(4)$	0.072(1)	$-0.034(4)$
α_1	0.103(2)	0.188(1)	0.066(2)	0.030(4)	0.044(2)
α_2	$-0.015(2)$	$-0.012(1)$	0.034(2)	$-0.014(4)$	0.041(2)
α_3					
α_4					
γ_1	$-0.104(3)$				0.038(6)
γ_2	0.159(3)				$-0.062(6)$
γ_3					
γ_4					
β_{LT}	0.003(4)	0.003(3)	0.002(3)	0.002(3)	0.003(1)
ω_{LT}					
β_{N1}		$-0.028(5)$	0.022(5)	0.030(5)	
β_{N2}		$-0.016(5)$	$-0.019(5)$	0.004(5)	
β_{P1}				$-0.017(6)$	0.008(5)
β_{P2}				0.007(6)	$-0.015(5)$

Table 1: Period of data availability and estimated parameters for the best model for total sea level in each location. The priority order (given in brackets) indicates the importance of each factor in the definition of the best model.

	Period	2020	2050	2080
Gdansk	1951-1999	-7 . . . 10 (86%)		
Cuxhaven	1843-2008	-5 . . . 21 (79%)	1 . . . 29	6 . . . 34
Ostend	1925-1999	-1 . . . 11 (81%)	6 . . . 24	
Devonport	1962-2008	-3 . . . 4 (80%)	-6 . . . 22	
Santander	1944-2009	-3 . . . 11 (69%)	1 . . . 20	
Trieste	1939-2009	-3 . . . 7 (67%)	12 . . . 23	
Varna	1929-2006	-4 . . . 7 (67%)	-6 . . . 18	

Table 2: Relative mean sea level changes in cm relative to 2010 based on the extrapolation of decadal trends from observations. Data for Devonport were kindly provided by Dr. Ivan Haigh; see Haigh et al. (2009). Numbers in brackets indicate the skill of the model when applied to the historical time series.

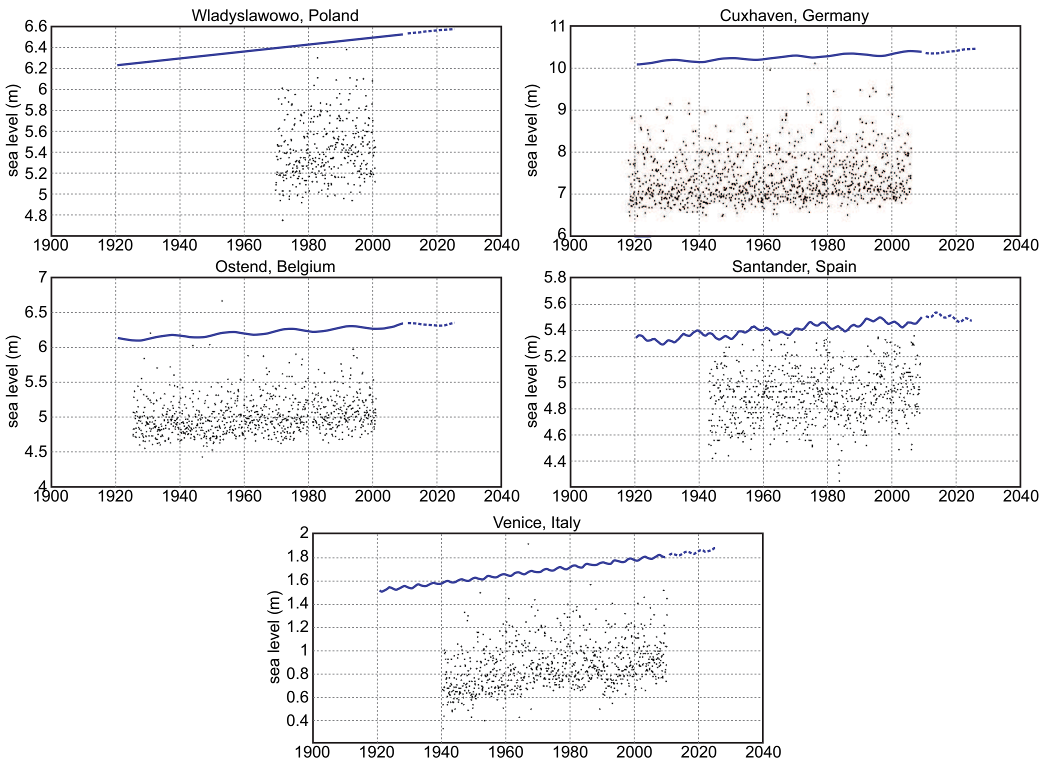

Figure 1: Monthly maxima (dots) and 50 year return values of extreme sea levels (solid, blue) estimated from hourly observations at five tide gauges in various places in Europe. Additionally a short-term extrapolation of the 50-year return value is shown (dashed, blue).

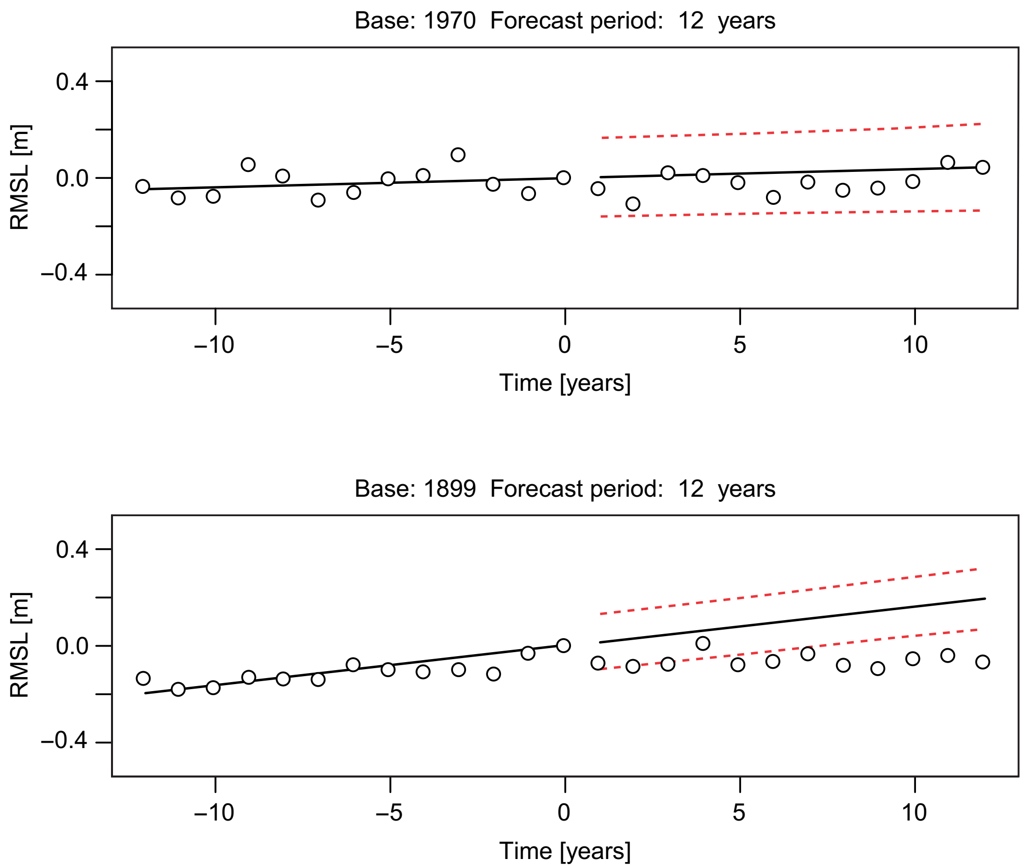

Figure 2: Skill of the simple model for extrapolating observed decadal sea level trends in the Elbe estuary. Good example (top), bad example (bottom). Observations relative to the year from which the fit and forecast are initiated are shown as dots; solid lines denote the decadal trend fitted to the previous 15 years and used for predicting the next 15 years. Red dashed lines denote the 95% confidence intervals of the forecast.

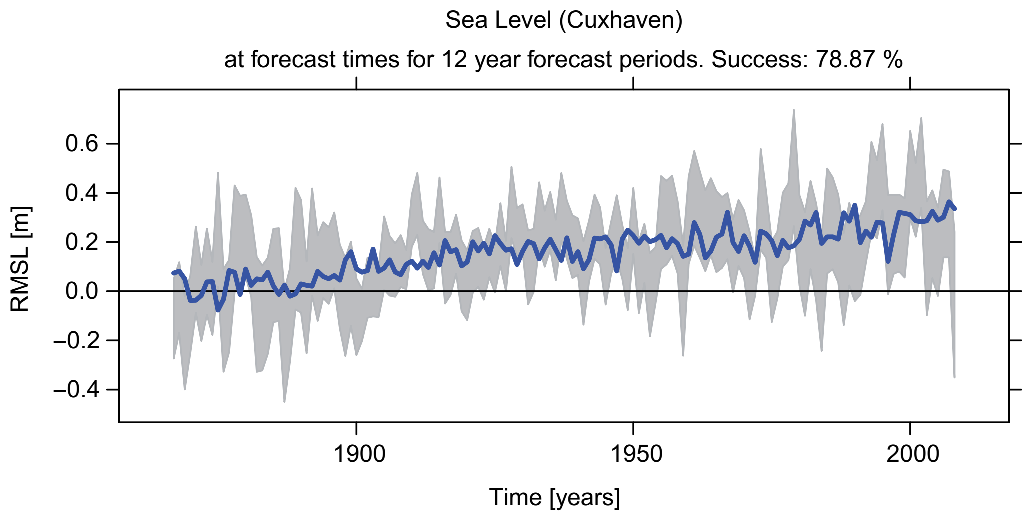

Figure 3: Skill of the simple model for extrapolating observed decadal sea level trends in Cuxhaven. Forecast range (grey) and observed values (blue, solid line).

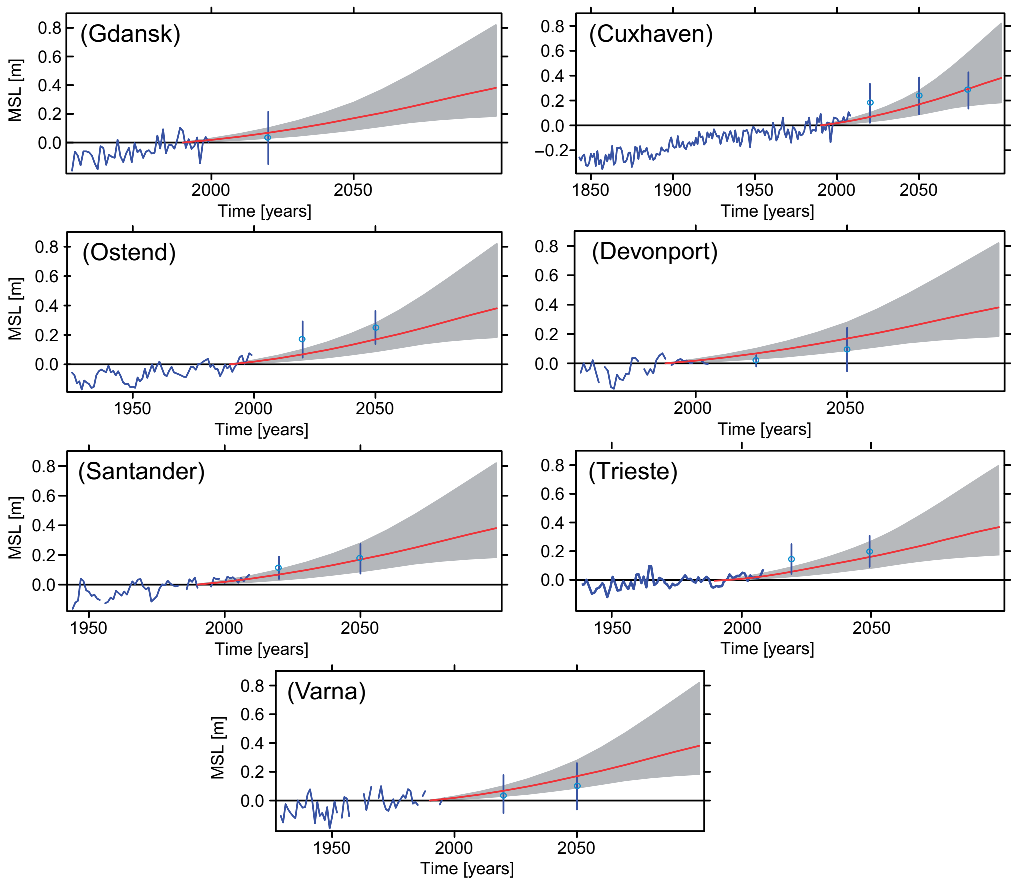

Figure 4: Observed (blue) and projected mean sea level changes relative to 1990. Circles with blue vertical lines indicate projections for relative regional mean sea level changes in 2020, 2050, and 2080. The grey shaded area provides the adjusted 5-percentile minima and 95-percentile maxima of global mean sea level derived from the IPCC projections; the red line represents the corresponding median. For details see http://www.cmar.csiro.au/sealevel/sl_proj_21st.html.

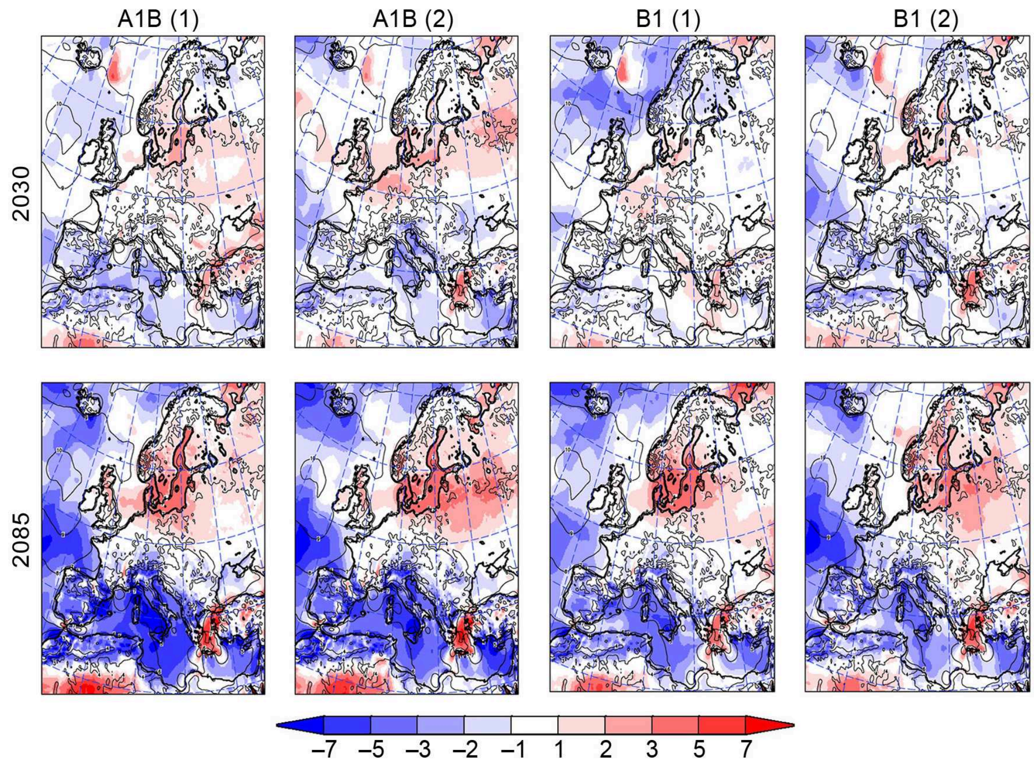

Figure 5: Percent changes in mean wind speed around 2030 (top) and towards the end of the century (bottom) relative to present day conditions obtained from the COSMO-CLM runs driven by the A1B (left two columns) and the B1 (right two columns) emission scenario. Note that for each emission scenario two different simulations from slightly different initial conditions were produced (A1B(1), A1B(2) and B1(1), B1(2) respectively).

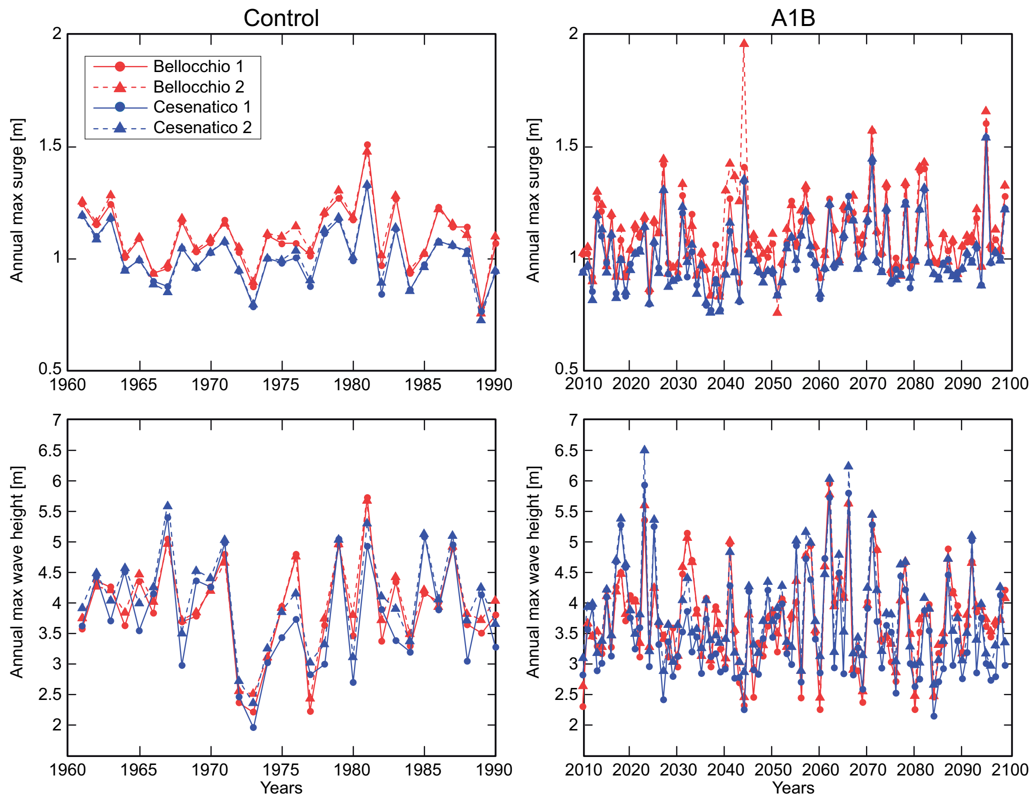

Figure 6: Annual surge (top) and significant wave height (bottom) maxima for the control period 1960-1990 (left panels) and for the IPCC A1B scenario 2010-2100 for the four considered points, Bellocchio1 and Cesenatico1, located more inshore and Bellocchio2 and Cesenatico2, a few kilometres offshore of the Emilia Romagna coast.

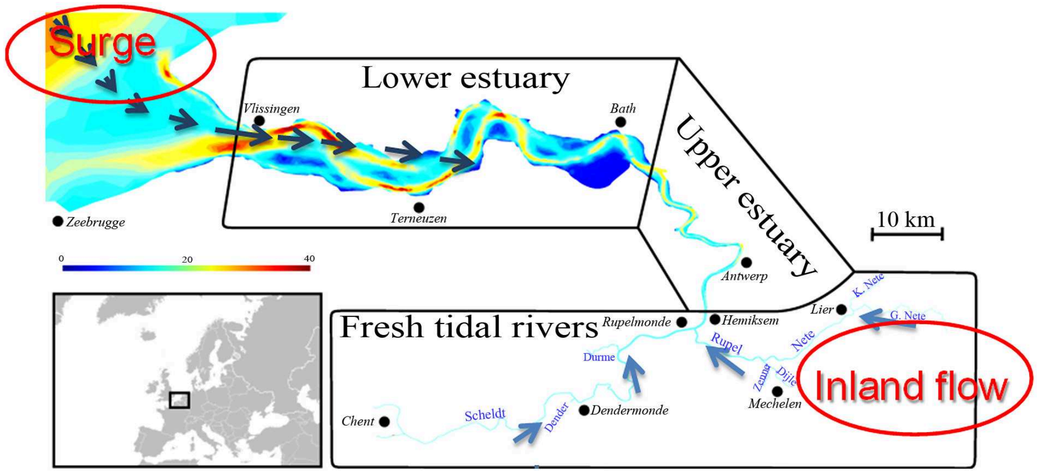

Figure 7: The lower, upper and fresh tidal rivers regions of the Scheldt estuary, the upstream inland river flow boundaries in the fresh tidal rivers region, and the downstream coastal boundary at Vlissingen influenced by the mean sea level and the surge, adapted from de Brye et al. (2010).

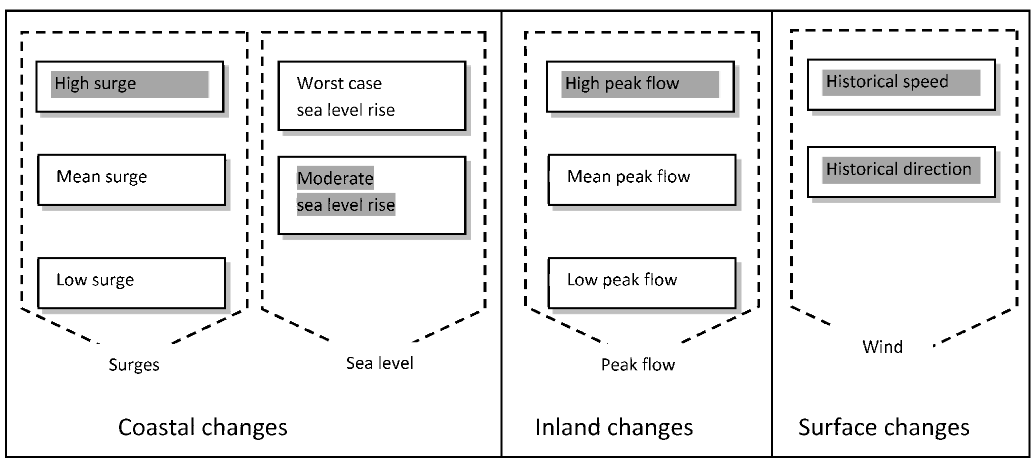

Figure 8: Climate change scenarios for the coastal, inland and surface boundary conditions of the Scheldt estuary. The high impact scenario combinations for the three boundary conditions are shaded grey.

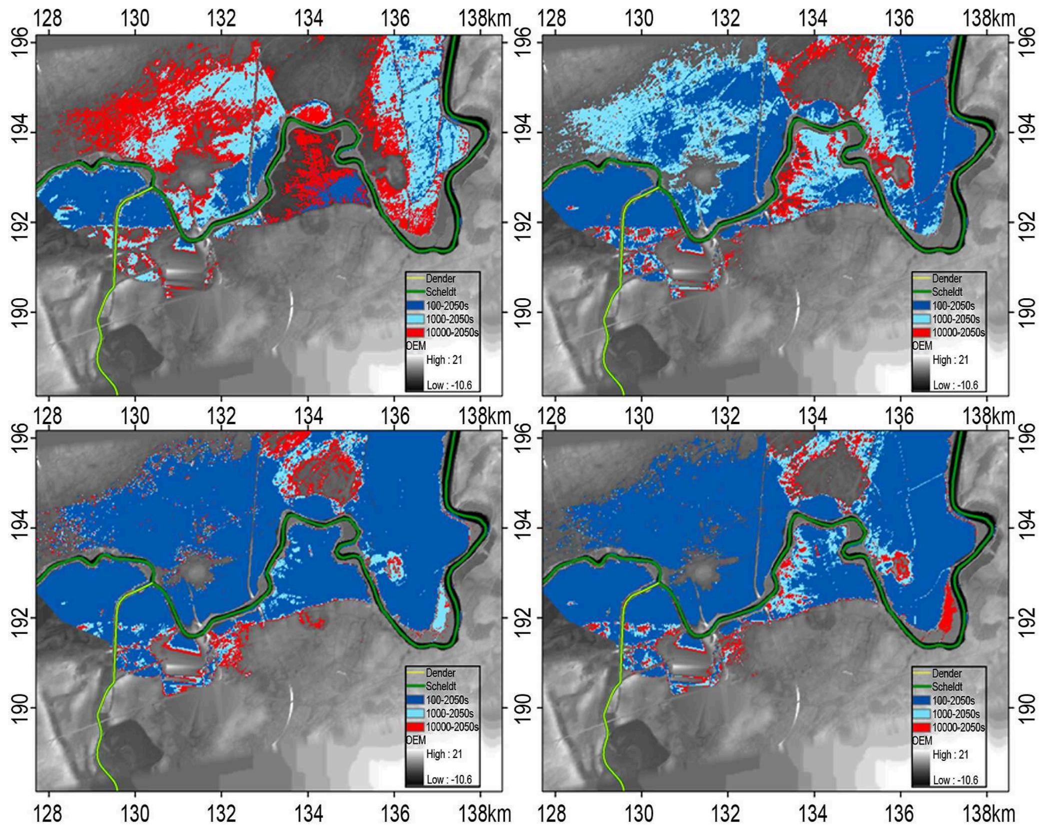

Figure 9: Flood hazard maps (top left, 1990s; top right, 2020s; bottom right, 2050s; bottom left, 2080s) for return periods of 100, 1000 and 10000 years, after simulation of the correlated upstream composite hydrographs and downstream limnigraphs for the high impact scenario combinations for the three boundary conditions, at the Dendermonde area, confluence of rivers Scheldt and Dender