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Simulated extreme sea levels at Helsinki

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We present an assessment of the exceedance probabilities of sea levels at Helsinki, on the coast of the Gulf of Finland in the Baltic Sea, based on an 850-year numerical sea-level simulation. The internal sea-level variations in the Baltic Sea are calculated with a two-dimensional hydrodynamic model, whereas the variations in the Baltic Sea water volume are evaluated using a statistical model based on the geostrophic wind speeds near Bornholm. The atmospheric data used for the sea-level simulation is taken from downscaled regional climate scenario simulations. The simulated sea-level extremes at Helsinki in the current climate are slightly smaller than the previous estimates which were based on measured data only. The extrapolation of simulated data gives an estimate of sea level 227 cm at Helsinki for the exceedance frequency of 10^{-4} events per year. The sum of the maxima of the model components during a short 30-year verification period indicates that sea level 225 cm is possible at Helsinki if all the components simultaneously attain their maxima.

Introduction

The Baltic Sea (Fig. 1) is a semi-enclosed basin, connected to the North Sea through the Danish Straits. The long-term changes in the Baltic Sea level (on multi-year time scale) are governed by the postglacial land uplift and the mean sea-level rise due to global mean sea-level rise which is predominantly due to global warming. In the Baltic Sea, the main factors causing short-term sea-level variation on a timescale of days are wind, air pressure and seiche (internal oscillation). The range of the tidal variation in the Baltic Sea is typically small, but in the Gulf of Finland it is somewhat greater than elsewhere: 12 cm at Helsinki and 15 cm at Hamina (values are based on our new analyses of tide gauge observations). On a timescale from weeks to months, the most important factor affecting the sea level is the water volume in the Baltic Sea, which is mainly controlled by the water inflow and outflow through the Danish Straits. The extreme values of the Baltic Sea level are due to these factors, and the greatest extremes always result from their joint effect.

The sea level has great significance for the people living in the vicinity of the seashore. A major sea flooding can cause great damage, as has often been the case in St. Petersburg at the easternmost end of the Gulf of Finland, and sometimes even in the entire Gulf of Finland, e.g., during the flood in January 2005 (Suursaar *et al*. 2006b, Tõnisson *et al*. 2008, Averkiev and Klevannyy 2010). The effects of climate change on the mean and extreme values of the sea level have been studied using regional climate simu-

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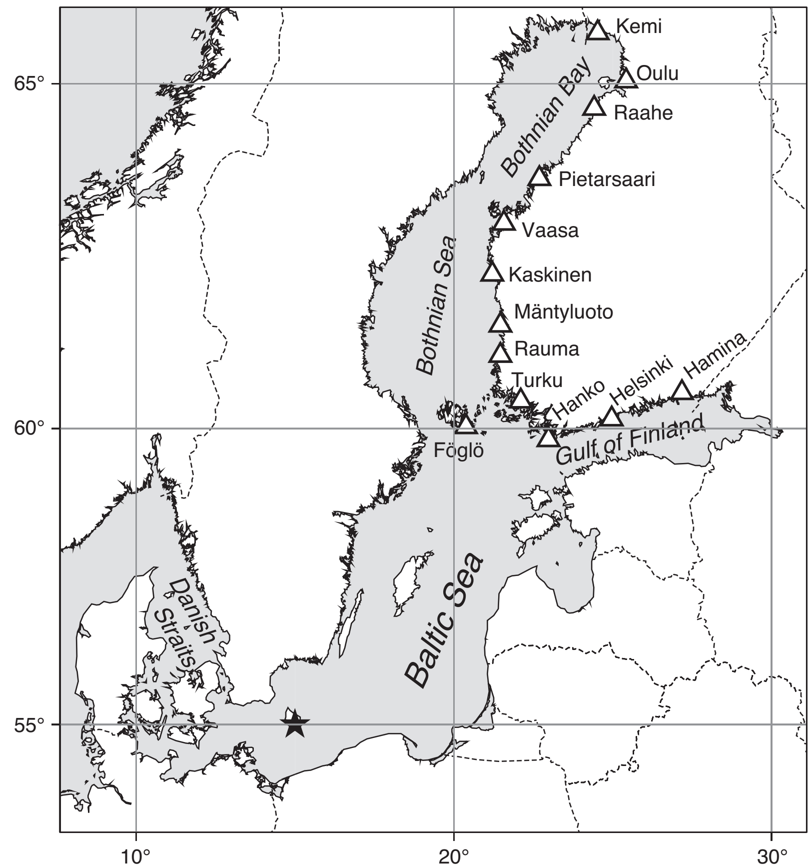

Fig. 1. Map of the Baltic Sea. Locations of the Finnish tide gauge stations are marked with triangles. The star denotes the point (55°N, 15°E, on Bornholm) from which the geostrophic wind was used for calculating the water balance sea level component.

lation data. These studies encompass, e.g., the entire Baltic Sea (Meier *et al*. 2004, Suursaar *et al*. 2006a, Hünicke 2010), the western Baltic Sea (Gräwe and Burchard 2012), and the North Sea (Woth *et al*. 2006, Sterl *et al*. 2009, Gaslikova *et al*. 2013).

The evaluation of flooding risks is important for guaranteeing the safety of coastal infrastructure, for maritime transportation, and for urban planning. Evaluations of flooding risks and return periods of high sea levels have been made for the Estonian coast (Suursaar and Sooäär 2007, Eelsalu *et al*. 2014), the eastern Baltic Sea (Soomere and Pindsoo 2016) and for selected stations on the Baltic Sea coast (Wolski *et al*. 2014). For the Finnish coast, future probabilities of sea floods have been estimated from exceedance frequency 1/20 to 1/250 events per year from present up to the year 2100 (Kahma *et al*. 2014). The focus in Kahma *et al*. (2014) was to estimate the combined effect of the global mean sea-level rise and short-term variations, the latter being based on statistics of sea-level measurements. The non-stationarity of the measured sea level (even when the land uplift and global mean sea level rise has been removed; *see* Johansson *et al*. 2001) reduces the about 110 years of measured data in Helsinki to the most recent 30 years. In 2100, the uncertainties of the global mean sea-level rise dominate, and therefore the uncertainties from the short 30-year time range are of secondary importance. However, there are places, such as the entrances into metro tunnels or other tunnels containing vital infrastructure under Helsinki, where an exceedance frequency of 1/250 events per year even at present is not safe enough. Estimating the smaller exceedance frequencies than 1/250 using the measured sea level data would be very uncertain. Hence, it is imperative to perform long-term sea-level simulations that exceed the length of the available sea level observation data. The present three-dimen-

Table 1. Climate data used in the present study.

Institute	Time range	Time resolution (hours)	Global climate model	Regional climate model	Climate simulation type	Symbol of simulated sea levels
ECMWF	1961–2000	6	–	ERA-40	Reanalysis	z_{ERA}
ECMWF	1979–2012	6	–	ERA-Interim	Reanalysis	z_{ERA}
C4I (Ireland)	1961–2000	6	ERA-40	RCA3	Control	z_C
ETHZ (Switzerland)	1961–2000	3	ERA-40	CLM	Control	z_C
MPI (Germany)	1961–2000	6	ERA-40	MPI-M-REMO	Control	z_C
KNMI (Netherlands)	1961–2000	3	ERA-40	RACMO2	Control	z_C
SMHI (Sweden)	1961–2000	3	ERA-40	RCA	Control	z_C
C4I (Ireland)	1951–2100	6	HadCM3Q16	RCA3	Scenario	z_S
ETHZ (Switzerland)	1951–2100	3	HadCM3Q0	CLM	Scenario	z_S
MPI (Germany)	1951–2080	6	ECHAM5	MPI-M-REMO	Scenario	z_S
KNMI (Netherlands)	1951–2100	3	ECHAM5r3	RACMO2	Scenario	z_S
SMHI (Sweden)	1961–2100	3	BCM	RCA	Scenario	z_S
SMHI (Sweden)	1961–2100	3	HadCM3Q3	RCA	Scenario	z_S

sional ocean models demand so much computing power that a simulation of 1000 years would take several years with our present computing resources. Therefore, we have developed a new, combined model approach, which enables several centuries of sea-level simulations to be run in a couple of hours with essentially the same accuracy as the present three-dimensional models.

In this study, we extended the sea-level observation data by modelling to 850 years. Besides the new sea-level model, in which the sea level components were analysed and modelled separately rather than making simulations by a single comprehensive model, we took advantage of the large set of meteorological simulations. These simulations are based on climate models and used 850-year atmospheric data taken from the downscaled regional climate scenario simulations produced in the ENSEMBLES research project, forced by different global climate models used in CMIP3 modelling experiments (van der Linden and Mitchell 2009). The simulations based on greenhouse gas scenario A1B were used in our study. Finally, extreme value analysis was applied to the simulated sea level data to estimate the exceedance probabilities of extreme sea levels.

Material and methods

Climate data

The observed meteorological time series cover 100 or at most 200 years. For longer timescales, synthetic meteorological conditions from climate models can be used as an atmospheric forcing for a sea-level model to estimate the extremes. There are several global and regional climate model simulations available in various databases. Some of these simulations have been conducted to project future climate conditions, while some simulate climate under past external forcings, including responses to, e.g., greenhouse gas concentrations and volcanic eruptions.

Table 1 summarises the data and boundary forcing used in this study. The sea-level model was calibrated using the ERA-40 reanalysis data set (Uppala *et al*. 2005), followed by the validation with the ERA-Interim reanalysis data (Dee *et al*. 2011). Regional climate models from the ENSEMBLES research project (van der Linden and Mitchell 2009) were selected for the extreme sea level simulations instead of global models, because regional models are able to increase spatial variability by reproducing the medium- and small-scale low pressure systems not simulated by global models. At the time of data collection, the most up-to-date European regional simulations from the CORDEX project (Jacob *et al*. 2013) were not published yet.

Derivation of surface winds

Since surface winds were not available from all climate models, a downscaling procedure was applied to derive them from the sea-level air-pressure fields, from which the geostrophic winds were first calculated. In the procedure, the linear regression coefficients between the geostrophic and surface winds of the ERA-Interim were derived separately for wind direction and speed in each cell of the numerical grid, and these coefficients were then applied to the geostrophic wind fields of all climate models to get the surface winds.

Validation of regional climate models

In the ENSEMBLES project, ERA-40 was used to force the regional climate models for the period 1961–2000. In our study, these hindcast simulations were used to validate the performance of the regional climate models by comparing the sea level results from hindcast runs with the results when ERA-40 was used directly as input for the sea level model. Additionally, the quality of the meteorological regional climate data was evaluated by studying the differences between the hindcast simulations and the ERA-40 as indicated by (1) the root mean square error of the sea-level air-pressure fields, (2) the distributions of the meridional air-pressure gradient over the Baltic Sea, and (3) the distributions of shape parameters describing the spatial extent and intensity of the low-pressure systems. Based on these comparisons, out of 11 models we selected six best-performing regional climate models to be used in this study (Table 1).

Climate scenario simulations

For the synthetic input for the sea-level model, the regional climate model simulations conducted using the CMIP3 global climate model output as boundary forcing were used for the period 1951–2100 (Meehl *et al*. 2007). Altogether 850 years of synthetic atmospheric forcing data was collected from the output of six quality-controlled regional models. The greenhouse gas forcing for the future part of the simulations, A1B, represents a moderate or moderate-pessimistic increase of greenhouse gases in the atmosphere, and is comparable with the RCP6.0 forcing of the more recent CMIP5 simulations (Taylor *et al*. 2012). As both the CMIP3 and CMIP5 indicate similar results for future winds, with multi-model mean climate change signal for the wind speed being weak and the inter-model variability being rather large (Haarsma *et al*. 2013, Lee *et al*. 2013), we expect that the use of the older CMIP3 background data instead of the newer CMIP5 is adequate.

Sea level data

Measurements from 13 tide gauges in 1961–2012 on the Finnish coast (Fig. 1 and Table 2) were used for the calibration and verification of the sea level model. Up to 1970, sea-level measurements are available in digital form with resolution of four hours; from 1971 onwards hourly sea-level data are available for all tide-gauge sites. The observed sea levels are given in the Finnish height system N2000, based on the third precise levelling of Finland (1978–2006). The datum corresponds to the Normaal Amsterdams Peil (NAP), as in the common European Vertical Reference Frame 2000 (EVRF2000; Saaranen *et al*. 2009).

Sea level modelling

The numerical sea-level model used in our study consists of five components: an intra-basin component that treats the Baltic Sea as a closed basin, a water-balance component describing the variations of the water volume of the Baltic Sea, a tidal component, a land-uplift component and a global mean sea-level-rise component.

The short-term local variations in the Baltic Sea level are mainly described by the intra-basin component. To model the intra-basin variations, we used a numerical sea-level model (Häkkinen 1980), based on the sea-level model developed by Hansen (Hansen 1956). This model captures short-term sea-level dynamics (periods and heights of sea level oscillations) well even on a sparse grid, enabling extremely fast numerical simulations. The Hansen sea-level model is a one-layer model derived from the Navier-Stokes equations. The model uses the surface winds as input data, and as output the model gives the mean water flow, from which the height coordinate is integrated out. The equations of the Hansen model were solved numerically using a finite difference method. The original model (Hansen 1956) did not include the direct effect of atmospheric air pressure; this was added to the model later (Häkkinen 1980). The spacing of the numerical grid was 0.25° in the meridional direction and 0.5° in the zonal direction. The model gives valid results even with this grid resolution.

The variations of the water volume of the Baltic Sea are described by the water balance component. The water volume of the Baltic Sea is mainly determined by the water exchange through the Danish Straits. This water exchange depends on the air pressure conditions in the Baltic Sea region and its vicinity. The variations in the Baltic Sea level can thus be connected with the NAO index (Johansson *et al*. 2001, Andersson 2002, Dailidiene *et al*. 2006, Suursaar and Sooäär 2007), the air pressure gradient across the North Sea (Gustafsson and Andersson 2001), or the sea level pressure field on the North Atlantic (Hünicke *et al*. 2008).

The evaluation of the Baltic Sea water volume in the present study was based on the recently found high correlation (r = 0.91–0.94) between the annual averages of the zonal wind at the location 55.0°N and 15.0°E (situated on Bornholm) and the annual averages of the sea level at the Finnish tide gauges (Johansson *et al*. 2014). There also exists a correlation (r = 0.5–0.8) between the monthly averages of the zonal wind at the same location and the monthly mean sea levels in the Baltic Sea excepting the southwestern part (*see* Johansson and Kahma 2016). As there is also a correlation between daily averages of the zonal wind in Bornholm and hourly sea level values of the Finnish tide gauge sites, we can express the water balance component $h_{WB}(t)$ as a function of the regression coefficients $\alpha(T)$ and the zonal Bornholm winds $\nu_B(t)$ of the preceding 65 days

$$h_{WB}(t) = \sum_{T=1}^{65} \alpha(T)\nu_B(t-T), \qquad (1)$$

where t is the time in days and T is the difference in days between the Bornholm wind and sea level. We applied the Fourier transform to calculate the regression coefficients for all the Finnish tide gauge sites, using the measured sea levels of years 1961–2000 and ERA-40 reanalysis data for the calculation of both the zonal wind at Bornholm ν_B and the intra-basin sea-level component (Fig. 2). It turned out that the regression coefficients were almost identical for all the Finnish tide gauges when the first four days were excluded. This can be understood if the water balance term describes the changes in the total water volume of the Baltic Sea instead of representing a location-dependent local effect of wind on sea levels. We fitted an exponential function to the regression coefficients, $\alpha(T)$, after four days, and

Table 2. Finnish tide gauges used in the verification of the sea level modelling. Coordinates are given in ETRS89 (WGS84) system. Tide gauge observations 1961–2012 were used in the present study.

Tide gauge site	Coordinates
Kemi	65.67291N, 24.51526E
Oulu	65.04030N, 25.41820E
Raahe	64.66590N, 24.40708E
Pietarsaari	63.70857N, 22.68958E
Vaasa	63.08150N, 21.57118E
Kaskinen	62.34395N, 21.21483E
Mäntyluoto	61.59438N, 21.46343E
Rauma	61.13353N, 21.42582E
Föglö	60.03188N, 20.38482E
Turku	60.42828N, 22.10053E
Hanko	59.82287N, 22.97658E
Helsinki	60.15363N, 24.95622E
Hamina	60.56277N, 27.17920E

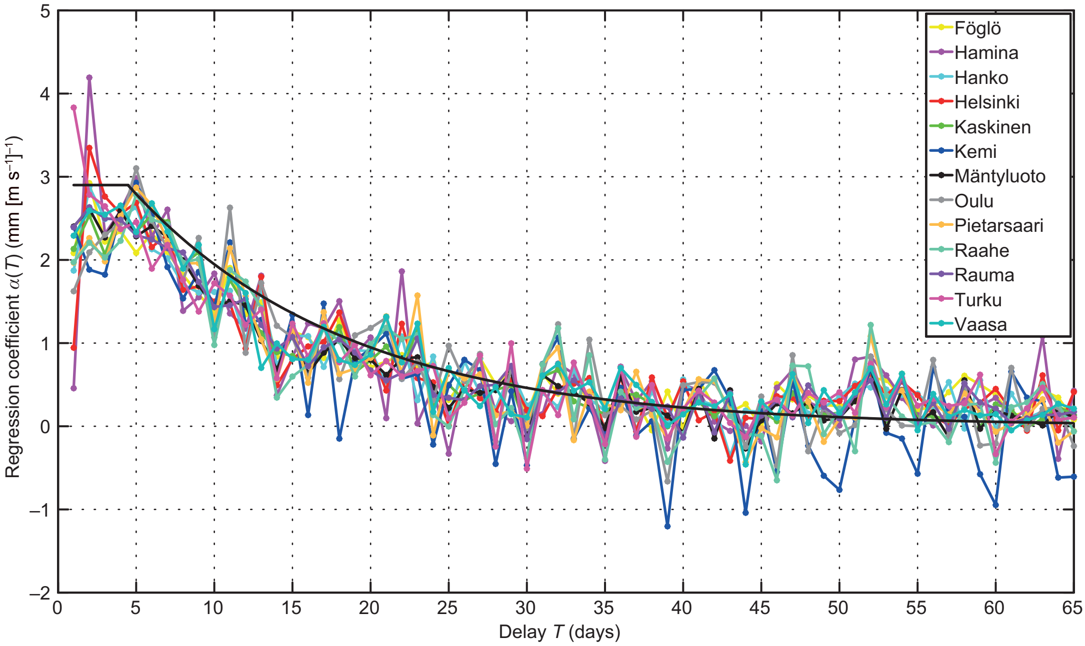

Fig. 2. Regression coefficients of the water-balance sea level component as a function of the delay between time of the sea level at the Finnish coast and time of the geostrophic wind on Bornholm. Solid line is the regression $\alpha(T)$ = 4 mm [m s^{-1}]$^{-1}$ × exp(–0.072T) when $T > 4$ fitted to the coefficients that is used in the sea level model to describe the water balance of the Baltic Sea. When $1 \le T \le 4$, $\alpha(T) = 2.9$.

chose a constant value 2.9 mm [m s^{-1}]$^{-1}$ for the coefficients of the first four days ($1 \le T \le 4$) that maximized the correlation between the measured and simulated sea levels (*see* Fig. 2). The correlation did not increase if more than 65 previous days of the Bornholm winds were included; thus we limited the regression function to 65 previous days: $\alpha(T)$ = 4 mm [m s^{-1}]$^{-1}$ × exp(–0.072T) when $4 < T \le 65$.

The tidal variation component is determined from the tidal components extracted from the Helsinki tide gauge data; the maximum tidal range at Helsinki is 12 cm. The land uplift causes the decrease of mean sea level in the N2000 height system. The land uplift rate differs between tide gauge sites; at Helsinki it is 4.4 mm year^{-1} (Johansson *et al*. 2014). The global mean sea-level rise resulting from global warming affects the mean sea level in the Baltic Sea. As the sea-level model must be comparable to the Finnish tide gauge observations in the N2000 height system, the land uplift and global mean sea-level-rise components are needed in the model to set the sea level at Helsinki to a correct level in N2000. The combined effect of the land uplift and global mean sea level rise at Helsinki can be estimated by studying the reduced sea level, where the simulated intra-basin, water-balance and tidal sea level components are subtracted from the observed sea levels. The linear trend of the annual means of reduced sea level at Helsinki 1982–2011, calculated with Mann-Kendall test, is –1.5 mm year^{-1} (Fig. 3). This indicates that the land uplift and global mean sea-level rise — or its local effect as it is not geographically evenly distributed (Johansson *et al*. 2014) — have counteracted each other with 5 cm accuracy at Helsinki during the past 30 years, so we can omit them from the model in this special case and study only the three remaining sea-level components. The land uplift and global mean sea-level-rise components cannot be omitted for all the Finnish tide gauge sites, as the land uplift rate varies spatially on the Finnish coast. At Vaasa, the reduced sea levels have clearly declined due to the higher land uplift rate (*see* fig. 7.1 in Johansson 2014).

When the combined sea-level model was applied using the reanalysis data as atmospheric forcing, the correlations between simulated

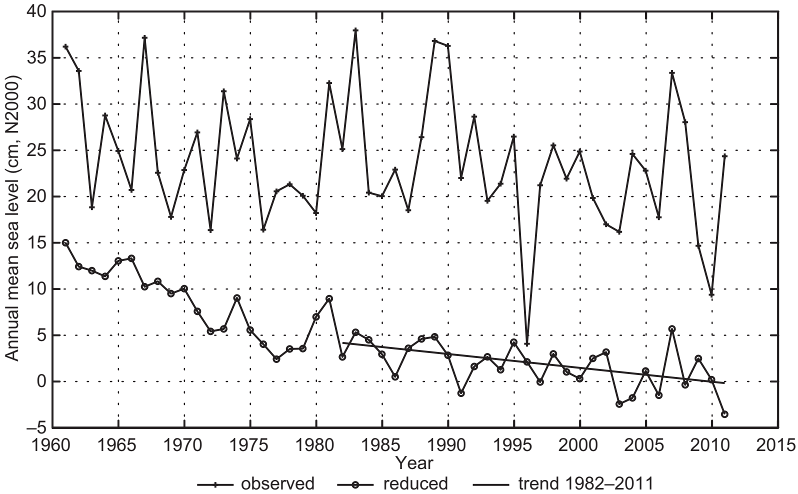

Fig. 3. Observed and reduced annual mean sea levels at Helsinki 1961–2011. Reduced sea levels, representing the combined effect of land uplift and global mean sea level rise, are obtained by subtracting the simulated intra-basin, tidal and Baltic Sea water volume variations from the observed sea levels. The trend of the annual means 1982–2011 is –1.5 mm year^{-1}. Similar behaviour is also seen at Hanko, but at Vaasa the reduced sea levels show a clearly declining trend (*see* fig. 7.1 in Johansson 2014).

hourly sea levels and sea level observations varied between $r = 0.91$ and $r = 0.94$ for the Finnish tide gauges. We calculated a so-called "unmodelled sea level component" as the difference z_{eC} between the simulated sea level z_C (atmospheric input for the sea level model from regional climate models, *see* Table 1) and measured sea level z in 1971–2000. Due to the temporal resolution of the atmospheric data (three or six hours) the sharp sea level peaks are often delayed by few hours in the simulation data compared with the observation data. For this reason the difference of simulated and observed daily maxima was used in the calculation of the distribution of the unmodelled component instead of using the hourly difference data. This component was then included into the sea level model results by combining statistically the distribution of the unmodelled component with the distribution of the simulated sea levels.

We used the 850-year set of regional climate scenario simulations between 1951 and 2100 (*see* Table 1) as atmospheric input for the sea level model to create an 850-year set of artificial but physically plausible simulated sea levels z_S. The exceedance frequency distributions of z_S and z_{eC} were calculated, and the distribution of the sum $z_S + z_{eC}$ was used for the evaluation of the sea-level extremes in the present climate. As the climate scenario simulations are not related to historical weather events, the hourly values of simulated and observed sea levels cannot be directly used to make the error estimate of the simulation. Therefore, the error estimate of the sea levels was based on the regional climate control simulations having ERA-40 as boundary forcing. Finally, we applied extreme value analysis methods to estimate the probabilities of extreme sea levels at Helsinki in the present climate.

As an example of the performance of the model, we compared the observed and modelled sea level at Helsinki during the sea flood in January 2005 (Fig. 4). The simulated maximum (160 cm) was 10 cm below the observed maximum (170 cm). The simulation followed the observations reasonably well (root mean square error of the simulation 1961–2012 is 10 cm), but the six-hour time resolution of the wind input was insufficient to allow the sea-level model to fully reproduce the rapid sea-level changes. While the tide is usually not included when modelling the sea level in the Baltic Sea, this comparison shows its importance: the maximum sea level would have been 12 cm higher if the tidal maximum had coincided with the storm surge peak.

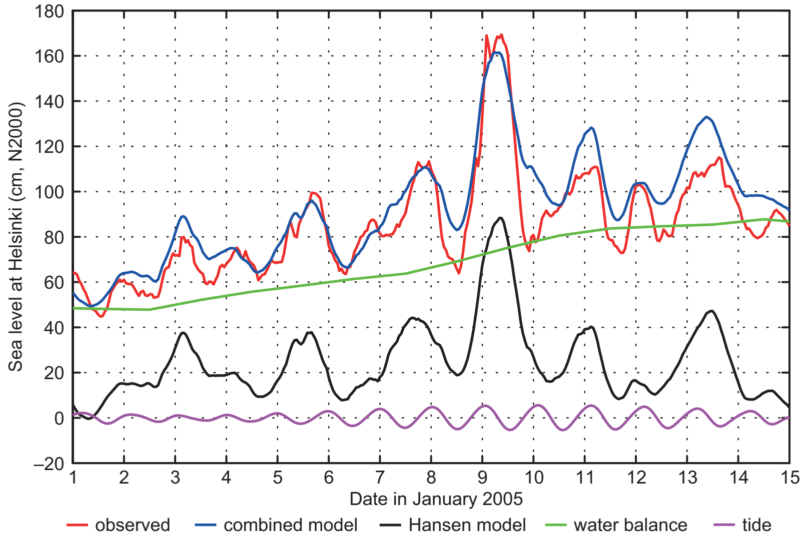

Fig. 4. Simulated (combined model with ERA-Interim forcing) and observed sea levels at Helsinki during the record high sea-level event in January 2005. Three model components are shown: Hansen model component describing intra-basin variation, water balance component describing the water volume variation in the Baltic Sea and tidal variation component.

Extreme value analysis

The sea-level variability in the Baltic Sea has changed during about 110 years of observations at Helsinki (Johansson *et al*. 2001), and thus the data from the earlier decades are not representative for the present conditions even if the land uplift and the global mean sea level change are taken into account. As far as the measured data are concerned, we therefore followed the standard practice in climatology and used the period of 30 years for the analysis of the present-day conditions. Our simulations, on the other hand, provide an 850-year time series of present conditions, and sea levels that were extrapolated in Kahma *et al*. (2014) from 30-year measurements can now be estimated without extrapolation.

The sea-level exceedance distribution given by the 850-year simulation can be extended one order of magnitude further, to the exceedance frequency level 10^{-4}, by extrapolating with a suitable probability distribution. The choice of the probability distribution is not straightforward. The sea levels in the Baltic Sea have a strong serial correlation, predominantly through the water balance component, but also through other physical phenomena. The use of generalized extreme value (GEV) distribution for extreme value analysis requires that the extremes are independent and random (Coles 2001). The correlation does not completely vanish even on the annual time scale and therefore it is not clear whether even the annual maxima sufficiently well fulfill the requirement of independence and convergence of the GEV analysis. We therefore made also the extreme value analysis by finding the best approximation for the tail of the exceedance distribution.

In the Baltic Sea, the duration of a sea-level peak rarely exceeds 12 hours. Daily maxima therefore have an independent component even though its other components are correlated. Hence, we have calculated the distributions of daily maxima as well as the annual maxima. The tail of the distribution of the daily maxima stabilizes to Weibull's distribution. In case of annual maxima, this stabilization occurs with much higher sea level as the maximum exceedance frequency for annual maxima is one event per year. The daily maxima provide a much wider range to fit the distribution and we therefore used in our analysis the daily maxima in addition to annual maxima.

For the extrapolation, we tested exponential, Fréchet, Gumbel and Weibull fits to the daily maxima, as these are often used in the extreme value analyses of sea level (Arns *et al*. 2013). We also used the standard extreme value methods by making a GEV fit to simulated annual maxima. In addition, we studied the sea-level maxima by calculating the sum of the maxima of simulated sea-level components to estimate the large but

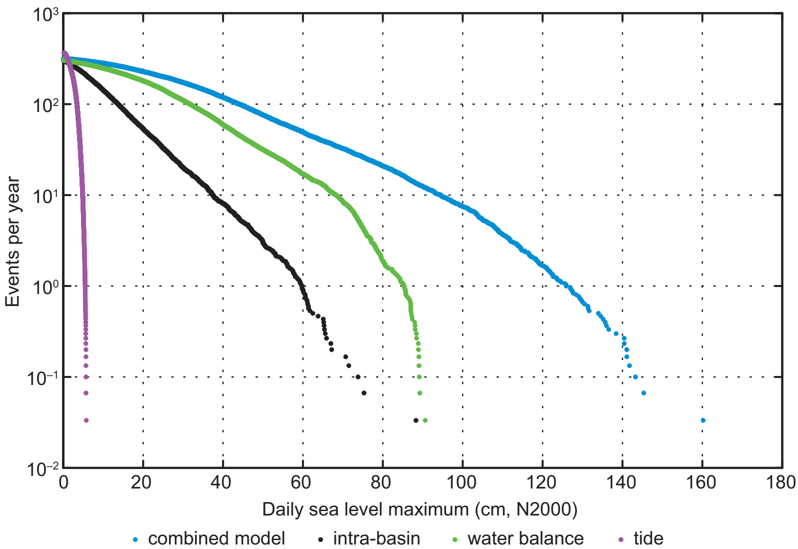

Fig. 5. Distributions of daily maxima of the different simulated sea-level components and combined sea-level model at Helsinki 1983–2012 (ERA-Interim forcing).

still in principle possible values for the extreme sea levels.

We performed the extreme sea-level analysis using three sets of the sea-level data: observations and sea-level simulations for the last 30 years (1983–2012), and the 850-year set of sea levels based on six climate scenario simulations covering the years 1951–2100. For the simulation of the years 1983–2012, the climate data were taken from the reanalyzed ERA-Interim data set (Dee *et al*. 2011).

Results

Sea level analysis based on the years 1983–2012

Component analysis of the 30-year simulation (1983–2012)

The aim of the separate investigation of each sea-level component was to evaluate the highest possible sea-level maximum from the sum of the components. The combined sea-level model allowed us to study separately the distributions of daily maxima of each component 1983–2012 (Fig. 5). The sum of the maximum values of the components was then compared with the exceedance levels given by the extreme value analysis of the sea-level simulations.

As the land uplift and global mean sea level rise cancel each other at Helsinki during the 30-year period (*see* Fig. 3), they were omitted from the component analysis. The maximum tide (*see* Fig. 5) is 6 cm. The sum of the maximum tide, the simulated maximum value of water-balance component (91 cm), and the simulated maximum value of the intra-basin component (88 cm, *see* Fig. 5) in the period 1983–2012 is 185 cm. This is 25 cm more than the simulated maximum value of the combined sea-level model, 160 cm (*see* Fig. 5), because the components did not reach their maxima simultaneously.

The maximum positive error, i.e. the difference between observed and simulated sea level in this period, is 40 cm. When we added this maximum error (i.e. the maximum of the unmodelled component) to the sum of the maxima of the simulated components 185 cm, we got the value of 225 cm. As a summary, the component analysis for the period 1983–2012 suggested that sea level 225 cm at Helsinki can be exceeded in the current climate by observed phenomena and without any assumptions about the extrapolation of the exceedance distribution.

Exceedance distributions

We extrapolated the exceedance frequency distributions of the observed and simulated daily

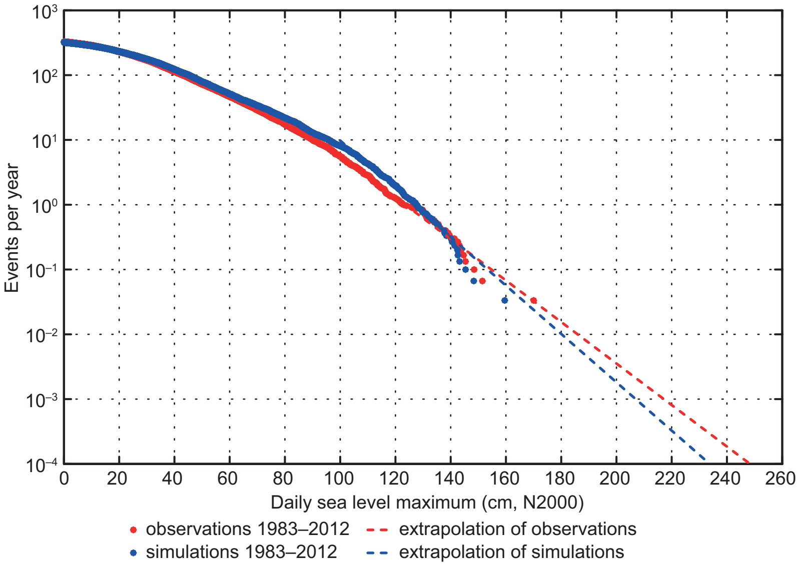

Fig. 6. Distributions of observed daily sea-level maxima at Helsinki 1983-2012 and simulated daily sea-level maxima (ERA-Interim 1983–2012 as atmospheric forcing) with exponential extrapolation to the simulation data points above 100 cm.

sea level maxima at Helsinki for the years 1983–2012 with an exponential fit to maxima exceeding 100 cm (Fig. 6). Exponential distribution has one adjustable parameter less than the more general Weibull distribution and was therefore chosen here to avoid overdetermination. The distributions of the simulated and observed sea level daily maxima were very similar. The extrapolated height of the observed daily sea level maximum with an exceedance frequency 10^{-4} times per year (occurring once in ten thousand years in unchanging climate) is 248 cm, and for the simulated daily sea level maxima the corresponding extrapolated value is 234 cm.

Analysis of long-term sea level simulations

Component analysis of the 850-year sea level simulation

We performed a component analysis of the 850-year sea-level simulation similar to that made for the 30-year simulation, based on the distributions of the daily maxima of the sea level components for the 850-year simulation (Fig. 7). The sum of the maximum tide 6 cm, the simulated maximum value of water-balance component 107 cm, and the simulated maximum intra-basin component 154 cm (*see* Fig. 7) is 267 cm. Because the components did not reach their maxima simultaneously, this is 62 cm higher than the simulated maximum of the combined model, 205 cm (*see* Fig. 7), and 82 cm higher than the results from the analysis of 30-year observation data. The component analysis showed that 267 cm may be exceeded in the present climate by modelled phenomena without any assumptions about extrapolation if all six climate scenarios are used.

The maximum error, i.e. the difference between daily maxima of the observed and simulated sea level (simulated with regional climate model, Fig. 8), is 71 cm. When we added this maximum error to the sum of the maxima of the simulated components, 267 cm, we got the value of 338 cm. The sea-level maximum obtained by the summing of the component maxima is an evaluation of a sea level that can be produced by different physical mechanisms. It should be noted that no probability value is attached to this maximum value, as it merely describes a worst-case scenario in which all sea level components attain their maxima at the same time in the same place. As a summary, the component analysis for the 850-year simulation suggested that without any assumptions about the extrapolation of the exceedance distribution, the sea level 338 cm can be exceeded in the present climate by mod-

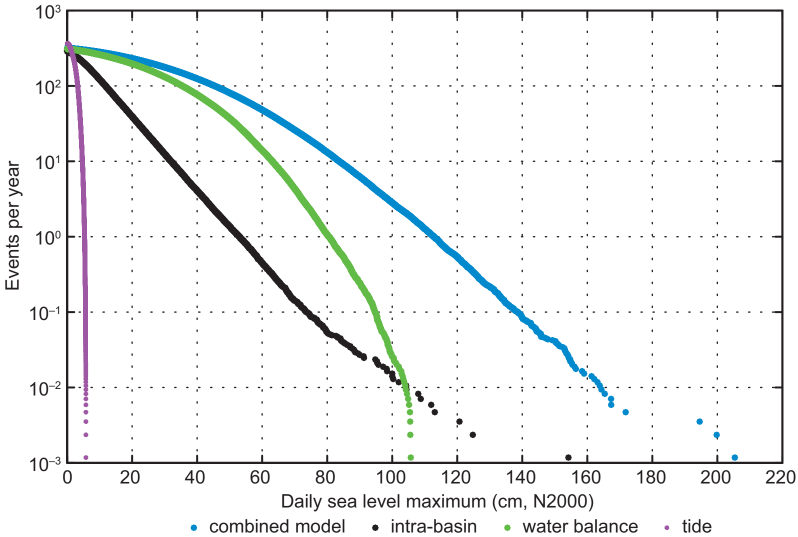

Fig. 7. Distributions of daily maxima of the different simulated sea-level components and combined sea level model at Helsinki for the 850-year simulation.

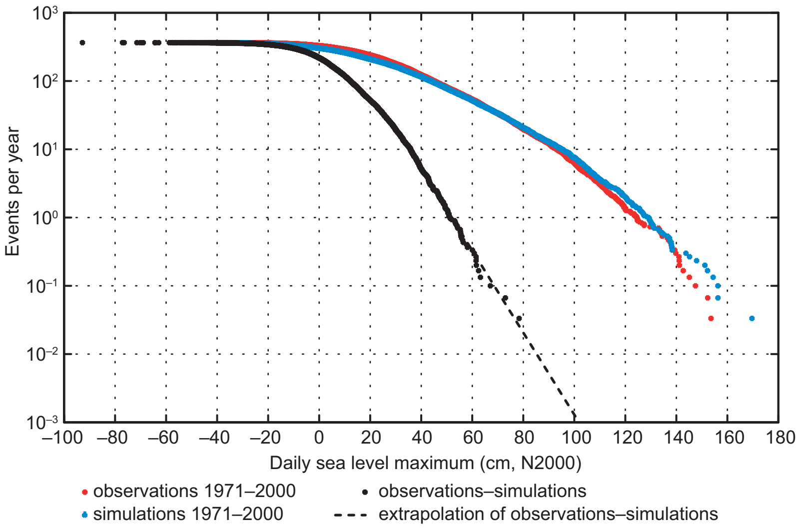

Fig. 8. Distributions of observed (z) and simulated (z_C) daily sea-level maxima at Helsinki 1971-2000: sea-level observations, sea-level simulations, and error of the simulated sea level (z_{eC}, observations–simulations). Sea-level simulation was calculated using regional climate control simulation with ERA-40 boundary forcing. The error was extrapolated exponentially.

elled phenomena and their estimated maximum errors.

Exceedance distributions

We compared the distribution of the daily maxima of the 850-year sea-level simulation with the distributions of the observed sea level z 1983–2012 and simulated sea level z_{ERA} 1983–2012 (Fig. 9). In the regional and global climate models, the wind speeds are often underestimated (Rockel and Woth 2007, Meier *et al*. 2011). As the water-balance sea-level component is proportional to the geostrophic wind speeds at Bornholm, the underestimated wind speeds result in means for the sea levels simulated with regional climate models that are too small by comparison with the sea levels simulated with reanalysis data. This difference was removed by adding a constant bias correction (+9 cm) to the simulated sea level values, calculated from the difference between the 30-year means of simulated sea level z_S and the ERA-Interim forced sea level z_{ERA} (Fig. 10).

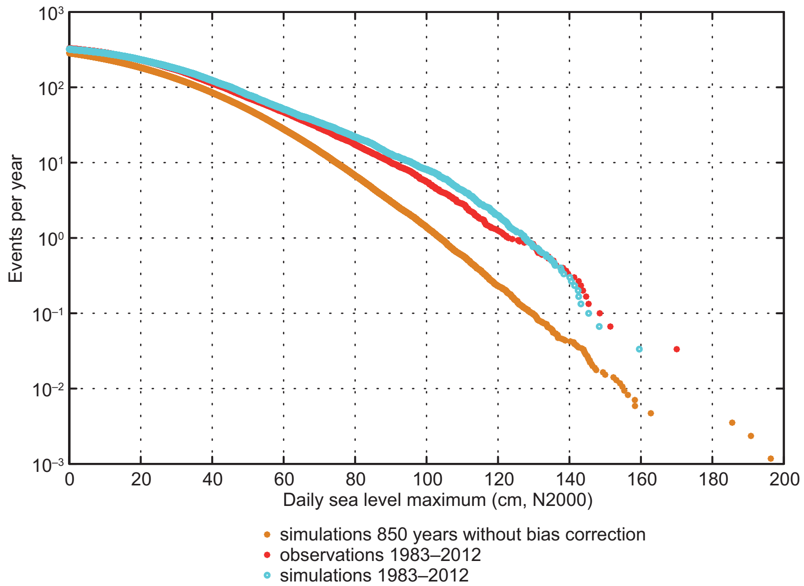

Fig. 9. Distributions of daily sea-level maxima of the simulated sea levels based on six regional climate scenario simulations (z_S) covering 850 years without correction of the bias in the sea-level model results.

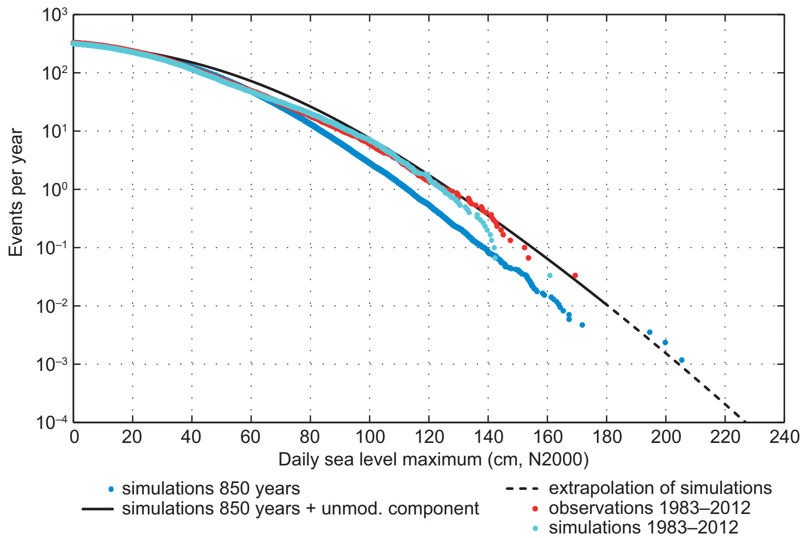

Fig. 10. Simulated daily sea-level maxima of the combined sea-level model at Helsinki based on six regional climate scenario simulations (z_S) covering 850 years with the correction for the bias in the sea level-model results (+9 cm). Simulated sea-level distribution was extrapolated with Weibull fit.

Extrapolation of exceedance distributions

As discussed in the section 'Extreme value analysis', the use of GEV distribution for extreme value analysis requires that the extremes are independent and random. We used GEV methods to the annual maxima, which are less correlated than the daily maxima. For the daily maxima, we fitted different distributions to the observed sea level data from years 1983–2012, and compared the extrapolations of these distributions with the simulated data.

The starting point of the fit was set at a sea level of 100 cm because the water balance term was almost always below 100 cm in the 850-year simulation (*see* Fig. 7), and the simulated values above 100 cm represent peaks that are clearly above the long-term background sea level. We calculated the distribution of the sum of the simulated sea level z_S and the unmodelled sea-level component of the regional climate control simulation z_{eC} (*see* Fig. 8) from the distributions of z_S and z_{eC} (*see* Fig. 10). It is not possible to use measurements for the calculation of the unmod-

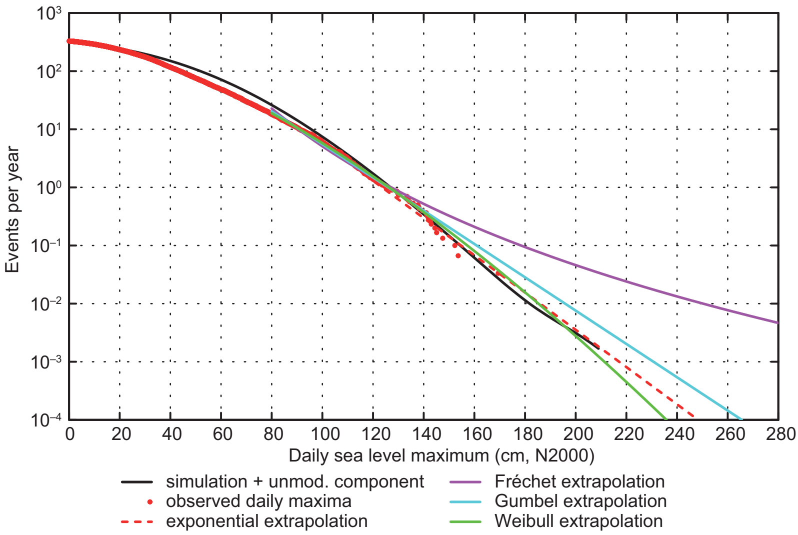

Fig. 11. Observed (1983–2012) and simulated (850-year simulation) daily sea-level maxima at Helsinki. Observations were extrapolated with exponential, Fréchet, Gumbel, and Weibull fits. The bending of the distribution of the sum for the greatest sea levels is caused by the three greatest-extreme points (*see* Fig. 10).

elled component of the regional scenario simulation z_{eS}, as z_S is calculated from climate models and does not simulate historical events. Instead, the distribution of the sum of the sea level and its unmodelled component was calculated from the distributions of z_S and z_{eC}. The distribution does not bend upwards in the end, because the distribution of the simulated sea levels above 100 cm has been replaced with a Weibull fit to the distribution, and the three greatest simulated maxima do not affect the distribution of the sum.

The exponential, Fréchet, Gumbel and Weibull fits to observed daily maxima above 80 cm were compared together with the distribution of the sum $z_S + z_{eC}$ (Fig. 11). As the simulated exceedance distribution of daily maxima extends down to 850 years, we estimated the suitability of different extrapolation methods by comparing the shape of the extrapolation with that of the distribution of the sum of simulated sea level and the unmodelled component on exceedance frequencies between 1/30 and 1/850 events per year. The tail of Fréchet distribution bends upwards, but the simulated distribution does not show such a feature. Gumbel fit resembles exponential fit in this range having smaller slope than exponential fit to observations (same fit as in Fig. 6) has. The Weibull fit is closest to the shape of the simulated distribution on frequencies above 10^{-2}. The bending of the tail of the simulated distribution, however, brings it closer to the exponential fit on lowest frequencies. The bending is caused by the three greatest simulated extremes that are clearly higher than the other extremes (*see* Fig. 10). The values given by different methods for the sea level exceedance frequency 10^{-4} are all between 230 cm and 270 cm (except Fréchet which is clearly incompatible with the simulations), indicating that the choice of fitting method does not substantially affect the result at exceedance frequency 10^{-4} when a fit is made to the 850-year simulation data.

Based on the comparison of the different extrapolation methods, we chose the Weibull fit to the simulated sea-level daily maxima for further extreme value analyses. The bias correction (+9 cm) raises the distribution of the sum of the simulated sea level and unmodelled component to the same level with the observed and simulated 30-year sea-level distributions (*see* Fig. 10). The Weibull fit continues the small downward curvature that is present in the simulated sea level distribution above 100 cm. The sea-level exceeded with a probability of 10^{-4} occurrences per year given by Weibull fit is 227 cm. The simulated sea levels corresponding to different exceedance frequencies are given in Table 3.

We compared these results with a GEV fit to the entire distribution of simulated annual maxima. The best estimate and 95% confidence limits (CLs) were calculated for different exceedance frequencies. The same bias cor-

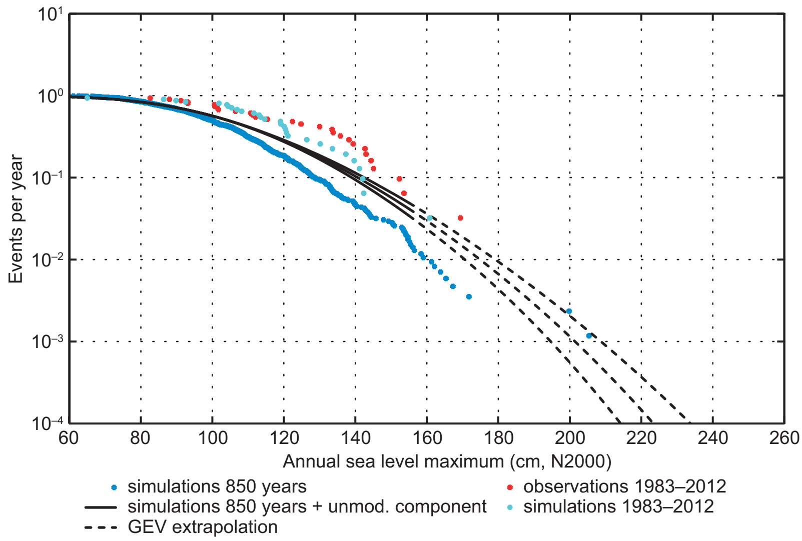

Fig. 12. Simulated annual sea-level maxima of the combined sea-level model at Helsinki based on six regional climate scenario simulations (z_S) covering 850 years with the correction for the bias in the sea-level model results (+9 cm). The simulated sea level is extrapolated using the GEV method; the three dashed lines represent the best estimate and 95% upper and lower confidence limits.

rection (+9 cm) was made as in the case of simulated daily maxima, as the bias correction is calculated from the mean of simulated hourly sea-level values. The distribution of the simulated annual maxima, continued with the GEV fit, was combined with the distribution of the unmodelled component of the control simulation (i.e., the distribution of the sum $z_S + z_{eC}$ was calculated). The annual maxima simulated with climate simulation data are clearly below the annual maxima simulated with ERA-Interim data and observed annual maxima 1983–2012 (Fig. 12). It indicates that local and deep low pressures are not well represented in the climate simulation data. The sea-level peaks are often caused by such low pressure systems. The difference between the observed sea-level distribution and sea-level distribution simulated with climate simulation forcing is more pronounced when annual maxima are used instead of daily maxima. This might be caused by the greater proportion of the sea-level peaks induced by the local low pressures in the ensemble of annual maxima as compared with that in the statistics derived from the daily maxima. The exceedance levels for different frequencies (best estimate and 95%CLs) extracted from the distributions of simulated annual maxima are given in Table 3. For the exceedance frequencies below 1/50, the two methods yield quite similar results.

Summary and discussion

We applied five methods to evaluate the extreme sea levels in the present climate conditions at

Table 3. Exceedance frequencies for the 850-year simulation of the combined sea level model at Helsinki (*see* Fig. 10 for daily maxima and Fig. 12 for annual maxima).

Exceedance frequency per year	Sea level estimate with Weibull extrapolation of daily maxima (cm, N2000)	Sea level best estimate with GEV extrapolation of annual maxima (cm, N2000)	Sea level 95% CLs with GEV extrapolation of annual maxima (cm, N2000)
1/10	155	141	139–143
1/20	163	152	150–155
1/50	173	166	162–169
1/100	180	175	171–179
10^{-3}	204	201	195–209
10^{-4}	227	223	214–234

Helsinki having an exceedance frequency 10^{-4} (in unchanging climate and ignoring land uplift this would correspond to one event in ten thousand years). The exponential extrapolation of 30-year simulation data gave an estimate of 234 cm. The sum of the simulated 30-year component maxima was 225 cm. From the simulated 850 years of data, the estimates by different distributions were close to each other. At exceedance frequency 10^{-4}, Weibull's distribution fitted to daily maxima gave an estimate 227 cm and the GEV fit to simulated annual maxima 223 cm. The value obtained using Weibull's fit is inside the 95% confidence limits (214–234 cm) of the GEV estimate. As the shapes of the simulated and observed distributions of the daily maxima are more similar than in the case of distributions of annual maxima, it is reasonable to choose the result given by the extrapolation to the daily maxima, 227 cm, as a more reliable value than the 223 cm given by the GEV analysis.

We estimate the uncertainty range of the value 227 cm obtained from the Weibull fit to be of the order of ±10 cm, based on the 95% confidence limits of the GEV fit. Considered that the sharp sea-level peaks are likely underrepresented in the simulation data, the sea level 227 cm should be regarded as a lower limit estimate. This value should be re-evaluated in the future with new climate simulation data. The fifth evaluation method, the summing of the simulated 850-year component maxima, gave an estimate 338 cm. This value approximated the physically feasible sea level that would occur if all sea level components reached their maximum value at the same time at Helsinki. The probability of such an event is significantly smaller than 10^{-4} occurrences per year.

To date, the highest observed sea level at Helsinki was 170 cm on 9 January 2005. This corresponded to the exceedance frequency of once in 50–100 years given by the simulations (*see* Table 3). This means that the flood in the Gulf of Finland in 2005 was not entirely extraordinary, and a flood with equal height could happen again soon.

The rise in the annual mean sea levels between 1951 and 2100 was between 5 and 20 cm depending on the climate scenario used for the sea level simulation. This rise was due to the changes in the wind climate of the scenarios, causing an increase in the water balance component. The result agrees well with Johansson *et al*. (2014), who suggested the mean sea level changes related to modelled future changes in zonal geostrophic winds to range from a 4 cm decrease to a 19 cm increase on the Finnish coast. The climate change signal for winds is weak, leading to small changes in the water balance. The changes are of the same order than the error of the sea-level model, and small as compared with the height of the simulated sea level extremes. The simulation data could thus be used to describe sea-level extremes in the present climate, as the wind-induced mean sea-level change does not significantly affect the sea level statistics. However, the shape of the frequency distribution of the short-term sea-level variability could also change in the simulation, due to potential changes in wind and air pressure conditions. Such a possibility is supported by the fact that the sea level frequency distributions have changed in the past on time scales of several decades (Johansson *et al*. 2001). In order to further assess the suitability of the century-long climate simulations in estimating the exceedance frequencies of high sea levels in the present climate, such changes should be analyzed. We will leave this as a topic for further studies, as it is also linked to the broader question about the ability of the current climate models to simulate past and potential future changes in short-term wind and air pressure variability.

The estimates of the sea-level extremes at Helsinki presented in this study represent a novel approach that utilises regional climate scenario simulation data for determining probabilities of high sea levels. As the simulation extends to nearly one thousand years, the method chosen for the extrapolation of the simulated frequency distribution has a smaller significance in the estimation of the exceedance levels than in studies based on 30-year or even 100-year observation data. The latest recommendations for elevations of regular buildings on the Finnish coast are based on flooding levels of one event per 250 years in 2100 (Kahma *et al*. 2014). The new estimates for the exceedance frequencies from the 850-year simulation are all slightly smaller than the estimates in 2011 given in Kahma *et al*.

(2014), and will allow refining the recommendations. In the present study, the scenarios of future mean sea-level rise were not included in the analysis, but the simulation results can be used to evaluate the reliability of the results of previous sea level studies for the flooding risks at Helsinki in the present day so that important infrastructure can be protected from damage.

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