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Global sea level rise scenarios adapted to the Finnish coast

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ABSTRACT

We calculate scenarios for the mean sea level on the Finnish coast by combining the land uplift, wind-induced changes in the local sea level, and large-scale sea level rise due to changes in ocean density and circulation and melting of land-based ice. The wind-induced changes were estimated by utilising their correlation with the zonal geostrophic wind, which explains 84–89% of the observed interannual variability of sea level on the Finnish coast. Future scenarios were based on the geostrophic wind projections from nine global circulation models. Land uplift rates are 4.1–9.9 mm/yr, determined from the observations after filtering out the wind-induced effect. A 26–155 cm range for the global mean sea level rise up to 2100 was obtained by combining several recently published scenarios. This rise is geographically unevenly distributed, and on the Finnish coast it is estimated to be only 24–126 cm. Relative sea level change in the Gulf of Finland in 2000–2100 is projected to be +29 cm (−22 to +92 cm). A change of −5 cm (−66 to +65 cm) is projected for the Bothnian Sea, and −27 cm (−72 to +28 cm) for the Bothnian Bay, where the land uplift is stronger.

1. Introduction

Estimates of the future behaviour of the sea level are important for coastal activities, including construction and planning, as well as flood protection. Thus, there is a continuous interest in sea level scenarios based on the most recent knowledge of the effects of climate change. For practical applications like risk analyses, not only an ensemble of possible scenarios, but also estimates of their probabilities are of interest. This study responds to this need on the Finnish coast in the north-eastern Baltic Sea.

The semi-enclosed Baltic Sea is connected to the North Atlantic Ocean through the narrow and shallow Danish Straits. The water flows in and out through the straits, allowing the sea level changes in the global ocean to penetrate into the Baltic Sea as well. The long-term changes in the relative sea level on the coastline of Finland are thus determined by a combination of local and large-scale processes: local meteorologically induced changes in the sea level and local postglacial land uplift, as well as the large-scale sea level rise due to melting of ice sheets, glaciers and ice caps, thermal expansion of the oceans, and changes in ocean dynamics (Johansson et al., 2004). All these factors need to be taken into account when analysing the past and projecting the future behaviour of the local sea level.

The Baltic Sea level varies remarkably due to regional meteorological conditions. The interannual fluctuations in the annual average sea levels on the Finnish coast are of the order of 20 cm. In earlier studies, this variability was found to be related to the North Atlantic Oscillation (NAO) index, the correlation being especially strong in winter and in the northeastern part of the Baltic Sea (e.g., Andersson, 2002; Johansson et al., 2003; Kahma, 1999; Suursaar and Sooäär, 2007; Suursaar et al., 2006). A positive NAO index coincides with anomalously strong westerlies over the North Atlantic. This westerly flow tends to push water through the Danish Straits into the Baltic Sea, thus altering the total water volume in the semi-enclosed basin. Such variations affect the Baltic Sea level by several tens of centimetres on an intra-annual time scale. In addition, a prevailing westerly flow redistributes water inside the Baltic Sea basin in such a way that the sea level is highest in the northeastern part of the basin; this sea level tilt reinforces the effect of water volume changes on the Finnish coast (Johansson et al., 2003). Other phenomena might also contribute to the link between a high NAO index and high sea levels in the Baltic Sea: e.g. a high NAO index correlates with high precipitation, which through river runoff affects the salinity gradient in the Baltic Sea. However, compared to the fluctuations induced by the water transport, such phenomena are of secondary importance.

The variability of the NAO index, and the corresponding fluctuations in sea level are also visible on a decadal time scale. For instance, in the 1980s and 1990s the mean sea level on the Finnish coast was anomalously high. This behaviour coincides with a high NAO index during these decades (Johansson et al., 2003). Thus, this meteorological contribution is relevant in studies of long-term mean sea level scenarios.

In Scandinavia the postglacial land uplift, i.e., the slow recovery of the Earth's crust from the pressure of the ice masses during the last ice age, is still ongoing and has been extensively analysed. Traditionally, the most accurate data for studying the land uplift were the long-term time series of mean sea level measured by tide gauges.

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These data yield the vertical land movement in relation to the sea surface (e.g. Hela, 1953; Lisitzin, 1964; Vermeer et al., 1988). In some earlier papers, it was customary to call this relative movement relative land uplift (Johansson et al., 2004; Vermeer et al., 1988), although actually it is a combination of the sea level change and the crustal movement. Recently, new data obtained from permanent GPS stations allow the calculation of vertical land movement independently of the sea level change (Lidberg et al., 2007; Richter et al., 2011; Vestøl, 2006). To avoid misinterpretation, in this paper we denote the absolute crustal movements as "land uplift", while the term "relative sea level change" refers to the change from a coastal viewpoint as measured by the tide gauges (sea level change minus land uplift).

In this paper we use the term "large-scale sea level change" to refer to sea level changes which have their main sources outside the Baltic Sea, but which still affect the Baltic Sea. These include melting of ice sheets, glaciers and ice caps as well as thermal expansion of the oceans, and changes in ocean dynamics. These phenomena cause global-scale sea level changes. The average rate of the global mean sea level rise during the 20th century was 1.7 ± 0.5 mm/yr, as estimated in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC; Bindoff et al., 2007). There is evidence that the global mean sea level rise has accelerated. Satellite altimetry measurements show a rate of 3.3 ± 0.4 mm/yr in 1993–2007 (Cazenave and Llovel, 2010).

The Third Assessment Report (TAR) of the IPCC (Church et al., 2001) projected a global average sea level rise of 9–88 cm by the end of this century. Johansson et al. (2004) calculated sea level scenarios for the Finnish coast by combining the TAR scenarios with local land uplift and scenarios for meteorological forcing. The possibility that the large-scale sea level rise due to thermal expansion and melting of land-based ice might be geographically unevenly distributed was not taken into account in that paper: the global average scenarios were applied to the Baltic Sea unchanged. Johansson et al. (2004) concluded that the decline of the relative sea level observed on the Finnish coast during the 20th century is likely to cease in the Gulf of Finland. The mean of six different emission scenarios projected a −4 to +5 cm change from 2000 to 2093, while the whole scenario range extended from −30 to +47 cm. In the Gulf of Bothnia, where land uplift is stronger, the decline of the sea level was projected to continue. The intermediate projection ranged from −49 to −18 cm, while the entire scenario range extended from −74 to +25 cm. The differences among the local values mainly originated from different land uplift rates, ranging from 3.1 to 9.0 mm/yr. The uncertainty of several tens of centimetres in the global sea level rise scenarios was reflected on the Finnish coast as well.

Meier et al. (2004) presented sea level scenarios for the Baltic Sea based on dynamical modelling of the local processes combined with the global sea level scenarios of the TAR. The scenarios showed that land uplift will compensate for the sea level rise for low-end scenarios, and in the northern parts of the Baltic Sea even for the intermediate scenario, but according to the maximum scenario the relative sea level would rise over the entire Baltic Sea area.

Since TAR, new knowledge on global sea level rise and its spatial distribution has been obtained, and thus the sea level projections for the Finnish coast by Johansson et al. (2004) are outdated. The AR4 provided updates for the global sea level scenarios. The sea level was projected to rise by 18–59 cm in the 21st century (Meehl et al., 2007). In addition, an ice-sheet discharge term of up to 17 cm was suggested to account for the possible effect of rapid dynamical changes in the Greenland and Antarctic ice sheets. Because current models lack the ability to simulate such changes, this estimate was based on an assumed link between the sea level rise induced by these dynamical changes, and the global mean surface temperature.

The new IPCC scenarios have encountered criticism as being too conservative, because the full effect of ice sheet dynamics was not included in the numerical estimate (e.g. Hansen, 2007). Since 1990, global mean sea level has been rising faster than the models predict (Rahmstorf et al., 2007), indicating possible deficiencies in the ability of the models to handle this issue. After AR4, a number of higher sea level projections have been published. Several authors (Grinsted et al., 2010; Horton et al., 2008; Jevrejeva et al., 2010; Jevrejeva et al., 2012; Rahmstorf, 2007; Vermeer and Rahmstorf, 2009) used semi-empirical relations between sea level and temperature (or radiative forcing); projections of sea-level rise ranging from 36 to 190 cm were obtained. Pfeffer et al. (2008) made an effort to estimate the highest possible rate of ice discharge from the Greenland and West Antarctic ice sheets, concluding an upper limit of 200 cm for the sea level rise by 2100.

The global-scale sea level rise is not distributed evenly, as revealed by satellite altimetry (e.g. Cazenave and Llovel, 2010). These regional differences arise from changes in ocean density and dynamics as well as gravitational effects and land movements due to redistribution of water and ice on the Earth's surface (Bindoff et al., 2007). Large ice masses attract sea water by gravitation, causing the water to pile up around the ice mass. When the ice melts, the gravitational attraction is relieved, and the water retreats. According to modelling results, the sea level will decline near the melting ice mass, while in areas far away it will rise more than on average (Mitrovica et al., 2001; Tamisiea et al., 2003). Thus, depending on whether the global average sea level rise is caused by thermal expansion, melting of the Greenland ice sheet, of the Antarctic ice sheet, or of the small glaciers and ice caps around the world, the result is a different regional contribution on the Finnish coast. From the Finnish viewpoint, the source of the projected sea level rise thus is of great importance.

This study aims at updating the sea level scenarios of Johansson et al. (2004). In Section 2 the data are presented. In Section 3 the local effects of meteorological forcing and land uplift are considered. We examine the possibility of more efficiently explaining the meteorologically-induced component of sea level variations by the local time-mean geostrophic wind rather than the NAO index used in previous studies (Johansson et al. 2003, 2004). The land uplift rates are estimated from the sea level time series after subtracting the response to meteorological forcing and the past large-scale sea level rise. In Section 4, scenarios are constructed. To obtain a probability distribution for future large-scale sea level rise, we combine different global sea level projections presented in literature. The uneven geographical distribution of the sea level rise and specifically the regional contribution on the Finnish coast is estimated. This has not been done previously for the Finnish coast, as the earlier projections were based on the TAR global mean sea level scenarios solely. To respond to the practical demands, the probability distributions for the large-scale sea level scenarios are estimated. Finally, the large-scale sea level rise is combined with the land uplift and meteorologically induced variations to obtain projections for the local relative sea level change on the Finnish coast.

2. Data

2.1. Sea level data

The sea level is continuously measured at 13 tide gauge stations on the Finnish coast, most of which have been operating since the 1920s (Fig. 1, Table 1). The longest time series, beginning in October 1887, comes from Hanko, and the shortest one, beginning in January 1933, from Rauma. The sea level was generally recorded at 4-hour intervals up to 1970 and at 1-hour intervals since then. In this study, the sea level values are given relative to the Finnish height reference N2000 (Saaranen et al., 2009).

Annual mean sea levels were calculated from the observations after an extensive check of data quality. For a detailed discussion on the data quality and associated problems, see Johansson et al. (2001). For various reasons, observations are missing occasionally.