Geophysica (2014), 50(2), 49–64

Land Uplift at Kvarken Archipelago / High Coast UNESCO World Heritage area

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(Received August 2014; Accepted November 2014)

Abstract

The land uplift is a well-known process at the coastal areas of the Gulf of Bothnia in Finland and Sweden. Today, about 700 hectares of new land is rising from the sea every year. This is changing the landscape rapidly, especially at the shallow coastlines and archipelago of Kvarken in Finland where during the last century the uplift rate relative to the sea has been almost 9 mm/year. At the opposite side in Sweden, the High Coast has much steeper landscape and changes there are less prominent during one generation. Due to its unique nature, the area has received the UNESCO World Heritage status.

The area is near the uplift maximum of the Fennoscandian postglacial rebound. Since the end of the deglaciation, a total of at least 286 meters of uplift has occurred up to now, which corresponds to the highest point of the ancient shoreline at Skuleberget at the High Coast. The area is expected to almost linearly rise from the sea in the next few thousand years until the remaining about 100 m of depression due to the former ice load are isostatically balanced. With the help of geophysical and climate models future scenarios of land emergence are predicted based on current observations. The apparent uplift rate relative to the sea depends on the future global sea level rise. We also discuss future scenarios of the landscape in this UNESCO World Heritage area.

Keywords: land uplift, Glacial Isostatic Adjustment, geophysical modelling, sea level change, UNESCO World Heritage

1 Introduction

Land uplift is the most notable geodynamic process in Fennoscandia and it has been known for centuries at the coastal areas of Finland and Sweden at the Gulf of Bothnia. The source of land uplift today is found in the past, in times where northern Europe was covered with a huge ice sheet. The Last Glacial Maximum (LGM), the time of maximum ice coverage in Fennoscandia, occurred about 20 000 years ago. The thickness of the ice was about 2500-3000 metres, and its weight pressed the crust down by 500-900 meters. The melting period started 18 000 years ago, and about 10 500 years ago the Kvarken Archipelago / High Coast area in the central Gulf of Bothnia was ice-free (*Peltier*, 1994; *Berglund*, 2004).

The load of the ice sheet followed by the melting and release of the load caused a rapid elastic rebound of the crust. The uplift rate at the High Coast was even 8 (*Berglund*, 2004) to 12 (*Lidén*, 1911) cm/year, and the total of 500 m uplift occurred in 8000

Published by the Geophysical Society of Finland, Helsinki

years. This was accompanied by strong earthquakes due to the release of accumulated stress in the crust (e.g. *Poutanen et al*., 2009). Traces of these events are mainly found in the northern parts of Norway, Sweden and Finland, and recently also south of the High Coast area near Bollnäs (*Smith et al*., 2014). After the fast elastic rebound, a slower viscoelastic rebound dominates, and it will continue thousands of years also in the future. About 300 m of uplift has occurred during 10 000 years (*Berglund* 2004, 2012; see Fig. 1) and about 90-130 m of uplift is still expected to come in the area, depending on geodynamic models used (*Steffen and Wu*, 2011; Fig. 2). The uplift rate slows down gradually until the remaining depression is isostatically balanced, but during the next centuries it can be assumed almost linear.

This remarkable area near the uplift maximum is nowadays the UNESCO World Heritage site Kvarken Archipelago / High Coast. The Kvarken Archipelago at the Finnish side is very shallow, where the landscape is changing rapidly (Fig 3a). Even during one generation the retreat of the shoreline is clearly visible. At the opposite side in Sweden, the changes are less prominent. This is due to the much steeper landscape of the area fittingly called the High Coast (Fig. 3b). This unique nature of steep hills on the western Gulf of Bothnia coast and almost flat planes on the other side has received the UNESCO World Heritage status in 2000 (the High Coast) and 2006 (Kvarken Archipelago added).

The land uplift maximum is near the city of Umeå (*Steffen and Wu*, 2011), where the current absolute uplift is about 10 mm/year, and during the last century the uplift rate relative to the sea has been almost 9 mm/year. The apparent uplift rate depends on the sea level rise, and thus the apparent uplift rate will most likely change in future. In this paper, we will review observations of land uplift and sea level change in northern Europe and discuss how the apparent uplift is affected. We further evaluate future scenarios on variable sea level rise and consequences on the landscape at Kvarken Archipelago / High Coast.

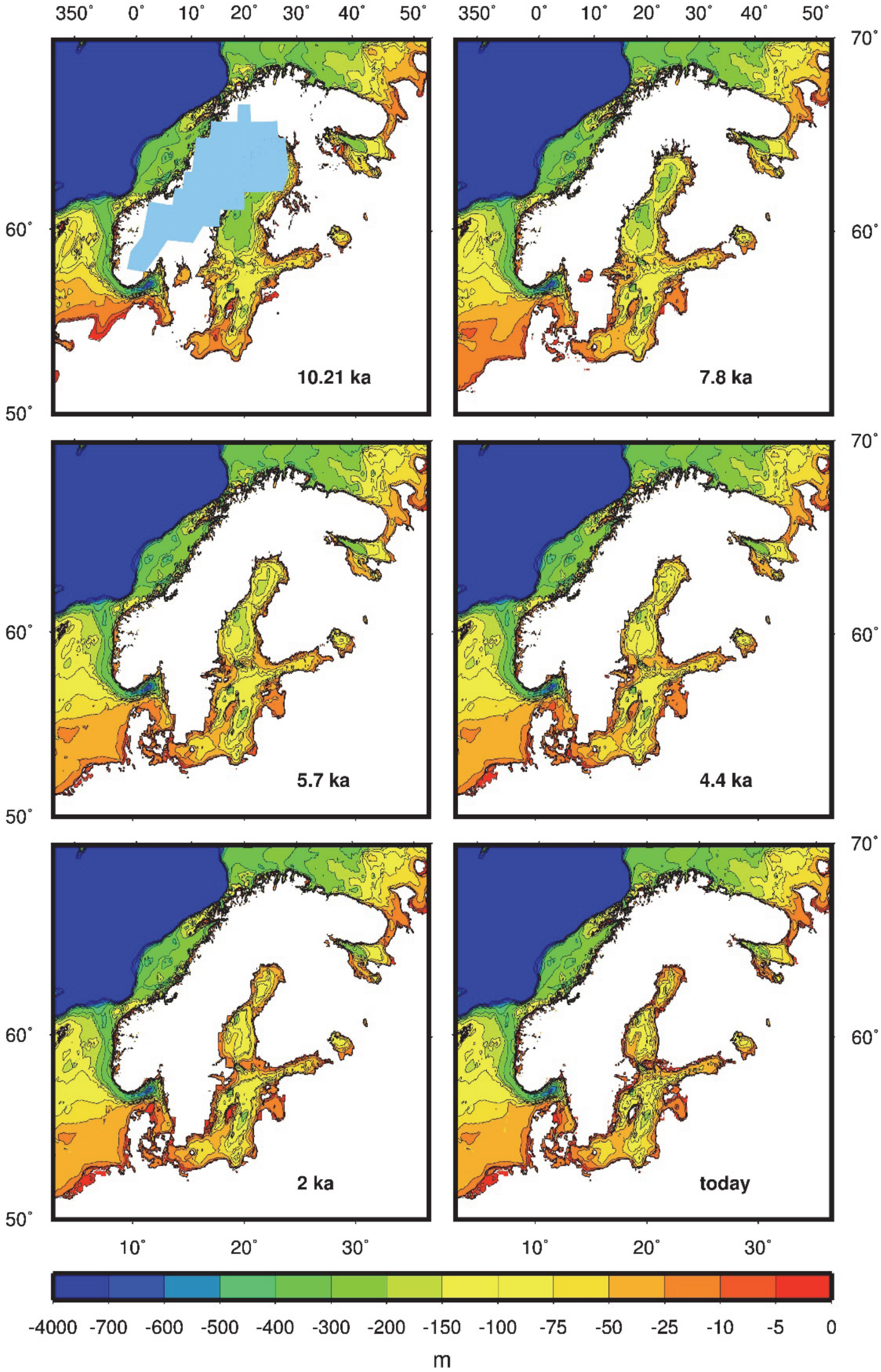

Fig. 1. Development of the Baltic Sea from 10.21 ka before present until today from a geodynamic model used in *Steffen and Kaufmann* (2005). Ice coverage at 10.21 ka (light blue) is from ice history model RSES (*Lambeck et al.*, 1998). White area was/is land. Depth in m. Due to the coarse resolution of the ice history model the World Heritage area appears to be still glaciated at 10.21 ka. Topography and bathymetry of the northern Gulf of Bothnia from ETOPO1 data (*Amante and Eakins*, 2009).

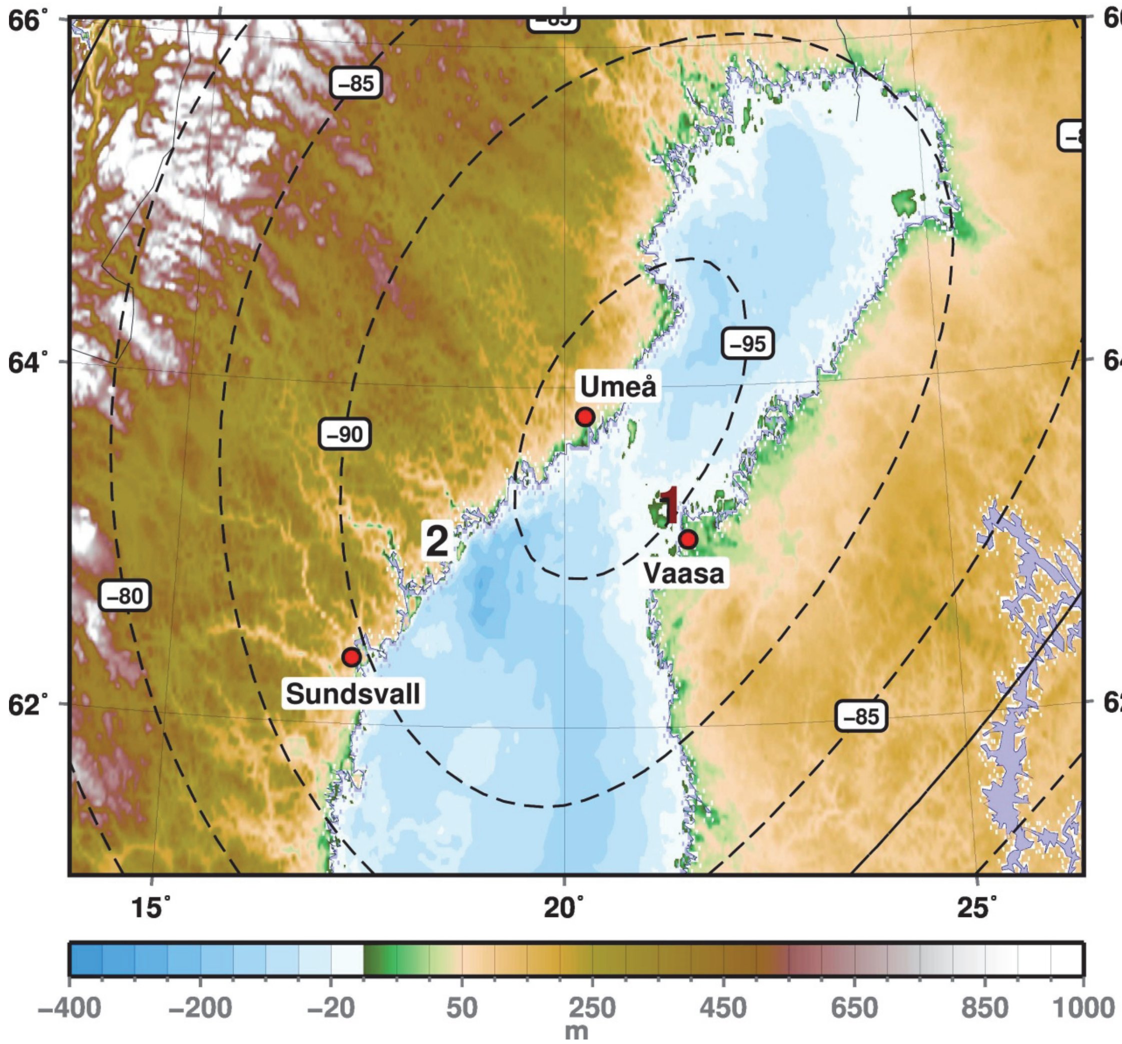

Fig. 2. Topography and bathymetry of the northern Gulf of Bothnia from ETOPO1 data (*Amante and Eakins*, 2009). 1: Kvarken Archipelago. 2: High Coast area. Isolines indicate the remaining uplift as calculated with a geodynamic model used in *Steffen and Kaufmann* (2005). Contour interval 5 m. Unit in m.

Fig. 3a. Kvarken Archipelago near Mustasaari. View from Observation Tower Saltkaret.

Fig. 3b. High Coast in Skuleskogen Nationalpark. View from Slåttdalsberget.

2 *Land uplift observation and sea-level change*

Land uplift has practical consequences, especially at the shallow shorelines of Finland, where harbours, even cities, have to be moved because of retreat of the shoreline. Precise geodetic observations have been made during the last 100 years, including repeated precise levelling and tide gauge time series. With these two methods, only the vertical motion was possible to detect. Contemporary observations are made with continuous GNSS (Global Navigation Satellite Systems, most notably GPS, Global Positioning System). They are accurate enough to detect both horizontal and vertical motions in a few year time series (e.g. *Calais et al*., 2006; *Bouin and Wöppelmann*, 2010). From relatively short (less than 10 years) time series of GNSS observations, the absolute uplift rate can be obtained more accurately than with a 100 year history of repeated precise levelling. For longer time scales, up to the LGM, we have to use indirect methods, like timing of ancient shorelines, and geophysical modelling.

Land uplift is only one of the processes related to Glacial Isostatic Adjustment (GIA) which is the response of the solid Earth to the changing mass of glaciers and ice sheets. GIA also leads to changes in the gravity field, Earth rotation and the stress in the crust (see e.g. *Steffen and Wu*, 2011), which (can) affect the sea level. Gravity influences sea level due to changing attraction of sea water by changing masses such as ice sheets and mantle rocks. Changes in earth rotation are known to influence sea level by perturbed centrifugal potential (*Mitrovica and Milne,* 1998). Recent investigations also show that stress changes in the crust such as released in earthquakes affect sea level (*Melini et al.,* 2010; *Broerse et al.,* 2014).

The height change of the sea level at a tide gauge is a sum of the vertical motions of the land and variations of the surface of the sea. One can distinguish three different cases in the land uplift: absolute, apparent and relative (*Ekman*, 1989). At one tide gauge, one observes apparent uplift, i.e. change of the shoreline relative to the sea. Between two tide gauges one may observe uplift difference, the relative uplift. Finally, with GNSS one observes the absolute land uplift which is the change in the height of the

Earth's crust relative to the centre of the Earth. The absolute uplift is independent of the sea level rise. When the apparent uplift is subtracted, the residual shows approximately the amount of the sea level rise. The relative uplift shows the fingerprint of a melting ice sheet or glacier. However, the fingerprint is only a minor contributor to the relative land uplift, and very difficult to detect from the observations.

There are several reasons for the sea level rise. Eustatic rise, the actual increase of the sea water due to the melting of land-based glaciers is the component we are mostly interested in. A considerably larger effect causing temporal variation of the sea level is the thermal expansion of the sea water. For example the El Niño/La Niña in Pacific is causing up to 20-30 cm sub-decadal variation (*Becker et al*, 2012). When removing inter-annual or sub-decadal variations, the best current estimation for the global sea level rise is 3.3 ± 0.4 mm/yr (e.g. *Cazenave et al.*, 2012). The measurements are done since 1990's with satellite altimetry, enabling us to cover the whole sea area, not only coastal areas like tide gauges. The sea level rise is not even but the trend has regional variability (*Cazenave and Llovel*, 2010).

The sea level will not change remarkably near the ice sheet. This is due to the changing gravity in the near vicinity of the ice sheet. As an example, melting of the Greenland Ice Sheet causes only a minimal change in the sea level of the Baltic Sea but a prominent increase in the sea level on the Southern Hemisphere as the water is flown there (*Mitrovica et al*., 2001; *Riva et al*., 2010).

There are a lot of studies of uplift and related sea level changes of Fennoscandia and the Baltic Sea. Based on levelling and tide gauge time series during last 100 years, we refer the reader to *Ekman* and *Mäkinen* (1996), *Kakkuri* (1997), *Mäkinen and Saaranen* (1998) and *Saaranen and Mäkinen* (2002) for more information. The latest Nordic uplift models (Fig. 4), based on levelling, tide gauges and geophysical modelling have been published by *Vestøl* (2006), and *Ågren and Svensson* (2007). New Nordic uplift models are currently in preparation which take the latest advances in observation techniques and modelling into account.

The project BIFROST (Baseline Inferences for Fennoscandian Rebound Observations, Sea Level, and Tectonics) initiated already in 1993 uses tens of permanent GPS stations in Finland and Sweden. Results are discussed e.g. in *Milne et al*. (2001), *Johansson et al*. (2002), and *Scherneck et al.* (2002). Maps based on GPS time series were published e.g. by *Mäkinen et al*. (2003), *Lidberg et al*. (2007, 2010; see Fig. 5b) and *Kierulf et al*. (2014).

An additional method is to use the ancient shorelines. While the shorelines may reveal both the uplift history and pattern, the accuracy of shoreline timing can be a limiting factor (e.g. *Lambeck et al.* 1998, 2010; *Tikkanen and Oksanen*, 2002).

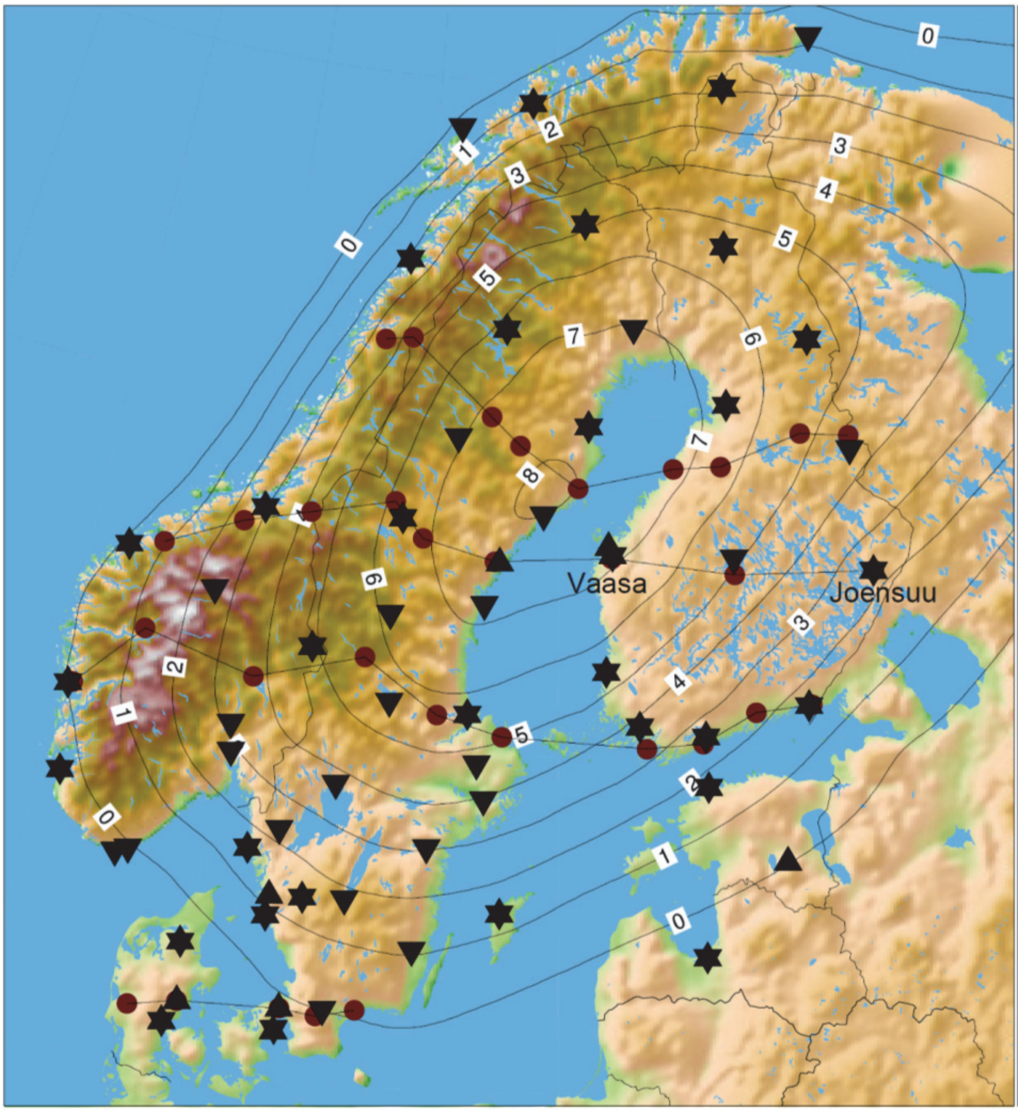

Fig. 4. Fennoscandian apparent land uplift in mm/year. The upside-down triangles on the map are permanent GNSS stations, triangles stations where absolute gravity is regularly measured, and dots with joining lines are the land uplift gravity lines, measured since the mid-1960s. Contour lines show the apparent land uplift relative to the Baltic mean sea level 1892–1991, based on Nordic uplift model NKG2005LU (*Vestøl*, 2006; *Ågren and Svensson*, 2007).

3 *Land uplift modelling*

Since the acceptance of the land uplift theory (which was introduced in 1765 by Ephraim Runeberg and Bengt Ferner independently (*Ekman*, 1991)), geodynamic models were developed to understand this process, to determine the Earth's structure and to predict future land uplift and related processes. The types of such models vary from rather simple introduction of a theory in the beginning to high resolution finite element models of the Earth nowadays. We will not discuss the different methods here though, and kindly refer the reader to *Steffen and Wu* (2011) for an overview of the model development since the mid-1970s.

Recent models are generally composed of an ice history model and an earth model. The latter consists of a lithosphere as the outer shell or top layer, and the underlying mantle, which is often subdivided in at least two layers. Both lithosphere and mantle can be laterally heterogeneous, e.g. in lithospheric thickness variation or mantle viscosity distribution. In most cases, such models assume a linear Newtonian mantle rheology, which allows fast computation of results, but other rheologies are used as well (e.g. *van der Wal et al*., 2013).

Once a model with reliable earth model parameters is found, many quantities can be calculated as a function of time with the additional help of the ice history model. Next to land uplift, it is possible to compute among other things changes in sea level, geoid, Earth's rotation and stress in the crust. Applying further input from, for example, current sea-level change research and topography data, it is possible to predict future topographic changes. We will show such an example for northern Europe in Section 5.

4 Contemporary apparent land uplift

Based on geodetic observations, we understand the uplift of the Kvarken Archipelago / High Coast quite well. However, there is still some uncertainty in the absolute values when different techniques and time series are compared. It will not change the overall picture of the uplift but affecting on some details, especially when extrapolated in the future. In *Nordman et al*. (2014) one can find that the uncertainty in land uplift in the World Heritage area is about 1 mm/year when different techniques are considered.

In Fig. 5a, there is the apparent uplift rate based on the Nordic model NKG2005LU which is based on levelling, tide gauge recordings, and geophysical modelling in such areas where geodetic data are lacking. In Fig. 5b, there is the absolute rate which is calculated from *Lidberg et al*. (2010). They reanalysed the Nordic network of permanent GPS stations and determined the vertical rate from long time series, most of them longer than 10 years. The absolute uplift determined from this analysis is at least 1 cm/year near the city of Umeå.

Difference between Figs. 5b and 5a will give an approximation for the sea level rise. There are other minor effects, like the rise of the geoid due to the uplift, which changes the mass distribution, but these are less than 1 mm/year (*Ekman and Mäkinen,* 1996). One obtains here for the sea level rise about 2.5-3 mm/year which fit quite well with the contemporary rise of the global sea level (*Cazenave et al.*, 2012; *Cazenave and Llovel*, 2010), see also *Nordman et al.* (2014) where a value of 3.1 mm/year was obtained. Baltic Sea is, however, a complicated system because it is a semi-closed basin and a lot of decadal sea level variation is dominated by the water exchange between Baltic and the North Sea via the Danish Straits (e.g. *Johansson et al*., 2003). Therefore, it may not follow the general trend, but it may have even decadal-long cycles due to long-term changes in the North Atlantic Oscillation (NAO) index (*Johansson et al.*, 2003, 2014).

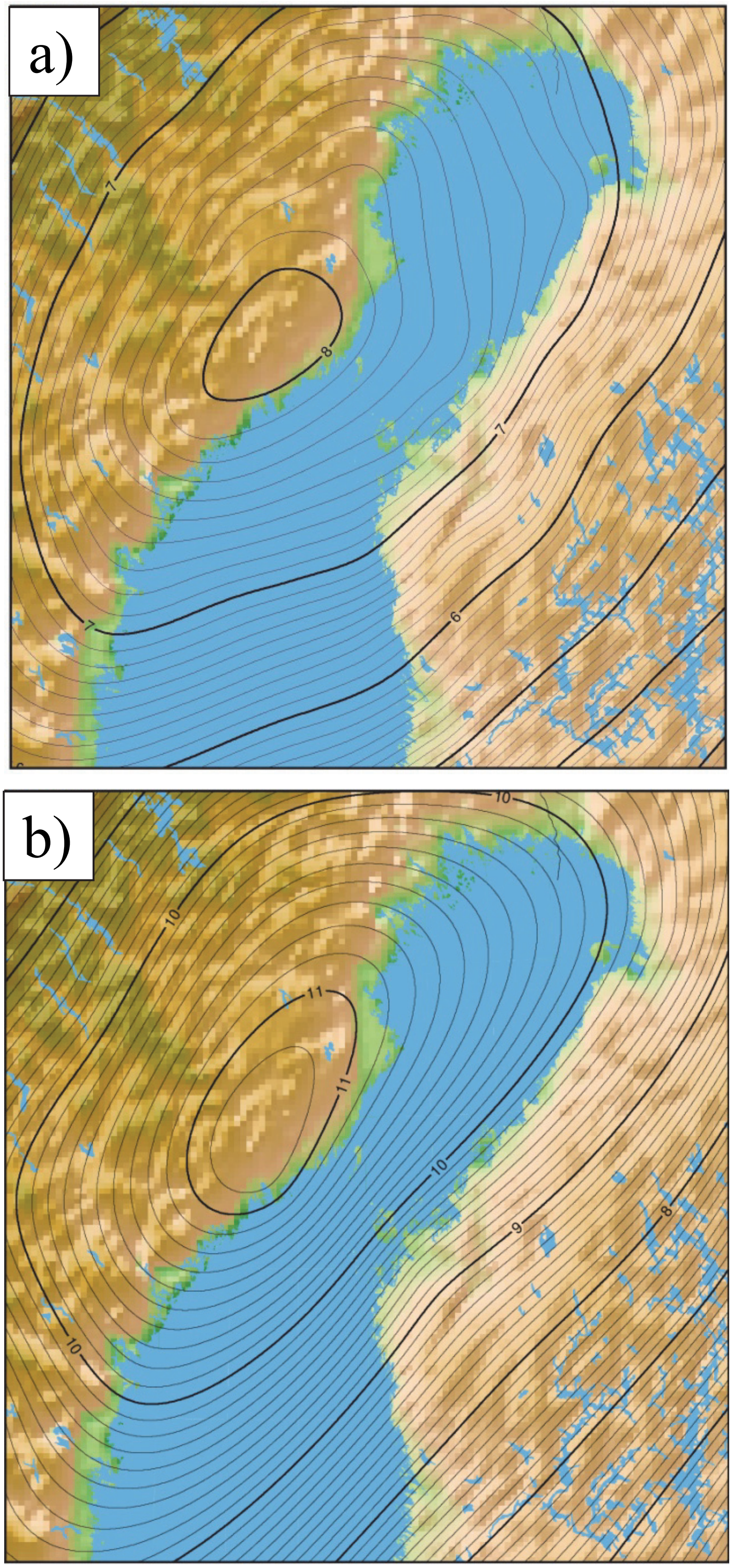

Fig. 5a**.** Apparent land uplift at Kvarken area based on Nordic uplift model NKG2005LU. 5b. Absolute uplift rate from GPS time series of *Lidberg et al.* (2010).Unit in mm/year.

5 *Current and future changes in the World Heritage area due to uplift*

Since the ice sheet vanished 8000 years ago, a total of 310 meters of uplift has occurred up to now (*Berglund*, 2004). This corresponds almost exactly to the highest point of the ancient shoreline at Skuleberget (286 m) at the High Coast. The remaining uplift to come may be up to 130 m, depending on the geophysical models.

The biggest uncertainty for the future scenarios is related to the sea level rise. It cannot be easily predicted as there are many effects and processes that first need to be understood and correctly modelled. As outlined above, current estimations vary between 3 and 9 mm/year (e.g. *IPCC,* 2013). Assuming the lower bound of about 3 mm/year, the apparent land uplift at the Kvarken Archipelago / High Coast area will remain like it is today. If the sea level rise is increasing, the apparent uplift will be smaller, but all plausible models will show apparent uplift in this area for at least the next 100 years. The more distant future is difficult to estimate because of the great uncertainties in the sea level rise. For example, considering the mentioned upper bound of 9 mm/year, land uplift and sea level rise almost equal in the Kvarken Archipelago / High Coast area and land emergence will hardly be observed. The absolute uplift values can be more easily extrapolated hundreds of years in the future with geodynamic models. The rate will slowly decrease but during the next few hundred years it can be considered almost linear.

When considering the bathymetry of the sea area (Fig. 2), one can notice the shallow archipelago at the Finnish side, and also the very shallow area between Vaasa and Umeå having a maximum depth of 25 m. With the current apparent uplift rate, this area will become mostly dry land in a few thousand years. Assuming a constant sea level rise of 3 mm/year and constant absolute uplift of 10 mm/year, we get 7 mm/year apparent uplift, which would lead to an isthmus in about 3600 years. A smaller sea level rate, e.g. of 2 mm/year, would result in an earlier connection in about 3100 years. In the extreme case of 9 mm/year, the land connection is postponed by additional 20 000 years. These times result with a constant absolute uplift rate. For a more likely scenario they need to be adjusted applying a decreasing absolute uplift rate over time, e.g. from a geodynamic model. Depending on such a model the connection is postponed a few tens to thousands of years. Assuming 9 mm/year, we note that the absolute uplift will be almost negligible by then and thus the World Heritage area would already be subject to transgression again. In all cases, most dramatic changes are at the Finnish side, whereas the steep shores at the High Coast make changes there less prominent. This means that a land bridge will be established mainly from the Finnish side.

In Fig. 6 and 7, we show an example of the future development of the Baltic Sea within the next 10 000 years based on geodynamic modelling. We use the software package ICEAGE (*Kaufmann,* 2004) to calculate the future topography based on ETOPO1 topography data (*Amante and Eakins,* 2009), ice model RSES (*Lambeck et al.,* 1998) and an earth model consisting of a 120 km thick lithosphere, an upper-mantle viscosity of 4×10^{20} Pa s and a lower-mantle viscosity of 10^{23} Pa s. This earth-ice model combination has been found to fit relative sea level data and the GPS velocity field in

Fennoscandia well (*Steffen and Kaufmann,* 2005), and we refer the reader to this study for more information regarding the modelling. In Fig. 6, we assume a constant land uplift as observed today and a constant sea level rise of 3 mm/year. The features as discussed above appear on the maps. In contrast to the land emergence in the northern parts

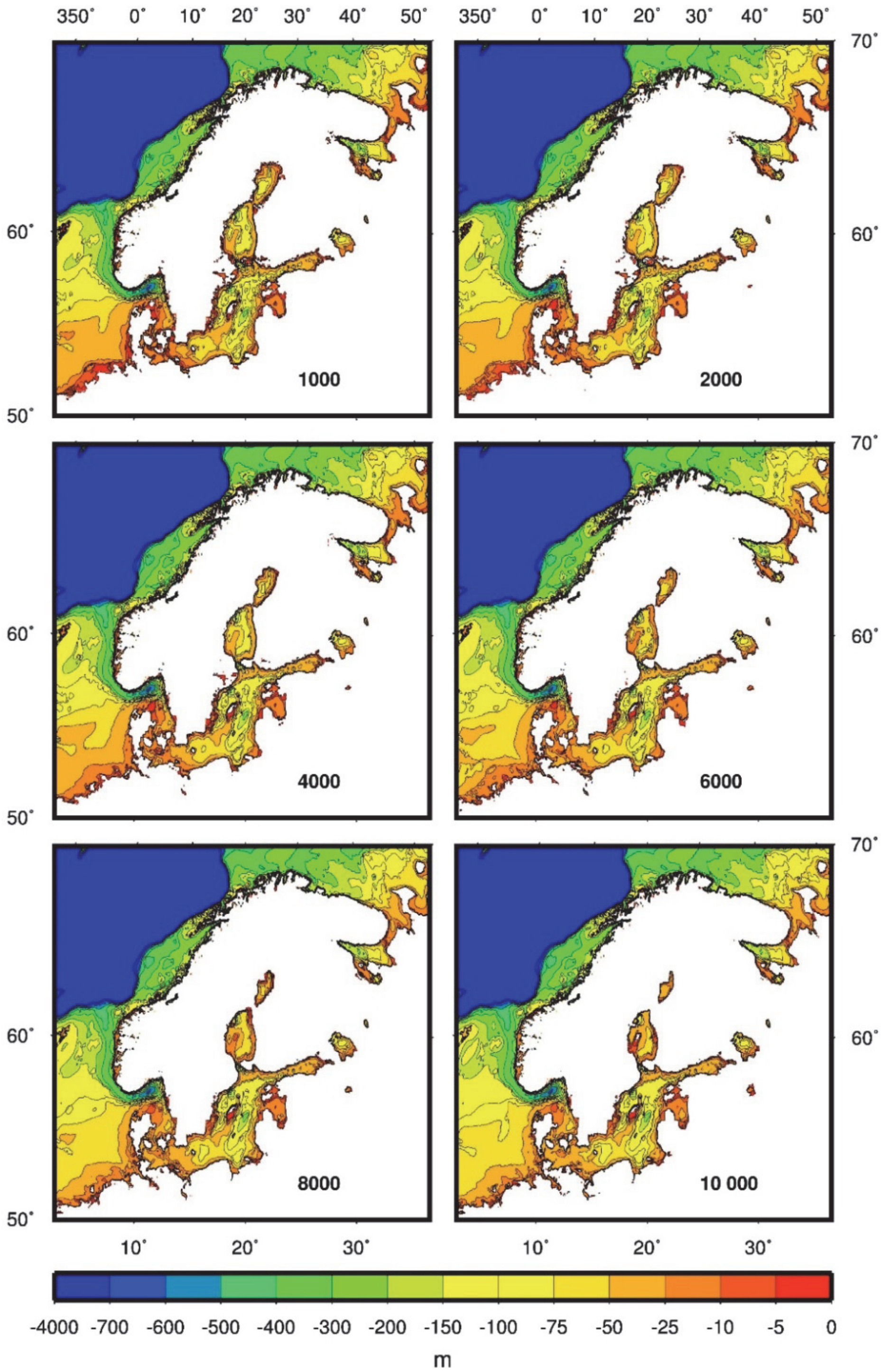

Fig. 6. Future development of the Baltic Sea based on the geodynamic model used in *Steffen and Kaufmann* (2005) assuming constant land uplift as today and constant sea-level rise of 3 mm/year (no sea-level fingerprinting). Years in the future are indicated in each subfigure. White area is (will be) land. Depth in m. Topography and bathymetry of the northern Gulf of Bothnia from ETOPO1 data (*Amante and Eakins*, 2009).

of the Baltic Sea, land at the southern coastline drowns due to sea level rise and the collapse of the forebulge. Fig. 7 shows the same as Fig. 6 but with changing absolute uplift rate as calculated with the geodynamic model. In the first few thousand years similar changes as with constant uplift rate appear, however, the land bridge in the Kvarken area is not established. Later on, rather drastic consequences in form of transgression are found along the southern Baltic Sea coasts and even Åland islands, parts of Central Sweden, southern Finland and Estonia.

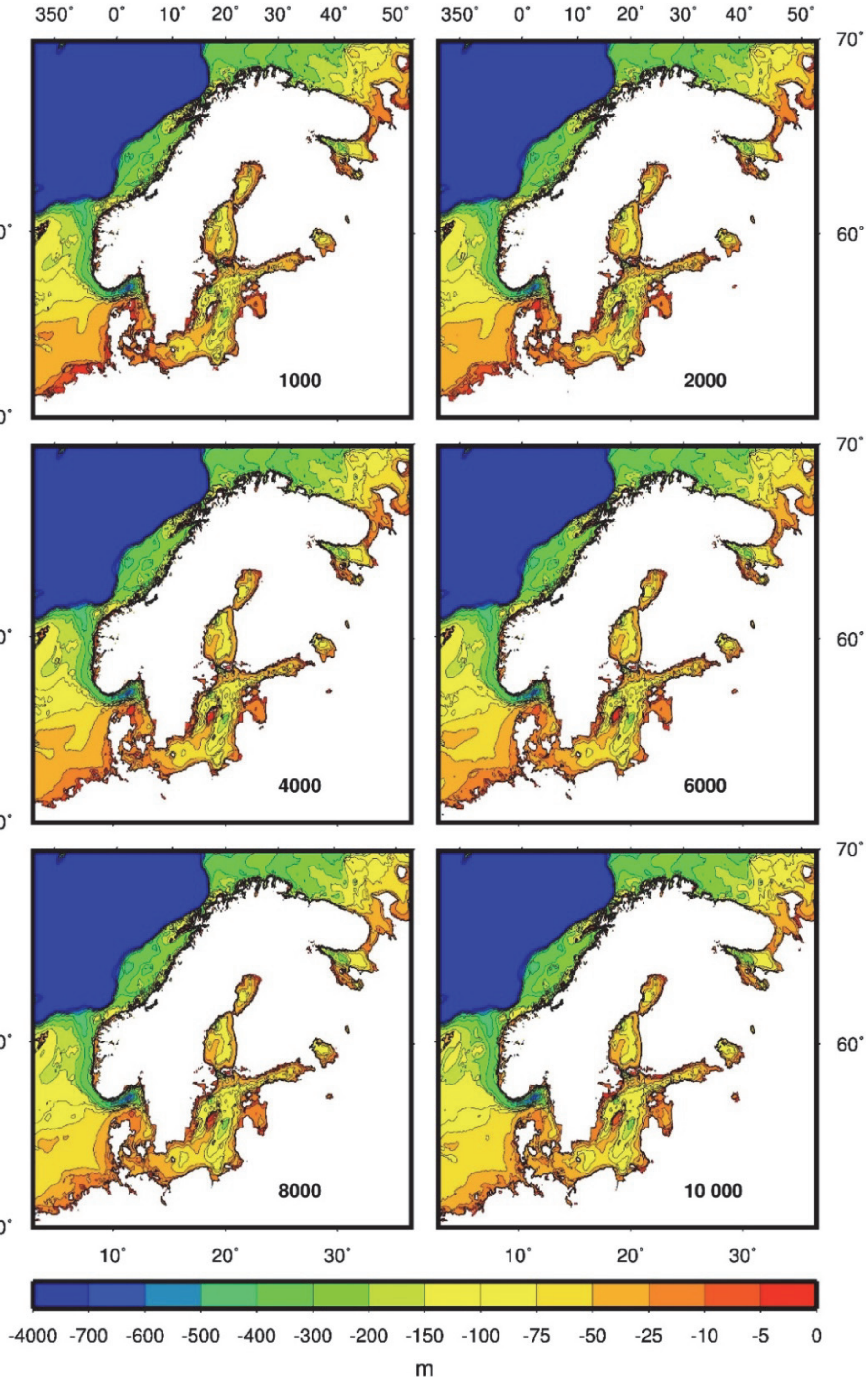

Fig. 7. Same as Figure 6 but with land uplift as a function of time calculated with the geodynamic model used in *Steffen and Kaufmann* (2005).

6 Conclusions

The Kvarken Archipelago / High Coast UNESCO World Heritage area will retain its remarkable landscape for centuries in the future. In the longer time scale the land connection between Finland and Sweden will be established and the Bay of Bothnia will become an inland lake in a few thousand years. However, the time scale strongly depends on climate change and the associated global sea level rise and may thus vary from hundreds to thousands of year, which highlights the need for accurate prediction of future sea level change. With plausible sea level rise scenarios the apparent uplift at the area is still positive, but with increasing sea level rise the rate becomes smaller than today. Moreover, with decreasing uplift rate in the distant future, the land connection between Finland and Sweden will most likely not be established, and transgression may occur in several thousands of years. Geophysical modelling and contemporary geodetic measurements give the absolute uplift rate with a 1 mm/year or less uncertainty. With future studies this uncertainty is expected to become smaller, and the biggest uncertainty will thus be related to the global sea level rise.

Acknowledgements

We would like to thank the Kvarken Council for organising the meeting and workshop between scientists and site managers from the World Natural Heritage Site Kvarken Archipelago / High Coast in Vaasa, Finland, in November 2013, which gave the idea for this paper. We also thank two anonymous reviewers for their helpful comments.

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