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Postglacial rebound and relative sea level changes in the Baltic Sea since the Litorina transgression

Alar Rosentau, Jan Harff, Tõnis Oja, Michael Meyer

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Abstract Based on geostatistical modelling the authors compared relative sea level records for the Litorina and post-Litorina Sea with tide gauge and GPS derived crustal velocity measurements in Fennoscandia and in the Baltic region. Results show good fit between the geological record and GPS derived crustal velocity measurements indicating that the postglacial rebound (PGR) centre on the northwest coast of the Bothnian Sea and the isostatic zero-line in the southern Baltic remained stable during the last 8000 ^{14}C yrs BP (8900 cal yrs BP). An average Baltic Sea level rise of 1.4±0.4 mm/y for the 20th century was estimated, which is found to be at about one fifth compared to the mid-Holocene sea level rise. However, considering the recent estimates of eustatic sea level rise for the 21st century the slowly uplifting coastal areas in southern Sweden, SE Finland, Estonia, Latvia and NW Russia, which have experienced a long term relative sea level fall, will probably also be affected by future sea level rise reminiscent of the mid-Holocene one.

Keywords *• Relative sea level • Tide-gauge measurements • Postglacial rebound • Litorina Sea • Eustatic sea level rise • Vertical crustal movements • Baltic Sea*

✉ *Alar Rosentau [alar.rosentau@ut.ee], Department of Geology, University of Tartu, Ravila 14A, 50411 Tartu, Estonia; Jan Harff, Michael Meyer, Baltic Sea Research Institute Warnemünde, Seestrasse 15, 18119 Rostock, Germany; Tõnis Oja, Department of Physics, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia.*

INTRODUCTION

Melting of the Fennoscandian Ice Sheet changed the mass load on the continent and in nearby oceans, including the Baltic Sea and resulted in isostatic adjustments throughout the region. Records of relative sea level (RSL) change differ along place to place and also with time because of the interaction between eustatic sea level rise and postglacial rebound (PGR) processes. RSL has been studied in Fennoscandia based on geological records, such as RSL curve data (for summary Lambeck *et al.* 1998; Harff *et al.* 2005, 2011), and for the last few hundred years by tide gauge measurements complemented by repeated levelling (Ekman 1996, 2009; Kakkuri 1997; Douglas, Peltier 2002). Recently, continuous point positioning (time series of the coordinates) from the BIFROST (Baseline Inferences from Fennoscandian Rebound Observations, Sealevel and Tectonics) permanent GPS network also became available for determination of crustal velocities with respect to the Earth centre of mass (Milne *et al.* 2001; Johansson *et al.* 2002; Scherneck *et al.* 2002; Lidberg *et al.* 2007). In the current paper authors compare geological records of the relative sea level for Litorina and post-Litorina Sea with tide gauge and GPS measurement data by using geostatistical modelling. The aim of the geostatistical modelling is to reconstruct the changes in postglacial rebound for the last and still on-going brackish water period in the history of the Baltic Sea for a better understanding of recent and future RSL changes.

MATERIAL AND METHODS

For comparison of relative sea level change and GPS-derived vertical crustal movement models, the relative sea level records and crustal velocity measurement data were interpolated into different surfaces using Ordinary Kriging method (Olea 1999) with grid size of 2 x 2 km. Interpolations utilized the isotropic coordinate system Universal Transverse Mercator (UTM, zone 33 N). The geometry of the calculated RSL and PGR velocity surfaces was analysed using a terrain slope operator by software package SURFER.

The data on RSL change during the last 8000 ^{14}C yrs BP (8900 cal years BP) are based on 36 published shore displacement curves around Fennoscandia and Baltic region (Fig. 1, Table 1). Age-elevation data from the RSL curves were used to compile spatially interpolated RSL surfaces with 10-year intervals from

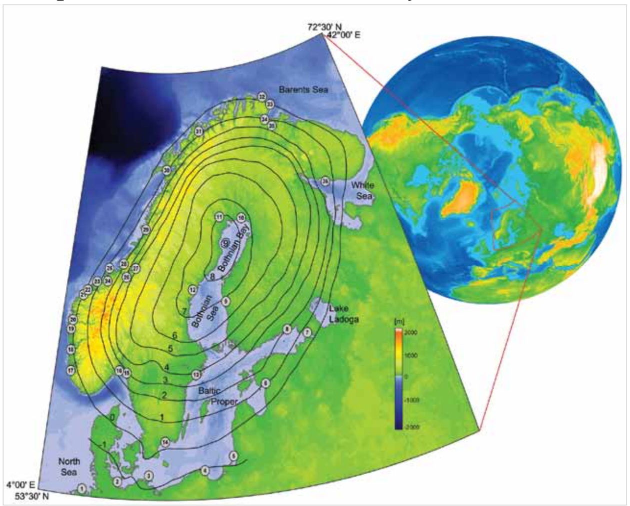

Fig. 1 Location of the study area in Fennoscandia with isobases of appearent vertical crustal movements (mm/y) relative to sea level (modified from Rosentau *et al.* 2007). The locations of numbered RSL curves listed in Table 1 are shown on the map. Compiled by A. Rosentau, M. Meyer, 2011.

Table 1 Catalogue of relative sea level curves. The locations of sites (ID) are shown in Fig. 1. A. Rosentau, M. Meyer, J.Harff, 2011.

ID	Reference	ID	Reference
1	Linke 1982	19	Kaland *et al.* 1984
2	Duphorn 1979	20	Kaland 1984
3	Schumacher 2000	21	Svendsen, Mangerud 1987
4	Uścinowicz 2006	22	Svendsen, Mangerud 1987
5	Gelumbauskaitė, Šečkus, 2005	23	Svendsen, Mangerud 1987
6	Veski *et al.* (pers. com., after Rosentau *et al.* 2007)	24	Svendsen, Mangerud 1987
7	Miettinen 2004	25	Kjemperud 1986
8	Miettinen 2004	26	Kjemperud 1981
9	Donner 1968	27	Sveian, Olsen 1984
10	Saarnisto 1981	28	Hafsten 1981 in Pirazzoli 1991
11	Linden *et al.* 2006	29	Grönlie 1981
12	Berglund 2004	30	Hafsten 1983
13	Karlsson, Risberg 2005	31	Hald, Vorren 1983
14	Berglund 1964	32	Kelletat 1985
15	Anundsen 1985	33	Kelletat 1985
16	Hafsten 1983	34	Donner *et al.* 1977
17	Hafsten 1983	35	Corner *et al.* 1999
18	Kaland 1984	36	Badyukov, Kaplin 1979

8000 to 0 ^{14}C yrs BP (Rosentau *et al.* 2007). Also, the terrain slope operator of the software package SURFER was applied for the RSL surfaces to calculate surface tilting gradients. From these models, time slices at 8000; 6500; 5000; 3500; 2000; and 500 ^{14}C yrs BP were selected and compared with GPS-derived crustal velocities and tide gauge measurements (Figs 1–3).

A map with the isobases (Fig. 1) of the recent postglacial rebound of Fennoscandia and Baltic region compiled initially by Ekman (1996) and improved by additional tide gauge measurements in southern Baltic Sea area by Rosentau *et al.* (2007) was used to reconstruct the relative sea level surface for the 100-year period (1892–1991). So called apparent uplift rates (relative to the mean sea level) on Ekman's map were calculated from the sea-level and lake-level records combined with repeated high-precision levelling results and the uncertainty of these was estimated to be better than ± 0.5 mm/a in most cases (Ekman 1996; Lidberg *et al.* 2009).

The data of absolute vertical crustal movements (relative to geocenter), taken from Lidberg *et al.* (2007), represent a newly-improved 3D velocity field for the Fennoscandian PGR area. The continuous observations of station coordinates from the extended BIFROST GPS network with the longest time series, being over eight years, were used to estimate the velocity for more than 50 stations. The average uncertainty of vertical velocity was estimated to be ± 0.3 mm/y. The version ITRF2000 of the International Terrestrial Reference Frame (ITRF) was used to determine absolute crustal velocities relative to the geocenter of the Earth's masses (ITRF web site, http://itrf.ensg.ign.fr/).

RESULTS AND DISCUSSION

Centre of the postglacial rebound and isostatic zero-line

Comparison of geological RSL model with tide gauge and GPS derived crustal velocity models (Figs 1-3) show similar NE–SW oriented elongated dome of the PGR. The area of Ångermanland, Sweden (site 12 in Fig. 1), is the area with the highest observed evidence of shore erosion in Fennoscandia since the last deglaciation (Berglund 2004). Geological RSL model shows that through the change of RSL surface, its maximum difference is located in the Ångermanland area reflecting the stable position of PGR centre (see Fig. 2). The GPS-derived crustal velocity model confirms this location for the present day conditions (see Fig. 3), although a shift of the PGR centre during the late Holocene has also been proposed (cf. Ekman 1996; Berglund 2004;

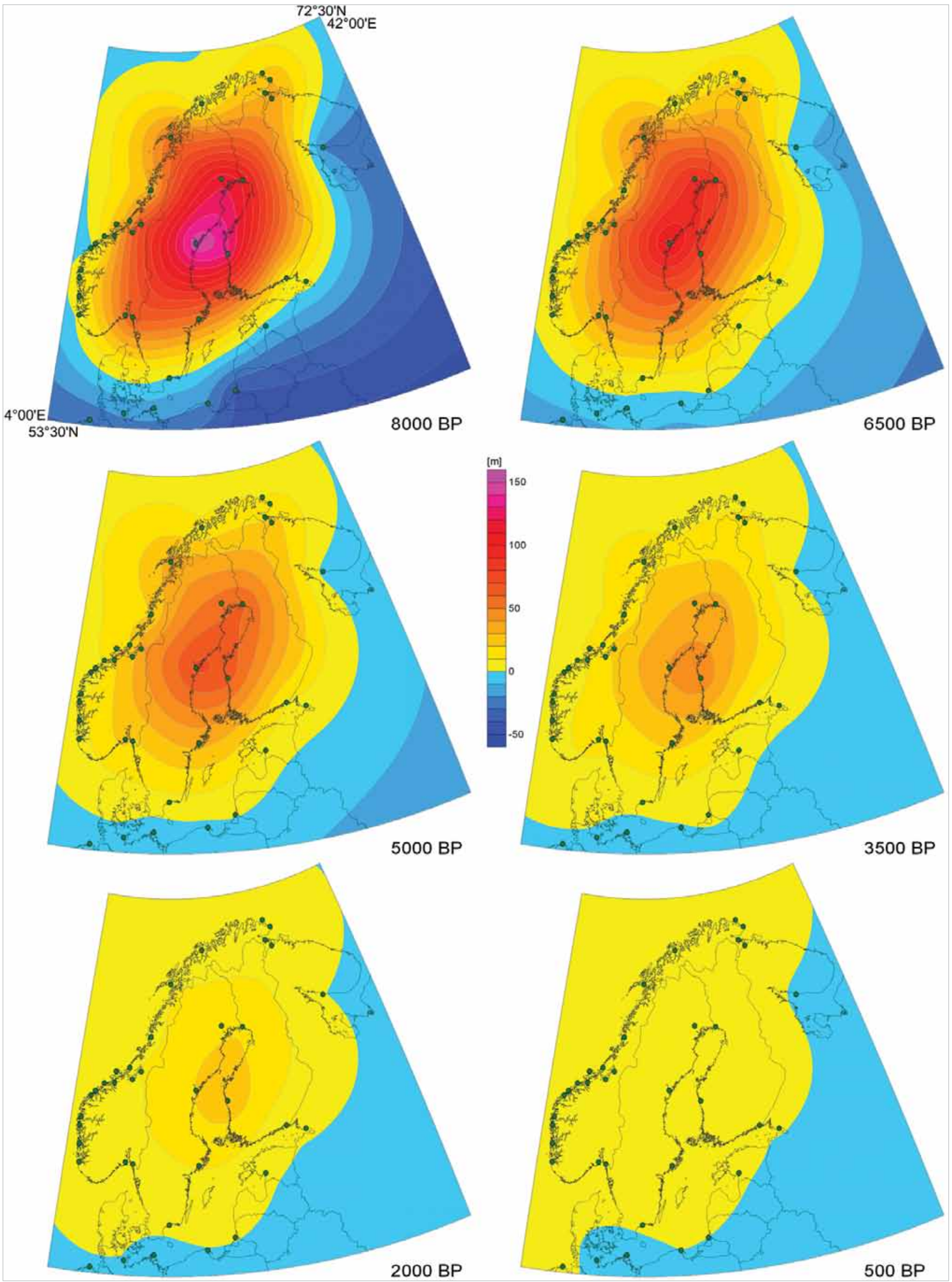

Fig. 2 RSL surfaces for six chronological equally spaced intervals between 8000–500 ^{14}C yrs BP. Dots in the maps mark the locations of RSL curves shown in Fig. 1 and Table 1. Compiled by A. Rosentau, M. Meyer, 2011.

Linden *et al.* 2006). The latter opinion is based on tide gauge measurement data (Ekman 1996) suggesting the location of a PGR centre in the Bothnian Bay area (see Fig. 1), about 300 km northeast of the geological PGR centre (see Fig. 2).

However, there is no evidence or explanation for such a shift from the geological RSL data. Comparisons of shore displacement curves from this area show up to 30 m higher water level on the western coast of Bothnian Sea compared to the Bothnian Bay area (Fig. 4) and does not indicate any migration of the PGR centre from 8000 to 500 ^{14}C yrs BP (see Fig. 3). This is verified also by Fennoscandian ice sheet thickness models based on glacial rebound modelling of visco-elastic Earth in combination with palaeoshoreline data showing the thickest ice cover in the Bothnian Sea area during the Last Glacial Maximum (Lambeck *et al.* 1998; Svendsen *et al.* 2004). In the light of such deviation between rebound centres it is probable that some errors or unexplained phenomena exist in the tide gauge data. It is important to keep in mind that noise and sometimes gross errors or outliers are associated with observation data.

Based on the realistic uncertainty estimation and statistical methods the reliability of different data sources and derived models can be evaluated. For example, in the frame of an extensive analysis combining the data from precise levelling, tide-gauge recordings and time series from continuous GPS stations into one solution using Least Squares Collocation, Vestøl (2006) removed several statistically significant outliers from the geodetic data, including one tide-gauge station (Furuögrund) from the rebound centre area.

To explore the extent of the area of PGR it is also interesting to follow the position of the isostatic zero-line at different time periods. In Fig. 5 authors compared the RSL data at 8000 ^{14}C yrs BP with the recent crustal movements (absolute velocities from GPS network) and tide gauge measurements (apparent velocities) along the SW-NE oriented transect crossing the GPS-stations. The measurements of apparent velocities place the isostatic zero-line in the southern part of the Baltic Proper about 100 km further north compared to data from vertical GPS velocities. The northern location of this so called "apparent zero-line" is caused most probably by the eustatic sea level rise and geoid surface change.

The signal from the eustatic sea level change is generally prevailing, thus for localization of isostatic zero-line relative to the geocentre in geological past an eustatic sea level history needs to be reconstructed for that time. Nearest estimation for eustatic sea level

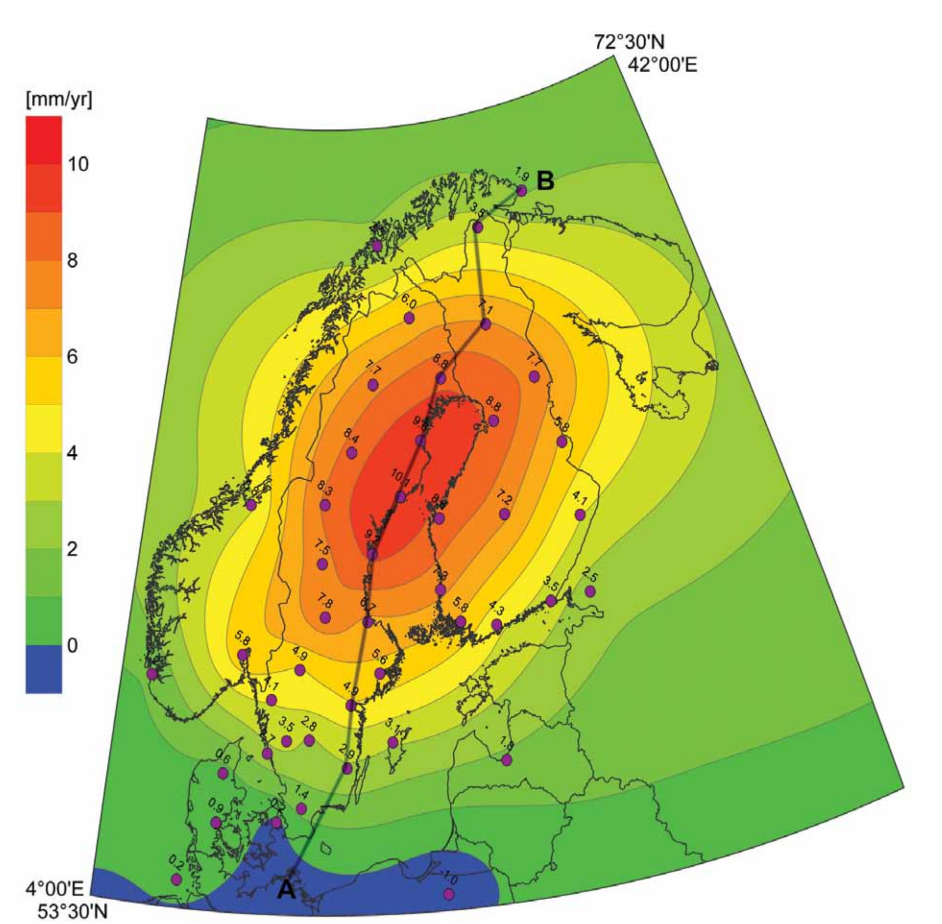

Fig. 3 Interpolated surface of crustal uplift rates (in mm/y) according to BIFROST permanent GPS network data (Lidberg *et al.* 2007) with indication of proxy data and location of cross-section shown in Fig. 5. Compiled by A. Rosentau, M. Meyer, 2011.

outside of the Baltic Sea basin is from Kattegat area indicating a sea level 15 m b.s.l. at 8000 ^{14}C yrs BP (Mörner 1976). Within the Baltic Sea the eustatic sea level at *c.* 13 m b.s.l. at 8000 ^{14}C yrs BP was recently estimated for the isostatically stable area in the Darss Peninsula (Lampe *et al.* 2011; Harff, Meyer 2011) which corresponds well with Mörner`s (1976) estimation. If the estimated eustatic sea level of about 15–13 m b.s.l holds true, it can be concluded that the zero-line remained rather stable in southern Baltic during the past 8000 ^{14}C yrs BP (see Fig. 5).

Differences in land uplift

Calculated shoreline tilt gradients for Fennoscandia and for the Baltic region indicate that the area between the PGR centre and the zero-line tilts rather unequally because of the differences in ice loading. These gradients show highest tilt in the areas of SW Finland and along the Norwegian coast (Fig. 6). In SW Finland the tilt of the Litorina shoreline at 8000 ^{14}C yrs BP reach up to 0.3 m km^{-1} and decrease to 0.2 m km^{-1} at 6500 ^{14}C yrs BP. This is in good accordance with estimated tilt gradients based on correlations of shoreline features of the Litorina Sea in the Helsinki area (Hyvärinen 1982). A gradient of 0.2 m km^{-1} for a 6500 ^{14}C yrs BP old shoreline can also be calculated by using the two detailed shore-displacement curves from Olkiluoto–Pyhäjärvi and Tammisaari–Perniö areas from the same region (Eronen 2001).

In the areas of lower land uplift the tilt of shorelines has been estimated by correlation of transgressive shoreline features. Svensson (1991) found that in the Oskarshamn area (SE Sweden) transgression shoreline of the Litorina Sea at 6500 ^{14}C yrs BP has a tilt of 0.14–0.12 m km^{-1}, while Saarse *et al.* (2003) show that the transgression shoreline of the Litorina Sea in Estonia tilt 0.13 m km^{-1}. Correlation of transgressive shoreline features may sometimes lead to overestimation of the shoreline tilt due to the time-transgressive nature of such shorelines (cf. Teller 2001). However, authors estimation of the shoreline tilt (see Fig. 6) fit relatively well with the estimation by Svensson (1991) and Saarse *et al.* (2003) indicating no evidences of time-transgressive nature of Litorina Sea shorelines.

Shoreline tilt gradients also decrease with time as a result of the slow-down of the land uplift. Time-gradient curves show that decrease in tilting is first nonlinear (exponent-like), but later during the last 3000 ^{14}C yrs BP almost linear (Fig. 7). Such decrease in tilting refers to the deceleration of the land-uplift process and its later turn into fairly steady state. In

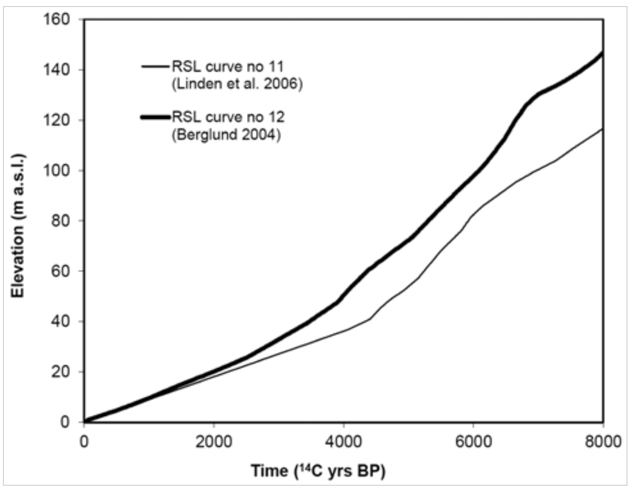

Fig. 4 Comparison of two shore displacement curves from the centre of Fennoscandian rebound. For location of the curves see Fig. 1. Note about 30 m higher RSL (curve 12) at the western coast of Bothnian Sea compared with Bothnian Bay (curve 11) at 8000 ^{14}C yrs BP. Compiled by A. Rosentau, M. Meyer, 2011.

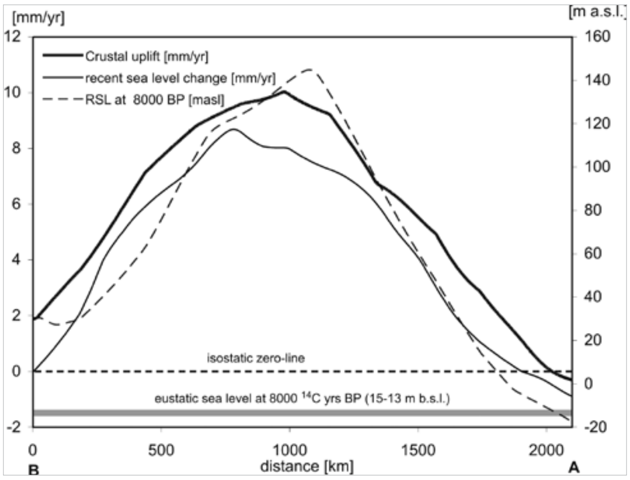

Fig. 5 Comparison of RSL difference surface at 8000 ^{14}C yrs BP (m a.s.l.) with appearent vertical crustal movement rates (mm/y) and with GPS derived crustal uplift rates (mm/y) along the SW–NE oriented profile. Location of the profile is given in Fig. 3. Eustatic sea level at 8000 ^{14}C yr BP is also shown and discussed in the text. Compiled by A. Rosentau, M. Meyer, 2011.

glacial isostatic adjustment (GIA) modelling the Earth described as viscoelastic Maxwell body displays both solid and fluid behaviour, so that at short timescale the material responds as if elastic, and at long timescale it flows as a viscous flow (Lambeck, Johnston 1998). The

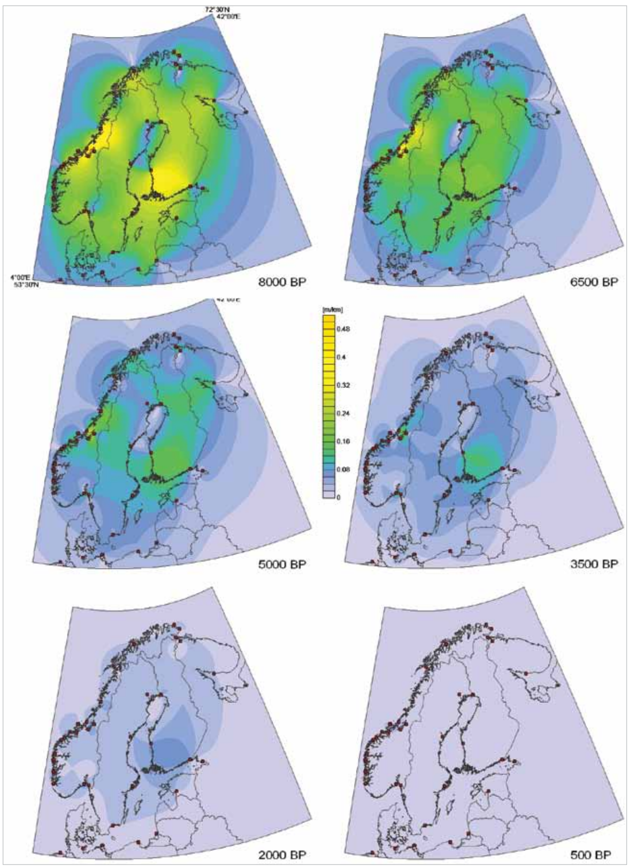

Fig. 6 Surface tilt gradients calculated from relative sea level surfaces in Fig. 2 and by terrain slope analyses. Compiled by A. Rosentau, M. Meyer, 2011.

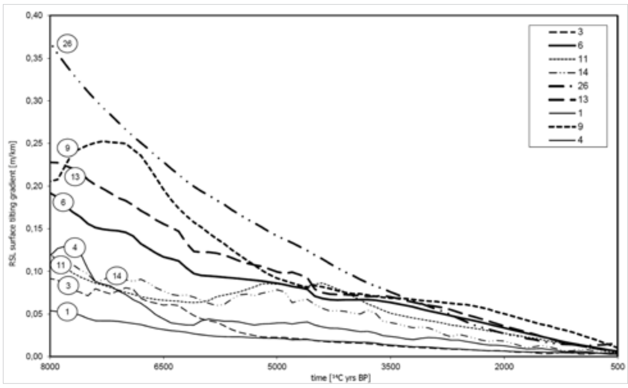

Fig. 7 Changes in RSL surface tilt gradients in time for selected locations from Baltic region and outside given in Fig. 1. Compiled by A. Rosentau, M. Meyer, 2011.

rapidly decreasing curve quite after the Last Glacial Maximum shows quick elastic rebound effect, later on the viscous relaxation prevails, showing decaying relaxation process.

Comparison of shoreline tilt gradients in the geological past (Figs 6-7) and present (see Fig. 1) shows that 65 % of the uplift between 8000–0 ^{14}C yrs BP occurs during the first 4000 ^{14}C yrs BP while around 0.3% during the last century. Some shoreline tilt gradient curves show episodes where decreasing (negative) trend is replaced with increasing (positive) trend during the first half of the Litorina Sea phase (Fig. 7). These anomalies could be associated with local events like short-term transgression events induced by increased westerly atmospheric circulation, irregularities in isostatic uplift or imply to the errors in the shore displacement curve data.

Eustatic sea level rise and climate change

A rough estimation of the average Baltic Sea level rise for the 20th century can be made by subtracting the relative sea level rates from the crustal uplift rates. The average sea level rise of 1.4±0.4 mm/y for the Baltic Sea along the SW–NE profile (Fig. 5) was calculated using models presented in Figs 1 and 3. This difference is affected by the uplift of the geoid surface (about 6% of absolute uplift value, see Vestol 2006), so that estimated eustatic sea level rise is a little bit lower than the figure above.

Although the geoid surface is rising +0.6 mm/y in the rebound centre, its influence on the aforementioned difference over the Baltic region is mostly some 0.1 mm/y. This rate of recent sea level rise is, however, at about one fifth than at the time at the beginning of the Litorina Sea at about 8000–6500 ^{14}C yrs BP when the last remnants of the continental ice sheets melted in Northern Hemisphere and sea level rose with an average rate of about 6 mm/per year (Lampe *et al.* 2011). This rapid sea level rise caused transgression also in areas of moderate land uplift in southern Sweden, SE Finland, Estonia, Latvia and NW Russia and led to burial of coastal lowlands and Stone Age settlements (Dolukhanov *et al.* 2009; Berglund *et al.* 2005; Veski *et al.* 2005; Miettinen 2004).

If the global warming will continue and the average air temperature will rise a few degrees (supposed estimate range is from 1.4°C to 5.8°C) within the 21st century as proposed by IPCC (2007) the eustatic sea level would quickly respond with acceleration and transgressive areas may expand. Jevrejeva *et al.* (2012), based on a new generation of climate change scenarios (Moss *et al.* 2010), have shown that recent global sea level acceleration continues over the 21st century even after stabilization of radiative forcing and that sea level will rise 0.57 m for the lowest predicted forcing and 1.10 m for the highest forcing by 2100. If these recent estimations hold true, the rate of sea level rise for the 21st century will be significantly higher compared to earlier suggestions (IPCC, 2001; Douglas, Peltier 2002; IPCC, 2007) and will be comparable with sea level rise rates during the mid-Holocene. The acceleration in recent mass loss for the largest glaciers and ice caps and thus their increasing contributions to global mean sea level rise have been recently detected from the monthly global gravity field solutions of the Gravity Recovery and Climate Experiment (GRACE) satellite mission (Rignot *et al.* 2011; Jacob *et al*. 2012). Considering the recent estimates of an acceleration in the global sea level in 21st century, the slowly uplifting coastal areas in southern Sweden, SE Finland, Estonia, Latvia and NW Russia which experienced a long term relative sea level fall could also be affected by a future sea level rise as they did during the mid-Holocene.

Beside the global-scale processes, the westerly atmospheric circulation controls the water level in the Baltic Sea. Increased strength of the westerly atmospheric circulation in Northern Europe during the last 60 years, as described by positive NAO index, has complementary impact on the eustatic sea level rise in the Baltic region (Suursaar *et al.* 2006).

CONCLUSIONS

Comparison of relative sea level records for Litorina and post-Litorina Sea with tide gauge and GPS derived crustal velocity measurements in Fennoscandia and in Baltic region show that the PGR centre at the west coast of the Bothnian Sea and zero-line in the southern Baltic remained relatively stable during the last 8000 ^{14}C yrs BP. Suggested PGR centre is about 300 km southwest from the PGR centre according to tide gauge measurements. This discrepancy may refer to unexplained phenomena in tide gauge data at the Swedish coast of the Bothnian Bay.

Shoreline tilt gradients, calculated from RSL curve data, decrease with time as a result of the slow-down of the land uplift and fit well with transgressive shoreline features of the Litorina Sea. Initially the decrease is exponent-like, but shows nearly a linear trend for the last 3000 ^{14}C yrs BP. Calculated shoreline tilt gradients for the Litorina Sea show highest values in the areas of SW Finland and reach up to 0.3 m km^{-1}.

An average Baltic Sea level rise of 1.4±0.4 mm/y for the 20th century was estimated, which is found to be at about one fifth compared to the mid-Holocene sea level rise. Recent estimations of eustatic sea level rise indicate that sea level rise accelerates during the 21st century to the comparable level as it was in mid-Holocene. As a result the slowly uplifting coastal areas in southern Sweden, SE Finland, Estonia, Latvia and NW Russia which have experienced long term relative sea level fall will probably also affected by future sea level rise reminding of the mid-Holocene one.

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