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Modelling prognostic coastline scenarios for the southern Baltic Sea

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The coastline development of the Baltic Sea is characterised by a large variability. During the last millennia the Litorina transgression has changed the land-sea distribution in an exceptional manner. But, this development is still going on. In forthcoming centuries, mankind will face continuing coastlines changes, caused by exogenous (eustatic) and endogenous (isostatic) forces. Modelling of prognostic coastline scenarios requires assumptions about the future eustasy and isostasy. This can be accomplished by the integration of climate model data and data of vertical movements of the Earth's crust. Data used for modelling prognostic coastline scenarios at the southern Baltic Sea are recently measured vertical crust movement published in the frame of the IGCP project No. 346 "Neogeodynamica Baltica" and modelled sea level data from the Climate Research Centre Hamburg, Germany. Two coastline scenarios at 2840 AD basing on modelled prognostic relative sea level rise are presented.

☐ *Isostasy, eustasy, relative sea level, Litorina transgression, sea level rise, Baltic Sea.*

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INTRODUCTION

Aim of this paper is the modelling of large scale prognostic coast line changes for the southern Baltic Sea for the next 800 years as a result of eustasy and isostasy, with the exclusion of sedimentary processes. The model considers two parameters mainly. First, the sea level may change due to climatically driven eustatic processes. Global warming and therefore thermal expansion of sea water as well as additional supply of melt water will cause sea level rise (Houghton *et al.* 2001). Second, interfering endogenous driven processes will translate vertically directed movements of the earth's crust into horizontal displacements of coastlines. In the past, these two components are recorded as a composite by ancient coastline markers (Tikkanen & Oksanen 2002) and documented by various authors as relative sea level curves (Pirazzoli 1991).

For modelling the future, model data and extrapolated measurements have to replace the database provided by the relative sea level curves. The eustatic component describing the forthcoming climatically forced sea level rise has to be derived from climate modelling (Voß *et al.* 1997). The isostatic component is expressed by movements of the earth's crust, which can be measured nowadays. The question is how to extrapolate available data into the future. To answer this question, the palaeo isostatic component has to be separated from relative sea level curves. A trend analysis of these data can highlight the stationarity of the recent isostatic pattern.

The Baltic Sea is an excellent area for the implementation of model scenarios. There are not only many and detailed data comprising recent vertical movements of the earth's crust, but also a large set of relative sea level curves is available, recording the development back to the beginning of the Litorina transgression. Climate modelling carried out by the German Climate Research Centre, Hamburg, provides prognostic eustatic data applicable to the Baltic Sea. These data rely on two different atmospheric CO_2 concentration scenarios proposed by the IPCC (Houghton *et al.* 1990). Therefore, two prognostic sea level scenarios were constructed emphasising the possible dimension of future coastline changes.

AREA OF INVESTIGATION

The Baltic Sea basin tectonically bridges between the West European Platform and the East European

Platform (Harff *et al.* 2001). The latter one consists of the Russian Plate with Vendian-Phanerozoic sediments resting on a basement of Precambrian and Proterozoic rocks. The Baltic Shield - also belonging to the East European Platform - is bordering the area of investigation to the north, and is composed of crystalline, high metamorphic rocks mainly (Schönenberg & Neugebauer 1987). Since the Proterozoic the Baltic Shield has been a high stand area mainly - an important evidence for long term crustal uplift.

Fig. 1: The Baltic Sea Area. Prognostic coastline modelling was applied to the grey shaded area.

The geological history of the Baltic Sea starts with the end of the Weichselian Glaciation about 13000 years BP (Björck 1995). But, the recent geographic picture was formed by the Litorina transgression mainly, starting around 8000 years BP (Lemke 1998). Sea level rise caused by global eustatic changes at the end of the Pleistocene has led to intense changes in coastlines. In the southern part of the Baltic Sea the initial phase of the transgression, with a sea level rise of 2 cm/year has caused a “drowning” of the coast (Kliewe & Janke 1982). Since 5700 years BP erosion, transport and accumulation of sediments controlled by wind and currents have been of major relevance (Lemke 1998). In the northern part of the Baltic area regression dominates the scenery, caused by the isostatic uplift of Scandinavia.

Today the Baltic Sea covers an area of 404364 km^2 and contains a volume of 21547 km^3 brackish water (HELCOM 2003). To the North and West the sea is surrounded by the highlands of Scandinavia, whereas in the south and east long-range lowlands are dominating. Through the Danish Straits the Baltic Sea is connected with the North Sea and therefore with the oceans of the world (Fig. 1). Roughly 85 million people are living near to the Baltic Sea coast (HELCOM 2001).

The water balance is positive. This means the outflow from the Baltic Sea towards the North Sea is larger than the inflow (Fennel 1995). The annual balance of 2505 km^3 outflow stands against 2000 km^3 inflow from the North Sea (Anderson *et al.* 1992). The water exchange regime is estuarine (Lass *et al.* 1987), controlled by thermohaline stratification typical for the Baltic Sea.

THE MODEL

Generally, modelling of large-scale coastal changes requires three main components. First, a digital elevation model describing the initial state of coastlines and the elevation of adjacent areas is needed. This structural model has to include both bathymetry and land relief.

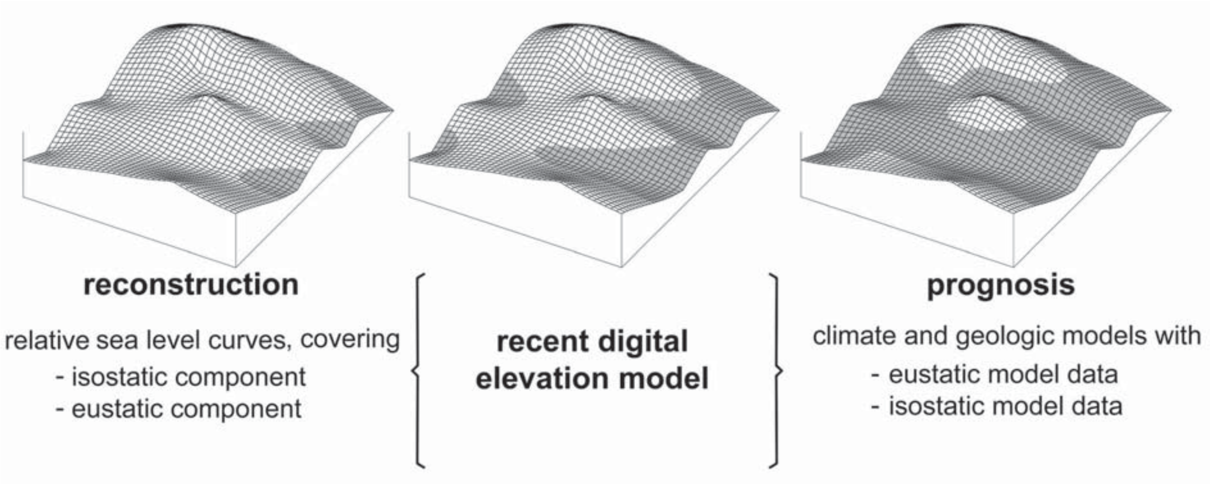

Fig. 2: Schematic for modelling coastline scenarios.

Second, data describing the eustatic component of sea level variations have to be provided by climate modellers. Third, vertical movements of the earth's crust have to be taken into account. These data come from measurements, which can be extrapolated to the future. A general sketch of the model is outlined in Fig. 2.

A digital elevation model (DEM) is a set of terrain elevations in an area **R** at a given time t. A single elevation value at a given location **r** at a time t is expressed by $dem_t(\mathbf{r})$.

$$DEM_t = \{dem_t(\mathbf{r})\} \qquad \forall \mathbf{r} \in \mathbf{R}, \forall t \in T \qquad (1)$$

For the deduction of the isostatic component IC_t with t>0 (future) a trend analysis of the acceleration of IC_t with t<0 (past) has to be carried out. By the analysis of relative sea level data and the comparison with a relative sea level curve from an isostatic inactive area palaeo isostatic curves can be constructed (Harff *et al.* 2001). Acceleration of the palaeo isostasy is described by the second derivative of a function fitting these data, e.g. polynomial approximation.

$$ic_t(\mathbf{r}) = f(\mathbf{r},t) \qquad \mathbf{r} \in \mathbf{R},\ t \in T,\ ic_t(\mathbf{r}) \in IC_t \qquad (2)$$

$ic_t(\mathbf{r})$ .. isostatic component at **r**
$f(\mathbf{r},t)$ .. trend function for the acceleration of IC

The eustatic component has to be defined by a transfer function W describing the interaction between the area of investigation and adjacent climate model cells recording eustatic sea level variations.

$$ec_t(\mathbf{r}) = \boldsymbol{\Omega}(ec_{Mt}(\mathbf{w})) \qquad \forall t \in T, \forall \mathbf{r} \in \mathbf{R}, \mathbf{w} \in \mathbf{W}, ec_{Mt}(\mathbf{w}) \in EC_{Mt} \qquad (3)$$

M .. climate model
w .. location in space **W** of the climatic model
EC_{Mt} .. eustatic component in the climate model for $t \in T$
$ec_t(\mathbf{r})$.. eustatic component at $\mathbf{r} \in \mathbf{R}$, for $t \in T$

For the modelling of prognostic digital elevation models, the recent DEM_t with t = 0 has to be superimposed with the prognostic eustasy (EC_t, t > 0) and the prognostic isostasy (IC_t, t > 0).

$$DEM_t = DEM_0 - (IC_t + EC_t) \qquad (4)$$

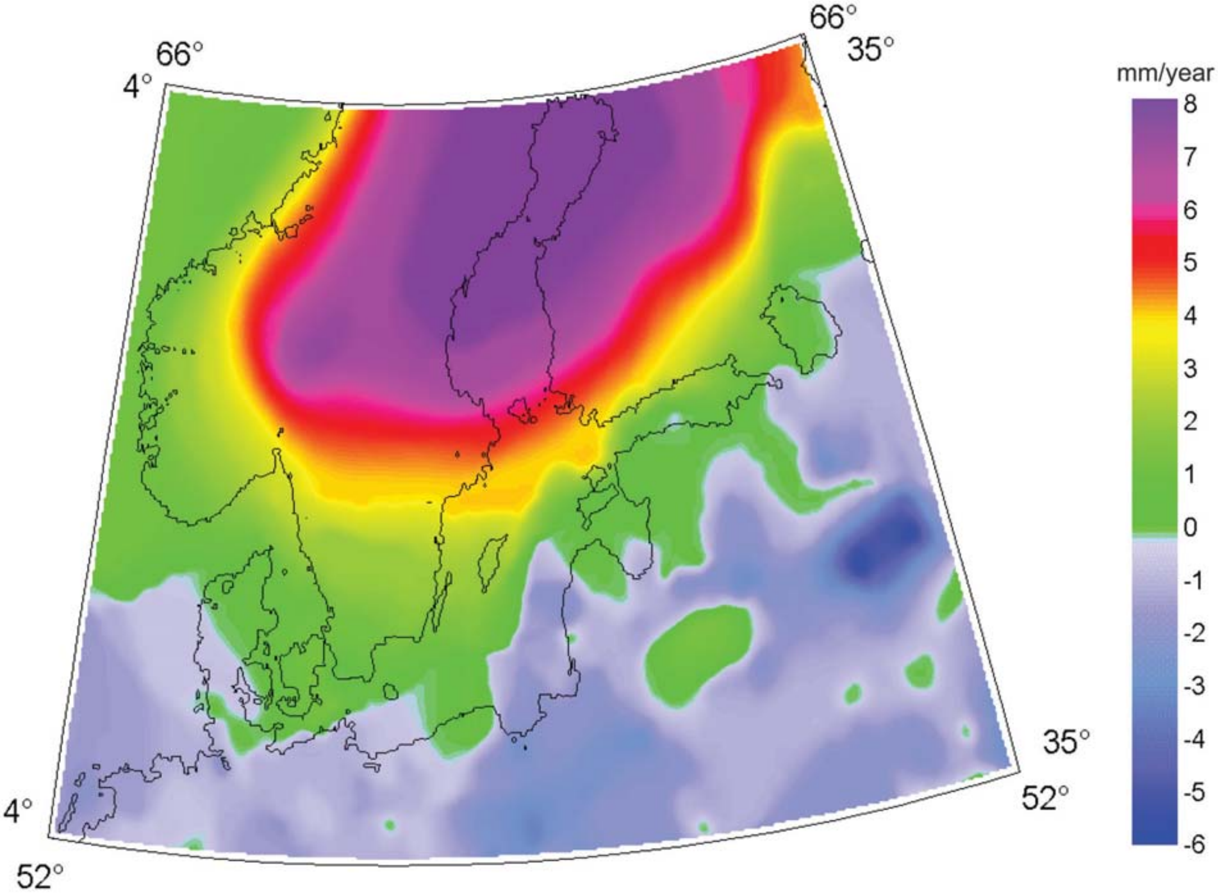

Fig. 3: Isostatic data grid. This map was created by interpolation of material provided by Garetsky *et al.* (2001).

ISOSTATIC MODEL COMPONENT

A map of recent movements of the earth's crust was used for the construction of the isostatic model component (Garetsky *et al.* 2001). These data, compiled in the frame of the IGCP-project No. 346 "Neogeodynamica Baltica", show uplift rates up to 8 mm per year in the area of the Bothnian Bay and coincide with earlier published material (Ekman 1996). A digital data grid of vertical movements of earth's crust in the area of investigation was generated by an interpolation of data of the map published by Garetsky *et al.* 2001 (Fig. 3). As interpolation method Ordinary Kriging was applied (Journel & Huijbregts 1978).

In order to prove the stationary of this model an analysis of palaeo isostatic data back to 4000 years BP was performed. 43 relative sea level curves covering the Baltic Sea area and the North Sea coast of Scandinavia were selected for the analysis (locations see Fig. 4). Only curves describing the time span continuously were used. Curves with gaps have not been taken into consideration.

The inclusion of data in regions neighbouring the area of investigation was necessary to analyse the general trend of the development of the isostatic movement of the Baltic Sea region. The small amount of usable relative sea level curves in the area of investigation requires such verification. Each of the relative sea level curves was fitted by a 6th order polynomial function aiming to remove the fluctuations. The palaeo isostasy was derived according to a procedure proposed in Harff *et al.* (2001) by a

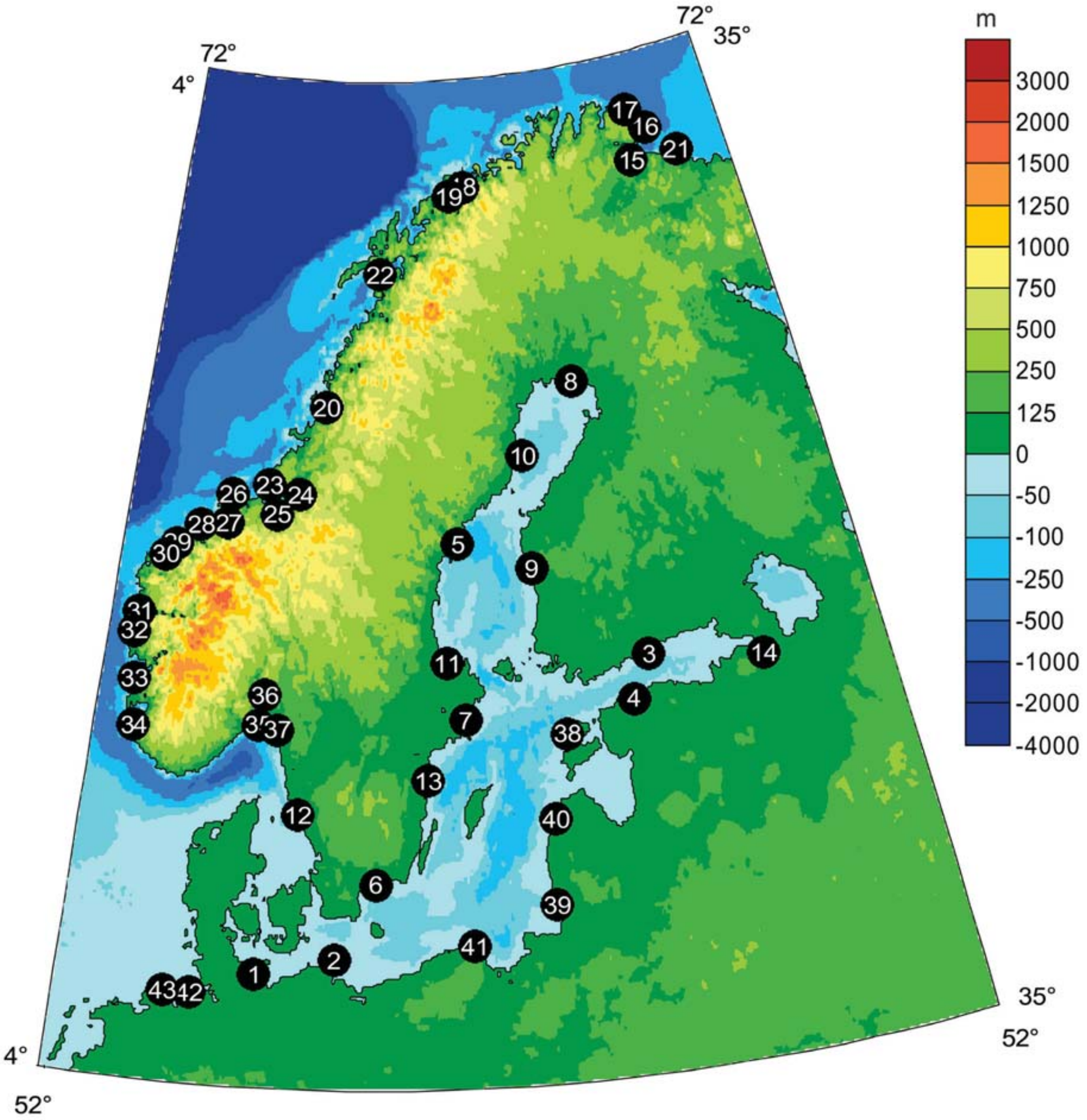

Fig. 4: Locations of relative sea level curves used for the analysis of palaeo isostasy. References see Table 1.

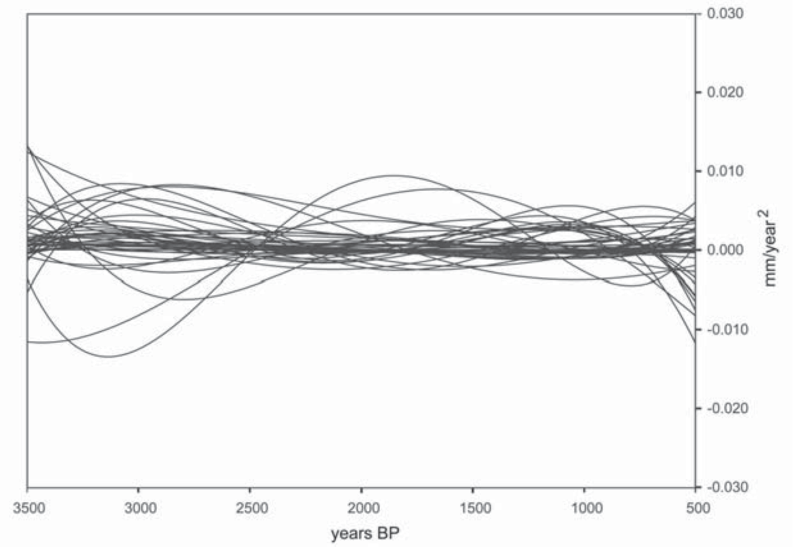

Fig. 5: Acceleration of movements of the Earth's crust in the Baltic area since 3500 years BP.

comparison of these polynomial functions with a eustatic model. The eustatic model used was published by Mörner (1979) and modified in Harff *et al.* (2001). The second derivative of the palaeo isostatic data marks the acceleration of the velocity of movements of the earth's crust. These data are shown in Fig. 5, narrowed to the time span between 3500 years BP and 500 years BP. The clipping was essential to remove border effects caused by the polynomial fitting of the relative sea level curves.

The acceleration shows a fluctuating trend around zero, indicating the steady state of the movement's pattern since 3500 years BP. Therefore, it seems feasible to extrapolate the isostatic data given in Fig. 3 linearly, at least for the next 800 years.

EUSTATIC MODEL COMPONENT

Prognostic eustasy is investigated by climate modellers (e.g. Houghton *et al.* 1990, 2001). The main idea is to propose greenhouse gas scenarios in order to derive global atmospheric temperature changes that influence the sea level variation. According to a warming or cooling sea, the water volume will expand or shrink resulting in sea level changes. Long term time series recording these processes and available for modelling have been compiled by Voß *et al.* (1997). Data were provided by Prof. U. Cubasch and Dr. R. Voss, Germany. The basic greenhouse gas scenario for these investigations is the IPCC-Scenario A ("business as usual") comprising two assumptions about the CO_2-increase through the next 700 years (Houghton *et al.* 1990, Fig. 6).

In the first case study CO_2 will be doubled by an emission rise kept constant through 60 years, then the concentration is assumed to be kept constant. In the second one, more pessimistic case study the concentration will be quadrupled after 120 years.

The resulting eustatic sea level change was calculated by Voss *et al.* (1997) with a coupled ocean-atmosphere model (ECHAM3/LSG). The model data for a global grid with a spatial resolution of 5.6 degree cover a time span of 840 years. Starting in 2000 AD, the model runs end in 2840 AD. In the climate model it is assumed that an increase of atmospheric CO_2 concentration will cause a global warming, and therefore a sea level rise due to the expanding sea water body. Fluctuations of the prognostic eustatic curves are caused by the dynamic of the coupled ocean-atmosphere model. From model grid cells covering the North Sea an averaged mean sea level rise was calculated. This value was used as the eustatic model for the Baltic Sea (Fig. 7). The eustatic sea level rise shows a nearly linear trend, continuing even after the time when CO_2

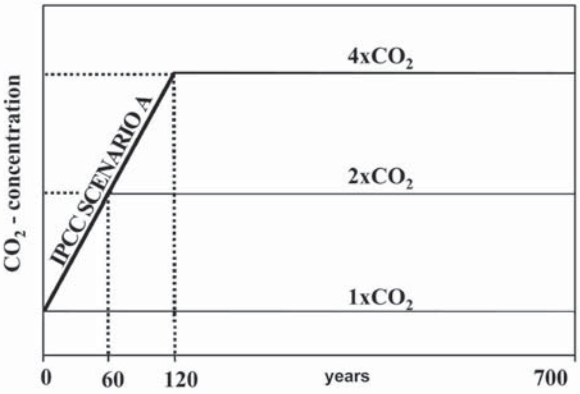

Fig. 6: IPCC - Scenario A (after Houghton *et al.* 1990). Case study I: CO_2-concentration doubled after 60 years, afterwards constant concentration. Case study II: CO_2-concentration quadrupled after 120 years, afterwards constant concentration.

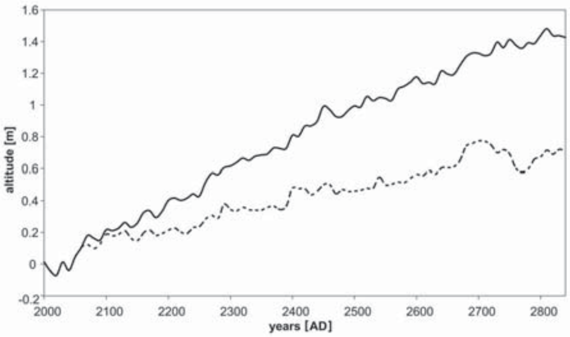

Fig. 7: Prognostic eustatic model functions for the Baltic Sea area according to the IPCC - assumptions in Fig. 6. Model I (dotted line) refers to case study I, whereas model II (solid line) describes the sea level rise according to case study II.

concentration has reached a constant level. The reason is a delay in the heat transfer from the atmosphere to the ocean.

The scenarios delivered by the IPCC (Fig. 6) and used within the climate modelling (Fig. 7) are estimations, basing on assumptions about the future industrial development. Generally, in all IPCC scenarios an increase of carbon dioxide concentration, globally averaged surface temperature, and sea level during the 21st century are assumed. In Houghton *et al.* (2001) more sea level rise scenarios are shown, ranging up to 2100 AD only. These scenarios are used by short-term sea level modelling in the frame of SEAREG (Hillka & Hanna 2003). It should be noted, that in 2100 AD the IPPC-scenario with the lowest sea level rise reaches 0.2 m (Houghton *et al.* 2001). This almost matches the amount of the modelled eustatic component used in this paper.

PROGNOSTIC COASTLINE SCENARIOS

As outlined in equation (4) prognostic digital elevation models are the result of a superposition of prognostic eustasy and isostasy onto a recent digital elevation model. The zone enclosed by the coastline today and the zero line of the prognostic digital elevation model will be influenced by the sea level change. Whether these areas will be drowned or not cannot be predicted. Sedimentary processes and hydrographic forces not included in the modelling presented here will have a significant impact. Also, in coastal plains or littoral meadows the growth of organic material as peat may keep pace with the sea level rise (Joosten 1995). And it is difficult to predict how man will influence coastal morphogenetic processes, e.g. by coastal zone protection or landscape architecture (Erchinger 2002). In addition, currents parallel to the coastline are common in the area of investigation (Lemke *et al.* 1994) and will complicate the implementation of sediment transport models as the Bruun rule (Bruun 1962). It has to be kept in mind that the prognostic coastline changes are only scenarios, created from assumptions and simplifications of various boundary conditions.

For the area of investigation a recent digital elevation model was compiled from various data sources. The land is covered by a subset of GTOPO30 (United States Geological Survey 1996), whereas the bathymetry has to be specified by sea side parts of Terrainbase (Row & Hastings 1995) and two high resolution data grids developed at the Baltic Sea Research Institute Warnemünde, Germany (Seifert & Kayser 1995). In summary, the digital elevation model used covers the area shown in Fig. 8. The spatial resolution was adjusted by an Inverse Distance Weighted interpolation to 1 km, aligning all data sets to the finest data grid provided by Seifert & Kayser (1995).

In the prognostic scenarios, created according to equation (4), large areas affected by the relative sea level rise are visible in areas around the island of Rügen mainly (see Fig. 9 and Fig. 10). This is caused by the relative low elevation of these coastal parts. In the Mecklenburgian Bight only a minor influence can be observed. Here, the steep cliff line diminishes the effect. Nevertheless, the overall budget calculation for land influenced by the sea level rise in the southern Baltic Sea area is considerable: 240 km^2 in coastline scenario I and 280 km^2 in coastline scenario II. This includes areas with direct access to the Baltic Sea only.

As a matter of fact, the difference between the two scenarios shown here is relatively small. The eustatic component will cause a sea level rise at 2840 AD of about 0.71 m (scenario I) respectively 1.43 m (scenario II), whereas the isostatic component is equal

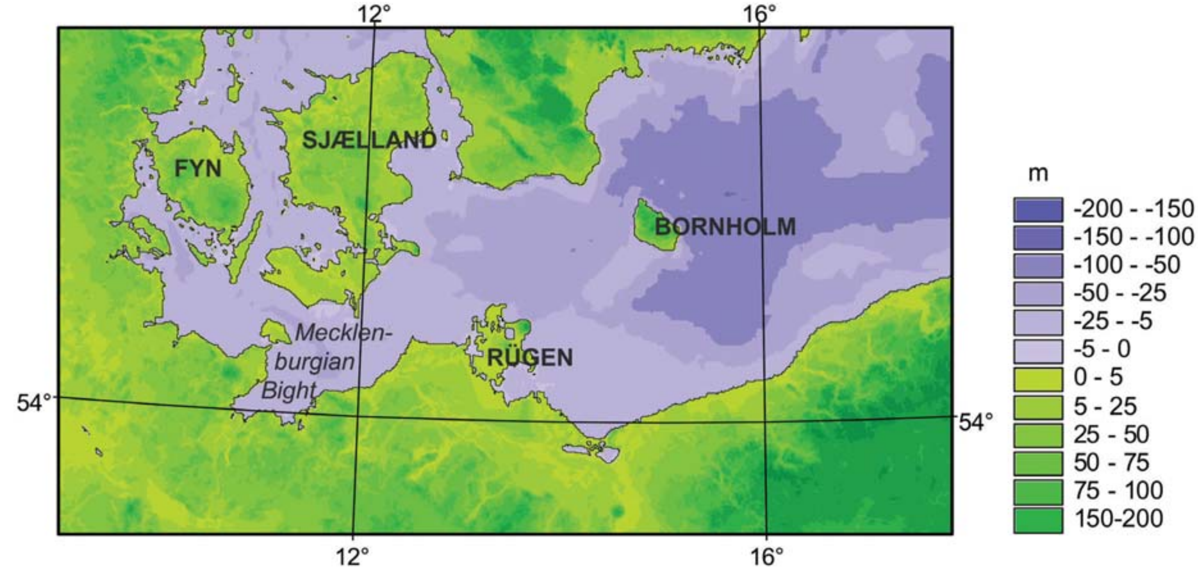

Fig. 8: Recent digital elevation model. The coastline is shown by the black line.

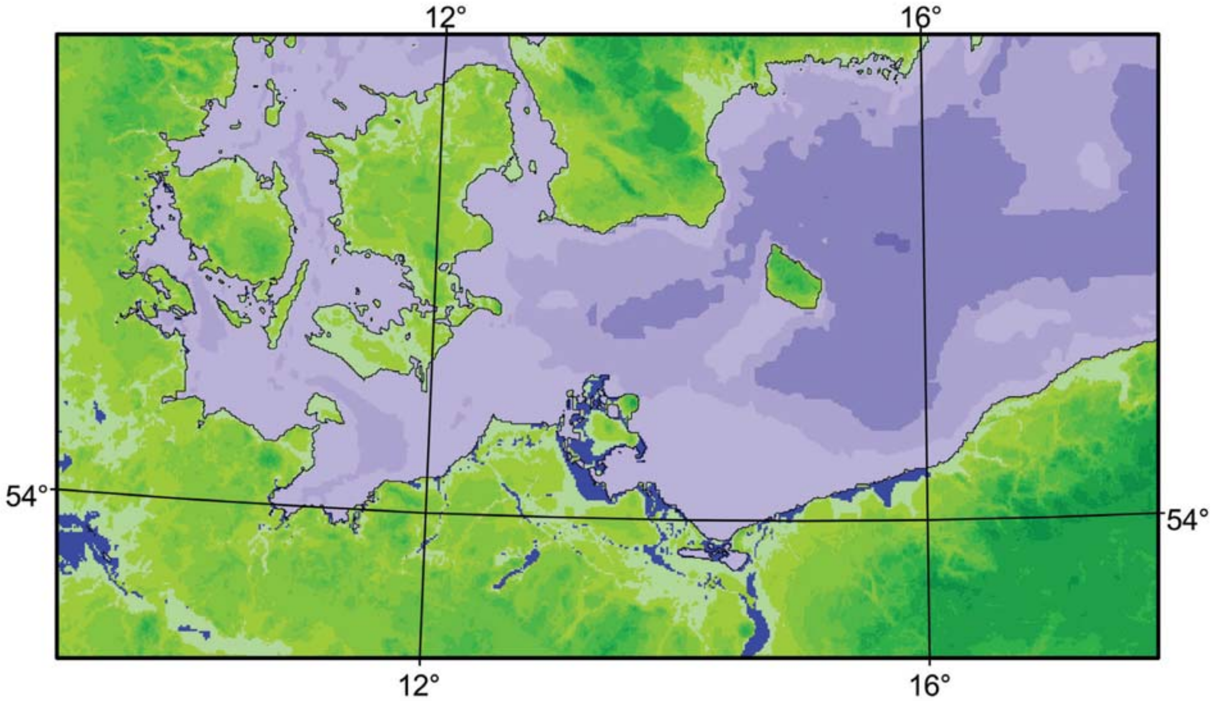

Fig. 9: Scenario I of the southern Baltic Sea coastline at 2840 AD according to eustatic model I. Areas in dark blue are affected by the sea level rise.

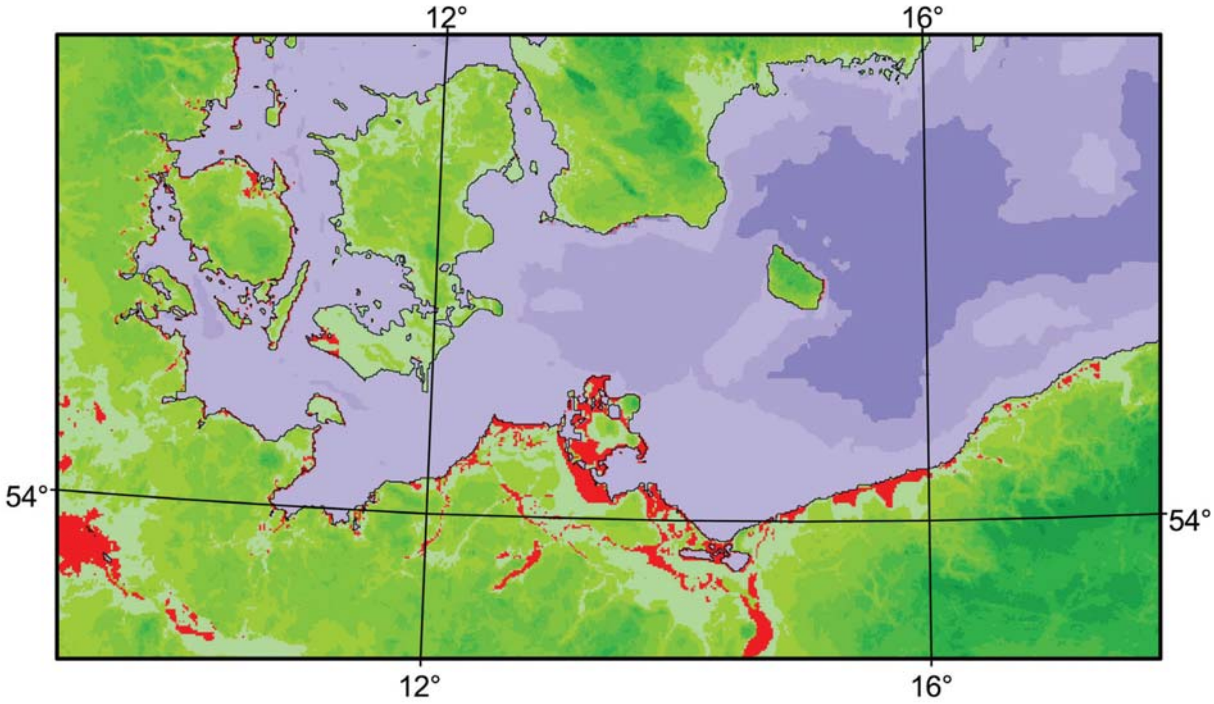

Fig. 10: Scenario II of the southern Baltic Sea coastline at 2840 AD according to eustatic model II. Areas in red are affected by the sea level rise.

in any case. So, at first view it seems that effects of an additional sea level rise of about 0.7m is negligible. But it has to be taken into account, that the digital elevation model used here has a vertical resolution of 1m. Modelling the effects of minor sea level changes requires a higher vertical resolution.

CONCLUSIONS

Palaeo coastline changes of the Baltic Sea show a remarkable shift in land-sea distribution during the last thousands of years. In the southern part of the Baltic Sea the Litorina transgression has caused great land loss. It is of vital interest for the population living near to the sea to investigate the future development of this process. To do this, assumptions about future isostasy and eustasy have to be taken into account. By the superposition of these components with a recent digital elevation model areas affected by the relative sea level rise can be outlined.

Future isostasy may be assumed through the extrapolation of recently measured data. For the Baltic Sea area a trend analysis of palaeo isostatic movements proves their steady state characteristic. Future eustasy can be derived from climate modelling and sea level scenarios. Using a transfer function the eustasy modelled for the North Sea can be applied to the Baltic Sea.

For the southern Baltic Sea area two prognostic sea level scenarios were modelled based on an isostatic component derived from Garetsky *et al.* (2001) and two eustatic scenarios from the German climate Research Centre, Hamburg (Voß *et al.* 1997). They show a dramatic coastline retreat especially at the German and the Polish coast. Around the island of Rügen large areas may fall beneath the future sea level, surely with consequences for settlements.

Table 1. Catalogue of relative sea level curves. Coordinates are given in decimal degree. Area classification (modified after HELCOM 1998): ATO - Atlantic Ocean, BAP - Baltic Proper, BAS - Barents Sea, BOB - Bothnian Bay, BOS - Bothnian Sea, GUF - Gulf of Finland, KAT - Kattegat, NOS - North Sea, OFJ - Oslo Fjord, WEB - Western Baltic Sea.

ID	Author	Longitude	Latitude	Coastal Area
1	Duphorn (1979)	10.71	54.26	WEB
2	Schumacher (2000)	13.43	54.59	BAP
3	Eronen & Haila (1982)	25.74	60.27	GUF
4	Kvasov (1979)	24.91	59.43	GUF
5	Mörner (1979)	18.37	62.82	BOS
6	Berglund (1964)	14.86	56.10	BAP
7	Åse & Bergström (1982)	18.32	59.33	BAP
8	Saarnisto (1981)	24.24	65.81	BOB
9	Donner (1968)	21.44	62.22	BOS
10	Grönlie (1981)	21.54	64.47	BOB
11	Grönlie (1981)	17.68	60.47	BOS
12	Sandegren (1952)	11.96	57.45	KAT
13	Granlund (1932)	16.78	58.15	BAP
14	Kvasov (1979)	30.17	59.85	GUF
15	Donner et al. (1977)	29.53	69.87	BAS
16	Kelletat (1985)	30.77	70.45	BAS
17	Kelletat (1985)	29.86	70.87	BAS
18	Hald & Vorren (1983)	19.70	69.87	ATO
19	Marthinussen (1962)	18.87	69.70	ATO
20	Grönlie (1981)	12.45	65.54	ATO
21	Nikonov (1977), in Pirazzoli (1991)	32.16	69.87	BAS
22	Hafsten (1983)	15.00	68.20	ATO
23	Hafsten (1981), in Pirazzoli (1991)	10.04	63.95	ATO
24	Sveian & Olsen (1984)	11.45	63.79	ATO
25	Kjemperud (1981)	10.45	63.37	ATO
26	Kjemperud (1986)	8.45	63.70	ATO
27	Svendsen & Mangerud (1987)	8.37	63.12	ATO
28	Svendsen & Mangerud (1987)	7.20	63.04	ATO
29	Svendsen & Mangerud (1987)	6.29	62.62	ATO
30	Svendsen & Mangerud (1987)	5.87	62.37	ATO
31	Kaland (1984)	5.12	61.20	ATO
32	Kaland et al. (1984)	5.04	60.79	ATO
33	Kaland (1984)	5.29	59.87	ATO
34	Hafsten (1983)	5.54	58.95	ATO
35	Hafsten (1983)	10.29	59.20	OFJ
36	Hafsten (1956)	10.45	59.79	OFJ
37	Anundsen 1985)	11.04	59.12	OFJ
38	Raukas & Teedumäe (1997)	22.17	58.91	BAP
39	Raukas & Teedumäe (1997)	21.20	55.56	BAP
40	Raukas & Teedumäe (1997)	21.42	57.25	BAP
41	Uścinowicz (2000)	18.25	54.83	BAP
42	Schütte (1939)	8.60	53.80	NOS
43	Linke (1982)	7.70	53.80	NOS

The demonstrated principle for modelling prognostic coastlines is applicable generally. It is not restricted to the Baltic Sea area - a sufficient amount of eustatic and isostatic data provided the development of any coastal zone area can be modelled. Also, the time scale is not limited to the time span investigated here. To acquire more detailed model results with improved significance, better input data like digital elevation models, isostatic maps and climate models are needed. This is also essential for the implementation of a sedimentary process component.

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