

## CHANGING SEA LEVEL AT SINKING COASTS – COMPETITION BETWEEN CLIMATE CHANGE AND GEOLOGICAL PROCESSES

Jan HARFF<sup>1</sup>, Michael MEYER<sup>1</sup>

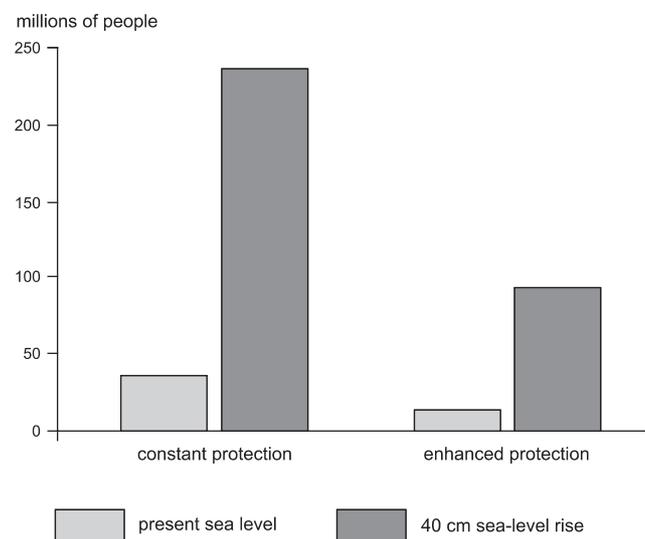
**Abstract.** Changes of coastlines have economic and social impact on the human population concentrated in coastal areas. The investigation of coastal change processes becomes important particularly at sinking-retreating-coast for future planning, and the derivation of scenarios must be based on the understanding of the driving processes. It is well known that coastal change is a complex result of an interaction of climate driven eustatic sea level change and vertical crustal movements. An index is given that allows to distinguish between coasts controlled by glacio-isostatic processes and those determined by the climatic forces of coastal morphogenesis. A simple model allows reconstructions of the palaeo-geographic history of sinking coasts. Prognostic scenarios of coastal change are possible by applying of parameterized vertical crustal movement data and sea level change data derived from climate modeling. These data have to be superimposed with the influence of storm events. The coupling of processes on different time scales between hours and millennia are questions under investigation.

**Key words:** sea level, coastline changes, modeling and future scenarios, Baltic Sea.

### INTRODUCTION

The problem of sea level change is one of the most important topics of scientific research programmes and inter-governmental discussions (Kohler *et al.*, 2004). The anthropogenic driving forces and future development of global sea level have been described by Cubasch (2001). In addition, scenarios of secular sea level rise have to be superimposed by the effect of short term events as storm surges (Fig 1).

The figure shows clearly the effect and need of coastal protection activities. But, for economic and effective planning of those activities local authorities need reliable information of future development along coastal zones. For this, geoscientists have to take into consideration not only global sea level changes, but also regional vertical crustal movement and coastal morphogenesis as regional/seasonal characteristics in climatically driven water level regularities. New results have been published during the last two years. For instance, a prediction of the deformation of the earth crust caused by loading and unloading of inland glaciers was given by Tarasov and Peltier (2002). They describe the interrelation of subsidence and sediment formation for the Lagoon of Venice. But, there is still a need for interdisciplinary studies of the in-



**Fig. 1. Adaptation and average annual number of people flooded by coastal storm surges in projection for 2080s (Watson *et al.*, 2001)**

<sup>1</sup> Baltic Sea Research Institute, Seestr. 15, Warnemünde, Germany; e-mail: jan.harff@io-warnemuende.de; michael.meyer@io-warnemuende.de

terrelation of crust deformation, sedimentological processes, climatically driven sea level variations and the depending variations of the coastal ecosystem. To fill the gap, during the 32nd International Geological Congress (2004) a session was held on “Coastline Changes – Interrelation of Climate and Geological Processes”. The papers presented there contribute to the understanding of the complex interrelation be-

tween geo-system, climate and socio-economic system along changing coastlines.

In this paper we deal with the cause and effect relation between climate change, vertical crustal movement and the change of the coastlines. We approach the reconstruction of palaeo-geographic scenes as well as future coastline scenarios coupled with IPCC sea level assumptions.

## A REGIONAL TRANSGRESSION/REGRESSION MODEL

The Baltic Sea serves as a model region. Here, changes in crustal subsidence and uplift as an expression of glacio-isostatic rebound interact with climatically driven eustatic sea level changes and can be studied in an exceptional manner.

For any time point  $t \in T$  the elevation of an area can be expressed by a digital elevation model  $DEM_t$  (Harff *et al.*, 2005) covering as a grid an area of investigation R. The  $DEM_0$  is the digital elevation model of today ( $t = 0$ ) for the area under investigation.

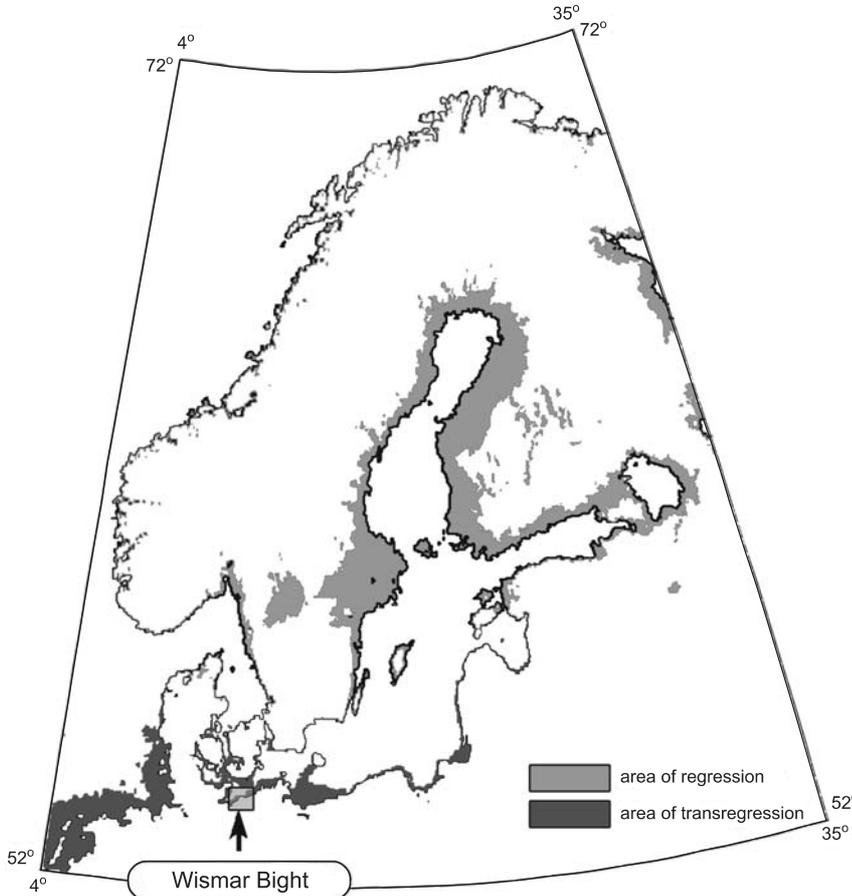
$$DEM_t = DEM_0 - \begin{cases} RSL_t, & \text{if } t < 0 \\ EC_t + IC_t, & \text{if } t \geq 0 \end{cases} \quad (1)$$

For the geological past ( $t < 0$ ) the  $DEM_0$  has to be compared with  $RSL_t$ , the difference model between palaeo- and recent elevations.  $RSL_t$  has to be determined by spatial interpolation of data from shoreline displacement curves

(relative sea level data,  $RSL$ ) to grids covering an area of investigation.

The relative sea level change  $RSL$  consists of two components:  $RSL = EC + IC$ . Here,  $EC$  marks the eustatic component controlled mainly by the change of the palaeo-atmospheric temperature which affects the volume of the oceanic water body.  $IC$  represents the deformation of the earth's crust. This is caused by glacial but also tectonic effects and changes in thickness of sedimentary layers in the underground (for instance compaction or salinar tectonics). The model is described more detailed by Harff *et al.*, (2005).

An application of the model to the Baltic Sea area since the Littorina transgression shows regions of regression caused by isostatic uplift of the Fennoscandian Shield in the north and zones of transgression within the zone of subsidence that surrounds the uplifting shield belt-like (Fig. 2).



**Fig. 2.** The Baltic Sea and the change of coastlines since the beginning of the Littorina transgression about 9000 BP (after Harff *et al.*, 2005)

## THE COAST INDEX

To distinguish between the main driving forces for the development of a coastline a coast index was introduced (Harff *et al.*, 2001). Two relative sea level curves,  $rsl_t(A)$ ,  $rsl_t(B) \in RSL_p$ , selected by Meyer and Harff (2005) are typical for the different coastal developments in the Baltic Sea: Whereas Saarnisto (1981) had published a curve (A) representing the continuously uplifting Fennoscandian Shield a curve (B) published by Uścińowicz (2000) stands for the sinking southern Baltic Sea coast. Figure 3 shows these two curves and their location at the Baltic Sea.

A comparison of the  $rsl$  curves with a curve from the tectonically stable Kattegat area published by Mörner (1976), expressing the regional eustatic process enables the identification of the main forcing process, either isostasy or eustasy (Harff *et al.*, 2001).

Figure 4 shows the  $rsl$  curve by Mörner (1976) fitted with a polynomial trend function of 6th order. This trend function is to be considered as the eustatic component  $ec$  valid for all locations within the area of investigation.

The isostatic component  $ic$  of a relative sea level curve  $rsl$  at location  $\mathbf{r}$  is expressed as difference between  $rsl$  and  $ec$   $\mathbf{R}$  defines the area of investigation.

$$ic_t(\mathbf{r}) = rsl_t(\mathbf{r}) - ec_t, \quad \mathbf{r} \in \mathbf{R}, \quad t \in T \quad (2)$$

In order to neglect local effects the  $rsl$  data has to be adapted by a polynomial trend function too.

For a quantitative comparison, we introduce a metric  $\rho$  expressing the average deviation of the altitude at the  $rsl$  data site from sea level, caused by vertical crustal movements.

$$\rho(\mathbf{r}) = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} |ic_t(\mathbf{r})| dt \quad (3)$$

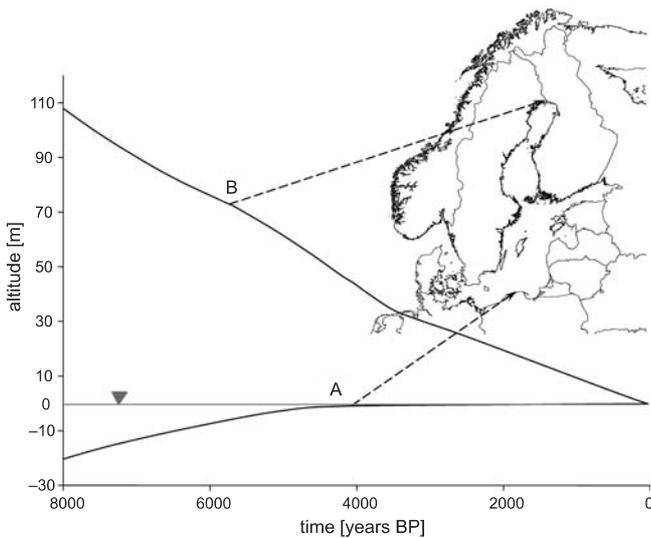


Fig. 3. Typical relative sea level curves from the Baltic Sea area (Meyer, Harff, 2005)

A – Uścińowicz (2000), B – Saarnisto (1981)

The eustatic index  $e$  describes the average eustatic deviation.

$$e = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} |ec_t| dt \quad (4)$$

The coast  $c$  index is defined in accordance with Harff *et al.* (2001) as

$$c(\mathbf{r}) = \rho(\mathbf{r})/e \quad (5)$$

Provided the  $ec$  curve reflects the general effect of climate change (melting ice shields, thermal expansion of the world ocean) and  $ic$  expresses the vertical crustal movement at a location, the index  $c(i)$  gives an estimation of the controlling factor at the location from which the  $rsl$  data are descending. Generally, coasts can be classified as “crustal-uplift/subsiding coasts” ( $c(i) > 1$ ), and “climate-controlled coasts” ( $c(i) < 1$ ).

If we calculate the coast index for the two curves in Figure 3 we receive  $c(B) = 14.38$  and  $c(A) = 0.21$ ,

consistent with the requirements of the definition of the index. We may also calculate the index for other  $rsl$ -curves from sites along the entire Baltic Sea coast. Figure 5 shows nine selected curves, each compared with the eustatic curve and the corresponding isostatic curve. Also the coast index is given to each site within the graph. It can clearly be seen that the sites on the Fennoscandian Shield show values  $c(i) > 1$  ( $i = 1, 2, 3, 4$ ), whereas the sites along the southern coast are marked by values  $c(i) < 1$  ( $i = 7, 8, 9$ ). But it can also be seen that there transition area in southern Sweden and the southern coast of the Finnish Gulf where the values of the coast index are close to 1 ( $c(5) = 3.5$ ,  $c(9) = 2.0$ ).

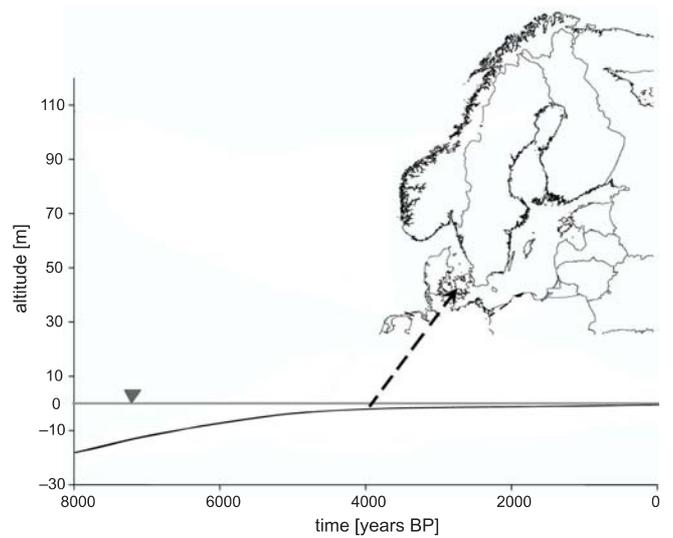
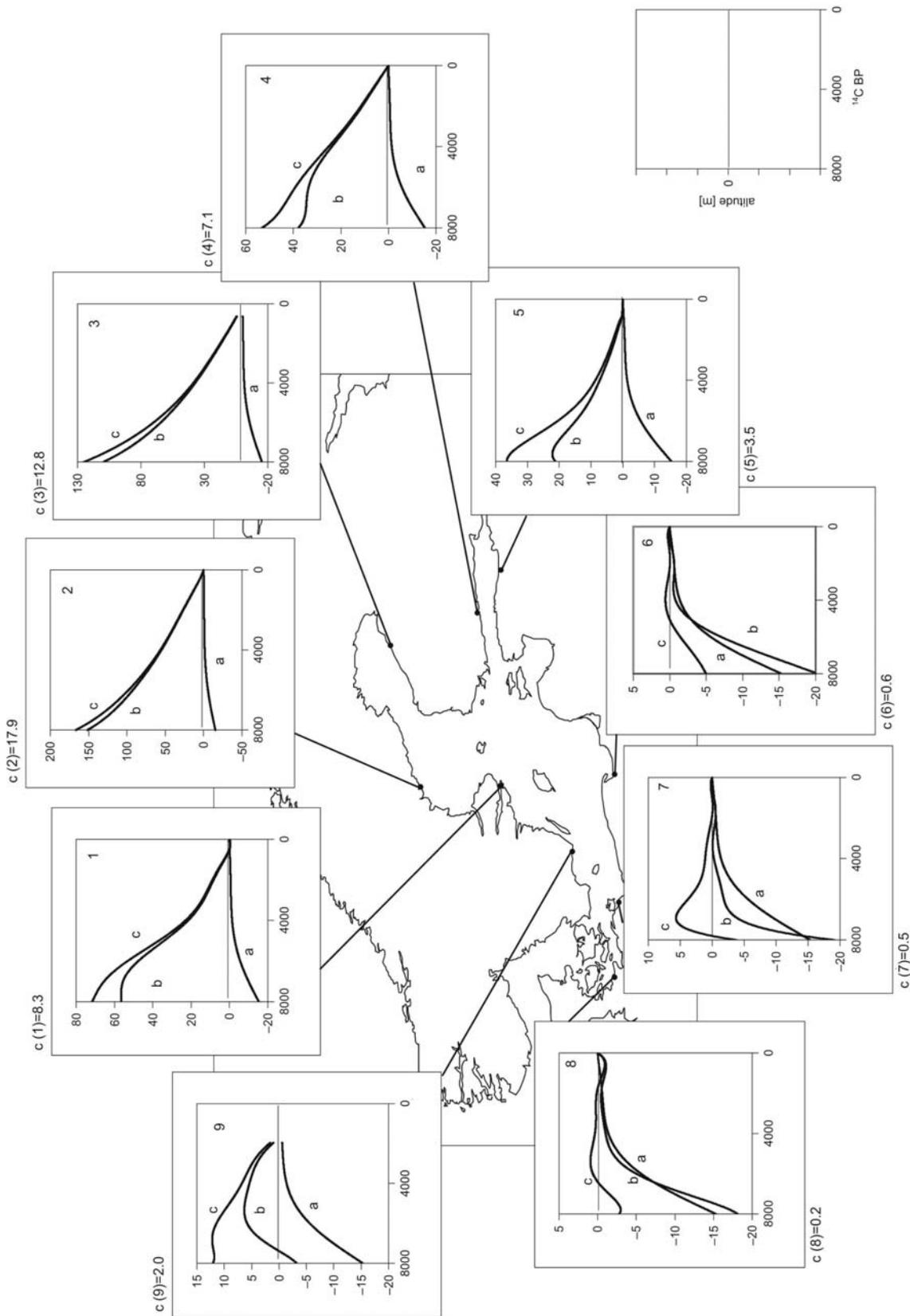


Fig. 4. Eustatic curve for the Kattegat area (after Harff *et al.*, 2001)



**Fig. 5. Relative sea-level change curves (b) compared to a eustatic curve (a) and the isostatic component (c) at 9 locations in the Baltic Sea coast area (after Harff *et al.*, 2001, modified)**

References of RSL-curves: 1 – Åse, Bergström (1982), 2 – Möller (1979), 3 – Donner (1983), 4 – Eronen, Haila (1982), 5 – Kessel, Raukas (1979), 6 – Uścińowicz (2000), 7 – Kliewe, Janke (1982), 8 – Duphorn (1979), 9 – Björck (1979).

## PALAEO AND FUTURE COASTLINE SCENARIOS

For historical reconstruction of coastlines on a subregional scale we have to take into account erosional processes and the accumulation of sediments. In the following term  $SED_t$  stands for the change of sediment thickness caused by erosion or accumulation.

$$DEM_t = DEM_0 + SED_t - RSL_t, \quad \text{if } t < 0 \quad (6)$$

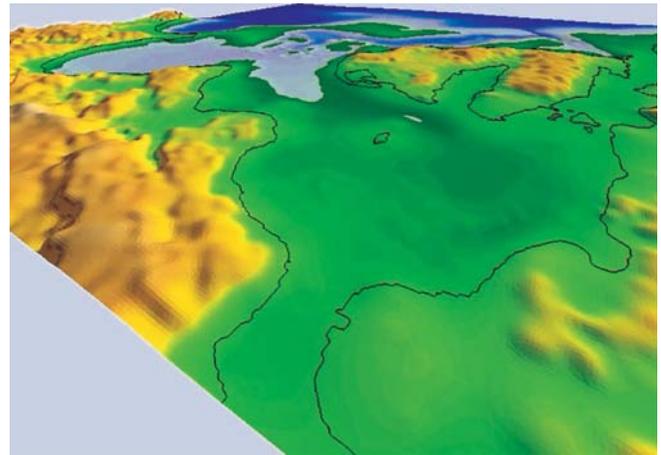
The method of palaeogeographical reconstruction has been described in detail by Meyer and Harff (2005). The method is based on the assumption that an eroded land surface can be reconstructed by an interpolation between those points that have been unaffected by erosional processes. In the area of the Wismar Bight the sediment body eroded by coastal processes has been reconstructed by an interpolation between the top of the recent coastal cliff and the sea bottom at 7 m water depth. The latter one has been proven as the palaeosurface by an archaeological/geomorphological survey of the current sea bottom. The relative sea level curve used was shown by Harff *et al.* (2005).

Figure 6 shows the modelled coastal landscape of the Wismar Bight at 6940 BP. The recent coastline is marked in the graph and delineate the area which has been transformed by the transgression from former main land to a coastal sea.

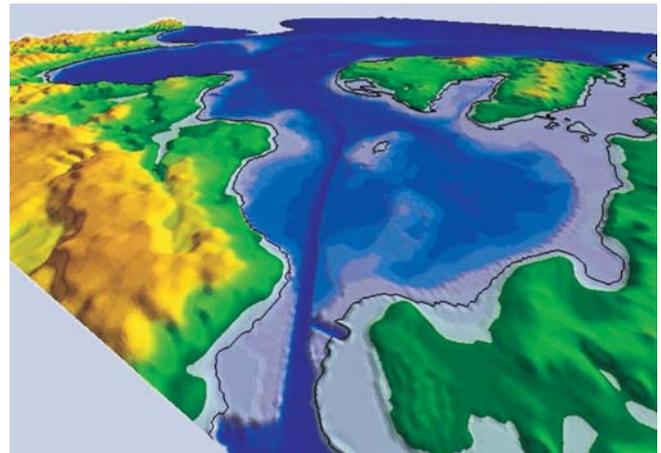
For future coastal development scenarios we apply the model also to the Wismar Bight. Here, we have to model eustatic sea level change and isostatic developments separately (Harff *et al.*, 2005):

$$DEM_t = DEM_0 - EC_t + IC_t, \quad \text{if } t > 0 \quad (7)$$

Methods for the derivation of palaeo and prognostic elevation models were published by Meyer (2003), Harff *et al.* (2005) and Meyer, Harff (2005). Eustatic scenarios are provided by climate forward modeling. Voss *et al.* (1997) have simulated the global sea level rise for the next 840 years based on the ECHAM/LSG global atmosphere-ocean circulation model for simulating global warming and the effect on thermal expansion of the ocean water. Meyer (2003) has described the transfer function for sea level data given by Voss *et al.* (1997) to the Baltic Sea. According to eq. (7) these data have to be superimposed with changes in elevations due to vertical crustal movement taken from recent measurements (Harff *et al.*, 2001). A sea level scenario according to eq. (7) for the Wismar Bight for the year 2840 AD is shown in Figure 7. The scenario shows the main land area which might fall be-



**Fig. 6. Reconstructed scenario of the Wismar Bight at 6940 BP**



**Fig. 7. Scenario for the development of the Wismar Bight at 2840 BP**

neath sea level due to the transgression of the Baltic Sea until 2840 AD. Judging this scenario it has to be regarded that no sediment transport and no coastal defence activities have been taken into account here.

## SUMMARY

The coastal development of can be reconstructed by dated sediments and archaeological remnants from ancient coastal zones. Local relative seal level data can be interpolated to grids covering an area of investigation. Digital elevation models are

used to display palaeo geographic scenarios. For the Holocene of Baltic Sea, these scenarios show clearly the difference between the Fennoscandian Shield with regression controlled by isostasy and the transgression processes in the southern Baltic

area. This transgression is caused by subsidence of the earth crust but in particular by the climatically controlled global sea level rise. A coastal index is defined by separating relative sea level data into eustatic and isostatic components which allows to classify any coastal zone. First attempts have been made to model erosional, transport and depositional processes along retreating coastal zones. Here, we consider gaps in knowledge, particularly on the regional balance of sediment transport processes. The transport of sedimentary material descending from coastal erosion is not understood sufficiently by now. This gap will be closed in the near future by scientific collaboration between sedimentologists and physical oceanogra-

phers in order to describe as well the longshore as the coast-basin transport by currents and waves. The development of future sea level scenarios plays a principal role in coastal zone management. The task can only be solved if sedimentologists, oceanographers and climatologists will strengthen their collaboration. Long-termed processes as average sea level change have to be taken into consideration here as well as the role of storm events for coastal morphogenesis. The coupling of processes on different time scales from hours to millennia has to be accomplished as one of the main challenges in coastal research in the current decade.

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