Coastal Research Library 19

Jan Harff
Kazimierz Furmańczyk
Hans von Storch *Editors*

# Coastline Changes of the Baltic Sea from South to East

## Past and Future Projection

cost
EUROPEAN COOPERATION
IN SCIENCE & TECHNOLOGY

Springer

# Coastal Research Library

Volume 19

**Series Editor**
Charles W. Finkl
Department of Geosciences
Florida Atlantic University
Boca Raton, FL, USA

The aim of this book series is to disseminate information to the coastal research community. The Series covers all aspects of coastal research including but not limited to relevant aspects of geological sciences, biology (incl. ecology and coastal marine ecosystems), geomorphology (physical geography), climate, littoral oceanography, coastal hydraulics, environmental (resource) management, engineering, and remote sensing. Policy, coastal law, and relevant issues such as conflict resolution and risk management would also be covered by the Series. The scope of the Series is broad and with a unique cross-disciplinary nature. The Series would tend to focus on topics that are of current interest and which carry some import as opposed to traditional titles that are esoteric and non-controversial. Monographs as well as contributed volumes are welcomed.

More information about this series at http://www.springer.com/series/8795

Jan Harff • Kazimierz Furmańczyk
Hans von Storch
Editors

# Coastline Changes of the Baltic Sea from South to East

## Past and Future Projection

Springer

*Editors*
Jan Harff
Institute of Marine and Coastal Sciences
University of Szczecin
Szczecin, Poland

Kazimierz Furmańczyk
Institute of Marine and Coastal Sciences
University of Szczecin
Szczecin, Poland

Hans von Storch
Centre for Materials and Coastal Research
Helmholtz-Zentrum Geesthacht
Geesthacht, Germany

ISSN 2211-0577 ISSN 2211-0585 (electronic)
Coastal Research Library
ISBN 978-3-319-49892-8 ISBN 978-3-319-49894-2 (eBook)
DOI 10.1007/978-3-319-49894-2

Library of Congress Control Number: 2017932925

© Springer International Publishing AG 2017
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

COST is supported by the EU
Framework Programme Horizon 2020

EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

COST (European Cooperation in Science and Technology) is a pan-European intergovernmental framework. Its mission is to enable break-through scientific and technological developments leading to new concepts and products and thereby contribute to strengthening Europe's research and innovation capacities. It allows researchers, engineers and scholars to jointly develop their own ideas and take new initiatives across all fields of science and technology, while promoting multi- and interdisciplinary approaches. COST aims at fostering a better integration of less research intensive countries to the knowledge hubs of the European Research Area. The COST Association, an International not-for-profit Association under Belgian Law, integrates all management, governing and administrative functions necessary for the operation of the framework. The COST Association has currently 36 Member Countries. www.cost.eu

# Contents

## Part I Concepts and Model Approaches

**Part II Regional Studies**

# Chapter 1
# Introduction

**Jan Harff, Kazimierz Furmańczyk, and Hans von Storch**

**Abstract** The importance of sea-level and coastline changes increases for the population living along the edge of the world's oceans and seas. This holds in particular where eustatic sea-level rise is superimposed on isostatic subsidence and storm induced coastal erosion. This is the case on the southern and eastern Baltic Sea coast. In the South, glacio-isostatic subsidence enhances the effect of climate induced sea-level rise and strong storm effects cause a continuous retreat of the coast. On the eastern coast the glacio-isostatic uplift compensates eustatic sea-level rise, but storm induced waves cause permanent morphodynamic changes of the coastline. Concepts for protection, defense but also for the economic use of the coastal zone adjusted to their different environments are required increasingly. The elaboration of these management concepts can be facilitated through models generating future projection of coastal developments in front of the modern climate change. The anthology comprises results of a research project "Coastline Changes of the southern Baltic Sea – Past and future projection (CoPaF)" which was run by a team of Estonian, German, and Polish geoscientists and coastal engineers from 2010 to 2013. In the first part, the chapters are devoted to the explanation of conceptual and dynamical models to describe morphodynamic changes along the Baltic Sea southern coasts consisting of Pleistocene and Holocene sediments. In the second part, regional studies are published ranging from the Mecklenburgian Bay to the Gulf of Finland. Here, not only local and regional effects of coastal dynamics are considered, but also methodological aspects, such as the use of historical maps for the parameterization of morphodynamic models. As the southern and eastern Baltic serves as a natural laboratory for the investigation of coastal processes – the achievements of the project will contribute not only to the solution of regional problems in Baltic coastal research and engineering, but, will also contribute to general problems in the description, modelling and parameterization of coastal processes and morphodynamics.

---

J. Harff (✉) • K. Furmańczyk
Institute of Marine and Coastal Sciences, University of Szczecin, Szczecin, Poland
e-mail: jan.harff@univ.szczecin.pl

H. von Storch
Institute of Coastal Research, Helmholtz-Zentrum Geesthacht, Geesthacht, Germany

J. Harff et al. (eds.), *Coastline Changes of the Baltic Sea from South to East*, Coastal Research Library 19, DOI 10.1007/978-3-319-49894-2_1

**Keywords** Relative sea-level change • Coastal retreat • Glacio-isostatic adjustment • Eustasy • Morphodynamics • Modelling • Future projection • Coastal protection

Sea-level and coastline change are becoming increasingly important topics to the population living along the edge of the world's oceans and seas. These topics are of special importance where eustatic sea-level rise superimposes on glacio-isostatic land subsidence and storm induced coastal erosion. This is the case on the southern Baltic Sea coast where climate change and glacio-isostatic subsidence cause a relative sea-level rise of up to 2 mm/year and more, and where strong storm events lead to continuous coastal retreat. Here, coastal protection and defence are increasingly required, whereby coastal zone planning needs long-term prognoses. Future projection requires reliable dynamical[1] models which describe the complex interaction between the natural driving forces of coastal processes and socio-economic responses and vice-versa.

The reliability of dynamical models can be tested and approved by their application to the reconstruction of historical morphogenetic coastal scenarios and validation by the comparison with historical data. As processes act on different time scales, time spans from millennia to hours have to be considered. While decadal to centennial changes are well recorded by measured data and historical documents, longer term processes require deciphering of proxy-data such as the facies of sedimentary sequences. For the southern Baltic Sea, modelling approaches on the regional and local scale confirm the value of dynamical simulation for basic research and the solution of applied tasks in coastal sciences. In a first approach, models for long-term coastal morphogenesis (up to the millennial scale) have been developed for the German Baltic Sea coast between 2002 and 2009 (Harff and Lüth 2011). This concept has been extended for the entire southern Baltic Sea coast and realized within the frame of an international research project CoPaF (Coastline changes of the southern Baltic Sea – past and future projection) co-ordinated at the University of Szczecin, Poland, and funded by the Polish Ministry of Science and Higher Education from 2010 to 2014. Dynamical models have been developed and applied to selected key areas of the southern Baltic Seacoast. To understand the basics of coastal processes and their driving forces along the subsiding coast, it was important to work across national borders as well as across disciplinary barriers. Therefore geologists, oceanographers, geodesists and coastal engineers from Germany, Poland, Lithuania and Estonia (from the Southwest to the East) followed the invitation to join forces and to form an international and interdisciplinary research team. The current collection of chapters gives an overview on the results of this

---

[1] When referring to "dynamical models", we mean computer programs, which operate with discretized differential equations, which describe the simultaneous effect of a variety of dynamical processes. Often, such models are named "numerical", which is however, a misnomer – the characteristic is not the dynamical treatment but the description of the dynamics of the considered system (cf., Müller and von Storch 2004).

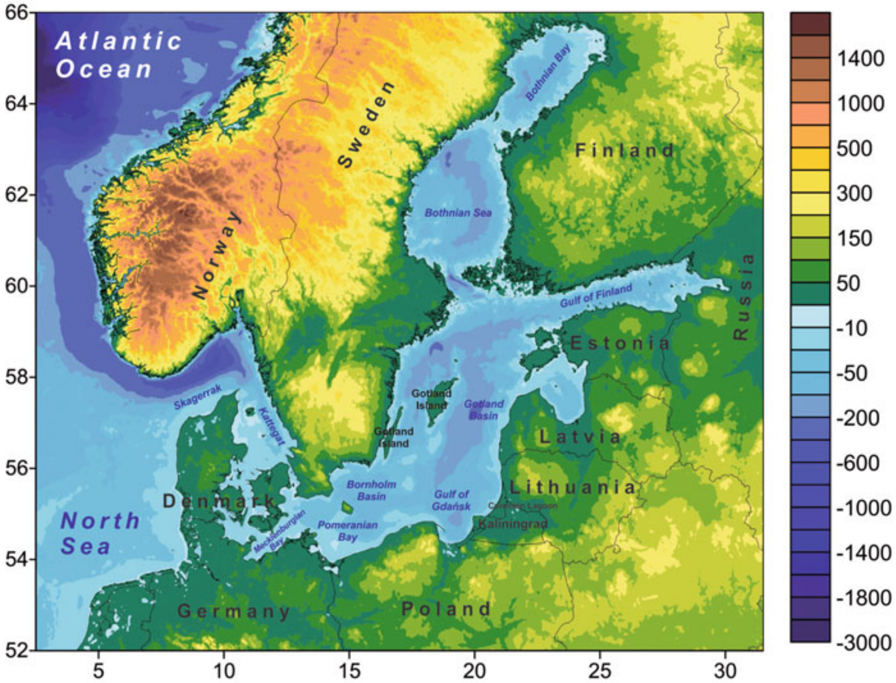

**Fig. 1.1** Map of the Baltic Sea Basin and surrounding areas. The scaling of elevations' color code is given in meters above sea level (m asl) (data: ETOPO5, Edwards 1989)

collaboration. This book is completed by another publication within the frame of Springer's Coastal Research Library (Bailey et al. 2017), which reports the results of a project SPLASHCOS – Submerged Prehistoric Archaeology and Landscapes of the Continental Shelf – a research network funded under the EU's COST programme (Cooperation in Science and Technology) as COST Action TD0902 (TD standing for Trans-Domain), which ran officially from November 2009 to November 2013. Regarding the Baltic Sea coastal areas, there was an overlap between the two projects— CoPaF and SPLASHCOS— both in thematic orientation and in membership so that the final conferences were held together in September 2013 at the University of Szczecin, Poland.

It should be mentioned here that the processes have been studied on the assumption that the southern Baltic Sea can be regarded as a natural laboratory, so that the models developed here should have the potential to be applied on coasts with rising relative sea level worldwide. Following this concept, the volume is structured into two parts.

In the *first* part, the chapters deal with explanation of conceptual and dynamical models to describe morphodynamic changes along the Baltic Sea's "sinking coasts" (Harff and Lüth 2011). In the *second* part, regional studies are published ranging from the Mecklenburgian Bay to the Gulf of Finland (Fig. 1.1). Here, not only local and regional effects of coastal dynamics are considered, but also methodological aspects, such as the use of historical maps for the parameterization of morphodynamic models.

Figure 1.1 shows a map of the area of investigation as part of the semi-enclosed Baltic Sea connected to the North Sea (and the Atlantic Ocean) through the Danish Straits and the Swedish Sound, the Kattegatt, and the Skagerrak. These Straits form the bottleneck regulating water exchange between the Baltic Basin and the World ocean. This water exchange follows an estuarine circulation system whereby the inflowing higher salinity water has to pass a sequence of regional basins, each separated by sills, from the entrance of the Baltic Sea to its center. The depth of these basins increases from West to the East (Mecklenburgian Bay: 25 m, Arkona Basin: 45 m, Bornholm Basin: 100 m, Gotland Basin: 250 m).

The geological structure and the regional tectonics determine general differences of the Baltic Sea coasts. According to Harff et al. (2017) the change of coastline positions of the Baltic Sea is mainly determined both by climatically controlled eustatic sea-level change and by glacio-isostatic adjustment (GIA). The authors explain the general difference between the uplifting North (coasts of Sweden and Finland), the subsiding South (coasts of Germany, Poland, Lithuania) and the coasts of Estonia and parts of Latvia on a transition between uplift and subsidence. For the reconstruction of the geological past, both factors operate together in determining the relative sea-level change signal which can be extracted from sediment proxy data. For future projections, however, eustatic sea-level change and glacio-isostatic adjustment have to be treated separately, as both processes are driven by different forces and demand special modelling approaches. In order to separate twentieth century eustatic change and vertical crustal movements, the authors combine gauge measurements with a GPS survey and a GIA model after Peltier (2007). This approach is described by Groh et al. (2017) in a separate chapter of this volume. Along uplifting coasts of Scandinavia emergence of former submarine, glacially shaped reliefs of Proterozoic crystalline rocks dominate coastal formation whereas morphodynamic processes play a subordinated role here. In the subsiding Southeast and South however, Quaternary sediments are permanently exposed to coastal erosion, sediment transport, and re-deposition. Meteorological forcing driving coastal wave dynamics together with aeolian processes steer the coastal morphodynamics here. The West-East directed atmospheric flow from the northern Atlantic Ocean to Eurasia results in a counterclockwise sediment transport along the entire southern to eastern coast, typically forming sandy peninsulas separating lagoons from the open Baltic Sea such as the Wisła and the Curonian spit. This process is made visible by the compilation of lateral sediment transport capacity models.

The sea level is regarded one of the main driving forces of morphodynamic changes on the Baltic coasts. Its variability is caused by different climatic and geological factors that render their understanding more difficult than for other areas of the Earth. Hünicke et al. (2017) explain the different factors needed to project[2] consistently sea-level rise in the Baltic Sea driven by natural and anthropogenic climate change. The authors illustrate this complexity by addressing general questions related to the identification of long-term trends of crustal displacements, the Baltic sea-level response to atmospheric forcing, and the difficulty of identifying an acceleration of sea-level rise in the observed records.

Groh et al. (2017) investigate decadal sea-level changes in the Baltic Sea region induced by past as well as by present-day continental ice-mass changes by the integration of geodetical data and modelling results. Peltier's (1998) sea level equation can be used as an appropriate tool to describe the effect of different driving forces on variations of regional relative sea level. The inducing mass-change patterns are inferred from 11 years of satellite gravimetry observations. Long-term changes in relative sea level and crustal deformation are derived from observations of tide gauges and GPS sites. The authors use both results to validate the GIA modelling results and to estimate a regional decadal (1901–1990) sea-level trend. This regional estimate amounts to 1.2±0.2 mm/year and is in agreement with other global estimates. The relative sea-level change on the southern Baltic Sea coast as a joint effect of eustatic rise and glacio-isostatically induced land subsidence amounts to an average of 2 mm/year. Together with frequent storm events this sea-level rise leads to continuous coastal retreat.

This fact causes an increasing need for dynamical models applicable to reconstruction and future projection of coastal morphogenesis within the frame of coastal zone management and planning. By adopting a concept of dynamic equilibrium changes of coastal profiles and three-dimensional generalization of the Bruun concept, Deng et al. (2017a) have developed the "Dynamic Equilibrium Shore Model" (DESM). This model can be applied to the study of coastal morphogenesis both for the reconstruction of the geological past, and future projection on decadal to centennial time scales. Historical maps can be used to retrieve information about ancient coastline configuration needed for the parameterization of the DESM model. Further requirements to run the model are a high-resolution modern Digital Elevation Model (DEM), tidal gauge data, and modelling data of long-shore sediment transport capacity. The authors have applied the DESM model to three research areas of the southern (Pomeranian Bay) Baltic Sea coast, Świna Gate, Łeba coast, and Hel Peninsula. These key areas stand for three distinct examples of morphodynamics in wave dominated environments: formation of barrier islands, development of open coasts, and processes at sandy spits. These areas are vulnerable to erosion and destruction due to their geological formation, glacio-isostatic subsidence, and exposure to the westerly and northern wind and storm tracks.

---

[2] We use the word "projection" instead of "prediction" when speaking about the future. A prediction is a most probable description of a future development, while projections, or scenarios, are possible and consistent descriptions (von Storch 2007). Future developments depend strongly on the anthropogenic forcing of the climate system, i.e., mostly the amount of greenhouse gases emitted, and predicting these amounts is impossible. Instead, scenarios of future emissions are employed and processed in dynamical models. The terms "projection" and "prediction" are the defined nomenclature of IPCC, but are often confused, even among climate scientists (see Bray and von Storch 2009).

Because of its general formulation, the DESM model can easily be applied outside the Baltic Sea to coasts vulnerable to erosion and destruction because of relative sea-level rise and storm induced wave action.

The morphogenesis of the Baltic coast cannot be understood without taking into account aeolian processes and the formation of dunes. Coastal foredunes are developed as a result of the interplay of wind and wave action in the transition zone between land and sea. Natural foredune ridges along the Świna Gate barrier coast (southern Pomeranian Bay) developed since 6000 cal BP provide an excellent laboratory to study dune formation processes. Here Zhang et al. (2017) investigate several basic driving mechanisms of coastal foredune morphodynamics as well as natural environmental factors involved in shaping the foredune geometry, using the application of a dynamical model. The model couples a process-based (deterministic) module for subaqueous sediment transport and a probabilistic-type module for subaerial aeolian transport of sand and the growth of vegetation. In a first step the authors validated the model for the time span 1951–2012 AD along a 1 km-long section of the Świna Gate barrier coast. Afterwards the validated model was applied to make a projection of change in the same area to 2050 AD using three different climate change scenarios. These climate change scenarios stand for three different impact levels regarding the effect of storm frequency, onshore sediment supply rate, and relative sea-level change and their capacity to shape the coastal morphology and determine foredune morphodynamics such as migration, bifurcation, destruction, and separation. According to the simulation result it is expected that after a low rate of relative sea-level rise during the last few decades, the accelerated rise over the twenty-first century suggested in the scientific literature will result in a dramatic and non-linear response in foredune development. The studies demonstrate that modelling of coastal morphodynmics needs hierarchically structured model components reflecting the interaction of driving forces on different spatial and temporal scales.

Musielak et al. (2017) introduce a conceptual model of morphodynamic processes and their parameters acting at the Polish coast on different temporal and spatial scales. Including basics in the geological structure of the coast between the Pomeranian and Gdansk Bay, sea-level fluctuations and hydro-dynamical patterns, the authors define six levels of coastal morphodynamic environments in a spatio-temporal system from millennia to hours and from hundreds of kilometers to centimeters. Each of these levels requires special modelling approaches weighting the critical factors. A crucial role is played by the dating of processes on the millennial time scale. A timing of historical processes is possible by proxy-data from sedimentary records.

Bitinas et al. (2017) explain the methodological problem of geological timing based on an example from the Polish-Lithuanian coast. Here, a sequence of radiocarbon ($^{14}$C), infrared optically stimulated luminescence (IR-OSL), and electron spin resonance (ESR) dates were compiled for a variety of materials from the Curonian and Vistula lagoons and spits of the southeastern Baltic Sea. These dated materials generally included lagoon sediments and mollusc shells, together with samples of fossil fish remains, peat, wood, and water bicarbonates. Unfortunately, an increasing number of $^{14}$C dates (conventional and AMS) seem to contradict corresponding IR-OSL dates and palaeobotanical investigations of contemporary materials. Detailed analyses of $^{14}$C, IR-OSL, and ESR chronologies and experimental $^{14}$C dating of modern live molluscs and water bicarbonates from the Curonian Lagoon and its main tributary – the Nemunas-Neris River system – reveal a remarkable influx of "old" carbonates into the lagoon causing this "reservoir effect". Special genetic scenarios have to be considered to explain the potential errors of radiocarbon dates. Some strategies to reduce those errors of sediment dating for future studies are recommended by the authors.

Understanding of long-term processes (on the millennial and centennial scale) requires the interpretation of environmental proxy-data from the sediment record. Witkowski et al. (2017) explain the paleoenvironmental reconstructions of processes influencing the long-term development of the southern Baltic Sea since the Last Glacial Maximum using lithological and diatom proxy-data of two sediment cores from two basins within the mouth of the Rega Valley, Poland. For quantitative reconstructions of paleosalinity ecological preferences of diatoms provide appropriate proxy-data records. The authors compare the consistent results of the two cores and demonstrate that both basins have experienced a series of marine transgressions, coastal aggradation, and lagoon development over the Late Glacial and Holocene. The results demonstrate the importance of terrestrial-hydrological processes for the evolution of long-term stability in the southern Baltic Sea coastal zone.

Comparable studies have been carried out by Borówka et al. (2017) on the postglacial evolution of the Odra River mouth, on the southern coast of the Pomeranian Bay. The investigation revealed that the Odra River mouth area was evolving during the Late Glacial and Holocene by changing from a glacio-fluvial environment via fluvio-limnic conditions to a marine environment. During the Late Pleistocene, the pre-Odra River discharged westward through the Toruń-Eberswalde ice-marginal valley to the North Sea Basin, like the rivers Elbe and Rhine. After the Scandinavian ice sheet retreat (ca. 14.5 ka BP), the ancient river changed its course to the Northeast into the Baltic Sea Basin, most likely close to the eastern part of today's Island of Rügen. Initially, the Odra was a braided river with many meandering channels and sandbanks. In the early Holocene, the river became anastomosing, before the Odra started to meander through swamps and bogs during the Mid-Holocene. During the Littorina transgression (ca. 7 ka BP), the river valley was transformed into a marine embayment extending southward down to the modern city of Szczecin where it formed an estuary. First, during the marine transgression the cores of two Islands have been formed in the outer part of the river mouth: Usedom Island in the West and Wolin Island in the East. Sediment dynamics along the northern coast of these islands during the later Holocene caused, step by step, the formation of sandy spits separating the Szczecin Lagoon from the Pomeranian Bay.

The conditions of these morphodynamic processes along the outer coast of Wolin and Usedom Island have been investigated by Dudzińska-Nowak (2017).

She focused her study on the so-called “Świna Strait”, the outflow system of the small Swina River connecting the Szczecin Lagoon with the Pomeranian Bay. By the comparison of morphological data along dune–beach–underwater bar profiles, using remote sensing images and aerial photographs, she studied the dynamics of accumulation and erosion. The coastline evolution was estimated based on 4 series of aerial photographs taken in 1938, 1951, 1973, and 1996. Changes in the location of dunes, beach and underwater bars were calculated over different time spans and used to analyse trends in coastal morphogenesis.

Dudzińska-Nowak’s investigations prove the importance of cartographic data for the identification of coastal dynamics on the centennial scale. To extend the research to the centennial time scale, historical maps can be effectively integrated into the investigation. Hartleib and Bobertz (2017) point at the increasing quantity of digitised historical maps and the corresponding opportunities for spatial comparison of habitats, landscape structural elements and landscape types. The authors provide the reader with examples from the region of the western Pomeranian Bay where historical Swedish and German maps have been used several times for coastal studies. The authors compare the co-called Swedish “Matrikel Maps” from the seventeenth century with the German “Meßtischblatt Maps” from the nineteenth and twentieth centuries and illustrate changes and limits using this kind of map as a source of scientific information.

Deng et al. (2017b) illustrate coastline changes on the decadal to centennial scale in the Pomeranian Bay by a set of historical maps covering almost 300 years of history. They find that in particular the “Messtischblatt” maps (starting at AD 1829) are suitable for geo-referencing and quantitative comparisons with modern Digital Elevation Models. The authors quantify the accuracy of these maps using the Root Mean Square Error of spatial differences of fixed points between the modern aerial photographs and historical topographic maps. The comparison of historical maps and the modern coastline derived from a Digital Elevation Model indicates that the coast can be subdivided into four zones (types) in terms of the trend of coastline changes: (1) continuously retreating (A-) or advancing coastline (A+); (2) relatively stable coastline (coastline changes are within the limits of accuracy of error bars); (3) anthropogenically influenced coastline changes; (4) randomly changing coastline. The calculation of longshore sediment transport capacity provides geomorphological support for the afore mentioned 4-type classification.

Changes in the Szczecin Lagoon shorelines as determined from selected historical maps of the seventeenth and nineteenth century are investigated by Siedlik (2017). A sea-level drop during the Little Ice Age (LIA, 1350–1820) coincides with the beginning of survey and cartography activities in Pomerania. The author formulates a hypothesis that the water level of the Szczecin Lagoon, recorded on seventeenth and eighteenth century maps, was about 1 m lower than the present one. He attempts to reconstruct fragments of the Lagoon shoreline based on selected historical maps. The comparative analysis examined Lagoon areas with broad and shallow slopes adjacent to the shoreline including the Nowowarpieński Sandbank, the Płocin Shallow, and the Pomeranian Shallow. A shift of the shoreline of the Island of Wolin between the Rów Peninsula and the village of Sułomino of

200–700 m happened most likely between 1695 and 1886, and bathymetric changes of the Szczecin Lagoon in 1755 and 1886 support the hypothesis of a 1-meter water-level rise since the LIA. The results coincide with a 1.8–2 km shift of the Szczecin Lagoon shore identified by the comparison of the Płocin Cove on four maps from the seventeenth century.

Wind- and wave-driven sediment morphodynamics play an important role on the southern and eastern Baltic Sea coast. Soomere et al. (2017) explore long-term variations in the properties of wave-driven sediment transport for 1970–2007 on the eastern Baltic Sea coast (including the Gulf of Riga) and temporal patterns of extreme wave-induced variations in the vicinity of City of Tallinn on the southern coast of the Gulf of Finland. The authors reconstruct the wave properties for 1981–2014 in the Baltic Proper (based on adjusted geostrophic winds from the Swedish Meteorological and Hydrological Institute) and in the Gulf of Finland (using wind data measured at Kalbådagrund) by applying the WAM model (Komen et al. 1994) with a moderate resolution of about 3 nautical miles and a higher resolution of about 470 m, respectively. In the Gulf of Riga and the Baltic Proper, the course of net and bulk transport is similar until 1990, but after that it starts to differ significantly. An increase in simulated bulk potential sediment transport along the Curonian Spit and along the entire eastern coast of the sea (including the Gulf of Riga) during the entire simulation interval goes along with a decrease of net transport starting at the end of the 1980s, and correlates with an abrupt turn of the geostrophic air-flow by about 40° over the southern Baltic Sea since 1987. This shift coincides with substantial fluctuations in the air-flow even at the latitudes of the Gulf of Finland. The authors hypothesize that additional to the impact of the rotation of wind directions on the wave fields and the course of coastal processes, this turn may serve as an alternative explanation for a radical decrease in the frequency of major inflows of North Sea water into the Baltic Sea since the mid-1980s.

When extending the study to the millennial time scale, glacio-isostatic displacements of the crust have to be considered too, in particular on the Estonian coast where glacioisostic uplift has dominated eustatic rise since the Late Atlantic. A special role in the northeastern margin of the area of investigation is played by its position at the transition between subsidence in the South and uplift in the North. Rosentau et al. (2017) review the Estonian data on relative sea level, land uplift and coastal floods and provide sea-level scenarios and risk assessment of coastal flooding in urban areas for the twenty-first century. Considering the present post-glacial land uplift rates of Estonian coastal areas and the global ocean level rise projections, the authors conclude that the long-existing trend of relative sea-level lowering may be replaced by a rising relative sea-level trend during the twenty-first century. At the end of the twenty-first century the relative sea level may rise about 20–40 cm or even 40–60 cm in relation to the present sea level in the case of the IPCC Representative Concentration Pathways (RCP) 4.5 or RCP 8.5 scenario, respectively. Sea-level rise together with an increased storm frequency and decreased period of winter ice cover will probably increase the extent of floods during the twenty-first century. Significant coastal flooding risks affect four Estonian cities:

Pärnu, Kuressaare, Haapsalu and Tallinn and eight smaller towns. The largest coastal flooding in Estonia is recorded in Pärnu, with a water-level maximum of 275 cm in 2005. Calculations show that due to the impact of projected climate change and in the case of certain weather conditions, coastal floods in Pärnu may affect areas up to 400 cm above the present mean sea level by the end of the twenty-first century. Environmental impact assessments, risk assessment, and restriction zones for construction in certain buffer and flood areas have already been prepared. Further integration of climate issues into existing laws, strategies, and land use plans is essential for reducing the vulnerability of populated areas and strengthening the adaptive capacity of the urban system against climate change.

**Acknowledgements** The editors would like to acknowledge first the Polish Ministry of Science and Higher Education. By funding the research project CoPaF (Grant N N306 340537) the base for very productive studies and in particular the cross-bordering research and international exchange was provided. Thanks are also due to the University of Szczecin for hosting several project workshops and the final conference held at Szczecin in October 2013. Prof. Dr. Geoff Bailey, University of York, UK, chairman of the SPLASHCOS project (COST Action TD0902) deserves thank for establishing fruitful interdisciplinary relationships between geoscientists and archaeologists. We express our gratitude also to the peers who have reviewed the chapters presented in this book that helped substantially to improve the scientific quality of this publication. Last but not least we have to thank emphatically mgr Agnieszka Kierzek, and mgr inż. Genowefa Daniszewska-Kowalczyk, both University of Szczecin, for their technical contribution to editing this book.

## References

Bailey G, Harff J, Sakellariou D (eds) (2017) Under the sea: archaeology and palaeolandscapes of the continental shelf. Coastal research library, vol 20. Springer, Cham

Bitinas A, Mažeika J, Buynevich IV, Damušytė A, Molodkov A, Grigienė A (2017) Constraints of radiocarbon dating in southeastern baltic lagoons: assessing the vital effects. In: Harff J, Furmanczyk K, von Storch H (eds) Coastline changes of the Baltic Sea from south to east – past and future projection. Coastal research library, vol 19. Springer, Cham, pp 137–171

Borówka RK, Osadczuk A, Osadczuk K, Witkowski A, Skowronek A, Latałowa M, Mianowicz K (2017) Postglacial evolution of Odra River Mouth, Poland-Germany. In: Harff J, Furmanczyk K, von Storch H (eds) Coastline changes of the Baltic Sea from south to east – past and future projection. Coastal research library, vol 19. Springer, Cham, pp 193–217

Bray D, von Storch H (2009) 'Prediction' or 'Projection'? The nomenclature of climate science. Sci Commun 30:534–543. doi:10.1177/1075547009333698

Deng J, Harff J, Zhang W, Schneider R, Dudzinska-Nowak J, Giza A, Terefenko P, Furmanczyk K (2017a) The dynamic equilibrium shore model for the reconstruction and future projection of coastal morphodynmics. In: Harff J, Furmanczyk K, von Storch H (eds) Coastline changes of the Baltic Sea from south to east – past and future projection. Coastal research library, vol 19. Springer, Cham, pp 87–106

Deng J, Harff J, Giza A, Hartleib J, Dudzinska-Nowak J, Bobertz B, Furmanczyk K, Zölitz R (2017b) Reconstructions of coastline changes by the comparisons of historical maps at the Pomeranian Bay, southern Baltic Sea. In: Harff J, Furmanczyk K, von Storch H (eds) Coastline changes of the Baltic Sea from south to east – past and future projection. Coastal research library, vol 19. Springer, Cham, pp 271–287

Dudzinska-Nowak J (2017) Trends in coast development of the Swina Gate area. In: Harff J, Furmanczyk K, von Storch H (eds) Coastline changes of the Baltic Sea from south to east – past and future projection. Coastal research library, vol 19. Springer, Cham, 219–255

Edwards MO (1989) Global gridded elevation and bathymetry (ETOPO5). Digital raster data on a 5-minute Geography (lat/lon) 2160 x 4320 (centoid-registered) grid. 9-track tape, Boulder: National Oceanographic and Atmospheric Administration (NOAA) National Geophysical Data Center, 18.6 MB

Groh A, Richter A, Dietrich R (2017) Recent Baltic Sea level changes induced by past and present ice masses. In: Harff J, Furmanczyk K, von Storch H (eds) Coastline changes of the Baltic Sea from south to east – past and future projection. Coastal research library, vol 19. Springer, Cham, 55–68

Harff J, Lüth F (eds) (2011) Sinking coasts – geosphere ecosphere and anthroposphere of the holocene Southern Baltic Sea II. Ber Röm-Germ Komm 92:1–380

Harff J, Deng J, Groh A, Dudzinska-Nowak J, Froehle P, Hünicke B, Soomere T, Zhang W (2017) What determines the change of coastlines in the Baltic Sea? In: Harff J, Furmanczyk K, von Storch H (eds) Coastline changes of the Baltic Sea from south to east – past and future projection. Coastal research library, vol 19. Springer, Cham, pp 15–35

Hartleib J, Bobertz B (2017) New demands on old maps – An approach for estimating aspects of accuracy of old maps as basis for landscape development research. In: Harff J, Furmanczyk K, von Storch H (eds) Coastline changes of the Baltic Sea from south to east – past and future projection. Coastal research library, vol 19. Springer, Cham, pp 257–270

Hünicke B, Zorita E, von Storch H (2017) The challenge of Baltic Sea level change. In: Harff J, Furmanczyk K, von Storch H (eds) Coastline changes of the Baltic Sea from south to east – past and future projection. Coastal research library, vol 19. Springer, Cham, pp 37–54

Komen GJ, Cavaleri L, Donelan M, Hasselmann K, Hasselmann S, Janssen PAEM (1994) Dynamics and modelling of Ocean Waves. Cambridge University Press, Cambridge, p 534

Peltier WR (1998) Postglacial variations in the level of the sea: implications for climate dynamics and solid-earth physics. Rev Geophys 36(4):603–689

Peltier WR (2007) Postglacial coastal evolution: ice-ocean-solid earth interactions in a period of rapid climate change. In: Harff J, Hay WW, Tetzlaff DM (eds) (2007) Coastline changes: interrelation of climate and geological processes. Geol Soc Am Spec Paper 426:5–28

Müller P, von Storch H (2004) Computer modelling in atmospheric and oceanic sciences – building knowledge. Springer Verlag Berlin/Heidelberg/New York, 304, 1437–028X

Musielak S, Furmańczyk K, Bugajny N (2017) Factors and processes forming the Polish Southern Baltic Sea coast on various temporal and spatial scales. In: Harff J, Furmanczyk K, von Storch H (eds) Coastline changes of the Baltic Sea from south to east – past and future projection. Coastal research library, vol 19. Springer, Cham, pp 69–85

Rosentau A, Muru M, Gauk M, Oja T, Liibusk A, Kall T, Karro E, Roose A, Sepp M, Tammepuu A, Tross J, Uppin M (2017) Sea-level change and flood risks at Estonian coastal zone. In: Harff J, Furmanczyk K, von Storch H (eds) Coastline changes of the Baltic Sea from south to east – past and future projection. Coastal research library, vol 19. Springer, Cham, pp 363–388

Siedlik K (2017) Changes in the Szczecin Lagoon shoreline as determined from selected 17th and 19th century maps. In: Harff J, Furmanczyk K, von Storch H (eds) Coastline changes of the Baltic Sea from south to east – past and future projection. Coastal research library, vol 19. Springer, Cham, pp 389–326

Soomere T, Viška M, Pindsoo K (2017) Retrieving the signal of climate change from numerically simulated sediment transport along the eastern Baltic Sea coast. In: Harff J, Furmanczyk K, von Storch H (eds) Coastline changes of the Baltic Sea from south to east – past and future projection. Coastal research library, vol 19. Springer, Cham, pp 327–361

von Storch H (2007) Climate change scenarios – purpose and construction. In: von Storch H, Tol RSJ, Flöser G (eds) Environmental crises. Science and policy. Springer, Berlin 978-3-540-75895-2, pp 5–16

Witkowski A, Cedro B, Dobosz S, Seddon AWR, Kierzek A (2017) Late glacial to holocene environmental changes (with particular reference to salinity) in the southern Baltic reconstructed from shallow water lagoon sediments. In: Harff J, Furmanczyk K, von Storch H (eds) Coastline changes of the Baltic Sea from south to east – past and future projection. Coastal research library, vol 19. Springer, Cham, pp 175–192

Zhang W, Harff J, Schneider R, Meyer M, Zorita E, Hünicke B (2017) Modelling of medium-term (decadal) coastal foredune morphogenesis – historical hindcast and future scenarios of the Swina Gate barrier coast (southern Baltic Sea). In: Harff J, Furmanczyk K, von Storch H (eds) Coastline changes of the Baltic Sea from south to east – past and future projection. Coastal research library, vol 19. Springer, Cham, pp 107–135

# Part I
# Concepts and Model Approaches

# Chapter 2
# What Determines the Change of Coastlines in the Baltic Sea?

**Jan Harff, Junjie Deng, Joanna Dudzińska-Nowak, Peter Fröhle, Andreas Groh, Birgit Hünicke, Tarmo Soomere, and Wenyan Zhang**

**Abstract** The change of coastline positions of the Baltic Sea is mainly determined by both the eustatic sea-level change and the glacio-isostatic adjustment (GIA). For changes on the Holocene time scale, the relative sea-level change can be reconstructed from paleo-coastline positions and correspondingly dated sediments and organic remains. On the decadal scale, tide gauge data are available. Both data sets display the relative value of sea-level change resulting from the superposition of climatically and meteorologically induced factors, vertical crustal displacement, and related gravitational forces. The isolation of the GIA signal from the compound relative sea-level change data plays a critical role for future projections of coastline changes within the frame of coastal zone management. To separate different components of sea-level data sets, statistical methods for the exploration of empirical water level, meteorological, and GPS data are combined with analytical methods to solve the sea-level equation. In the result, the pattern of vertical crustal movement can be displayed as maps covering the uplifting Fennoscandian Shield and its subsiding belt. Whereas along the uplifting coasts morphodynamic processes play a subordinated role, in the subsiding Southeast and South, Quaternary sediments are permanently exposed to coastal erosion, sediment transport, and

---

J. Harff (✉) • J. Dudzińska-Nowak
Institute of Marine and Coastal Sciences, University of Szczecin, Szczecin, Poland
e-mail: jan.harff@univ.szczecin.pl

J. Deng
School of Earth and Environmental Sciences, University of Wollongong,
Wollongong, NSW, Australia

P. Fröhle
Technical University Hamburg-Harburg, Hamburg, Germany

A. Groh
Technische Universität Dresden, Institut für Planetare Geodäsie, Dresden, Germany

B. Hünicke
Helmholtz Zentrum Geesthacht, Geesthacht, Germany

T. Soomere • W. Zhang
Institute of Coastal Research, Helmholtz-Zentrum Geesthacht, Geesthacht, Germany

J. Harff et al. (eds.), *Coastline Changes of the Baltic Sea from South to East*, Coastal Research Library 19, DOI 10.1007/978-3-319-49894-2_2

re-deposition. This mainly wave-driven sediment dynamics together with aeolian processes depend on meteorological forcing of the in general west-east directed air-flow from the northern Atlantic Ocean to Eurasia. Regional coastal morphogenesis can generally be described by alongshore sediment transport pattern deduced from the integration of subregional to local models of transport capacities. For future projection, coastlines and the morphology of the adjacent zones have to be regarded a function of its position related to the vertical displacement of the Earth's crust, the regional climatic and meteorological conditions, and the geological setting. Results of climate modelling, the Earth's visco-elastic response to the deglaciation, geological data and regional sediment transport capacities have to be interpreted comprehensively.

**Keywords** Coastal morphogenesis • Glacio-isostatic adjustment • Eustasy • Gavitational force • Relative sea-level change • Sea-level equation • Transgression • Regression • Wind waves • Alongsore sediment transport capacity • Coastal erosion • Cliff coasts • Sandy spits • Regional sediment balance

## 2.1 Introduction

Coastal processes and their sensitivity to a change of natural and anthropogenic forcing are of high priority in the international debate on the management and socio-economic use of the zone of interface between continents and the ocean. The Baltic Sea can play here a special role as a "model ocean" where processes and forcing change along short spatial distances. The special conditions steering sediment transport in the Baltic Sea can be summarized by adopting a scheme for shallow seas and continental shelves published by Nitrouer and Wright (1994). In Fig. 2.1 those processes determining the coastal morphogenesis of the Baltic Sea are depicted.

For the Baltic Sea's coastal morphodynamics four main circumstances and processes can be separated:

- Geological composition of the coast,
- Relative sea-level change determined by glacio-isostatic adjustment (GIA) superposed with climate-controlled eustatic change,
- Wind (wave) driven hydrodynamics and aeolian sediment transport,
- Changing sediment sources and sinks because of coastal erosion and accretion.

The Baltic Sea coasts can be regionalized along of a geologically related North-South gradient along which the influence of glacio-isostatic adjustment as the main driving force of coastal change is continuously replaced by the effect of atmospheric circulation on coastal dynamics. Geologically the Baltic area can generally be subdivided into the uplifting Fennoscandian Shield in the North and the subsiding lowlands – parts of the Central European Basin – in the South. For the isostatic control of the vertical displacement of the Earth's surface one has to mention the

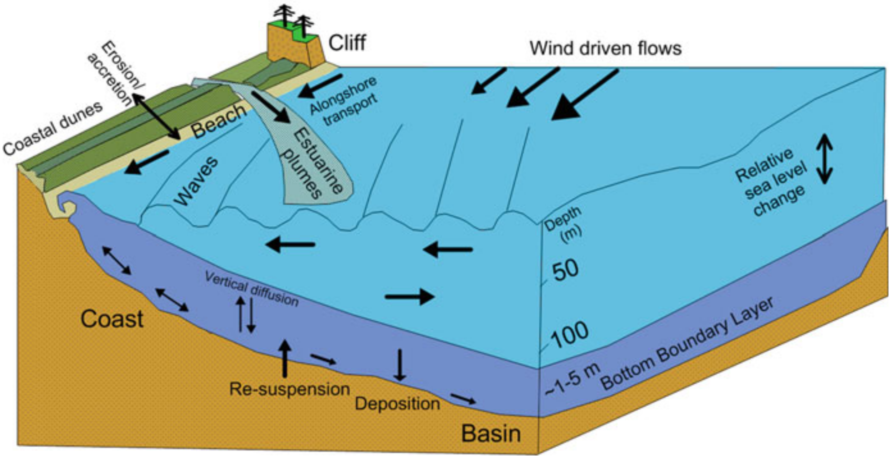

**Fig. 2.1** Summary of topographic features and sediment transport mechanisms in the Baltic Sea (modified from Nitrouer and Wright 1994). For explanation see the text

pioneering work of Peltier (2004, 2007) and Lambeck et al. (2010) who have described the isostatic deformation of the Earth's crust as the reaction to changing ice load during the last glacial cycle. The gradient from uplift of 9 mm/a in the North to a subsidence of 2 mm/a in the south causes a permanent marine regression at the Northern Baltic coasts and a marine transgression along the southern coasts. Harff et al. (2007, 2011) have described this process on the Holocene time scale by regional models considering glacio-isostatic adjustment superposed with eustatic changes. These studies are based on the reconstruction of relative sea-level change during the Late Pleistocene and Holocene along the coasts of the uplifting Fennoscandian Shield (Linden et al. 2006; Berglund 2004; Karlsson and Risberg 2005; and others) and the subsiding southern belt (Uścinowicz 2006; Lampe et al. 2007; and others). Rosentau et al. (2017) among others contributed to these studies by the investigation of the Late-Pleistocene to Holocene sea-level and coastline change at the transition area between uplift and subsidence: the southern coast of the Gulf of Finland. The morphogenesis along the southern and southeastern coast have been studied by numerous authors. As examples may serve the early studies of Kolp (1978) and Kliewe (1995) for the German coast, or Furmańczyk and Musielak (2015) for the Polish coast. For selected local key areas, Zhang et al. (2010a, b, 2013) and Deng et al. (2014) have investigated the coastal morphodynamics including coastal erosion, transport, and accumulation at the southern Baltic coast based on numerical modelling. Despite intense research activities in the development of modelling tools for coastal dynamics at the Baltic Sea, there are still left open questions. One of them is the separation of the crustal deformation signal in sea-level gauge data. Ekman (1996, 2009), Frischbutter and Schwab (1995) and Harff et al. (2001) have analyzed sea-level gauge data and compiled corresponding contour maps. None of them have solved the problem of separating the GIA signal from eustatic "contamination" despite the fact that a separation is needed for future projection of relative sea-level scenarios. Richter et al. (2012) and Groh et al. (2011,

2017) have used a GPS survey and mass displacement models for an estimate of vertical crustal displacement and gravitational effects to be used for the discrimination of the GIA component in sea-level gauge data. A second open question is the comprehensive view of lateral sediment transport capacity on a transect from the Mecklenburgain Bay to the Gulf of Riga. In this article, we will tackle these questions. In the first part, a map of the recent vertical crustal adjustment (GIA) will be derived from different data sources and in the second part we will regionalize the Baltic Sea coast based on the geological build up and a compilation of sediment transport capacity model results.

## 2.2 Geological Compartments and Coastal Types

Based on the geological structure we subdivide the Baltic coast into three main compartments which respond along the Baltic coastlines to sea-level change and wind-driven hydrographic and aeolian forces (Fig. 2.2) in a different manner (compare Lampe 1995):

The northern part – the Fennoscandian Shield – consists of Proterozoic crystalline rocks outcropping all along the coast between southern Sweden and the northern Gulf of Finland. The surface of this continuously uplifting craton has been polished by inland ice during the last glaciations and just emerges because of permanent marine regression forming a typical fjord –archipelago coast. At its southeastern prolongation Cambrian to Silurian sandstones, shales and limestones rest on the tectonically stable Precambrian basement of the Russian Plate. These horizontally resting tectonically undeformed sediments crop out along the southern Gulf of Finland to the Estonian Baltic Islands forming steep cliffs – the so-called Klint-Coast there. Gentle glacio-isostatic uplift rates cause marine regression along with wave-driven cliff erosion. To the Southwest of the Gulf of Riga, the coast strikes the Baltic-Belorussian Syneclise and the North-German-Polish Depression where the coast is built up by Quaternary sediments or their erosional products – remains of the Weichselian glaciations, the postglacial and the Holocene period. This zone is dominated by permanent transgression of the Baltic Sea, and wind-driven waves together with aeolian processes determine the morphogenesis of glacial till cliffs, sandy spits, dune fields and lagoons. Figure 2.2 depicts schematically the three morphogenetically dissimilar compartments of the Baltic Sea (For the regional tectonic structure of Northern Europe see Harff et al. 2001).

## 2.3 The Model

To describe changes of coastlines in an area **R** for a time span $\Delta t$ (extending from the initial instant 0 to some time instant $-t$) we compare a digital elevation model at time $t$, $DEM_t$, with a reference model $DEM_0$.

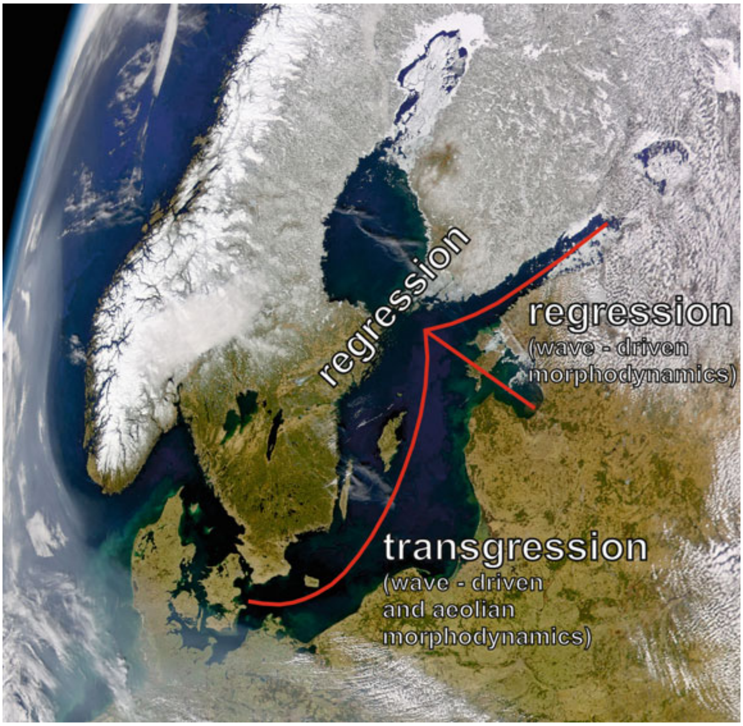

**Fig. 2.2** Regionalization of processes affecting coastal morphogenesis of the Baltic Sea depending on geological buildup and vertical crustal movements (satellite image: Subset of SeaWiFS, 1April 2004, SeaWiFS Project, NASA / GSFC, ORBIMAGE)

The change can be described quantitatively by superimposing $DEM_0$ with the sea-level change $\Delta RSL$ and the change of sediment thickness $\Delta SED$ (reduction by erosion or increase by accumulation).

$$DEM_t \;=\; DEM_0 - \Delta RSL + \Delta SED \tag{2.1}$$

The relative sea-level change $\Delta RSL$ depends on different factors

$$\Delta RSL \;=\; \Delta G - \Delta GIA + \Delta EC + \sum_i \Delta E_i \tag{2.2}$$

Here, $\Delta G$ describes the sea-level change induced by gravitational forcing of the uprising Earth's crust. $\Delta EC$ stands for the eustatic (climatically controlled) sea-level change, $\Delta GIA$ for the glacio-isostatic adjustment, and $\Delta E_i$ for meteorologically driven oceanographic fluctuations.

## 2.4 Relative Sea-Level Change and Glacio-Isostatic Adjustment

For the reconstruction of paleogeographic scenarios Eq. (2.1) can be easily used (Harff et al. 2011). Relative sea-level curves (reconstructed by dating of paleocoastlines) have been published for several ancient coastal sites around the Baltic Sea (Harff et al. 2007) and can be used as data source. Beginning with the opening of the Danish Straits and the Swedish Sound as a permanent connection between the Baltic Basin and the Atlantic Ocean (via the North Sea) about 8000 cal BP, the global eustatic signal of post-glacial sea-level rise is also reflected by the Baltic sea level. The glacio-isostatic uplifting of the Baltic (Fennoscandian) Shield is compensating the eustatic signal along the northern coasts of the Baltic Basin, so that we observe continuous marine regression there. Conversely, along the southern coast, glacio-isostatic subsidence is even amplifying the effect of eustatic sea-level rise causing permanent marine transgression there. Harff et al. (2011) have compiled by a regression/transgression model the coastline changes of the Baltic Basin since the Atlantic period (Fig. 2.3).

The map shows by its red coloured parts (area of marine regression) clearly consistency of the Baltic (Fennoscandian) Shield with the Fennoscandian Ice Shield having had covered the area during the Quaternary glaciations. Unloading by melting during the Late Pleistocene to early Holocene caused the glacio-isostatic uplift. However, it has to be considered that the Baltic Shield as an ancient tectonic unit is rising since Proterozoic time so that crystalline rocks that have been formed within the deeper crust are outcropping nowadays at Scandinavia and its coastlines. This uplift process has been converted to subsidence due to the load of inland ice

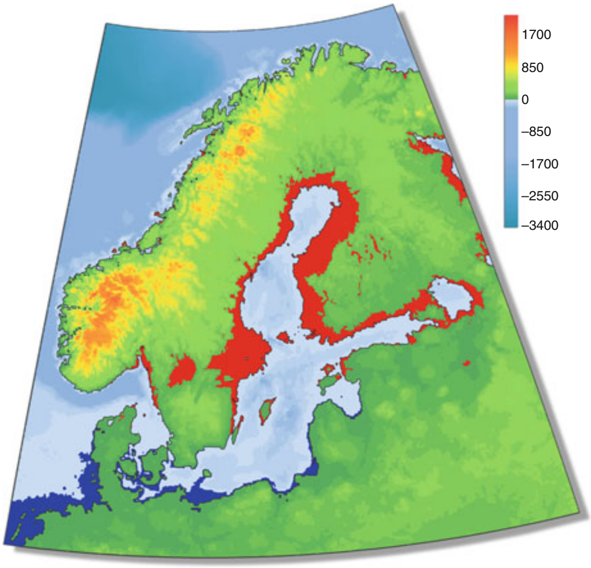

**Fig. 2.3** The Baltic Sea and the change of coastlines since about 8000 cal BP (Modified from Harff et al. 2007). See text for explanation. The scale shows colour codes for m above sea level (asl)

during the Quaternary glaciations. Climatically determined unloading by ice melting reinforced and accelerated even ancient tectonic uplift.

Dark blue areas at the southern Baltic Basin in Fig. 2.3 depict areas of inundation. Compared to the "regressive North" of the Baltic Basin where GIA is compensating eustatic rise, here in the "transgressive South" glacio-isostatic subsidence (as a result of the collapsing lithospheric bulge (Harff et al. 2001) and eustasy are in the same direction and complement each other causing permanent inundation and consequently landward retreat of the coastline.

For the countries along the southern Baltic coast facing permanent sea-level rise the protection against flooding and erosion plays an important role. For protection strategies, future scenarios based on numerical morphodynamic models are irreplaceable. Sea-level projections taking into account eustatic change as well as GIA-induced displacement of the crust are a base for these scenarios. Eustatic changes can be derived from coupled atmospheric-oceanographic models (Hünicke et al. 2011). For the GIA displacement of the crust on the regional scale the sea-level equation after Peltier (1998) can be used (Groh et al. 2017). For local high-resolution numerical models can be combined with measured data. By reordering Eq. (2.2) and neglecting $\sum_i \Delta E_i$one receives an empirical equation:

$$\Delta GIA^* \;=\; \Delta EC^*_{gauge/gps} - \Delta RSL^*_{gauge} + \;\Delta G \tag{2.3}$$

In this symbolism, $\Delta GIA^*$ stands for the estimate of glacio-isostatic deformation of the crust, $\Delta RSL^*_{gauge}$ for relative sea level measured by gauges, $\Delta EC^*_{gauge/gps}$ for the eustatic change estimated by a comparison of $RSL$ measured by gauges, and GIA measured by GPS observations of vertical crustal movements. Data of sea-level change induced by gravitational forcing of the uprising crust $\Delta G$-can be deduced from an analytical solution of the sea-level equation (Groh et al. 2011). The asterisks assigned to the quantities of Eq. (2.3) describe their estimation based on empirical data.

For a model describing relative sea-sea level changes by gauge data a map published by Ekman (1996) covering Scandinavia and the central and the northern Baltic Basin has been combined with gauge data from the southern Baltic Basin. Ekman (1998, 2009) constructed his map based on (sea) gauge data (60–100 years time series), lake-level records and repeated levellings. To exclude local effects the sea-level records for the Baltic Basin have been referred to Stockholm as the main reference station. The average sea-level change was estimated by linear regression approximation of the data. The location of the gauge stations used for the southern Baltic Basin is depicted in Fig. 2.4, top panel.

Data from different sources (time series between 60 and 100 years) have been homogenized, processed according to the PSMSL-standard (Permanent Service for Mean Sea Level) and uploaded to the PMSL-website (http://www.psmsl.org/data/) as described by Richter et al. (2012). As a reference station Warnemünde (war2) have been selected. Linear approximation lead to mean rsl-changes displayed in Fig. 2.4 (bottom panel).

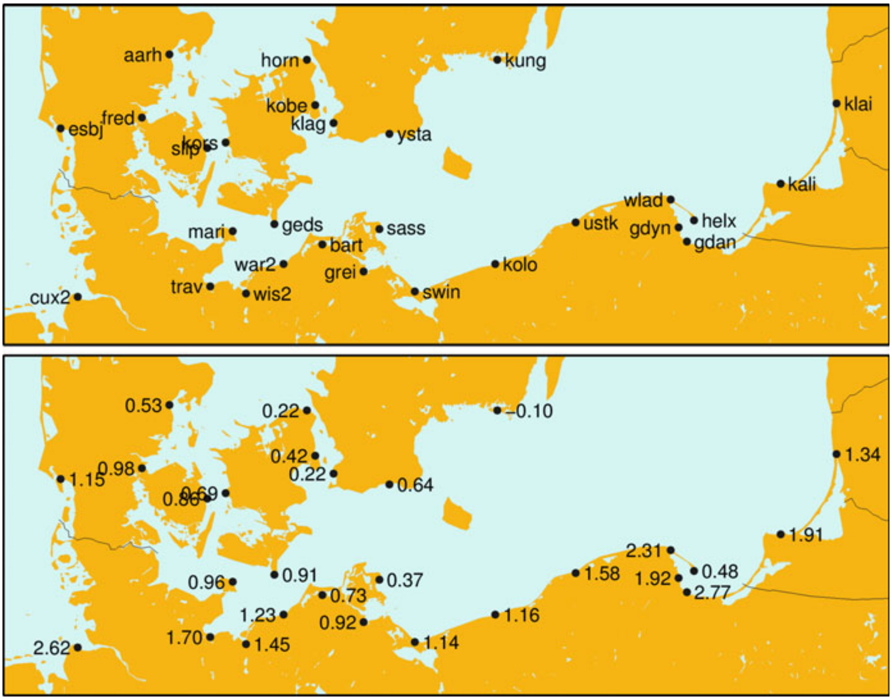

**Fig. 2.4** (*top*) Gauge sites and (*bottom*) mean relative sea level (rsl) changes (mm/a) used for interpolation of relative sea-level changes

In the model the relation describing the relative sea level change $\Delta RSL$ plays a central role.

For the compilation of sea-level data in Fig. 2.4 (bottom panel) and the analogue data of the map by Ekman (1996), this map has been digitized so that both data sets could be treated by a kriging interpolation. The resulting contour map is displayed

The data shown in Fig. 2.5 still contain information about sea-level change as volume effect and gravitational effect. In order to eliminate eustasy as a scalar value, constant over the whole Baltic basin, and the deformation of the sea surface as a function of the distance to the mass centre of the uprising Baltic Shield, GPS data and results from gravitational modelling have been involved into the procedure expressed by Eq. (2.3).

Vertical crustal deformation rates were derived from the analysis of a regional GPS network (Richter et al. 2012). This network consists of stations as parts of international projects plus some additional stations along the German coast which are combined with sea-level gauges and were used to complete the network. Data of vertical displacement were derived for the observation period from April 2001 to April 2008. The accuracy measures was estimated by Richter et al. (2012) ranging from ±1.4 to ±2.2 mm/a. For 13 stations tide gauges and permanent GPS station data are combined and plotted in Fig. 2.6. The long-term eustatic sea-level change was estimated by linear regression (Milne et al. 2001). The regional mean

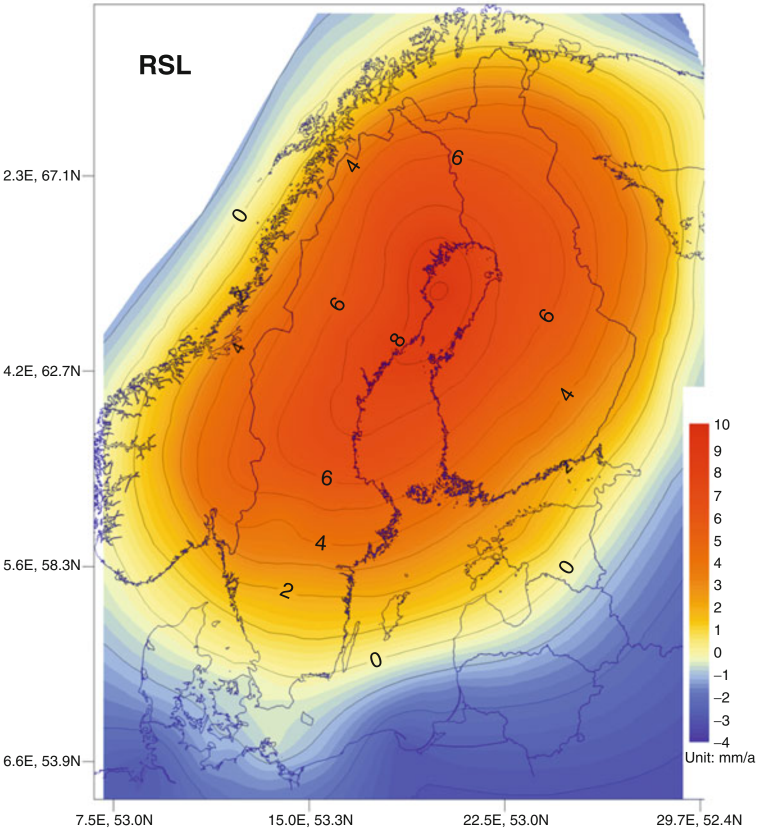

**Fig. 2.5** Map of vertical crustal movement relative to sea level. The data originate from Ekman (1996) and gauge records from the southern Baltic Sea basin (sites displayed in Fig. 2.4). For comparison see Rosentau et al. (2007)

eustatic sea-level change is indicated by the y-intercept of the best fitting line and amounts to $\Delta EC^{*}_{gauge/gps}$ =1.2 ± 0.2 mm/a (Compare the similar procedure applied by Groh et al. 2017, but note the difference in the sequence of numerical operations).

Present-day effects of GIA-induced changes in relative sea level, crustal deformation, and the gravity field (i.e. the geoid) can be derived by means of the sea-level equation after Peltier (1998). This requires information on the spatial and temporal evolution of the ice load as well as on the Earth's visco-elastic properties. Groh et al. (2017) made use of the ice load history ICE-5G and the corresponding Earth model VM2 (Peltier 2004) to solve the sea-level equation. The resulting present-day geoid rate is expressed in the map depicted in Fig. 2.7.

Superimposing relative sea level change, eustatic rise, and geoid deformation effect on the Baltic water level according to Eq. (2.3) leads to a map of glacio-isostatic deformation of the Baltic area as displayed in Fig. 2.8. Of particular interest is here the course of the 0-contour-line expressing a zone of glacioisostatic