Paleogeographic numerical modelling of marginal seas for the Holocene – an exemplary study of the Baltic Sea

Jakub Miluch[1,2], Wenyan Zhang[1], Jan Harff[2]Harff[3], Andreas Groh[3]Groh[4], Peter Arlinghaus[1], Celine Denker[1]

[1]Institute of Coastal Systems – Analysis and Modeling, Helmholtz-Zentrum Hereon, Geesthacht, 21502, Germany
[2]Polish Geological Institute – National Research Institute, Marine Geology Branch, Gdańsk, 80328, Poland
[2]Institute [3]Institute of Marine and Environmental Sciences, University of Szczecin, Szczecin, 70-453, Poland
[3]Institute [4]Institute of Planetary Geodesy, Technical University Dresden, 01062, Germany

Correspondence to: Wenyan Zhang (wenyan.zhang@hereon.de); Jakub Miluch (jmilu@pgi.gov.pljakub.miluch@usz.edu.pl)

Formatted: Not Superscript/ Subscript

Formatted: Not Superscript/ Subscript

Formatted: Not Superscript/ Subscript

Abstract. Sustainable management of marginal seas is based on a thorough understanding of their evolutionary trends in the past. Paleogeographic evolution of marginal seas is controlled by not only global and regional driving forces (eustatic sea level change and isostatic/tectonic movements) but also sediment erosion, transport, and deposition at smaller scales. Consistent paleogeographic reconstructions at a marginal sea scale considering the global, regional and local processes is yet to be derived, and this study presents an effort towards this goal. We present a high-resolution (0.01°×0.01°) paleogeographic reconstruction of the entire Baltic Sea and its coast for the Holocene period by combining eustatic sea-level change, glacio-isostatic movement, and sediment deposition. Our results are validated by comparison with field-based reconstructions of RSL and successfully reproduce the connection/disconnection between the Baltic Sea and the North Sea during the transitions between lake and sea phases. A consistent map of Holocene sediment thickness in the Baltic Sea has been generated, which shows that relatively thick Holocene sediment deposits (up to 36 m) are located in the southern and central parts of the Baltic Sea, corresponding to depressions of sub-basins including the Arkona Basin, the Bornholm Basin as well as the Eastern and Western Gotland Basins. In addition, some shallower coastal areas in the southern Baltic Sea also host locally confined deposits with thickness larger than 20 m and are mostly associated with alongshore sediment transport and formation of spits and barrier islands and spits. In contrast to the southern Baltic Sea, the Holocene sediment thickness in the northern Baltic Sea is relatively thin and mostly less than 6 m. Morphological evolution of the Baltic Sea and its coastline is featured by two distinct patterns. In the north-eastern part, change of the coastline and offshore morphology is dominated by regression caused by post-glacial rebound that outpaces the eustatic sea level rise, and the influence of sediment transport is very minor, whereas a transgression together with active sediment erosion, transport and deposition have constantly shaped the coastline and the offshore morphology in the south-eastern part, leading to formation of a wide variety of coastal landscapes and seascapes such as barrier islands, spits and lagoons.

1. Introduction

The majority of the Earth's coasts and shelf seas are experiencing dramatic morphological changes as a result of joint effects of natural processes and anthropogenic activities (Mentaschi et al., 2018). Coasts of marginal seas composed of erodible soft material (sands, mud and moraine) are most variable in this context (Harff et al. 2017; Luijendijk et al., 2018; Hulskamp et al., 2023). At short time scales, their morphology is constantly reshaped by atmospheric and oceanic forcing such as winds, tides and waves, and human interventions (Zhang et al., 2011a; Mentaschi et al., 2018; Weisse et al., 2021). At longer time scales, climate change-induced oscillations of sea level, ice-cover/retreat, isostatic-/ ttectonic movements and variations in sediment supply from coastal erosion as well as riverine transport, exert a major control on morphological development of marginal seas (Zhang and Arlinghaus, 2022). In the forthcoming centuries, relative sea-level rise will increasingly influence coastal morphological change and challenge the defencedefense of coastlines. Sustainable management of marginal seas therefore requires a thorough understanding of the past and future morphological trends of evolution (Hulskamp et al., 2023). Management strategies need to consider the "geo-environmental" change in the past and future to separate natural and anthropogenic driving forces (Neumann et al., 2015) and understand their interplay. Learning from paleo-geomorphological history, particularly the post glacial period, will help to understand the coastal change in future (Harff et al., 2017).

Paleogeographic evolution of marginal seas is strongly associated with global and regional driving forces. Global climatically Climatically controlled eustatic changes (Gale et al., 2002; Berra et al., 2010) interplay with regional settings such as tectonics (Watts 1982; Vött 2007), isostasy (Peltier 1999, 2007; Lambeck et al., 2010, Spada et al., 2012) or even local factors like sediment availability and dynamics (Einsele 1996). Combination of these overlapping forces influences the relative sea level and may lead to significantly different coastal behaviours in various sections of marginal seas due to spatial heterogeneity of described forces intensity (Rosentau et al., 2021).

Most paleogeographic reconstructions of marginal seas are based on a reversal of relative sea level composed of eustatic sea level change plus tectonic and glacio-isostatic crustal effects (Uehara et al., 2006; Harff et al., 2007; Yao et al., 2009; Sturt et al., 2013). A few studies have additionally incorporated sediment relocations based on empirical interpolation functions techniques and information from dated sediment cores, but are limited to local areas (Zhang et al., 2014; Xiong et al., 2020; Karle et al., 2021). This study presents a high-resolution numerical paleogeographic reconstruction of the entire Baltic Sea and its coasts for the Holocene period as a set of paleo-Digital Elevation Models, by taking into account not only eustatic sea-level change and glacio-isostatic movement but also sediment dynamicsdeposition., covering dynamic processes including sediment transport, deposition and erosion. As such, this work represents a further step for comprehensive paleogeographic reconstruction of marginal seas resolving spatial heterogeneity of driving forces across multi-scales. Our motivation is twofold: first to depict the morphological evolution of a complex marginal sea system in response to the impact of climate change and oceanic sedimentation; second, to provide a sediment budget analysis of the marginal sea for the

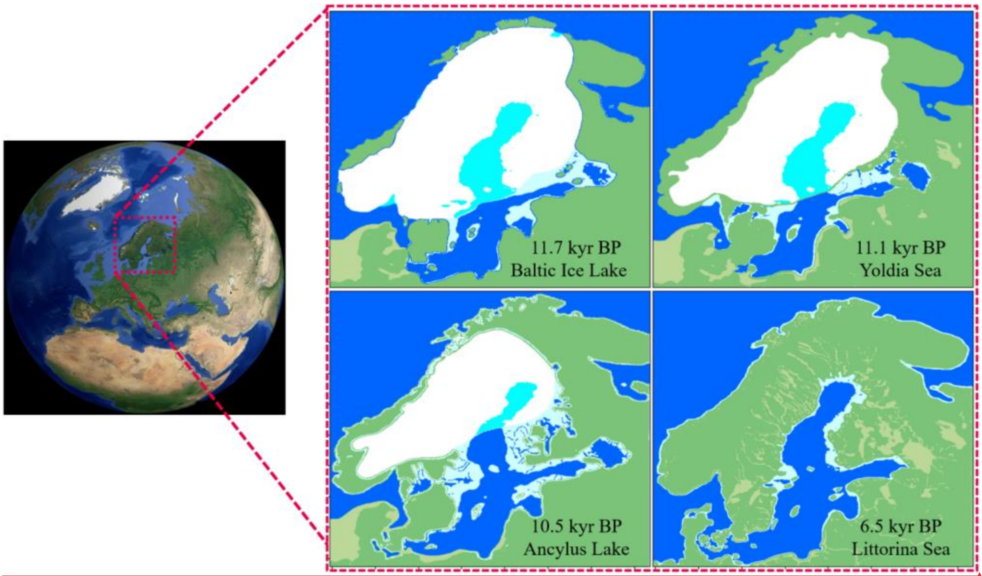
Holocene period and compare with present-day sediment fluxes from land to the sea ~~in order to~~to disentangle natural and anthropogenic impacts.

2. Geological setting

The Baltic Sea is a semi-enclosed intra-continental marginal sea, connected with the North Sea through the Danish Straits ~~and the Swedish Sound~~ (Rosentau et al., 2017). In terms of regional tectonics, the Baltic Sea Basin bridges between the Eastern European Platform Craton (EEC) consisting of~~with~~ the Fennoscandian (Baltic) Shield (BS) in the northeast~~NorthE~~ and the Russian East European Platforme (EEP) in the southeast~~SouthE~~ and the ~~CentralWestern~~Central Western European Platform Basin System in the ~~SW~~southwest (Maystrenko et al., 2008). The Eastern and Western European Platform~~EEC and CEBS~~ are separated by the deep NW-SE striking tectonic fault system of the Tornquist-Teisseyre Zone (TTZ) and its northwestern prolongation, the Sorgenfrei-Tornquist Zone (STZ) (Uścinowicz 2014).~~In terms of regional tectonics, the Baltic Sea Basin bridges between the Eastern European Platform consisting of the Fennoscandian (Baltic) Shield in the NE and the Russian Plate in the SE and the Western European Platform in the SW. Eastern and Western European Platform are separated by the deep NW-SE striking tectonic fault system of the Tornquist-Teisseyre Zone (TTZ) and its northwestern prolongation, the Sorgenfrei-Tornquist Zone (STZ) (Uścinowicz 2014).~~ Northeast of this zone, Precambrian crystalline rocks of the Baltic Shield and undeformed Phanerozoic sediments of the Russian Plate EEP on Precambrian basement form the coastal frame of the Baltic Sea. West of the TTZ, the Central Caledonides and Variscides together form the deep sedimentary basin of the Central European Depression ~~CEBS~~ filled mainly with Paleozoic and Mesozoic deposits on a basement at depth of up to depth of 10-15 km (Uścinowicz 2014).~~Northeast of this zone, Precambrian crystalline rocks of the Baltic Shield and undeformed Phanerozoic sediments of the Russian Plate on Precambrian basement form the coastal frame of the Baltic Sea. West of the TTZ, the Central Caledonides and Variscides together form the deep sedimentary basin of the Central European Depression filled mainly with Mesozoic deposits on a basement at depth of 10-15 km (Uścinowicz 2014).~~ The lowlands are mainly covered by Pleistocene sediments consisting of glacial, glacio-fluviatile and lacustrine deposits. The Holocene sediment is represented by coastal, lacustrine and brackish marine deposits (Rosentau et al., 2017). Glaciers have shaped the surface of the mainland surrounding the Baltic Sea, as well as the Baltic Sea Basin itself (with an average water depth of 55 m) where they formed a series of sub-basins separated by shallower sills (Hall and van Böckel 2020). The Danish Straits ~~and the Sound~~ connect the Baltic Sea ~~permanently~~ with the North Sea through the Kattegat. Humid climate and a positive water balance promote~~serve for~~ an estuarine circulation and a stratified water body with remarkable vertical and horizontal differences in salinity, density, and temperature in the present-day Baltic Sea ~~of the water body~~ (Matthäus and Franck, 1992; Wulff et al., 1990).

Advance and retreat of ~~inland ice~~glacier during the Quaternary glacial cycles have caused a change of isostatic loading and unloading of the Baltic Basin's crust leading to a cyclicity in vertical crustal movement correlated to the climate cycles. The relationship between the vertical crustal movement and the sea-level change determines the hydrographic communication between~~of~~ the open North S~~s~~ea and the ~~inner~~ Baltic Basin. ~~If the land uplift exceeds the rise in sea level, this means that the basin is closed off, while land subsidence exceeding sea-level drop leads to the connection of the open sea with the basin.~~ The ~~gates between these~~parts connecting the Baltic Basin and the North Sea ~~basins~~ thus ~~take on an~~serve a function of “gate” ~~isostatic/hydrograph~~that is opened or closed by eustacy-isostacy-ice interaction.~~ically controlled “gate function”.~~ Correspondingly, the paleogeographic history of the Baltic Basin during the Quaternary was ruled mainly by the glacial cycles following the Milankovitch cyclicity.~~–~~ However, because of the erosional effects of the ~~several times~~ advancing ~~inland ice~~ice sheet, sediments reflecting the geological history by proxy-data ~~the geological history~~ remained ~~just~~ scarcely from the ~~post~~pre-glacial period. Andrén et al. (2011) have depicted this postglacial history based on ~~the~~ interpretation of proxy data~~,~~ ~~such as~~including basin sediments and markers of paleo-coastlines by a set of~~n~~ paleogeographic maps (Fig. 1) which are used ~~here~~ in our study for ~~plausibility checks~~qualitative assessment of the results achieved by numerical modeling.

The evolution of the Baltic Sea since the Last Glacial Maximum ~~(Fig.1)~~ is characterized by ~~shift events~~shifts between fresh water and marine sedimentary environments ~~driven by an interplay of eustatic and glacio-isostatic forces~~ (Andrén~~Andren~~ et al., 2011). Starting from 16 kyr BP the Baltic Ice Lake (BIL) was formed in front of the retreating ice sheet filled with glacial melt water. Initially the water level in the lake was similar to global sea level and the melt water discharged to the Baltic Basin was flowing through ~~the~~ t~~T~~he ~~Öresund Sound~~ straights into the North Sea. The ~~drainage~~ connection was ~~has~~ however ceased due to glacio-isostatic uplift of ~~the~~ ~~T~~the ~~Öresund Sound~~straights area at around 14 kyr BP (Björck, 2008). Another ~~drainage~~ re-connection ~~event~~ occurred at ~13 kyr BP via the Central Swedish Lowlands as a result of rising water level caused by meltwater discharge to the BIL, ~~although~~ but was interrupted by ~~ca. 12.8 kyr BP~~ a short cooling phase of the Younger Dryas at ca. 12.8 kyr BP that caused glacial re-advance ~~and interrupted the water exchange between the Baltic Basin and the Paleo-North Sea~~ (Björck, 1995). As the influence of the isostatic uplift ~~rate~~ of the Baltic Shield ~~was generally exceeding~~ prevails~~the sea-level rise~~, the Baltic Basin remained disconnected from the ~~Paleo-~~North Seas (Fig. 1~~a~~) ~~so that the Ice Lake stage lasted~~ until the late stage of the BIL~~beginning of Holocene 11.7 kyr BP (Jakobsson et al., 2007)~~. ~~Inland ice~~Glacier retreat and global sea-level rise re-opened the gate connecting the Baltic Basin and the ~~Paleo-~~North Sea ~~Basin and~~ via the Central Swedish Lowlands (Fig. 1~~b~~), initiating the brackish~~-marine~~ Yoldia Sea stage at ~11.7 kyr BP (Heinsalu and Veski, 2007). ~~At~~ At ~10.7 kyr BP, isostatic uplift ~~,~~ again ~~surpassing the eustatic rise,~~ re-closed the gate of the Swedish Depression (Fig. 1~~c~~)~~,~~ and the Baltic Basin turned ~~again~~ to a freshwater (lake) environment again (Sohlenius et al., 2001). The initial ~~so-called~~ Ancylus Lake stage was characterized by a ~~continuously~~ rising water level because of meltwater discharge from ~~inland ice~~ice sheet ~~remains~~ until ~~it reached its~~reaching a ~~maximum~~ peak at ~10.5 kyr BP. Afterward~~,~~ a~~to~~ decrease of the water level occurred ~~afterwards~~ because of a drainage ~~processes~~ to the ~~Paleo-~~North Sea (Lemke et al., 2001; Rosentau et al., ~~2014~~2013). The ~~global~~ climat~~iceally~~-controlled Holocene sea-level rise in connection with the ~~collapsing~~ deforming lithospheric bulge surrounding the Baltic Shield re-opened the gate at the straights leading to the ~~pathway of the~~ Littorina Transgression starting at ~8.0 kyr BP~~-~~ ~~that connected the Baltic Basin permanently to the North Seas~~ (Fig. 1~~d~~). Since then, the water level in the Baltic Sea~~–~~ has been aligned with the sea level in the open North Sea until present day.



Formatted: Normal (Web), Line spacing: single

Formatted: Font: (Default) Times New Roman, 12 pt

Figure 1: Location of the Baltic Sea (© Google Earth Pro) and paleogeographic maps (modified after Andrén et al., 2011) representing different Holocene stages of the Baltic Sea ~~(modified after Andrén et al. (2011),~~ including ~~: namely~~ the Baltic Ice Lake ~~(just prior to the final drainage~~/Yoldia Sea transition~~)~~ at 11.7 kyr BP, the Yoldia Sea (end of the brackish phase) at 11.1 kyr BP, the Ancylus Lake (~~transgression~~ maximum transgression) at 10.5 kyr BP, and the Littorina Sea (most saline phase) at 6.5 kyr BP. Ice cover is shown by the mask in white, blue color stands for water, cyan corresponds to present-day water, green marks the land, whereas olive marks ~~past~~ land in the past.~~.~~

3. Data and methods

The main target of this study i~~wa~~s the generation of a set of paleo-~~Digital~~ digital ~~Elevation~~ elevation ~~Models~~ models (paleo-DEMs) corresponding to a high spatio-temporal resolution (~~-resolution, in both time~~ (500 years spacing) ~~and space~~ ~~(~~0.01 ×~~x~~ 0.01 degree and 500-years interval ~~resolution~~)~~,~~ reconstruction~~s~~ ~~of stages of~~of the Baltic Sea evolution during the Holocene. Such reconstruction~~s~~ play~~s~~ a critical role for the purpose of basin analysis (Allen and Allen, 2008), ~~leading to~~

visualisationvisualization of the past states of the basinmarginal seas (Xiong et al., 2020), morphogenetic interpretation (Miluch et al., 2021, Miluch et al., 2022) as well as hydro-morphodynamic modeling of circulation and sediment transport systems (Zhang et al., 2020). For the purpose ofSince investigation of the Baltic Sea basin evolution, the key factors are: eustatic sea level variations, isostatic vertical crust movements and sediment budget (Harff et al., 2007; Yao et al., 2009; Eq 1). As the study involves reconstruction of the Baltic Sea basin our reconstruction covers onlyfor a relatively short geological time span, i.e. from the beginning initial stage of the Holocene (11.7 kyr BP) till present day, the key influencing factors considered include eustatic sea level change, isostatic vertical crust movements and sediment deposition. Oother factorsvariables such as sediment compaction which play a secondary role atin such time scale (Schmedemann et al., 2008) and therefore are neglected here. The conceptual equations (simplified compared tofollowing Harff et al., (2017) eq. (1) and eq. (2) below wereas applied to generate the paleo-DEMs for anyalong a time span Δt extending from specific a time instant t during the Holocene with reference history of the basin to final time instantpresent day (t = 0) (standing for present time):The conceptual equations (Harff et al., 2017) below were applied to generate the paleo-DEMs:

$$DEM_t = DEM_0 - \Delta RSL + + \Delta SED, \quad (1)$$

where DEM_t is the Paleopaleo-digital elevation model at time t, DEM_0 is the present-day digital elevation modelDEM, ΔRSL is the relative sea-level change, and ΔSED is the change of sediment thickness by depositionaccumulation or erosion. referred to Δt. Integration of sediment thickness marks the major difference between our reconstruction and is a novelty in comparison to existing reconstructions and a step forward to improve the paleo-reconstruction metho.d.

The relative sea-level change ΔRSL is calculated is described in the following formulation following Harff et al. (2017) by neglecting minor effects by gravitational forcing and oceanographic fluctuations:

$$\Delta RSL = \Delta EC + \Delta GIA + \Delta SED, \quad (2)$$

where ΔEC is the global eustatic sea-level change corresponds to Δt current sea level EC_0, and ΔGIA refers to the Glacial Io-isostatic Isostatic Adjustment at time t with reference to present-day conditions referred to Δt.referred to current sea level EC_0, and ΔGIA refers to the Glacio-isostatic adjustment.

Expressions used in equations (1) and (2) stand for variables with values assigned to nodes of one and the same discrete georeferenced grid. After successful application of the conceptual equations in the South China Sea by Yao et al. (2009) and Xiong et al. (2020), we describe apply them for the first time its application to the Baltic Basin considering not only GIA and sediment accumulation but also differences in eustatic sea level and the water level in a regional basin following temporarily a separate regional hydrographic regime when it is disconnected from the open sea.

During the brackish-marine stages of the Baltic Sea, a 1:1 sea-level transfer functionthe sea level of the Baltic basin follows that of from the North Atlantic to the Baltic Sea basin is assumed. *EC* in these stages thus reflects the global (eustatic) sea level. in the entire study area (see Section 2, Geological-tectonic evolution of the Baltic Basin). When the Baltic Sea basin is decoupled from the World OceanDuring lake stages, *the variable EC* reflects the level of the relevant freshwater lake that fills the Baltic Sea basin and isis fed exclusively by precipitation and inlandprecipitation, inland ice's meltwater and rivers. In this case, *EC* in the areas of the "outer coast" ofcoast of Fennoscandia influenced by the North Sea,

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Highlight

Formatted: Font: Italic

Formatted: Font: Italic

~~Norwegian Sea and Barents Sea and~~ open ocean ~~must~~ is~~be~~ modeled separately from that in the ~~"inner"~~ Baltic ~~Sea (lake)~~ B~~b~~asin. ~~The border between the basins was set based on paleo-catchment areas.The Baltic Sea basin to be modeled is during the lake phases separated by watersheds on the surrounding mainland.~~

The ~~models were numerically handled and resulting maps~~reconstructed DEMs were plotted using Golden Software Surfer 18 program. The software allows to visualize surface relief with pre-defined spatial resolution (Bola and Kayode, 2014; Libina and Nikiforov, 2020), perform grid-on-grid mathematical operations (Liu et al., 2020) as well as interpolate the data (Gonet and Gonet, 2017; Razas et al., 2023; Yilmaz 2007), and therefore acts as a convenient, widely-used tool in basin analysis (Covington and Kenelly, 2018; ~~Grunt~~ Grund and Geiger, 2011). The general workflow for data collection, synthesis and interpretation is depicted in Fig. 2.

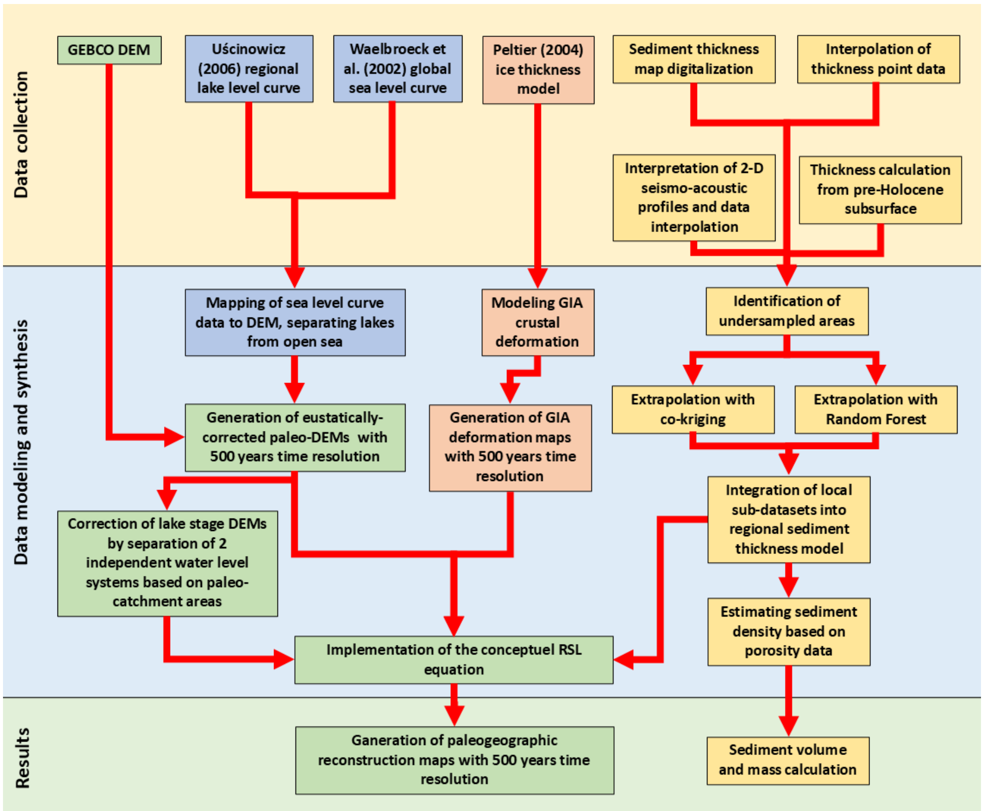


Figure 2: General workflow chart for data collection, synthesis and interpretation.

3.1. Digital Elevation Model (DEM_0)

The present day DEM_0 ~~initial grid~~ acting as a base for paleogeographic reconstruction was obtained from the Global Bathymetric Chart of the Ocean (~~Gebco~~GEBCO) (Sandwell et al., 2002; Becker et al., 2009). The DEM for the ~~From the present-day “amphibious” Digital Elevation Model (DEM_0), consisting of both bathymetric and onshore data (GEBCO, 2023),~~ Baltic Sea ~~basin~~ region ~~was extracted,~~ spans~~extending~~ from 9.5 to 31ºE in longitude and from 52 to 66.5ºN in latitude. The ~~initial~~ spatial resolution of the GEBCO grid ~~was diminished from~~is 15 arc seconds (0.004167° × ~~x~~ 0.004167°) and was interpolated to ourset to Baltic Sea grid (0.01° × 0.01°)0.01 degree. Maintaining original resolution was is unnecessary as other components of the conceptual paleogeographic modeling equation (eustatic and isostatic gradientscomponents) were characterized by significantly lower grid resolution. Such transformation had negligible influence on the quality of the generated maps, in parallel allowing to boost the map generation speed and save storage space.

3.2. Eustatic data (EC)

For the generation of the regional sea level curve, a dataset by Waelbroeck et al. (2002) was used as a base. However,– _adjustment to the regional paleogeographic setting is needed. The Baltic water level curve followed the Waelboeck et al. (2002) data for the brackish-marine stages, during which the Baltic water was connected with the North Sea , namely from– 11.7 kyr BP– _to 11 kyr BP (Yoldia Sea) and from 9.5 kyr BP tilluntil present day (Littorina Sea), respectively (AndrénAndren et al., 2011). Knowing that during the Ancylus Lake stage (11 to 9.5 kyr BP) the water (lake) level in the Baltic basins water was generally higher than that in the open global ocean due to blocked outflow routes, a local sea water level dataset of the southern Baltic region by from Uścinowicz (2006) was applied to adjust the curve correspondingly. Even though the local relative sea level curves areis strongly influenced by the Glacio-Isostatic Adjustment (AndrénAndren et al., 2002, 2011; Groh et al., 2017; Rosentau et al., 2012, 2021; Harff et al., 2017), the southern Baltic region is located near the isostaticalllyisostatically neutral hinge-line between uplift in the north and subsidence in the south of it (Statteger and Leszczyńska, 2023). Therefore glacio-isostatic adjustment rate played a minor role in estimation of the relative lake water level curve in the southern Baltic region. Such feature allowed to incorporate sea level values of the Ancylus Lake from Uścinowicz (2006) as “eustatic component” into the RSL conceptual equation (eEq. (2)). Moreover, lake phase of the Baltic region water required a subdivision intorefers to two independent water level systems, one for the: Ancylus Lake and the other for the North Sea separated by closed Danish Straits. The border between these two water bodies was set based on the paleo-catchment areas obtained using “Terrain Aspect” function in the Golden Software Surfer (Golden Software Surfer) on previously generated paleo-DEMs. In the lake phase, the eustatic water level in the Baltic basin followed the curve in Uścinowicz (2006) curve, whereas in the North Sea it followed the curve in Waelbroeck et al. (2002). Fig. 3 depicts the merged sea-/water- level curve for the Baltic Basin during the Holocene.These two curves are shown in Fig.3.

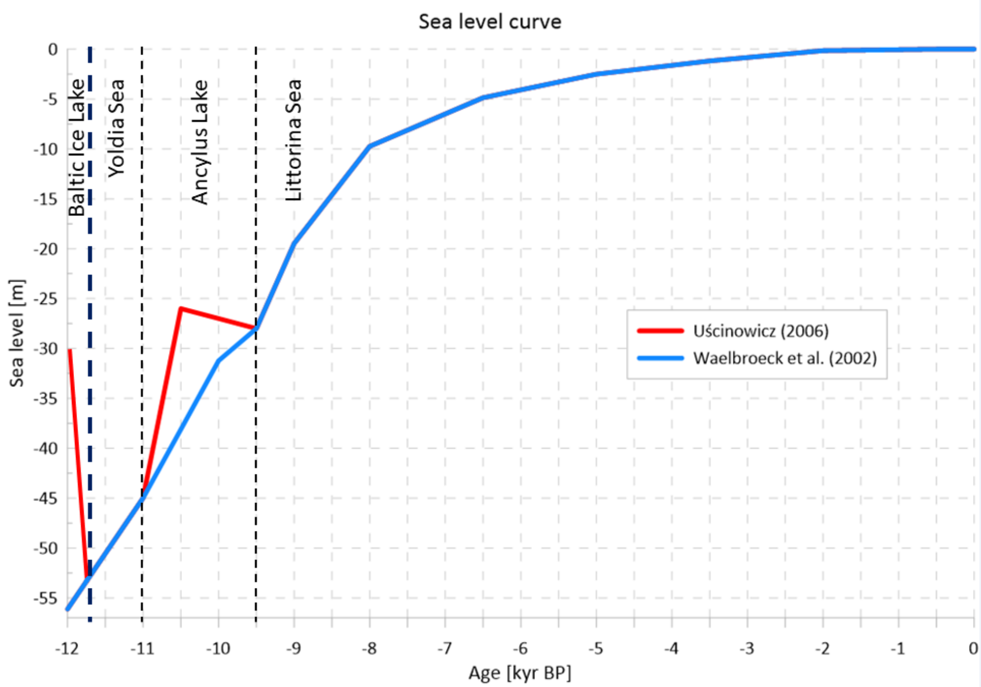


Figure 3: Holocene water level curve for the Baltic region generated by combination of Waelbroeck et al. (2002) and Uścinowicz (2006).

3.3. Vertical crustal movements - Glacio-Isostatic Adjustment (GIA) including paleo-ice-thickness model

The solid Earth's response to the changing surface loads of the vanishing Pleistocene ice sheets is known as glacial isostatic adjustment (GIA). This visco-elastic response comprises an instantaneous elastic and a delayed viscous component. GIA manifests in terms of deformations of the Earth's crust, changes in relative sea-level, i.e. sea level with respect to the Earth's deformable crust, and changes in gravitational potential (e.g. Peltier, 1998). The later originates from the redistribution surface masses, i.e. the melting of ice masses and the fresh water consequently added to the ocean, as well as from material in the Earth's mantle relocated as a reaction to the changing surface loads.

The decreased stress on the Earth's crust induced by the melting of the Laurentian Ice Sheet after last glacial maximum (LGM) about 21 kyr BP, caused a crustal deformation which is still ongoing at present (Root et al., 2015). The crust is uplifting in regions formerly covered by the ice load. Crustal subsidence can be observed in regions surrounding the former ice cover known as the peripheral bulge (Steffen and Wu., 2011). This subsidence originates from the relocation of mantle material back to its original location in the Earth's interior underneath the region formerly covered by the ice load (Vink et al., 2007). The crustal uplift is partly compensated by the additional water load stemming from the fresh-water influx. However, the melt water is unevenly distributed over the ocean according to the changing gravitational potential caused by the varying distribution of ice masses as well as by the water masses themselves. Thus, close to the melting ice sheets, a drop in relative sea-level can be observed due to both the decreasing gravitational attraction of the ice and the uplifting crust.

The complex interaction between changing ice and water loads, their gravitational potential as well as the induced crustal deformations is described in a gravitational self-consistent way by the sea-level equation (e.g., Farrell and Clark, 1976; Peltier, 1998). To solve the sea-level equation and in order to model the GIA-induced vertical crustal deformation we make use used the freely available software package SELEN (Spada and Stocchi, 2007). This software makes use of the ICE-5G ice load history (Peltier, 2004) to describe the spatio-temporal evolution of the ice sheets from LGM until present day at a temporal resolution of 1 kyr. A time interval of 500 years resolution required for this study was achieved by assuming thea linear trend between millenialeach millennium-step scenarios. Figure 4 depicts the ice thickness at LGM (21 kyr BP) according to the ICE-5G load history as implemented by the SELEN software package. Cumulated crustal deformations are modelled starting from an equilibrium state at LGM. Details of the applied model set-up are provided in Groh and Harff (2023). The initial resolution of The resultant GIA dataset was interpolated 0.5 x 0.5 degree and was manually transformed into our 0.01° × 0.01° grid. 0.01 x 0.01 degree cell size.

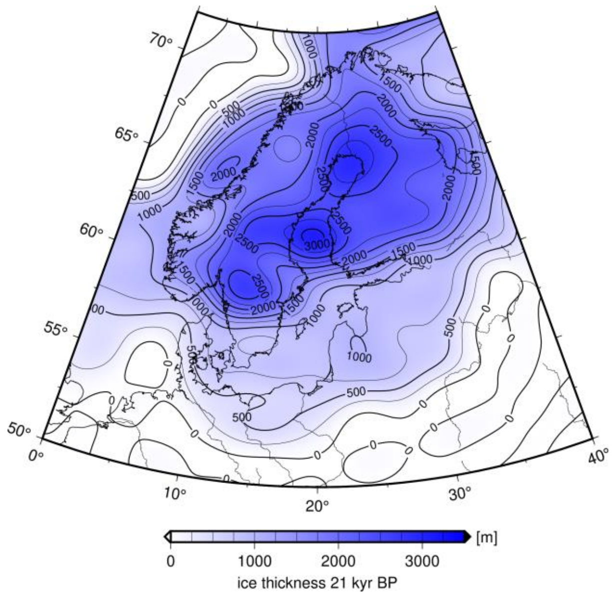


Figure 4. Present-day coastline and ice thickness at the Last Glacial Maximum (21 kyr BP) according to the ICE-5G ice load history (Peltier, 2004) as implemented by the software package of Spada and Stocchi (2007) after synthesising its spherical harmonic representation to space domain.

3.4. Sediment thickness (SED)

The Baltic Sea Basin is administrated by nine countries: Denmark, Germany, Poland, Sweden, Lithuania, Latvia, Estonia, Finland and Russia. Due to a fact that no joint Holocene sediment thickness database is available, it is necessary to identify and merge various~~the~~ existing local~~-scale~~ datasets from ~~various national or~~ publicly available sources. ~~In order to~~To generate a consistent regional sediment thickness model, eight local datasets were synthesized (~~see locations at~~ Fig. 5). These sub-datasets were derived by six methods of data acquisition, including~~:~~ digitalization of isopach maps~~ digitalization~~, recalculation of thickness from seismic reflector depth maps ~~Holocene bottom depth maps~~, interpretation of 2-D seismo-acoustic profiles and data interpolation with ordinary kriging, interpolation with ordinary kriging of point data from sediment cores, extrapolation using co-kriging, and extrapolation using convolutional neural network~~ machine learning method~~. ~~The areas with corresponding data acquisition methods are shown in Fig.5.~~ All ~~the~~ sub-datasets ~~are~~ were ~~characterized by~~produced at 0.01° × 0.01° resolution~~0.01 x 0.01 degree spatial resolution~~.

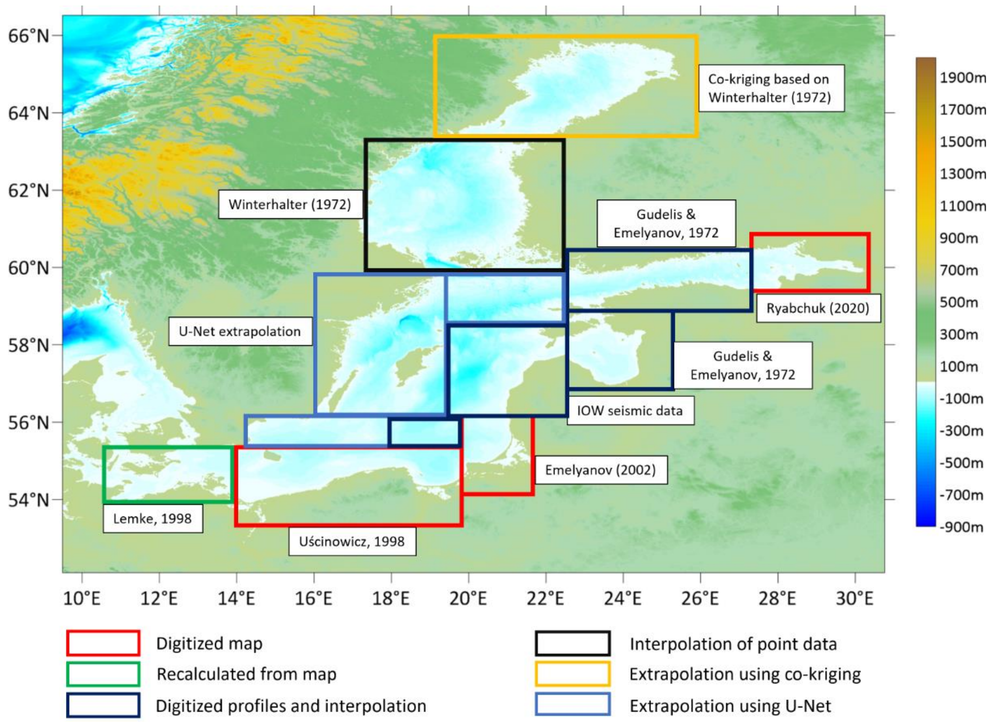


Figure 5:~~–~~ Map marking different types of data sources with ~~references for acquisition~~generation of sediment thickness sub-datasets ~~collected by:~~by digitalization of published Holocene ~~thickness~~ isopach maps (red), recalculation of thickness from seismic reflector depth maps (green), digitalization of profiles and data interpolation (dark blue), interpolation of point data (black)~~;~~ as well as ~~areas with data derived from~~ extrapolation using co-kriging (yellow) and convolutional neural network ~~machine learning~~ (bright blue).

Formatted: Font: Not Bold

3.4.1. Southern Baltic region

The southern Baltic Sea area consists of German, Danish, Polish, Russian (Kaliningrad area) and Lithuanian coastal waters ~~EEZs~~ and is characterized by ~~significant~~ well-~~investigated~~documented Holocene sediment thickness data ~~and~~ with satisfactory ~~data~~ quality. The sediment thickness model was generated as a result of merging three local-scale ~~grids~~datasets. The German and Danish parts were covered by data derived from Lemke (1998). ~~Maps representing the~~

~~depth~~The depth of the top layer of glacial till ~~were assumed to~~ corresponds to the Pleistocene basement, which~~.~~ ~~This gridded dataset~~ was ~~thus “~~subtracted” from the present-day ~~bathymetry (GEBCO, 2023)~~DEM in order to estimate the Holocene sediment thickness. The sediment thickness ~~model~~ data for the Polish waters was provided by Uścinowicz (1998), whereas data for the Russian (Kaliningrad area) and Lithuanian territories were~~as~~ retrieved from Emelyanov (2002). Due to slight differences in thickness values on the border between these two datasets, the values at the grid junction were averaged.

3.4.2. Central Baltic region

The central Baltic (Bornholm Basin, East Gotland Basin, and its surroundings) Holocene thickness grids were retrieved from 2-D seismo-acoustic profiles collected by Leibniz-Institute for Baltic Sea Research Warnemünde (IOW), Germany (courtesy of Dr. Peter Feldens). In ~~overall~~total 240 seismic lines, collected between 2005 and 2009, were investigated. The Holocene basement corresponds mostly to the top of glacial till (Late Pleistocene age, non-stratified seismic facies). The t~~T~~op of glacial till i~~wa~~s a well-visible seismic reflector on most ~~of~~ profiles, whereas the boundary~~order~~ between the ~~Baltic Ice Lake~~BIL and the Yoldia Sea ~~was in several cases~~ is difficult~~hard~~ to discern in some profiles~~etermine~~. ~~Due to fact that~~Since the BIL~~L sediment~~ ~~chronostratigraphically~~ belongs to the l~~L~~ate Pleistocene, the ~~modelled~~ thickness for the Holocene sediment may be slightly overestimated in these profiles. Maximum local thickness of BIL sediments up to 7 m ~~in the deepest part~~is found in the deepest parts of the basins ~~may reach 7m (Christiansen et al., 2002)~~ and diminishes towards the shallower areas ~~,~~according to Christiansen et al. (2002)~~where the unit is hard to follow~~. Therefore, our estimated thickness of the Holocene sediment might be~~have been~~ overestimated by ~20% in the deepest part of the basins, with~~only,~~ the uncertainty decreasing~~and~~ towards~~very little on~~ the ~~slopes and~~ shallower areas. ~~as well as to bottom of glacial varved sediments (Baltic Ice Lake – early Holocene age, stratified seismic facies).~~ The seismic reflector corresponding to the pre-Holocene basement was exported as depth data points (= shot points), transformed~~recalculated~~ from the two-way travel time to metric units assuming a sound velocity in sediment of~~to~~ 1600 m/s, and further interpolated using ordinary kriging ~~(Wackernagel and Wackernagel, 2003)~~ with nugget effect (Wackernagel and Wackernagel, 2003). The o~~O~~btained basement subsurface depth ~~grid data~~data were subtracted from ~~GEBCO bathymetry (GEBCO, 2023)~~the present-day DEM ~~in order~~ to generate the Holocene sediment thickness model.

3.4.3. Eastern Baltic region

Holocene sediment thickness data ~~grid~~ of the Gulf of Riga as well as of the Gulf of Finland was generated based on profiles provided by Gudelis and Emelyanov (1976). ~~Subdatasets~~Sub-datasets consisted of 5 N-S oriented profiles connecting edges of Gulf of Finland and 6 profiles (4 NW-SE, 1 N-S, 1 W-E oriented) across the Gulf o~~d~~f Riga. The reflector corresponding to the top of glacial till was digitized and exported as ~~data~~ point data~~s~~, and then interpolated using ordinary kriging with nugget effect ~~,~~ and subtracted from the present-day DEM. ~~GEBCO bathymetry (GEBCO, 2023).~~

Thickness data ~~grid~~ covering the Russian part of the Gulf of Finland ~~was~~ were derived from ~~the~~ a digitized sediment thickness map by Ryabchuk et al. (2020).

3.4.4. Northern Baltic region

Holocene thickness data in the northern Baltic region is ~~generally~~ scarce because the area is under-sampled. A mean post-glacial thickness dataset by Winterhalter (1972)~~,~~ consisting of ~~several~~ 72 polygons (0.5° × 0.5° resolution~~0.5 x 0,5 degree size~~)~~,~~ located in the Bothnia Sea ~~and representing mean post-glacial thickness~~ served as a base for interpolation. The central point of each polygon was exported as a data point and then ~~modelled~~ interpolated using ordinary kriging. To ~~solve the problem caused by~~fill the data gap in the severely under-sampled northern part of the~~most~~ Bothnian Bay, data points of thickness from Winterhalter (1972) were used for extrapolation by co-kriging (Goovaerts, 1998; Myers 1982, 1984). The co-kriging extrapolation method is commonly used in ~~environmental science, geology, and other fields~~geoscience for areas where correlated measurements of multivariate variables are available (Belkhiri et al. 2020; Leenaers et al. 2020; Konomi et al., 2023). In the northern Baltic region~~case~~, a two-dimensional variable consisting of a GIA-corrected paleo-bathymetry and thickness of Holocene sediments was used. Parameters of the corresponding semi-co-~~veriogram~~variogram were determined using those grid nodes where data of both variables were available. These parameters allowed a co-kriging estimation of thickness data northward for undersampled areas.

3.4.5. Filling of data gaps

Machine learning was applied to fill the remaining gaps in the Holocene sediment thickness data. The areas with data gaps mainly include the central western part of the Baltic Sea (see Fig. 5). A convolutional neural network (CNN), namely a *U-Net* (Ronneberger et al., 2015) was build using *PyTorch* (Paszke et al., 2019). *U-Net*s have been proven to be a robust and versatile tool for image and data analysis (Zhang et al., 2018; Liu et al., 2020) and are superior to pixel-based methods such as random forest (Boston et al., 2022). In this study four variables, namely the paleo-land-surface morphology, the median grain size of surface sediments and longitude and latitude values were used to predict sediment thickness. The reason for adding the latter two variables is their relationship with the GIA (Fig.4). The available data were randomly cut into 420 squares of 32×32 pixels size, excluding the Gulf of Finland and the Gulf of Bothnia. The reason for excluding the two regions is because they differ substantially in geological, tectonic, and depositional environment from the central, south, and southwest parts of the Baltic Sea (Harff et al., 2017). This helps to reduce the error in the predictions. In the 420 sub-datasets, 80% were used for model training and 20% for assessment of the model prediction. The input of the *U-Net* has the shape (32, 32, 4) and the output shape is (32, 32). The first layer consists of a double convolutional block performing 3×3 convolution with 64 output channels, padding, batch normalization and ReLU activation. The training was performed with 100 epochs and the mean squared error (MSE) was calculated as the loss function (*torch.nn.MSEloss*). Re-running the model with different random initializations and dropout yields different model results with the same general pattern but some local differences in sediment thickness. The result with the smallest value of MSE (6.1 m²) was chosen (Fig.6). This corresponds to an average deviation from the validation to the measured data of 5.8%.

3.4.6. Integration of ~~Merging thickness grids~~sub-datasets

Each local Holocene thickness ~~grid~~ sub-dataset was ~~unified to identical resolution of 0.01×0.01 degree and merged~~ integrated ~~in~~to one consistent regional grid with resolution of 0.01° × 0.01°. ~~In case of~~ ~~S~~small spatial gaps between the sub-datasets the thickness ~~was~~ were linearly interpolated. In case of dataset not covering the coastline, the solution proposed by Miluch et al. (2021) was used by setting equidistant pinpoints characterized by 0-thickness value along the coastlines and included into the dataset. Such solution allowed to linearly extrapolate the thickness data between the grid points and the coastline ~~in order to~~to completely close the remaining data gaps. It is worth to note that the synthesized sediment thickness dataset does not cover the present-day land parts except for barrier islands that have been developed during the Holocene. Details on the ~~primary~~ data ~~type~~source, ~~and~~ density~~density~~ as well as interpolation and extrapolation~~gridding~~ techniques are listed in Table 1.

Table 1: List of ~~all sediment thickness~~ sub-datasets of Holocene sediment thickness with ~~details~~ information on gridding techniques as well as primary data type and density.

Area	Sub-dataset	Gridding technique	Primary data type and data density
SW Baltic region	Lemke (1998)	Recalculation and digitalization of map	Isopach m~~M~~ap generated based on shallow seismic profiles (no. >300) and sediment cores (no. >250)
S Baltic region	Uścinowicz~~,~~ (1998)	Digitalization of map	Isopach ~~M~~map based on shallow seismic profiles and sediment cores
SE Baltic region	Emelyanov~~,~~ (2002)	Digitalization of map	Isopach m~~M~~ap based on shallow seismic profiles and sediment cores
Gulf of Riga	Gudelis and Emelyanov (~~,~~ 1972)	Digitalization of cross-sections, ~~then~~ ordinary kriging	6 seismic ~~profile~~lines

Formatted Table

Gulf of Finland	Gudelis and Emelyanov~~,~~ (1972)	Digitalization of cross-sections, ~~then~~ ordinary kriging	5 seismic lines~~profiles~~
East Gotland Basin	IOW seismic data	Seismic data interpretation, ~~then~~ ordinary kriging	240 seismic lines
E Gulf of Finland	Ryabchuk~~,~~ (2020)	Digitalization of map	Isopach map based on shallow seismic profiles and sediment cores ~~Map~~
S Bothnian Bay	Winterhalter~~,~~ (1972)	O~~Interpolation of point data with o~~rdinary kriging	72 data points
N Bothnian Bay	~~Extrapolation after~~ Winterhalter~~,~~ (1972)	Extrapolation with co-cringing	Not available~~-~~
W Baltic, N Baltic Proper	Extrapolation to undersampled areas	Extrapolation with U-Net	Not available~~-~~

3.5. Sediment budget analysis

Generation of thickness map allows~~ed~~ to perform sediment budget analysis that~~, being detailed analysis regarding~~helps identify sediment sources, sinks and transport pathways. ~~First, the~~The grid was transformed from the geographic coordinate system to UTM projection ~~in order to~~to conduct volume calculation~~ scaled in metric units~~. Applied volume calculation algorithms include the trapezoidal rule, the Simpson's rule and the Simpson's 3/8 rule (Atkinson, 1989). Each method approximates different 3-D connection shapes between the data points, which slightly influences the calculated volume. Results from the~~ each~~ algorithms wereas~~as~~ compared to assess the uncertainty. Sediment mass ~~modeling~~ calculation requires ~~requir~~information of~~ed taking into account~~ sediment bulk density~~,~~ that is~~being~~ related to~~correlated with~~ sediment particle density and porosity. Surface sediment porosity was calculated based on the present-day sediment grain size map of the Baltic Sea derived from the project DYNAS (Dynamics of ~~natural~~ Natural and A~~a~~nthropogenic S~~s~~edimentation) (Bobertz et al., 2009; Harff et al., 2011) and application of the empirical formula from Endler et al. (2015) to link porosity to the median grain size. Knowing that compaction rates of sandy and silty sediments is neglectable at a thickness scale of meter (Schmedemann et al., 2008), constant vertical porosity depending on the local grain size was assumed for the Holocene deposit. Pores volume was subtracted from the general volume. Knowing that Baltic Sea sediments are mainly clastic (Anthony et al., 2009), quartz density = 2.65 g/cm^3 ~~(Anthony et al., 2009)~~ was ~~assumed to correspond to hypothetical 0%-porosity~~used as the particle density~~sediment~~. ~~Combining modelled grid-based volume and sediment density led to estimation~~

~~of the~~With the ~~overall~~gridded data of porosity and sediment thickness and a constant particle density, the overall mass of the Baltic Sea Holocene sediments as well as annual rate of deposition averaged over the period are estimated.

3.6. Generation of paleogeographic maps

Having all the needed components described in Equation (1) and (2), namely the eustatic sea level change, the spatial distribution of the GIA and the sediment depositional thickness, the present-day DEM_0 was transformed into a set of paleo DEMs ~~geographic maps~~ for the Baltic Sea, mimicking the paleogeographic evolution of the region with fine ~~temporal~~ spatio-temporal resolution (Supplementary Materials). The thickness of sediment deposition for each time slice ($\Delta t = 500$ yrs) was subtracted from the total Holocene thickness assuming constant sediment accumulation rate.

4. Results

4.1. Holocene sediment thickness map

~~Combination~~ Integration of 8 local-scale sediment thickness datasets with~~and~~ ~~application of 3~~ extrapolation methods allowed to generate ~~the~~ a regional Holocene sediment thickness map (Fig. 6). Several sites characterized by high sediment thickness were identified in southern and central parts of the Baltic Sea, corresponding to depressions of sub-basins including the Arkona Basin, the Bornholm Basin as well as the Eastern and Western Gotland Basins. Maximum deposition thickness reaches up to 36 m in the Arkona Basin and the Eastern Gotland Basin. Although regions of enhanced sediment accumulation are usually located in deeper basins, some shallower coastal areas also host ~~locally-confined~~locally confined deposits with thickness larger than 20 m.~~–~~ These include the central sections of the Gulf of Finland, the Gulf of Riga (both coupled with local bathymetry, as reported by Jakobsson et al. (2019)) as well as the Gdańsk Basin. The thick Holocene deposit in the Gdańsk Basin is related to the formation of the Hel Peninsula that is driven by alongshore sediment transport (Uścinowicz, 2022). In contrast to the southern Baltic Sea, the Holocene sediment thickness in the northern Baltic Sea is relatively thin and mostly ~~less than~~within 6 m. Such feature may be related to the glacio-isostatic uplift resulting in a continuous reduction of accommodation space in the Bothnian Sea and the Bothnian Bay (Varela, 2015). The characteristics of seabed substrate of the northern Baltic Sea confirm the presence of glacial clay, hard bottom complexes and bedrocks covered by a thin layer of Holocene sand and gravel (Kaskela et al., 2012).

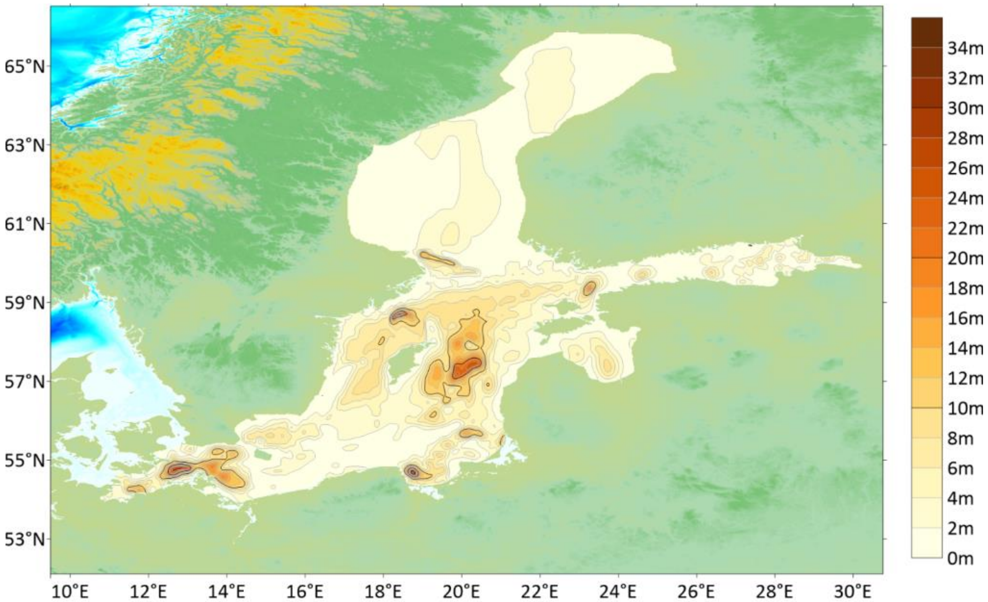


Figure 6: Regional Holocene thickness model derived from synthesis of 8 local sub-datasets and application of 3 extrapolation methods (Table 1).

4.2. Sediment budget

Sediment volume calculated using the trapezoidal rule, the Simpson's rule and the Simpson's 3/8 rule, respectively provided nearly identical results (<0.001% difference, see Supplementary MaterialsSupplement). The calculated total volume of Holocene sediment is 1.372×10^{12} m^3 in bulk. Subtracting the sediment porosity yields a zero-porosity sediment volume of 5.07×10^{11} m^3, corresponding to a a total Holocene sediment mass of 1.34×10^{12} t and an n annual sediment accumulation of 1.15×10^{8} t yr^{-1} (averaged over 11700 yrs) in the the present-day Baltic Sea.

Potential errors in the estimation may originate from several sources, including porosity, grain density, vertical compaction and unclear boundary between late Pleistocene and early Holocene in the seismic profiles. The standard deviation σ of porosity is ~0.15 according to the sediment samples analyzed by Endler et al. (2015). Applying the mean ± σ in the porosity data as the upper and lower estimates respectively indicates a range between 0.82×10^{12} t and 1.87×10^{12} t in the total sediment mass. Although the Holocene deposits mainly consist of silt and sand, the deeper basins (e.g. Arkona,

Formatted: Font: Not Bold

Formatted: Normal

Bornholm and Gotland) are covered by a layer of mixture of organic matter (up to 16%) and clay (Leipe et al., 2011) that is subjected to the impact of vertical compaction. The thickness of such layer can extend to several meters in the deep basins (Andrén et al., 2000; Ponomarenko, 2023). Assuming that the average thickness of this layer is 4 m (as indicated in a majority of sediment cores) in the basins, neglection of the vertical compaction results in an overestimation of the porosity by ~10% according to Schmedemann et al. (2008), corresponding to an underestimation of sediment mass of ~ 0.055×10^{12} t, which accounts for ~4% of the estimated mean total budget (1.34×10^{12} t). As described in section 3.4.2, unclear boundary between late Pleistocene and early Holocene sediment in the seismic profiles across the deep basins (e.g. the Gotland basin) may lead to overestimation of the Holocene sediment thickness by ~20% in the deepest part of the basins. The overestimation decreases toward shallower areas. A uniform overestimation of the deposition thickness in the basins by 20% corresponds to a sediment budget of 1.1×10^{11} t, which is ~8% of the estimated mean total budget (1.34×10^{12} t). In summary, considering the uncertainties related to the major identified sources mentioned above in the estimation yields a range of the total Holocene sediment budget between 0.81×10^{12} t and 1.82×10^{12} t, corresponding to annual sediment accumulation rate between 0.69×10^{8} t yr^{-1} and 1.56×10^{8} t yr^{-1}.

Formatted

4.3. Paleogeographic maps

A set of paleogeographic maps with a time interval of 500 years reflecting the evolution of the Baltic Sea region during the Holocene is provided in the Supplementary Materials, with maps for several periods marking a critical transition in the sea level change shown in Fig.7. To evaluate the paleogeographic maps, a reference is made to the widely used maps derived from proxy data interpretation (Fig. 1) produced by Andrén~~Andren~~ et al. (~~2010~~2011).

~~Starting A~~At ~11.7 kyr BP, a transition from the ~~Baltic Ice Lake (~~BIL~~)~~ to the Yoldia Sea stage occurred. At that time, a large part of the north of today's Baltic Sea basin was covered by the glaciers of the Fennoscandian Ice Sheet (FIS). The water level of the Baltic Ice Reservoir was dammed up to 25 m above the present-day sea level (Andrén~~Andren~~ et al., 2011) before the lake water made its way through the Central Swedish Depression in the southern border of the FIS and flowed into the paleo-North Sea basin in a drainage event ~~in the area of~~in today's Kattegat (Fig. 7a). Rising sea level outpacing the moderate uplift of the mainland in the immediate vicinity of south of the ice margin in the Central Swedish Depression sustained a free exchange of water through a gate between the Baltic Sea and the North Sea for several centuries that marks a brackish-marine phase ~~so-~~called the Yoldia Sea Stage (11.7 –11.0 kyr BP). Both ~~models~~maps, the paleo-DEM~~map~~ shown in Fig. 7b and that of Andrén~~Andren's~~ et al. (2011) shown in (Fig. 1b~~)~~ ~~results~~ confirm~~oincide in~~ the existence of such a gate. The maps clearly show the course of the inherent BIL drainage in the lowlands of the Central Swedish Depression through lakes Vänern and Vättern. This drainage course was near the margin of the FIS. According to Patton et al. (2017), Shaw et al. (2006) and Stokes et al., (2015), the continental ice front ~~is not to be consered~~is not considered as a stable line but rather consists of multiple glacial-fluvial channels between large ice blocks. The central Swedish lowlands were characterized by such an environment, enabling the water flow between the Baltic Sea and the North

Formatted: Indent: First line: 0.5"

Sea during the Yoldia Sea period (Fig. 7a and 7b). During the Yoldia Sea stage (Fig. 7b) the sea level in the open North Sea and the water~~lake~~ level in the Baltic Sea basin converged and ~~, which~~ lasted until ~11.0 kyr BP. As the ice front continued to retreat northwards, the increasing uplift of Scandinavia outpaced the eustatic sea level rise and closed the gate in the central Swedish lowlands. The Baltic Sea consequently reverted to a freshwater environment, namely the Ancylus Lake, fed primarily by meltwater from the remnants of the FIS, which still covered the highlands of Scandinavia. The increasing flow of meltwater into the Ancylus Basin led to a~~ permanent~~ rise in the lake level (so-called "Ancylus Transgression") ~~having reached~~reaching ~~ its maximum~~a peak at ~10.5 kyr BP and a subsequent drainage of the lake water into the paleo-North Sea (Fig. 7c). Different from the drainage through the central Swedish lowlands in the later stage of the BIL, the freshwater outflow in the late stage of the Ancylus Lake moved to the south due to the increasing glacio-isostatic uplift of Scandinavia and took place through the area of today's western Baltic Sea, namely the ~~Belt and the Sound~~Danish Straights. In the generation of the maps, we distinguished the water levels between the Lake Ancylus and the open North Sea from 11.0 to 9.5 kyr BP according to Uścinowicz (2006), which are shown in Fig. 3.

At ~~around ~~~~8~~9.~~0~~ 5 kyr BP, the one-way drainage from the Baltic Sea (Lake Ancylus) to the North Sea ceased due to a rise of the eustatic sea level which caught up with the water level in the Lake Ancylus (Harff et al. 2017), and the Littorina transgression enabled a free exchange between the Baltic Sea and the open North Sea again (Fig. 7d). Since then, the global sea-level change has dominated the hydrographic regime in the Baltic Sea. Glacio-isostatic movements of the region lead to persistent transgression in the south and regression in the north of the Baltic Sea (Harff et al. 2017). The paleogeographic setting at 6.5 kyr BP is illustrated by the map shown in Fig. 7d. A comparison with the map generated by Andrén et al. (2011) ~~according to~~based on proxy data shown in Fig. 1c ~~according to Andren et al. (2011) ~~shows a general agreement in ~~both in the course of the coasts and in ~~the reconnection~~s~~ of the Baltic Sea basin to the open ~~paleo-~~North Sea and ~~contributes to the verification of~~verifies our model result~~the modeling undertaken here~~.

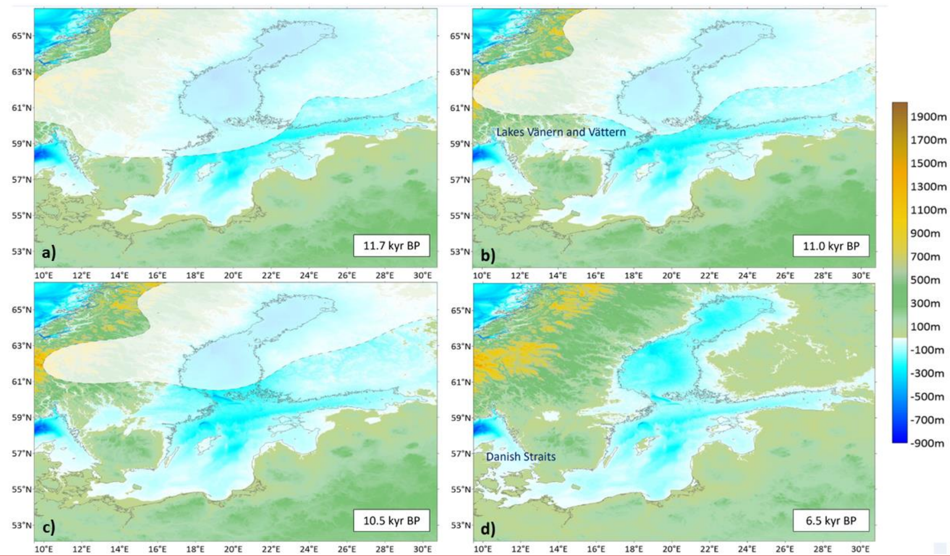


Figure 7: Reconstructed paleogeographic maps representing different stages of the Baltic Sea. Four exemplary maps are depicted here for comparison with the paleogeographic maps generated by AndrénAndren et al., (2011). a) Baltic Ice Lake/Yoldia Sea transitionBaltic Ice Lake (just prior to the final drainage), at 11.7 kyr BP; b) Yoldia Sea (end of the brackish phase) at , 11.0 kyr BP; c) Ancylus Lake (transgression maximum transgression) at , 10.5 kyr BP; d) Littorina Sea (most saline phase) at, 6.5 kyr BP. Gray line depicts the The present-day coastline is depicted by the gray line and the ice cover is indicated by the transparent mask.

Formatted: Font: Not Bold

4.4 Validation of the paleogeographic reconstruction

An interplay between eustasy and spatially varied rates of isostatic rebound is mirrored in various local RSL curves. Reconstructed curves for all subareas of the Baltic Sea Basin gathered by Rosentau et al. (2021) allowed to locally validate assess ourthe numerically modelled paleogeographic maps. All station datacurves located along the eastern (Berglund, 2012; Hansson et al., 2018) and the northern Swedish coast (Linden et al., 2006) as well as the all Finnish coastdatasets (Glückert, 1976; Saarnisto, 1981; Mietinen, 2003) – _ infersuggest a decreasing RSL trendsince 11.7 kyr BP , dominated by isostatic uplift, whereas stations inof the southern Baltic coast mirror fast a consistent rising RSL_ rise that starts to slows down and stabilizes after 6.0 kyr BP (Lampe et al., 2004, 2011; Gelumbauskaite, 2009; Uścinowicz et al., 2011) ; Miotk-Szpiganowicz et al., 2013,). Stations along the Latvian and Estonian coast (Grudzińska et al., 2013, 2014; Lougas, and Tomek, 2013; Berzins et al., 2016) infer a general decreasing RSLtrend interrupteddistorted by the Ancylus transgression. The reportedDescribed local RSL curvestrends -show discrepancy differences with our modelled results mainly for the initial stage between 11.7- 10 kyr BP and afterward a general agreement is reached. were well-mirrored in obtained maps (Fig.8). The opposite patterns of the RSL change between the northern and southern coasts gradually converge towards the central Baltic area where eustatic and isostatic components neutralize each other. This is seen at the stations in Latvia and Blekinge which show a relatively flat RSL curve with small-scale up-and-down variations (Damusyte, 2011; Rosentau et al., 2013; Habicht et al., 2017). Such relatively stable RSL is reproduced in our results, albeit with fluctuations discrepancy in the period between 11.7 and 10 kyr BP for the Blekinge station and between 11 and 8 kyr BP for the Latvia station (Fig.8). Comparison of thA general agreement between our modelled RSLe obtained paleogeographic scenarios and fit relatively well both regional field-observation-based reconstructions as well as local RSL curves compiled by Rosentau et al. (2021) as well as an agreement in the connection/disconnection between the open North Sea and the Baltic basin described in the previous section (Fig.8), which validates the approach applied in this studythe applied paleogeographic modeling methodology.

Formatted: Font: (Default) +Body (Times New Roman), 10 pt, , Check spelling and grammar

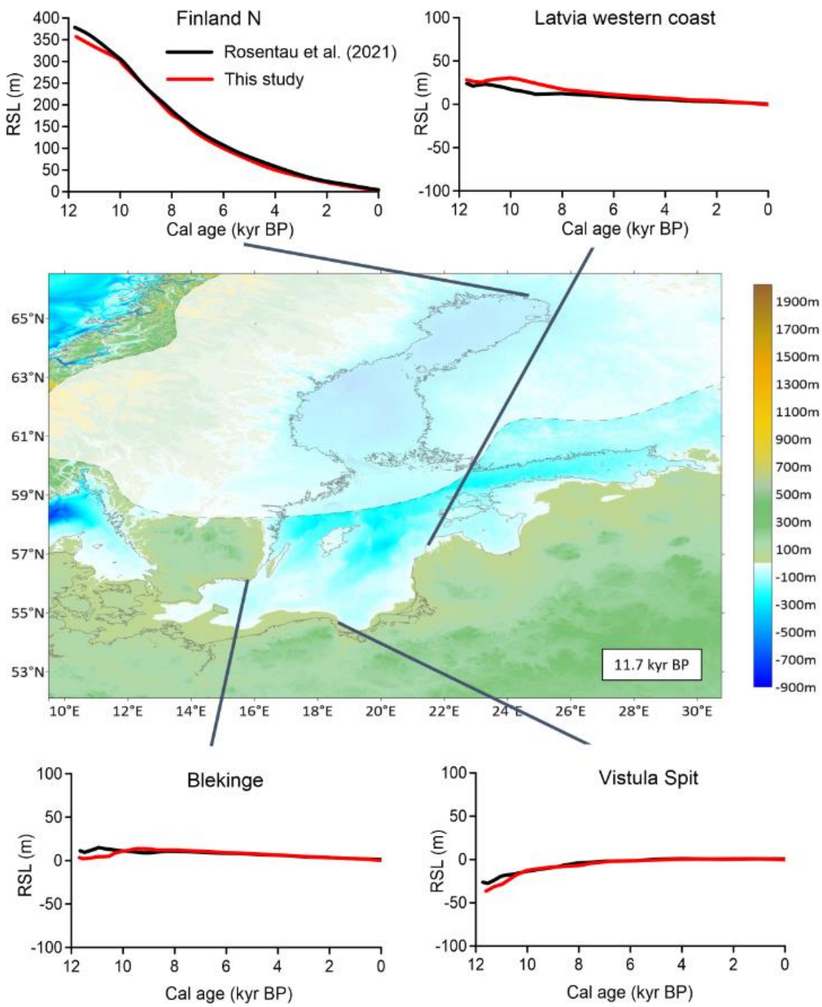


Figure 8. Comparison of our~~the~~ modelled RSL (red curves) and local RSL curves (black curves) derived from the ICE-5G ~~ICE-5G~~ model with 120 km lithosphere thickness ~~derived from field data~~ ~~compiled~~ by Rosentau et al. (2021).

Formatted: Font: 10 pt

5. Discussion

5.1. Comparison with existing reconstructions

The maps generated in this study are further assessed by comparison with existing field-based local reconstructions. AThe comparison of proxy-data based RSL black curves published bybetween those by Rosentau et al. (2021) and our resultsthe model driven red curves shows a general agreement except for the early Holocene period, as described in the previous sectionwell interpretable similarities. In three stations, namely Finland N, Blekinge and Vistula Spit, our results show a lower RSL at 11.7 kyr BP than those in Rosentau et al. (2021) adopting 120 km lithosphere thickness (Fig. 8). It should be noted that there exist remarkable differences in the reconstructed local RSLs for the early Holocene period among the scenarios adopting different lithosphere thickness values as shown in Rosentau et al (2021). As pointed out by Rosentau et al. (2021), the reconstructed curves using global ICE-5G and ICE-6G_C ice histories overestimate the RSL and fail to capture a mid-Holocene high-stand (~7.5-6.5 kyr BP) inferred from the proxy data in the transitional area. This overestimation seems to originate from an overestimation of ice loading in the ICE-5G and especially in the ICE-6G_C models. Our modelled curves lie in the lower limit of the RSLs in Rosentau et al. (2021), and therefore may provide results closer to proxy data. The curves from northern Finland represent a straight sea-level fall because of the dominating regional GIA uplift of the regional Earth's crust, whereas the Vistula Spit curves shows continuous sea-level fall rise caused by additive effect of eustatic sea-level rise and local GIA controlled land subsidence because of the collapsing lithospheric bulge. The Blekinge curve displays relative stable conditions closed to the isostatically neutral hinge line that separates the "uplifting Baltic North" from the "subsiding Baltic South". _At the Latvian west coast, the model data show the effect of damming during the Ancylus Lage stage up to ca. 10 cal. kyr BP and afterwards the sea-level drop caused by the lake drainage.

To aid the comparison, the coastline and the edge of the ice cover from Obtained maps were compared with regional paleogeographic reconstructions providedWe also compared our modelled paleo-DEMs with the maps fromby Andrén et al. (2011) , which have been widely referred to in existing literaturein a qualitative manner and identified a ., were overlaid with our maps (Fig. 9). The map shown in Fig. 9a represents the sScenario for 11.7 kyr BP, corresponding corresponds to the beginning of the Holocene and the Baltic Ice Lake/Yoldia Sea transition. gGeneral paleogeographic features are consistent between our map and the one from Andrén et al. (2011).consistency between the two sets of maps in the location of the gates between the Baltic basin and the open North Sea as well as the timing of their closing and opening (section 4.3). Nevertheless, The Danish straits are closed at that time, whereas a connection between the Baltic Sea and the North Sea is being formed throughout the Central Swedish Lowlands. A majorsome local scale differences are also seen between our results and the maps of Andrén et al. (2011), e.g. is on the morphology of the Bornholm Island and the Gotland Island. In Andrén'sthe map of Andrén et al. (2011) reconstruction, both islands are are emerged already in 11.7 kyr BP. By contrast, our map shows that the Island of Bornholm is still connected to the mainland and the Gotland Island is largely submerged at that time. The shape of the coastline remains similar, however ~~depicts~~ a higher RSL in the southern part and lower RSL in the western and eastern parts of the Baltic Sea are seen in Andrén et al. (2011) ~~in Andrén's reconstruction~~ compared to our result. S~~The explanation of s~~uch difference may be attributed to ~~a fact,~~ that the ~~Andren's~~ map of Andrén et al. (2011) represents still the ~~last~~late stage of BIL~~,~~ when the water level was higher in the Baltic basin than the North Sea,~~;~~ whereas our ~~the~~ result~~reconstructed scenario~~ corresponds to the beginning of the post-drainage ~~-~~phase when the water level of these two seas converged. ~~However, Andren (2011) depicted a hydrographic connection between Baltic and Kattegat via The Sound, making the "BIL prior to drainage" description imprecise. Fig. 9b corresponds to the end of Yoldia Sea phase at 11.0 kyr BP. In both reconstructions of 11.0 kyr BP, standing for end of Yoldia Sea phase, the connection between the Baltic Sea and the North Sea via the Central Swedish Lowlands is being closed, and the Bornholm Island is connected to the mainland. The~~ For the ~~Maps depicting~~ maximum of Ancylus transgression at 10.5 kyr BP, ~~show~~ a state when~~is depicted in Fig.9c. In both reconstructions~~ the North Sea and the Baltic Sea are disconnected, ~~. Coastlines in the southern part are similar between two maps. However, a~~the difference in the coastline location of the northern Baltic region between the two maps is seen.~~increases northwards,~~ The difference indicates~~inferring~~ a lower RSL leading to emerging of the w~~W~~est Estonian archipelago and Finland in the map of Andrén et al. (2011) ~~Andrén's reconstruction~~ compared to our result. Noteworthy is~~,~~ that even though the difference in ~~area~~ the coastline position seems to be huge~~vast~~, the difference in the elevation is relatively small (mostly within 10 m), suggesting that the land-sea transition in this part is highly sensitive to the change of RSL and therefore slight modification of isostatic or eustatic components~~model parameters~~ may have significant ~~visual~~ influence in the coastline position. Our reconstructed morphology of the Littorina Sea at 6.5 kyr BP is characterized by an open connection between the Baltic Sea and the North Sea through the Danish Straits, which persists until today. In the reconstruction by Andrén et al. (2011), the Baltic-North Sea connection at 6.5 kyr BP exists only via the Great Belt, whereas all three straits are already opened in our result at that ~~time.~~ time. The timing of events such as opening of straits varies between reconstructions. Some local-scale ~~variabilities of narrow~~topographic structures such as straits may not be well resolved ~~visible~~ in regional reconstructions due to~~on the regional scale maps due to coarse map~~ insufficient spatial resolution or ~~difference in the~~ data coverage ~~and/or reconstruction methods, making it non-comparable between regional studies on local-scale features, which do not have sufficient data coverage.~~ Similar to earlier scenarios, the RSL in the northern and central parts of the Baltic Sea is generally lower in the map of Andrén et al. (2011) compared to our result. ~~In summary, major features of the paleogeographic evolution of the Baltic Sea are well mirrored and consistent in both reconstructions. Differences are mainly related to the location of the paleo-coastline due to higher RSL in the central and northern parts and lower RSL in the southern part of the Baltic Sea in our result compared to that of Andrén et al. (2011), which also affects the timing for the emergence of the islands.~~

An earlier effort in mapping Holocene sediment thickness in the Baltic Sea has been made by ,Jakobson et al. (2007)~~. attempted to reconstruct Holocene thickness in the Baltic Sea,~~ **T**~~however~~**he mapping**, **was**~~characterized by low~~

Formatted

Formatted: Indent: First line: 0.5"

Formatted

resolution and `limited to southern and central parts (without Bothnian Bay), through assembling information from available sediment distribution maps and information retrieved from the Swedish Geological Survey's mapping archives which unfortunately do not provide an open access. **The resultant map is characterized by relatively low spatial resolution and limited to the southern and central parts (without Bothnian Bay) of the Baltic Sea (Jakobson et al., 2007).** A comparison between our map (Figure 5) and the map**that** from Jakobson et al. (2007) shows a general agreement in the Borholm basin and along the Swedish coast near the Gotland. However, there exists a large descrepency**discrepancy** in the thickness value in other basins (e.g. Arkona basin, Gotland basin) between the two maps. The thickness values in Jakobson et al. (2007) for these basins are much smaller than previous published values from Lemke (1998) and Uścinowicz (1998) focusing on these local areas. **Despite a likely overestimation of the Holocene sediment thickness in the deep Gotland basin as pointed out in section 3.4.2, integrated**Compiled thickness data from the difference sources within this study show more consistent patterns covering both deep basins and shallow coastal areas and therefore provides a more accurate distribution of Holocene sediment thickness compared to earlier publications.

Formatted

Formatted

Formatted

Formatted: Font: (Default) +Body (Times New Roman),

Formatted: Font: (Default) Times New Roman, English (United Kingdom)

Formatted: Font: 11 pt

5.2. Holocene sediment budgetMajor source and sink terms in the Holocene Baltic Seain the Baltic Sea

Our calculated sediment mass of the Holocene deposit in the Baltic Sea is 1.34×10^{12} t, corresponding to an annual sediment accumulation rate of 1.15×10^{8} t yr^{-1}. Potential errors in the estimation may originate from several sources, including porosity, grain density and vertical compaction. The standard deviation σ of porosity is ~0.15 according to the sediment samples analyzed by Endler et al. (2015). Applying the mean ± σ in the porosity data as the upper and lower estimates respectively indicates a range between 0.82×10^{12} t and 1.87×10^{12} t in the total sediment mass, corresponding to annual sediment accumulation rate between 0.69×10^{8} t yr^{-1} and 1.61×10^{8} t yr^{-1}. Although the Holocene deposits mainly consists of silt and sand, the deeper basins (e.g. Arkona, Bornholm and Gotland) are covered by a layer of mixture of organic matter (up to 16%) and clay (Leipe et al., 2011). The thickness of such layer can extend to several meters in the deep basins (Andrén et al., 2000; Ponomarenko, 2023). Assuming that the average thickness of this layer is 4 m (as indicated in a majority of sediment cores) in the basins, neglection of the vertical compaction results in an overestimation of the porosity by ~10% according to Schmedemann et al. (2008), corresponding to an underestimation of sediment mass of ~ 0.055×10^{12} t, which accounts for ~4% of the estimated mean total budget (1.34×10^{12} t).

A comparison of the annual sediment accumulation rate averaged over the Holocene with the present day's estimation by Porz et al. (2021) suggests that they are at the same order of magnitude for the SW Baltic Sea. The Holocene-averaged accumulation rate is $8.8\pm4.1\times10^{6}$ t yr^{-1} in the SW Baltic Sea according to our data in this study. In the budget analysis done by Porz et al. (2021), the annual accumulation rate of fine-grained sediment in the SW Baltic Sea basins is between 5.5×10^6 and 8.2×10^6 t yr^{-1}.

~~, with~~ C~~c~~oastal erosion, namely erosion of the glacial-till cliffs, serves as~~as~~ the main source that contributes at least ~~30-~~8~~5~~0% of the annual deposition in the basins (Wallmann et al., 2022). ~~River~~ Sediment supply from major central European rivers, namely Oder, Vistula, Nemunas, Daugava and Neva, is on the order of 1×10^7 t yr^{-1} (Porz et al., 2021; Pruszak et al., 2005; Lajczak and Jansson, 1993) with the largest contribution from the river Vistula (0.16-0.4×10^7 t yr^{-1}). This indicates that the riverine sediment supply accounts for less than 10% of the total Holocene sediment budget in the Baltic Sea. B~~and b~~iogenic production contributes to ~~are an order of magnitude smaller than coastal erosion and account for ~5% and~~ 4-15% of the annual deposition budget (Wallmann et al., 2022; Porz et al., 2021)~~, respectively~~. In addition, sediment input from the North Sea is estimated to be on the order of 1×10^6 t yr^{-1}, contributing to 10-30% of the annual deposition in the SW Baltic Sea (Porz et al., 2021). However, this input is almost negligible (accounting for ~1%) compared to the total annual accumulation rate in the Baltic Sea. ~~Since during the Ancylus Lake stage the connection between the Baltic Sea and the North Sea was closed, the sediment supply from the North Sea was halted for that period which lasted for ~1.5 kyrs. This implies a compensation of this gap by~~Additional ~~enhanced land~~ supply of sediment ~~e.g.~~ from melting of the ice cover on the Scandinavia may occur during early Holocene stages. However, such supply might also be negligible compared to the total Holocene sediment budget given that the Scandinavian mountains provide only a very small suspended sediment yield that is on the order of 1×10^5 t yr^{-1} (Lajczak and Jansson, 1993). ~~ia, which is larger than present-day values.~~

It is worth to note that our ~~Generated~~ Holocene sediment thickness map i~~wa~~s spatially confined~~limited~~ by~~to~~ the present-day Baltic Sea coast. Although~~Even though~~ Holocene sedimentation may also occur~~occurred~~ on parts of the present-day mainland especially~~(mainly~~ in the northern Baltic coast when they were submerged~~)~~, ~~after this area was emerged the~~ the deposited sediment~~s~~ was~~ere~~ subjected to reworking~~erosion~~ when these parts became emerged and therefore is difficult to quantify due to lack of data. ~~any estimation of marine sediment thickness would be difficult to obtain and justify~~ Moreover, the Holocene sediment thickness of the northern Baltic Sea and its coast is generally scarce (Fig.6), therefore ~~any extrapolation to~~omission of deposit on the mainland is considered to have minor~~would have no visual~~ impact on the paleo-DEMs and ~~very minor impact on~~ the total Holocene ~~estimated~~ sediment budget in the Baltic Sea~~of the Holocene~~.

5.3. Importance of integrating sediment dynamics in paleogeographic reconstructions

Depending on the regional or local setting, the individual impact of eustatic, isostatic/tectonic and sediment dynamics on geographical and morphological development of marginal seas may vary significantly. Inclusion of sediment dynamics in paleogeographic reconstruction of coastal regions and continental shelves that are fed by significant terrestrial sediment input has critical influence on the location of the paleo-coastline and general morphology of the seabed. This has been demonstrated in the paleo-reconstructions of the Beibu Gulf in the northern South China Sea (Xiong et al., 2020; Zhang et al., 2020), the Pearl River delta and its estuary (Wu et al., 2010), the Mekong River delta and adjacent shelf (Wang et al., 2024), the southwestern coast of Bohai Sea (Liu et al., 2016) and the southern North Sea (Van der Molen and Van Dijck, 2000).

The integration of sediment dynamics is also important for understanding the evolution of large-scale sedimentary systems which are not directly fed by riverine sediment but are formed and/or shaped by sediment transport, such as barrier islands (Zhang et al., 2011a; Zhang et al., 2014; Karle et al., 2021) and mud depocenters (Porz et al., 2021). This process is especially important for evolution of the southern Baltic Sea where various barrier islands have developed since mid-Holocene when the sea level has approached a relatively stable level (Uścinowicz et al., 2011; Zhang et al., 2011b; Dudzińska-Nowak, 2017). It is worth noting that although many paleogeographic reconstructions exist at local scales by considering sediment transport dynamics, our work represents the first attempt for a consistent reconstruction at a marginal sea scale. Comprehensive information of dated sediment thickness for a marginal sea such as the Baltic Sea is difficult to obtain, as most of relevant datasets are derived locally and it requires extensive effort in collection, integration, harmonization and synthesis of such datasets and filling of gaps between them. A consistent paleogeographic reconstruction of a marginal sea considering not only regional processes such as eustatic sea level change and isostatic/tectonic movement but also sediment ~~transport~~ deposition provides indispensable information on the historical development of the marginal sea especially its coast. ~~Such information is critical for assessment of the future state of marginal seacoast in response to climate change and human impacts.~~

A future challenge towards improvement ~~of sediment dynamics aspect~~ of paleogeographic reconstructions ~~would~~ requires differentiation of sediment accumulation and erosion rates. Although sediment accumulation rate may varys ~~varied~~ throughout the Holocene, ~~for the purpose of Baltic Sea~~ we adopted a constant rate in this study due to poor data constraint~~was assumed~~. ~~Even though these~~The reported rates were mostly derived~~could be estimated~~ based on analysis of sparsely distributed sediment cores and it is ~~(being point data), expanding it to other sections of Baltic Sea basin would be~~ difficult to ~~justify as sedimentary environments of~~ extrapolate a few tens of point data to the entire Baltic Sea~~vary not only in time but also in space~~. Therefore, more measurement data is needed to provide a sound database for extrapolation. ~~Moreover in the Baltic Sea, the magnitude of *ASED* remains relatively small compared to the magnitudes of *AEC* and *AGIA*. Also, the highest sedimentation rates are situated in the deeper basins. Therefore assuming different sedimentation rates would have only minor, barely noticeable, influence on the paleo-bathymetry.~~Mass-balanced reconstruction methods have been proposed for backstripping of depositional areas and backfilling of erosional areas at geological time scales (Hay et al., 1989; Feng et al., 2023). However, these are of high uncertainty for reconstructions at a millennial scale due to insufficient resolution in the seismo-acoustic profiles. An attempt to reconstruct the eroded coastal landscape in mid Holocene has been done by Zhang et al. (2014) at a local scale. The reconstruction was based on an extrapolation of the shape of present-day remnants of erodible coast by a fitted spline function using the morphology of the backland as a reference. Based on the identified major source and sink terms as well as the associated transport pathways exemplified in this study, it might also be feasible to apply the same method to reconstruct eroded coasts at a centennial-to-millennial time scale. ~~Moreover, with the current state of~~

~~knowledge, incorporating complicated paleo-morphodynamic models of sediment accumulation, erosion, redeposition or compaction as well as sediment fluxes will bear high uncertainty due to insufficient data for model forcing, boundary configuration, calibration and validation. Incorporation of such variables is a future challenge,~~

6. Conclusions

This study presents a spatially high-resolution (0.01°×0.01°) paleogeographic reconstruction of the Baltic Basin including the coastal evolution of the Baltic Sea for the Holocene since the end of the Baltic Ice Lake stage at 11.7 kyr BP ~~based on the application of a conceptual equation to link empirical (primary) and model (secondary) data~~. These data describe the surface structure of the study area, climate-induced eustatic sea level changes, ~~as well as~~ glacio-isostatic (GIA) vertical Earth's crust movement and the thickness ~~evolution~~ of sediment deposition in the Baltic Sea b~~B~~asin ~~starting with the end of the Baltic Ice Lake stage 11.7 kyr BP~~. Local datasets of sediment thickness from open sources including existing literature and data portals with public access were compiled and complemented by numerical interpolation~~-~~ and extrapolation~~s~~ to generate a consistent regional map of Holocene sediment thickness for the entire Baltic Sea. The map shows that relatively thick Holocene sediments are deposited in the southern and central parts of the Baltic Sea, filling the sub-basins, including Arkona ~~Basin~~, Bornholm ~~Basin~~, Eastern and Western Gotland ~~Basins~~ and Northern Central Basins, with a maximum thickness of up to 36 m. In addition, some shallower coastal areas in the southern Baltic Sea also ~~have~~ host localized deposits with a thickness of more than 20 m, mostly associated with alongshore sediment transport and formation of barrier islands and spits ~~such as: Hel Peninsula, Vistula Spit or Curonian Spit~~. In contrast to the southern Baltic Sea, the thickness of Holocene sediments in the northern Baltic Sea is relatively low, mostly less than 6 m. The total mass of Holocene sediment in the Baltic Sea ~~according to the thickness map and corresponding porosity data~~ is estimated to be between 0.81×10^{12} t and 1.82×10^{12} t, corresponding to annual sediment accumulation rate between 0.69×10^{8} t yr^{-1} and 1.56×10^{8} t yr^{-1}~~$1.34\pm0.53\times10^{12}$ t, which corresponds to a sediment accumulation of $1.15\pm0.46\times10^{8}$ t per year~~.

For the first time, the paleogeographic reconstruction of the Baltic Sea for the Holocene was achieved by a combination of crustal deformation (GIA), eustatic water level change and sediment ~~accumulation~~ thickness considering the disconnection of paleo-North Sea and the easterly freshwater body during the Ancylus Lake stage. The model results ~~and thus the functionality of the model expressed by the conceptual equation is~~are validated by comparison with field-based proxy data interpretation. This comparison improves the reconstruction of the hydrographic ~~dynamics~~ connection between the Baltic Sea and the North Sea~~s Basin~~ in~~,~~ the marginal zone of the former Fennoscandian Ice Sheet~~FIS~~. ~~In the northern part of the Baltic Basin the differences in coastlines reconstructed by field (proxy) data and model results lead to the assumption that the model underestimated the GIA in the central areas of former FIS, so that model parameters should be improved.~~ Our work thus represents a further step towards a consistent methodology to reconstruct the formation of marginal seas during transgression/regression cycles including not only tropic and subtropic climate zones but also polar and~~,~~ subpolar marginal

Formatted: Indent: First line: 0.5"

seas impacted by the regional dynamics of inland ice sheets. The comparison of model results with proxy-data interpretation allows the improvements of GIA model parameters. in paleogeographic reconstruction on a marginal marine sea scale.

Acknowledgements

This study is an outcome of the project "Morphological evolution of coastal seas – past and future" (https://marginalseas.ddeworld.org/margseas-rd-research-project) funded by the Deep-time Digital Earth program (https://www.ddeworld.org/). It is also supported by the Helmholtz PoF programme "The Changing Earth – Sustaining our Future" on its Topic 4: Coastal zones at a time of global change.

Authors contribution

Wenyan Zhang designed and supervised the study. Jakub Miluch collected, digitized, and processed sediment data and eustatic sea level curve of the study area. He also generated the paleogeographic maps by numerical modeling supervised by Jan Harff. Andreas Groh provided the data and GIA scenarios used for paleogeographic modeling and contributed related text descriptions. Peter Arlinghaus applied the convolutional neural network to fill the data gaps in the sediment thickness. Celine Denker assisted in collection, digitization, and generation of the sediment thickness map. Jakub Miluch and Wenyan Zhang wrote the original manuscript. All authors have contributed to manuscript revision. We thank for Peter Feldens for providing seismic data; and for Celine Denker and Labiqa Zahid for hertheir assistance in collection, digitization, and generation of the sediment thickness map.

Data availability

Publicly available datasets were analyzed in this study. Present-day digital elevation model of the Baltic Sea is derived from GEBCO 2023 Grid (doi:10.5285/f98b053b-0cbc-6c23-e053-6c86abc0af7b). Seismic profiles in the Gotland Basin were kindly provided by Dr. Peter Feldens from the Leibniz Institute for Baltic Sea Research (IOW). Gridded Holocene sediment thickness data produced in this study can be found at the Mendeley Data with doi: 10.17632/k45mff2ccy.1

Competing interests

The contact author has declared that none of the authors has any competing interests.

References

Andrén, E., Andrén, T., Sohlenius, G.: The Holocene history of the southwestern Baltic Sea as reflected in a sediment core from the Bornholm Basin. Boreas, 29(3), 233-250, https://doi.org/10.1111/j.1502-3885.2000.tb00981.x, 2000.

Andrén, T., Lindeberg, G., Andrén, E.: Evidence of the final drainage of the Baltic Ice Lake and the brackish phase of the Yoldia Sea in glacialvarves from the Baltic Sea. Boreas 31, 226 238, https://doi.org/10.1111/j.1502-3885.2002.tb01069.x, 2002.

Andrén, T., Björck, S., Andrén, E., Conley, D., Zillén, L., Anjar, J.: The Development of the Baltic Sea Basin During the Last 130 ka. In: Harff, J., Björck, S., Hoth, P. (eds) The Baltic Sea Basin. Central and Eastern European Development Studies (CEEDES). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-17220-5_4, 2011.

Anthony, J.W., Bideaux, R.A., Bladh, K.W., Nichols, M.C.: Handbook of Mineralogy III (Halides, Hydroxides, Oxides). Mineralogical Society of America, Chantilly, VA, United States, 2009.

Allen, P.A., Allen, J.R.: Basin Analysis – Priciples and Applications. Blackwell Publishing, Oxford, pp. 1–549., 2008.

Atkinson, K.E.: An Introduction to Numerical Analysis, second ed. John Wiley   Sons, New York, United States, 1989.

Becker, J. J., Sandwell, D. T., Smith, W. H. F., Braud, J., Binder, B., Depner, J., Fabre, D., Factor, J., Ingalls, S., Kim, S-H., Ladner, R., Marks, K., Nelson, S., Pharaoh, A., Trimmer, R., Von Rosenberg, J., Wallace, G., Weatherall, P.: Global Bathymetry and Elevation Data at 30 Arc Seconds Resolution: SRTM30_PLUS. Marine Geodesy, 32(4), 355–371. https://doi.org/10.1080/01490410903297766, 2009.

Belkhiri, L., Tiri, A., Mouni, L.: Spatial distribution of the groundwater quality using kriging and Co-kriging interpolations. Groundwater for Sustainable Development, 11, 100473, 2020.

Berglund, M.: Early Holocene in Gästrikland, east central Sweden: shore displacement and isostatic recovery. Boreas, 41(2), 263-276, https://doi.org/10.1111/j.1502-3885.2011.00228.x, 2012.

Berra, F., Jadoul, F.,   Anelli, A.: Environmental control on the end of the Dolomia Principale/Hauptdolomit depositional system in the central Alps: coupling sea-level and climate changes. Palaeogeography, Palaeoclimatology, Palaeoecology, 290(1-4), 138-150, https://doi.org/10.1016/j.palaeo.2009.06.037 , 2010.

Bērziņš, V., Lübke, H., Berga, L., Ceriņa, A., Kalniņa, L., Meadows, J., Muižniece, S., Paegle, S., Rudzīte, M.,   Zagorska, I.: Recurrent Mesolithic–Neolithic occupation at Sise (western Latvia) and shoreline displacement in the Baltic Sea Basin. The Holocene, 26(8), 1319-1325. https://doi.org/10.1177/0959683616638434, 2016.

Björck, S.: A review of the history of the Baltic Sea, 13.0-8.0 ka BP. Quaternary international, 27, 19-40, https://doi.org/10.1016/1040-6182(94)00057-C, 1995.

Björck, S.: The late Quaternary development of the Baltic Sea basin. In Assessment of climate change for the Baltic Sea Basin (pp. 398-407). Springer, 2008.

Bola, A., Kayode, J.S.: An evaluation of digital elevation modeling in GIS and Cartography, Geo-spatial Information Science, 17:2, 139-144, https://doi.org/10.1080/10095020.2013.772808, 2014.

Bobertz, B., Harff, J.   Bohling, B.: Parameterisation of clastic sediments including benthic structures. Journal of Marine Systems, 75 (3-4). pp. 371-381. https://doi.org/10.1016/j.jmarsys.2007.06.010, 2009.

Boston, T., Van Dijk, A., Larraondo, P.R., Thackway, R.: Comparing CNNs and Random Forests for Landsat Image Segmentation Trained on a Large Proxy Land Cover Dataset. Remote Sens., 14, 3396. https://doi.org/10.3390/rs14143396, 2022.

Covington, J.H., P., Kennelly, P.: Paleotopographic influences of the Cretaceous/Tertiary angular unconformity on uranium mineralization in the Shirley Basin, Wyoming, Journal of Maps, 14:2, 589-596, https://doi.org/10.1080/17445647.2018.1512014, 2018.

Christiansen, C., Kunzendorf, H., Emeis, K.-C., Endler, R., Struck, U., Neumann, T., Sivkov, V., Temporal and spatial sedimentation rate variabilities in the eastern Gotland Basin, the Baltic Sea. Boreas, Vol. 31, pp. 65–74, https://doi.org/10.1111/j.1502-3885.2002.tb01056.x, 2002.

Damušytė, A.: Post-glacial geological history of the Lithuanian coastal area, Doctoral Dissertation, Physical Sciences, Geology, Vilnus. 2011.

Dudzińska-Nowak, J.: Morphodynamic processes of the Swina Gate coastal zone development (southern Baltic Sea). Coastline Changes of the Baltic Sea from South to East: Past and Future Projection, 219-255, 2017.

Einsele, G.: Event deposits: the role of sediment supply and relative sea-level changes—overview. Sedimentary Geology, 104(1-4), 11-37, https://doi.org/10.1016/0037-0738(95)00118-2, 1996.

Emelyanov E.: Geology of the Gdańsk Basin, Russian Academy of Sciences, Atlantic Branch of P. P. Shirshov Institute of Oceanology, Yantarny skaz, Russian Federation, 2002.

Endler, M., Endler, R., Bobertz, B., Leipe, T., Arz, H.W.: Linkage between acoustic parameters and seabed sediment properties in the south-western Baltic Sea. Geo-Marine Letters, 35, 145-160, https://doi.org/10.1007/s00367-015-0397-3, 2015.

Formatted: Font: Not Italic

Formatted: Font: Not Italic

Farrell, W., Clark, J.:. On Postglacial Sea Level. Geophys. J. Int. 46, 647—667, https://doi.org/10.1111/j.1365-246X.1976.tb01252.x, 1976.
Feng, B., He, Y., Li, H., Li, T., Du, X., Huang, X., Zhou, X.: Paleogeographic reconstruction of an ancient source-to-sink system in a lacustrine basin from the Paleogene Shahejie formation in the Miaoxibei area (Bohai Bay basin, east China). *Front. Earth Sci.* 11:1247723. doi: 10.3389/feart.2023.1247723, 2023.
Gale, A. S., Hardenbol, J., Hathway, B., Kennedy, W. J., Young, J. R., Phansalkar, V.: Global correlation of Cenomanian (Upper Cretaceous) sequences: Evidence for Milankovitch control on sea level. Geology, 30(4), 291-294, https://doi.org/10.1130/0091-7613(2002)030%3C0291:GCOCUC%3E2.0.CO;2 , 2002.
GEBCO Compilation Group (2023) GEBCO 2023 Grid (doi:10.5285/f98b053b-0cbc-6c23-e053-6c86abc0af7b)
Gelumbauskaitė, L. Ž.: Character of sea level changes in the subsiding south-eastern Baltic Sea during Late Quaternary. Baltica, 22(1), 23-36, 2009.
Glückert, G.: Post-glacial shore-level displacement of the Baltic in SW Finland. Ann. Acad. Sci. Fenn., Ser. A III 118, 1976.
Golden Software Surfer User's Guide (p. 446–448). Available on-line https://gis.fns.uniba.sk/vyuka/DTM_ako_sucast_GIS/Kriging/2/Surfer_8_Guide.pdf (last accessed 16th December 2023).
Gonet, T. and Gonet, K.: Alternative Approach to Evaluating Interpolation Methods of Small and Imbalanced Data Sets, Geomatics and Environmental Engineering 11(3), 49-65, http://dx.doi.org/10.7494/geom.2017.11.3.49, 2017.
Goovaerts, P.: Ordinary cokriging revisited. Mathematical Geology, 30, 21-42, 1998.
Groh, A., Harff, J.: Relative sea-level changes induced by glacial isostatic adjustment and sediment loads in the Beibu Gulf, South China Sea. Oceanologia 65(1), 249—259. https://doi.org/10.1016/j.oceano.2022.09.001, 2023.
Grudzinska, I., Saarse, L., Vassiljev, J., Heinsalu, A.: Mid-and late-Holocene shoreline changes along the southern coast of the Gulf of Finland. Bulletin of the Geological Society of Finland, 85, 2013.
Grudzinska, I., Saarse, L., Vassiljev, J., Heinsalu, A.: Biostratigraphy, shoreline changes and origin of the Limnea Sea lagoons in northern Estonia: the case study of Lake Harku. Baltica, 27(1), https://doi.org/10.5200/baltica.2014.27.02, 2014.
Grund, S., Geiger, J.: Sedimentologic modelling of the Ap-13 hydrocarbon reservoir. Central European Geology, 54/4, pp. 327–344, https://doi.org/10.1556/CEuGeol.54.2011.4.2, 2011.
Groh, A., Richter, A., Dietrich, R.: Recent Baltic Sea Level Changes Induced by Past and Present Ice Masses. In: Harff, J., Furmańczyk, K., von Storch, H. (eds) Coastline Changes of the Baltic Sea from South to East. Coastal Research Library, vol 19. Springer, Cham. https://doi.org/10.1007/978-3-319-49894-2_4, 2017.
Gudelis, V., Emelyanov, E. (eds.): Geology of the Baltic Sea, Mokslas Publishers, 1976.
Habicht, H. L., Rosentau, A., Jõeleht, A., Heinsalu, A., Kriiska, A., Kohv, M., Hang, T., Aunap, R.: GIS-based multiproxy coastline reconstruction of the eastern Gulf of Riga, Baltic Sea, during the Stone Age. Boreas, 46(1), 83-99, https://doi.org/10.1111/bor.12157, 2017.
Hall, A., van Boeckel, M.: Origin of the Baltic Sea basin by Pleistocene glacial erosion. Gff, 142(3), 237-252, https://doi.org/10.1080/11035897.2020.1781246, 2020.
Hansson, A., Nilsson, B., Sjöström, A., Björck, S., Holmgren, S., Linderson, H., Magnell, O., Rundgren, M., Hammarlund, D., A submerged Mesolithic lagoonal landscape in the Baltic Sea, south-eastern Sweden–Early Holocene environmental reconstruction and shore-level displacement based on a multiproxy approach. Quaternary International, 463, 110-123, https://doi.org/10.1016/j.quaint.2016.07.059, 2018.
Harff, J.; Lemke, W.; Lampe, R.; Lüth, F.; Lübke, R.; Meyer, M.; Tauber, F.; Schmölcke, U.: The Baltic Sea Coast – a Model of Interrelations between Geosphere, Climate and Anthroposphere. – In: Harff, J.; Hay, W.W.; Tetzlaff, D. (eds.): Coastline Change – Interrelation of Climate and Geological Processes. – The Geological Society of America, Spec. Pap. 426, pp. 133-142, 2007.
Harff , J., Endler, R., Emelyanov, E., Kotov, S., Leipe, T., Moros, M., Olea, R.A., Tomczak, M., Witkowski, A.: Late Quaternary Climate Variations reflected in Baltic Sea Sediments.- in. Harff, J., Björck, S., Hoth, P. (eds,). The Baltic Sea Basin.- Springer. Berlin et al., p. 99-132, 2011.
Harff, J., Deng, J., Dudzinska-Nowak, J., Fröhle, P., Groh, A., Hünicke, B., Soomere, T., Zhang, W.: What Determines the Change of Coastlines in the Baltic Sea? 2017, in: Harff, J., Furmanczyk, K., von Storch, H. (eds) 2017. Coastline Changes of the Baltic Sea from South to East - Past and Future Projection Coastal Research Library, vol 19. Springer, Heidelberg, pp 15-35, https://doi.org/10.1007/978-3-319-49894-2_4, 2017.

Hay, W.W., Shaw, C.A., Wold, C.N.: Mass-balanced paleogeographic reconstructions. Geol Rundsch 78, 207–242. https://doi.org/10.1007/BF01988362, 1989.
Heinsalu, A., Veski, S.: The history of the Yoldia Sea in Northern Estonia: palaeoenvironmental conditions and climatic oscillations. Geological Quarterly, 51, 295-306, 2007.
Hulskamp, R., Luijendijk, A., van Maren, B. et al. Global distribution and dynamics of muddy coasts. Nat Commun 14, 8259, https://doi.org/10.1038/s41467-023-43819-6, 2013.
Jakobsson, M., Björck, S., Alm, G., Andrén, T., Lindeberg, G., Svensson, N. O.: Reconstructing the Younger Dryas ice dammed lake in the Baltic Basin: Bathymetry, area and volume. Global and Planetary Change, 57(3-4), 355-370, https://doi.org/10.1016/j.gloplacha.2007.01.006, 2007.
Jakobsson, M., Stranne, C., O'Regan, M., Greenwood, S. L.,Gustafsson, B., Humborg, C., and Weidner, E.: Bathymetric properties of the Baltic Sea, Ocean Sci., 15, 905–924, https://doi.org/10.5194/os-15-905-2019, 2019.
Karle M, Bungenstock F, Wehrmann A.: Holocene coastal landscape development in response to rising sea level in the Central Wadden Sea coastal region. Netherlands Journal of Geosciences 100, e12. https://doi.org/10.1017/njg.2021.10, 2021.
Kaskela, A. M., Kotilainen, A. T., Al-Hamdani, Z., Leth, J. O., Reker, J.: Seabed geomorphic features in a glaciated shelf of the Baltic Sea. Estuarine, Coastal and Shelf Science, 100, 150-161., https://doi.org/10.1016/j.ecss.2012.01.008 , 2012.
Konomi, B. A., Kang, E. L., Almomani, A., Hobbs, J.: Bayesian Latent Variable Co-kriging Model in Remote Sensing for Quality Flagged Observations. Journal of Agricultural, Biological and Environmental Statistics, 1-19, 2023.
Lambeck, K., Purcell, A., Zhao, J., Svensson, N. O.: The Scandinavian ice sheet: from MIS 4 to the end of the last glacial maximum. Boreas, 39(2), 410-435, https://doi.org/10.1111/j.1502-3885.2010.00140.x, 2010.
Lampe, R., Janke, W.: The Holocene sea level rise in the Southern Baltic as reflected in coastal peat sequences. Polish geological institute Special papers, 11, 19-29, 2004.
Lampe, R., Endtmann, E., Janke, W., Meyer, H.: Relative sea-level development and isostasy along the NE German Baltic Sea coast during the past 9 ka. E&G Quaternary Science Journal, 59(1/2), 3-20, https://doi.org/10.3285/eg.59.1-2.01, 2011.
Leenaers, H., Burrough, P. A., Okx, J. P.: Efficient mapping of heavy metal pollution on floodplains by co-kriging from elevation data. In Three Dimensional Applications in GIS (pp. 37-50). CRC Press, 2020.
Leipe, T., Tauber, F., Vallius, H., Virtasalo, J., Uścinowicz, S., Kowalski, N., Hille, S., Lindgren, S., Myllyvirta, T.:Particulate organic carbon (POC) in surface sediments of the Baltic Sea. *Geo-Mar Lett* **31**, 175–188, https://doi.org/10.1007/s00367-010-0223-x, 2011.
Lemke, W.: Sedimentation und paläogeographische Entwicklung im westlichen Ostseeraum (Mecklenburger Bucht bis Arkonabecken) vom Ende der Weichselvereisung bis zur Litorinatransgression. Institut für Ostseeforschung Warnemünde, 1998.
Lemke, W., Jensen, J. B., Bennike, O., Endler, R., Witkowski, A., Kuijpers, A.: Hydrographic thresholds in the western Baltic Sea: Late Quaternary geology and the Dana River concept. Marine Geology, 176(1-4), 191-201, https://doi.org/10.1016/S0025-3227(01)00152-9, 2001.
Libina, N.V., Nikiforov, S.L.: Digital Elevation Models of the Bottom in the Operational Oceanography System. Oceanology 60, 854–860, https://doi.org/10.1134/S0001437020050124, 2020.
Lindén, M., Möller, P. E. R., Björck, S., Sandgren, P. E. R., Holocene shore displacement and deglaciation chronology in Norrbotten, Sweden. Boreas, 35(1), 1-22, https://doi.org/10.1111/j.1502-3885.2006.tb01109.x, 2006.
Liu, L., Xing, F., Li, Y., Han, Y., Wang, Z., Zhi, X., Wang, G., Feng, L., Yang., B., Lei., Y., Fan, Z., Du., W.: Study of the geostatistical grid maths operation method of quantifying water movement in soil layers of a cotton field, Irrig and Drain, 69:1146–1156, https://doi.org/10.1002/ird.2513, 2020.
Liu, N., He, T., Tian, Y., Wu, B., Gao, J., Xu, Z.: Common azimuth seismic data fault analysis using residual U-Net. Interpretation. 8. 1-41. https://doi.org/10.1190/int-2019-0173.1, 2020.
Liu, Y., Huang, H., Qi, Y., Liu, X., Yang, X.: Holocene coastal morphologies and shoreline reconstruction for the southwestern coast of the Bohai Sea, China. Quaternary Research, 86(2):144-161. https://doi.org/10.1016/j.yqres.2016.06.002, 2016.

Lõugas, L., Tomek, T.:Marginal effect at the coastal area of Tallinn Bay: The marine, terrestrial and avian fauna as a source of subsistence during the Late Neolithic. Man, his time, artefacts, and paces. Collection of articles dedicated to Richard Indreko. Muinasaja teadus, 19, 463-485, 2013.

Luijendijk, A., Hagenaars, G., Ranasinghe, R., Baart, F., Donchyts, G., Aarninkhof, S.: The State of the World's Beaches. *Sci Rep* **8**, 6641, https://doi.org/10.1038/s41598-018-24630-6, 2018.

Lajczak, A., Jansson, M.B.: Suspended Sediment Yield in the Baltic Drainage Basin. *Hydrology Research* 24 (1): 31–52. doi: https://doi.org/10.2166/nh.1993.0003, 1993.

Maystrenko, Y., Bayer, U., Brink, H. J., Littke, R.: The Central European Basin System – an Overview. In: Littke, R., Bayer, U., Gajewski, D., Nelskamp, S. (eds) Dynamics of Complex Intracontinental Basins. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-85085-4_2, 2008.

Matthäus, W., Franck, H.: Characteristics of major Baltic inflows—a statistical analysis. Continental Shelf Research, 12(12), 1375-1400, https://doi.org/10.1016/0278-4343(92)90060-W, 1992.

Mentaschi, L., Vousdoukas, M. I., Pekel, J. F., Voukouvalas, E., Feyen, L.: Global long-term observations of coastal erosion and accretion. *Sci Rep* **8**, 12876, https://doi.org/10.1038/s41598-018-30904-w, 2018.

Miettinen, A. I.: Relative sea level changes in the eastern part of the Gulf of Finland during the last 8000 years, 2003.

Miluch, J., Osadczuk, A., Feldens, P., Harff, J., Maciąg, Ł., Chen, H., 2021.: Seismic profiling-based investigation of geometry and sedimentary architecture of the late Pleistocene delta in the Beibu Gulf, SW of Hainan Island. J. Asian Earth Sci. 205, 104611. https://doi.org/10.1016/j.jseaes.2020.104611, 2021.

Miluch J., Maciąg Ł., Osadczuk A., Harff J., Jiang T., Chen H., Borówka R.K., McCartney, K.: Multivariate geostatistical modeling of seismic data: Case study of the Late Pleistocene paleodelta architecture (SW off-shore Hainan Island, South China Sea), Marine and Petroleum Geology, Marine and Petroleum Geology 136, 105467, https://doi.org/10.1016/j.marpetgeo.2021.105467, 2022.

Myers, D. E.: Matrix formulation of co-kriging. Journal of the International Association for Mathematical Geology, 14, 249-257, 1982.

Myers, D. E.: Co-kriging—new developments. In Geostatistics for Natural Resources Characterization: Part 1 (pp. 295-305). Dordrecht: Springer Netherlands, 1984.

Neumann, B., Vafeidis, A. T., Zimmermann, J., Nicholls, R. J.: 2015. Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding—A Global Assessment. PLoS ONE 10, e0118571, https://doi.org/10.1371/journal.pone.0118571, 2015.

Paszke, A., Gross, S., Massa, F., Lerer, A., Bradbury, J., Chanan, G., Kileen, T., Lin, Z., Gimelshein, N., Antiga, L., Desmaison, A., Kopf, A., Yang, E., DeVito, Z., Raison, M., Tejani, A., Chilamkurthy, S., Steiner, B., Fang, L., Bai, J., Chintala, S.: PyTorch: An Imperative Style, High-Performance Deep Learning Library. In Advances in Neural Information Processing Systems 32, edited by H. Wallach, H. Larochelle, A. Beygelzimer, F. d'Alché-Buc, E. Fox, and R. Garnett, Pp. 8024–8035. Curran Associates, Inc. Publisher's Version, 2019.

Patton, H., Hubbard, A., Andreassen, K., Auriac, A., Whitehouse, P. L., Stroeven, A. P., Shackleton, C., Winsborrow, M., Heyman, J., Hall, A. M.: Deglaciation of the Eurasian ice sheet complex. Quaternary Science Reviews, 169, 148-172, https://doi.org/10.1016/j.quascirev.2017.05.019 , 2017.

Peltier, W., Postglacial variations in the level of the sea: Implications for climate dynamics and solid-earth geophysics. Rev. Geophys. 36, 603—689. https://doi.org/10.1029/98RG02638, 1998.

Peltier, W. R.: Global sea level rise and glacial isostatic adjustment. Global and planetary change, 20(2-3), 93-123, https://doi.org/10.1016/S0921-8181(98)00066-6, 1999.

Peltier, W.: Global glacial isostasy and the surface of the ice-age Earth: the ICE-5G (VM2) model and GRACE. Annu. Rev. Earth Pl. Sc. 32, 111—149. https://doi.org/10.1146/annurev.earth.32.082503.144359, 2004.

Peltier, W. R.: Postglacial coastal evolution: ice–ocean–solid Earth interactions in a period of rapid climate change, https://doi.org/10.1130/2007.2426(02), 2007.

Ponomarenko, E.: Holocene palaeoenvironment of the central Baltic Sea based on sediment records from the Gotland Basin, Regional Studies in Marine Science, Volume 63, 102992, https://doi.org/10.1016/j.rsma.2023.102992, 2023.

Porz, L., Zhang, W.,Schrum, C.: Density-driven bottom currents control development of muddy basins in the southwestern Baltic Sea. Marine Geology, Volume 438, 106523, https://doi.org/10.1016/j.margeo.2021.106523, 2021.

Pruszak, Z., van Ninh, P., Szmytkiewicz, M., Manh Hung, N., Ostrowski, R.: Hydrology and morphology of two river mouth regions (temperate Vistula Delta and subtropical Red River Delta), Oceanologia, 47 (3), 365–385, 2005.

Razas, M.A., Hassan, A., Khan, M.U., Emach, M.Z., Saki, S.A.: A critical comparison of interpolation techniques for digital terrain modelling in mining. Journal of the Southern African Institute of Mining and Metallurgy, 123(2), 53-62. https://dx.doi.org/10.17159/2411-9717/2271/2023, 2023.

Ronneberger, O., Fischer, P., Brox, T U-Net: Convolutional Networks for Biomedical Image Segmentation. Medical Image Computing and Computer-Assisted Intervention (MICCAI), Springer, LNCS, Vol.9351: 234-241, 2015.

Root, B. C., van der Wal, W., Novák, P., Ebbing, J., Vermeersen, L. L. A.: Glacial isostatic adjustment in the static gravity field of Fennoscandia. Journal of Geophysical Research: Solid Earth, 120(1), 503-518, https://doi.org/10.1002/2014JB011508, 2015.

Rosentau, A., Harff, J., Oja, T., Meyer, M.: Postglacial rebound and relative sea level changes in the Baltic Sea since the Litorina transgression, Baltica 25 (2), 113 120, https://doi.org/10.5200/baltica.2012.25.11, 2012.

Rosentau, A., Muru, M., Kriiska, A., Subetto, D. A., Vassiljev, J., Hang, T., Gerasimov, D., Nordqvist, K., Ludikova, A., Lõugas, L., Raig, H., Kihno, K., Aunap, R., Letyka, N.: Stone Age settlement and Holocene shore displacement in the Narva-Luga Klint Bay area, eastern Gulf of Finland. Boreas, 42, 912–931, https://doi.org/10.1111/bor.12004, 2013.

Rosentau, A., Bennike, O., Uścinowicz, S., Miotk-Szpiganowicz, G.: The Baltic Sea Basin. Submerged landscapes of the European continental shelf: quaternary paleoenvironments, 103-133, https://doi.org/10.1002/9781118927823.ch5, 2017.

Rosentau, A., Klemann, V., Bennike, O., Steffen, H., Wehr, J., Latinović, M., Bagge, M., Ojala, A., Berglund, M., Becher, G. P., et al.: A Holocene relative sea-level database for the Baltic Sea, Quaternary Science Reviews, 266, 107 071, https://doi.org/10.1016/j.quascirev.2021.107071, 2021.

Ryabchuk, D.V., Sergeev, A.Y., Prishchepenko, D.V., Zhamoida, V.A., Elkina, D.V., Piskarev, A.L., Bashirova, L.D., Ponomarenko, E.P., Budanov, L.M., Grigoriev, A.G., Evdokimenko, A.V.: Impact of climate change on sedimentation processes in the eastern Gulf of Finland during the Middle to Late Holocene. Boreas 50, 381-403. https://doi.org/10.1111/bor.12500, 2020.

Saarnisto, M.: Holocene emergence history and stratigraphy in the area north of the Gulf of Bothnia. Suomalainen tiedeakatemia, 1981.

Sandwell, D.T., Gille, S.T., Smith, W.H.F., eds., Bathymetry from Space: Oceanography, Geophysics, and Climate, Geoscience Professional Services, Bethesda, Maryland,, 24pp., 2002.

Schmedemann, N., Schafmeister, M. T., Hoffmann, G.: Numeric de-compaction of Holocene sediments. Polish Geological Institute Special Papers, 23, 87-94, 2008.

Shaw, J., Piper, D. J. W., Fader, G. B. J., King, E. L., Todd, B. J., Bell, T., Batterson, M.J., Liverman, D. G. E.: A conceptual model of the deglaciation of Atlantic Canada. Quaternary Science Reviews, 25(17-18), 2059-2081, https://doi.org/10.1016/j.quascirev.2006.03.002, 2006.

Sohlenius, G., Emeis, K. C., Andrén, E., Andrén, T., Kohly, A. Development of anoxia during the Holocene fresh–brackish water transition in the Baltic Sea. Marine Geology, 177(3-4), 221-242, https://doi.org/10.1016/S0025-3227(01)00174-8, 2001.

Spada, G., Stocchi, P.:SELEN: A Fortran 90 program for solving the ‘‘sea-level equation’’. Comput. Geosci. 33, 538—562. https://doi.org/10.1016/j.cageo.2006.08.006, 2007.

Spada, G., Melini, D., Galassi, G., Colleoni, F.: Modeling sea level changes and geodetic variations by glacial isostasy: the improved SELEN code. arXiv preprint arXiv:1212.5061, https://doi.org/10.48550/arXiv.1212.5061, 2012.

Statteger, K., Leszczyńska, K.: Rapid sea-level rise during the first phase of the Littorina transgression in the western Baltic Sea, Oceanologia, 65 (1), 202-210, https://doi.org/10.1016/j.oceano.2022.05.001, 2023.

Steffen, H., Wu, P. Glacial isostatic adjustment in Fennoscandia—a review of data and modeling. Journal of geodynamics, 52(3-4), 169-204, https://doi.org/10.1016/j.jog.2011.03.002, 2011.

Stokes, C. R., Tarasov, L., Blomdin, R., Cronin, T. M., Fisher, T. G., Gyllencreutz, R., Hätterstand, C., Heyman, J., Hindmarsh, R. C. A., Hughes, A. L. C., Jakobsson, M., Kirchner, N., Livingstonen, S. J., Margold, M., Murton, J. B., Noormets, R., Peltier, W. R., Peteet, D. M., Piper, D. J. W., Preusser, F., Renssen, H., Roberts, D. H., Rocher, D. M., Saint-Ange, F., Stroven, A. P. Teller, J. T.: On the reconstruction of palaeo-ice sheets: recent advances and future challenges. Quaternary Science Reviews 125, 15–49., https://doi.org/10.1016/j.quascirev.2015.07.016 , 2015.

Sturt, F., Garrow, D., Bradley, S.: New models of North West European Holocene paleogeography and inundation. Journal of Archaeological Science 40 (11), 3963-3976, https://doi.org/10.1016/j.jas.2013.05.023, 2013.
Uehara, K., J. D. Scourse, K. J. Horsburgh, K. Lambeck, and A. P. Purcell: Tidal evolution of the northwest European shelf seas from the Last Glacial Maximum to the present, *J. Geophys. Res.*, 111, C09025, doi:10.1029/2006JC003531, 2006.
Uścinowicz, S.: Geological Atlas of the Southern Baltic – Holocene thickness, Polish Geological Institute, 1998.
Uścinowicz, S.: A relative sea-level curve for the Polish Southern Baltic Sea, Quaternary International, 145–146, 86-105, https://doi.org/10.1016/j.quaint.2005.07.007, 2006.
Uścinowicz, S.: The Baltic Sea continental shelf. In Chiocci, F. L, Chivas, A. R (eds.) Continental Shelves of the World: Their Evolution During the Last Glacio-Eustatic Cycle. Geological Society Memoir, 41, 69-89, https://doi.org/10.1144/m41.7, 2014.
Uścinowicz, S., Miotk-Szpiganowicz, G., Krąpiec, M., Witak, M., Harff, J., Lübke, H., Tauber, F.: Drowned forests in the Gulf of Gdańsk (Southern Baltic) as an indicator of the Holocene shoreline changes. The Baltic Sea Basin, 219-231, 2011.
Uścinowicz, S.: Hel Peninsula–geological structure and history. Assessing the Baltic Sea Earth System, 4th Baltic Earth Conference, Jastarnia, Poland, 30 May – 3 June 2022.
Van der Molen, J., and Van Dijck, B.: The evolution of the Dutch and Belgian coasts and the role of sand supply from the North Sea. Glob. Planet. Chang. 27 (1-4), 223-244. 2000.
Varela, A. N.: Tectonic control of accommodation space and sediment supply within the Mata Amarilla Formation (lower Upper Cretaceous) Patagonia, Argentina. Sedimentology, 62(3), 867-896, https://doi.org/10.1111/sed.12164, 2015.
Vink, A., Steffen, H., Reinhardt, L., Kaufmann, G.: Holocene relative sea-level change, isostatic subsidence and the radial viscosity structure of the mantle of northwest Europe (Belgium, the Netherlands, Germany, southern North Sea). Quaternary Science Reviews, 26(25-28), 3249-3275, https://doi.org/10.1016/j.quascirev.2007.07.014, 2007.
Vött, A.: Relative sea level changes and regional tectonic evolution of seven coastal areas in NW Greece since the mid-Holocene. Quaternary Science Reviews, 26(7-8), 894-919, https://doi.org/10.1016/j.quascirev.2007.01.004, 2007.
Wackernagel, H.,Wackernagel, H.: Ordinary kriging. Multivariate geostatistics: an introduction with applications, 79-88, 2003.
Waelbroeck, C., Labeyrie, L., Michel, E., Duplessy, J.C., McManus, J.F., Lambeck, K., Balbon, E., Labracherie, M.: Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records. Quat. Sci. Rev. 21, 295–305. https://doi.org/10.1016/S0277-3791(01)00101-9, 2002.
Wallmann, K., Diesing, M., Scholz, F., Rehder, G., Dale, A.W., Fuhr, M. Suess, E.: Erosion of carbonate-bearing sedimentary rocks may close the alkalinity budget of the Baltic Sea and support atmospheric CO_2 uptake in coastal seas. *Front. Mar. Sci.* 9:968069. doi: 10.3389/fmars.2022.968069, 2022.
Wang, X., Zhang, W., Xie, X., Chen, H., and Chen, B.: Holocene sedimentary distribution and morphological characteristics reworked by East Asian monsoon dynamics in the Mekong River shelf, South Vietnam. Estuarine, Coastal and Shelf Science, Vol 302, 108784, https://doi.org/10.1016/j.ecss.2024.108784, 2024.
Watts, A. B.: Tectonic subsidence, flexure and global changes of sea level. Nature, 297(5866), 469-474, 1982.
Weisse, R., Dailidienė, I., Hünicke, B., Kahma, K., Madsen, K., Omstedt, A., Parnell, K., Schöne, T., Soomere, T., Zhang, W., Zorita, E. (2021): Sea level dynamics and coastal erosion in the Baltic Sea region. Earth Syst. Dynam., 12, 871–898, https://doi.org/10.5194/esd-12-871-2021, 2021.
Winterhalter, B.: On the geology of the Bothnian Sea, an epeiric sea that has undergone Pleistocene glaciation, Geological Survey of Finland Bulletin 258, Geologinen Tutkimuslaitos, Otaniemi, Finland, 1972.
Wu, C.Y., Wei X., Ren, J., Bao, Y., He, Z.G., Lei, Y.P., Shi, H.Y., Zhang, W.: Morphodynamics of the rock-bound outlets of the Pearl River estuary, South China – A preliminary study, Journal of Marine Systems, 82(1), 17- 27, https://doi.org/10.1016/j.jmarsys.2010.02.002 , 2010.
Wulff, F., Stigebrandt, A., Rahm, L.: Nutrient dynamics of the Baltic Sea. Ambio, 126-133, 1990.
Xiong, P., Dudzińska-Nowak, J., Harff, J., Xie, X., Zhang, W., Chen, H., Jiang, T., Chen, H., Miluch, J., Feldens, P., Maciąg, Ł., Osadczuk, A., Meng, Q., Zorita, E.: Modeling paleogeographic scenarios of the last glacial cycle as a base for source-to-sink studies: an example from the northwestern shelf of the South China Sea. J. Asian Earth Sci. 203, 104542. https://doi.org/10.1016/j.jseaes.2020.104542, 2020.

Yang, S.L., Xu, K.H., Milliman, J.D., Yang, H.F., Wu, C.S.: Decline of Yangtze River sediment discharge: impact from natural and anthropogenic changes. Sci. Rep. 5, 12581. https://doi.org/10.1038/srep12581, 2014.

Yao, Y., Harff, J., Meyer, M., Zhan, W.: Reconstruction of paleocoastlines for the northwestern south China sea since the last glacial maximum. Sci. China Earth Sci. 52, 1127–1136. https://doi.org/10.1007/s11430-009-0098-8, 2009.

Yilmaz, H.M.: The effect of interpolation methods in surface definition: an experimental study, Earth Surf. Process. Landforms 32, 1346–1361, https://doi.org/10.1002/esp.1473, 2007.

Zhang, P., Ke, Y., Zhang, Z., Wang, M., Li, P. Zhang, S. Urban Land Use and Land Cover Classification Using Novel Deep Learning Models Based on High Spatial Resolution Satellite Imagery. Sensors, 18, 3717. https://doi.org/10.3390/s18113717, 2018.

Zhang, W., Arlinghaus, P.: Climate, Coast, and Morphology. In: Oxford Research Encyclopedia of Climate Science. Oxford University Press, https://doi.org/10.1093/acrefore/9780190228620.013.814, 2022.

Zhang, W., Xiong, P., Meng, Q., Dudzińska-Nowak, J., Chen, H., Zhang, H., Zhou, F., Miluch, J., Harff, J.: Morphogenesis of a late Pleistocene delta off the southwestern Hainan Island unraveled by numerical modeling. J. Asian Earth Sci. 195, 104351. https://doi.org/10.1016/j.jseaes.2020.104351, 2020.

Zhang, W., Harff, J., Schneider, R., Meyer, M., Zorita, E., Hünicke, B.: Holocene morphogenesis at the southern Baltic Sea: simulation of multiscale processes and their interactions for the Darss-Zingst peninsula. Journal of Marine Systems, 129, 4-18, https://doi.org/10.1016/j.jmarsys.2013.06.003, 2014.

Zhang, W., Harff, J., Schneider, R., Meyer, M., Wu, C.Y.: A multi-scale centennial morphodynamic model for the southern Baltic coast. Journal of Coastal Research, 27, 890-917. https://doi.org/10.2112/JCOASTRES-D-10-00055.1, 2011a.

Zhang, W., Harff. J and Schneider, R.: Analysis of 50-year wind data of the southern Baltic Sea for modelling coastal morphological evolution - a case study from the Darss-Zingst Peninsula. Oceanologia, 53 (1-TI), 489-518. doi:10.5697/oc.53-1-TI.489, 2011b.

Andrén, E., Andrén, T., Sohlenius, G.: The Holocene history of the southwestern Baltic Sea as reflected in a sediment core from the Bornholm Basin. Boreas, 29(3), 233-250, https://doi.org/10.1111/j.1502-3885.2000.tb00981.x, 2000.

Andrén, T., Lindeberg, G., Andrén, E.: Evidence of the final drainage of the Baltic Ice Lake and the brackish phase of the Yoldia Sea in glacialvarves from the Baltic Sea. Boreas 31, 226-238, https://doi.org/10.1111/j.1502-3885.2002.tb01069.x, 2002.

Andrén, T., Björck, S., Andrén, E., Conley, D., Zillén, L., Anjar, J.: The Development of the Baltic Sea Basin During the Last 130 ka. In: Harff, J., Björck, S., Hoth, P. (eds) The Baltic Sea Basin. Central and Eastern European Development Studies (CEEDES). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-17220-5_4, 2011.

Anthony, J.W., Bideaux, R.A., Bladh, K.W., Nichols, M.C.: Handbook of Mineralogy III (Halides, Hydroxides, Oxides). Mineralogical Society of America, Chantilly, VA, United States, 2009.

Allen, P.A., Allen, J.R.: Basin Analysis – Priciples and Applications. Blackwell Publishing, Oxford, pp. 1–549., 2008

Atkinson, K.E.: An Introduction to Numerical Analysis, second ed. John Wiley – Sons, New York, United States, 1989.

Becker, J. J., Sandwell, D. T., Smith, W. H. F., Braud, J., Binder, B., Depner, J., Fabre, D., Factor, J., Ingalls, S., Kim, S-H., Ladner, R., Marks, K., Nelson, S., Pharaoh, A., Trimmer, R., Von Rosenberg, J., Wallace, G., Weatherall, P.: Global Bathymetry and Elevation Data at 30 Arc Seconds Resolution: SRTM30_PLUS. Marine Geodesy, 32(4), 355–371. https://doi.org/10.1080/01490410903297766, 2009.

Belkhiri, L., Tiri, A., Mouni, L.: Spatial distribution of the groundwater quality using kriging and Co-kriging interpolations. Groundwater for Sustainable Development, 11, 100473, 2020.

Berglund, M.: Early Holocene in Gästrikland, east central Sweden: shore displacement and isostatic recovery. Boreas, 41(2), 263-276, https://doi.org/10.1111/j.1502-3885.2011.00228.x, 2012.

Berra, F., Jadoul, F., Anelli, A.: Environmental control on the end of the Dolomia Principale/Hauptdolomit depositional system in the central Alps: coupling sea-level and climate changes. Palaeogeography, Palaeoclimatology, Palaeoecology, 290(1-4), 138-150, https://doi.org/10.1016/j.palaeo.2009.06.037 , 2010.

Bērziņš, V., Lübke, H., Berga, L., Ceriņa, A., Kalniņa, L., Meadows, J., Muižniece, S., Paegle, S., Rudzīte, M., Zagorska, I.: Recurrent Mesolithic–Neolithic occupation at Sise (western Latvia) and shoreline displacement in the Baltic Sea Basin. The Holocene, 26(8), 1319-1325. https://doi.org/10.1177/0959683616638434, 2016.

Björck, S.: A review of the history of the Baltic Sea, 13.0-8.0 ka BP. Quaternary international, 27, 19-40, https://doi.org/10.1016/1040-6182(94)00057-C, 1995.

Björck, S.: The late Quaternary development of the Baltic Sea basin. In Assessment of climate change for the Baltic Sea Basin (pp. 398-407). Springer, 2008.

Bola, A., Kayode, J.S.: An evaluation of digital elevation modeling in GIS and Cartography, Geo-spatial Information Science, 17:2, 139-144, DOI:10.1080/10095020.2013.772808, 2014.

Bobertz, B., Harff, J., Bohling, B.: Parameterisation of clastic sediments including benthic structures. Journal of Marine Systems, 75 (3-4). pp. 371-381. DOI 10.1016/j.jmarsys.2007.06.010, 2009.

Boston, T., Van Dijk, A., Larraondo, P.R., Thackway, R.: Comparing CNNs and Random Forests for Landsat Image Segmentation Trained on a Large Proxy Land Cover Dataset. Remote Sens., 14, 3396. https://doi.org/10.3390/rs14143396, 2022

Covington, J.H., P., Kennelly, P.: Paleotopographic influences of the Cretaceous/Tertiary angular unconformity on uranium mineralization in the Shirley Basin, Wyoming, Journal of Maps, 14:2, 589-596, https://doi.org/10.1080/17445647.2018.1512014, 2018.

Christiansen, C., Kunzendorf, H., Emeis, K.-C., Endler, R., Struck, U., Neumann, T., Sivkov, V., Temporal and spatial sedimentation rate variabilities in the eastern Gotland Basin, the Baltic Sea. Boreas, Vol. 31, pp. 65–74, https://doi.org/10.1111/j.1502-3885.2002.tb01056.x, 2002.

Damušytė, A.: Post-glacial geological history of the Lithuanian coastal area, Doctoral Dissertation, Physical Sciences, Geology, Vilnus. 2011.

Dudzińska-Nowak, J.: Morphodynamic processes of the Swina Gate coastal zone development (southern Baltic Sea). Coastline Changes of the Baltic Sea from South to East: Past and Future Projection, 219-255, 2017.

Einsele, G.: Event deposits: the role of sediment supply and relative sea-level changes—overview. Sedimentary Geology, 104(1-4), 11-37, https://doi.org/10.1016/0037-0738(95)00118-2, 1996.

Emelyanov E.: Geology of the Gdańsk Basin, Russian Academy of Sciences, Atlantic Branch of P. P. Shirshov Institute of Oceanology, Yantarny skaz, Russian Federation, 2002.

Endler, M., Endler, R., Bobertz, B., Leipe, T., Arz, H.W.: Linkage between acoustic parameters and seabed sediment properties in the south-western Baltic Sea. Geo-Marine Letters, 35, 145-160, https://doi.org/10.1007/s00367-015-0397-3, 2015.

Farrell, W., Clark, J.:. On Postglacial Sea Level. Geophys. J. Int. 46, 647 – 667, https://doi.org/10.1111/j.1365-246X.1976.tb01252.x, 1976.

Gale, A. S., Hardenbol, J., Hathway, B., Kennedy, W. J., Young, J. R., Phansalkar, V.: Global correlation of Cenomanian (Upper Cretaceous) sequences: Evidence for Milankovitch control on sea level. Geology, 30(4), 291-294, https://doi.org/10.1130/0091-7613(2002)030%3C0291:GCOCUC%3E2.0.CO;2 , 2002.

GEBCO Compilation Group (2023) GEBCO 2023 Grid (doi:10.5285/f98b053b-0cbc-6c23-e053-6c86abc0af7b)

Gelumbauskaitė, L. Ž.: Character of sea level changes in the subsiding south-eastern Baltic Sea during Late Quaternary. Baltica, 22(1), 23-36, 2009.

Glückert, G.: Post-glacial shore-level displacement of the Baltic in SW Finland. Ann. Acad. Sci. Fenn., Ser. A III 118, 1976.

Golden Software Surfer User's Guide (p. 446–448). Available on-line https://gis.fns.uniba.sk/vyuka/DTM_ako_sucast_GIS/Kriging/2/Surfer_8_Guide.pdf (last accessed 16th December 2023).

Gonet, T. and Gonet, K.: Alternative Approach to Evaluating Interpolation Methods of Small and Imbalanced Data Sets, Geomatics and Environmental Engineering 11(3), 49-65, http://dx.doi.org/10.7494/geom.2017.11.3.49, 2017.

Goovaerts, P.: Ordinary cokriging revisited. Mathematical Geology, 30, 21-42, 1998.

Groh, A., Harff, J.: Relative sea-level changes induced by glacial isostatic adjustment and sediment loads in the Beibu Gulf, South China Sea. Oceanologia 65(1), 249 – 259. https://doi.org/10.1016/j.oceano.2022.09.001, 2023.

Grudzinska, I., Saarse, L., Vassiljev, J., Heinsalu, A.: Mid-and late-Holocene shoreline changes along the southern coast of the Gulf of Finland. Bulletin of the Geological Society of Finland, 85, 2013.

Grudzinska, I., Saarse, L., Vassiljev, J., Heinsalu, A.: Biostratigraphy, shoreline changes and origin of the Limnea Sea lagoons in northern Estonia: the case study of Lake Harku. Baltica, 27(1), https://doi.org/10.5200/baltica.2014.27.02, 2014.

Grund, S., Geiger, J.: Sedimentologic modelling of the Ap-13 hydrocarbon reservoir. Central European Geology, 54/4, pp. 327–344, DOI: 10.1556/CEuGeol.54.2011.4.2, 2011.

Groh, A., Richter, A., Dietrich, R.: Recent Baltic Sea Level Changes Induced by Past and Present Ice Masses. In: Harff, J., Furmańczyk, K., von Storch, H. (eds) Coastline Changes of the Baltic Sea from South to East. Coastal Research Library, vol 19. Springer, Cham. https://doi.org/10.1007/978-3-319-49894-2_4, 2017.

Gudelis, V., Emelyanov, E. (eds.): Geology of the Baltic Sea, Mokslas Publishers, 1976.

Habicht, H. L., Rosentau, A., Jõeleht, A., Heinsalu, A., Kriiska, A., Kohv, M., Hang, T., Aunap, R.: GIS-based multiproxy coastline reconstruction of the eastern Gulf of Riga, Baltic Sea, during the Stone Age. Boreas, 46(1), 83-99, https://doi.org/10.1111/bor.12157, 2017.

Hall, A., van Boeckel, M.: Origin of the Baltic Sea basin by Pleistocene glacial erosion. Gff, 142(3), 237-252, https://doi.org/10.1080/11035897.2020.1781246, 2020.

Hansson, A., Nilsson, B., Sjöström, A., Björck, S., Holmgren, S., Linderson, H., Magnell, O., Rundgren, M., Hammarlund, D., A submerged Mesolithic lagoonal landscape in the Baltic Sea, south-eastern Sweden–Early Holocene environmental reconstruction and shore-level displacement based on a multiproxy approach. Quaternary International, 463, 110-123, https://doi.org/10.1016/j.quaint.2016.07.059, 2018.

Harff, J.; Lemke, W.; Lampe, R.; Lüth, F.; Lübke, R.; Meyer, M.; Tauber, F.; Schmölcke, U.: The Baltic Sea Coast – a Model of Interrelations between Geosphere, Climate and Anthroposphere. – In: Harff, J.; Hay, W.W.; Tetzlaff, D. (eds.): Coastline Change – Interrelation of Climate and Geological Processes. – The Geological Society of America, Spec. Pap. 426, pp. 133-142, 2007.

Harff , J., Endler, R., Emelyanov, E., Kotov, S., Leipe, T., Moros, M., Olea, R.A., Tomczak, M., Witkowski, A.: Late Quaternary Climate Variations reflected in Baltic Sea Sediments.- in. Harff, J., Björck, S., Hoth, P. (eds,). The Baltic Sea Basin.- Springer. Berlin et al., p. 99-132, 2011.

Harff, J., Deng, J., Dudzinska-Nowak, J., Fröhle, P., Groh, A., Hünicke, B., Soomere, T., Zhang, W.: What Determines the Change of Coastlines in the Baltic Sea? 2017, in: Harff, J., Furmanczyk, K., von Storch, H. (eds) 2017. Coastline Changes of the Baltic Sea from South to East - Past and Future Projection Coastal Research Library, vol 19. Springer, Heidelberg, pp 15-35, doi:10.1007/978-3-319-49894-2_4.

Heinsalu, A., Veski, S.: The history of the Yoldia Sea in Northern Estonia: palaeoenvironmental conditions and climatic oscillations. Geological Quarterly, 51, 295-306, 2007.

Hulskamp, R., Luijendijk, A., van Maren, B. *et al.* Global distribution and dynamics of muddy coasts. *Nat Commun* **14**, 8259 (2023). https://doi.org/10.1038/s41467-023-43819-6

Jakobsson, M., Björck, S., Alm, G., Andrén, T., Lindeberg, G., Svensson, N. O.: Reconstructing the Younger Dryas ice dammed lake in the Baltic Basin: Bathymetry, area and volume. Global and Planetary Change, 57(3-4), 355-370, https://doi.org/10.1016/j.gloplacha.2007.01.006, 2007.

Jakobsson, M., Stranne, C., O'Regan, M., Greenwood, S. L.,Gustafsson, B., Humborg, C., and Weidner, E.: Bathymetric properties of the Baltic Sea, Ocean Sci., 15, 905–924, https://doi.org/10.5194/os-15-905-2019, 2019.

Karle M, Bungenstock F, Wehrmann A.: Holocene coastal landscape development in response to rising sea level in the Central Wadden Sea coastal region. *Netherlands Journal of Geosciences* 100, e12. doi:10.1017/njg.2021.10, 2021.

Kaskela, A. M., Kotilainen, A. T., Al-Hamdani, Z., Leth, J. O., Reker, J.: Seabed geomorphic features in a glaciated shelf of the Baltic Sea. Estuarine, Coastal and Shelf Science, 100, 150-161., https://doi.org/10.1016/j.ecss.2012.01.008 , 2012.

Konomi, B. A., Kang, E. L., Almomani, A., Hobbs, J.: Bayesian Latent Variable Co-kriging Model in Remote Sensing for Quality Flagged Observations. Journal of Agricultural, Biological and Environmental Statistics, 1-19, 2023.

Lambeck, K., Purcell, A., Zhao, J., Svensson, N. O.: The Scandinavian ice sheet: from MIS 4 to the end of the last glacial maximum. Boreas, 39(2), 410-435, https://doi.org/10.1111/j.1502-3885.2010.00140.x, 2010.

Lampe, R., Janke, W.: The Holocene sea level rise in the Southern Baltic as reflected in coastal peat sequences. Polish geological institute Special papers, 11, 19-29, 2004.

Lampe, R., Endtmann, E., Janke, W., Meyer, H.: Relative sea-level development and isostasy along the NE German Baltic Sea coast during the past 9 ka. E&G Quaternary Science Journal, 59(1/2), 3-20, https://doi.org/10.3285/eg.59.1-2.01, 2011.

Leenaers, H., Burrough, P. A., Okx, J. P.: Efficient mapping of heavy metal pollution on floodplains by co-kriging from elevation data. In Three Dimensional Applications in GIS (pp. 37-50). CRC Press, 2020.

Leipe, T., Tauber, F., Vallius, H., Virtasalo, J., Uścinowicz, S., Kowalski, N., Hille, S., Lindgren, S., Myllyvirta, T.:Particulate organic carbon (POC) in surface sediments of the Baltic Sea. *Geo-Mar Lett* **31**, 175–188, https://doi.org/10.1007/s00367-010-0223-x, 2011.

Lemke, W.: Sedimentation und paläogeographische Entwicklung im westlichen Ostseeraum (Mecklenburger Bucht bis Arkonabecken) vom Ende der Weichselvereisung bis zur Litorinatransgression. Institut für Ostseeforschung Warnemünde, 1998.

Lemke, W., Jensen, J. B., Bennike, O., Endler, R., Witkowski, A., Kuijpers, A.: Hydrographic thresholds in the western Baltic Sea: Late Quaternary geology and the Dana River concept. Marine Geology, 176(1-4), 191-201, https://doi.org/10.1016/S0025-3227(01)00152-9, 2001.

Libina, N.V., Nikiforov, S.L.: Digital Elevation Models of the Bottom in the Operational Oceanography System. Oceanology 60, 854–860, https://doi.org/10.1134/S0001437020050124, 2020.

Lindén, M., Möller, P. E. R., Björck, S., Sandgren, P. E. R., Holocene shore displacement and deglaciation chronology in Norrbotten, Sweden. Boreas, 35(1), 1-22, https://doi.org/10.1111/j.1502-3885.2006.tb01109.x, 2006.

Liu, L., Xing, F., Li, Y., Han, Y., Wang, Z., Zhi, X., Wang, G., Feng, L., Yang., B., Lei., Y., Fan, Z., Du., W.: Study of the geostatistical grid maths operation method of quantifying water movement in soil layers of a cotton field, Irrig and Drain, 69:1146–1156, https://doi.org/10.1002/ird.2513, 2020.

Liu, N., He, T., Tian, Y., Wu, B., Gao, J., Xu, Z.: Common azimuth seismic data fault analysis using residual U-Net. Interpretation. 8. 1-41. 10.1190/int-2019-0173.1, 2020.

Liu, Y., Huang, H., Qi, Y., Liu, X., Yang, X.: Holocene coastal morphologies and shoreline reconstruction for the southwestern coast of the Bohai Sea, China. Quaternary Research, 86(2):144-161. doi:10.1016/j.yqres.2016.06.002. 2016

Lõugas, L., Tomek, T.:Marginal effect at the coastal area of Tallinn Bay: The marine, terrestrial and avian fauna as a source of subsistence during the Late Neolithic. Man, his time, artefacts, and paces. Collection of articles dedicated to Richard Indreko. Muinasaja teadus, 19, 463-485, 2013.

Luijendijk, A., Hagenaars, G., Ranasinghe, R., Baart, F., Donchyts, G., Aarninkhof, S.: The State of the World's Beaches. *Sci Rep* **8**, 6641, https://doi.org/10.1038/s41598-018-24630-6, 2018.

Maystrenko, Y., Bayer, U., Brink, H. J., Littke, R.: The Central European Basin System – an Overview. In: Littke, R., Bayer, U., Gajewski, D., Nelskamp, S. (eds) Dynamics of Complex Intracontinental Basins. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-85085-4_2, 2008.

Matthäus, W., Franck, H.: Characteristics of major Baltic inflows – a statistical analysis. Continental Shelf Research, 12(12), 1375-1400, https://doi.org/10.1016/0278-4343(92)90060-W, 1992.

Mentaschi, L., Vousdoukas, M. I., Pekel, J. F., Voukouvalas, E., Feyen, L.: Global long-term observations of coastal erosion and accretion. *Sci Rep* **8**, 12876, https://doi.org/10.1038/s41598-018-30904-w, 2018.

Miettinen, A. I.: Relative sea level changes in the eastern part of the Gulf of Finland during the last 8000 years, 2003.

Miluch, J., Osadczuk, A., Feldens, P., Harff, J., Maciąg, Ł., Chen, H., 2021.: Seismic profiling-based investigation of geometry and sedimentary architecture of the late Pleistocene delta in the Beibu Gulf, SW of Hainan Island. J. Asian Earth Sci. 205, 104611. https://doi.org/10.1016/j.jseaes.2020.104611, 2021.

Miluch J., Maciąg Ł., Osadczuk A., Harff J., Jiang T., Chen H., Borówka R.K., McCartney, K.: Multivariate geostatistical modeling of seismic data: Case study of the Late Pleistocene paleodelta architecture (SW off-shore Hainan Island, South China Sea), Marine and Petroleum Geology, Marine and Petroleum Geology 136, 105467, https://doi.org/10.1016/j.marpetgeo.2021.105467, 2022.

Myers, D. E.: Matrix formulation of co-kriging. Journal of the International Association for Mathematical Geology, 14, 249-257, 1982.

Myers, D. E.: Co-kriging – new developments. In Geostatistics for Natural Resources Characterization: Part 1 (pp. 295-305). Dordrecht: Springer Netherlands, 1984.

Neumann, B., Vafeidis, A. T., Zimmermann, J., Nicholls, R. J.: 2015. Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding – A Global Assessment. PLoS ONE 10, e0118571, https://doi.org/10.1371/journal.pone.0118571, 2015.

Paszke, A., Gross, S., Massa, F., Lerer, A., Bradbury, J., Chanan, G., Kileen, T., Lin, Z., Gimelshein, N., Antiga, L., Desmaison, A., Kopf, A., Yang, E., DeVito, Z., Raison, M., Tejani, A., Chilamkurthy, S., Steiner, B., Fang, L., Bai, J., Chintala, S.: PyTorch: An Imperative Style, High-Performance Deep Learning Library. In Advances in Neural

Formatted: English (United States)

Field Code Changed

Field Code Changed

Field Code Changed

Information Processing Systems 32, edited by H. Wallach, H. Larochelle, A. Beygelzimer, F. d'Alché-Buc, E. Fox, and R. Garnett, Pp. 8024–8035. Curran Associates, Inc. Publisher's Version, 2019.

Patton, H., Hubbard, A., Andreassen, K., Auriac, A., Whitehouse, P. L., Stroeven, A. P., Shackleton, C., Winsborrow, M., Heyman, J., Hall, A. M.: Deglaciation of the Eurasian ice sheet complex. Quaternary Science Reviews, 169, 148-172, https://doi.org/10.1016/j.quascirev.2017.05.019 , 2017.

Peltier, W.:Postglacial variations in the level of the sea: Implications for climate dynamics and solid-earth geophysics. Rev. Geophys. 36, 603 – 689. https://doi.org/10.1029/98RG02638, 1998.

Peltier, W. R.: Global sea level rise and glacial isostatic adjustment. Global and planetary change, 20(2-3), 93-123, https://doi.org/10.1016/S0921-8181(98)00066-6, 1999.

Peltier, W.: Global glacial isostasy and the surface of the ice-age Earth: the ICE-5G (VM2) model and GRACE. Annu. Rev. Earth Pl. Sc. 32, 111 – 149. https://doi.org/10.1146/annurev.earth.32.082503.144359, 2004.

Peltier, W. R.: Postglacial coastal evolution: ice–ocean–solid Earth interactions in a period of rapid climate change, https://doi.org/10.1130/2007.2426(02), 2007.

Ponomarenko, E.: Holocene palaeoenvironment of the central Baltic Sea based on sediment records from the Gotland Basin, Regional Studies in Marine Science, Volume 63, 102992, https://doi.org/10.1016/j.rsma.2023.102992, 2023.

Porz, L., Zhang, W.,Schrum, C.: Density-driven bottom currents control development of muddy basins in the southwestern Baltic Sea. Marine Geology, Volume 438, 106523, https://doi.org/10.1016/j.margeo.2021.106523, 2021.

Razas, M.A., Hassan, A., Khan, M.U., Emach, M.Z., Saki, S.A.: A critical comparison of interpolation techniques for digital terrain modelling in mining. Journal of the Southern African Institute of Mining and Metallurgy, 123(2), 53-62. https://dx.doi.org/10.17159/2411-9717/2271/2023, 2023.

Ronneberger, O., Fischer, P., Brox, T U-Net: Convolutional Networks for Biomedical Image Segmentation. Medical Image Computing and Computer-Assisted Intervention (MICCAI), Springer, LNCS, Vol.9351: 234-241, 2015.

Root, B. C., van der Wal, W., Novák, P., Ebbing, J., Vermeersen, L. L. A.: Glacial isostatic adjustment in the static gravity field of Fennoscandia. Journal of Geophysical Research: Solid Earth, 120(1), 503-518, https://doi.org/10.1002/2014JB011508, 2015.

Rosentau, A., Harff, J., Oja, T., Meyer, M.: Postglacial rebound and relative sea level changes in the Baltic Sea since the Litorina transgression, Baltica 25 (2), 113-120, https://doi.org/10.5200/baltica.2012.25.11, 2012.

Rosentau, A., Muru, M., Kriiska, A., Subetto, D. A., Vassiljev, J., Hang, T., Gerasimov, D., Nordqvist, K., Ludikova, A., Lõugas, L., Raig, H., Kihno, K., Aunap, R., Letyka, N.: Stone Age settlement and Holocene shore displacement in the Narva-Luga Klint Bay area, eastern Gulf of Finland. Boreas, 42, 912–931, https://doi.org/10.1111/bor.12004, 2013.

Rosentau, A., Bennike, O., Uścinowicz, S., Miotk-Szpiganowicz, G.: The Baltic Sea Basin. Submerged landscapes of the European continental shelf: quaternary paleoenvironments, 103-133, https://doi.org/10.1002/9781118927823.ch5, 2017.

Rosentau, A., Klemann, V., Bennike, O., Steffen, H., Wehr, J., Latinoviˊc, M., Bagge, M., Ojala, A., Berglund, M., Becher, G. P., et al.: A Holocene relative sea-level database for the Baltic Sea, Quaternary Science Reviews, 266, 107 071, https://doi.org/10.1016/j.quascirev.2021.107071, 2021.

Ryabchuk, D.V., Sergeev, A.Y., Prishchepenko, D.V., Zhamoida, V.A., Elkina, D.V., Piskarev, A.L., Bashirova, L.D., Ponomarenko, E.P., Budanov, L.M., Grigoriev, A.G., Evdokimenko, A.V.: Impact of climate change on sedimentation processes in the eastern Gulf of Finland during the Middle to Late Holocene. Boreas 50, 381-403. https://doi.org/10.1111/bor.12500, 2020.

Saarnisto, M.: Holocene emergence history and stratigraphy in the area north of the Gulf of Bothnia. Suomalainen tiedeakatemia, 1981.

Sandwell, D.T., Gille, S.T., Smith, W.H.F., eds., Bathymetry from Space: Oceanography, Geophysics, and Climate, Geoscience Professional Services, Bethesda, Maryland,, 24pp., 2002.

Schmedemann, N., Schafmeister, M. T., Hoffmann, G.: Numeric de-compaction of Holocene sediments. Polish Geological Institute Special Papers, 23, 87-94, 2008.

Shaw, J., Piper, D. J. W., Fader, G. B. J., King, E. L., Todd, B. J., Bell, T., Batterson, M.J., Liverman, D. G. E.: A conceptual model of the deglaciation of Atlantic Canada. Quaternary Science Reviews, 25(17-18), 2059-2081, https://doi.org/10.1016/j.quascirev.2006.03.002, 2006.

Sohlenius, G., Emeis, K. C., Andrén, E., Andrén, T., Kohly, A. Development of anoxia during the Holocene fresh–brackish water transition in the Baltic Sea. Marine Geology, 177(3-4), 221-242, https://doi.org/10.1016/S0025-3227(01)00174-8, 2001.

Spada, G., Stocchi, P.:SELEN: A Fortran 90 program for solving the ''sea-level equation''. Comput. Geosci. 33, 538 – 562. https://doi.org/10.1016/j.cageo.2006.08.006, 2007.

Spada, G., Melini, D., Galassi, G., Colleoni, F.: Modeling sea level changes and geodetic variations by glacial isostasy: the improved SELEN code. arXiv preprint arXiv:1212.5061, https://doi.org/10.48550/arXiv.1212.5061, 2012.

Statteger, K., Leszczyńska, K.: Rapid sea-level rise during the first phase of the Littorina transgression in the western Baltic Sea, Oceanologia, 65 (1), 202-210, https://doi.org/10.1016/j.oceano.2022.05.001, 2023.

Steffen, H., Wu, P. Glacial isostatic adjustment in Fennoscandia—a review of data and modeling. Journal of geodynamics, 52(3-4), 169-204, https://doi.org/10.1016/j.jog.2011.03.002, 2011.

Stokes, C. R., Tarasov, L., Blomdin, R., Cronin, T. M., Fisher, T. G., Gyllencreutz, R., Hätterstand, C., Heyman, J., Hindmarsh, R. C. A., Hughes, A. L. C., Jakobsson, M., Kirchner, N., Livingstonen, S. J., Margold, M., Murton, J. B., Noormets, R., Peltier, W. R., Peteet, D. M., Piper, D. J. W., Preusser, F., Renssen, H., Roberts, D. H., Rocher, D. M., Saint-Ange, F., Stroven, A. P. Teller, J. T.: On the reconstruction of palaeo-ice sheets: recent advances and future challenges. Quaternary Science Reviews 125, 15–49., https://doi.org/10.1016/j.quascirev.2015.07.016 , 2015.

Sturt, F., Garrow, D., Bradley, S.: New models of North West European Holocene paleogeography and inundation. Journal of Archaeological Science 40 (11), 3963-3976, https://doi.org/10.1016/j.jas.2013.05.023, 2013.

Uehara, K., J. D. Scourse, K. J. Horsburgh, K. Lambeck, and A. P. Purcell: Tidal evolution of the northwest European shelf seas from the Last Glacial Maximum to the present, *J. Geophys. Res.*, 111, C09025, doi:10.1029/2006JC003531, 2006.

Uścinowicz, S.: Geological Atlas of the Southern Baltic – Holocene thickness, Polish Geological Institute, 1998.

Uścinowicz, S.: A relative sea-level curve for the Polish Southern Baltic Sea, Quaternary International, 145–146, 86-105, https://doi.org/10.1016/j.quaint.2005.07.007, 2006.

Uścinowicz, S.: The Baltic Sea continental shelf. In Chiocci, F. L, Chivas, A. R (eds.) Continental Shelves of the World: Their Evolution During the Last Glacio-Eustatic Cycle. Geological Society Memoir, 41, 69-89, https://doi.org/10.1144/m41.7, 2014.

Uścinowicz, S., Miotk-Szpiganowicz, G., Krąpiec, M., Witak, M., Harff, J., Lübke, H., Tauber, F.: Drowned forests in the Gulf of Gdańsk (Southern Baltic) as an indicator of the Holocene shoreline changes. The Baltic Sea Basin, 219-231, 2011.

Uścinowicz, S.: Hel Peninsula–geological structure and history. Assessing the Baltic Sea Earth System, 4th Baltic Earth Conference, Jastarnia, Poland, 30 May – 3 June 2022.

Van der Molen, J., and Van Dijck, B.: The evolution of the Dutch and Belgian coasts and the role of sand supply from the North Sea. Glob. Planet. Chang. 27 (1-4), 223-244. 2000.

Varela, A. N.: Tectonic control of accommodation space and sediment supply within the Mata Amarilla Formation (lower Upper Cretaceous) Patagonia, Argentina. Sedimentology, 62(3), 867-896, https://doi.org/10.1111/sed.12164, 2015.

Vink, A., Steffen, H., Reinhardt, L., Kaufmann, G.: Holocene relative sea-level change, isostatic subsidence and the radial viscosity structure of the mantle of northwest Europe (Belgium, the Netherlands, Germany, southern North Sea). Quaternary Science Reviews, 26(25-28), 3249-3275, https://doi.org/10.1016/j.quascirev.2007.07.014, 2007.

Vött, A.: Relative sea level changes and regional tectonic evolution of seven coastal areas in NW Greece since the mid-Holocene. Quaternary Science Reviews, 26(7-8), 894-919, https://doi.org/10.1016/j.quascirev.2007.01.004, 2007.

Wackernagel, H.,Wackernagel, H.: Ordinary kriging. Multivariate geostatistics: an introduction with applications, 79-88, 2003.

Waelbroeck, C., Labeyrie, L., Michel, E., Duplessy, J.C., McManus, J.F., Lambeck, K., Balbon, E., Labracherie, M.: Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records. Quat. Sci. Rev. 21, 295–305. https://doi.org/10.1016/S0277-3791(01)00101-9, 2002.

Wang, X., Zhang, W., Xie, X., Chen, H., and Chen, B.: Holocene sedimentary distribution and morphological characteristics reworked by East Asian monsoon dynamics in the Mekong River shelf, South Vietnam. Estuarine, Coastal and Shelf Science, Vol 302, 108784, doi:10.1016/j.ecss.2024.108784, 2024.

Watts, A. B.: Tectonic subsidence, flexure and global changes of sea level. Nature, 297(5866), 469-474, 1982.

Weisse, R., Dailidienė, I., Hünicke, B., Kahma, K., Madsen, K., Omstedt, A., Parnell, K., Schöne, T., Soomere, T., Zhang, W., Zorita, E. (2021): Sea level dynamics and coastal erosion in the Baltic Sea region. Earth Syst. Dynam., 12, 871–898, https://doi.org/10.5194/esd-12-871-2021, 2021.

Winterhalter, B.: On the geology of the Bothnian Sea, an epeiric sea that has undergone Pleistocene glaciation, Geological Survey of Finland Bulletin 258, Geologinen Tutkimuslaitos, Otaniemi, Finland, 1972.

Wu, C.Y., Wei X., Ren, J., Bao, Y., He, Z.G., Lei, Y.P., Shi, H.Y., Zhang, W.: Morphodynamics of the rock-bound outlets of the Pearl River estuary, South China — A preliminary study, Journal of Marine Systems, 82(1), 17–27, https://doi.org/10.1016/j.jmarsys.2010.02.002 , 2010.

Wulff, F., Stigebrandt, A., Rahm, L.: Nutrient dynamics of the Baltic Sea. Ambio, 126-133, 1990.

Xiong, P., Dudzińska-Nowak, J., Harff, J., Xie, X., Zhang, W., Chen, H., Jiang, T., Chen, H., Miluch, J., Feldens, P., Maciąg, L., Osadczuk, A., Meng, Q., Zorita, E.: Modeling paleogeographic scenarios of the last glacial cycle as a base for source-to-sink studies: an example from the northwestern shelf of the South China Sea. J. Asian Earth Sci. 203, 104542. https://doi.org/10.1016/j.jseaes.2020.104542, 2020.

Yang, S.L., Xu, K.H., Milliman, J.D., Yang, H.F., Wu, C.S.: Decline of Yangtze River sediment discharge: impact from natural and anthropogenic changes. Sci. Rep. 5, 12581. https://doi.org/10.1038/srep12581, 2014.

Yao, Y., Harff, J., Meyer, M., Zhan, W.: Reconstruction of paleocoastlines for the northwestern south China sea since the last glacial maximum. Sci. China Earth Sci. 52, 1127–1136. https://doi.org/10.1007/s11430-009-0098-8, 2009.

Yilmaz, H.M.: The effect of interpolation methods in surface definition: an experimental study, Earth Surf. Process. Landforms 32, 1346–1361, https://doi.org/10.1002/esp.1473, 2007.

Zhang, P., Ke, Y., Zhang, Z., Wang, M., Li, P. Zhang, S. Urban Land Use and Land Cover Classification Using Novel Deep Learning Models Based on High Spatial Resolution Satellite Imagery. Sensors, 18, 3717. https://doi.org/10.3390/s18113717, 2018.

Zhang, W., Arlinghaus, P.: Climate, Coast, and Morphology. In: Oxford Research Encyclopedia of Climate Science. Oxford University Press, https://doi.org/10.1093/acrefore/9780190228620.013.814, 2022.

Zhang, W., Xiong, P., Meng, Q., Dudzińska-Nowak, J., Chen, H., Zhang, H., Zhou, F., Miluch, J., Harff, J.: Morphogenesis of a late Pleistocene delta off the southwestern Hainan Island unraveled by numerical modeling. J. Asian Earth Sci. 195, 104351. https://doi.org/10.1016/j.jseaes.2020.104351, 2020.

Zhang, W., Harff, J., Schneider, R., Meyer, M., Zorita, E., Hünicke, B.: Holocene morphogenesis at the southern Baltic Sea: simulation of multiscale processes and their interactions for the Darss-Zingst peninsula. Journal of Marine Systems, 129, 4-18, https://doi.org/10.1016/j.jmarsys.2013.06.003, 2014.

Zhang, W., Harff, J., Schneider, R., Meyer, M., Wu, C.Y.: A multi-scale centennial morphodynamic model for the southern Baltic coast. Journal of Coastal Research, 27, 890-917. https://doi.org/10.2112/JCOASTRES-D-10-00055.1, 2011a.

Zhang, W., Harff. J and Schneider, R.: Analysis of 50-year wind data of the southern Baltic Sea for modelling coastal morphological evolution - a case study from the Darss-Zingst Peninsula. Oceanologia, 53 (1-TI), 489-518. doi:10.5697/oc.53-1-TI.489, 2011b.