A Holocene sea-level database for the Baltic Sea, Supplement 2: The country-wise data description

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Contents

1 Country-wise data description

The following subsections summarize the sea-level data submitted for each country and explain its quality, its relation to the Baltic Sea evolution and which corrections have been applied. We start with Finland in the northeast and, then, move anticlockwise around the Baltic Sea, finishing with Russia. Some countries (Sweden, Denmark and Germany) have two or three individual contributions to the database. The locations of the samples are displayed in Fig. 3 of the main document and the temporal distribution of the data is presented in Fig. 5 of the main document. During the discussions, we refer to the (unique) Sample IDs presented in the workbook table (Suppl. 1) by [#], and refer to the respective column number given therein. For details on the column definitions, see the HOLSEA Workbook documentation which follows the recommendations by Hijma et al. (2015) and was recently updated in 2019 at https://www.holsea.org/archive-your-data.

The respective compilations and their discussion were provided by following authors: Finland by Antti E. K. Ojala; central Sweden by Mikael Berglund; southern Sweden by Anton Hansson, Gustaf Peterson, Kristian Schoning; Denmark, overview by Ole Bennike; Denmark, Samsø by Lars Nielsen, Lars B. Clemmensen, Mikkel U. Hede, Aart Kroon, Morten Pejrup and Lasse Sander; Germany, Schleswig-Holstein by Karl Stattegger, Klaus Schwarzer and Volker Klemann; Germany, Mecklenburg-Vorpommern by Reinhard Lampe and Matthias Lampe; Poland by Szymon Uścinowicz; Lithuania by Albertas Bitinas; Latvia by Ieva Grudzinska and Jüri Vassiljev; Estonia and Russia, Narva–Luga by Alar Rosentau; Russia by Yuriy A. Kublitskiy and Dmitry A. Subetto. Jasmin Wehr developed the parsing software; Volker Klemann set up the database system; Milena Latinović did the calibration of radiocarbon dates; Meike Bagge and Holger Steffen provided GIA-modelling results.

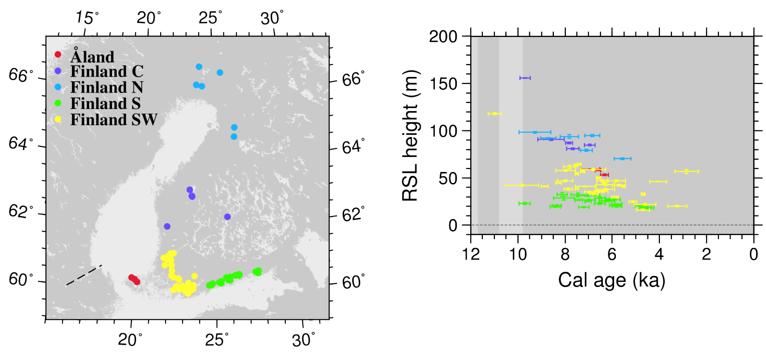

Figure S2.1: Location of Finnish sea-level data points in the HOLSEA database. Samples of respective sub-regions are distinguished by different colours. Left: geographic location. Right: time–RSL-height dependency, i.e., sea-level curve with respective uncertainties. TL and ML are distinguished from SLIPs by vertical lines pinning down and up, respectively (see Figs. S2.3ff); rejected sea-level data points are not shown on the right. Light grey parts indicate the considered timings of the Baltic Ice Lake termination and duration of the Ancylus Lake.

1.1 Finland

The majority of studies on shoreline displacement and Baltic-Sea stages in Finland has been carried out in the 1970s and 1980s. Among those, Eronen (1974, 1976) studied the history of the LS and Ancylus transgressions. Eronen and Haila (1982) investigated shoreline displacement in the Helsinki region in southern Finland. Shoreline displacement and land uplift studies in the Olkiluoto-Pyhäjärvi area were conducted by Eronen et al. (1995a), whereas Ristaniemi and Glückert (1987, 1988) put their focus on the Ancylus and Littorina transgressions in southern Finland.

The post-glacial radiocarbon-dated and lake isolation-based shoreline data of the Baltic Sea basin have been summarized by Eronen et al. (1995a). The data were used and updated by Eronen et al. (1995b), and since then, new shoreline displacement data have been published by Eronen et al. (2001), Glückert et al. (1993), Hyvärinen (1999), Miettinen et al. (2007a,b), Miettinen et al. (1999), Seppä et al. (2000), and Seppä and Tikkanen (1998). A recent review on shoreline displacement of the Baltic-Sea basin in Finland was given by Vuorela et al. (2009), who provided an updated list of radiocarbon-dated SLIPs for entire Finland.

Ojala et al. (2013) compiled an ArcGIS database called the Ancient Shoreline Database (ASD) to systematically collect and classify all relevant shoreline displacement information related to the highest shoreline and the maximum extension of the LS stage in Finland. The ASD data points and reconstructions are available through the HAKKU spatial data product services (https://hakku.gtk.fi/en) and the MAANKAMARA map services (http://gtkdata.gtk.fi/maankamara/) provided by the Geological Survey of Finland. The ASD was conceived in a way that it will be constantly updated and can be used to document shoreline and lake isolation data related to any of the shoreline stages of the Baltic Sea basin or great lakes in Finland. The ASD database comprises of two separate sections, the isolation observations and the shoreline landform observations, of which the former contains dated sedimentary sections of isolated lakes and mires and this one is considered here.

The authors used airborne LiDAR digital elevation models to validate all published information and to produce additional shoreline data points in areas that lacked information. Eventually, they reconstructed the diachronous maximum extension of the LS and the highest shoreline of the Baltic Sea basin in Finland.

The presented compilation was uploaded in 2017 and was transferred into the HOLSEA format. A re-inventory was not performed and only rules were specified to transfer the information into the columns of the HOLSEA format (see Suppl. 2). For details of the original compilation, we refer to Ojala et al. (2013) and Vuorela et al. (2009). The data was split into five sub-regions representing the south, the south-west, the central, the north and the Åland Islands (Fig. S2.1). The compilation contains 106 samples from which about 70 percent passed the author's quality check to be better than Reliability Class 5 (Column 55) – denoting uncertain or non-validated site and/or observation – or samples containing prominent uncertainties or ambiguities in dating which were not calibrated. The other classes were used to define the indicative range uncertainties.

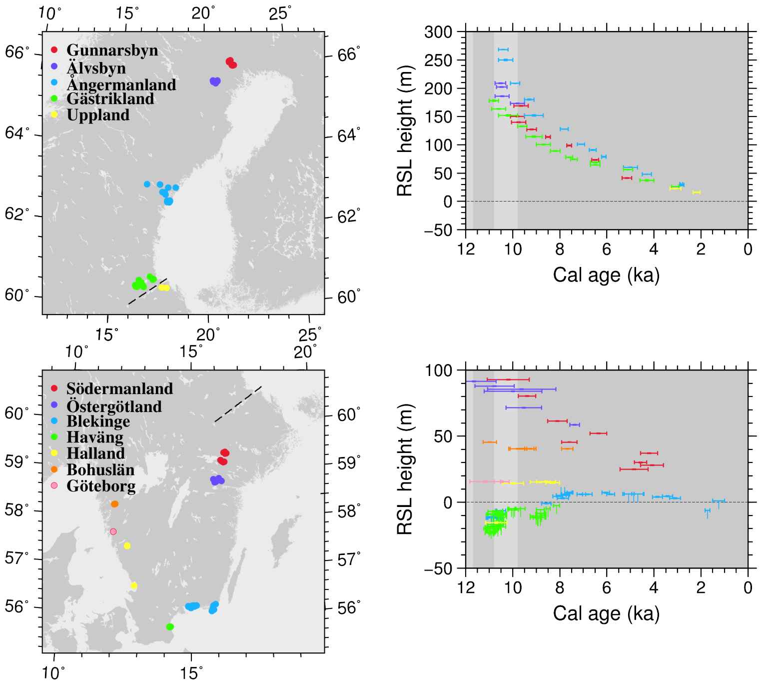

Figure S2.2: Location of Swedish sea-level data points in the HOLSEA database. The data is split for better visualisation into a northern part and a southern part. Dashed line separates data points from the northern- and southern-Sweden compilations. The sites of Haväng and Blekinge are discussed separately in Sec. 1.2.3 of this supplement. For details see Fig. S2.1.

1.2 Sweden

There are three contributing parties from Sweden to the database which cover parts in the north, the southwest and in the southeast of Sweden. Further data, e.g., in southeast Sweden north of Blekinge were not provided so far by respective authors, i.e., this compilation incorporates only a small portion of published data available. As we want to keep the information provided by each party, we discuss the three regions separately.

1.2.1 Northern section

This section presents the shore-displacement data available from two areas in eastern Sweden, central Gästrikland and southern Ångermanland (with adjacent easternmost Jämtland), some 250 km further north (Fig. S2.2). Local deglaciation and formation of the highest postglacial shore level took place during the early Holocene, ca 11 ka BP in the Gästrikland area and ca 10.5 to 10.2 ka BP in the Ångermanland area. Both areas show falling relative sea level (RSL) during the Holocene. A further region which is described briefly at the end of this section describes a small dataset from Norrbotten.

In the Gästrikland area the highest shore level in the area is at ca 200 m hrsl (height of relative sea level), increasing to the north. The following regression is most rapid (ca 5 to 6 cm/yr) during early Holocene and decreases with time. For the period of ca 7 to 6 ka BP, Asklund and Sandegren (1934) suggested the occurrence of brief RSL standstill(s) as a result of global sea-level rise. But recent investigations do not support such a dominance of global sea-level rise vs. isostatic uplift (Berglund, 2010; Berglund, 2005).

In the Ångermanland area, the highest shore level was found at Mt. Skuleberget, ca 286 m hrsl, and is the highest reported in the world. The following regression is rapid during early Holocene, but decreases subsequently from ca 10 cm/yr to currently just below 1 cm/yr. The area is furthermore of significance in that a shore-level reconstruction was made along the adjacent Ångerman River (Lidén, 1938) supplying a fairly reliable pre-radiocarbon chronology through annual-varves counting for both, local deglaciation and Holocene shore displacement. Thus, there are two independent "Ångermanland" RSL curves in the literature. The differences between the older material and recent data are discussed in Berglund (2004).

Most of the shore level data from Gästrikland is presented in Berglund (2005) and represent isolation events. Minor changes are discussed in Berglund (2010, 2012) for the Mid and Early Holocene, respectively. The data from Ångermanland considered in this database are discussed in Berglund (2004). In that paper, data by Wallin (1996) (originally in a paper in Swedish 1994) were included, in which annual lake varves were employed for dating, but which gave less detailed information on microfossil or sediment content. This is indicated in the HOLSEA database. Berglund (2008) presented a correction in RSL for the time interval ca 10 to 9.5 ka BP based on sites further west (eastern Jämtland) with more datings and microfossil control. Hence, the RSL curve for this time interval in Berglund (2004) should be corrected according to observations in Berglund (2008).

For some sites, the altitude was corrected based on a recent digital land elevation model (DEM) provided by Lantmäteriet, the Swedish Mapping, Cadastral and Land Registration Authority, https://www.lantmateriet.se/en/maps-and-geographic-information/Hojddata/GSD-Hojddata-grid-2. Application of this method allowed a control on older topographical measurements (see below).

For most sites in Gästrikland, altitude estimations presented in earlier work by SGU (Swedish Geological Survey) were used (Asklund and Sandegren, 1934; Sandegren et al., 1939). These were based upon levelling from available benchmarks or known lake levels, and were further discussed in Berglund (2005). The sites Ballsen [13] and Skessen [16] (Berglund, 2012) have lake level altitudes presented on modern topographical maps that were used as threshold altitude estimates.

The thresholds of the sites Toretorp [27] (Berglund, 2005) and Koppartjärnen [10] (Berglund, 2010), were newly levelled from benchmarks provided by Lantmäteriet. For the lake site Koppartjärnen, the likelihood of threshold erosion was discussed, and an adjusted value higher than the current threshold is included. The coring altitude at the site Tingtjärn [26], a peatland surface, was measured using DGPS in 2009 and the subsequently corrected (lower) threshold altitude is considered valid (Berglund, 2012). A reanalysis of Österbo [22] (Berglund, 2010; Berglund, 2005) is based on new microfossil and sediment studies, and a review of archive data behind the Asklund and Sandegren (1934) investigation, which suggested a distinct halt in RSL fall.

For a number of sites, the original threshold elevation was corrected after analysis of recent DEM and LiDAR images, with the updated figures included in the database. For the Lake Axen [12] and Lake Ballsen [13], a lower lake level of ca 1 m was included even though the representativeness of the DEM lake levels is unknown (Col 30). At the peat bogs St Ängstjärn [24], Skrånksmyran [23] and Åsmundshyttan [1], the threshold elevation was corrected by -1.5 m, -2.5 m and +1.0 m, respectively (Berglund, 2005).

Threshold elevations at Ångermanland and adjacent Jämtland were in most cases determined from exact benchmarks, provided by Lantmäteriet referenced to RH70. Data releveled with recent DEM and LiDAR images appear to the RH2000 datum and do not have to be corrected. For the sites Frättentjärn [6], Lomtjärn [18] and Värptjärn [28], the threshold level is assumed to be the current lake level, presented on a topographical map, and giving wider error estimates in the database (Col 30). Applying LiDAR images and DEM, the threshold elevation at Lomtjärn [18], Frättentjärn [6] and Mårtensmyran [19] had to be corrected by 4 m, -1 m and ca -1.5 m, respectively (Berglund, 2004).

The isolation events were sampled using a Russian corer, working from peatland surface or from winter lake ice with cm-accuracy in depth and sample thickness. Compaction is considered to be negligible since the critical sampling took place well below any loose, shallow peat or sediment and below groundwater level. At some sites, the threshold area is hidden by peat overgrowth. In these cases, the threshold location was determined by systematic probing or coring in the relevant area.

The radiocarbon datings have been made at Uppsala University and Poznan University and were corrected for fractionation via measurement of δ^{13}C. Between one and four samples were used for dating each site. The samples were extracted as near as possible to the identified isolation interval in the core. The dated material was plant fragments (stems, leaf remains, etc., where identification to species was not possible). In several instances the samples cut from cores contained none or too little plant remains; sometimes samples where combined resulting in varying radiocarbon-dated sample size and depth. Accordingly, age errors given in the HOLSEA database (Group C) are not the statistical error directly from dating or calibration given in the radiocarbon sheet, but an estimate relevant for each site considering the datings, sample selection and size, and isolation indicators.

The procedure resulting in estimation of isolation age (Col C10) can be exemplified: A 300 cm long core may be dated with the centre of the dated sample 5 cm above the assumed isolation event, with an age of 6000 cal BP. Each cm in the core corresponds to on average 20 yr. The 5 cm give an extra age of 100 yr, and the isolation age is assumed to be 6100 cal BP +/- the double standard deviation dating error and an estimation of further uncertainty based upon site-specific matters such as the sharpness of the isolation signals or variation in sedimentation rate, the latter difficult to quantify. A varying number of datings was applied for each site indicated in the comments.

The isolation horizon was identified in two different ways, sedimentology (observing, in the field and by loss on ignition measurement, the organic content, which rises markedly as a basin is isolated), or through microfossils (mainly increase of pollen concentration, as dominant types fluctuate at isolation, and increase in *Pediastrum* freshwater algae). For the sites [3, 10, 15, 17, 22] also diatom analysis was used.

Norbotton

The data from Norbotton stem from two sites Gunnarsbyn and Älvsbyn and are described in Lindén et al., 2006. The dataset contains 12 isolation events and 2 minimum ages of deglaciation which are not considered as SLIPs. The threshold heights were determined from the corresponding lake levels picked from ordnance maps, the isolations are based on the analysis of sediment cores taken at the centre of the respective lakes. All samples were AMS dated at Poznan Radiocarbon Laboratory and were calibrated applying OxCAL with INTCAL98. The detailed description of this data set we do not repeat here, as we did not apply any changes to this dataset.

1.2.2 Southern section

For the region of southern Sweden, the Swedish Geological Survey (SGU) archives were inventoried. The search of the SGU resulted in a total of 12 publications, where seven were not suitable due to lack of datings or of documenting original data (Caldenius et al., 1966; Caldenius and Linnman, 1949; Cato, 1992; Lundquist, 1962; Påsse, 1986, 1988, 1990). The remaining five publications, which are considered in the HOLSEA database, cover three regions along the west coast, Bohuslän (Persson, 1973), Halland (Mörner, 1969), and Göteborg (Mörner, 1969) and three regions from the east coast around the greater Stockholm region, Östergötland (Persson, 1979), Södermanland (Robertsson, 1991), and Uppland (Hedenström and Risberg, 2003) (Fig. S2.1). In contrast to northern Sweden, only isolation basins, where the isolation was "directly" dated, were used, excluding SLIPs, where the age was interpolated from datings above and below the isolation level.

Each region reported here coincides with one study presenting an individual RSL curve. The sea-level data discussed by Mörner (1969) is focused at the Viskan Valley in Halland and could very well be used to create an RSL curve. In Mörners work, two datapoints from Göteborg city are also included.

The sample ID from each publication was used as a sample id, which is now placed in the sub-region (Col. 4). For older publications, the description therein was used to find the geographic position of each sample on modern maps (SWEREF 99TM) and the LiDAR-based elevation model (Col. 4, 5) (the national digital elevation model, RH2000 (EPSG:5845, https://epsg.io/5845) from Lantmäteriet).

Also here, the isolation stratigraphy and basin threshold were combined to one sample (e.g., Hedenström and Risberg, 2003; Persson, 1979; Persson, 1973; Robertsson, 1991). Thresholds were re-determined using the RH model. Mörner (1969) used samples retrieved from coring in a former fjord-setting. Here, the borehole (and sample) positions were considered to be accurate in the original report. However, the elevation of the sampling location, taken from the logs in the original report, was re-determined using the RH model.

All but two of the dates collected [90, 91] are conventional radiocarbon datings with generally little information on dating methodology in the text. When δ^{13}C-values existed in the publication these were listed. In studies that did not include this (Mörner, 1969; Persson, 1979; one date in Robertsson, 1991), δ^{13}C was estimated to -28 ‰(Col. 7 in radiocarbon sheet). The original ages, uncertainties and δ^{13}C-values were used to calculate the corrected age and uncertainty to account for isotopic fractionation (Col. 8, 9) following the scheme in the workbook. All information on stratigraphy (Col. 13, 14, 15) was transferred from the stratigraphic descriptions in the original publications into the HOLSEA format and the overburden depth (Col. 17) was picked from the figures therein.

1.2.3 Southeastern section

For the southern-most curves of Blekinge and Haväng we consulted individual compilations of Yu et al. (2007) and Hansson (2018) and the respective references therein. The data of Blekinge can be split into two epochs, one around 10 ka BP compiled by Hansson (2018) and Hansson et al. (2019) and one set based on Berglund (1964, 1971) and Yu et al. (2003, 2005) covering the time range of 8.5 ka BP to present, revisited in Yu et al. (2007) regarding the temporary readvance of sea level during the mid-Holocene or Litorina transgression around 7 ka BP.

This younger data distributed along the Blekinge coast consists of corings of lakes, ponds, in case of Smygen a modern lagoon with a submarine bedrock sill at -1 m hrsl and a beach ridge at Björkärr. The cores often show a sequence of terrestrial and marine layers indicating subsequent events of transgression and isolation. The samples extracted from the cores and which are documented in the respective publications are marine or terrestrial. The reservoir correction applied is under debate and varies between -220 yr and -108 $\pm$ 24 ^{14}C yr (Berglund, 1971). Bulk sediment datings show no large deviation from the fossil samples and are considered as reliable therefore (Yu et al., 2007).

A The sample ID convention orients at Berglund (1971), and we follow this scheme for the more recently compiled data.

B The locations distribute along the south coast east of Karlshamn, mainly fens or lakes were cored in order to identify isolation and ingression horizons.

C The radiocarbon dating was performed at Lund and Stockholm with measured δ^{13}C corrections. For marine samples a reservoir correction of 200 yr was assumed to be more likely than the general assumption of 440 yr (Berglund, 1964). In more recent datings, this was replaced by a DeltaR of -108 $\pm$ 24 yr. For two transgression events, Hunnamara and Smygen, indicators from above and below were used to interpolate the respective ages for which the respective weighting is given.

D1-2 Stratigraphies of samples from Berglund (1964), Yu (2003, 2005) are represented in detail whereas for the more recent corings the information was directly taken from Yu et al. (2007).

D3 For the levelling of the threshold, which are here set as [sample elevation col. 38] we did a rather conservative assumption of its error [Col. 30] to amount to 0.40 m according to Yu et al. (2007). The coordinates were picked from the map.

D4 Tides, are not applicable in this region.

D5 Besides the archaeological samples of Bjorkärr, all corings are associated with lagoonal or lake environments. Accordingly, the indicator height of these was associated with the levelled threshold. Ingression as well as isolation was associated with an isolation basin. Only at Hallarums mosse where the basin was interpreted as a lagoon the ingressions were considered as lower limiting points. The charcoal samples of Bjärkärr are associated with prehistorical settlements on aeolian sand dunes or beach ridges.

D6 Further compaction or changes of the threshold level are not considered, and a tectonic correction is not applicable.

D7 No further comments were added.

E Only the sample Inlängans-56 was rejected due to possibly erroneous dating.

The older samples provided by Anton Hansson from western Blekinge are organic sediments and tree stumps found on the seafloor and are complemented by a data set at Haväng further south.

Haväng is located in the Hanö Bay in the Baltic Sea. The site is a submerged landscape formed during times of lower water levels during the Yoldia Sea, Ancylus Lake and Initial Littorina Sea Stages, around 11500-8000 cal BP. The site is situated at the mouth of the Verkeån River, where outside the present coastline the remains of the old river mouth is preserved. On the sandy sea floor organic sediments representing the river and lagoon, as well as tree stumps representing the river shores are found. This Blekinge site was formed at the same time as the Haväng site. However, contrary to Haväng, these samples do not represent a river mouth. Instead, the site in Blekinge was part of an archipelago that was partially submerged during the Ancylus transgression.

The sampled tree stumps are most often from pine and can be found still rooted on the seafloor or locked in organic sediments. The rooted samples have no overburden facies, whereas the fallen stems have a gyttja cover. The radiocarbon date has been extracted from five consecutive rings, however not always the outermost part of the tree has been sampled. In this database entry no correction for the rings (years) outside the sampled rings have been performed. The stumps have been positioned by a GPS-buoy floating above the divers, and the depth have been measured at the base of the tree stump with a diving computer. The depth has been corrected for deviations from the mean water surface. The trees were drowned and preserved during the Ancylus transgression, so the elevation of the samples represent the water level at the time of death. Therefore, the rooted trees are index points. The non-rooted tree stems could have moved since they fell and are therefore of terrestrial type. However, the depth and age of the non-rooted trees correlate very well with the depth and age of the rooted stumps. When comparing to modern-day coastal pine stands, they grow at least 2-3 m above the water surface, indicating that the now submerged trees likely died due to the rise in groundwater, when the water level reached about 2-3 m below the tree.

Bone material and wood from fishing constructions are archaeological material found in the organic sediments on the seafloor. This material represents the groups of people that lived at the Haväng site. The bones have preserved slaughter marks and have been thrown in the river as waste. They represent a terrestrial type. The fishing constructions were used for large scale fishing in the lagoon just inside the coastline. The fishing constructions should have been placed at just 1 or maximum 2 m depth in the lagoon, which is assumed to have more or less the same water level as the sea outside the lagoon. However, here in the database entry fishing constructions are categorized as a terrestrial type. The bones and fishing constructions have been positioned by a GPS-buoy floating above the divers, and the depth has been measured at the base of the tree stump with a diving computer. The depth has been corrected for deviations from the mean water surface.

The organic sediments can be divided into two categories: sediment corings and samples taken by divers. The sediments represent the river and lagoon sediments inside the ancient coastline. The cored sediment sequences have been sampled with a vibro-corer from the ship R/V Ocean Surveyor. The depth was measured by the crew on the ship. The hand-cored samples collected by divers are gyttja sediments adjacent to the sampled tree stumps. They have been positioned by a GPS-buoy floating above the divers, and the depth has been measured at the base of the tree stump with a diving computer. The depth has been corrected for deviations from the mean water surface which was referenced to the Swedish RH2000 (EVRS).

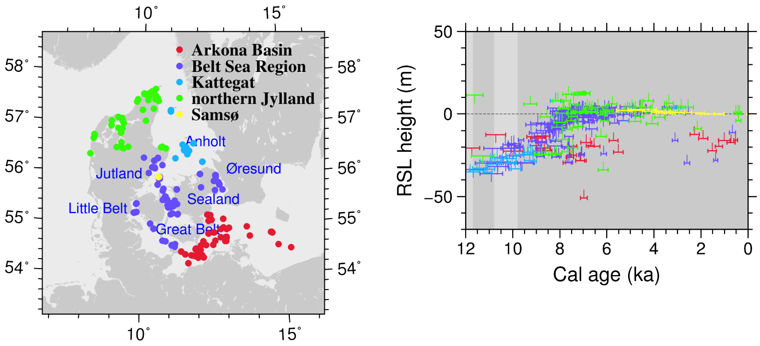

Figure S2.3: Location of Danish sea-level data points in the HOLSEA database. For details see Fig. S2.1. The lake stages only hold for SLDs south of the Belt-Sea region

1.3 Denmark

The first part of this section presents an overview of sea-level data from studies conducted in Denmark, while the second section introduces a specific study on the combination of Ground Penetrating Radar (GPR) data with Optically Stimulated Luminescence (OSL) dating on the island of Samsø. The locations of all data are shown in Fig. S2.3.

1.3.1 Denmark, overview

The sea-level database for Denmark includes radiocarbon ages from the Arkona Basin, the Belt Sea region, Kattegat and northern Jutland that borders on Kattegat, an area that is usually considered part of the Baltic Sea (Rosentau et al., 2017). The database comprises ages younger than the last deglaciation of the region, hence both lateglacial and Holocene ages are included. It was decided to include only published ages in the database to avoid insufficiently documented material.

The application of a marine correction for some of the material demands some discussion. Material from the former radiocarbon-dating laboratory in Copenhagen (K-#) was conventionally dated. From 1952 to 1975 the laboratory did not measure nor correct for δ^{13}C as isotopic fractionation was unknown. After that, applying a conventional mass spectrometer, δ^{13}C was corrected normalizing non-marine samples to -25 ‰ on the PDB (Pee Dee Belemnite) scale marine samples to a δ^{13}C value of 0 ‰ implying a 400 yr reservoir correction, valid for this region (Mangerud, 1972). Accordingly, we added back 400 yr and apply the respective marine calibration curve in OxCal.

This approach deviates from the currently recommended method to correct all ages for isotopic fractionation by normalizing to a δ^{13}C value of -25 ‰ on the PDB scale (Stuiver and Polach, 1977), but avoids the documentation of deviating radiocarbon ages from the same laboratory. Furthermore, not for all ages the measured δ^{13}C values are documented, and we have to use assumed δ^{13}C values, which adds uncertainty to the dating. We should leave it open to the reader to apply another method for the respective samples.

Samples from the German and Danish waters, conventionally dated at the laboratory in Kiel (Ki-) (Erlenkeuser et al., 1975; Erlenkeuser and Willkomm, 1971, 1973), comprise sediment samples with low organic content, are considered dubious, and are not included in the database. Also a few recent ages of organic-poor sediment samples were rejected according to Olsson (1979), because dating of organic-poor samples can give erroneous results.

The samples dated with AMS (accelerometer mass spectroscopy) and marked with AAR (Aarhus, Denmark), KIA (Kiel, Germany), Poz (Poznan, Poland) and Ua (Uppsala, Sweden) have been corrected for isotopic fractionation by normalizing to a δ^{13}C value of -25 ‰. For those samples the marine curve was applied with no further δR correction, usually considered in the western Baltic. *Macoma balthica* shells may give older ages due to sediment eating, the Portlandia effect (England et al., 2013), and should be treated with caution. Furthermore, south of the Belt-Sea region the mixing of fresh and sea water may lead to variations in the basin age correction which is difficult to quantify.

Krog and Tauber (1974) and Krog (1979) provided the first radiocarbon dated sea-level studies for Denmark which are listed in the compilation. Radiocarbon dating, mainly on wood, was used by Christensen (1982) who discussed RSL changes during the mid-Holocene in the Vedbæk area (north-east Sealand) based on wood samples. Main focus was the evolution of the main marine transgression in the Great-Belt region (Bennike et al., 2004; Christensen et al., 1997; Hede et al., 2015; Hede, 2003; Petersen, 1978; Sander et al., 2015, 2016; Winn et al., 1986), see also Sec. 1.4.1.

Christensen and Nielsen (2008) and Clemmensen et al. (2001) discussed Holocene sea levels in northernmost Jutland. Late-glacial RSL changes in the same region were documented by Petersen (1984) and Richardt (1996). Sea-level changes in the Kattegat were documented by Bendixen et al. (2017) and Jensen et al. (2002) based on studies of submarine deposits. Clemmensen et al. (2012) found a marked drop in sea level between 4300 and 3600 years BP on the island of Anholt. Christensen (1995, 1998) focused on mid-Holocene RSL changes mainly in southern Denmark. Late- and postglacial shore-level changes in the SW Baltic Sea were discussed by Bennike and Jensen (1998), Jensen et al. (1997), and Jensen et al. (1999) based on sub-marine deposits. Holocene shore-level changes in the Little Belt were discussed by Bennike and Jensen (2011), partly based on archaeological data (Andersen, 2013). Holocene sea-level changes in Øresund were discussed by Bennike et al. (2012) and Fischer (2005).

1.3.2 Samsø

This section focusses on RSL data constructed from a wide beach-ridge system on the island of Samsø (Belt Sea, central Denmark) based on GPR reflection profiling and OSL dating of sediment samples collected along a cross-ridge profile. A detailed description of the field site and data collection, GPR data interpretation, uncertainties and consideration regarding RSL is given by Hede et al. (2015). Therein, the internal beach ridge architecture is described and the depositional development of the island of Samsø during the past ca 5 kyr is interpreted. Nielsen and Clemmensen (2009) and Tamura et al. (2008) have outlined how GPR reflections may be used for identification of sea-level markers in beach sediments. The summary presented here focuses on GPR-based sea-level markers and their integration with OSL dates.

SLIPs are interpreted as the transition from the upper shoreface to the beach face. The elevation of these downlap points was shown to represent sea level at the time of deposition (Hede et al., 2013; Nielsen and Clemmensen, 2009). Due to the micro-tidal regime at Samsø with a spring-tide range of 0.3 m, we consider this value as a natural scatter of the SLIs read from the GPR data. Levelling is represented in the modern Danish height system DVR90 which only differs at some cm from EVRS. Accordingly we apply no further correction.

The OSL ages have been corrected for burial depth, including estimated aeolian cover (Hede et al., 2015), were recorded in 2011 CE and were dated at the Nordic Laboratory of Luminescence Dating, University of Aarhus. Uncertainties of the reported ages fluctuate between 6 % and 9 % of the estimated age value. Such uncertainties are typical for this type of OSL dating. However, the youngest age of 0.008 ka has an uncertainty of 30 %. Unknown biases in the OSL-estimated ages may occur, if the water saturation history of the sediment is incompletely known or if changes in burial depth are not properly accounted for (e.g., Bjørnsen et al., 2008; Clemmensen et al., 2009).

The downlap points picked as SLIPs in the GPR data are typically located 1 to 2 m below the surface, whereas the samples for OSL dating were collected between 0.6 and 1.0 m below the surface as the downlap points typically are located below current groundwater table; except the sample on the modern beach, which constrains the youngest age and was sampled at only 0.25 m depth.

Numerous downlap points are marking sea level during the time span where deposition of the beachface upper-shoreface system took place, and the SLIPs obtained from the combined GRP and OSL data allow for a detailed reconstruction of RSL through the past ca 5 kyr (Hede et al., 2015). However, the detailed RSL curve presented therein relies on an interpolated age model to infer age information at all locations where sea-level markers were identified along the profile. In order to reduce this uncertainty, SLIPs are here shown as one point for every place that has been directly dated. In the data set, the age of each point is presented along with the elevation to the downlap point at the relevant profile distance. Moreover, the downlap point reading is based on the downlap point closest to the sediment sample used for OSL dating extracted from the data set of Hede et al. (2015).

In Sander et al. (2016), the RSL data obtained by the integration of GPR and

OSL has been combined with RSL reconstructions from lagoonal deposits on Samsø in order to obtain continuous information for periods of, both, rising and falling RSL. Further discussion of this comparative study is beyond the scope of the present contribution.

Similar GPR and OSL studies have been performed on the island of Anholt in the sea of Kattegat and at Feddet, SE Sjælland, Denmark (Clemmensen and Nielsen, 2010; Hede et al., 2013). However, continuous RSL reconstructions through significant parts of the Holocene are still under development for those areas and have still not fully matured for presentation in this contribution.

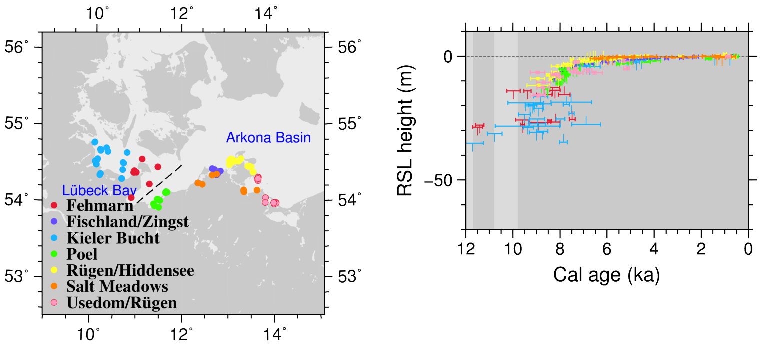

Figure S2.4: Location of German sea-level data points in the HOLSEA database. Dashed line separates indicators from the S.-H. and M.-V. sections. For details see Fig. S2.1.

1.4 Germany

Administratively, the German Baltic coast belongs to two federal states, Schleswig-Holstein and Mecklenburg-West Pomerania. From Travemünde in the inner Lübeck Bay the Schleswig-Holstein (S.-H.) section stretches northwards to the Danish border, the Mecklenburg-West Pomerania (M.-V.) section extends eastward to the Polish border near Swinoujscie (Fig. S2.4).

1.4.1 Schleswig-Holstein section

Kiel Bay in the western Baltic Sea is located south of the Great Belt, the principal gateway to the North Atlantic via the Kattegat and Skagerrak regions. All data in the compilation was gained from sediment cores taken by German research vessels at sea in different water depths down to -35 m hrsl. No correction for compaction was applied, as dated material was taken at core depths < 2.5 m below sea floor, covered by marine mud. All terrestrial, limnic and marine samples were radiocarbon-dated.

The most complete data set documenting the Littorina Transgression in the area of Kiel Bay is provided by Winn et al. (1986). The authors investigated sediment cores taken at positions selected from seismic profiles which show a sharp reflector at the onset of the transgression. Radiocarbon-dated horizons are restricted to the sediments either overlying or underlying the transgression level containing a great variety of sediment types ranging from lake marls to clayey gyttja and peat immediately underlying the marine succession. Incomplete sedimentary records may mask the true age of the Littorina transgression. Peats and lacustrine sediments are not direct data points of sea level, but mark the oldest possible age of the following marine transgression. On the other hand, oldest marine sediments close to the base of the marine succession indicate the youngest possible transgression age. Direct datings on the crucial transgression horizon are rare. Moreover, the exact age of the transgression is often obscured in a hi-

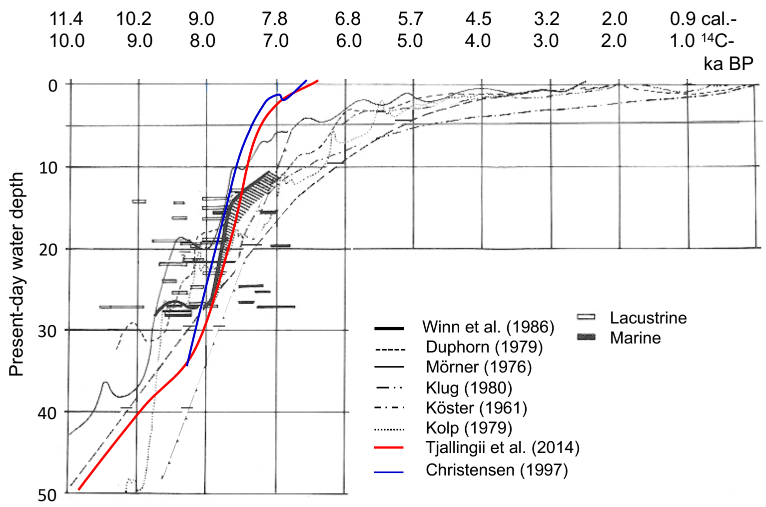

Figure S2.5: Sea-level curves for the Schleswig-Holstein sector of the western Baltic Sea, and comparison to findings Great Belt region, blue, and from Vietnam Shelf, red (adapted from Winn et al., 1986).

atus with the missing interval either due to non-deposition or later erosion of sediments.

The first phase of the Littorina transgression in the westernmost Baltic Sea is characterized by a highly accelerated relative sea-level rise of 2.6 cm/yr (Fig. S2.5). Sea level rose from -27 m to -14 m hrsl between 9.0 and 8.5 ka BP in the Kiel Bay close to the Great Belt gateway according to Winn et al. (1986). Christensen et al. (1997) discussed a similar rapid sea-level rise from the Great Belt in Denmark (Fig. S2.5; see also Sec. 1.3.1). Some of the older available sea-level curves for the western Baltic Sea show also phases of rapid sea-level rise (Duphorn, 1979; Kolp, 1979; Mörner, 1976) but the age control in these studies is poor. Rates of relative sea-level rise slowed down after 8.5 ka BP to 0.6 cm/yr or less. After 5.0 ka BP sea level rose slowly from -2.5 m hrsl and reached the present-day sea level between 2.5 and 1.0 ka BP, modulated by minor secondary oscillations (Duphorn, 1979; Ernst, 1974; Jakobsen et al., 2004; Klug, 1980; Mörner, 1976). From 8.5 ka BP onwards, sea-level curves from the Schleswig-Holstein sector show a good agreement with those from the Mecklenburg-West Pomerania section (Sec. 1.4.2).

The initial phase of the Littorina transgression is also recorded from the southern Fehmarn Belt. A piece of wood in silty sediments [1681] from the gradual fluvial/limnic–marine transition after the AL regression provided an AMS radiocarbon age of 8.43 ka BP (Feldens and Schwarzer, 2012). A 5-cm-thick conglomerate layer marks the base of the Littorina transgression in Lübeck Bay at -25.65 hrsl (Harders et al., 2005). AMS radiocarbon datings 5 cm below and 9 cm above the transgression horizon yielded 9.64 and 7.45 ka BP [1679, 1680], respectively, indicating erosional gaps associated with the transgression. The topmost gyttja horizon 20 cm below marine mud of the Littorina stage in the Fehmarn Belt at -27.8 m hrsl was dated by Heinrich et al., 2017 with 9.915 ka BP [1683].

1.4.2 Mecklenburg-West Pomerania section

The Mecklenburg-West Pomerania section of the Baltic-Sea coast (Fig. S2.4) is a paraglacial, medium to low energy coast, where tides can be neglected. The eastern segment (Western Pomerania section, east of the Fischland/Zingst peninsula) is characterized by the occurrence of numerous lagoons. While the western segment (Mecklenburg section) is mainly a cliff coast built from Pleistocene till and sand, the eastern segment is built to a greater extent from Holocene spits, barriers and dune belts. Their evolution is closely related to the Holocene sea-level rise and thus, historically, the sea-level research in Mecklenburg-West Pomerania has focused on this coastal segment (Hurtig, 1954; Kliewe, 1960; Kliewe and Janke, 1982).

The data set presented focuses on four spatially limited areas, Poel, Fischland/Zingst, Rügen/Hiddensee and Usedom/Rügen and regionally more dispersed salt meadows (Fig. S2.4). Other sparsely published data with mostly uncertain locations or sampling/treatment conditions were not included in the data set. For the five areas mentioned, sea-level curves were recently published and described in detail (Hoffmann et al., 2009; Lampe et al., 2011, 2005; Lampe and Janke, 2004; Naumann and Lampe, 2014). Wherever possible samples from terrestrial, telmatic and shallow marine environments were combined to narrow the error band of sea-level position.

This compilation focuses on sea-level data which is related to the Littorina transgression, as the Pleistocene surface in the coastal onshore and near coastal offshore zone is generally located higher than -15 m NHN (German Ordnance Datum, very close to the recent SW Baltic mean sea level), too high to host sediments of the Late Glacial and Early Holocene predecessors of the Baltic Sea.

The onset of this transgression is synchronous with the inundation of the Danish straits which occurred about 8.1 ka BP (Bennike et al., 2004; Jensen et al., 2005, 1997). The Littorina transgression took place at 8 ka BP in the Mecklenburg Bay and reached the Arkona Basin ca 7.2 ka BP (Rößler et al., 2011), see also Fig. S2.5.

Samples from the siliciclastic barriers were taken mostly with window samplers of one or two metres length and five centimetres in diameter driven by a motor hammer with which depths up to 20 m can be reached. Compaction due to the drilling process is negligible but sample dislocation may occur. Samples from coastal mires were taken with a piston corer. In salt meadows and during archaeological excavations samples were taken in open pits from the outcrop. Whenever possible, macro-remains from land plants were picked for dating. From highly decomposed organic samples, where no macro-remains were found, bulk samples, carefully purified from roots, or leaching residuals from humic matter were used (Lampe et al., 2011). Additionally, samples taken from archaeological underwater excavations and from drowned rooted tree stumps provided valuable data as limiting points above the former sea level (tree trunks, settlement finds) or below (wasted materials found in shallow water deposits) (Hartz et al., 2014).

The environment/facies from which a sample is taken determines its meaning as SLIP (mostly telmatic) or as limiting point (terrestrial, limnic, marine) and is described in Col. 13 ”dated facies“. Traditionally, age and altitudinal data from telmatic deposits are used to trace the phase of rapid rise of the Littorina transgression until 6 ka BP. Such basal peat deposits (sensu Lange and Menke, 1967) reveal a transgression tendency, are of minor thickness and, thus, are less sensitive to compaction. Intercalated peat layers are mostly absent in the clastic marine sediment sequences. During the past 6000 years when slower sea-level rise occurred, no basal peat developed at altitudes above -4 m NHN. For this period, fenland Phragmites/sedge peat profiles accumulated in wave-sheltered areas were sampled, where the growth kept up with water-table rise. For the last thousand years, when the sea level was already close to the recent one, bulk samples from salt meadow peat deposits were used for dating. In these profiles small-scale sea-level fluctuations are indicated by black layers of silty, highly decomposed peat, indicating marsh drying and, thus, periods of falling sea level such as during the Little Ice Age (Lampe and Janke, 2004).

The dated material is indicated in Col. 56 ”Secondary indicator type“. Only terrestrial organic remains were dated avoiding reservoir or hardwater effects. Contamination especially in bulk samples cannot be excluded, but are not considered in the error analysis. All age data are radiocarbon data, corrected for isotopic fractionation.

All sample positions are related to standard elevation zero (NHN) corresponding with mean sea level (Col. 38 ”Sample elevation“). A ”compaction corr.” (Col. 64) was only advisable for data by Hoffmann et al. (2009), who considered intercalated organic deposits or peat above compactable limnic sediment, and who applied a numerical decompaction calculation to their data. ”Levelling uncertainty” (Col. 30) was categorised along source errors in considering the many sources of errors in sample-depth determination, such as linear interpolation between map contour lines, levelling errors, sediment dislocation due to the drilling process, instrumental errors of echosounders etc. A value of ±0.2 m was considered for precisely levelled samples and ±0.5 m otherwise.

The position of the former sea level relative to the sample position is estimated to -0.3 m (the mean height of recent coastal marshland) for basal peat, salt meadow peat and peat of coastal mires, to be lower than -0.5 m for tree stumps from drowned forests (because trees can mostly not grow in lower positions) or samples from other terrestrial or limnic environments, and to be higher than 0.5

m for samples from marine sediments (which is the estimated mean depth of recent nearshore environments). Except for terrestrial and some marine samples, Col. 56 ”sample indicative meaning” in the workbook deviates from this. Also, whenever a finite range is given in Col. 56, the former sea level (Col. 68) has been calculated using the mid-point of this range. As a result, the former sea level given in the workbook deviates up to 0.25 m from the original data. For these, we refer to the literature list.

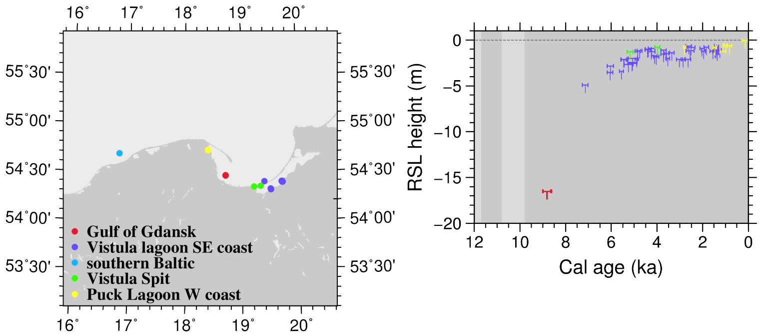

Figure S2.6: Location of Polish sea-level data points in the HOLSEA database. For details see Fig. S2.1.

1.5 Poland

The Polish sea-level data documents water-level changes mainly in the Gulf of Gdańsk and to the Ustka stump to the west, southern Baltic (Fig. S2.6). The data is grouped into 4 regions: Vistula Lagoon, Puck Lagoon, Southern part of Gulf of Gdansk and Southern Baltic with the Ustka stump [458, 459] (Miotk-Szpiganowicz et al., 2009). Some of the samples are not strictly related to sea level and, so, were rejected: the lower parts of the cores ŁR 0 [405–407], ŁR 1 [410, 411], and Tolkmicko 2, 3 [419, 422] in the Vistula Lagoon. In the Puck Lagoon, some samples indicate a large range of erosion of the top of the peat ([446, 448, 449]) or inversion of ages ([444, 445] – a possible error in sampling or contamination of the sample) and, also, are not recommended for construction of RSL curves.

All data refer to recent projects and are based on precise geodetic dating. The accuracy of the horizontal position for all cores and samples from the coast is better than 1 m while the accuracy of the vertical position is ±1 cm. The accuracy of the vertical position from samples taken from the seabed is ±10 cm. In the survey reports of the different scientific projects since the 1990s, elevetions were determined with an accuracy better than 0.02 m and the ellipsoidal coordinates (EUREF'89) were reduced to mean sea level (NN Amsterdam). Only few additional sampling sites (ZR 1 to ZR 8 and P1 to P6 in shallow waters of Vistula and Puck Lagoons) were measured with a Trimble SPS 881 mobile receiver. So, leveling uncertainty can reach 0.1 m. The calibration of the radiocarbon-dated samples was performed with OxCal considering the atmospheric calibration curve.

Data from the Vistula lagoon region, the Puck Lagoon and the southern part of the Gulf of Gdańsk are complementary and can be used together for construction of the RSL curve for the Gulf of Gdańsk. Together with older, published data from the Vistula Lagoon (Spit) and the Puck Lagoon (Uscinowicz, 2003; Uścinowicz et al., 2007) the Polish data document well the sea-level changes in the Gulf of Gdansk during the last 8 ka. The effect of local tectonics is not exactly known. Existing data show slight subsidence for the Vistula Lagoon and the southern Gulf of Gdańsk regions but a stable situation or slight uplift for the Puck Lagoon. However, different studies show different rates of present subsidence or uplift. Compaction occurs, especially if peat thickness is high (e.g., cores ŁR 0 and ŁR 1), but the total effect of compaction was never estimated and is thus not known yet. In some cases, erosion is evident and needs to be taken into account when the RSL curve is constructed. This is obvious when comparing ages of the top of the peat and shells buried in sediment laying on it (e.g., cores Bauda 00, Frombork 1, Frombork 2, ŁR 0).

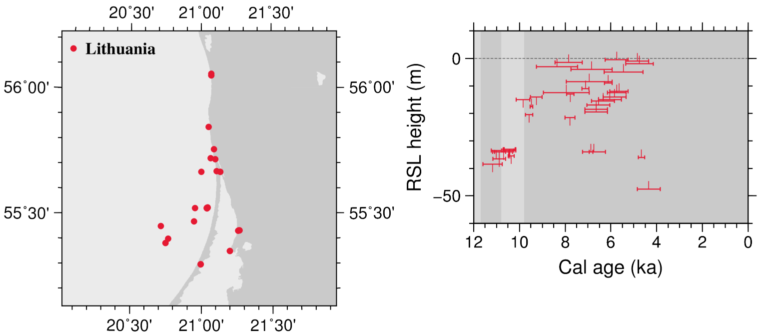

Figure S2.7: Location of Lithuanian sea-level data points in the HOLSEA database. For details see Fig. S2.1.

1.6 Lithuania

Reconstructions of the water-level changes at the Lithuanian coastal zone and adjacent offshore of the southeastern Baltic since the Late Glacial resulted in rather contradicting RSL curves (e.g., Bitinas and Damušytė, 2004; Damušytė, 2011; Gelumbauskaitė, 2009; Kabailienė, 1997). This can be ascribed to the fact that the respective authors were guided by differing concepts of data interpretation, that they prioritized or, in opposite, ignored geochronologically dated objects, that they estimated or neglected GIA and other neotectonic movements, etc. In some publications, it was attempted to estimate GIA, or the separate RSL curves were presented for the different parts of the Lithuanian coast (Damušytė, 2011; Gelumbauskaitė, 2009) and corresponding palaeogeographic reconstructions with modelling of possible neotectonic oscillatory movements of separate Earth crust blocks (Šečkus, 2009). Figure S2.7 shows the locations of the Lithuanian SLIs discussed below.

The sea-level data compilation at the Lithuanian coast is based on two principles: (1) selection of reliably dated objects indicating sea-level position (key-SLDs), and (2) estimation of GIA character and amplitudes in the coastal zone.

Regarding (1), the sea-level position at the Lithuanian coast is reconstructed using a very limited amount of reliable key-SLDs [460–482]: rooted tree trunks (in situ) at the sea bottom; submerged footprints of human activity (in our case wooden fishing fence); marine shells (in situ); some selected layers of peat and freshwater gyttja (in situ). Further luminescence dates identified by diatom and mollusc analysis as sand of marine and lagoon origin are also included [483–502].

The key-SLDs are radiocarbon dated: wood, peat, gyttja, marine shells (bulk samples only); marine and lagoon sand was dated by OSL or infrared, IR-OSL. The calibration of the samples was performed with OxCal considering the atmospheric calibration curve.

A large set of former datings of gyttja, freshwater molluscs and fossil fish bones, collected from the areas of south-eastern Baltic lagoons (Curonian, Vistula as well as smaller ancient freshwater palaeo-lagoons) was recently discussed to be unreliable due to a large hard-water effect by river's impact and post-sedimentation geochemical processes (Bitinas et al., 2017). Furthermore, the majority of peat samples was received from buried fen-peat layers which formed in unclear palaeogeographic conditions with unknown depth of the palaeobasin and their relation to sea-level position. Thus, the mentioned results were not considered in the compilation. All sea-level data points in this compilation are already published (Bitinas and Damušytė, 2004; Bitinas et al., 2000, 2002, 2017; Damušytė, 2011; Gelumbauskaitė, 2009; Girininkas and Žulkus, 2017; Trimonis et al., 2007; Žulkus and Girininkas, 2012). The off-shore data points are referenced to mean sea level. The orthometric heights of the on-shore data were taken from Soviet Army military maps presented in old (1942) system of coordinates. These maps were produced in 1970s or 1980s. Due to the fact that these are more precise than the recently produced topographic maps in the current national system of coordinates LKS-94, they are still applied for geological fieldworks. Accordingly the uncertainty is considered to be 0.5 m only.

The most important sea-level data points are dated rooted tree trunks (in situ) [460–462, 471, 476–482] discovered at the sea bottom during underwater archaeological excavations (Bitinas et al., 2003; Girininkas and Žulkus, 2017; Žulkus and Girininkas, 2012). All of them are very well preserved, i.e., the sea level never drops lower after their submergence. On the other hand, well preserved tree remnants had to be submerged not very late after the plant's destruction.

The very recent finding of submerged remnants of a wooden fishing fence [463], which dates to 9.5 ka BP (Girininkas and Žulkus, 2017), points to likely usage in the river (the AL inlet) near its mouth; recalculated level of -8.5 m hrsl suggests that the ancient basin level should not have been much lower than that of the mentioned fishing equipment, supporting the scenario of the fast AL transgression about 10.0 to 9.8 ka BP.

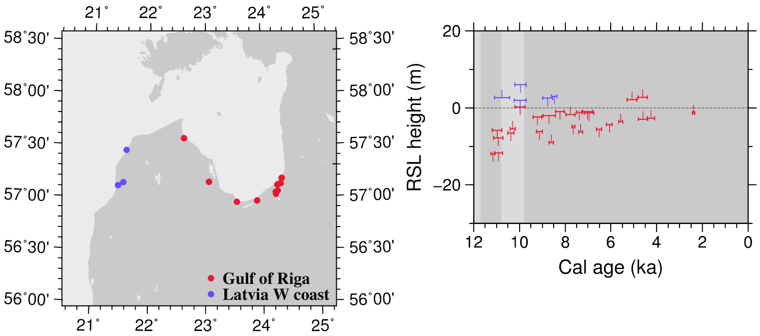

Figure S2.8: Location of Latvian sea-level data points in the HOLSEA database. For details see Fig. S2.1.

1.7 Latvia

The radiocarbon dates from Latvia included in the database are mainly based on a recent study of RSL changes of the southern part of the Gulf of Riga (Grudzinska, 2015; Grudzinska et al., 2017) where sediments from seven lakes, Lilaste, Ataru, Laveru, Pulkstenu, Jugu, Linu and Slokas, were studied (Fig. S2.8). Peat layers at Lake Ataru [37, 38] (-7.8 to -6.1 m hrsl) and Lake Pulkstenu (-5.7 to -5.57 m hrsl) indicate low water level from 10.94 to 9.1 ka BP. A low water level is also supported by wood remains from Lake Lilaste [36] (-11 to -11.7 m hrsl; 11.16 to 10.89 ka BP) and Lake Laveru [41] (-6.5 m hrsl; 10.37 ka BP). The evidence of the sea-level rise is found from Lake Lilaste sediments [34], where brackish water diatoms first appear about 8.6 ka BP, indicating that sea level was higher than -10 m hrsl (sediment surface in the lake). Peat layer and wood remains from Lake Slokas [47] indicate that at ca 8.27 (8.04 to 8.42) ka BP the RSL was lower than -1 m. The published sea-level data points were referenced to the Baltic Height System 77 and are transformed to the Latvian Height System LAS-2000,5 (Balodis et al., 2016; Celms et al., 2015).

A radiocarbon dated peat layer from the Priedaine archaeological site (Eberhards, 2008) also supports a sea level lower than -1.35 m hrsl about 7.38 ka BP.

Peat layers covered by gyttja from Lakes Engure [53] (-2.35 m hrsl) and Gipka [54] (0.28 m hrsl) support low sea level earlier than 9.2 and 10.015 ka BP, respectively (Eberhards, 2006; Grudzinska, 2011; Pujate, 2015; Punning et al., 1973).

At archaeological sites from the western coast of Latvia, a peat layer from the Sarnate [59] (Murniece et al., 1999) and a hazel pile at Sise [61] (Bėrziņš et al., 2016) suggest that at ca 10 ka BP the sea level was lower than 2 and 6 m hrsl, respectively. In Sarnate, the peat accumulation was interrupted in between 10 and 8.68 ka BP, probably due to sea-level rise. At Staldzene [60], a layer of sand with organics and shells (2.7 m hrsl) was dated 10.7 ka BP indicating the proximity of the beach (Veinbergs, 1996).

Only the data which comprise the most complete information were added to the database. Several radiocarbon dates from coastal sites such as Bazu Mire (Pakalne and Kalnina, 2005), Varves Bog and Ventspils ancient lagoon (Veinbergs, 1996), as well as some radiocarbon dates from Gipka (Eberhards, 2006; Veinbergs, 1996) were excluded from the database because precise information about the location and absolute elevation of the coring sites was missing.

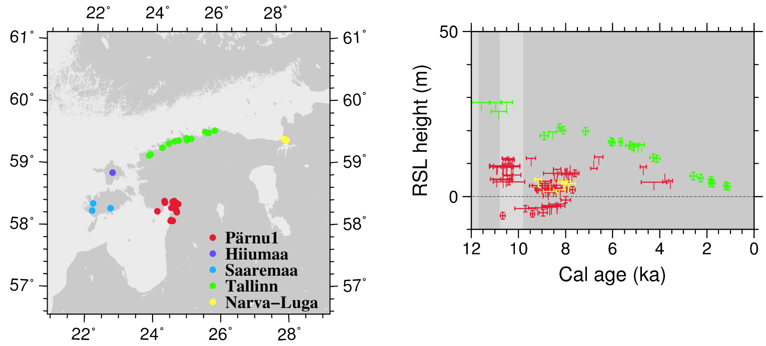

Figure S2.9: Location of Estonian sea-level data points in the HOLSEA database. For details see Fig. S2.1

1.8 Estonia

The Estonian coastal zone (Fig. S2.9) has experienced a complex shore displacement since deglaciation. Two major Holocene transgression took place here in connection with the AL up-damming around 10.9 to 10.2 ka BP and when a rapid eustatic sea-level rise exceeded the local rate of uplift at the beginning of the LS around 8.5 to 7.3 ka BP. Shore displacement data from four characteristic study areas from Estonia and adjacent area of NW Russia (Pärnu, Saaremaa, Hiiuma, Tallinn and Narva-Luga) were included into the database (Fig. S2.9).

1.8.1 Pärnu

The shore-displacement data pointsfrom the Pärnu area are based on geological data from the coastal lowland and the shallow offshore of the Pärnu Bay, elevations of highest AL and LS shorelines, and archaeological data from the Mesolithic and Neolithic coastal settlements (Nirgi et al., 2019). According to the seismo-acoustic data, the buried initial channel of River Pärnu can be traced in the seabed to a water-depth up to 5.5 m, which marks the lowest RSL before the AL transgression. Dated terrestrial plant remains at the lower contact of the channel sediments, suggest the beginning of the AL transgression at about 10.76–10.57 ka BP [1355]. The transgression, which culminated around 10.2 ka BP, is recorded in the area by the flooding of the organic sediments in Paikuse [1362–1364], Urge [1381], Sindi-Lodja [1405] and Kõdu [1361] and the cultural layer of the Early Mesolithic Pulli settlement site [1368–1377]. A well-developed geomorphological shoreline evidence marks the culmination of the AL transgression at an altitude of ca 12 m hrsl in the northern part (Rosentau et al., 2011) and ca 6.5 m hrsl in the southern part of the area (Habicht et al., 2017). Thus, the water level rose at least 17.5 m at an average rate of 35 mm/a. Due to the AL drainage into the ocean, the transgression was followed by ca 15 m regression at around 10.2–9.8 ka BP. The sedimentological and pollen data from the buried channel infill indicates the sea level of ca –4 m hrsl at 9.0–8.1 ka BP, which is further confirmed by the data from the Reiu sequence [1399] and the palaeochannel sediments at the bottom of the Pärnu Bay [1356], with upper surface visible in the geophysical and in coring data up to the same elevation. The RSL data from the Pärnu area indicates ca 1500 years long period of low water level during the ILS. The beginning of the LS transgression is marked by the flooding of the Sindi-Lodja I [1402–1409], Sindi-Lodja II [1404] settlement sites and multiple sites with buried organic layers. The LS rose about 14 m at an average rate of 12 mm/a and reached its maximum transgressional RSL ca 10 m hrsl just after 7.6 ka BP, most probably around 7.3 ka BP (Veski et al., 2005). Around 7.0 ka BP, the isostatic land uplift started to dominate, giving rise to regressive shore displacement and paludification between the highest LS and the present-day coastline (Rosentau et al., 2011). The cultural layers in the Sindi-Lodja III, Lemmetsa II, Malda and Metsaääre III settlement sites and the post-Litorina Sea organic deposits [1432–1438] indicate slightly slower regression rates of the LS at 7.0–4.5 ka BP, compared to the regression rates at 4.5–2.7 ka BP.

1.8.2 Saaremaa

For the RSL curve of Saaremaa Island, Saarse et al. (2009b) studied six Holocene lagoonal profiles and performed biostratigraphical, sedimentological and magnetic susceptibility analyses and radiocarbon datings. The elevations of beach formations and the data about settlement pattern were also included. The highest AL shoreline on Saaremaa Island is located at elevations of 25–35 m hrsl. Due to the gradual water level drop during the AL regression, several lagoons were isolated and turned into coastal lakes, which later paludified. These were later inundated by the LS waters and buried under marine sediments. The upper limits of the buried peats at 15–17 m hrsl have been roughly associated with the lowest AL level and indicate the lake regression of about 13–15 m. The age of peat and calcareous silty gyttja contact at Kihelkonna site [103] indicates low water level up until 8.3 ka BP, which is further confirmed by a radiocarbon date from the upper limit of the buried peat at Lümanda [112] (up to 8.2 ka BP). The subsequent LS transgression caused the water-level rise in the lakes and triggered the deposition of calcareous-rich sediments. The LS transgression began about 8.2 ka BP and lasted up to 7.7 ka BP or even longer. The latter is confirmed by the age of the isolation contact in Ohtja (7735±55 a BP) and age of detritus gyttja in Vedruka (7715±80 a BP), where the basal part contained marine plankton Hystrix. The water level rose about 5 m during the LS transgression and reached ca 20.5 m hrsl based on the geomorphological shoreline evidence.

1.8.3 Hiiumaa

The RSL data from the Kõivasoo basin, from the Kõpu coastal ridge system and archaeological sites (Rosentau et al., 2020) and from the Loopsoo, Prassi, Tihu and Pihla basins (Vassiljev et al., 2015) were used to reconstruct Holocene RSL changes for Hiiumaa Island. First appearance of ostracods and large lake diatoms in the Kõivasoo basin refers to the rising level of the AL before 10.3 ka BP and well-developed geomorphological shoreline evidence mark the culmination of the transgression at ca 47 m hrsl. The RSL data from the Kõpu area suggests the subsequent water-level lowering from 47 to 27 m hrsl due to the AL drainage. Diatom and ostracod data in the Kõivasoo basin suggests that this lagoon continued to exist also during the ILS and was isolated from the BSB around 8.8–8.6 ka BP likely due to the balance between eustatic and isostatic movements in the BSB. Therefore, it can be estimated that about 20 m of RSL lowering took place in connection with the drainage of the AL and the subsequent 3 m regression during the Initial Litorina Sea period was caused by isostatic land uplift. The lowest water level in the Kõivasoo basin around 24 m hrsl was established between 8.2 and 7.7 ka BP represented by an about 500-years hiatus indicated by shallow water molluscs within the medium sand deposit in the middle of the basin [1739, 1752]. Water-level rise and the beginning of the accumulation of gyttja deposit in the Kõivasoo basin around 7.7 ka BP was probably triggered by the rising groundwater level driven by the LS transgression. However, according to the diatom data the sea level did not exceed the threshold elevation at 27 m hrsl and thus, the transgression was less than 4 m in this area. Luminescence dates from the beach-dune contacts [1783–1786], coastal settlement data [1769–1775; 1778–1780] and RSL data from the Loopsoo [1755, 1756], Prassi [1763–1767], Tihu [1759, 1761] and Pihla [1768] isolation basins suggest a gradually lower RSL after ca 7.4 ka BP. The average regression rate between 7.4–6.0 ka BP was about 4.3 mm/a and for the last 6000 years about 3.3 mm/a, suggesting deceleration in the isostatic rebound. The luminescence samples were measured in 2014 CE. Accordingly we had to subtract 64 a from the datings to synchronise it with 1950 CE defining the BP reference.

1.8.4 Tallinn

The compilation representing the Tallinn study area is based on geological records from isolated lake basins, elevations of highest shorelines of the AL and LS and archaeological data from the Neolithic coastal settlement at Vabaduse Väljak [131–133] (Muru et al., 2017). The wood remains from the bottom of Lake Maardu [116] and peat/peaty gyttja accumulation at Jõelähtme [197–199] (Veski, 1998) indicate water levels in the Baltic Basin below 25 m hrsl before the AL transgression and a rise up to 34 to 36 m hrsl during the lake transgression in the Tallinn area. The timing and the changes in the water level during the LS transgression in the Tallinn study area were determined according to bio- and chronostratigraphic records from the Vääna lagoon (Saarse et al., 2009a). The first appearance of the diatom species *Mastogloia baltica*, indicating the start of the marine phase at Vääna [128] is dated to ca 9 ka BP and suggests that the sea level was near the threshold level of the lagoon, i.e., 18.2 m hrsl at that time. The RSL rise was initially slow and accelerated at about 8.1 ka BP. The Kroodi peat [107] and the Aabla coastal lake [92] suggest that the transgression maximum occurred after 8.1 ka BP and the shore marks of the raised beaches indicate that the maximum sea level reached 21 to 22 m hrsl. The exact timing of the maximum LS level is not well defined, but bio- and chronostratigraphic evidence suggests that the sea level dropped below the threshold of Vääna lagoon at about 6.8 ka BP, and continuous peat accumulation started there at ca 6.2 ka BP [125]. Archaeological and osteological material from the Vabaduse Väljak settlement site [131–133] suggests the proximity of the seashore during the occupation and that RSL has been dropped below 15 m hrsl at about 5.0 ka BP. Studies of lake isolation from lakes Harku [93–96], Käsmu [100–102], Lohja [108–110], Klooga [104–106] and Tänavjärv [119–122] indicate that the RSL decreased quasi-linearly during the Late Holocene.

1.8.5 Narva-Luga

The sea-level data points from the Narva-Luga study area are based on geological data from isolated lake basins, elevations of highest shorelines of the AL and LS, and archaeological data from the Mesolithic and Neolithic coastal settlements (Rosentau et al., 2013). That part of the data set which is located in Russia is presented in Fig. S2.9, but also discussed in this section. During the AL transgression the lake level rose by about 9 m at an average rate of ca 13 mm/a. According to the diatom and radiocarbon data from the Lake Babinskoye basin [1198, 1199] (Sandgren et al., 2004), the culmination of the AL transgression must have occurred between 10.9 and 9.5 ka BP, most probably ca 10.2 ka BP. This is further supported by the formation of Sininõmme spit deposits [1200, 1201] at an altitude of 2.5–9 (10) m hrsl, which started to form at 10.4 ka BP. The beginning of the LS transgression is recorded by the flooding of peat and palaeosoil layers in Tõrvajõe [180–182], Leekovasoo [153, 154], Tõrvala [183] and Fedorovka [143], by the submergence of the Siivertsi archaeological site and by the appearance of brackish water diatoms in the Leekovasoo [153, 154], Lake Babinskoye [137–141], Lake Khabalovskoye [149–151] and Lake Leshy [156–159] basins. Radiocarbon ages and elevations of transgression contacts indicate that sea-level rise during the Littorina transgression was relatively slow between 8.5 and 7.8 ka BP, and rapid between 7.8 and 7.6 ka BP. The culmination of the LS transgression is marked by a well-developed shoreline at an altitude of 14 m hrsl in the northern part and of 6 m hrsl in the southern part of the study area. According to the diatom evidence and radiocarbon data from the Lake Glubokoye basin [146, 147], the culmination occurred between 7.7 and 6.9 ka BP, most probably ca 7.3 ka BP. Around 7.3 ka BP the relative sea-level rise turned to a sea-level drop, which was faster initially and presumably slowed down after 5.0 ka BP. This is supported by archaeological data from Mesolithic and Early Neolithic coastal settlement sites from the Narva-Luga area.

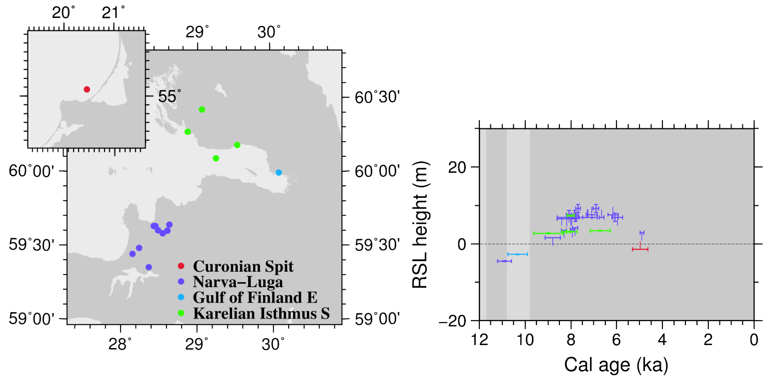

Figure S2.10: Location of Russian sea-level data points in the HOLSEA database. For details see Fig. S2.1.

1.9 Russia

For the reconstruction of Baltic sea-level changes during the Holocene at the Russian coast line, isolation basins were used. The selected records are located at different hypsometric levels in key parts of the Baltic coast of Russia (Fig. S2.10): the Curonian Spit and the Narva-Luga lowland (lakes Babinskoye, Leshy, Glubokoye). To form a complete data set, the data for Narva-Luga Lowland are also documented in the Estonian data set (Sec. 1.8) except for record [208]. Further data from the Lakhta Bay (Lakhtinsky Razliv) and the Karelian Isthmus (outcrop of Tchernaya River, lakes: Vysokinskoye, Privetninskoe, Stavok; peat bog Privetninskoe) were considered. Sediment sequences of these objects are studied with palynological, lithological, radiocarbon and diatom methods that allow to reconstruct transgressive-regressive cycles of the Baltic Sea during the Holocene. All samples are radiocarbon-dated. The calibration was performed with OxCal considering the atmospheric calibration curve, a basin correction was not considered. The elevations were referenced in the Baltic Height System 77, which was corrected to the neighboring EH2000 (EVRS) with respective corrections. For the Curonian Spit, correction due to GIA is rather small. Accordingly we do not consider a shift, but increased the leveling uncertainty to 0.1 m.

The Ancylus transgression stage has been detected in the sediment of Lake Babinskoye (6.9 m hrsl) and is dated between 11.2 and 10.9 ka BP [208]. During this period, the lithological composition of bottom sediments has changed from detrital gyttja to gyttja clay (Miettinen et al., 2007b). The regression of the AL is discovered in the deposits of the Lakhtinsky Razliy [219] and in the north of the Karelian Isthmus (Stavok Lake [221]) and has an age between 10.4 and 10.2 ka BP. During this period, the type of sedimentation changed for these lakes: clay gyttja was replaced by organogenic gyttja (Morozov, 2014). It followed a phase of isolation for the lakes in the western part of the Karelian Isthmus (Lake

Vysokinskoye [206, 207], peat bog Privetninskoe [204, 205]) and the Narva-Luga Lowland (Lake Babinskoye [134–136] and Lake Leshy [155]).

The beginning of the first Littorina transgression 8.18 to 8.10 ka BP [155] was identified by an overlapping of the clay gyttja with sand in sediments of Lake Leshy (7.7 m hrsl). In the interval 7.8 to 7.7 ka BP transgression exceeded the absolute level of 9.2 m, inundating Lake Glubokoye in the Narva-Luga lowland. This was indicated by a transitional horizon (8.22 to 8.26 cm) (Sandgren et al., 2004). According to some authors, the maximum stage of transgression was reached and exceeded the 10-m level (Lepland et al., 1996; Miettinen, 2002). In the interval 7.3 to 7.1 ka BP [147] regression led to the isolation of Lake Glubokoye [146, 147] (9.2 m hrsl). The isolation of Lake Vysokinskoye [207] (10 m hrsl) (Karelian Isthmus) from the LS occurred at 7.2 to 6.6 ka BP. Due to continued water level decline, Lake Babinskoye (6.9 m hrsl) became isolated during the interval 6.2 to 5.9 ka BP [142] (Sandgren et al., 2004). At the coast of the Curonian spit (Kaliningrad region), the final phase of the LS occurred in the interval 5.3 to 4.6 ka BP [220], an event that is marked by the formation of peat at a level of -1.4 m hrsl and indicates a lower sea level in this area at that time (Sergeev et al., 2015).

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