Recent Change—Sea Level and Wind Waves

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Abstract

This chapter describes observed changes in sea level and wind waves in the Baltic Sea basin over the past 200 years and the main climate drivers of this change. The datasets available for studying these are described in detail. Recent climate change and land uplift are causing changes in sea level. Relative sea level is falling by 8.2 mm year^{-1} in the Gulf of Bothnia and slightly rising in parts of the southern Baltic Sea. Absolute sea level (ASL) is rising by 1.3–1.8 mm year^{-1}, which is within the range of recent global estimates. The 30-year trends of Baltic Sea tide gauge records tend to increase, but similar or even slightly higher rates were observed around 1900 and 1950. Sea level in the Baltic Sea shows higher values during winter and lower values during spring and this seasonal amplitude increased between 1800 and 2000. The intensity of storm surges (extreme sea levels) may have increased in recent decades in some parts of the Baltic Sea. This may be linked to a long-term shift in storm tracks.

9.1 Introduction

Sea surface height (SSH) is an important indicator of variability and long-term change in climate. An understanding of the processes driving future trends in SSH on global to regional scales requires an understanding of the interannual to decadal (long-term) variability in the observational period. This requires an accurate assessment of past and recent change in global and regional SSH, including changes in mean sea level (MSL), extreme sea level (storm surges) and wind-generated waves. This chapter reviews what is known about change in SSH in the Baltic Sea region over the observational period (effectively the past 200 years) and the main drivers of this change. This includes a description of the datasets available for studying sea level and wind waves and a review of major findings for the Baltic Sea region.

Box 9.1 Definition of key sea level terms

Change in the mean Baltic Sea sea level is the sum of global, regional and local effects. There are several definitions of the key terms necessary for understanding these effects in the literature. Thus, a clear definition of such terms is essential.

Mean sea level (MSL) is defined as the average height of the sea surface at a specific location, neglecting short-term effects of tides and storm surges. Some studies, for instance Woodworth et al. (2011), consider annual means to define MSL, although other studies focus on monthly or seasonal means. The MSL can in turn be absolute or relative.

Absolute sea level (ASL) is the height of the sea surface at a given location relative to a geocentric

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reference such as the reference ellipsoid and is measured by satellite altimetry.

Relative sea level (RSL) is the height of the sea surface relative to the sea floor, and thus to land, at a given location, and is estimated using tide gauges or sea level reconstructions using information from the geological record. Relative sea level is more important than ASL for impact studies (see Chaps. 15–22). The land surface may undergo vertical movements that may occur at millennial timescales (e.g. the glacial isostatic adjustment, GIA) or at shorter timescales (e.g. due to water extraction or oil mining), or sudden changes (e.g. during earthquakes). In the Baltic Sea basin, GIA has a very important influence on RSL, stronger in the northern Baltic Sea and weaker in the southern Baltic Sea. The GIA is caused by the adjustment of the Earth's crust and mantle to the disappearance of the ice sheets of the last glacial age. Thus, RSL trends may differ strongly from ASL trends in the Baltic Sea region.

Global mean sea level (GMSL) is the average of sea level over the global ocean and over a period longer than the timescales for tides and surges.

Local sea level (LSL) reflects changes owing to tides and surges down to timescales of a few minutes, including *extreme sea level* variations, at a specific locality.

9.2 Sea Level Observations

9.2.1 Tide Gauges

The most direct measurement of RSL is from tide gauges. Globally, the coverage of sea level data from tide gauges is limited in time and space. Most data are from the Northern Hemisphere and are for the latter half of the twentieth century. The Baltic Sea has one of the longest running and most densely spaced tide gauge networks in the world; many stations have been in continuous operation since the late nineteenth century. For example, the Stockholm time series is one of the oldest sea level records (Ekman 2003; see also Woodworth 1999 for comparison with other similar records). A remarkable number of long and high-quality sea level records are available for the Baltic Sea basin and, to date, more than 45 stations provide at least 60 years of data.

Many of the sea level time series are freely available online through the Permanent Service for Mean Sea Level (PSMSL), which provides monthly and annual MSL measurements from around the world (Woodworth and Player 2003, www.psmsl.org), processed from high-frequency datasets. In these archives, stations with a full history of reference levels (benchmark datum history) have had their data adjusted to a fixed, revised local reference (RLR). Although the RLR time series are constructed to be continuous and relative to landmarks on the nearby land, corrections for the vertical movement of the reference (e.g. due to GIA) are not applied, because this requires a careful estimation of these movements usually involving a geodynamic model, which is not always available. Users of RLR data are aware of these limitations. The PSMSL RLR records are the most commonly used data bank for global and regional studies of historic sea level rise. However, as is the case for many other climate datasets (e.g. near-surface air temperature) for some locations significant differences exist relative to other datasets. The differences may stem from the original data source or from different error correction methods (e.g. Dimke and Fröhle 2009).

Historic sea level time series are available from several other sources, for example, for Stockholm (Sweden) (1774–2000; Ekman 2003), Kronstadt (Russia) (1816–1999; Bogdanov et al. 2000), Travemünde (Germany) (since 1826; Jensen and Töppe 1986) and various national institutions.

To illustrate possible data limitations, Richter et al. (2007) analysed RSL data from archives of six different national state authorities for the German southern Baltic Sea coast. The records in these archives were often incomplete and lacked important additional information and a systematic cataloguing. To produce homogeneous datasets from such documents (written on paper) requires considerable effort. This is not only due to obvious sources of uncertainty, such as different measurement techniques and sampling frequencies (e.g. Richter et al. 2007; Ekman 2009), but also to change in the reference points. Such change could arise from the relocation of landmarks and to vertical landmark movements caused by geodynamic processes or to man-made modification of the tide gauge surroundings (e.g. coastal or port construction activities) (e.g. Bogdanov et al. 2000). Long Baltic Sea sea level records from different sources (not only PSMSL) have been used in a wide range of research papers for global sea level studies (e.g. Douglas 1992; Nakada and Inoue 2005; Jevrejeva et al. 2006, 2008; Merrifield et al. 2009; Woodworth et al. 2009; Church and White 2011; Houston and Dean 2011) and regional Baltic Sea studies (e.g. Andersson 2002; Omstedt et al. 2004; Chen and Omstedt 2005; Jevrejeva et al. 2006; Hünicke et al. 2008) (Table 9.1). Figure 9.1 shows sea level records for the Baltic Sea with at least 60 years of data through to recent times from the PSMSL together with other long Baltic Sea sea level datasets used in the published literature.

Tide gauge operation, and the processing, distribution and archiving of the data are the responsibility of a single national agency per country, for instance the Swedish Meteorological and Hydrographical Institute (SMHI), the Danish Meteorological Institute (DMI), the Estonian Meteorological and Hydrographical Institute (EMHI), the Finnish

Table 9.1 Sources of sea level information used in the published literature organised according to the geographic regions of interest

Region	Source
North Atlantic and Europe, including Baltic Sea	Jevrejeva et al. (2005), Barbosa et al. (2008)
Baltic Sea basin wide	Omstedt and Nyberg (1991), Heyen et al. (1996), Carlsson (1997, 1998a, 1998b), Liebsch (1997), Janssen (2002), Baerens et al. (2003), Meier et al. (2004), Novotny et al. (2006), Hünicke and Zorita (2006, 2007, 2008, 2011), Barbosa (2008), Hünicke et al. (2008), Ekman (2009) and references therein; Hünicke (2010), Donner et al. (2012)
Southern Baltic Sea coast	Richter et al. (2007, 2011)
Lithuania	Dailidienė et al. (2004, 2005, 2006, 2011, 2012), Jarmalavicius et al. (2007)
Russia	Bogdanov et al. (2000), Averkiev and Klevannyy (2010), Navrotskaya and Chubarenko (2012)
Estonia	Suursaar et al. (2002, 2006a, 2010), Suursaar and Kullas (2006, 2009b), Suursaar and Sooäär (2007), Suursaar (2010), Tõnisson et al. (2011)
Poland	Pruszak and Zawadzka (2005, 2008), Richter et al. (2007, 2011)
Germany	Jensen and Töppe (1986), Liebsch (1997), Dietrich and Liebsch (2000), Liebsch et al. (2000, 2002), Jensen and Mudersbach (2004), Richter et al. (2007, 2011), Lampe et al. (2010), Dailidienė et al. (2011)
Denmark	Duun-Christensen (1990), Hansen (2007), Knudsen and Vognsen (2010), Barbosa and Madsen (2011), Hansen et al. (2011), Madsen (2011)
Sweden	Gustafsson and Andersson (2001), Kauker and Meier (2003), Omstedt et al. (2004), Chen and Omstedt (2005), Hagen and Feistel (2005), Madsen et al. (2007), Hammarklint (2009), Ekman (2009) and references therein
Finland	Johansson et al. (2001, 2003, 2004)
Gulf of Bothnia	Lisitzin (1973)

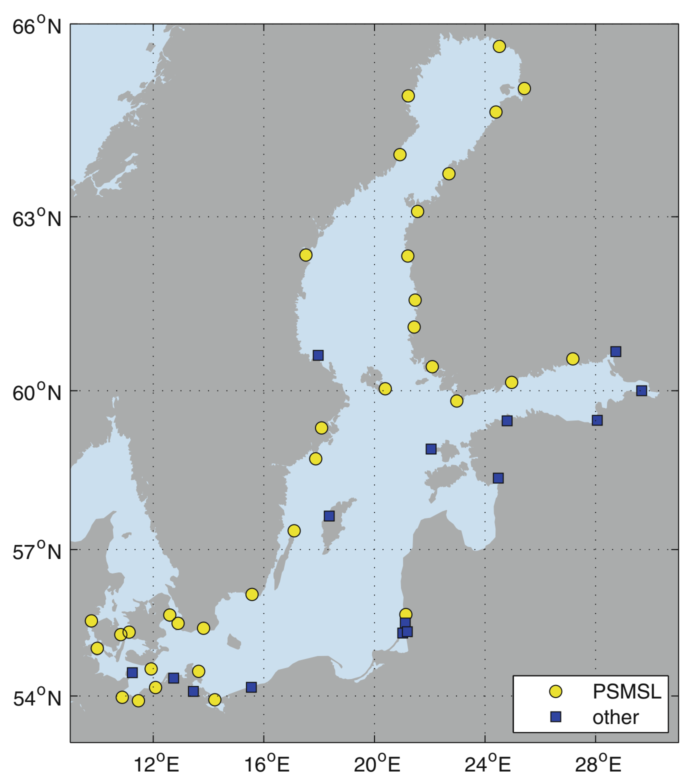


Fig. 9.1 Location of sea level records for the Baltic Sea containing at least 60 years of data through to recent times, from the Permanent Service for Mean Sea Level (PSMSL) and other long sea level datasets for this region used in the published literature (see also Table 9.1)

Meteorological Institute (FMI) and the Wasser-und Schifffahrtsamt (WSA) in Germany. Because some agencies do not supply their data to the PSMSL database, there is no basinwide freely accessible network that combines all long sea level records from Baltic Sea tide gauges.

For some applications, such as the study of extreme sea levels and storm surges, higher frequency data (more frequent than monthly average data) are needed. Some high-frequency data are available from the PSMSL/British Oceanographic Data Centre (BODC) and the University of Hawaii Sea Level Center (UHSLC, http://uhslc.soest.hawaii.edu/). However, most of the historic data are generally only available through the national agencies responsible for their collection. Real-time observations are available through the Baltic Operational Oceanographic System (BOOS, www.boos.org).

Tide gauge-derived sea level records are based on local observations of RSL presenting the position of sea level with respect to land. Thus, these data include changes in ASL as well as vertical crustal movements, which can be of different origin and take various forms. In the Baltic Sea region, the most obvious phenomenon is the long-term and more or less constant change in the Earth's crust caused by the GIA (e.g. Milne et al. 2001).

The GIA evolves on millennial timescales and so can be assumed to be approximately linear on timescales of a few centuries. However, other short-term geodynamic phenomena can lead to a contamination of tide gauge-derived sea level records. For example, sinking of piers due to unstable foundations or land sinking due to groundwater extraction, etc., which occur on timescales of years and decades, must be taken into account in the analysis of tide gauge data.

Owing to uncertainty in estimating the strong GIA signal in tide gauge records (measured relative to land), the dense network of Baltic Sea sea level observations is not generally used in the estimation of linear trends in global average sea level. For example, Baltic Sea tide gauge data are excluded from some well-known reconstructions of GMSL (e.g. Jevrejeva et al. 2006). The authors justified this exclusion by arguing that the trend in Baltic Sea sea level is strongly influenced by limited water exchange with the North Sea which leads to sea level rate curves being dissimilar from those for other regions. The strong GIA signal in the Baltic Sea region means that the RLR records must be carefully corrected before they can be used to estimate climate-driven trends in sea level.

9.2.2 Satellite Altimetry and GPS Measurements

Satellite altimetry enables continuous and spatially resolved measurements over the global ocean of SSH relative to a reference geopotential ellipsoid. The use of satellite radar altimeters to measure global SSH began in 1978 with a measurement accuracy of tens of metres. More recent high-quality satellite altimeter missions started with TOPEX/Poseidon, launched in 1992, and were continued with Jason-1 and Jason-2. These satellites were specifically designed to measure SSH with a space-time point accuracy of a few centimetres. Since then, satellite altimetry has been an independent source of SSH measurements of the open ocean, allowing for more accurate estimates of globally averaged and large-scale sea level change (Cazenave et al. 2008) than point tide gauge data. The development of satellite radar altimetry techniques, complemented in 2002 by satellite measurements of the temporal development of the gravity field, made precise quasi-global and near-continuous measurements of SSH available for the study of sea level variability and change (Woodworth et al. 2011). These data have been used extensively to map global sea level change in recent years, verifying the suggestion (based on tide gauge records) that sea level change is not spatially uniform (e.g. Cazenave and Lovell 2010, see also Fig. 9.2).

Satellite altimeter holdings are usually available as 'along track' datasets (with a time series of heights at a number of latitude grid points for each satellite pass) or as 'gridded' datasets (mapped and gridded, for example on a 1 × 1° resolution). The spatial coverage of these monthly datasets is limited to the latitude band between 65°S and 65°N due to satellite orbit constraints. Several satellite datasets combining subsequent satellite missions, thus providing time-continuous records, are freely available from different sources (e.g. www.aviso.oceanobs.com, http://sealevel.colerado.edu, www.cmar.csiro.au/sealevel). These datasets may include several corrections, such as the barometer correction (due to the air pressure at the sea surface), seasonal cycles (annual + semi-annual) or GIA correction (due to the effect of the crust and mantle adjustment on the geopotential ellipsoid). While interest in global sea level studies often concerns ASL variability, satellite data must be treated with great care for regional purposes. For instance, the comparison of tide gauge data with data derived from satellite altimetry in the Baltic Sea region requires several corrections, such as for the GIA-related strong vertical movement of land and for the GIA-related change in the geoid. Furthermore, atmospheric pressure also influences sea level. Whether or not this latter effect should be included in the corrections may for instance depend on whether the objective of study is to determine long-term trends due to increased ocean temperature (correction required), or comparison to tide gauge data (correction not required) (Barbosa 2011). For example, Fernandes et al. (2006) showed that a specific atmospheric correction applied to altimetry observations can significantly affect the resulting sea level information, as the atmospheric pressure varies geographically and covers a wide range of spatial and temporal scales. Thus,

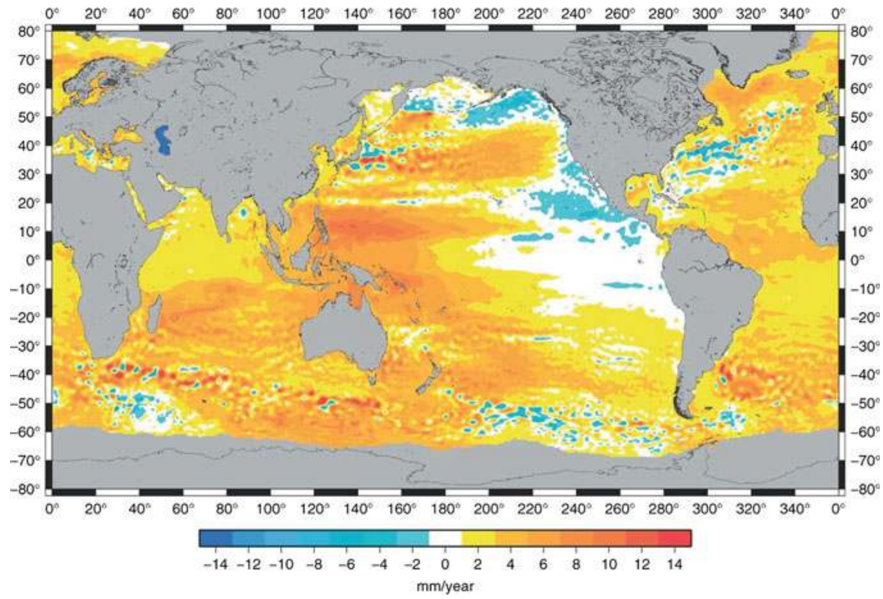


Fig. 9.2 Spatial trends in sea level rise between January 1993 and October 2010 computed from the multi-mission (Topex/Poseidon, Jason-1, Jason-2, ERS, and Envisat satellites) gridded sea level products available from the CLS/AVISO Website at weekly intervals (Cazenave and Remy 2011)

the application of these corrections strongly depends on the research question.

In contrast to global studies, only a few studies for the Baltic Sea region have so far (to 2012) used satellite datasets together with tide gauge readings to address different research questions (e.g. Liebsch et al. 2002; Novotny et al. 2005, 2006; Madsen et al. 2007; Hünicke and Zorita 2011; Madsen 2011).

There are two other factors to consider when using satellite altimetry products in the near-coastal zone, in general and specifically for comparison with tide gauge observations. First, some of the applied corrections to the raw satellite data are not valid in the near-coastal zone, typically 50 km from any coast or island (Madsen et al. 2007). The most important is the wet tropospheric correction (Obligis et al. 2011): the altimetry estimation from the satellite radar travel-time is routinely recalibrated for the effect of changing tropospheric humidity, which is simultaneously retrieved by an on-board microwave sensor. This retrieval is erroneous in coastal regions and must be corrected. Second, the gridded altimetry products are interpolated in space and time, and across missing data. Interpolation should be undertaken with great care in the coastal zone, where the variability in space and time is much greater than in the open ocean. Some products include many interpolated data, while others permanently mask out areas which may have periods with invalid measurements, for instance in the case of seasonal ice cover. Along-track data with customisable processing are available from the Radar Altimeter Database System (RADS) database (Naeije et al. 2008; http://rads.tudelft.nl/).

Another important feature of the satellite era is the application of the Global Positioning System (GPS) to measure continuously the vertical land movements (stated hereafter also as station velocities). Before the satellite era, change in sea level could only be assessed relative to points on land. Permanent GPS observations since the 1990s have accumulated sufficiently long time series to allow determination of the isostatic uplift (that is, the GIA). Uncertainty in the determination of the station vertical velocity may be strongly dependent on the station and on the model assumed for the measurement noise. Vestøl (2006) indicated an accuracy of between ±0.4 mm year^{-1} and ±0.5 mm year^{-1} for Fennoscandia, Lidberg et al. (2007, 2010) between 0.05 and 1.96 mm year^{-1} for Fennoscandia, and Richter et al. (2011) between ±1.4 and ±2.2 mm year^{-1} for the southern Baltic Sea. In the latter study, it became evident that the determination of reliable station velocities in the southern Baltic Sea poses a challenge (as the uncertainties exceed the small rates of land movement themselves; see Sect. 9.3.1.2 for more information).

GPS measurements of vertical velocities within the Baltic Sea area are collected through different networks and projects, such as the BIFROST (Baseline Inferences for Fennoscandian Rebound Observations, Sea level and Tectonics) and the European Terrestrial Reference System (EUREF) Permanent Network (EPN) (EUREF 2011) networks as well as by the Satellite Positioning Service of the German State Survey (SAPOS). Good coverage exists for Germany, Denmark, Sweden and Finland, while coverage in other countries around the Baltic Sea is more limited (Lidberg et al. 2007; Knudsen and Vognsen 2010; Richter et al. 2011). The BIFROST network started in 1993 and comprises the permanent GPS network SWEPOS (SWEPOS™, SWEPOS 2011) in Sweden and FinnRef (FinnRef®, FGI 2011) in Finland. There is also a GPS station network in Norway (SATREF®, SATREF 2011). A combined study of

GPS stations relevant for the GIA process in Fennoscandia was reported by Lidberg et al. (2010).

The advantage of GPS measurements is that they measure rates of vertical land movement, whether or not they are due to GIA or to other geological processes. Their disadvantage lies in their relatively short time span (since the 1990s). The determination of vertical crustal deformation rates finds application for the calculation of trends in ASL (see Sect. 9.3.2.1). Analysis of the GPS data in the Baltic Sea area yields a spatial pattern that demonstrates that ongoing crustal deformation in Fennoscandia is dominated by GIA.

9.3 Change in Mean Sea Level

9.3.1 Main Factors Driving Sea Level Change

The overall change in MSL at the Baltic Sea coast is the combined result of, on the one hand, factors acting at large spatial scales, such as the postglacial rebound and the change in global ocean mass, and on the other, the contribution of regional and local oceanographic and atmospheric factors. Sea level within the Baltic Sea can deviate markedly from that of the North Sea immediately outside the Danish Straits (Madsen 2011).

9.3.1.1 Large-Scale Factors

Long-term trends in GMSL for the past century have been mainly determined by the thermosteric contribution, that is, the thermal expansion of the sea water with rising ocean temperatures. Although the global mean trend is positive, there is strong regional variability due to the large-scale ocean circulation that modulates heat uptake by the ocean. Another large-scale contribution to the rise in GMSL has been the melting of land ice (glaciers and the polar ice sheets), although there is considerable uncertainty about the net contribution from the Antarctic Ice Sheet over recent decades (Cazenave and Remy 2011). This uncertainty originates in determining the net mass balance between melting, calving and precipitation over the ice sheet. Climate model simulations indicate that rising temperatures may have caused an increase in precipitation over polar ice sheets. Observations, however, do not show a trend in precipitation, but in these areas, they are sparse and do not have good spatial coverage. A third large-scale contribution to the rise in GMSL is land water storage and the use of subsurface water. The former limits sea level rise because some of the water that would normally flow into the ocean remains stored on land; while the latter increases sea level because it mobilises water into the ocean that would otherwise remain on continental areas.

Long tide gauge observations over the twentieth century indicate that GMSL has risen on average by 1.7 mm year^{-1} (Bindoff et al. 2007). Tide gauges are located at the coast and are not fully representative of the ocean regions. Satellite altimetry data for the global ocean within the latitude band between 65°N and 65°S (see Sect. 9.2.2) indicate an average sea level rise for 1993–2007 of 3.1 mm year^{-1} (±0.4 mm year^{-1}) with smaller values since 2003 of 2.5 mm year^{-1} (Cazenave et al. 2009). For more detailed information about the global sea level budget, see Chap. 14.

9.3.1.2 Regional and Local Factors

Land Movement

The Baltic Sea is a region strongly influenced by GIA, which results even today in a maximum uplift of the Earth's crust in the Gulf of Bothnia of roughly 10 mm year^{-1} (resulting in a negative trend in RSL) (e.g. Hammarklint 2009) and subsidence in parts of the southern Baltic Sea coast of about 1 mm year^{-1} (e.g. Richter et al. 2011). The local pattern of land movement may be modified by local natural or man-made land uplift or subsidence (see Sect. 9.2).

Nowadays, different methods exist to study land movement effects. Traditionally, land uplift rates in the Baltic Sea region have been determined from sea level measurements (e.g. Vermeer et al. 1988). They are based on local (e.g. tide gauge) observations of long-term trends in RSL, present the position of sea level with respect to land and, therefore, include both the signal related to vertical crustal movements and to changes in ASL. The first consistent map of the postglacial uplift of Fennoscandia was constructed by Ekman (1996), mainly on the basis of RSL records reduced to the common 100-year period 1892–1991, but also taking into account lake-level records and repeated high precision levelling. Two years later, Ekman (1998) presented an updated map of absolute vertical velocities (based on the results of Ekman 1996) by applying a GMSL rise of 1.2 mm year^{-1}, deriving the rise of the geoid (relative to the ellipsoid) from computations of Ekman and Mäkinen (1996). In 2007, Rosentau et al. (2007) augmented the map of Ekman (1996) with data from tide gauge measurements from the southern Baltic Sea (e.g. from Dietrich and Liebsch 2000), and Ågren and Svensson (2007) presented an apparent land uplift map based on a combination of sea level results, GPS results and repeated levelling.

Hansen et al. (2011) obtained an alternative estimate of the land uplift in the south-western Baltic Sea region based on tide gauge data and their determination of an ASL curve at the island of Læsø in Kattegat. After grouping the tide gauge stations, this study indicates a jump in the land rise coefficients across southern Denmark (not seen in other studies including precise levelling campaigns).

In Estonian studies, the applied land uplift rates are still based on a map compiled on the basis of national high precision levelling (1933–1943, 1956–1970, 1977–1985) by Vallner et al. (1988). Along the Estonian coast, uplift rates vary between 0.5 and 2.8 mm $year^{-1}$. According to Suursaar et al. (2006a), the accuracy of these rates, compared to the map of Ekman (1996) of the postglacial uplift of Fennoscandia, lies in the range ±0.4 mm $year^{-1}$.

Lithuanian sea level studies do not consider any land movement effects in their analysis of sea level variability because 'researchers recommend different estimates of land sinking in the Lithuanian Region' (0–2 mm $year^{-1}$) (Dailidienė et al. 2006).

Land movement due to the GIA effect can be calculated with an ice load model (e.g. Peltier 1998). This estimation does not consider other land motions (e.g. sinking piers or short-term motion due to earthquakes). Milne et al. (2001) considered the GIA correction for the Baltic tide gauge records as critical because of the large GIA amplitude ($\sim$10 mm $year^{-1}$) relative to the global trend ($\sim$1–3 mm $year^{-1}$).

However, recently, new geodetic techniques such as the application of GPS (see Sect. 9.2.2) allow for measurements of more precise absolute rates of vertical land movements and lead to considerable progress by comparison with those derived from tide gauges, ice load models or corrections from geological data. Vertical land movements (station velocities) based on observations at permanent GPS stations in Sweden and Finland (1993–2000) were presented by Johansson et al. (2002), Scherneck et al. (2002) and used by Milne et al. (2001, 2004), for example for the estimation of regional sea level rise, together with Fennoscandian tide gauge records. An update of station velocities was presented by Lidberg et al. (2007) for the period 1996 to mid-2004, including some additional sites in Norway, Denmark and northern Europe, and showing much smaller uncertainties in station velocity compared to Johansson et al. (2002). An overview of published station velocities was provided by Lidberg et al. (2010). Figure 9.3 shows the vertical velocity rates for Scandinavia from the analysis of a regional GPS network by Richter et al. (2011). The application of these rates to the presented map of RSL changes in Fig. 9.7 (left) can be used to estimate ASL changes in the Baltic Sea region.

Hill et al. (2010) introduced a new technique to combine geodetic observations and models for GIA fields in

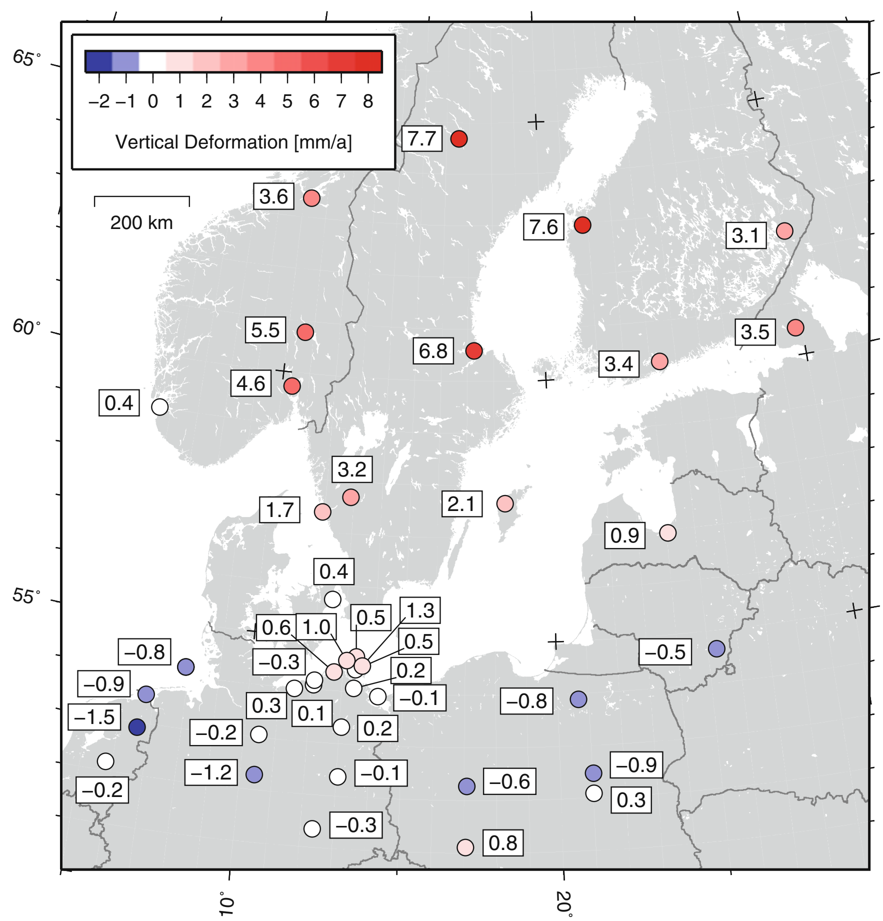


Fig. 9.3 Estimation of vertical velocities (crustal deformation rates) in the Baltic Sea region (for tide gauge correction) (Richter et al. 2011)

Fennoscandia by assimilating GPS-derived and tide gauge data together with gravity rates from the Gravity Recovery and Climate Experiment (GRACE) into their model approach (see also Chap. 14). The updated model shows a spatial pattern and magnitude of peak uplift (9.5 ±0. 4 mm $year^{-1}$) that is relatively consistent with previous findings (e.g. Johansson et al. 2002; Milne et al. 2004), but with a different—more easterly—peak uplift location in the middle of the northern Gulf of Bothnia. Previous studies (e.g. Milne et al. 2001; Johansson et al. 2002) indicated the peak uplift slightly to the west of the northern Gulf of Bothnia.

Meteorological Influence

In addition to the long-term global sea level rise and land movements, sea level in the semi-enclosed Baltic Sea is modulated by meteorological factors, especially wind forcing. Winds play a key role, as persistent winds from the south-west or north-east transport water into or out of the Baltic Sea, respectively, thereby raising or lowering Baltic Sea sea level as a whole. According to Ekman (2007), temporary winds redistribute the water within the Baltic Sea, producing high or low sea levels at the ends of the basin depending on wind direction.

Sea level variations in the Baltic Sea at interannual to decadal timescales are strongly influenced by the strength of westerly winds, closely related to the North Atlantic Oscillation (NAO). The NAO represents the large-scale circulation over the north-west Atlantic (see Chap. 4, Box 4.1 for detailed information). A positive NAO (strong Azores High and Icelandic Low) is associated with warm and humid winters and strong westerly winds in the Baltic Sea area, which causes sea level to rise; a negative NAO (weak Azores High and Icelandic Low) is associated with cold and dry winters which causes sea level to fall. The correlation between the NAO and Baltic Sea sea level is especially strong in winter (e.g. Andersson 2002; Dailidienė et al. 2006; Hünicke and Zorita 2006; Suursaar and Sooäär 2007), and in northern and eastern parts of the Baltic Sea (Johansson et al. 2004; Suursaar et al. 2006a) (see Fig. 9.4, right panel). However, in the southern Baltic Sea, the correlation between the winter NAO index and winter sea level is low (Hünicke and Zorita 2006; Jevrejeva et al. 2005). In addition, in the Baltic Sea basin as a whole, the strength of the correlation between the winter NAO index and winter MSL changes significantly over time (Fig. 9.4, left panel; also shown by Jevrejeva et al. 2005).

Although the NAO is the dominant sea level pressure (SLP) large-scale pattern of the North Atlantic in wintertime, it explains (on average) only 32 % of the total variability of sea level at interannual timescales (e.g. Kauker and Meier 2003; Jevrejeva et al. 2006). Thus, estimation of the full amount of variability that can be explained by the atmospheric circulation (and not only by the NAO) must consider the whole SLP field of the North Atlantic–West European region. Such an analysis was presented for the first time for the Baltic Sea by Heyen et al. (1996).

In a more recent study, Hünicke et al. (2008) statistically analysed the influence of different atmospheric forcing factors (temperature, SLP and precipitation) and found that decadal sea level change in the Baltic Sea basin varies geographically. In the central and eastern parts of the Baltic Sea,

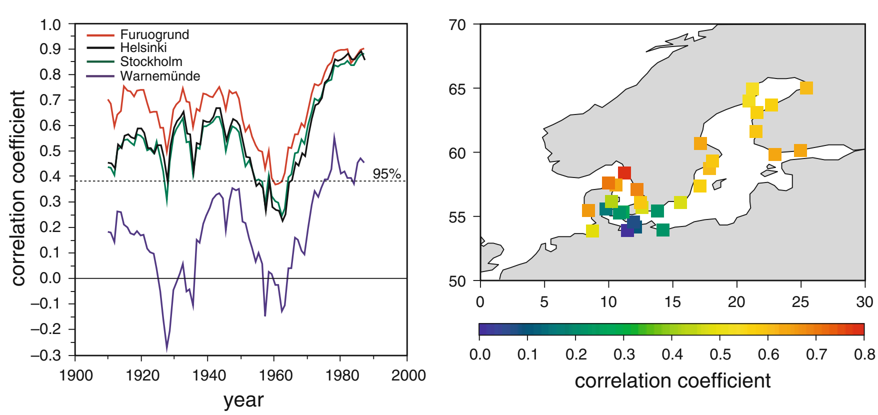


Fig. 9.4 *Left* Sliding correlation (21-year window) between four sea level stations that should be representative of the behaviour of sea level in the Baltic Sea and the winter NAO index (DJF); *Right* Correlation between winter means of the **NAO** index and winter mean (linearly detrended) Baltic Sea sea level 1900–1998 (redrawn from Hünicke and Zorita 2006)

winter sea level variations at decadal timescales are explained well by SLP variations (and not only the NAO). For the southern part, area-averaged precipitation seems to better explain statistically the decadal variations. Thus, depending on future climate trends (see Chaps. 11–14), a different behaviour of future sea level trends in southern and eastern and northern parts of the Baltic Sea might be possible.

On the other hand, Ekman (2009) offered a different, purely dynamic, explanation for the observed correlation between SLP and the southern Baltic (low correlation) and northern Baltic (high correlation). This explanation involves the basinwide response of SSH to sustained westerly winds (long-term response). The variations should be greater away from the connection to the North Sea and smaller closer to it. However, questions remain, such as the instability of the correlation with the NAO over time and the long-term correlation between southern Baltic Sea sea level and precipitation, which is evident in low-pass filtered decadal time series.

Omstedt et al. (2004) investigated variability and trends in observed time series for the Baltic Sea region from the past two centuries and found pronounced positive trends in Stockholm sea level variations and anti-cyclonic circulations. For the period 1985–2000, trends in air temperature and sea level anomalies were found to be positive, lying outside the range of normal variation for the past 200 years (see also Sect. 9.3.2.1).

Getzlaff et al. (2011) observed an offset in detrended monthly MSL anomalies (taken from PSMSL) for the periods 1970–1988 and 1989–2008 and associated it with a shift in strong wind events and with the change in prevailing wind directions (as a result of an increased positive NAO) (Lehmann et al. 2011). The shift was found to occur uni-directionally over the whole Baltic Sea area, which suggests a change in the prevailing westerly wind situation controlling MSL variations. The results agree with findings of a numerical model simulation and confirm findings of recent studies of historic sea level time series (e.g. Johansson et al. 2004).

Dailidienė et al. (2011) studied water level and surface temperatures of coastal lagoons along the southern and south-eastern shores of the Baltic Sea (Curonian and Vistula Lagoons and Darß-Zingst Bodden chain), relating the observed increase in water level (greatest in the east) and water temperature since the 1980s to changes in the NAO.

9.3.2 Variations Within the Observational Period (Past 200 Years)

Within the Baltic Sea, the trends in coastal sea level display a strong influence of the isostatic dynamics following the last deglaciation. Thus, RSL is falling in the northern Baltic Sea and rising in the southern Baltic Sea, due to the combined effect of crustal deformation and volumetric sea level changes. Superimposed on the long-term trends that affect RSL, many climate factors, such as changes in water density, changes in the total volume of the Baltic Sea and currents, can modulate ASL within the whole or parts of the Baltic Sea basin. Sea level may thus display considerable variability on timescales ranging from minutes through the annual cycle, to decades.

9.3.2.1 Long-Term Trends and Decadal Variations

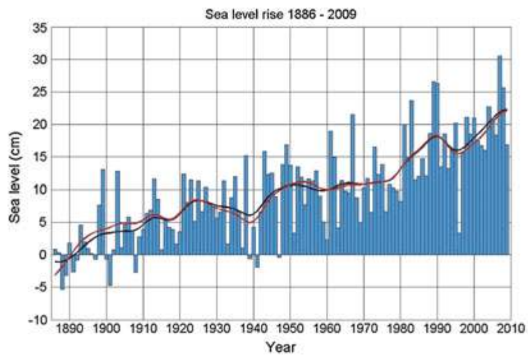
Absolute Sea Level

Some studies have analysed observations from permanent GPS stations to determine crustal deformation rates and used these and repeated levelling data to derive ASL changes from tide gauges. For instance, Milne et al. (2001) estimated a regional ASL rise of 2.1 ± 0.3 mm year^{-1} using annual tide gauge means from records (provided by PSMSL) at 20 sites in Fennoscandia spanning 35 years or more, and using only data acquired during or after 1930. Hill et al. (2010) combined geodetic observations and models and estimated a spatially averaged rate of ASL change of around 1.5 mm year^{-1}, based on monthly RLR tide gauge means (from PSMSL) from records at 40 sites in Fennoscandia that provide more than 40 years of data. Richter et al. (2011) derived a mean ASL value of around 1.3 mm year^{-1} for 13 tide gauges for which a GPS station is located nearby. Nine of these gauges were sites on the southern Baltic Sea coast, spanning almost 200 years, and complemented by monthly tide gauge means from 51 (basinwide) PSMSL sites that report more than 60 years of data in the period 1908–2007.

Additionally, regional focused studies that combined geodetic and tide gauge data information found ASL values of around 1.3 mm year^{-1} for the Scandinavian coast (1891–1990, Vestøl 2006), 1.8 mm year^{-1} for Danish sea level stations (1900–2000, Knudsen and Vognsen 2010) and 1.5 mm year^{-1} for Swedish tide gauge stations (1886–2009, Hammarklint 2009, see Fig. 9.5). Ekman (2009) indicated a rate of climate-driven sea level rise in Stockholm of about 1 mm year^{-1}. For more detailed information, see the original references.

When the reported uncertainty is considered, the results of all the previously cited studies lie within the error bars of the rate of GMSL rise of 1.7 ± 0.5 mm year^{-1} reported in the Fourth Assessment of the Intergovernmental Panel on Climate Change (Bindoff et al. 2007). However, it should be remembered that regional long-term trends in sea level can deviate substantially from the global mean.

This was also demonstrated by Madsen (2011), who estimated linear sea level trends from a gridded satellite altimetry dataset (1992–2008, multi-satellite open ocean



Nr	Time series	Start	a (cm/year)
1	Furuögrund	1916	1.00
2	Ratan	1891	0.94
3	Draghällan/Spikarna	1897	0.88
4	Björn/Forsmark	1891	0.78
5	Stockholm	1774	0.52
6	Landsort	1886	0.43
7	Visby	1916	0.32
8	Ölands Norra Udde	1851	0.25
9	Kungsholmsfort	1886	0.14
10	Ystad/Skanör	1886	0.06
11	Malmö/Klagshamn	1924	0.12
12	Varberg/Ringhals	1886	0.20
13	Göteborg	1887	0.30
14	Smögen	1910	0.32

Fig. 9.5 Annual sea level means averaged for 14 Swedish sea level records corrected for land uplift (shown in the right table for each location) and compared to the 1886 level. *Black line* time-filtered version together with the filtered Stockholm sea level time series (*red line*) (Hammarklint 2009)

product with 1-degree, 10-day resolution). This resulted in a best estimate mean trend of 5.8 mm $year^{-1}$ for the Baltic Sea area, but with a high uncertainty in the trends of a few millimetres per year (Fig. 9.6). For comparison, the global mean value (3.23 ± 0.04 mm $year^{-1}$) and the Atlantic mean (3.3 ± 0.1 mm $year^{-1}$) were also calculated for the same dataset and time period. Madsen (2011) concluded that the uncertainty in the estimation of regional trends is much greater, both because of the smaller number of samples and, especially for the Baltic Sea, because of the large natural variability. This also means that the trends are sensitive to the choice of time period. With these reservations, it can be seen that the North Sea trend is likely to be lower than the global mean and that the Baltic Sea trend is very likely to be higher than the global mean and perhaps just as interesting for the Danish area, higher than the North Sea trend.

Relative Sea Level

In recent years, changes in Baltic Sea RSL, as the most important factor in impact studies, have been the subject of a wider range of publications, mainly on the regional (e.g. national) to local (e.g. only one tide gauge) level. However, a comparison of the different results is hampered by different observation periods (and the treatment of data gaps therein) and analysis techniques. Thus, the cited RSL trend values that follow must be treated with great care.

Navrotskaya and Chubarenko (2012) studied annual (and extreme) sea levels in the Russian sector of the Vistula Lagoon situated in the south-eastern part of the Baltic Sea. They found annual mean linear RSL trends in the range 1.7–1.9 mm $year^{-1}$ (Baltiisk, 1860–2006; Kaliningrad, 1901–2006) to 3.6–3.7 mm $year^{-1}$ (Kaliningrad, Baltiisk, Krasnoflotskoe, 1959–2006). On the sea coast (Pionerskii,

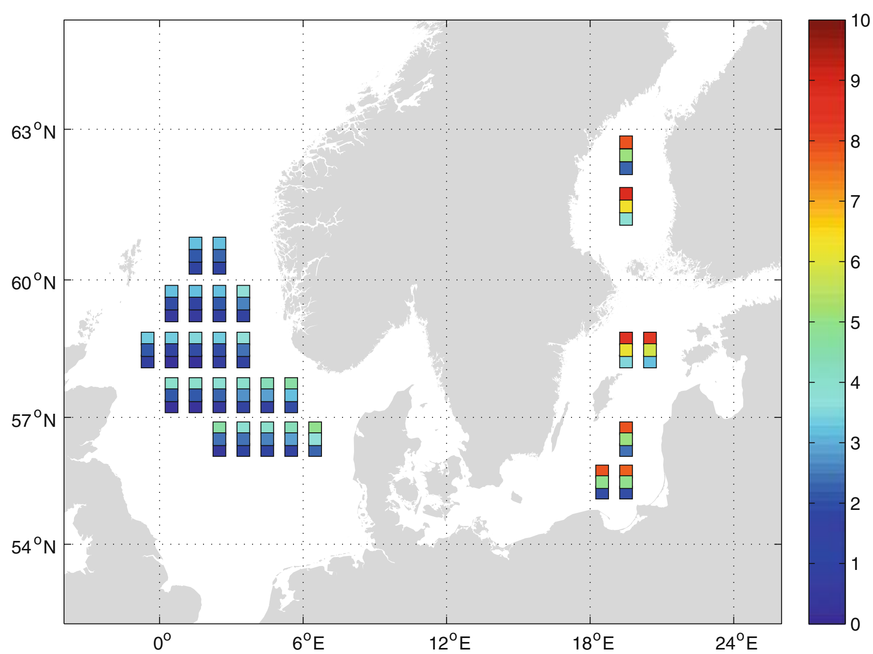


Fig. 9.6 Linear trends in sea surface height (mm $year^{-1}$, *centre boxes*) and 90 % confidence intervals (*upper and lower boxes*) as calculated from satellite altimetry (Madsen 2011)

1959–2006), the trend in the latter half of the twentieth century amounted to 2.6 mm year^{-1} only.

To the authors' knowledge, no published sea level studies are available for the Latvian coasts, but linear trend estimations at two sites (Liepaja 1865–1936 and Daugavgriva 1872–1938) are available through PSMSL.

For the Estonian coastline, Suursaar and Kullas (2009b) estimated linear RSL trends of 1.5 mm year^{-1} (Pärnu 1924–2008), 1.8 mm year^{-1} (Tallinn, 1899–2005) and 0.5 mm year^{-1} (Narva-J. 1899–2008).

Dailidienė et al. (2006, 2012) estimated linear annual mean RSL long-term trends for Lithuanian tide gauges, ranging from 1.3 mm year^{-1} for the centennial trend (Klaipeda Strait 1998–2002; situated on the open Baltic Sea coast) to 2.4–2.9 mm year^{-1} for sea level stations reporting between 1961 and 2002 (Juodkranté, Vida, Venté; situated in the Curonian Lagoon).

Figure 9.7 displays maps of the secular (100 years) RSL changes compiled by Richter et al. (2011) based on long tide gauge measurements of the Baltic Sea region based on data from PSMSL (including Polish, German, Danish, Swedish and Finnish tide gauges) and data compiled on the basis of historic documents (at German and Polish sites).

The pattern in RSL trends (Fig. 9.7, left panel) shows a clear north–south gradient within the Baltic Sea region, reflecting the crustal deformation due to the GIA effect. In the northern part, stations indicate large negative RSL trends. A maximum rate of 8.2 mm year^{-1} is found in the Gulf of Bothnia, in the area of predicted maximum GIA-induced crustal uplift (e.g. Peltier 2004). Tide gauge measurements along the southern Baltic Sea coast yield positive rates of around 1 mm year^{-1}, which implies a rising sea level relative to the Earth's crust. However, the pattern of trends over the southern region is not uniform and displays a clear gradient in the north-easterly direction (Fig. 9.7, lower right panel).

The spatial pattern in long-term trends in sea level should, in general, also reflect the spatially varying fingerprints of sea level change due to recent mass changes in the polar ice sheets and, accordingly, the change in the gravity field of the Earth's surface (Tamisiea et al. 2003; Milne et al. 2009). As demonstrated by Mitrovica et al. (2001), the pattern caused by the melting of the Greenland Ice Sheet is negligible for the Baltic Sea region, as its zero-line intersects this region, and the remaining variations are below the accuracy of the derived RSL rates, ranging between 0.1 and 0.3 mm year^{-1}. On the other hand, the pattern caused by the melting of the Antarctic Ice Sheet does affect the Baltic Sea region, but can be expected to be nearly constant over the entire region (see also Chap. 14). There exists, however, considerable uncertainty about the sign of the mass balance of the Antarctic Ice Sheet in the twentieth century, due to the competing effects of melting, calving and precipitation.

Richter et al. (2011) also analysed the variation in the annual mean RSL at long tide gauge records, such as the Polish tide gauges Swinoujscie and Kolobrzeg (Fig. 9.7, upper right panel). Both time series show consistent behaviour with a slight negative trend throughout the first decades of the time series up until 1860, followed by an increasing trend of around 1 mm year^{-1}. The authors suggested, as a possible explanation for this trend, climatic effects related to the Little Ice Age. This is consistent with Ekman (2009 and references therein) for the GIA-corrected ASL trend of 1.01 mm year^{-1} for the Stockholm time series. (Figure 9.7 includes, for illustration, the RSL Stockholm series that displays a strong negative trend due to the GIA). However, it should be remembered that due to decadal

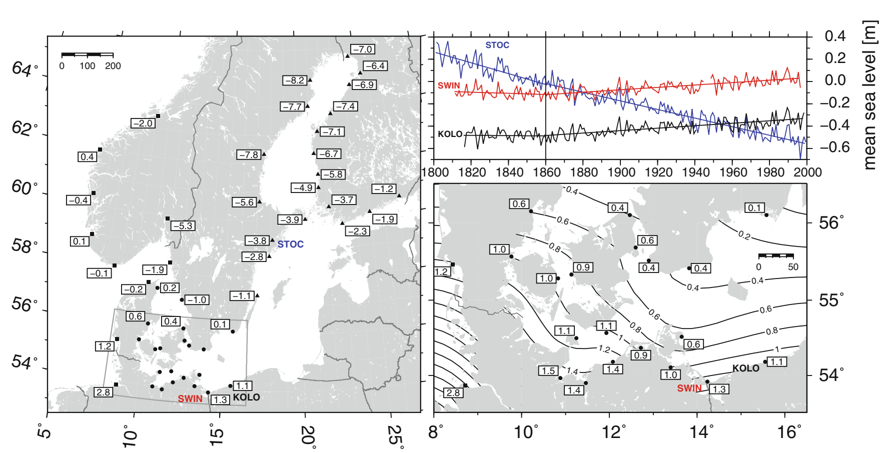


Fig. 9.7 Maps of secular (100 years) RSL changes, based on tide gauge measurements of the entire Baltic Sea region (*left panel*) and, in more detail, the southern Baltic Sea coast (*right panel below*) together with changes in the linear trend of the (arbitrarily shifted) annual RSLs at Stockholm, Swinoujscie (SWIN) and Kolobrzeg (KOL) between the period before and after 1860. The *symbols* represent the affiliation to different reference stations (*dots* warnemünde, *triangles* Stockholm, *squares* Smögen) (redrawn from Richter et al. 2011)

variations in the RSL trend, a comparable determination of secular RSL changes at different stations requires the application of identical observation periods (Richter et al. 2011) and analyses techniques.

The long-term trends of Baltic Sea RSL in the period with direct observations have been analysed by Barbosa (2008) and Donner et al. (2012). As well as estimating trends in the median sea level, they also estimated trends in the quantile of the probability distributions of monthly MSL at different gauges along the Baltic Sea coast (Fig. 9.8). The trends clearly exhibit the effect of the GIA. Interestingly, the trends in the median sea level do not always coincide with the trends in the extreme high and low quantiles.

Whereas the low quantiles of the distributions show basically the same trend as the median, the upper quantiles tend to display a more positive trend. Therefore, the higher values of RSL are increasing more rapidly, or decreasing more slowly in the regions with isostatic uplift. This happens more markedly in the northern Baltic Sea and has also been confirmed by more locally focused studies on Estonian sea level (Suursaar and Kullas 2006).

The reasons for this different behaviour are not clear, and many factors such as the atmospheric circulation could contribute. In the Estonian case, due to the form of the coastlines, the fingerprint of forcing by the atmospheric circulation at interannual timescales is clearly detectable. Therefore, a reasonable conjecture is that the atmospheric circulation, in particular the NAO, may also be involved in the long-term trends of the upper sea level quantiles in wintertime. However, the NAO exhibits a positive trend only in the last decades of the instrumental record, and not over the whole twentieth century. Also, the NAO trend in the very last two decades has been negative (Pinto and Raible 2012). Other atmospheric circulation patterns different from the NAO may also play a role (see Sect. 9.3.1.2 *Meteorological influence*). For example, Omstedt et al. (2004) found that the frequency of anti-cyclonic situations over the Baltic Sea increased in the late twentieth century imprinting its influence on several climate variables, also on the Stockholm sea level data. The causes of linear trends in sea level, therefore, may depend on the timescale over which these trends are calculated. At decadal and multi-decadal timescales, the internal variations of the atmospheric circulation may exert a strong influence. The NAO, as previously indicated, undergoes multi-decadal phases of increase and decrease. Over longer timescales, such as the centennial scale, the influence of the atmospheric circulation is strongly averaged out and is likely to become weaker relative to other external forcing. In this respect, Ekman (2009) found that the probability distribution of monthly sea level in Stockholm

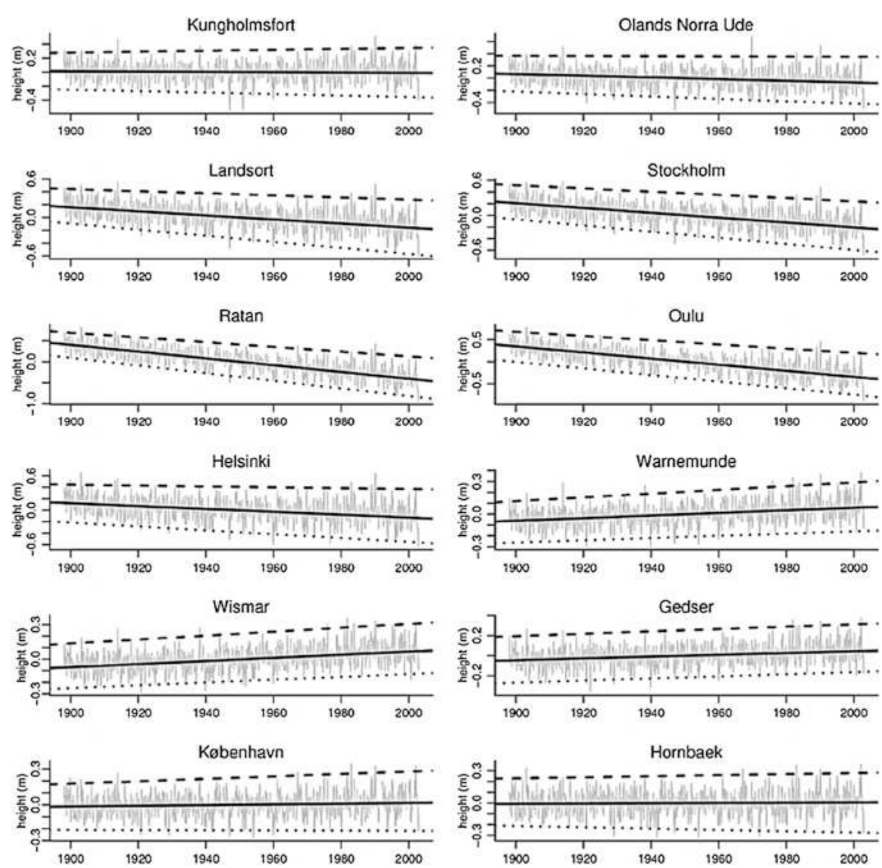


Fig. 9.8 Time series of three quantiles (median, and the 1 and 99 % quantiles) of the distribution of de-seasonalised monthly sea level at several stations of the Baltic Sea in the period 1890–2010 (Barbosa 2008)

has also undergone large changes over time, with a much narrower spread prior to 1950 than in later decades.

Baltic Sea sea level has undergone decadal variations around the quasi-linear long-term trend dominated by the GIA. These decadal variations were found to depend on the season. For example, Chen and Omstedt (2005) found for the Stockholm sea level record that all months except June and August display positive sea level trends. The authors connected the negative trends in June and August to a negative long-term trend in Baltic Sea precipitation during these months. However, they stated that these findings have still to be justified by a detailed analysis of the hydrological budget.

An illustration of decadal long-term wintertime variations in sea level for the past 200 years was presented by Hünicke et al. (2008) for four different sites (Fig. 9.9).

Ignoring the GIA-related trend, winter Baltic Sea sea level generally displays higher values around 1820, 1910 and in the most recent decade, and lower values around 1875, 1940 and 1970. However, the homogeneity of the data may be compromised at the beginning of the record. Since the decadal variations are not totally coherent through time, the precise mechanisms responsible for them have not been ascertained. The decadal variations may have been caused mainly by atmospheric circulation, but also by precipitation and variations in ocean currents.

Scotto et al. (2009) analysed the spatial coherence of long (>30 years) monthly records of RSL from 14 tide gauges in the Baltic Sea by applying cluster analysis. The coherent regions were defined in terms of the statistical properties regarding their serial auto-correlation. At timescales of up to three months, the usual Baltic Sea sub-basins emerged as individual clusters. For longer timescales, up to six months, all regions with the exception of the areas close to the North Sea displayed high coherency.

9.3.2.2 Changes in Seasonal Variability

The long-term changes in Baltic Sea sea level have been also found to depend on the season. Sea level displays an annual cycle and is generally higher during winter months and lower during spring (as demonstrated by Hünicke and Zorita 2008, see Fig. 9.10).

Changes in the annual sea level cycle were studied by Ekman and Stigebrandt (1990), Ekman (1999) for the Stockholm sea level record (covering the ninetieth and twentieth centuries). The authors associated the increase in the amplitude of the dominant annual component to changes in winter wind condition. Hünicke and Zorita (2008) statistically analysed 30 sea level records from PSMSL (covering the twentieth century) and four long historic sea level records (covering the ninetieth and twentieth centuries, including Stockholm), together with climatic datasets, to investigate centennial trends in the amplitude of the annual cycle. They detected a statistically significant increase in amplitude (winter-spring sea level) in the annual cycle in almost all sea level records investigated, but of a weaker sign than the decadal variations in the annual cycle. As the magnitude of the trends appeared almost uniform, with the exception of the Skagerrak area, they concluded that the driving mechanism for the trends in the annual cycle is very likely to be of non-regional origin. Testing several hypothesised factors to explain these centennial trends (wind through the SLP field, the barometric effect, temperature and precipitation), only precipitation remained a plausible candidate in their analysis. The physical mechanisms responsible for the long-term trend due to changes in precipitation could be related to salinity changes and their effect on changes on water density. This remains to be resolved.

Plag and Tsimplis (1999) investigated the spatial and temporal variability in the seasonal cycle of sea level for PSMSL tide gauge records in the North Sea and Baltic Sea.

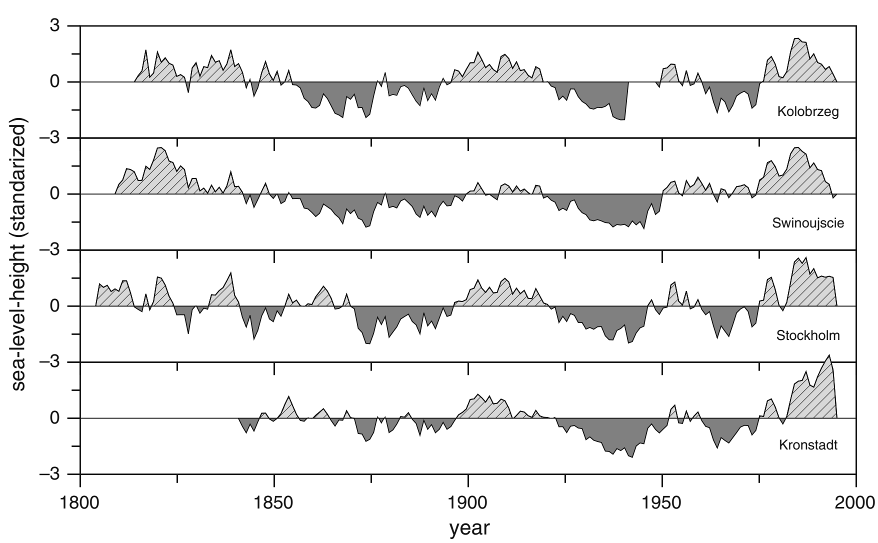


Fig. 9.9 Relative winter mean (DJF) sea level heights in the Baltic Sea. The series are smoothed by an 11-year running mean to highlight the decadal variations and are standardised by unit standard deviation. The long-term trend was eliminated (redrawn from Hünicke et al. 2008)

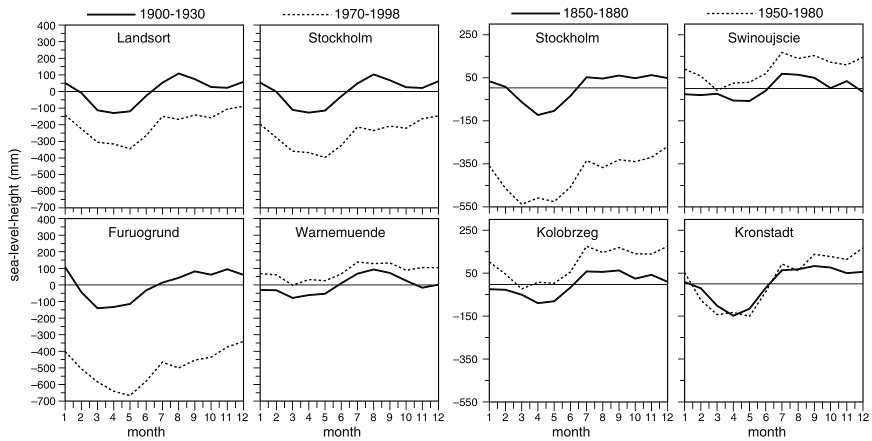


Fig. 9.10 Annual sea level cycle at various Baltic Sea sites derived from monthly means. *Left panel*: early and late twentieth century (1900–1930 *solid line*, 1970–1998 *dashed line*). *Right panel*: mid-nineteenth and mid-twentieth century (1850–1880 *solid line*, 1950–1980 *dashed line*) (redrawn from Hünicke and Zorita 2008)

They related the variability detected to changes in the position and extent of the separation zone between maritime and continental climate regions.

However, the decadal variations in the amplitude of the annual sea level cycle can be due to slow variation in the wind forcing, especially at regional scales and at locations where the geometry of the coastline is favourable for wind-driven change to become evident. For instance, in the Gulf of Riga and Väinameri area, results from a two-dimensional hydrodynamic model indicate that a relatively modest increase in wind speed (2 m s^{-1}) could be responsible for a mean increase in sea level of up to 5 cm, in addition to an analogous change in the Baltic Sea MSL (Suursaar and Kullas 2006). Consequently, a total wind-induced average sea level rise of 7–10 cm could occur at locations like Pärnu and Matsalu, Estonia. In these areas, changes of a similar magnitude probably occurred between 1950 and 1990 (Suursaar and Kullas 2006).

9.3.2.3 Is Sea Level Rise Within the Baltic Sea Accelerating?

A relevant question in the context of climate change is, whether the rise in global sea level is accelerating? Projections of the future magnitude of global sea level rise are still very uncertain, mainly due to the difficulty in estimating the effects of warming on the dynamics of the polar ice sheets. Also, there is a wide spread in the projections of the future thermosteric effect simulated by the suite of climate models for 2100, between about 10 and 40 cm in the global mean (see also Chap. 14). Global sea level is currently rising at about 3.2 mm $year^{-1}$ (Church and White 2011). If this trend continues through the twenty-first century, sea level rise by 2100 would be about 30 cm. The projections from global climate models, augmented by the more uncertain estimates of the dynamics of ice sheets and coastal glaciers, imply therefore an acceleration from the present rate of global sea level rise (see also Chap. 14). This is not necessarily the case for regional sea level rise, however, especially for the Baltic Sea with its complex coastline and the many different processes modulating its response to global warming. Nevertheless, the question as to whether the rate of sea level rise in the Baltic Sea is accelerating is relevant for adaptation to climate change and other planning purposes over the coming decades.

A preliminary indication of acceleration may be conveyed by a change in the long-term linear trends in two different periods of the recent past. Ekman (2009) suggested that the rise identified in the Stockholm sea level record is accelerating because the trends before and after 1950 look different (Fig. 9.7, upper right panel). However, this simplistic view should be complemented, if possible, by studies that analyse jointly the observed evolution of sea level and the theoretical evolution that sea level should display as a response to anthropogenic climate change. A change in the rate of sea level rise may not necessarily be projected by numerical climate models.

Most studies implicitly define the concept of ‘acceleration’ of sea level rise, possibly influenced by anthropogenic climate change, in one of two ways. The first approach is to look for a long-term increase in the *rate of* sea level rise, while the other compares the recent rate of sea level rise against rates observed in the past. The difference between both approaches can be illustrated by the following example. Given a sea level record, the linear trend of sea level change in sliding windows of fixed length (such as 30 or 50 years) can be calculated (Richter et al. 2011). If the linear rate in the most recent window is the highest, it could be claimed, following the second approach, that the present rate of increase is unprecedented, and thus possibly related to anthropogenic climate forcing. However, due to decadal variability in the rate of change, the linear rate in the most recent window may not be the highest over the whole record length. However, if the linear trends over the sliding windows itself display a linear trend, it could be claimed, following the first approach, that sea level rise is accelerating in that particular record. In a variant of the first approach, the

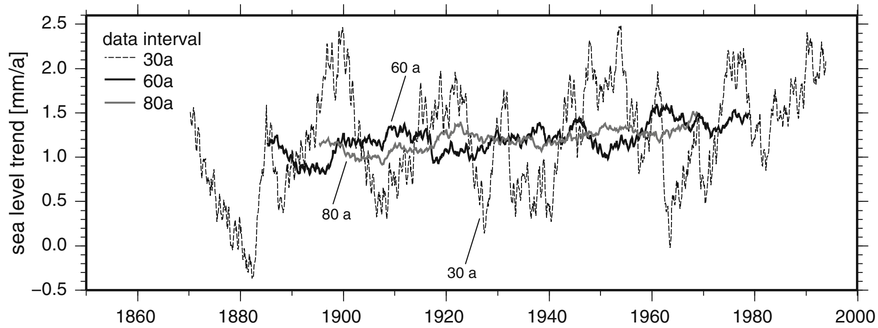


Fig. 9.11 Linear trends calculated in sliding windows of fixed length for the annual sea level record in Warnemünde (Germany), a station in the southern Baltic Sea. The three series show the results for different window lengths (redrawn from Richter et al. 2011)

long-term trends in sea level rise is determined by fitting a second-order polynomial in time to a sea level record (Church and White 2006; Woodworth et al. 2009). If the quadratic coefficient is found to be significantly different from zero, acceleration could claim to have been identified. More loosely, if abrupt changes are identified in the linear trends—denoted inflexion points—these may be attributed to acceleration or deceleration. Sea level acceleration has been looked for using both approaches in global studies. For the Baltic Sea, these approaches have yielded contradictory results. Woodworth et al. (2009) found a positive quadratic term for the rate of rise in mean Baltic Sea sea level of the order of 0.005 mm year^{-2}, derived from the global sea level reconstructions of Church and White (2006) and consistent with values found specifically for the Stockholm sea level record (Woodworth et al. 2011). However, the Baltic Sea series provided by Jevrejeva et al. (2008) displayed a *deceleration* inflexion point around 1920.

The different perspectives on acceleration may be illustrated by the results of Richter et al. (2011) (Fig. 9.11) for the Warnemünde sea level record, a station in the southern Baltic Sea. The 30-year trends indicate that the present rate of rise is not unprecedented in the record. Although the recent linear trends are high, similar or even slightly higher rates were observed around 1900 and 1950. These findings generally agree with the (non-peer-reviewed) results of Zorita and Hünicke (2010), who presented sliding linear trends of long sea level records, estimated by linear fit in moving 31-year windows for Stockholm (Sweden), Kronstadt (Russia), Kolobrzeg and Swinoujscie (Poland).

The time series of sliding 30-year trends (Fig. 9.11) illustrates the very high variability in sea level rise in the southern Baltic Sea over relatively short periods. Although the 30-year trend time series displays a slight positive upward trend, its statistical significance is low due to the large decadal variability. For trends over wider sliding windows (such as 60 or 80 years—see Fig. 9.11), the variability is reduced and a long-term increase in the linear rates of rise is easier to see. However, wider windows reduce the number of independent degrees of freedom which also compromises any estimate of statistical significance.

It is clear therefore that, depending on which approach is used, the same long-term sea level record may appear to exhibit both the presence and absence of a significant acceleration in sea level rise.

In cases where acceleration in sea level rise has been identified, this should ideally be accompanied by an estimate of its level of statistical significance. As in any statistical test, a general algorithm to attach a certain level of statistical significance of an estimated value cannot exist, since the significance level depends on the formulation of the null-hypothesis, against which the statistical test is conducted. This formulation is subjective, and different authors may consider different null-hypotheses to describe the statistical properties of the natural fluctuations in the rate of sea level change. Donner et al. (2012) reported different levels of statistical significance for the estimated acceleration depending on whether the data were assumed to be serially correlated or serially independent. The authors also attempted to estimate the acceleration in the rates of change of the quantiles of the distribution of monthly sea level for a set of Baltic Sea coastal stations. The record length across the dataset is not uniform and so the spatial patterns of the acceleration estimate and its level of statistical significance may be strongly influenced by data availability. When the analysis is applied to the period covered by all sea level records (1951–2000), none of the quantiles of the probability distribution display statistically significant accelerations if the de-seasonalised monthly sea level data are assumed to be serially correlated. However, they do underline that statistical detection of acceleration in only 50 years of data may not be possible due to the short record length.

9.4 Extreme Sea Levels

Extremes in coastal sea level oscillations pose a serious threat to coastal populations as their impacts can be catastrophic. At many coasts around the world, extreme sea levels are essentially determined by tides; however, this effect is negligible in the Baltic Sea due to the semi-enclosed nature of the basin. Lowe et al. (2010) reviewed change in extreme sea levels in recent decades and concluded that—globally—there is little evidence of change in extreme sea levels over an extended period, a behaviour which differs significantly from the change in GMSL. In their quasi-global investigation, Menendez and Woodworth (2010) showed that recent change in extreme sea levels is mostly due to the change in MSL (by a shift in the frequency distribution), while meteorological contributions vary on timescales of years and decades but mostly show no clear long-term trend. Thus, the question arises as to whether the amplitude and frequency of extreme sea level events in the Baltic Sea is changing and if so, how they compare to changes in Baltic Sea MSL.

9.4.1 Main Factors Affecting Extreme Sea Levels in the Baltic Sea

Because of its elongated shape, semi-enclosed configuration and presence of shallow bays exposed to the direction of strong winds, storm surges occur frequently on exposed coasts of the Baltic Sea. In contrast to tide-dominated basins, extreme sea levels in the Baltic Sea are mainly due to wind (wind set-up). Other contributors include the inverse barometer effect, standing waves (seiches) and the propagation or amplification of remotely generated long waves. Winds affect sea level in two main ways (e.g. Samuelsson and Stigebrandt 1996; Ekman 2007). First, wind may build up a sea level slope within the Baltic Sea, resulting in the strongest deviations at the 'ends' of the Baltic Sea (in the Belt Sea and the gulfs of Finland, Bothnia and Riga). Second, when a strong persistent wind from the south-west or north-east is blowing over the Baltic Sea and its entrance, water is transported into or out of the Baltic Sea, thereby raising or lowering sea level in the basin as a whole. Although the amplitude of such events is normally less than 50 cm, they can provide preconditions for much larger local-scale storm surges when combined with short-term storm winds during cyclones (Hupfer et al. 2003). All over the sea, both extreme high and low sea level events tend to occur in the meteorologically more variable winter months (e.g. Sztobryn et al. 2009; Suursaar 2011).

Owing to the large meridional extent of the Baltic Sea, the required forcing conditions, as well as storm surge risks, may vary strongly in different parts of the basin. As a general rule, in the eastern section near the coasts of Lithuania, Latvia, Estonia, Russia and Finland, strong easterly winds tend to lower sea level, and westerly winds to raise it (Suursaar et al. 2002, 2006a). This applies for short-time variations, as well as for low-frequency variations through the corresponding changes in the Baltic Sea sea water volume. The lowest recorded sea level in the Gulf of Riga (−130 cm at Riga, −125 at Pärnu) occurred in December 1959 after a month with strong (20 m s^{-1}) easterly winds during an anti-cyclonic blocking pattern (Suursaar et al. 2002).

The highest surges usually occur in the eastern part of the Gulf of Finland (Fig. 9.12). Such events have been analysed by Klevannyy et al. (2001), Nekrasov et al. (2007), Averkiev and Klevannyy (2010). As most of the cyclones over Scandinavia and the Baltic Sea travel from south-west or west to the east, storm surges are usually generated in the eastern or north-eastern sections of the basin. The surges are particularly pronounced in bays away of the nodal (central) part of the sea, such as the Neva Bay of St Petersburg (up to 421 cm). At the same time, negative surges or sea level lowering occur along the opposite, Swedish, Danish or German coasts. Those high and low sea level areas evolve in time, as the cyclones travel through a particular area.

For extreme surges to occur in the coastal waters of Estonia and St Petersburg (and for negative surges on the Swedish and Danish coasts), the centre of a powerful cyclone should bypass Estonia to the north over the Scandinavian Peninsula and Bothnian Sea to make the local wind direction veer from south-west to north-west (Suursaar et al. 2006b; Averkiev and Klevannyy 2010). As the strongest winds occur a few hundred kilometres to the right of the cyclone track, reduced friction on the sea surface and the elongated shape of the Baltic Sea together with the Pärnu Bay (in case of Pärnu tide gauge) or Gulf of Finland (for Narva-Jõesuu and St Petersburg) provides a span for surge waves to increase towards the east. The diminishing water depth and narrowing gulf width reinforce this effect. Since 1703, there have been about 300 flooding events in St Petersburg due to a sea level rise above the critical value of 160 cm (Bogdanov et al. 2000). In 1970, a decision was taken to build a 25-km-long dam with huge closable gates to protect the city. This structure was finished in 2011.

A map of historical water-level maxima around the Baltic Sea coast was recently compiled by Averkiev and Klevannyy (2010) (Fig. 9.12). The authors compiled information from various sources and reported the data according to the relevant national water-level reference system. Data from stations of short duration using tide gauges are also included. Thus, the map is not homogeneous and must be considered a rough picture of extreme water-level maxima in the Baltic Sea (see also Fig. 9.13 for comparison). More detailed information is available from the original references (e.g. Hupfer et al. 2003; Sztobryn et al. 2005 and references therein; Dailidienė et al. 2006; Suursaar et al. 2006a; Kowalewska-Kalkowska and Wisniewski 2009).

Cyclone Gudrun on 9 January 2005, which attained a hurricane-like intensity according to the mean wind speed measurements (up to 34 m s^{-1}) in Denmark, produced its highest sea level at most of the Estonian tide gauges (275 cm at Pärnu; the previous highest was 253 cm on 19 October 1967) and some Finnish tide gauges (Helsinki 151 cm,

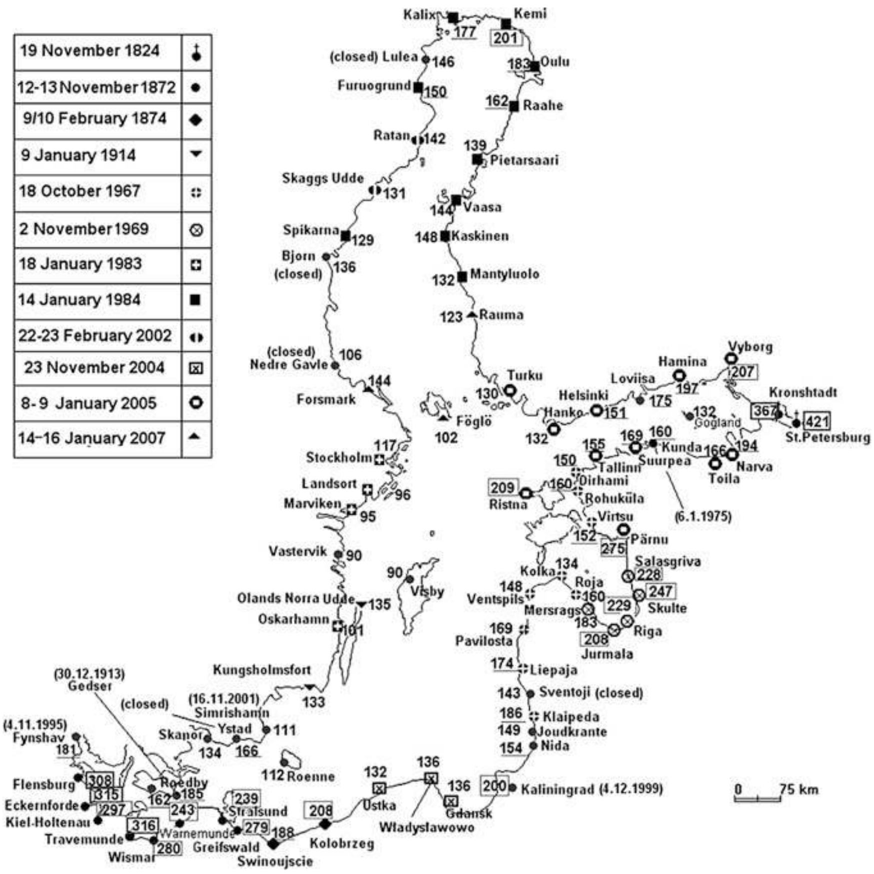


Fig. 9.12 Historical water level maxima (cm) in the Baltic Sea (Averkiev and Klevannyy 2010)

Hamina 197 cm, Hanko 132 cm, Turku 130 cm). However, previous records were not surpassed in the Gulf of Bothnia (Kemi 201 cm in 1982) or in St Petersburg, where sea level reached a relatively modest 230 cm. Gudrun's eye passed 300 km north of Estonia, heading north-east and creating strong south-westerly winds (and later west–north-westerly winds once it had passed) reaching an average speed of 28 m s^{-1} over one hour. Another factor contributing to Gudrun's storm surge was the relatively high background sea level (70 cm) in the Baltic Sea at the time (Suursaar et al. 2006b). The high background sea level was due to strong cyclonic activity during the preceding month, which had funnelled additional water through the Danish Straits into the Baltic Sea.

Narrow bays in the Belt Sea and in the south-western Baltic Sea have experienced the second highest storm surges (see Fig. 9.13), but also the strongest negative surges. Sztobryn et al. (2009) described the characteristics of negative surges in the southern Baltic Sea using data (1955–2005) from three German gauge stations (Wismar, Warnemünde,

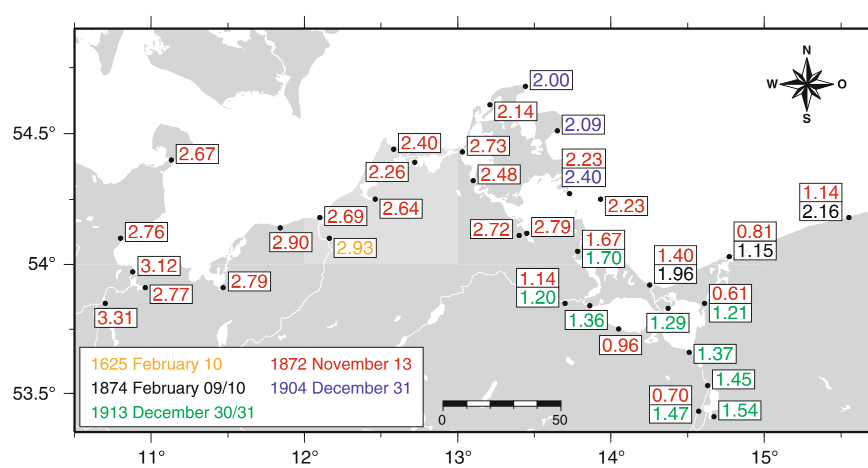


Fig. 9.13 Absolute water levels (in m relative to the NN height system) along the southern Baltic Sea coast according to data from tide gauge observations and storm surge marks (redrawn from Richter et al. 2011)

Sassnitz) and two Polish gauges (Swinoujscie, Kolobrzeg). Their results confirmed that strong offshore winds (usually accompanied by low-pressure systems crossing the Baltic Sea) or storms driving the water away from the coast are the most important factor for the development of negative surges. The frequency and severity of negative surge events on the south-western Baltic Sea coast was found to decrease from west to east due to the baylike shape of the coast with an eastward opening (Sztobryn et al. 2009).

The maxima in many tide gauge records of the area were established by one spectacular north-easterly storm in November 1872 (see Fig. 9.13). A negative surge of about 1 m occurred in the Gulf of Finland (Ekman 2009). Colding (1881) analysed the event in Denmark. The author concluded that a storm raises sea level at the coast proportional to the square of the wind velocity and that the effect is also proportional to the fetch and inversely proportional to the sea depth.

Other major storm surge prone areas include the Gulf of Riga, and particularly Pärnu Bay (up to 275 cm) and the northern part of the Bothnian Bay (Kemi, 201 cm). Located close to the nodal line of the sea, the line of no vertical displacement in standing, basinwide oscillations—the Lithuanian and Latvian coasts in the Baltic Proper, the islands of Gotland, Åland and the Swedish coasts located leeward—will not experience high sea level events even during extreme storms. For a discussion of impacts on the coastlines of the Baltic Sea due to extreme sea level events, see Chap. 20.

9.4.2 Statistics and Long-Term Trends in Extreme Sea Levels

Richter et al. (2011) analysed long time series of extreme sea levels inferred from tide gauge records and historical documents of flood marks at the south-western Baltic Sea coast (Fig. 9.13). Changes in the magnitude of climate-driven extremes over the past 200 years could not be detected. This result contrasts with the findings of Sztobryn et al. (2005), who analysed extreme sea levels at the southern Baltic Sea coast (western and central parts) between 1950 and 2000 and found an increase in storm surges in the decades to 1990.

Woodworth and Blackman (2004) analysed the Stockholm time series (Fig. 9.14) and showed that the spread of higher percentiles is greater than that of the lower percentiles. They explained this result primarily by asymmetries in air pressure data and the wind fields. Also, the higher percentiles have similar time dependence on MSL which means that sea level extremes have a greater response to changes in the winter NAO index than MSL.

To summarise, Donner et al. (2012), Barbosa 2008 (see Sect. 9.3.2.1 and Fig. 9.8) found that trends in median sea level do not always coincide with the trends in extreme high and low quantiles. Upper quantiles tend to display a more positive trend than the median and the lower quantiles. This is consistent with the findings of Johansson et al. (2001), who investigated temporal changes in extreme sea level in Finland. They used homogenised Finnish series (13 stations, mostly covering the period 1923–1999) and found a significant 2–4 mm year^{-1} rise in annual sea level maxima. At the same time, the rise in annual sea level minima was only around 1 mm year^{-1}. Along the Lithuanian coast, the average rise in maxima was around 2–3 mm year^{-1} (Dailidienė et al. 2006).

Studies at the Estonian coastline showed a remarkable rise in annual sea level maxima of 3.5–11 mm year^{-1} after correcting for local uplift rates (Vallner et al. 1988; Suursaar and Sooäär 2007). Even excluding the prominent event of 2005, the rise in annual sea level maxima was significantly higher than the rise in MSL (1–2.6 mm year^{-1}) and the rise in annual sea level minima (0.8–3.1 mm year^{-1}). The hydrodynamic mechanism responsible for these differences appears linked to the location of Estonian and Finnish tide gauges with respect to the predominant strong winds

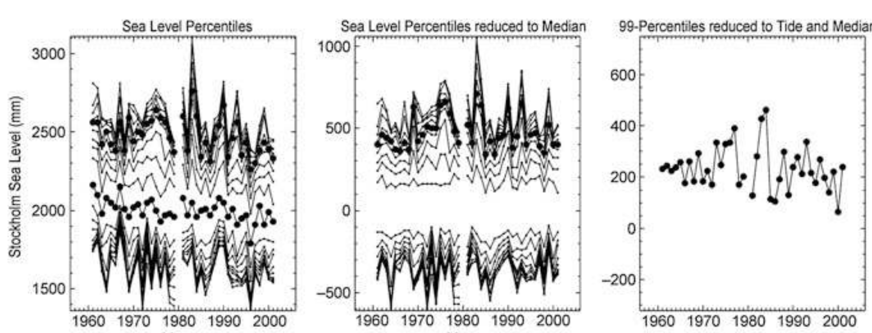


Fig. 9.14 An example of percentile time series from Stockholm, Sweden, showing the 19 separate percentile series. The 50th percentile or median (no. 10 of 19) and 99th percentile (no. 15 of 19) series are shown by *large dots*; (*middle*) as in (*left*) but with each percentile time series reduced to the median values; (*right*) the difference between the observed 99th percentile series and that from tidal analysis of each year of data (redrawn from Woodworth and Blackman 2004)

(Suursaar et al. 2006a, Suursaar and Kullas 2006). Analysis of local wind data from Estonian coastal stations has shown that, although the mean wind speed is likely to have decreased over the past 50 years, the westerly wind component and the extreme wind events have increased (e.g. Suursaar and Kullas 2009a, b; Jaagus 2009, Jaagus and Kull 2011, see also Chap. 4, Sect. 4.3). This is in good agreement with findings on changes in cyclone trajectories above the Baltic Sea (Sepp et al. 2005; Jaagus et al. 2008). The magnitude of an expected extreme event at a given location is usually described by the magnitude of the expected maximum extreme event over a certain period, such as 100 years or 1000 years. Alternatively, an observed extreme event may be described as the one expected to occur once in a certain period. Normally, a storm surge prone area (city, port) has established critical sea level values, usually based on statistical analyses of long tide gauge records. However, these projections are only truly valid in an unchanging climate. To incorporate the effects of future climate change requires additional information, climate simulations from numerical models and/or extrapolation of recently observed trends. However, as extreme events are by definition rare, empirical extrapolation carries large uncertainties.

There are many examples worldwide of 'storms of the century' or 'one in a thousand years' surge events that occur more frequently than expected from statistical analysis. This may be due to the limited number of observations available for estimating the magnitude of extreme events. For example, a comparison of empirical return periods against the corresponding theoretical distributions shows a reasonable fit for three Estonian tide gauges, but no fit in the case of Pärnu maxima (Suursaar and Sooäär 2007). The same situation exists for the Travemünde tide gauge in Germany, where sea level in 1872 was extraordinarily high and appeared to be an outlier in relation to the observed distribution of extreme events. However, when the tide gauge data were supplemented by historic storm surge water levels and simulations from numerical models, the 1872 value fitted well with the distribution based on this larger dataset (see Mudersbach and Jensen 2009). This is in general agreement with the findings of the MUSTOK project (model-based investigation of extreme water levels at the German Baltic Sea coast, see Jensen et al. 2009 and references therein). One of the assumptions in extreme value analysis is that there is no physical limit that an extreme event can attain, which is not a totally valid assumption in the case of storm surges. MUSTOK aimed at combining model-based estimates of the maximum attainable storm surge, high-quality data from instrumental measurements, and the more uncertain information from historical sources, to provide better estimates of storm surge return periods at several sites in the Baltic Sea. Including physically based limits for the possible extremes can substantially modify the probability of storm surge occurrence. For instance, using recent instrumental data only would have suggested that the storm surge in Travemünde was a once-in-10,000 year event, whereas including all three datasets in the projection would shorten the return period to 3400 years.

9.5 Wind Waves

The properties of wind waves depend primarily on wind speed and duration, and effective fetch length. In semi-enclosed shallow basins, wave properties are also modified through wave–seabed interaction (via refraction, shoaling, breaking or reflection) and diffraction behind obstacles. The Baltic Sea is a challenging location for wave scientists; the area has a very complex geometry and the associated high variability in wind fields gives rise to extensive spatio-temporal variability in the wave fields. Wave simulations therefore require a high spatial resolution and a careful choice for the location of wave measurements. The presence of sea ice (see Chap. 8) may substantially affect wave patterns and complicates wave measurements in winter. As floating devices are normally removed before the ice season (Kahma et al. 2003; Tuomi et al. 2011), measured wave data (especially in the northern Baltic Sea) display extensive time gaps and estimates of commonly used variables (e.g. annual mean wave height or period) become biased for seasonally ice-covered seas (Tuomi et al. 2011). Relatively shallow areas and convergent wind patterns may lead to unexpectedly high waves, formed through occasional wave energy concentration in some areas (Soomere 2003, 2005; Soomere et al. 2008a). Also, specific wave generation conditions for offshore winds over irregular coastlines (Kahma 1981; Kahma and Calkoen 1992) or under so-called slanting fetch (when wind blows obliquely across the coastline) frequently occur in some sub-basins (Pettersson et al. 2010).

9.5.1 Instrumental Measurements

Long-term (>10 years) instrumentally measured wave data are available only at three sites (Fig. 9.15). In terms of climate change, only data from upward-looking echo sounders at Almagrundet (1977–2003, Broman et al. 2006) and from a directional wave-rider at Darss Sill have been analysed (Soomere and Kurkina 2011; Soomere et al. 2012). The data from the wave-rider in the northern Baltic Proper were discussed by Kahma et al. (2003), Tuomi et al. (2011). Numerous relatively short-term wave measurement sites around Finland in the 1980s and 1990s were briefly described by Soomere (2008). Satellite altimeter data for wave properties have been used in a very small number of studies (Cieślikiewicz and Paplińska-Swerpel 2008; Tuomi et al. 2011).

9.5.2 Visual Observations

Historic wave observations from ships in offshore regions combined with the results of hindcast simulations have been used to generate wave atlases for the Baltic Sea (Rzheplinsky 1965; Russian Shipping Registry 1974; DWD 2006; Lopatukhin et al. 2006) and its sub-basins (Rzheplinsky and Brekhovskikh 1967; Druet et al. 1972; Schmager 1979; Sparre 1982).

Visual observations from anchored lightships and permanent coastal stations (Fig. 9.15, Table 9.2) cover a much longer time interval than instrumental measurements. Visually observed wave heights generally agree well with significant wave heights, whereas the visually estimated wave period is, on average, a few tenths of a second shorter than the peak period from hindcast simulations (Gulev and Hasse 1998, 1999). In contrast to offshore ship-based wave observations for estimates of wave climate (Gulev and Hasse 1999; Gulev et al. 2003), use of observations from coastal sites is more problematic. On the one hand, such data pose intrinsic quality and interpretation problems, have a poor temporal resolution, contain a large element of subjectivity and a substantial amount of noise (Zaitseva-Pärnaste et al. 2009), and only partially characterise the open sea wave fields (Soomere 2005). On the other hand, they have exceptional temporal coverage: regular observations have been carried out using a unified procedure at several locations for almost seven decades (Zaitseva-Pärnaste et al. 2011; Pindsoo et al. 2012).

Visual wave observations from Danish lightships have been made at multiple locations including Gedser Rev and Halsskov Rev and a permanent station at Drogden with six to eight observations per day (Sparre 1982; Fig. 9.15). The data are digitised from 1931 until the withdrawal of the ships in the 1970s and 1980s. Observations from Drogden continued until 1994. The ships were located at shallow sites of particular danger to ship traffic. This may affect the wave field statistics. Also, the lightships were relocated short distances on several occasions and there are some temporal gaps. Nevertheless, the dataset constitutes a unique source of information on the western Baltic Sea historic wave climate.

Wave observations on the eastern coast of the Baltic Sea have been made in many locations since the mid-1940s or 1950s (Table 9.2) usually three times per day using perspectometers (binoculars with specific scaling) and/or buoys or bottom-fixed structures to better characterise wave properties. The observers scanned areas at least 4 m deep about 200–400 m from the waterline. The observation conditions vary considerably between locations; for example at Pakri (Estonia), the observer was located on top of a 20-m-high cliff and the water depth of the area observed was 8–11 m. All sites of visual observations presented in Fig. 9.15 only

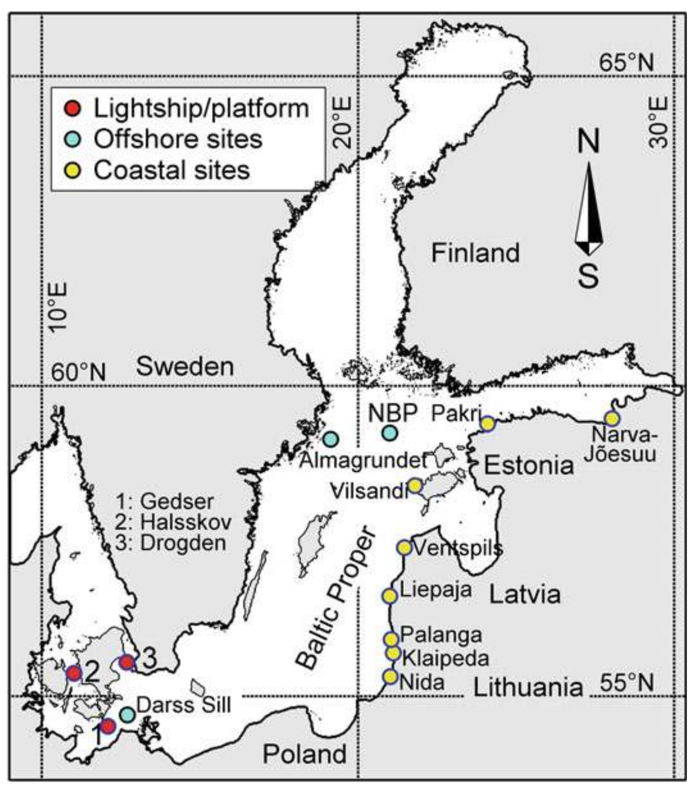


Fig. 9.15 Location of long-term (>15 years) instrumental wave measurements in the Baltic Sea (including information from Soomere and Räämet 2011; Sparre 1982)

Table 9.2 Sources of climatic wave information in the published literature

Location	Time series	Analysis of temporal change?	Source
Instrumental measurements			
Almagrundet, upward-looking echo sounders	1977–2003	Yes	Broman et al. (2006)
Darss Sill, directional wave-rider	Since 1991, excl. ice seasons	Yes	Soomere et al. (2012)
Northern Baltic Proper	Since 1996, excl. ice seasons	No	Tuomi et al. (2011)
Visual observations			
Global, including Baltic Sea (observations from ships)	1958–1997	No	Gulev et al. (2003)
	1970–2011	No	Gulev et al. (2005)
Danish waters (Drogden, multiple locations of lightships)	1931–1994	–	Sparre (1982)
Swedish waters (multiple locations and lightships)	1965–1972	No	Wahl (1974)
Lithuanian waters (Nida, Palanga, Klaipeda)	1954–2009	Yes	Kelpšaitė et al. (2008, 2011), Zaitseva-Pärnaste et al. (2009, 2011)
Latvian waters (Ventspils, Liepaja)	1946–2011	Yes	Pindsoo et al. (2012)
Estonian waters, NE Baltic Proper (Vilsandi) and the Gulf of Finland (Pakri, Narva-Jõesuu)	1946–2009	Yes	Soomere and Zaitseva (2007), Zaitseva-Pärnaste et al. (2009), Soomere et al. (2011)
Hindcasts			
Global, including Baltic Sea	KNMI/ERA-40 Wave Atlas	Yes	Sterl and Caires 2005; low spatial resolution (1.5° × 1.5°)
Baltic Sea basinwide	1999	No	Jönsson et al. (2003)
	2001–2007	No	Tuomi et al. (2011)
	1947–1988	No	Mietus and von Storch (1997)
	1958–2001	No	Cieślikiewicz and Paplińska-Swerpel (2008)
	1992–2002	No	Schmager et al. (2008)
	1958–2002	No	Augustin (2005), Schmager et al. (2008)
	1970–2007	Yes	Räämet and Soomere (2010, 2011)
Southern Baltic Sea	1978–1996	No	Blomgren et al. (2001)
Entrance to Warnemünde harbour	1956–1993 (single storms) 1988–1993	No	Gayer et al. (1995)
Pomeranian Bay	1997–1998	No	Paplińska (1999)
Tallinn Bay, Gulf of Finland	1981–2000	No	Soomere (2005)
	1981–2007, single-point winds	Yes	Kelpšaitė et al. (2009)
Hindcasts for single points in north-eastern Baltic Proper and Gulf of Finland		Yes	Suursaar and Kullas (2009a, b), Suursaar (2010, 2013), Suursaar et al. (2010, 2012)

partially represent the open sea wave conditions. Although the potential distortions due to the sheltering effect of the shoreline and the relatively shallow water depth may affect the results of individual observations, it is likely that long-term variations and trends in offshore wave properties would be evident through the analysis of large pools of visual observations. Owing to short daylight duration, only one to two observations per day are possible in northern areas in autumn and winter. To avoid the bias caused by a varying number of observations per day, the analysis of wave data is mostly based on the set of daily mean wave heights (Soomere and Zaitseva 2007; Zaitseva-Pärnaste et al. 2009, 2011).

9.5.3 Hindcast Simulations

The spatial resolution of numerically reconstructed global wave datasets such as the KNMI/ERA-40 Wave Atlas (1.5° × 1.5°) (Sterl and Caires 2005) is insufficient for the Baltic Sea. Several attempts to numerically reconstruct the wave climate in the Baltic Sea using a better resolution (down to about 3 nautical miles or about 5 km) have been undertaken for many areas and single locations (Table 9.2). Schmager et al. (2008), Soomere (2008) reviewed the relevant literature until 2007 and described the basic features of the wave climate.

Long-term reconstructions of the Baltic Sea wave fields are a complicated task and usually contain high uncertainties (Cieślikiewicz and Paplińska-Swerpel 2008; Kriezi and Broman 2008). The largest source of uncertainty is the wind information. The quality and spatial resolution of the wind data (down to about 10 km, Tuomi et al. 2011) have increased over the past decade. Simulations of long-term change in wave fields are, however, hampered by substantial temporal inhomogeneity (Tuomi et al. 2011), large spatial differences in data quality (Räämet et al. 2009; Soomere and Räämet 2011), and by the inability of even the most advanced atmospheric models to reproduce air flow accurately in several Baltic Sea sub-basins (Keevallik and Soomere 2010). Nevertheless, long-term numerical reconstructions of change in the Baltic Sea wave climate are available for 1958–2002 based on output from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCAR/NCEP) wind reconstructions (Augustin 2005; Schmager et al. 2008; Weisse and von Storch 2010) and for 1970–2007 based on adjusted geostrophic winds (Räämet and Soomere 2010; Soomere and Räämet 2011).

The relatively small size of the Baltic Sea, frequent large-scale homogeneity in the wind fields and the short saturation time and memory of wave fields make it possible to use simplified wave hindcast schemes (Soomere 2005), high-quality wind data from a few points (Blomgren et al. 2001) and/or properly calibrated simple fetch-based wave models (Suursaar and Kullas 2009a, b; Suursaar 2010) to reproduce local wave statistics with an acceptable accuracy. The use of such models for identifying spatial change in wave statistics is limited, however, as they can basically only reproduce change in the local wind field.

9.5.3.1 Long-Term and Extreme Wave Properties

Existing sources of Baltic Sea wave information make it possible to identify basic long-term wave properties (average and extreme height, occurrence distribution and height–period combinations) and their spatial variations. The Baltic Sea wave climate is, on average, very mild. The typical long-term significant wave heights are about 1 m offshore in the Baltic Proper (Kahma et al. 2003; Broman et al. 2006; Schmager et al. 2008; Tuomi et al. 2011), 0.6–0.8 m in the open parts of larger sub-basins such as the Gulf of Finland (Soomere et al. 2010) or Arkona Basin (Soomere et al. 2012) according to measurements and numerical simulations, and well below 0.5 m in semi-sheltered bays such as Tallinn Bay (Soomere 2005; Kelpšaitė et al. 2009) according to simulations (Fig. 9.16). These values are 10–20 % lower in the nearshore regions (Suursaar and Kullas 2009a, b; Suursaar 2010). The most frequent wave heights are also about 20 % lower than the long-term average wave height (Kahma et al. 2003; Soomere 2008; Soomere et al. 2012).

The spatial pattern of hindcast average wave heights (Fig. 9.16, left panel) contains either an elongated maximum

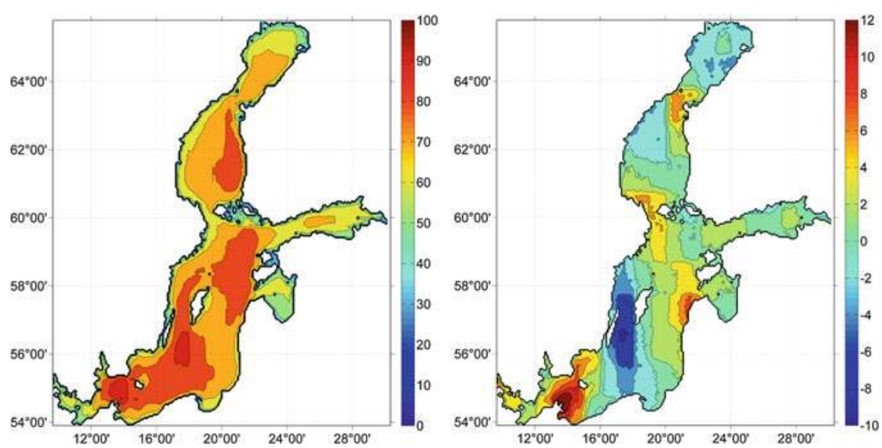


Fig. 9.16 *Left* Numerically simulated average significant wave height (colour bar, cm; isolines plotted after each 10 cm) in the Baltic Sea in 1970–2007 based on adjusted geostrophic winds from the Swedish Meteorological and Hydrological Institute (Räämet and Soomere 2010); *Right* Long-term change in the annual average significant wave height (cm, based on the linear trend, isolines plotted after each 2 cm) for 1970–2007 (Soomere and Räämet 2011). Note that a local maximum in the Arkona Basin is evidently caused by overestimation of the 10-m wind speeds from the geostrophic wind data

(Augustin 2005; Tuomi et al. 2011) or several local maxima in the eastern Baltic Proper (Jönsson et al. 2003). A hindcast using geostrophic winds indicates another maximum to the south of Gotland (Räämet and Soomere 2010). This may be explained by large interannual and decadal variability in wind patterns over the area that naturally causes extensive variations in both average and extreme wave patterns. A very similar spatial pattern of heights to the one shown in Fig. 9.16 (left panel) is found for extreme waves (threshold of the 1 % or the 99th percentile of significant wave height for each year) based on geostrophic winds (Soomere and Räämet 2011).

The empirical distributions of the occurrence of different wave heights at offshore measurement sites (such as Almagrundet, Bogskär, the wave-rider in the northern Baltic Proper and at the Darss Sill) resemble a Rayleigh distribution, with typical values of the shape parameter of 1.5–1.8 (Soomere 2008; Soomere et al. 2011). The most frequent wave heights are usually in the range 0.5–0.75 m. Significant wave heights greater than 4 m occur offshore with a probability of about 1 %, that is, during about 60 h per year. Significant wave heights over 7 m have been measured, on average, about twice per decade in the northern Baltic Proper (Soomere 2008; Tuomi et al. 2011) and so can be considered extreme conditions.

The wave climate is, however, highly intermittent and the sea occasionally experiences very high waves. The largest instrumentally measured values of significant wave heights (H_s) are H_s = 8.2 m in the northern Baltic Proper on 22 December 2004 (Directional Waverider, Tuomi et al. 2011) and H_s = 7.82 m on 13/14 January 1984 at Almagrundet [upward-looking echo sounder; estimated from the 10th highest waves based on Rayleigh distribution; an alternative estimate from the wave spectrum is H_s = 7.28 m (Broman et al. 2006)]. The highest individual instrumentally measured waves were 14 and 12.75 m, respectively. Numerical simulations indicate that H_s may reach 9.5–10 m in the north-eastern Baltic Proper at the entrance to the Gulf of Finland, to the north-west of the Latvian coast and in the south-eastern part of the Gulf of Gdansk (Schmager et al. 2008; Soomere et al. 2008a; Tuomi et al. 2011). The properties of waves in a particular region and storm event depend on the match of the geometry of the sea area and the wind pattern of the storm (Augustin 2005; Soomere et al. 2008a; Schmager et al. 2008).

Typical and extreme wave heights are much lower in sub-basins of the Baltic Sea. A large proportion of the low waves (H_s < 0.25 m) for most of the coastal visual observation sites (except for Vilsandi) (Zaitseva-Pärnaste et al. 2009, 2011) resembles an analogous property of simulated distribution in semi-sheltered bays (Soomere 2005). The frequency of occurrence of waves with H_s > 4 m is very low for all sub-basins except the Bothnian Sea (Tuomi et al. 2011) and waves with H_s > 2 m may be considered extreme for semi-sheltered areas such as the Darss Sill (Soomere and Kurkina 2011; Soomere et al. 2012). However, even sheltered bays may experience very strong waves during violent storms from unfavourable directions; for instance, H_s > 4 m apparently occurred in the interior of Tallinn Bay on 15 November 2001 (Soomere 2005). The maximum measured significant and single wave height in the Gulf of Finland was 5.2 and 9 m, respectively, on 15 November 2001 (Tuomi et al. 2011). Other sub-basins are not covered by regular wave measurements. The largest instrumentally measured wave height in the southern Sea of Bothnia (6.5 m) was recorded on 26 December 2011 (Pettersson et al. 2012). The maximum H_s recorded at the Darss Sill is 4.47 m (Soomere et al. 2012). Numerically simulated maxima of H_s are 7.6 m in the Sea of Bothnia, about 5 m in the Gulf of Finland and Gulf of Riga, and 6.7 m in the Arkona Basin (6.23 m according to another simulation).

The most frequent periods are 3–5 s offshore and 2–4 s in coastal areas (Soomere 2008). Most of the combinations of wave heights and periods roughly correspond to wave fields with a Pierson-Moskowitz (PM) spectrum (Soomere 2008; Räämet et al. 2010; Soomere et al. 2012). This indicates a large proportion of fully saturated seas in this region at wind speeds up to about 8 m s^{-1} (Schmager et al. 2008). The properties of the roughest seas, however, match better a JONSWAP spectrum (corresponding to fetch-limited seas and characterised by shorter periods than wave fields with a PM spectrum), especially in areas with limited fetch such as the Darss Sill (Soomere et al. 2012). Swells are very limited in all parts of the Baltic Sea.

9.5.3.2 Spatio-Temporal Variations

Several observation sites reveal short-term (weekly) features in the wave activity that reappear regularly, for example, a relatively calm period at the end of December and beginning of January in the northern Baltic Sea (Soomere et al. 2011). These features are probably site-specific and only persist for a few decades (Soomere et al. 2012). The extensive seasonal variation in wind speed (Mietus 1998) causes substantial variability (by a factor of two in coastal areas and up to three in offshore regions) in wave height at monthly scales (Schmager et al. 2008; Soomere and Räämet 2011) (Fig. 9.17). The calmest months are April to July and the windiest October to January (see also Chap. 4).

The most extensive interannual and decadal variations in wave properties exist in the visually observed wave data (Fig. 9.18). The appearance and spatial coherence of such variations has undergone major change. Short-term (inter-annual and up to 3 years) variability in annual mean wave height displays a consistent pattern (with a typical spatial scale of more than 500 km) from the southern Baltic Proper to the eastern Gulf of Finland from the mid-1950s to the mid-1980s. The coherence is lost in the mid-1980s (Soomere et al. 2011): since then, years with relatively large wave heights at the coasts of the Baltic Proper correspond to calm years in the eastern Gulf of Finland and vice versa.

Studies of variations at longer timescales reflect greater spatial variability of wave properties at different sites. Augustin (2005) identified an increase of 0.3 m in the simulated annual 99th percentile of H_s in the Baltic Proper (58° N, 20° E) that was mostly due to an increase in the frequency of severe wave events (Sect. 2.3.5 in BACC Author Team 2008). Simulations over the period 1970–2007 (Soomere and Räämet 2011) confirmed the presence of an increasing trend at this location but also indicated a complex spatio-temporal pattern of change (with scales down to about 100 km) in the Baltic Sea wave fields (Fig. 9.16). Moreover, the change in wave height over time in the northern Baltic Sea does not follow the gradual increase in annual mean wind speed in the northern Baltic Proper (Island of Utö, Soomere and Räämet 2011).

Analogous changes of even greater magnitude were identified from visual observations for the eastern Baltic Sea coast and from instrumental measurements at Almagrundet (Fig. 9.18). There is an overall decrease in wave height from about 1960 until the end of the 1970s (Soomere et al. 2011). Wave height increases substantially in the northern Baltic Proper from the mid-1980s until the mid-1990s (Broman et al. 2006; Soomere and Zaitseva 2007), similar to what happens in the south-western Baltic Sea and North Atlantic Ocean (Gulev and Hasse 1999; Weisse and Günther 2007). The increase was followed by a considerable decrease since 1997 (Broman et al. 2006; Soomere and Zaitseva 2007). Wave height at the south-eastern Baltic Sea (Lithuanian) coast showed the opposite: a rapid decrease until about 1996 followed by a rapid increase (Zaitseva-Pärnaste et al. 2011). The variations were weaker in the simulations of Soomere and Räämet (2011) and in reconstructions using a fetch-based model and local wind data (Suursaar and Kullas 2009a, b; Suursaar 2010).

Such extensive variations raise the issue of the significance of factors such as instrument error, observers' error or

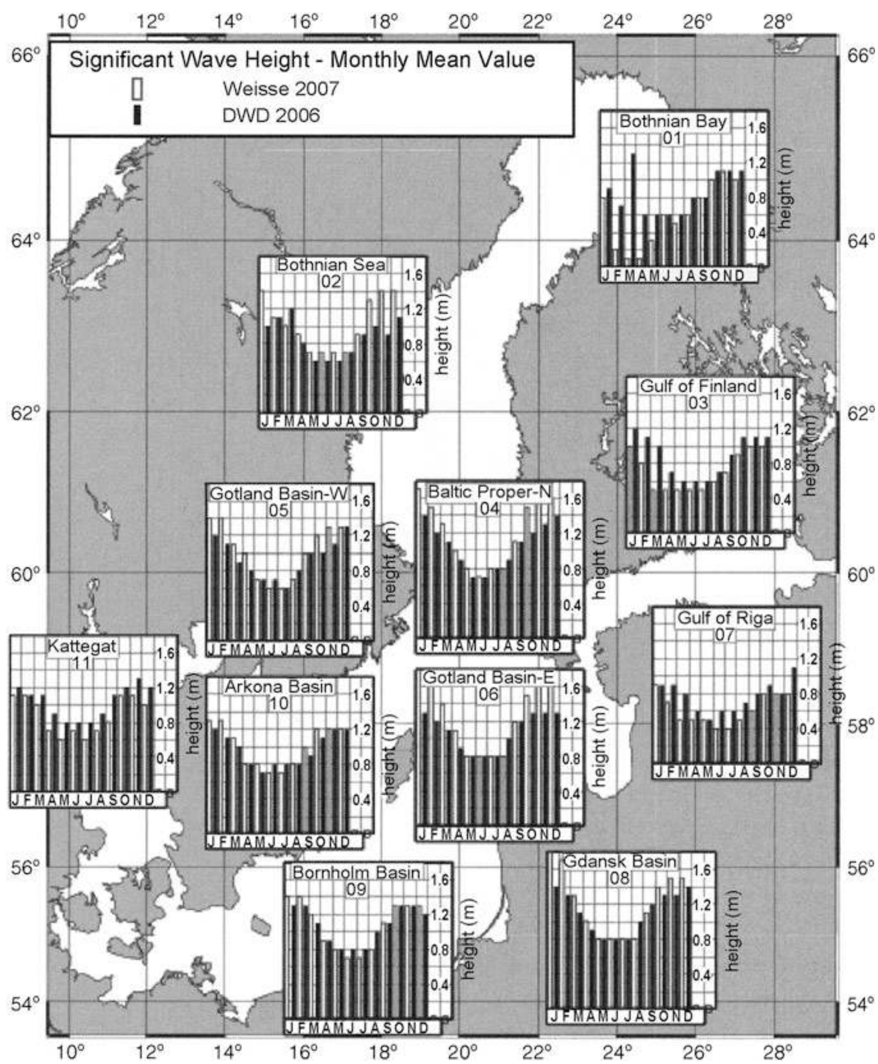


Fig. 9.17 Monthly mean significant wave height at selected sites in the Baltic Sea based on numerical simulations and DWD (German Weather Service) observations (Schmager et al. 2008)

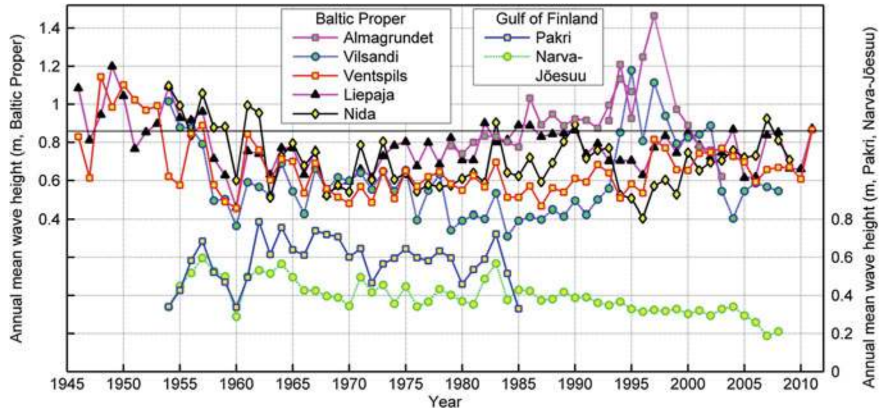


Fig. 9.18 Annual mean observed (Nida, Vilsandi, Pakri, Narva-Jõesuu, Liepaja, Ventspils) and instrumentally measured (Almagrundet) wave heights in the Gulf of Finland and Baltic Proper (redrawn from Soomere et al. 2011, including information from Soomere 2013)

noise in the data. The quality of data showing a decrease in wave intensity at Almagrundet for 1997–2003 was questioned by Broman et al. (2006), but the similarity of the changes at Almagrundet and Vilsandi still suggests that both datasets probably reflect real change (even if magnitude is possibly overestimated). The timing of the variations matches an almost twofold increase in the number of atmospheric low-pressure observations at Härnosand in the 1990s (Bärring and von Storch 2004) and so may simply reflect a change in the trajectories of cyclones.

For some locations along the Estonian coast, simplified fetch-based models using one-point coastal wind have demonstrated that wave intensity changes quasi-periodically and reveals no statistically significant trend (Suursaar and Kullas 2009a, b; Suursaar 2010). Quite large variations in the average wave periods (from about 2.3 s in the mid-1970s to 2.65 s around 1990) were found for selected sites (Suursaar and Kullas 2009b). This is apparently a local effect, because in most of the Baltic Sea the most frequent wave periods and the distribution of the different wave periods are effectively unchanged (Soomere et al. 2012).

Substantial changes (up to 90° from NW to SW) in the most frequently observed wave directions occurred at Narva-Jõesuu during the latter half of the twentieth century (Räämet et al. 2010) probably as a reflection of substantial change in local wind direction (Jaagus 2009; Jaagus and Kull 2011). Similar changes (of much smaller amplitude) were observed at the Lithuanian coast and were interpreted as a possible reason for change in the distribution of erosion and accumulation areas (Kelpšaitė et al. 2011). In general, it is likely that change in the simulated directions of wave propagation may result in substantial changes in the patterns of wave-driven sediment transport (Viška and Soomere 2012).

The changes discussed here are not necessarily evident in all sub-basins of the Baltic Sea. For instance, there has been effectively no change in the annual mean H_s at the Darss Sill (Soomere et al. 2012). The overall course in the wave activity in several other parts of the Baltic Sea also reveals no clear long-term trend (Soomere and Zaitseva 2007; Soomere 2008; Soomere et al. 2012). Only at Narva-Jõesuu in the Gulf of Finland is the wave intensity gradually decreasing (Soomere et al. 2011).

As previously mentioned, numerical simulations have revealed a complicated pattern of trends in wave intensity (Fig. 9.16, right panel). The spatial pattern of changes in the extreme (99th percentile) wave heights largely follows the pattern of changes in average wave height (Soomere and Räämet 2011). The decrease in wave intensity has been greatest between Öland and Gotland, and to the south of these islands to the Polish coast. In agreement with Augustin (2005) and the BACC Author Team (2008), a considerable increase in wave activity was indicated by the model in most of the northern Baltic Proper. The local maximum in the Arkona Basin and a rapid increase in simulated wave height in this region may stem from the overestimation of geostrophic wind speed in this part of the basin (see Pryor and Barthelmie 2003). There is a very slow decrease (about 0.01 m s^{-1} $year^{-1}$) in the annual mean wind speed at Kalbådagrund, Gulf of Finland (Soomere et al. 2010) where numerical simulations indicate very minor change in wave intensity (Suursaar and Kullas 2009b; Suursaar 2010; Soomere et al. 2010).

In some areas, change in average wave height and extreme wave height have opposite signs (Augustin 2005; Soomere and Healy 2008). For example, no long-term trend in average wave height exists at this site but the 99th percentile considerably decreased over 1991–2010. Hindcast simulations suggest a sawtooth-like behaviour for the 99th percentile, with a gradual increase for 1958–1990 from about 4 to about 5 m, a sudden decrease in 1991–1992 and a subsequent increase (Soomere and Kurkina 2011). Suursaar and Kullas (2009b) noted a negative trend in the 99th percentile near the north Estonian coast and a weak, opposite, gradually positive trend in average wave height. Simulations using the WAM wave model (Komen et al. 1994) showed that, unlike for average wave height, there has been a substantial decrease (of about 10 %) in maximum wave height near the southern coast of the Gulf of Finland and an almost equal increase to the north of the axis of the Gulf of Finland (Soomere and Räämet 2011). This feature may potentially cause enhanced coastal erosion in the affected areas in the north-eastern Gulf of Finland (Ryabchuk et al. 2011). It is apparently related to the major change in wind direction over the Estonian mainland: the frequency of south-westerly winds has increased considerably over the past 40 years (Jaagus 2009; Jaagus and Kull 2011).

9.6 Conclusion

The GIA—a readjustment of the Earth's crust to the off-loading of the ice sheets in the northern hemisphere that formed during the last glaciation—exerts a strong influence on sea level relative to land. Land uplift is stronger in the northern Baltic Sea, attaining rates close to 10 mm year^{-1}, whereas in the southern Baltic Sea, it is close to equilibrium with some areas sinking by about 1 mm year^{-1}. Analysis of individual records of land-locked tide gauge measurements corrected for the vertical land movements indicate that Baltic Sea sea level may have risen during the twentieth century at rates of around 1.5 mm year^{-1}, which are close to the rate of global sea level rise. However, uncertainty is large because the margin of error of the estimates of land uplift—based on GPS data—may be locally of the order of 1 mm year^{-1}, and the time overlap between tide gauges and GPS measurements is short. An accurate estimate of absolute, climate-induced, Baltic Sea sea level rise over the twentieth century, is still not available, but is unlikely to deviate much from the global average. In more recent decades, as satellite altimetry data have become available, the basinwide rate of sea level rise may be around 5 mm year^{-1} (with an uncertainty of roughly ±3 mm year^{-1}) with the central estimate thus higher than the recent global mean of 3.2 mm year^{-1}.

Sea level records display long-term developments that are still not fully explained. These include (1) the long-term widening of the annual cycle of sea level (winter maxima minus spring minima), (2) the more positive long-term trends of upper-range sea level measurements as opposed to lower-range sea levels—thus implying a long-term widening in the range of sea level observations, and (3) the time-varying correlation between sea level records and the main patterns of atmospheric climate variability, such as the NAO.

Extreme sea level is caused by storm surges driven by the passage of atmospheric cyclones. There is some evidence that the intensity of storm surges may have increased in recent decades in some parts of the Baltic Sea, and this has been attributed to long-term shifts in the tracks of some types of cyclone rather than to long-term change in the intensity of storminess. Analyses of storm surges have focused on local records, however, and there is no systematic basinwide analysis of change in storm surges yet available (see Chap. 4).

Since the first Baltic Sea Assessment (BACC Author Team 2008), new long-term series of instrumental wave data (longer than 20 years) and visually observed wave data (longer than 60 years) as well as several new high-resolution (~3 miles) long-term wave hindcast simulations have become available. New estimates of the basic properties of the wave climate in the Baltic Sea as a whole and its sub-basins have been derived, such as distributions of various wave properties (periods, height), spatial patterns of long-term change and decadal variations on timescales of 20–30 years. Analyses show no significant change in average wave activity in the Baltic Sea basin. However, extensive spatial patterns of changes within the basin exist, possibly leading to long-term variations in areas with the greatest wave intensity. Regional studies have even revealed different trends in average and extreme wave conditions that are probably due to systematic change in wind direction.

References

Ågren J, Svensson R (2007) Postglacial land uplift model and system definition for the new Swedish height system RH 2000. National Land Survey of Sweden, Reports in Geodesy and Geographical Information Systems, 2007/4

Andersson HC (2002) Influence of long-term regional and large-scale atmospheric circulation on the Baltic Sea level. Tellus A 54:76-88

Augustin J (2005) Das Seegangsklima der Ostsee zwischen 1958–2002 auf Grundlage numerischer Daten [Sea state climate of the Baltic Sea 1958–2002 based on numerical data]. Diploma Thesis. Institute for Coastal Research, Germany

Averkiev S, Klevannyy KA (2010) A case study of the impact of cyclonic trajectories on sea level extremes in the Gulf of Finland. Cont Shelf Res 30:707-714

BACC Author Team (2008) Assessment of Climate Change for the Baltic Sea Basin. Springer Verlag, Berlin, Heidelberg

Baerens C, Baudler H, Beckmann BR, Birr HD, Dick S, Hofstede J, Kleine E, Lampe R, Lemke W, Meinke I, Meyer M, Müller R, Müller-Navarra SH, Schmager G, Schwarzer K, Zenz T (2003) Die Wasserstände an der Ostseeküste. Entwicklung – Stumfluten – Klimawandel [Water levels at the Baltic Sea coast. Trends – storm surges – climate change]. In: Hupfer P, Hartt J, Horst S, Stigge HJ (eds), Die Küste [The Coast] Archive for research and technology on the North Sea and Baltic Sea coast. Boyens &Co, Heide in Holstein

Barbosa SM (2008) Quantile trends in Baltic Sea level. Geophys Res Lett 35:L22704. doi:10.1029/2008GL035182

Barbosa SM (2011) Atmospheric correction of satellite altimetry observations and sea level variability in the NE Atlantic. Adv Space Res 50:1077-1084

Barbosa SM, Madsen KS (2011) Quantile analysis of relative sea level at the Hornbæk and Gedser tide gauges. IAG Symp 136:565-569

Barbosa SM, Silva ME, Fernandes MJ (2008) Changing seasonality in the North Atlantic coastal sea level from the analysis of ling tide gauge records. Tellus A 60:165-177
Bärring L, von Storch H (2004) Scandinavian storminess since about 1800. Geophys Res Lett 31: L20202. doi:10.1029/2004GL020441
Bindoff NL, Willebrand J, Artale V, Cazenave A, Gregory J, Gulev S, Hanawa, K, Quéré CLe, Levitus S, Nojiri Y, Shum CK, Talley LD, Unnikrishnan A (2007) Observations: Oceanic climate change and sea level. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, UK
Blomgren S, Larson M, Hanson H (2001) Numerical modeling of the wave climate in the Southern Baltic Sea. J Coastal Res 17:342-352
Bogdanov VI, Medvedev MYu, Solodov VA, Trapeznikov YuA, Troshkov GA, Trubitsina AA (2000) Mean monthly series of sea level observations (1777-1993) at the Kronstadt gauge. Reports of the Finnish Geodetic Institute 2000:1, Kirkkonummi, Finland
Broman B, Hammarklint T, Rannat K, Soomere T, Valdmann A (2006) Trends and extremes of wave fields in the north-eastern part of the Baltic Proper. Oceanologia 48(S):165-184
Carlsson M (1997) Sea level and salinity variations in the Baltic Sea – an oceanographic study using historical data. PhD Thesis, Göteborg University, Sweden
Carlsson M (1998a) A coupled three-basin sea level model for the Baltic Sea. Cont Shelf Res 18:1015-1038
Carlsson M (1998b) The mean sea level topography in the Baltic Sea determined by oceanographic methods. Mar Geodes 21:203-217
Cazenave M, Lovell W (2010) Contemporary sea level rise. Annu Rev Mar Sci 2:145-73
Cazenave M, Remy F (2011) Sea level and climate: measurements and causes of changes. WIREs Clim Change 2:647-662
Cazenave A, Lombard A, Lovell (2008) Present-day sea level rise: A synthesis. Geosciences 340:761-770
Cazenave A, Dominh K, Guinehut S, Bethier E, Llovel W, Ramillien G, Ablain M, Larnicol G (2009) Sea level budget over 2003–2008: A reevaluation from GRACE space gravimetry, satellite altimetry and Argo. Global Planet Change 65:83-88
Chen D, Omstedt A (2005) Climate-induced variability of sea level in Stockholm: Influence of air temperature and atmospheric circulation. Adv Atmos Sci 22:655-664
Church JA, White NJ (2006) A 20th century acceleration in global sea level rise. Geophys Res Lett 33:LO1602. doi:10.1029/2005GL024826
Church JA, White NJ (2011) Sea level rise from the late 19th to the early 21st century. Surv Geophys 32:585-602
Cieślikiewicz W, Paplińska-Swerpel B (2008) A 44-year hindcast of wind wave fields over the Baltic Sea. Coast Eng 55:894-905
Colding A (1881) Nogle Undersøgelser over Stormen over Nord- og Mellem-Europa af 12te–14de November 1872 og over den derved fremkaldte Vandflod i Østersøen [Some investigations of the storm over north and central Europe on November 12–14 1872 and of the generated storm surge in the Baltic Sea, in Danish with French resumé]. Bianco Lunos Kgl. Hof-Bogtrykkeri, Copenhagen
Dailidienė I, Tilickis B, Stankevičius A (2004) General peculiarities of long-term fluctuations of the Baltic Sea and the Curonian lagoon water level in the region Lithuania. Environ Res Eng Manag 4:3-10
Dailidienė I, Davuliene L, Tilickis B, Myrberg K, Stankevičius A, Paršeliūnas E (2005) Investigations of sea level change in the Curonian Lagoon. Environ Res Eng Manag 4:20-29
Dailidienė I, Davuliene L, Tilickis B, Stankevičius A, Myrberg K (2006) Sea level variability at the Lithuanian coast of the Baltic Sea. Boreal Environ Res 11:109-121
Dailidienė I, Baudler H, Chubarenko B, Navrotskaya S (2011) Long-term water level and surface temperature changes in the lagoons of the southern and eastern Baltic. Oceanologica 53:293-308
Dailidienė I, Davulienė L, Kelpšaitė L, Razinkovas A (2012) Analysis of the climate change in Lithuanian coastal areas of the Baltic Sea. J Coast Res 28:557-569
Dietrich R, Liebsch G (2000) Zur Variabilität des Meeresspiegels an der Küste von Mecklenburg-Vorpommern. Z Geol Wiss 28:615-623 (in German)
Dimke S, Fröhle F (2009) Measured sea level rise at the Baltic Sea coast of Mecklenburg -Vorpommern and implications for the design of coastal structures. In: Proceedings of the International Conference on Climate Change, University of Szczecin, Poland
Donner RV, Ehrcke R, Barbossa SM, Wagner J, Donges JF, Kurths J (2012) Spatial patterns of linear and nonparametric long-term trends in Baltic sea level variability. Nonlinear Process Geophys 19:95-111
Douglas BC (1992) Global sea level acceleration. J Geophys Res C 97:12699-12706
Druet C, Massel S, Zeidler R (1972) Statistical characteristics of wind waves in the Baltic coastal zone in the Gulf of Gdansk and open Baltic Sea. Rozprawy Hydrotechnictne, Zeszyt 30:49-84
Duun-Christensen JT (1990) Long-term variations in sea level at the Danish coast during the recent 100 years. J Coast Res 9:45-61
DWD (2006) Seegangsklimatologie der Ostsee (1952 bis 2002). Deutscher Wetterdienst, Hamburg
Ekman M (1996) A consistent map of the postglacial uplift of Fennoscandia. Terra Nova 8:158-165
Ekman M (1998) Postglacial uplift rates for reducing vertical positions in geodetic reference systems. In: Jonsson B (ed), In: Proceedings of the General Assembly of the Nordic Geodetic Commission, 25–29 May
Ekman M (1999) Climate changes detected through the world's longest sea level series. Global Planet Change 21:215-224
Ekman M (2003) The world's longest sea level series and a winter oscillation index for northern Europe 1774–2000. Small Publ Hist Geophys 12
Ekman M (2007) A secular change in storm activity over the Baltic Sea detected through analysis of sea level data. Small Publ Hist Geophys 16
Ekman M (2009) The changing level of the Baltic Sea during 300 years: A clue to understanding the Earth. Summer Institute for Historical Geophysics
Ekman M, Mäkinen J (1996) Mean sea-surface topography in the Baltic Sea and its transition area to the North Sea: A geodetic solution and comparison with ocean models. J Geophys Res 101:11993-11999
Ekman M, Stigebrandt A (1990) Secular change of the seasonal variation in sea level and of the Pole Tide in the Baltic Sea. J Geophys Res 95:5379-5383
EUREF (2011) EUREF Permanent Network. www.epncb.oma.be (accessed Dec 2011)
Fernandes MJ, Barbosa SM, Lazaro C (2006) Impact of altimeter data processing on sea level studies. Sensors 6:131-163
FGI (2011) The Finnish Permanent GPS Network (FinnRef). www.fgi.fi/asemat/gps eng.php (accessed Dec 2011)
Gayer G, Günther H, Winkel N (1995) Wave climatology and extreme value analysis for the Baltic Sea area off the Warnemünde harbour entrance. Deutsche Hydrog Z 47:109-130
Getzlaff K, Lehmann A, Harlaß J (2011) The response of the general circulation of the Baltic Sea to climate variability. BALTEX Newsletter 14:13-16
Gulev SK, Hasse L (1998) North Atlantic wind waves and wind stress fields from voluntary observing ship data. J Phys Oceanogr 28:1107-1130
Gulev SK, Hasse L (1999) Changes of wind waves in the North Atlantic over the last 30 years. Int J Climatol 19:1091-1117
Gulev SK, Grigorieva V, Sterl A, Woolf D (2003) Assessment of the reliability of wave observations from voluntary observing ships: insights from the validation of a global wind wave climatology based on voluntary observing ship data. J Geophys Res C 108:3236

Gulev SK, Grigorieva V, Sterl A (2005) Global Atlas of Ocean Waves based on VOS observations. www.sail.msk.ru/atlas/index.htm (accessed 05 May 2014)
Gustafsson BG, Andersson HC (2001) Modeling the exchange of the Baltic Sea from the meridional atmospheric pressure difference across the North Sea. J Geophys Res C 106:19,731-19,744
Hagen E, Feistel R (2005) Climatic turning points and regime shifts in the Baltic Sea region: the Baltic winter index (WIBIX) 1659-2002. Boreal Environ Res 10:211-224
Hammarklint T (2009) Swedish Sea Level Series – A Climate Indicator. Swedish Meteorological and Hydrological Institute
Hansen L (2007) Hourly values of sea level observations from two stations in Denmark. Hornbæk 1890–2005 and Gedser 1891–2005. Danish Meteorological Institute Technical Report 07-09
Hansen JM, Agard T, Binderup M (2011) Absolute sea levels and isostatic changes of the eastern North Sea to central Baltic region during the last 900 years. Boreas 41:180-208
Heyen H, Zorita E, von Storch H (1996) Statistical downscaling of monthly mean North Atlantic air-pressure to sea level anomalies in the Baltic Sea. Tellus A 48:312-323
Hill EM, Davis JL, Tamisiea ME, Lidberg M (2010) Combination of geodetic observations and models for glacial isostatic adjustment fields in Fennoscandia. J Geophys Res 115:B07403. doi:10.1029/2009JB006967
Houston JR, Dean RG (2011) Sea level acceleration based on US tide gauges and extensions of previous global-gauge analyses. J Coastal Res 27:409-417
Hünicke B (2010) Contribution of regional climate drivers on future winter sea level changes in the Baltic Sea estimated by statistical methods and simulations of climate models. Int J Earth Sci 99:1721-1730
Hünicke B, Zorita E (2006) Influence of temperature and precipitation on decadal Baltic Sea level variations in the 20th century. Tellus A 58:141-153
Hünicke B, Zorita E (2007) Estimation of the influence of regional climate on the recent past and future sea level changes in the Baltic Sea with statistical methods and simulations of climate models. In: SINCOS -Sinking Coasts. Geosphere, Ecosphere and Anthroposphere of the Holocene Southern Baltic Sea, 88:219-240
Hünicke B, Zorita E (2008) Trends in the amplitude of Baltic Sea level annual cycle. Tellus A 60:154-164
Hünicke B, Zorita E (2011) Decadal sea level changes in the Baltic Sea. In: Abstracts of Baltic Sea Science Congress 2011, St. Petersburg, Russia
Hünicke B, Luterbacher J, Pauling A, Zorita E (2008) Regional differences in winter sea level variations in the Baltic Sea for the past 200 years. Tellus A 60:384-393
Hupfer P, Harff J, Sterr H, Stigge H.J (2003) Die Wasserstände an der Ostseeküste. Entwicklung-Sturmfluten-Klimawandel. Sonderheft. Die Küste 66
Jaagus J (2009) Long-term changes in frequencies of wind directions on the western coast of Estonia. In: Kont A, Tõnisson H (eds), Climate Change Impact on Estonian Coasts, Tallinn University, Tallinn, Estonia (in Estonian)
Jaagus J, Kull A (2011) Changes in surface wind directions in Estonia during 1966-2008 and their relationships with large-scale atmospheric circulation. Estonian J Earth Sci 60:220-231
Jaagus J, Post P, Tomingas O (2008) Changes in storminess on the western coast of Estonia in relation to large-scale atmospheric circulation. Clim Res 36:29-40
Janssen F (2002) Statistical analysis of multi-year variability of the hydrography in the North Sea and Baltic Sea. PhD Thesis, University of Hamburg, Germany (in German)
Jarmalavicius D, Zilinskas G, Dubra V (2007) Pattern of long-term seasonal sea level fluctuations in the Baltic Sea near the Lithuanian coast. Baltica 20:28-34
Jensen J, Mudersbach C (2004) Analyses of variations in water level time-series at the southern Baltic Sea coastline. In: Schernewski G, Löser N (eds), Managing the Baltic Sea, Coastline Reports 2:175-185
Jensen J, Töppe A (1986) Composition and evaluation of original records of the gauge at Travemünde/ Baltic Sea since 1826. Deutsche Gewässerkundliche Mitteilungen 30:99-107 (in German)
Jensen JP, Fröhle R, Mayerle R, Müller-Navarra S, von Storch H (2009) Schlussfolgerungen und Empfehlungen aus dem Verbundprojekt MUSTOK und zukünftiger Forschungsbedarf. Die Küste 75:255-266
Jevrejeva S, Moore JC, Woodworth PL, Grinsted A (2005) Influence of large-scale atmospheric circulation on European sea level: results based on the wavelet transform method. Tellus A 57:183-193
Jevrejeva S, Grinsted A, Moore JC, Holgate S (2006) Nonlinear trends and multiyear cycles in sea level records. J Geophys Res 111: C09012. doi:10.1029/2005JC003229
Jevrejeva S, Moore JC, Grinsted A, Woodworth PL (2008) Recent global sea level acceleration started over 200 years ago? Geophys Res Lett 35:L08715. doi:10.1029/2008GL033611
Johansson M, Boman H, Kahma KK, Launiainen J (2001) Trends in sea level variability in the Baltic Sea. Boreal Environ Res 6:1959-1979
Johansson JM, Davis JL, Scherneck HG, Milne GA, Vermeer M, Mitrovica JX, Bennet RA, Jonsson B, Elgered G, Elósegui P, Koivula H, Poutanen M, Rönnäng BO, Shapiro II (2002) Continuous GPS measurements of postglacial adjustment in Fennoscandia 1 Geodetic results. J Geophys Res B 107:10.1029/2001JB000400
Johansson MM, Kahma KK, Boman H (2003) An improved estimate for the long-term mean sea level on the Finnish coast. Geophysica 39:51-73
Johansson M, Kahma KK, Boman H, Launiainen J (2004) Scenarios for sea level on the Finnish coast. Boreal Environ Res 9:153-166
Jönsson A, Broman B, Rahm L (2003) Variations in the Baltic Sea wave fields. Ocean Eng 30:107-126
Kahma K (1981) A study of the growth of the wave spectrum with fetch. J Phys Oceanogr 11:1503-1515
Kahma KK, Calkoen CJ (1992) Reconciling discrepancies in the observed growth of wind generated waves. J Phys Oceanogr 22:1389-1405
Kahma K, Pettersson H, Tuomi L (2003) Scatter diagram wave statistics from the northern Baltic Sea. Report Series of the Finnish Institute of Marine Research 49:15-32
Kauker F, Meier MHB (2003) Modeling decadal variability of the Baltic Sea: 1. Reconstructing atmospheric surface data for the period 1902-1998. J Geophys Res C 108:3267. doi:10.1029/2003JC001797
Keevallik S, Soomere T (2010) Towards quantifying variations in wind parameters across the Gulf of Finland. Estonian J Earth Sci 59:288-297
Kelpšaitė L, Herrmann H, Soomere T (2008) Wave regime differences along the eastern coast of the Baltic Proper. Proc Estonian Acad Sci 57:225-231
Kelpšaitė L, Parnell KE, Soomere T (2009) Energy pollution: the relative influence of wind-wave and vessel-wake energy in Tallinn Bay, the Baltic Sea. J Coast Res SI 56:812-816
Kelpšaitė L, Dailidienė I, Soomere T (2011) Changes in wave dynamics at the south-eastern coast of the Baltic Proper during 1993–2008. Boreal Environ Res A 16:220-232
Klevannyy KA, Gubareva VP, Mostamandi SW, Ozerova LB (2001) Water level forecasts for the eastern Gulf of Finland. B Marit Inst Gdansk 28:71-87
Knudsen P, Vognsen K (2010) Metode til at følge vandstandsstigningstakten i de danske farvande. [Method to follow sea level rise in the Danish seas]. KMS Technical Report 08 (in Danish)
Komen GJ, Cavaleri L, Donelan M, Hasselmann K, Hasselmann S, Janssen PAEM (1994) Dynamics and modelling of ocean waves. Cambridge University Press, Cambridge, UK

Kowalewska-Kalkowska H, Wisniewski B (2009) Storm surges in the Odra mouth area during the 1997–2006 decade. Boreal Environ Res 14:183-192

Kriezi EE, Broman B (2008) Past and future wave climate in the Baltic Sea produced by the SWAN model with forcing from the regional climate model RCA of the Rossby Centre. IEEE/OES US/EU-Baltic International Symposium, 27–29 May 2008, Tallinn, Estonia, p 360-366

Lampe R, Endtmann E, Janke W, Meyer H (2010) Relative sea level development and isostasy along the NE German Baltic Sea coast during the past 9 ka. Quaternary Sci 59:3-20

Lehmann A, Getzlaff K, Harlaß J (2011) Detailed assessment of climate variability in the Baltic Sea area for the period 1958 to 2009. Clim Res 46:185-196

Lidberg M, Johansson JM, Scherneck HG, Davis JL (2007) An improved and extended GPS-derived 3D velocity field of the glacial isostatic adjustment (GIA) in Fennoscandia. J Geodes 81:213-230

Lidberg M, Johansson JM, Scherneck HG, Milne GA (2010) Recent results based on continuous GPS observations of the GIA process in Fennoscandia from BIFROST. J Geodyn 50:8-18

Liebsch G (1997) Aufbereitung und Nutzung von Pegelmessungen für geodätische und geodynamische Zielstellungen. PhD Thesis Dresden University (in German)

Liebsch G, Dietrich R, Ballani L, Langer G (2000) Die Reduktion langjähriger Wasserstandsmessungen an der Küste Mecklenburg-Vorpommerns auf das Höhensystem HN76. Die Küste 62/00:3-28 (in German)

Liebsch G, Novotny K, Dietrich R, Shum CK (2002) Comparison of multimission altimetric sea-surface heights with tide gauge observations in the southern Baltic Sea. Mar Geodes 25:213-234

Lisitzin E (1973) Sea level variations in the Gulf of Bothnia. Nordic Hydrology 4:41-53

Lopatukhin LI, Bukhanovsky AV, Ivanov SV, Tshernyshova ES (eds) (2006) Handbook of wind and wave regimes in the Baltic Sea, North Sea, Black Sea, Azov Sea and the Mediterranean. Russian Shipping Registry, St. Petersburg (in Russian)

Lowe JA, Woodworth PL, Knutson T, McDonald RE, McInnes L, Woth K, von Storch H, Wolf J, Swail V, Bernier NB, Gulev S, Horsburgh J, Unnikrishnan AS, Hunter JR, Weisse R (2010) Past and future changes in extreme sea levels and waves. In: Church JA, Woodworth PL, Aarup T, Wilson WS (eds), Understanding sea level rise and variability. Blackwell Publishing, p 326-361

Madsen KS (2011) Recent and future climatic changes of the North Sea and the Baltic Sea – Temperature, salinity, and sea level. LAMBERT Academic Publishing, Germany

Madsen KS, Hoyer JL, Tscherning CC (2007) Near coastal satellite altimetry: Sea surface height variability in the North Sea-Baltic Sea area. Geophys Res Lett 34:L14601. doi:10.1029/2007GL029965

Meier HEM, Broman B, Kjellström E (2004) Simulated sea level in past and future climates of the Baltic Sea. Clim Res 27:59-75

Menendez M, Woodworth PL (2010) Changes in extreme high water levels based on a quasi-global tide gauge data set. J Geophys Res 115: *C10011. doi:*10.1029/2009JC005997

Merrifield MA, Merrifield ST, Mitchum GT (2009) An anomalous recent acceleration of global sea level rise. J Clim 22:5772-5781

Mietus M (coordinator) (1998) The Climate of the Baltic Sea Basin. Marine Meteorology and Related Oceanographic Activities. Report No. 41. World Meteorological Organisation

Mietus M, von Storch H (1997) Reconstruction of the wave climate in the Proper Baltic Basin, April 1947–March 1988. GKSS Report 97/E/28

Milne GA, Davis JL, Mitrovica JX, Scherneck H-G, Johansson JM, Vermeer M, Koivula H (2001) Space-geodetic constraints on glacial isostatic adjustments in Fennoscandia. Science 291:2381-2385

Milne GA, Mitrovica JX, Scherneck H-G, Davis JL, Johansson JM, Koivula H, Vermeer M. (2004) Continuous GPS measurements of postglacial adjustment in Fennoscandia. 2. Modeling results. J Geophys Res 109:B02412. doi:10.1029/2003JB002619

Milne GA, Gehrels WR, Hughes CW, Tamisiea ME (2009) Identifying the causes of sea level change. Nat Geosci 2:471-478

Mitrovica JX, Tamisiea ME, Davis JL, Milne GA (2001) Recent mass balance of polar ice sheets inferred from patterns of global sea level change. Nature 409:1026-1029

Mudersbach CH, Jensen J (2009) Extremwertstatistische Analyse von historischen, beobachteten und modellierten Wasserständen an der Deutschen Ostseeküste, Die Küste, Heft 75, Sonderheft MUSTOK, S. 131-162, Boyens Medien GmbH, Heide i. Holstein

Naeije M, Scharroo, R, Doornbos, E, Schrama, E (2008) GLobal Altimetry Sea level Service: GLASS, Final Report. NIVR/DEOS publ NUSP-2 report GO 52320 DEO

Nakada M, Inoue H (2005) Rates and causes of recent global sea level rise inferred from long tide gauge records. Quaternary Sci Rev 24:1217-1222

Navrotskaya SE, Chubarenko BV (2012) On the sea level rise in the Russian part of the Vistula Lagoon. Russ Meteorol Hydrol 37:39-46

Nekrasov AV, Averkiev AS, Klevannyy KA, Martyanov SD (2007) Estimation of long-wave contribution to storm sea level rise in St. Petersburg. In: International Workshop on Extreme Water Levels in the Eastern Baltic. NATO Science for Peace Project, St. Petersburg, p 27-28

Novotny K, Liebsch G, Dietrich E, Lehmann A (2005) Combination of sea level observations and an oceanographic model for geodetic applications in the Baltic Sea. In: A Window on the Future of Geodesy. IAG Symp 128:195-200

Novotny K, Liebsch G, Lehmann A, Dietrich R (2006) Variability of sea surface heights in the Baltic Sea: An intercomparison of observations and model simulations. Mar Geodes 29:113-134

Obligis E, Desportes C, Eymard L, Fernandes J, Lazaro C, Nunes A (2011) Tropospheric corrections for coastal altimetry. In: Vignudelli S, Kostianoy A, Cipollini P, Benveniste J (eds) Coastal Altimetry, Springer, p 147-176

Omstedt A and Nyberg L (1991) Sea level variations during ice-covered periods in the Baltic Sea. Geophysica 27:41-61

Omstedt A, Pettersen C, Rohde J, Winsor P (2004) Baltic Sea climate: 200 yr of data on air temperature, sea level variation, ice cover, and atmospheric circulation. Clim Res 25:205-216

Paplińska B (1999) Wave analysis at Lubiatowo and in the Pomeranian Bay based on measurements from 1997/1998 – comparison with modelled data (WAM4 model). Oceanologia 41:241-254

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

Peltier WR (2004) Global glacial isostasy and the surface of the ice-age earth: the ICE-5 G (VM2) model and GRACE. Annu Rev Earth Planet Sci 32:111-149

Pettersson H, Kahma KK, Tuomi L (2010) Predicting wave directions in a narrow bay. J Phys Oceanogr 40:155-169

Pettersson H, Lindow H, Schrader D (2012) Wave climate in the Baltic Sea 2011. HELCOM Baltic Sea Environment Fact Sheets. www.helcom.fi/baltic-sea-trends/environment-fact-sheets (accessed 10 July 2014)

Pindsoo K, Soomere T, Zujev M (2012) Decadal and long-term variations in the wave climate at the Latvian coast of the Baltic Proper. In: Proceedings of the IEEE/OES Baltic 2012 International Symposium on Ocean: Past, Present and Future, 8–11 May 2012, Klaipėda, Lithuania

Pinto JG, Raible CC (2012) Past and recent changes in the North Atlantic oscillation. Clim Change 3:79-90

Plag HP, Tsimplis MN (1999) Temporal variability of the seasonal sea level cycle in the North Sea and Baltic Sea in relation to climate variability. Global Planet Change 20:173-203

Pruszak Z, Zawadzka E (2005) Vulnerability of Poland's coast to sea level rise. Coastal Eng J 47:131-155
Pruszak Z, Zawadzka E (2008) Potential implications of sea level rise for Poland. J Coast Res 24:410-422
Pryor SC, Barthelmie RJ (2003) Long-term trends in near-surface flow over the Baltic. Int J Climatol 23:271-289
Räämet A, Soomere T (2010) The wave climate and its seasonal variability in the northeastern Baltic Sea. Estonian J Earth Sci 59:100-113
Räämet A, Suursaar Ü, Kullas T, Soomere T (2009) Reconsidering uncertainties of wave conditions in the coastal areas of the northern Baltic Sea. J Coast Res SI 56:257-261
Räämet A, Soomere T, Zaitseva-Pärnaste I (2010) Variations in extreme wave heights and wave directions in the north-eastern Baltic Sea. Proc Estonian Acad Sci 59:182-192
Richter A, Dietrich R, Liebsch G (2007) Sea level changes and crustal deformations at the southern Baltic Sea during the last 200 years. In: SINCOS -Sinking Coasts. Geosphere, Ecosphere and Anthroposphere of the Holocene Southern Baltic Sea, 88:81-95
Richter A, Groh A, Dietrich R (2011) Geodetic observation of sea level change and crustal deformation in the Baltic Sea region. Phys Chem Earth 53-54:43-53
Rosentau R, Meyer M, Harff J, Dietrich R, Richter A (2007) Relative sea level change in the Baltic Sea since the Littorina Transgression. Z Geol Wiss 35:3-16
Russian Shipping Registry (1974) Wind and waves in oceans and seas. Part II. Data about wind and wave regime in [semi-enclosed] seas. Volume 1 – The Baltic Sea
Ryabchuk D, Kolesov A, Chubarenko B, Spiridonov M, Kurennoy D, Soomere T (2011). Coastal erosion processes in the eastern Gulf of Finland and their links with geological and hydrometeorological factors. Boreal Environ Res A 16:117-137
Rzheplinsky GV (ed) (1965) Wave and wind atlas for the Baltic Sea. Gidrometeoizdat, Leningrad (in Russian)
Rzheplinsky GV, Brekhovskikh YuP (1967) Wave atlas for Gulf of Finland, Gidrometeoizdat, Leningrad (in Russian)
Samuelsson M, Stigebrandt A (1996) Main characteristics of the long-term sea level variability in the Baltic Sea. Tellus A 48:672-683
SATREF (2011) SATREF. www.satref.no (accessed Dec 2011)
Scherneck HG, Johansson JM, Elgered G, Davis JL, Jonsson B, Hedling G, Koivula H, Ollikainen M, Poutanen M, Vermeer M, Mitrovica JX, Milne GA (2002) BIFROST: Observing the three-dimensional deformation of Fennoscandia. In: Mitrovica JX, Vermeersen BL (eds), Ice Sheets, Sea Level and the Dynamic Earth. American Geophysical Union, Geodynamics Series vol 29, Washington DC, p 69-93
Schmager WG (1979) Atlas zur Ermittlung der Wellenhöhe in der südlichen Ostsee. Seehydrographischer Dienst der DDR. XIV, Rostock
Schmager G, Fröhle P, Schrader D, Weisse R, Müller-Navarra S (2008) Sea state, tides. In: Feistel R, Nausch G, Wasmund N (eds), State and Evolution of the Baltic Sea 1952-2005. Wiley, p 143-198
Scotto MG, Barbosa SM, Alonso AM (2009) Model-based clustering of Baltic sea level. Appl Ocean Res 31:4-11
Sepp M, Post P, Jaagus J (2005) Long-term changes in the frequency of cyclones and their trajectories in Central and Northern Europe. Nord Hydrol 36:297-309
Soomere T (2003) Anisotropy of wind and wave regimes in the Baltic Proper. J Sea Res 49:305-316
Soomere T (2005) Wind wave statistics in Tallinn Bay. Boreal Environ Res 10:103-118
Soomere T (2008) Extremes and decadal variations of the northern Baltic Sea wave conditions. In: Pelinovsky E, Kharif C (eds), Extreme Ocean Waves, Springer, p 139-157
Soomere T (2013) Extending the observed Baltic Sea wave climate back to the 1940s. J Coast Res SI 65:1969-1974
Soomere T, Healy T (2008) Extreme wave and water level conditions in the Baltic Sea in January 2005 and their reflection in teaching of coastal engineering. In: Wallendorf L, Ewing L, Jones C, Jaffe B (eds), Solutions to Coastal Disasters 2008, p 129-138
Soomere T, Kurkina O (2011) Statistics of extreme wave conditions in the south-western Baltic Sea. Fund Appl Hydrophys 4:43-57 [in Russian]
Soomere T, Räämet A (2011) Spatial patterns of the wave climate in the Baltic Proper and the Gulf of Finland. Oceanologia 53:335-371
Soomere T, Zaitseva I (2007) Estimates of wave climate in the northern Baltic Proper derived from visual wave observations at Vilsandi. Proc Estonian Acad Sci Eng 13:48-64
Soomere T, Behrens A, Tuomi L, Nielsen JW (2008a) Wave conditions in the Baltic Proper and in the Gulf of Finland during windstorm Gudrun. Nat Hazards Earth System Sci 8:37-46
Soomere T, Zaitseva-Pärnaste I, Räämet A, Kurennoy D (2010) Spatio-temporal variations of wave fields in the Gulf of Finland. Fund Appl Hydrophys 4:90-101 (in Russian)
Soomere T, Zaitseva-Pärnaste I, Räämet A (2011) Variations in wave conditions in Estonian coastal waters from weekly to decadal scales. Boreal Environ Res A 16:175-190
Soomere T, Weisse R, Behrens A (2012). Wave climate in the Arkona basin, the Baltic Sea. Ocean Sci 8:287-300
Sparre A (1982) The climate of Denmark: Summaries of observations from light vessels II: Waves and currents at the surface. Danish Meteorological Institute Climatological Papers 9
Sterl A, Caires S (2005) Climatology, variability and extrema of ocean waves - the web-based KNMI/ERA-40 wave atlas. Int J Climatol 25:963-977
Suursaar Ü (2010) Waves, currents and sea level variations along the Letipea –Sillamäe coastal section of the southern Gulf of Finland. Oceanologia 52:391-416
Suursaar Ü (2011) Sea level variations along the Estonian coast of the Baltic Sea. In: Wright L (ed), Sea Level Rise, Coastal Engineering, Shorelines and Tides. Nova Science Publisher Inc, New York, p 105-122
Suursaar Ü (2013) Locally calibrated wave hindcasts in the Estonian coastal sea in 1966–2011. Estonian J Earth Sci 62:42-56
Suursaar Ü, Kullas T (2006) Influence of wind climate changes and the mean sea level and current regime in the coastal waters of west Estonia, Baltic Sea. Oceanologia 48:361-383
Suursaar Ü, Kullas T (2009a) Decadal variations in wave heights off Cape Kelba, Saaremaa Island, and their relationships with changes in wind climate. Oceanologia 51:39-61
Suursaar Ü, Kullas T (2009b) Decadal changes in wave climate and sea level regime: the main causes of the recent intensification of coastal geomorphic processes along the coasts of Western Estonia? WIT Trans Ecol Envir 126:105-116
Suursaar Ü, Sooäär J (2007) Decadal variations in mean and extreme sea level values along the Estonian coast of the Baltic Sea. Tellus A 59:249-260
Suursaar Ü, Kullas T, Otsmann M (2002) A model study of sea level variations in the Gulf of Riga and the Väinameri Sea. Cont Shelf Res 22:2001-2019
Suursaar Ü, Jaagus J, Kullas T (2006a) Past and future changes in sea level near the Estonian coast in relation to changes in wind climate. Boreal Environ Res 11:123-142
Suursaar Ü, Kullas T, Otsmann M, Saaremäe I, Kuik J, Merilain M (2006b) Cyclone Gudrun in January 2005 and modelling its hydrodynamic consequences in the Estonian coastal waters. Boreal Environ Res 11:143-159
Suursaar Ü, Kullas T, Szava-Kovats R (2010) Wind- and wave storms, storm surges and sea level rise along the Estonian coast of the Baltic

Sea. In: Ravage of the Planet II. WIT Transactions on Ecology and Environment 127, p 149-160

Suursaar Ü, Kullas T, Aps R (2012) Currents and waves in the northern Gulf of Riga: measurement and long-term hindcast. Oceanologia 54:421-447

SWEPOS (2011) SWEPOS, A national network of reference stations for GPS. http://swepos.lmv.lm.se/english/index.htm (accessed December 2011)

Sztobryn M, Stigge H-J, Wieblińśki D, Weidig B, Stanisławczyk I (2005) Sturmfluten in der südlichen Ostsee (westlicher und mittlerer Teil), Berichte des Bundesamtes für Seeschifffahrt und Hydrographie Nr. 39

Sztobryn M, Weidig B, Stanislawcyk I, Holfort J, Kowalska B, Mykita M, Kanska A, Krysztofik K, Perlet I (2009) Negative surges in the southern Baltic Sea (western and central parts), Berichte des Bundesamtes für Seeschifffahrt und Hydrographie Nr. 45

Tamisiea ME, Mitrovica JX, Davis JL, Milne GA (2003) Long wavelength sea level and solid surface perturbations driven by polar ice mass variations: fingerprinting Greenland and Antarctic ice sheet flux. Space Sci Rev 108:81-93

Tõnisson H, Suursaar Ü, Orviku K, Jaagus J, Kont A, Willis DA, Rivis R (2011) Changes in coastal processes in relation to changes in large-scale atmospheric circulation, wave parameters and sea levels in Estonia. J Coastal Res SI 64:701-705

Tuomi L, Kahma KK, Pettersson H (2011) Wave hindcast statistics in the seasonally ice-covered Baltic Sea. Boreal Environ Res 16:451-472

Vallner L, Sildvee H, Torim A (1988) Recent crustal movements in Estonia. J Geodynamics 9:215-223

Vermeer M, Kakkuri J, Mälkki P, Boman H, Kahma KK, Leppäranta M (1988) Land uplift and sea level variability spectrum using fully measured monthly means of tide gauge readings. Finn Mar Res 256:1-75

Vestøl O (2006) Determination of postglacial land uplift in Fennoscandia from leveling, tide-gauges and continuous GPS stations using least squares collocation. J Geod 80:248-258

Viška M, Soomere T (2012) Hindcast of sediment flow along the Curonian Spit under different wave climates. In: Proceedings of the IEEE/OES Baltic 2012 International Symposium on Ocean: Past, Present and Future. Climate Change Research, Ocean Observation & Advanced Technologies for Regional Sustainability, 8–11 May, Klaipėda, Lithuania

Wahl G (1974) Wave statistics from Swedish coastal waters. In: Proceedings of International Symposium on Dynamics of Marine Vehicles and Structures in Waves. Institute of Mechanical Engineering, London, p 33-40

Weisse R, Günther H (2007) Wave climate and long-term changes for the southern North Sea obtained from a high-resolution hindcast 1958–2002. Ocean Dynam 57:161-172

Weisse R, von Storch H (2010) Marine climate and climate change. Storms, wind waves and storm surges, Springer, Berlin, Heidelberg

Woodworth PL (1999) High Wwters at Liverpool since 1768: the UK's longest sea level record. Geophys Res Let 26:1589-1592

Woodworth PL, Blackman DL (2004) Evidence for systematic changes in extreme high waters since the mid-1970s. J Clim 17:1190-1197

Woodworth PL, Player R (2003) The permanent service for mean sea level: an update to the 21st century. J Coastal Res 19:287-295

Woodworth PL, White NJ, Jevrejeva S, Holgate SJ, Church JA, Gehrels WR (2009) Evidence for the accelerations of sea level on multi-decade and century timescales (Review). Int J Climatol 29:777-789

Woodworth PL, Gehrels WR, Nerem RS (2011) Nineteenth and twentieth century changes in sea level. Oceanography 24:80-93

Zaitseva-Pärnaste I, Suursaar Ü, Kullas T, Lapimaa S, Soomere T (2009) Seasonal and long-term variations of wave conditions in the northern Baltic Sea. J Coast Res SI 56:277-281

Zaitseva-Pärnaste I, Soomere T, Tribštok O (2011) Spatial variations in the wave climate change in the eastern part of the Baltic Sea. J Coast Res SI 64:195-199

Zorita E, Hünicke B (2010) Is Baltic sea level change accelerating? In: Proceedings of the 6th Study Conference on BALTEX, June 2010, Island of Wolin, Poland