DOCTORAL THESIS

Water Level Dynamics in the Eastern Baltic Sea, 1961–2018

Rain Männikus

TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY
TALLINN 2021

TALLINN UNIVERSITY OF TECHNOLOGY
DOCTORAL THESIS
12/2021

Water Level Dynamics in the Eastern Baltic Sea, 1961–2018

RAIN MÄNNIKUS

TALTECH PRESS

TALLINN UNIVERSITY OF TECHNOLOGY
Department of Cybernetics, School of Science
Laboratory of Wave Engineering
This dissertation was accepted for the defence of the degree on 21/01/2021

Supervisor: Prof. Dr. Tarmo Soomere
Department of Cybernetics, School of Science
Tallinn University of Technology
Tallinn, Estonia

Co-supervisor: Prof. Dr. Kevin Ellis Parnell
Department of Cybernetics, School of Science
Tallinn University of Technology
Tallinn, Estonia

Opponents: Prof. Dr. Hans von Storch
Institute of Coastal Systems
Helmholtz-Zentrum Geesthacht
Geesthacht, Germany

Dr. Kai Myrberg
Leading Research Scientist
Finnish Environment Institute (SYKE)
Professor, Marine Research Institute
Klaipėda University
Klaipėda, Lithuania

Defence of the thesis: 05/03/2021, Tallinn

Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

Rain Männikus

----
signature

European Union
European Regional
Development Fund

Investing
in your future

ISSN 2585-6898 (publication)
ISBN 978-9949-83-666-6 (publication)
ISSN 2585-6901 (PDF)
ISBN 978-9949-83-667-3 (PDF)
Printed by Koopia Niini & Rauam

TALLINNA TEHNIKAÜLIKOOL
DOKTORITÖÖ
12/2021

Läänemere idaranniku ja Liivi lahe veetaseme dünaamika 1961–2018

RAIN MÄNNIKUS

TALTECH KIRJASTUS

Contents

List of publications constituting the thesis **6**
Author's contribution to the publications **6**
Introduction **7**
Water level in the Baltic Sea 7
Water level extremes in the eastern Baltic Sea 9
Water level components in the Baltic Sea 10
Assessing the joint impact of water levels and waves 11
Study area 13
The objectives and outline of the thesis 14
Public presentation of the results 15
1. Observed water level data in Latvian waters **16**
1.1. Water level observation network in Latvia 16
1.2. Inhomogeneity, local features, and land uplift 17
1.3. Annual average water level 19
1.4. Empirical probability distributions of water level 22
2. Cyclic features of water levels **24**
2.1. Seasonal course 24
2.2. Water level maxima and minima 28
2.3. Variability of water level and the NAO index 30
2.4. Vilsandi wind data and water levels 31
3. Identifying mechanisms behind water level extremes **34**
3.1. Elevated water levels in the Gulf of Riga 34
3.2. Separation of components of water levels 35
3.3. Episodes with substantially different water levels 40
3.4. Changes in the properties of episodes of large water level differences 42
3.5. Magnitude of water level differences 44
4. Water-level-adjusted closure depth **47**
4.1. Reconstruction of wave and water level properties 47
4.2. Longshore variations in classic and adjusted closure depths 50
4.3. Impact of water levels on closure depths 52
Conclusions **55**
Summary of the results 55
Main conclusions proposed to defend 56
Recommendations for further work 57
List of figures **59**
References **62**
Acknowledgements **71**
Abstract **72**
Lühikokkuvõte **73**
Appendix: Papers constituting the thesis **75**
Curriculum Vitae **129**
Elulookirjeldus **132**

List of publications constituting the thesis

The thesis is based on three academic publications which are referred to in the text as Paper I, Paper II and Paper III. All papers are indexed by the ISI Web of Science and SCOPUS.

Paper I **Männikus, R.**, Soomere, T., Viška, M. 2020. Variations in the mean, seasonal and extreme water level on the Latvian coast, the eastern Baltic Sea, during 1961–2018. *Estuarine*, *Coastal and Shelf Science*, 245, art. no. 106827, doi: 10.1016/j. ecss.2020.106827.

Paper II **Männikus, R.**, Soomere, T., Kudryavtseva, N. 2019. Identification of mechanisms that drive water level extremes from in situ measurements in the Gulf of Riga during 1961−2017. *Continental Shelf Research*, 182, 22−36, doi: 10.1016/j.csr.2019.05.014.

Paper III Soomere, T., **Männikus, R.**, Pindsoo, K., Kudryavtseva, N., Eelsalu, M. 2017. Modification of closure depths by synchronisation of severe seas and high water levels. *Geo-Marine Letters*, 37(1), 35−46, doi: 10.1007/s00367-016-0471-5.

Author's contribution to the publications

Paper I I gathered and analysed the water level data, visited the water level measurement sites in Latvia, prepared most figures, wrote about 2/3 of the manuscript, and acted as the corresponding author.

Paper II I gathered and analysed the water level data, wrote about 1/2 of the manuscript, prepared most figures, and acted as the corresponding author.

Paper III I performed part of the calculations, visualised several aspects, contributed to the analysis of results, and wrote the associated parts of the manuscript.

Introduction

Water level in the Baltic Sea

The most discussed aspects of sea level are its long-term rise and devastating coastal flooding during extreme storms (Kirezci et al., 2020). The rise in mean sea level over the 20^{th} century, a well-documented phenomenon for several decades already (IPCC, 2013), is one of the most significant threats to coastal communities (Nicholls, 2011). Several authors warn that even if the targets of the Paris Climate Agreement are attained, global sea level will continue to rise at a significant rate for a long time, even for centuries (Wigley, 2018). An increase in the mean sea level may increase the probability of elevated water levels and extreme water levels (Stephens et al., 2020).

Even though extreme water levels are, by definition, rare events, they play a central role in all major coastal management and engineering decisions (Kamphuis, 2010; Stephens et al., 2020). However, it is not only the water level extremes that matter. For example, extreme events of coastal erosion may occur when high waves from an unfavourable direction attack unprotected areas (e.g., not frozen sediment; Orviku et al., 2003; Ryabchuk et al., 2011) at levels higher than the usual reach of breaking waves (Pruszak and Zawadzka, 2008). It is thus equally important to understand the course, timing and statistical properties of water level, and to quantify the relevant quantiles and their trends. These quantities are systematically used in the design of the height required for coastal protection structures (EurOtop, 2018), assessing sediment budgets, and estimating the intensity of erosion and accumulation. It is therefore necessary to carefully analyse all available water level data and various projections of extreme water levels in order to avoid expensive and ineffective solutions to coastal management and engineering challanges.

The actual water level may contribute to the way different processes shape or affect the nearshore, the position of the waterline, and impact coastal engineering structures:

- An area or structure may be exposed to different risks for different water levels. While the risk of overtopping, damage to property and the threat to lives usually occurs at elevated water levels, navigation during very low water conditions may be complicated or impossible (Medyna and Sobkowicz, 2017).
- The wave height at a particular shallow-water location is often limited by depth-induced breaking before arriving at a structure or beach under usual water levels. Higher than normal wave energy may cause enhanced erosion and unacceptable loads during elevated water level events.
- Most flooding damage occurs during high (but not necessarily extremely high; Dissanayake et al., 2015) water level.
- Construction and maintenance of various coastal engineering structures is generally affected by the overall water level regime (CIRIA et al., 2007).

The development of high-resolution hydrodynamic models (Meier et al., 2004) and implementation of various kinds of satellite-based (Liu et al., 2017; Fernandez-Montblanc et al., 2020) and airborne (Varbla et al., 2020) measurements have considerably increased the pool of options for receiving information about water level in the nearshore. All these methods generally require validation against actually measured water level data. As the temporal coverage of these methods is quite limited, the most available and reliable source for extracting water level means, trends, extremes, quantiles and various distributions in the past and for the construction of projections for future events for a specific coastal segment still are long-term observations. The Baltic Sea has some of the longest time-series of water levels in the world (Ekman, 1988). The course of water levels in many parts of the Baltic Sea has been addressed in numerous international publications, e.g., for Finland (Johansson et al., 2001), Sweden (Ekman, 2003), Lithuania (Dailidienė et al., 2006), Estonia (Suursaar and Sooäär, 2007), Germany and Poland (Richter et al., 2007, 2011). The regional analyses are complemented with many results of basin-wide research efforts (Meier et al., 2004; Hünicke and Zorita, 2008; Hünicke et al., 2015; among others). It is thus safe to say that the overall properties of the course of water level, the basic statistical properties of high and low water levels, and spatial patterns of their changes in much of the Baltic Sea are well understood (Hünicke et al., 2015; Weisse and Hünicke, 2019).

For the Latvian open coast and the Gulf of Riga (Figure 1), however, there is very limited information available. Averkiev and Klevannyy (2010) present a few records of the all-time highest water levels. Koltsova and Belakova (2007, 2009) analyse surges for one river (Lielupe) mouth in the gulf, and several other local publications (Pastors, 1965; Iljina and Pastors, 1976) simply describe available information. This situation is somewhat surprising because water levels have been recorded in this area for almost two centuries

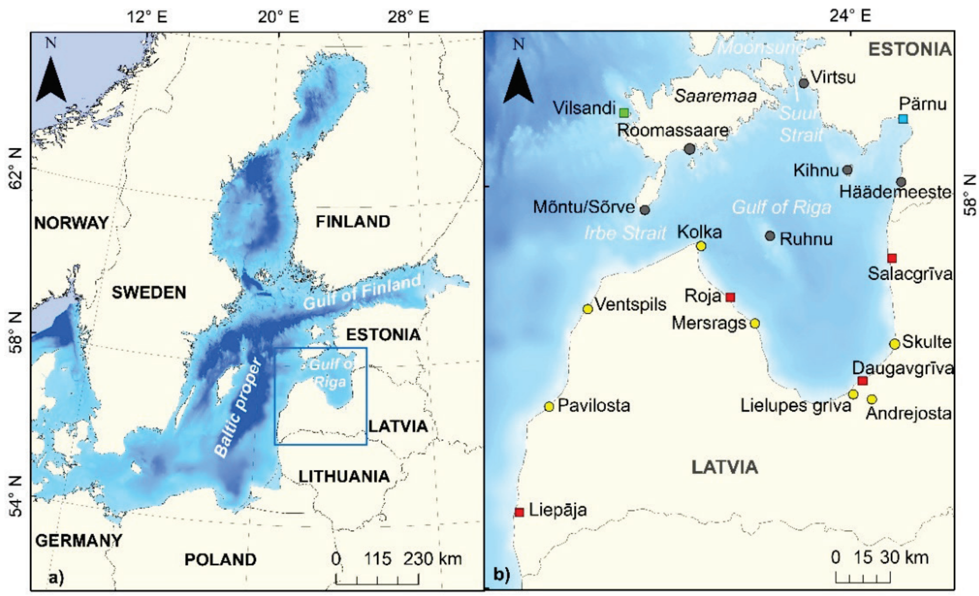


Figure 1. Water level measurement sites in the Gulf of Riga and on the open coast of Latvia. Red squares show locations with the highest quality and coverage of observations (Table 1 and Table 2). Yellow circles depict stations where measurements were less frequent and/or had long gaps. Grey markers indicate some measurement stations outside Latvia. The blue square indicates measurement station Pärnu which is used in this thesis. The green square shows the Estonian meteorological station at the island of Vilsandi which serves as the source of wind information. Adapted from Paper I.

(Dailidienė et al., 2006; Suursaar et al., 2006; Kudure, 2009). Hence, one of the main aims of this thesis is to fill the gap in the analysis of water levels in Latvian waters from the viewpoint of possible changes to the overall water level regime. A straightforward extension of this analysis is the evaluation of the impact of frequent high water levels on the estimates of closure depth. Both these aspects have direct implications for coastal management and the design of coastal engineering structures in the Gulf of Riga and on the Latvian shore of the Baltic proper (open central part of the Baltic Sea).

Water level extremes in the eastern Baltic Sea

The eastern shores have experienced some of the highest water levels in the Baltic Sea (Suursaar and Sooäär, 2007; Averkiev and Klevannyy, 2010; Hünicke et al., 2015). The all-time highest surges have been observed at Saint Petersburg in the eastern end of the Gulf of Finland (Figure 1). Several locations in the Gulf of Riga are also subject to extremely large variations in the water level. Extreme water levels (both water level maxima and minima) in the Gulf of Riga are among the largest ever recorded in the Baltic Sea (Dailidienė et al., 2006; Averkiev and Klevannyy, 2010). Only on a very few occasions have even higher levels been recorded in the south-western Baltic Sea on the shores of Germany (Averkiev and Klevannyy, 2010). The largest storm surges in the northern extremity of the Bay of Bothnia have been much smaller (Johansson et al., 2001; Averkiev and Klevannyy, 2010).

This spatial distribution of extremes is likely to persist in the future as Soomere and Pindsoo (2016) revealed that the annual maxima of modelled water levels have increased rapidly (at a rate up to 10 mm/yr) in the eastern Gulf of Finland and Gulf of Riga 1970–2005. This increase is consistent with measurements made in the eastern Gulf of Finland (Ryabchuk et al., 2011). The rate of the increase in these two regions is much larger than the rate for other Baltic Sea shores. This stresses the importance of better understanding of how the water levels have varied in this region in the past.

Extreme water levels are formed differently in different parts of the Baltic Sea. For example, very high water levels in the eastern Gulf of Finland are usually attributed to deep cyclones that travel along a specific trajectory and with a particular velocity (Averkiev and Klevannyy, 2010). When the storm ends, the release of the surge creates a gulf-scale seiche (or, more likely, a Baltic Sea basin-scale seiche; Jönsson et al., 2008) that may endanger Saint Petersburg (Kulikov and Medvedev, 2013). However, excess water will not remain in the Gulf of Finland for a long time because there is no sill between the gulf and the Baltic Proper.

The highest water levels in the Gulf of Riga are driven by specific storms that may push large amounts of water into the gulf (Suursaar et al., 2002, 2003; Paper II). This process works as follows. Many storms that cross the Baltic Sea move from the south-west or west to the north-east or east (Post and Kõuts, 2014) over the Baltic proper or the Sea of Bothnia. The wind direction thus is from south-west or west at the beginning of these storms. This pattern creates a slope of the sea surface towards the east or north-east and leads to elevated water levels in the eastern and northern regions of the Baltic Sea, including the Gulf of Riga. Moreover, it is likely that westerly winds push additional water into the gulf by Ekman transport. When such a storm progresses to the east, the wind direction turns more to the north-west and north and prevents water from flowing out of the Gulf of Riga via Moonsund (Figure 1). It takes a few days for this water to flow out of the gulf via the relatively narrow and shallow straits that connect it with the Baltic proper. The impact of this mechanism may be one of the reasons why the match of the estimates of the rates of increase of extreme water levels based on modelled data with the outcome of a similar analysis of *in situ* data is poor for the north-eastern Gulf of Riga (Soomere and Pindsoo, 2016).

Water level components in the Baltic Sea

The analysis of water levels for practical (including engineering) purposes can not be limited to the observations of sea surface fluctuations and their statistical properties. For many purposes it is equally important to explain the driving forces and forecast possible changes. The deviations of the water level from its long-term mean are caused by a variety of drivers of different origins and different spatial and temporal scales. Even though these drivers are often interconnected, the first step towards understanding the reaction of the water level, is to separate the observed water level into components with different spatial and temporal scales. On some occasions the water level difference from average is driven by a single physical driver, but more frequently the observed water level is the result of the combination and interaction of many drivers (Hünicke et al., 2015; Weisse and Hünicke, 2019).

The contribution of astronomical tides to the water level is very small in the eastern Baltic Sea. It is usually up to a few centimetres[1] and only in rare specific cases more than 10 cm (Koltsova and Belakova, 2009; Leppäranta and Myrberg, 2009; Medvedev et al., 2013). Halosteric effects become only important at scales larger than the Gulf of Riga or the Baltic proper shore of Latvia. The difference between the water level in Kattegat and in the northernmost almost freshwater parts of the sea reaches about 30–35 cm (Ekman and Mäkinen, 1996) but the associated water level slope is very small. These effects may play a certain role at the mouths of Daugava and Lielupe rivers.

Atmospheric pressure (inverted barometric effect), wind-driven surge, basin-wide seiches and wave-induced set-up are usually the largest contributors to total water levels in water bodies like the Baltic Sea (e.g., Talley et al., 2011). Some of these components may jointly contribute to the changes in the water level and superimpose each other. Correlations often exist between components of meteorological origin, such as storm surge, wind set-up and even seiches. For example, the observation locations with the largest maxima in the Gulf of Riga are open to the predominant strong wind and wave directions (south-west or north-north-west; Soomere and Keevallik, 2001). It is therefore certain that local storm surge and wave-driven set-up often jointly contribute to single water level readings at some stations.

For the purpose of analysis, traditionally, it has been assumed that, at least to a first approximation, these mechanisms impact the local water level independently of each other. This assumption allows signals of single mechanisms to be separated in the observed water level record and makes it possible to analyse the behaviour and contribution of each component to the total water level (Howard et al., 2014; Weisse et al., 2014). This approach allows projections of extreme water levels and return periods to be calculated to a first

[1] I use in this thesis centimetres to represent water level deviations from its long-term value for better readability.

approximation without taking into account complicated interactions of various drivers. This approach has been used in areas where local water level is driven by changes in the long-term mean, tides and storms (Pugh and Vassie, 1978, 1980). Usually, the water level record is separated into periodic and random components and then the contribution of different drivers is analysed (Haigh et al., 2010).

Water level fluctuations are more complicated in semi-enclosed water bodies where substantial aperiodic variations in the sea level occur at subtidal to intra-seasonal (daily to multi-month) scales. Such variations occur in several basins worldwide, such as the Baltic Sea (Leppäranta and Myrberg, 2009), Chesapeake Bay (Bosley and Hess, 2001) or the Venice lagoon (Zecchetto et al., 1997). In the Baltic Sea the typical time scale of these variations is a few weeks (Leppäranta and Myrberg, 2009). Variations at the longer time scales are caused by sequences of atmospheric events that result in strong winds from particular directions over the Danish straits. Moderate and strong westerly or north-westerly winds may bring substantial amounts of water into the Baltic Sea (Lehmann and Post, 2015; Lehmann et al., 2017). These events may result in the elevation of the water surface of the entire sea by almost 1 m over its long-term level for several days (Soomere and Pindsoo, 2016) and by about 50 cm in terms of monthly averages (Johansson et al., 2003).

As these water elevation events can persist for long periods of time, the impact of storms can increase when they occur with a background of an elevated water level in the entire sea. This feature can give rise to sequences of unusually high water levels (Soomere and Pindsoo, 2016), and it is one of the most likely reasons for the existence of extremely high outliers in some locations in the eastern Baltic Sea. Suursaar and Sooäär (2007) called such occasions at Pärnu, Estonia, "statistically almost impossible water levels". To properly understand their nature and frequency, it is important to single out the signal of each component (and mechanism behind it) from the overall course of water level and analyse separately its behaviour and contribution to the total water level (e.g., Losada et al., 2013). This approach is employed in Paper II. It greatly simplifies the analysis and forecast of water levels. It also allows in-depth analysis of gradual changes in the averages and extremes caused by a single driver (e.g., Soomere and Pindsoo, 2016; Vousdoukas et al., 2017).

This method is not always justified in the sense that the total water level (especially the residual after removing the tidal signal in shallow-water areas; Frison, 2000) often cannot be perfectly decoupled into a linear superposition of the contributing processes. For example, the height of the local storm surge depends on the magnitude of the inverse barometric effect. Also, much higher waves may reach the shoreline (Viitak et al., 2016) and drive set-up during elevated water level events.

Assessing the joint impact of water levels and waves

Flooding caused by high water levels is a dangerous event in low-lying coastal areas. Its possible damaging effects can be significantly amplified when it is coupled with high waves. The quantification of their potential joint impact generally requires an analysis of the joint probability of water levels and high waves from specific directions. The synchronisation of these drivers may have severe consequences in various ways.

The most rapid coastal evolution occurs when strong waves reach unprotected sediment during periods of elevated water levels (Kamphuis, 2010). Additionally, the overtopping rates of structures may become unacceptable (EurOtop, 2018).

The joint extremes can be calculated and presented for either inshore or offshore situations. The estimates for inshore conditions (that is, for single short sections of the coast) are site-specific and generally applicable only in a small area. On the other hand, the results for offshore water level and wave conditions are suitable for a larger area, but must be transformed to inshore conditions before further use (CIRIA et al., 2007).

A suitable selection of the approach to the analysis of joint extremes is usually dictated by data availability. Although there is an extensive network of observation stations in the Gulf of Riga, described below and in Paper I and Paper II, the recorded water level time series have sufficiently fine temporal resolution and coverage (in terms of hourly completeness of more than 99.5%) for this analysis at only three stations. Most of records of tide gauges in Latvian waters have long gaps. For this reason the analysis in Paper III relies on modelled values of water level and wave parameters which cover the whole coast with a suitable spatial resolution and temporal coverage.

Most of the relevant analysis in the literature addresses the joint occurrence of high water levels and strong waves. For example, Hawkes et al. (2002) present a method for joint probability analysis, using the Monte Carlo simulation approach, based on distributions fitted to water level, wave height and wave steepness. Hanson and Larson (2008) incorporated water level and wave parameters into the calculated value of run-up height and identified the return periods of the joint occurrence of water levels and high waves. Similarly, instantaneous water levels and wave parameters can be combined to estimate other parameters, e.g., overtopping discharges.

In this thesis a classic parameter of sedimentary beaches – closure depth – was used as one way to assess the joint impacts of water levels and waves. This quantity has the meaning of the maximum depth at which the breaking waves effectively adjust the whole coastal profile (Hallermeier, 1978, 1981). It is a key parameter in the coastal zone for a variety of engineering and ecosystem applications. In the so-called equilibrium beach profile theory (Dean, 1991), the closure depth sets a limit to where wave conditions have significant influence on the beach profile.

The values of closure depth are commonly estimated with respect to the long-term mean water level. If elevated water levels are systematically synchronised with strong waves and variations in the water level have the same order of magnitude as closure depth (as is generally the case in the Baltic Sea), the closure depth becomes a function of joint probability of water level and wave heights. The difference between the classic closure depth (with respect to the average water level) and its values evaluated using the time series of water level and wave properties may serve as a useful proxy of the synchronisation of water level and wave conditions at single coastal sections. The modified values of closure depth can also be an input to morphological and intervention analyses (such as planning beach nourishment schemes) and thus could greatly impact coastal management decisions since most of the coasts of the study area consists of mobile sediment (Pranzini and Williams, 2013).

Study area

The study area (Figure 1) consists of two coastal segments with different water level regimes in open-coastal Latvian waters and in Latvian and Estonian waters in the western, southern and eastern Gulf of Riga. The analysis of the implications of synchronisation of water level and wave properties in terms of closure depth extends from the shore of Lithuania and along the shores of Estonia to the eastern Gulf of Finland.

One of the coastal segments for the analysis of water level dynamics is the Latvian shore of the open Baltic Sea from the border of Lithuania in the south to Irbe Strait in the north (Figure 1b). It has an approximately 150 km long, mostly straight, shoreline. The nearshore of this region is relatively shallow. The 10 m isobath follows the coast at a distance about 7.5 km from the coast. The 20 m isobath is about 15 km from the coast. On the open Baltic Sea coast, underwater slope is most gentle at the port of Liepaja (Maritime Administration of Latvia, 2014).

The second area for the detailed analysis of water level dynamics is the Gulf of Riga (Figure 1b). It is a semi-enclosed water body with an area of about 130 × 140 km (Suursaar et al., 2002). Its surface area is 17,913 km², volume 406 km³, average depth about 23 m and maximal depth 52 m. Irbe Strait, its main connection with the Baltic proper, is 27 km wide. The water depth in the strait is generally less than 10 m, except for a 20–22 m deep ravine in its northwestern part (Maritime Administration of Latvia, 2014). Another outlet of the Gulf of Riga in the north is Suur Strait which is much narrower (4–5 km) and shallower (the sill depth is about 5 m) than Irbe Strait. It connects the Gulf of Riga with the Väinameri (Moonsund) sub-basin of the Baltic Sea. As the cross-section of Suur Strait is much smaller than for Irbe Strait, most of the water exchange between the Gulf of Riga and northern Baltic proper usually occurs through Irbe Strait. The Pärnu River and Daugava River provide the largest discharge in the north-eastern and southern parts of the gulf, respectively. The mean annual river inflow to the gulf is about 33 km³/yr (Suursaar et al., 2002).

The nearshore coastal slope is steeper on the southern side of the Gulf of Riga than on the Latvian segment of the Baltic proper. Generally, in the southern Gulf of Riga, the 10 m isobath is located approximately 2 km from shore and the 20 m isobath 3.5–8 km from the shore. As the magnitude of wind-driven local surge over shallow coastal areas is roughly inversely proportional to the water depth and proportional to the width of the shallow area (Dean and Dalrymple, 2002), the contribution of local effects to water level, e.g., wind driven setup, is generally higher on the shores of the Baltic proper than in the Gulf of Riga. A substantial contribution of local effects into the observed water levels is likely in some locations on the eastern and southern shores of the Gulf of Riga that host wide shallow-water nearshore areas. For example, the bayhead of the shallow Bay of Pärnu, with typical depth of about 5 m, is prone to high wind driven water level setup (Suursaar and Sooäär, 2007).

As the Gulf of Riga is connected with the Baltic Sea via relatively narrow and shallow straits, it is natural to assume that water volumes pushed into the gulf by westerly winds will remain in the gulf for a certain time. This delay in the outflow is a likely reason for the difference between water levels in the Baltic proper and the Gulf of Riga. When a strong storm from an unfavourable direction arrives during such an elevated water level event in the gulf, it may cause extremely high water levels in the affected coastal sections. It is likely that such storms also create strong waves in these coastal sections. The combination of waves with an elevated water level poses increased risks which could result in strong erosion of the shores, make low-lying households or infrastructure inaccessible, and damage coastal engineering structures. If those conditions persist for a longer time, the effects will be more serious.

To properly analyse frequency and magnitude of the differences in water level in the Baltic Proper and in the interior of the Gulf of Riga, I employ the highest quality time series of hourly measured water levels at Liepaja (representing water level in the open Baltic Sea), Daugavgriva and Pärnu (at the southern and north-eastern ends of the gulf, respectively) to quantify the excess water level in the Gulf of Riga. The results in Paper II also give an insight into changes in the frequency of events with elevated water levels in the gulf. These changes apparently reflect the local consequences of climate change.

The objectives and outline of the thesis

This thesis analyses the course and statistical properties of water levels and potential joint impact of wave storms and variations in the water level in the eastern Baltic Sea with the focus on the Gulf of Riga and the Latvian coast of the Baltic proper.

The main objectives are to:

- establish the basic properties of water level in the study area in terms of water level extremes, empirical probability distributions and the seasonal course of mean and maximum water levels;
- investigate long-term changes in these distributions, the seasonal course and annual mean and extreme water levels;
- separate the major components of the course of water level based on their typical timescales;
- detect properties of episodes when the water level in the Gulf of Riga is considerably higher than in the rest of the Baltic Sea for extended periods of time;
- analyse the synchronisation of high waves and variations in the water level in the eastern part of the Baltic Sea by calculating an alternative estimate of closure depths.

To meet these objectives, Chapter 1 provides the description of observed water level data on Latvian shores and discusses the observation network, quality and inhomogeneity of the data, and local features, including land uplift rates. The core outcome is an estimate of the shape of probability distributions of water levels and their temporal changes. This chapter follows Paper I.

Chapter 2 proceeds with an analysis of changes to statistical properties of water level in Latvian waters. The changes in the seasonal pattern and in the annual water level are examined. The context of the identified changes is explored using the NAO index and wind data from the island of Vilsandi. This chapter is also based on Paper I.

Chapter 3 focuses on single components of observed water levels at Liepaja, Daugavgriva and Pärnu which may have different causes and outcomes. The focus is on the difference between water levels in the Baltic proper and Gulf of Riga. This chapter follows the work presented in Paper II.

Chapter 4 focuses on calculating an alternative estimate of the closure depth in the coastal area of the entire eastern Baltic Sea based on the modelled wave and water level properties. The calculations are based on time series of wave parameters from the wave model WAM provided by Dr. A. Räämet. The time-series of water levels are extracted from the Rossby Centre Ocean Model (RCO). This chapter follows Paper III.

Public presentation of the results

The basic results described in this thesis have been presented by the author at the following international conferences:

Männikus, R., Soomere, T., Kudryavtseva, N. 2019. Identifying water level extremes from in situ measurements in the Gulf of Riga, Baltic Sea, during 1961–2017. *4th International Conference on Advances in Extreme Value Analysis and Application to Natural Hazard (EVAN)* (17–19 September 2019, Chatou, France. Presented by N. Kudryavtseva).

Männikus, R., Soomere, T. 2019. Joint impact of the height and duration of high water level events from in situ measurements in the Gulf of Riga, Baltic Sea, 1961–2018. *Short Course/Conference on Applied Coastal Research* (9–11 September 2019, Bari, Italy).

Männikus, R., Soomere, T., Kudryavtseva, N. 2018. On the water level measurements in the Gulf of Riga during 1961–2016. *2nd Baltic Earth Conference. The Baltic Sea in Transition* (11–15 June 2018, Helsingør, Denmark).

Männikus, R., Soomere, T., Kudryavtseva, N. 2018. Superelevations of water level in the Gulf of Riga. *2nd Baltic Earth Workshop on Multiple Drivers for Earth System Changes in the Baltic Sea Region* (26–27 November 2018, Tallinn, Estonia).

1. Observed water level data in Latvian waters

Systematic water level measurements on the Latvian coast in the central Baltic Sea have been carried out since 1865. The first location for such measurements was at Liepaja. About 20 years later the observation network was extended to Ventspils, Daugavgriva and Kolka (Figure 1). The digitised recordings of observations at 11 Latvian stations from 1961 are now available at the Latvian Environment, Geology and Meteorology Centre website (LEGMC, http://www.meteo.lv). Even though the data is presented "as is", this data set makes it possible to establish the basic features of the course and main statistical properties of water level for different sections of the Latvian coast.

This chapter is based on the first thorough description of this water level data resource published in the international literature in Paper I. It addresses the quality and reliability of the data sets, presents an insight into long-term variations in the water level at the measurement sites, demonstrates that the empirical probability distributions of different water levels have undergone statistically significant changes at several locations, and links the outcome of this analysis with the known properties of similar data sets in the neighbouring countries – Estonia (Suursaar and Sooäär, 2007), Finland (Johansson et al., 2001, 2004), Lithuania (Dailidienė et al., 2006), and Poland (Wisniewski et al., 2011; Hünicke et al., 2015; Kowalczyk, 2019).

The analysis follows recommendations of Soomere and Pindsoo (2016). Namely, the analysis of properties of long-term behaviour of water level extremes are best undertaken, with annual data organised over a time period that includes the relatively windy autumn and winter season in a single year, rather than the calendar year. This time period, from 01 July to 30 June of the subsequent year, is called a stormy season.

1.1. Water level observation network in Latvia

The earliest still-recording water level stations in Latvia were established at Liepaja and Ventspils more than 150 years ago (Table 1). These measurement sites are located on the 150 km long Latvian shore of the Baltic Sea proper and are completely open to the central Baltic Sea. Liepaja is situated about 40 km north of the border with Lithuania and Ventspils is about 60 km to the south of Kolka Cape and Irbe Strait (Figure 1). Water level observations were also undertaken at Pavilosta, between Liepaja and Ventspils, until 2003.

As discussed above, the water level regime on the Baltic proper coast may be different from the regime on the south-western and eastern shore of the Gulf of Riga. This coastal system is longer (with a length of about 350 km) than the Baltic proper coast of Latvia. It hosts seven observation stations, at Kolka, Roja, Mersrags, Lielupes griva (the eastern part of Jurmala), Daugavgriva, Skulte and Salacgriva. Another tide gauge is located at Andrejosta in the Port of Riga, a few kilometres inland from the River Daugava mouth (Kudure, 2009, Paper I). The data of observations and measurements are available in digital form for these 11 Latvian stations (Table 1) from 1961. The analysis of *in situ* water level data from these stations is reported for the period 1961–2018 in Paper I and Paper II.

The measurements were performed using a classic water level graduated staff until the 2000s. Automatic tide gauges were installed in 2004–2006 at ten locations (including Andrejosta) by the Latvian Environment, Geology and Meteorology Centre (LEGMC, http://www.meteo.lv). The measurements are made from the "zero" datum and are thus not been corrected against uplift rates. The local benchmark is a horizontal plate in the

Table 1. The basic properties of water level (presented in the BK77 system) and hourly data completeness for 01 January 1961–31 December 2018 in the LEGMC data set. Adapted from Paper I.

Location	**Measurements since**	**Mean level (cm)**	**Maximum level (cm), with date**	**Minimum level (cm), with date**	**Hourly data completeness 1961–2018**
Liepaja	01.01.1865	2.0	174, 18.10.1967	–86, 18.01.1972	99.69%
Pavilosta	1930–31.12.2003	0.3	150, 18.10.1967	–87, 31.12.1978	12.28%
Ventspils	01.01.1873	0.9	141, 18.10.1967	–76, 28.01.2010	65.19%
Kolka	01.01.1884	1.2	161, 09.01.2005	–113, 03.11.2000	35.25%
Roja	01.01.1932 01.11.1949	–1.0	167, 09.01.2005	–89, 28.01.2010	30.28%
Mersrags	01.01.1928	0.9	166, 02.11.1969	–94, 29.09.1967	30.17%
Lielupes griva	01.01.1946	6.9	208, 02.11.1969	–107, 14.10.1976	96.46%
Andrejosta (Port of Riga)	14.01.1930	11.4	225, 02.11.1969	–121, 14.10.1976	99.78%
Daugavgriva	01.01.1875	9.2	224, 02.11.1969	–107, 14.10.1976	99.98%
Skulte	01.01.1939	6.1	231, 02.11.1969	–109, 14.10.1976	93.65%
Salacgriva	01.10.1928	5.8	215, 28.03.1968	–116, 14.10.1976	29.16%

vicinity of the tide gauge. It is levelled carefully to the 1st class points of the national geodetic network with Level 1 precision levelling and its constant absolute height is linked to the tide gauge height staff. Therefore, the long-term water level at a single location (Table 1) does not necessarily match the formal zero level of the gauge. The deviations are up to 11 cm at Andrejosta, around 6 cm at Lielupes griva, Skulte and Salacgriva, and less than 2 cm at other locations.

The water levels in Estonia and Latvia were measured in the Baltic Height System BK77 height system which is associated with the Kronstadt zero. This benchmark is defined as the average water level at Kronstadt in 1825–1840 (Lazarenko, 1986). The BK77 system also differs from the Scandinavian and Finnish tide gauge benchmarks (e.g., Johansson et al., 2001). From 01 December 2014 the BK77 system in Latvia was replaced by the height system LAS200.5 (European Vertical Reference System, EVRS). A similar system associated with the Amsterdam Ordnance Datum was implemented in Estonia from 01 January 2018 (Kollo and Ellmann, 2019). The difference of heights (and water levels) in the BK77 and LAS200.5 system is mostly in the range of 15–24 cm. Therefore, the long-term formal average of water level at the Latvian and Estonian observation sites will be about 20–30 cm in the EVRS framework. However, as the existing information about water levels in Estonia and Latvia published in the international literature until 2018–2019 (including Paper I and Paper II) is given in BK77, this system is used in this thesis.

1.2. Inhomogeneity, local features, and land uplift

The observed water level time series are not fully homogeneous as the sampling procedure, frequency, and devices have undergone changes in the period 1961–2018. Also, the time series at some sites have longer gaps (Table 1) and water level at several tide gauges are impacted by river flow. The automatic hourly measurements implemented in 2004–2006 are mostly homogeneous and contain only minor gaps with a length of a few hours. The uncertainty of individual measurements is less than 2 cm (Paper II).

The sampling frequency, coverage and completeness of the recordings vary greatly between locations (Table 1). The visual sampling at several stations was only performed 2, 3 or 4 times a day. The sampling rate varied over time at some locations. For example, observations at Salacgriva were carried out three times a day in 1961–1981 and twice a day from 1982 until mid-October 2006 (Paper I).

The most comprehensive hourly data sets are available for Liepaja, Lielupes griva, Daugavgriva, Andrejosta, and Skulte during the entire study period (Table 1). Single gaps in the Liepaja and Daugavgriva data sets are mostly shorter than 8 hours and only in a few cases extend to a few weeks (Paper II).

A few recordings in the LEGMC data set are questionable (Paper II). Namely, several events of large and rapid variations in the water level might be erroneous. The highest water level at Liepaja (174 cm, 18 October 1967 at 14:00) can be attributed to the strong storm Lena on 17–18 October 1967 (Wikipedia, 2020). However, the course of the recorded water level during this storm is peculiar. The water level readings increased within 2 hours from 60 cm to 174 cm, remained constant for 5 hours and then dropped to 100 cm in one hour (Paper II). This passage may reflect specific features of the course of water level at the location of the measurement site in a narrow canal between a coastal lake and the sea (Paper II). As water level was high at Pärnu and Daugavgriva also during this event, the values are not excluded from the analysis in Paper II.

The implementation of automatic hourly measurements at many stations (e.g., Kolka and Salacgriva) in 2004–2006 led to a dramatic increase in the number of observations per day. This change apparently introduced inhomogeneity of the water level time series and may affect the estimates of annual and seasonal properties of water level. To minimise the impact of this change and the presence of smaller gaps in the data sets, the analysis in Papers I and II mostly uses monthly mean and extreme values for the evaluation of long-term trends. The calculation of monthly values and all results presented in Table 2 and in the text is straightforward for Liepaja, Daugavgriva, and Salacgriva. All months contain enough measurements and have 100% coverage in terms of monthly properties at these locations. To fill the longer measurement gaps at other stations, The analysis in Paper I makes use of the strong correlation (correlation coefficient $R > 0.95$) between the recordings at the neighbouring stations. The time series of monthly values at Roja were completed with a certain number of interpolated values from Mersrags and Kolka. The distance between these stations is about 20 km and the hydrometeorological conditions at both locations are fairly similar.

The correlation between the recordings made on the shores of the Baltic proper and in the Gulf of Riga is clearly weaker but still relatively high. For example, the correlation coefficient of the hourly values at Liepaja and Daugavgriva is $R = 0.889$. This feature suggests that recordings in the Gulf of Riga to a large extent reflect the instantaneous course of water level in the rest of the Baltic Sea. In other words, large excess water volumes in the Gulf of Riga (Paper II) do not substantially affect the long-term parameters of water level, except for extreme values.

It is necessary to take into account potential changes in the benchmark height at every station, in order to properly interpret the long-term changes in the absolute water level. The rate of vertical crust movements in the study area can be estimated from the total vertical movement (uplift/subsidence) rates in Latvia (Reiniks et al., 2010). The northwestern coast of Latvia uplifts with a rate of approximately 1 mm/yr. The southeastern part of Latvia

Table 2. Annual and seasonal changes in the relative average water level 1961–2018 (mm). The total changes are evaluated according to the linear trend. Three different descriptive periods for a year are used: calendar year (A), stormy season (from July to June of the subsequent year, S) and winter months (from December to March, W). Slopes of the relevant linear trendlines, local uplift rates U, and estimates of the slope of linear trendlines of the absolute average water level as $S+U$, $A+U$, or $W+U$ are presented in mm/yr. Statistically significant nonzero trends at a 95% and higher level are indicated in bold italics; and at a 90% to 95% level in italics. The trends are evaluated based on monthly mean and extreme water levels (Paper I).

Location		Change			Slope			U	Slope + U		
		A	S	W	A	S	W		A	S	W
Liepaja	mean	49	57	128	*0.85*	*0.98*	*2.20*	–0.10	0.76	0.89	2.10
	max	55	29	190	0.94	0.50	3.28		0.84	0.40	3.18
	min	25	35	46	0.43	0.61	0.80		0.33	0.51	0.70
Roja	mean	12	23	97	0.20	0.39	1.68	0.80	*1.00*	***1.18***	*2.46*
	max	46	13	229	0.80	0.23	3.95		1.59	1.01	*4.73*
	min	–60	–36	–19	–1.04	–0.62	–0.33		–0.25	0.16	0.45
Daugavgriva	mean	22	32	119	0.38	0.56	2.05	–0.25	0.14	0.31	1.81
	max	–97	–89	213	–1.67	–1.54	3.67		–1.91	–1.79	3.42
	min	5	19	–26	0.08	0.32	–0.44		–0.17	0.07	–0.68
Salacgriva	mean	57	68	168	0.98	*1.18*	*2.89*	0.20	*1.18*	***1.37***	***3.05***
	max	–5	–117	63	–0.08	–2.02	1.08		0.11	–1.82	1.28
	min	12	45	11	0.21	0.78	0.19		0.41	0.98	0.39

subsides at a rate of about 1.7 mm/yr. The zero line of the Earth's crust movement crosses the territory of Latvia from the vicinity of Liepaja towards Rujiena in the north-east of Latvia (Reiniks et al., 2010; Paper I).

The uplift rates of the Earth's crust change very slowly in the study area (Harff et al., 2017). This feature suggests that it is acceptable to perform the analysis of the changes in the resulting absolute water levels under the assumption that the land uplift rate has been constant during the entire study period. This view simplifies the analysis of long-term changes in the water level. Namely, under this assumption the slopes of trends in the parameters of the absolute water level can be expressed as the sum of the relevant slope for the relative water level and the uplift or downlift rate (cf. Table 2). As the uplift rates are fairly small, Paper I focuses on the behaviour of the relative water level and presents the results for the trends in the absolute water level in terms of modifications in their level of statistical significance.

1.3. Annual average water level

The annual average relative water level at all Latvian measurement sites is calculated in Paper I based on monthly averages. Consistent with the overall perception of the increase in the water level in the central and southern Baltic Sea (Hünicke et al., 2015), the water level shows a gradual increase 1961–2018 at all stations except for Lielupes griva (Figure 2). The reasons for this exception are unclear but it could be apparently related to the particular location of the Lielupes griva tide gauge, a few kilometres upstream of the Lielupe River.

The rate of annual water level increase varies from almost zero at Roja at the northern tip of the Kurzeme Peninsula up to 0.98 mm/yr at Salacgriva on the eastern shore of the

Gulf of Riga. These rates of increase are much smaller than on the shores of neighbouring countries. The data from Lielupes griva even shows a decrease of –0.14 mm/yr. The increase in the annual and stormy season water level is statistically significant at a relatively low level of significance at some locations (Table 2). The largest trends in the stormy season at Salacgriva (1.18 mm/yr) and Liepaja (0.98 mm/yr) are significant at a 93% level. No trend is statistically significant at a >95% level (Paper I).

A proxy of the absolute average water level is obtained (in Paper I) by means of adding the the long-term crust uplift rate to the water level time series at single locations (Table 2). This operation is equivalent to adding the uplift rate to the slope of the trendline of the relative water level. The result is the slope of the trendline of the absolute water level. This operation, however, modifies the estimates of confidence intervals of the resulting slope and thus also affects the level of statistical significance of the evaluated trends.

The rate of change in the absolute average water level varies from 0.31 mm/yr at Daugavgriva to 1.37 mm/yr at Salacgriva (Paper I) for stormy season. These values are smaller than the signal of global ocean level rise at the entrance to the Baltic Sea (1.63 mm/yr; Gräwe et al., 2019). They are also different from rates in the neighbouring countries. The average sea level has risen faster than in the global ocean on both Lithuanian (Dailidienė et al., 2006) and Estonian shores (Suursaar and Sooäär, 2007).

The described features are interpreted in Paper I in the context of joint effect of several drivers of water level on the Baltic Sea water level course following Hünicke et al. (2015). As described above, this course reflects the joint effect of (i) the global sea level rise, (ii) the impact of (westerly) winds that may fill the Baltic Sea with excess water, (iii) properties of drivers that create local storm surge and wave set-up. For the observation stations in the Gulf of Riga (iv) the impact of westerly winds that push extra water into the gulf may also play a role. The global sea level rise evidently affects the entire interior of the Baltic Sea homogeneously. A comparison of the outcome of the analysis in Paper I (Table 2) with the conclusions of Dailidienė et al. (2006), Suursaar et al. (2006), Suursaar and Sooäär (2007) signals that changes in local drivers (ii)–(iv) apparently have systematically mitigated the impact of global ocean level rise in Latvian waters during the period 1961–2018.

The water level “climate” in the Baltic Sea has strong seasonal cycle (Hünicke and Zorita, 2008). Paper I clarifies which part of this cycle is mostly responsible for the described changes. To do so, it is necessary to specify the seasons.

Different authors differently single out the windy autumn and winter season. While Dailidienė et al. (2006) select the time period from December to March (DJFM) to represent winter in the study area, Suursaar and Sooäär (2007) define winter months as the period from January to March (JFM). The trends extracted in Suursaar and Sooäär (2007) are generally more pronounced than those found in Dailidienė et al. (2006).

Paper I presents the analysis of the average relative water level in winter defined as DJFM and the whole year. The average water level in winter exhibits a much more rapid increase than the annual water level (Table 2). The slopes of the relevant trendlines are mostly >2.05 mm/yr. This seasonal variation in the trends of the average water level is similar in Lithuania and Estonia (Dailidienė et al., 2006; Jarmalavičius et al., 2007; Suursaar and Sooäär, 2007).

The question about statistical significance of the trends of winter average water level remained partially open in Paper I. None of these trends is statistically significant at a 95% or higher level.

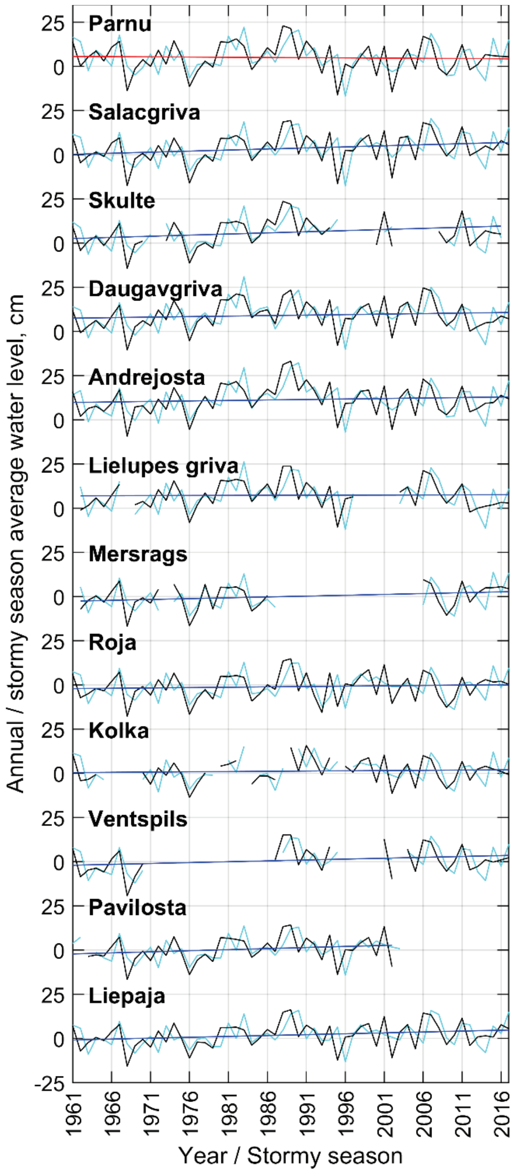


Figure 2. The temporal course of annual average water level and its trendline 1961–2018 at all Latvian stations listed in Table 1 and at Pärnu. The black lines mark the average evaluated for stormy seasons (the time intervals from 01 July to 30 June of the subsequent year) and cyan lines indicate the annual average for the calendar year. Note small, but important, differences between the lines depending on the definition of year. Adapted from Paper I.

A possible reason for this feature is much stronger interannual variability of winter average water levels compared to the annual averages. Formally, the trend for December–March is statistically significant at a 93% level at Liepaja and Salacgriva, and at a 89% level at Daugavgriva.

1.4. Empirical probability distributions of water level

The shape of the empirical probability distributions of the occurrence of different water levels provides further information about the water level regime. These distributions are calculated in Paper I and Paper II using the highest quality data sets of water level (in terms of homogeneity and temporal coverage) from Daugavgriva and Liepaja (Table 1). The overall shape of such distributions (Figure 3) reflects a quasi-Gaussian appearance of similar distributions in the north-eastern Baltic Sea (Johansson et al., 2001).

The distribution for storm surges is evaluated in Paper II using a proxy of the storm-driven component of water level. This proxy is defined as the difference between the visually observed or instrumentally measured water level and its smoothed value over a certain time interval following Soomere et al. (2015b). This residual usually follows an exponential distribution in the adjacent areas of the Baltic Sea (Soomere et al., 2015b) similar to the non-tidal residual of the water level in the English Channel (Schmitt et al., 2018). The water level readings that reflect changes to the volume of the entire Baltic Sea follow a Gaussian distribution (Soomere et al., 2015b).

The shape of this distribution for water level in the study area substantially deviates from the shape of analogous distributions in the North Sea (e.g., Schmitt et al., 2018). It is therefore likely that the quasi-Gaussian shape is caused by the joint contribution of large volumes of excess water pumped into the Baltic Sea by certain sequences of atmospheric processes (Leppäranta and Myrberg, 2009) and local storm surges into the recorded water level.

The distribution of water levels is asymmetric (Figure 3). This feature mirrors the well-known fact that elevated water levels are more likely in the eastern Baltic Sea than negative surges (Johansson et al., 2001; Suursaar and Sooäär, 2007). It apparently reflects the asymmetry of wind fields (the predominance of westerly winds) in the study area.

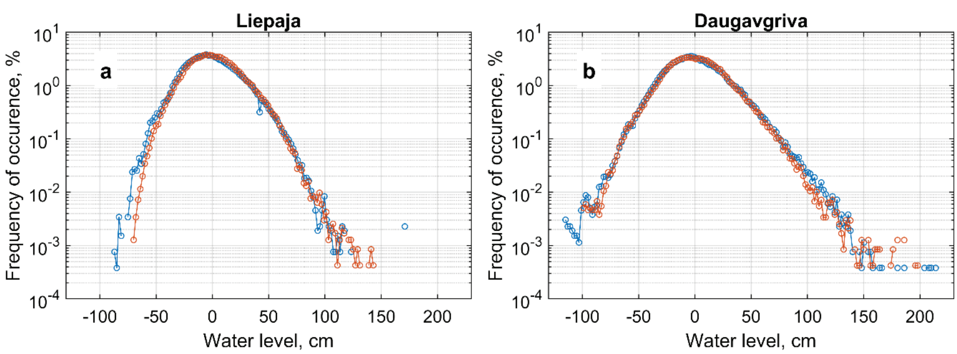


Figure 3. Empirical probability distributions of occurrence of different water levels at Liepaja (a) and Daugavgriva (b) for the 30-year period of 1961–1990 (blue) and 28-year period of 1991–2018 (red). The horizontally aligned markers for high water levels at the frequency of ~0.0003% correspond to the recorded surge heights that happened exactly once in the period 1961–2018. The outlier at 174 cm for Liepaja corresponds to five equal entries on 18 October 1967. Adapted from Paper I.

These distributions may change over time in the Baltic Sea basin (Johansson et al., 2001). The changes in the shape of these distributions for different climatic periods (1961–1990 and 1991–2018) are highlighted using a standard Kolmogorov–Smirnov test as a significance test. This test is sensitive to differences in both location and shape of the empirical cumulative distribution functions of the two samples.

These distributions have undergone certain changes over the two time periods (Paper I). The largest alteration is that very low water levels (below –40 cm) have become less frequent at Liepaja (Figure 3). The frequencies of occurrence of elevated water levels have remained practically unchanged. The distribution has thus become narrower.

The change in kurtosis for both locations (Paper I) can be interpreted as showing a decrease in the probability of extremely low and extremely high water levels (Paper I). This change apparently reflects certain changes in the properties of storms that produce the largest deviations of water level from the long-term average. A possible conjecture formulated in Paper I is that such storms have not become stronger in the central Baltic Sea. This conjecture matches well the outcome of recent research into properties of meteorological forcing in the Baltic Sea (Rutgersson et al., 2014; Hünicke et al., 2015). The demonstrated feature also suggests that projections of water level extremes (e.g., Särkkä et al., 2017; Vousdoukas et al., 2017) may overestimate the rate of increase in these extremes in the eastern Baltic Sea.

The changes in the shape of the empirical probability distribution of the occurrence of different water level heights are clearly seen at Liepaja. The shape of this distribution has changed at Liepaja at a 95% level of statistical significance. The changes at Daugavgriva are less pronounced and not statistically significant (74%). The level of statistical significance of changes depends on the particular time period of comparison. This level was much higher (at 87%) for time intervals 1961–1985 and 1991–2015 at Daugavgriva (Paper I).

Paper I also demonstrates that notable changes have occurred to the seasonal distributions of the occurrence of different water levels. The most pronounced variations to these distributions occurred for the windy autumn and winter season (understood as the period from October until March of the subsequent year). The changes to these distributions were much smaller in the relatively calm spring and summer season (from April to September). These results are in line with the outcome of the analysis in Johansson et al. (2001).

2. Cyclic features of water levels

While Chapter 1 provides an insight into the basic properties of water level data at Latvian observation stations and highlights several key changes in the statistical properties of water level at Liepaja and Daugavgriva, Chapter 2 further explores the behaviour of water levels over time on Latvian shores. To complement the study for the whole Gulf of Riga, time-series of water level observations and measurements from Pärnu are also included in a part of the analysis. These data were provided by Estonian Weather Service (http://www.ilmateenistus.ee). Consistent with the Latvian time series, data for 1961–2018 are used.

The main aim of Chapter 2 is to identify possible differences in the water level regime in different regions by studying alterations of the seasonal course of the water level and changes in water level minima and maxima at single locations. The extracted signals of climate changes in these records are presented in a wider context by means of an analysis of interrelations of the established variations with changes in the NAO index and the properties of strong winds at a location to the north of the Gulf of Riga. The material presented in this chapter also largely follows Paper I.

2.1. Seasonal course

There is a pronounced cyclic feature of water level in the entire Baltic Sea – its seasonal course (Weisse and Hünicke, 2019). Similar to other locations in this water body (Hünicke and Zorita, 2008), water level is generally below the long-term average during the relatively calm season (March–May) and well above average during the relatively windy autumn (September–December) and part of winter (notably January) at all Latvian stations (Figure 4). The average total range of the annual cycle is 30–35 cm at all stations

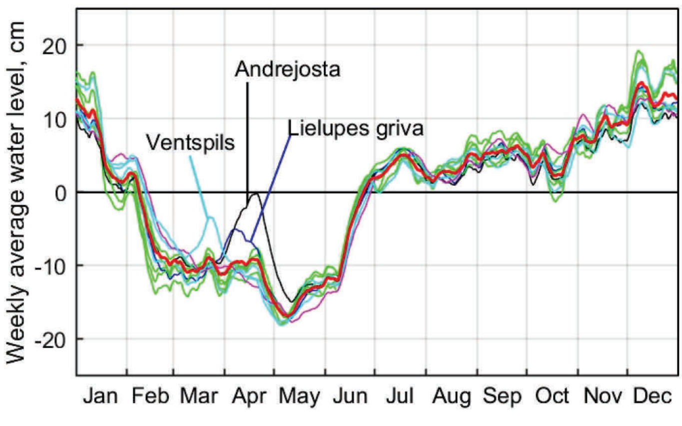


Figure 4. Seasonal variation in the weekly water level at all 11 stations listed in Table 1 with respect to the long-term average at single measurement locations (thin lines) and in the average over nine stations (excluding Pavilosta and Andrejosta, thick red line). Differently from the rest of the analysis, de-meaned values of water level are used here for better comparison of data from different locations. The values of water level at single stations are first evaluated for each calendar day and then smoothed using a running average over seven days. The magenta line shows the variation at Pavilosta in 1961–2003, cyan lines represent other stations on the Baltic proper coast and green lines show other stations in the Gulf of Riga. Adapted from Paper I.

in the study area (Paper I). This range is somewhat larger than observed at Finnish stations (Johansson et al., 2001) and on the southern coast of the Gulf of Finland (Raudsepp et al., 1999). It is much larger than experienced on the Polish coast (Pajak and Kowalczyk, 2019). Part of this difference may stem from the slightly different routine of the analysis in Paper I. Namely, it is based on weekly averages while most of the previous research has considered monthly averages of the water level.

The seasonal cycles at all stations, except for Andrejosta, Ventspils and Lielupes griva, follow each other almost exactly. The largest deviations of the weekly average at single stations (apart from the three stations mentioned) from the average over all stations are less than ±6 cm. A substantial deviation of the seasonal course at Andrejosta during April is apparently caused by the spring discharge maximum of the Daugava River. Moreover, the analysis in Laiz et al. (2014) suggests that the run-off from large rivers (also the Daugava River) during warm winters with heavy precipitation could additionally raise the water level at the river mouth. This effect may cause the elevated long-term water level at this location. For these reasons the data from Andrejosta is excluded from the detailed analysis of the course of water level in Paper I.

Similar spring maxima are also evident in the water level course at Ventspils in the Venta River mouth and at Lielupes griva about 3 km upstream in the Lielupe River. As the amplitude and duration of these deviations are much smaller at Ventspils and Lielupes griva than at Andrejosta, the relevant data sets are included in the further analysis.

The distinct maximum of water level from mid-November to mid-January (Figure 4) is unusual in the older (19th century) data from the southern and western Baltic Sea as demonstrated in Hünicke and Zorita (2008). This maximum has frequently occurred (most notably in the eastern Baltic Sea) since the middle of the 20th century. The deep spring minimum (March–May) is followed by four months (July–October) when the average water level slightly (by up to 6 cm) exceeds the long-term value (Figure 4). The presence of the midsummer maximum (July) apparently contributes to a strong semi-annual peak of the Baltic Sea seasonal variability in Stramska (2013) whereas the small local maximum in September may substantially contribute to the spectral peak that is interpreted as an evidence of pole tide (Medvedev et al., 2017).

A qualitatively similar seasonal course is evident for other water level parameters, such as the absolute and average maximum and minimum for a given month (Figure 5). Consequently, seasonality is an important feature of water level variability in the entire study area.

The largest range of water level variations in the entire study area exceeds 3 m at Daugavgriva in the southernmost bayhead of the Gulf of Riga (Paper I). As the largest deviations from the long-term water level are characteristic to the months with the largest average water level, it is likely that these variations are mostly driven by wind stress as suggested in Karabil et al. (2018). The total range of variations is smaller at Roja (256 cm) near the entrance of the Gulf of Riga. The water level course at this location apparently follows mostly that of the Baltic proper represented by the Liepaja data. The largest values of the extremes (highest ever and lowest ever water levels) in single months as well as the average monthly maxima and minima qualitatively follow the same seasonal course along the entire Latvian coast (Figure 5) even though they may occur in different months at different locations.

Contrary to previous findings about the seasonal cycles of water level or its components in the Baltic Sea (Ekman and Stigebrandt, 1990; Hünicke and Zorita, 2008), the Latvian data shows a decrease in the amplitude of the seasonal cycle (Paper I). The changes in the weekly average water level (Figure 6) from 1961–1990 to 1991–2018 are almost opposite to the pattern of seasonal variations shown in Figure 4. The average water level in February–June has risen more than 5 cm (Paper I). On the contrary, there has been a decrease by up to 10 cm in July–November. In December–January there is a transmission from decreasing to increasing water level change. These changes have apparently enhanced the winter maximum shown in Figure 4. This change is visible on the Latvian shores of the Baltic proper and in the Gulf of Riga. An obvious outlier is here Andrejosta. The recordings at this location are apparently impacted by the Riga hydroelectric power plant. Hence, the data from Andrejosta have been excluded from the calculation of the average over all locations.

The ranges of seasonal variations in the monthly means and averages in minima and maxima have decreased in the period 1991–2018 compared with the similar amplitudes in the period 1961–1990 (Figure 7). All these parameters have increased at the beginning of the year (from January to June) and decreased in autumn (from September to November). The consistency of this pattern of changes in all data sets suggests that the relevant changes are characteristic for quite a large area of the central Baltic Sea.

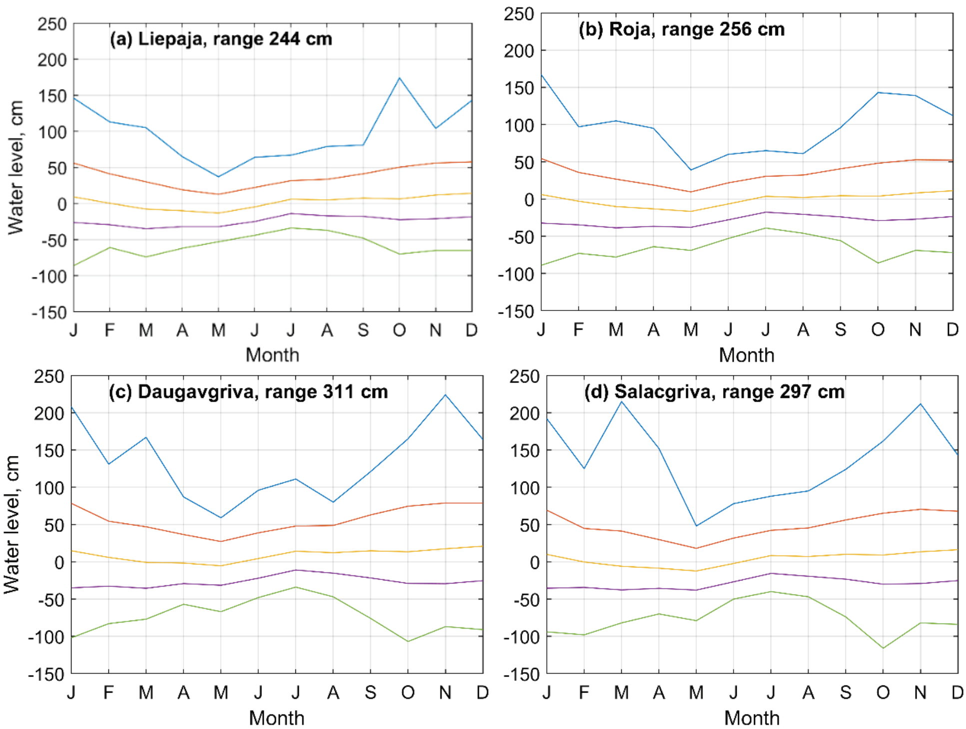


Figure 5. Seasonal variations in monthly water level properties 1961–2018. Lines from top: absolute maximum for a given month, average monthly maximum, mean, average monthly minimum, and absolute minimum for a given month. From Paper I.

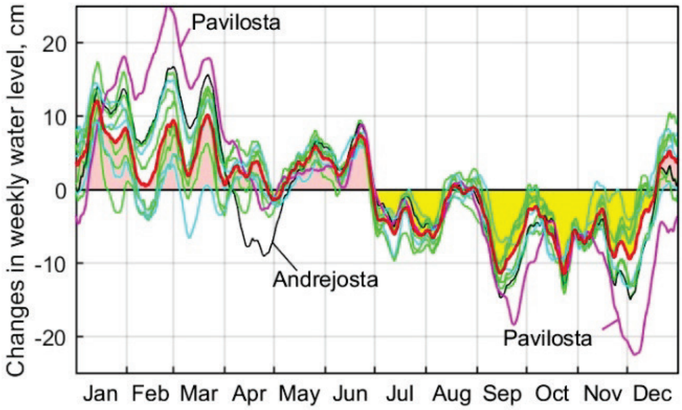


Figure 6. Changes in the weekly average water level at single measurement locations (thin lines) and in the average over all locations (excluding Pavilosta and Andrejosta, thick red line) between the years 1961–1990 and 1991–2018. The variations at Pavilosta (magenta line) can be only evaluated for 1961–1990 and 1991–2003 and are thus ignored in the calculation of the average over all locations. Cyan lines represent the other stations on the Baltic proper coast (Liepaja and Ventspils) and green lines the other locations in the Gulf of Riga. Light red and yellow areas show the time interval for which the average water level has increased, or decreased, respectively. From Paper I.

The reasons for the described changes are unclear. A decrease in the extent of ice cover and an associated increase in the impact of wind on the water surface may have caused an increase in the mean and maximum winter water levels. Another possible cause could be changes in the air pressure and wind patterns. Karabil et al. (2018) showed that the water level in the interior of the Baltic Sea is predominantly governed by atmospheric pressure. Ideally, variations in the atmospheric pressure can explain up to 88% and 34% of the water level variability in wintertime and summertime, respectively. The net energy flux of the wind on the water level surface explains up to 35% of the sea level variability in wintertime (Karabil et al., 2018).

The impact of wind is considerably smaller in summertime. Hence, the changes in summer months may mirror modifications in the large-scale pattern of atmospheric

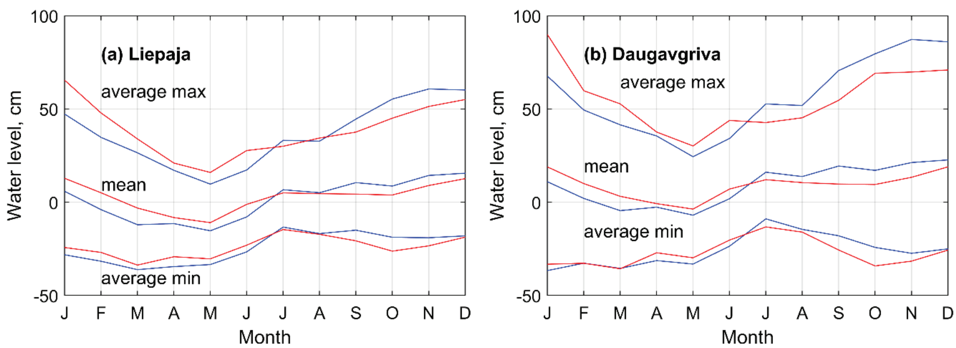


Figure 7. Seasonal variations in monthly mean, maximum and minimum sea level at (a) Liepaja and (b) Daugavgriva for the 30-year periods 1961–1990 (blue lines) and 1991–2018 (red lines). Lines from top: average of monthly maxima, mean, and average of monthly minima of water level. From Paper I.

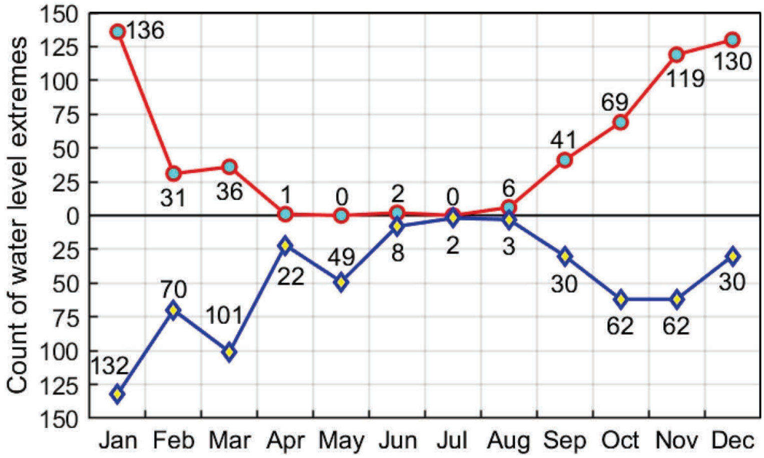


Figure 8. The count (numbers at markers) of annual extremes at all 11 stations listed in Table 1 in different months 1961–2018. Red: water level maxima, blue: water level minima. From Paper I.

pressure whereas the changes in the winter probably signal changes in the wind regime (Paper I).

The presence of the demonstrated extensive seasonal variability may impact the results of the analysis of long-term changes in some parameters of the water level regime. For example, water level maxima in successive calendar years may be correlated. This feature complicates the calculation of return periods of extreme water levels using the block maximum method as this method requires that water level extremes in successive time intervals are uncorrelated (Coles, 2001).

Figure 8 shows that the calendar year maxima of water level are concentrated in five months from September to January. In particular, annual maxima that occur in December and in January of the subsequent year may be caused by a sequence of storms at the end of a year that pushes a large amount of water into the Baltic Sea so that its water level remains high over a longer time period. This means that the water level maxima of successive calendar years may be correlated (Soomere and Pindsoo, 2016). Figure 8 suggests that it is convenient to use the time interval from 01 July to 30 June of the following year to ensure that the subsequent water level maxima over 12 months are uncorrelated. This choice evidently leads to a more consistent interpretation of changes to the water level in wintertime (that otherwise may be split between two calendar years). In particular, it ensures that the selected water level maxima or minima are separated by a calm season and are correlated as weakly as possible.

2.2. Water level maxima and minima

The above discussion has demonstrated that there is no distinct pattern of trends of annual or stormy season water level extremes (Chapter 1, Table 2). The calculated trends are not statistically significant at any reasonable level. However, the maxima generally increase and the absolute values of the minima decrease to some extent. As the minima are usually driven in this area by joint impact of high atmospheric pressure and persistent easterly winds, this feature signals that the intensity and/or duration of easterly winds may have decreased during the last half century (Paper I).

The monthly maxima generally increase in January–June and decrease in July–December (Paper I). These changes apparently mirror the overall increase and decrease in the water level in these months. The increase is statistically significant at a 90–95% level in January and June.

The winter (DJFM) maxima exhibit relatively steep increase at almost all locations. The relevant trends differ from those evaluated for the annual maxima. For example, the annual maxima at Daugavgriva show a strong decrease (–1.67 mm/yr without taking

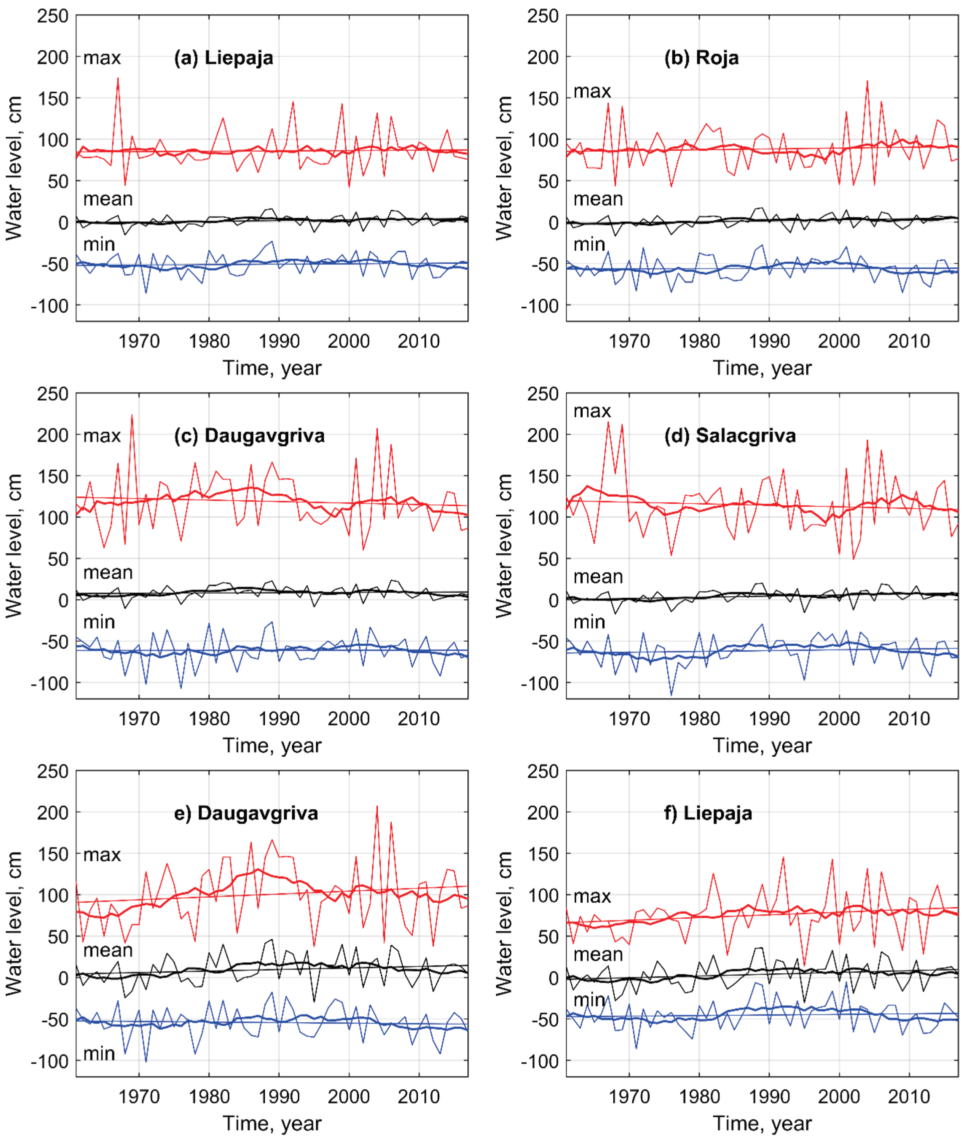


Figure 9. Stormy season mean (middle lines), maximum (upper lines) and minimum (lower lines) water level and their 11-yr moving averages and trends, evaluated for time intervals from July to June subsequent year (a–d) and for winter (from December to March (e, f)). From Paper I.

land uplift into account), but the winter maxima have the second largest increase rate among all the stations (3.67 mm/yr; Table 2). These trends for winter maxima and the decrease of monthly maxima in November and December together suggest that the season of strongest winds (in terms of their impact on the water level) is moving from November–December to January–February (Paper I).

The winter water level minima show no distinct trend. Both annual and winter (DJFM) minima have become smaller at all stations (except for Roja where the annual minima have decreased by 1.04 mm/yr).

The highlighted changes may mirror certain changes in the seasonal pattern of water level in the study area. These changes could be partially explained by a rotation of strong winds in the winter season. The most sensitive to such changes in the wind pattern are measurement sites at Daugavgriva and Lielupes griva which are located in the shallow south-eastern bayhead of the Gulf of Riga. An increasing strength or growing number of storms from north-north-west may lead to an increase in both mean and extreme water level at these locations. The slopes of trends of annual and stormy season water level maxima at Liepaja and Roja are positive (Table 2) and negative at Daugavgriva and Salacgriva. This suggests that the established set of trends of annual and stormy season maxima in the interior of the Gulf of Riga reflects certain local features of the gulf that are not necessarily characteristic in the Baltic proper.

A moving average of stormy season mean, maximum, and minimum water level evaluated using an 11-yr time window (Figure 9) further highlights the presence of the trends described in Table 2. Contrary to the situation on the Polish shores (Wisniewski et al., 2011), there is no visible cyclic behaviour in any of the considered quantities on Latvian shores. Only maximum water levels at Daugavgriva and Salacgriva exhibit some features of cyclic behaviour but these features remain indistinct. There are systematic positive deviations from the long-term average at Daugavgriva in the 1980s. These deviations are more pronounced in the winter season (DJFM). This feature was also noted in the analysis of Lithuanian water levels (Dailidienė et al., 2006) and is apparently related to warm winters that occurred in the 1980s. Such winters are associated with the advection of wet and warm air masses during the cold period. This process leads to rising temperature and more intense movement of air from the west to the east (Ekman, 2003, Hurrell et al., 2003).

2.3. Variability of water level and the NAO index

A convenient parameter to characterise the variability of the temporal course of water level is the annual standard deviation (SD) of the water level calculated on the basis of single measurements. The values of SD at Liepaja and Daugavgriva (21.4 cm and 24.4 cm, respectively) are close to those in Lithuania (Dailidiene et al., 2006) and have not altered significantly in the period 1961–2018. The course of SD is different in Finland (Johansson et al., 2001) and Pärnu (Suursaar and Sooäär, 2007) where this quantity has clearly increased.

The relationships between observed water levels and climate variations are explored in terms of the correlations between the water level and the NAO index in Paper I. This index reflects the difference in surface air pressure between Stykkisholmur, Iceland and Gibraltar (Jones et al., 1997) or Ponta Delgada, Portugal (Hurrell, 1995). As the NAO Gibraltar index offers slightly more consistent results in the analysis of the changes in the

Table 2. Correlation coefficients between the annual NAO index and annual, minimum, mean, maximum, and standard deviation (SD) of water level, and the listed quantities in winter (from December to March). SD is calculated from hourly data that are available only for Liepaja and Daugavgriva.

Location	Minimum		Mean		Maximum		SD	
	all	winter	all	winter	all	winter	all	winter
Liepaja	0.32	0.72	0.33	0.68	0.29	0.51	0.16	0.32
Roja	0.38	0.73	0.43	0.70	0.38	0.55	–	–
Daugavgriva	0.34	0.72	0.32	0.68	0.27	0.48	0.22	0.40
Salacgriva	0.26	0.68	0.35	0.72	0.36	0.61	–	–

climate of Estonia (near the study area) (Jaagus, 2006), the NAO Gibraltar index is used in Paper I for the Latvian coast.

The annual water level mean, minimum and maximum values are all positively correlated with the annual mean NAO index (Table 3). The correlation coefficients are mostly in the range of 0.3–0.4 and vary insignificantly. These quantities for wintertime (DJFM), especially the values of water level minima and mean, have much stronger correlation ($R > 0.68$) with the NAO index than those for other seasons. The latter correlations are statistically significant at a 99.9% level at Liepaja, Roja, Daugavgriva and Salacgriva. This outcome is fully consistent with the above-mentioned conclusion of (Karabil et al., 2018) that some 88% of winter water level variations in the Baltic Sea can be explained by the pattern of atmospheric pressure over the Baltic Sea. The correlation of the SD of water level for both single years and winter seasons (DJFM) with the NAO index is weaker than for other analysed pairs and is not significant at a 95% level (Paper I).

These results are consistent with the general perception that variations in the dynamics of air masses in the North Atlantic storm track largely drive the variations in the statistical properties of water level in the Baltic Sea. The water level at southern and north-eastern bayheads of semi-enclosed basins (such as Pärnu; Suursaar et al., 2003) are particularly sensitive to changes in the direction of stormy winds. Currently, many strong winds blow from south-west or west. These winds are caused by frequent cyclones that cross the Baltic Sea towards the north-east or east (Post and Kõuts, 2014). The changes in their trajectories or a decrease of storm density per unit area, possibly caused by the lengthening of the North Atlantic storm track to the north-east (Lehmann et al., 2011) may have an impact on water level statistics in the study area.

2.4. Vilsandi wind data and water levels

Orviku et al. (2003) define a storm day as a day during which a wind speed of at least 15 m/s is recorded at least once. The variations in the number of storm days defined in this manner at the Vilsandi meteorological station to the east of the island of Saaremaa in Estonia (Figure 10) characterise to some extent possible changes in storminess in the Gulf of Riga. The wind data recorded at Vilsandi represents generally well, wind properties in the northern Baltic proper, but may distort the properties of easterly winds (Soomere and Keevallik, 2001). However, east and, in particular, south-east winds are generally less frequent and much weaker in the study area than south-west or north-north-west winds.

The empirical probability distribution of wind directions (wind rose) has two peaks at Vilsandi (Figure 10). The most frequent winds blow from the south-west. North-north-west

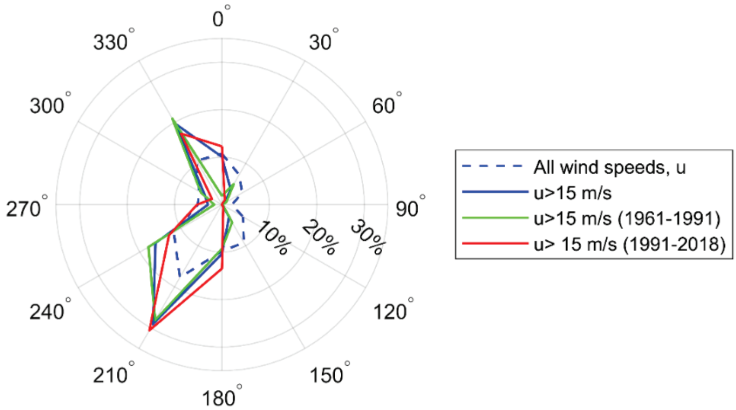


Figure 10. Frequency of occurrence of all wind speeds and strong winds (>15 m/s) at Vilsandi 1961–2018. From Paper I.

winds are somewhat less frequent but in the long term they may be even stronger. For strong winds (>15 m/s) a two peak directional distribution is especially pronounced.

A comparison between two time periods (1961–1991 and 1991–2018) reveal an increase in the frequency of strong south-west winds and a decrease in the frequency of strong north-north-west winds. Additionally, no strong east and especially south-east winds have occurred at Vilsandi since 1991. These changes are consistent with the basically unchanging intensity of water level maxima in the Gulf of Riga and a decrease in the magnitude of low water levels (that are caused by strong easterly winds).

The monthly count of storm days at Vilsandi has no correlation with the monthly mean water level for relatively calm months from April to August (Figure 11). Similarly, the NAO index is almost uncorrelated with the mean water level for these months. Therefore, large-scale pressure differences expressed by the NAO index are only a minor driver of the Baltic Sea water level in these months.

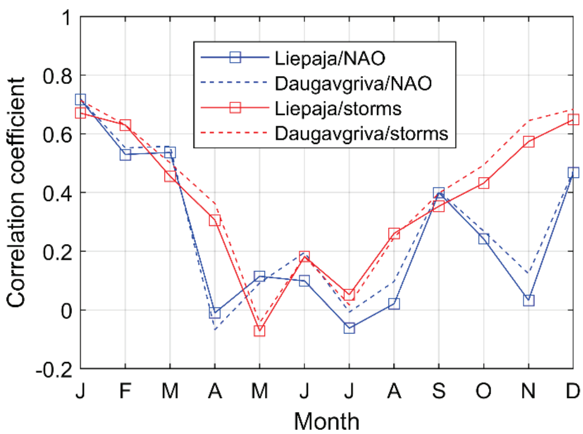


Figure 11. Monthly variations in the correlation coefficient between the monthly mean water level and the NAO index (blue lines) and the monthly mean water level and the number of storm days at Vilsandi (red lines). From Paper I.

The correlation between water levels at Liepaja and Daugavgriva and the monthly count of storm days and the NAO index is relatively strong (R about 0.5–0.7) for September and January–March. This suggests that in these months local strong winds follow the large-scale pressure difference and that both wind fields and pressure variations substantially contribute to the formation of the water level in the study area.

Stronger correlation between the water level and the number of storm days compared to the correlation between the water level and the NAO index is characteristic for October, November, and December (Figure 11). This hints that local storms may have much stronger impact on sea level than the large-scale pressure difference over the Northern Atlantic in these months. This feature thus confirms the conjecture of Karabil et al. (2018) that local winds are a major driver of water levels in the windy season in the study area.

3. Identifying mechanisms behind water level extremes

The main aim of this chapter is to diagnose and quantify the situations in which the water level in the Gulf of Riga considerably exceeds the water level in the Baltic Sea proper. Such occasions are particularly dangerous when the Baltic Sea water level is already substantially elevated. The material is based on Paper II. The chapter starts with an example of elevated water levels in the Gulf of Riga. An attempt to separate the water levels into components driven by different mechanisms is described next. The focus is on the analysis of the magnitude of the events of different water levels and temporal changes in this quantity.

Differently from previous chapters that mostly rely on the water level data from Latvian observation stations, the material in this chapter substantially uses the data from Pärnu, Estonia. Pärnu is located in the north-eastern corner of the Gulf of Riga (Figure 1). The data from this location for 1961–2018, together with similar data at Liepaja and Daugavgriva, enables the quantification of specific mechanisms that drive water level extremes in the Gulf of Riga. Doing so makes it possible to more reliably analyse the difference in water level in the Gulf of Riga (represented by Daugavgriva and Pärnu) and in the Baltic Sea proper (reflected by the data of Liepaja).

3.1. Elevated water levels in the Gulf of Riga

An example of the magnitude of the difference in water level in the Gulf of Riga compared to the Baltic proper is presented in Figure 12. The time slice from 05 to 25 January 1993 reflects one of the situations when the water level in the entire Baltic Sea was highly elevated apparently because a large amount of water was pushed into the sea through the Danish straits by a sequence of storms. A proxy of the water level of the entire sea can be obtained using an 8.25-day average of the local water level (Soomere et al., 2015b). This procedure is applied to water level recordings at Liepaja in Figure 12. As this measurement site is open to the Baltic sea proper, this average apparently mirrors well the sea level in the Baltic Sea.

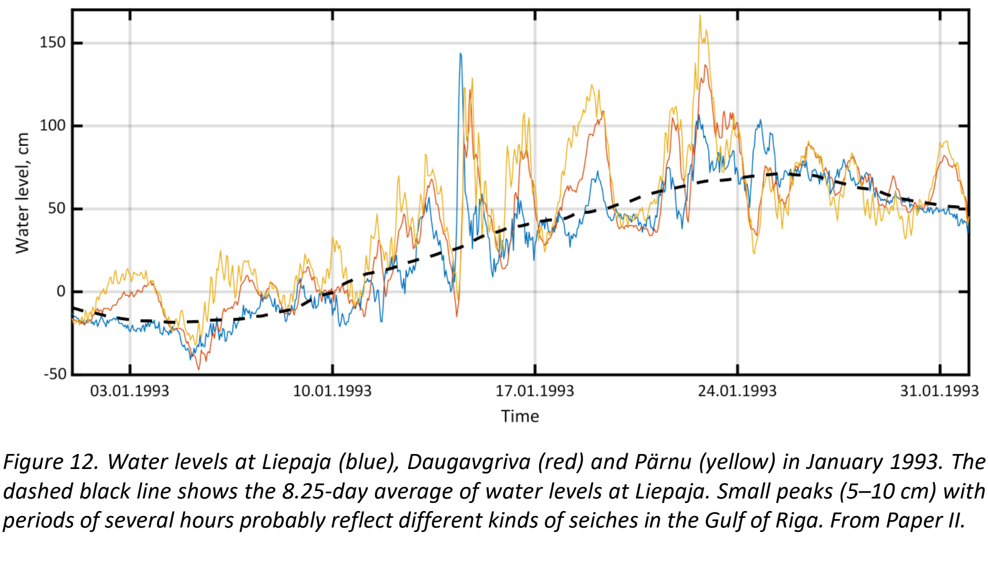


Figure 12. Water levels at Liepaja (blue), Daugavgriva (red) and Pärnu (yellow) in January 1993. The dashed black line shows the 8.25-day average of water levels at Liepaja. Small peaks (5–10 cm) with periods of several hours probably reflect different kinds of seiches in the Gulf of Riga. From Paper II.

A comparison of the data from Liepaja with water level recordings from Pärnu and Daugavgriva to some extent characterises the difference between the water level in the Baltic proper and the Gulf of Riga. Figure 12 demonstrates that the course of water levels at the two stations in the Gulf of Riga are often phase-locked and that the water level at Daugavgriva is usually lower than at Pärnu. These locations are open to different directions (north-west and south-west, respectively). Therefore, very high local storm surges are normally created by winds from different directions at these locations.

Figure 12 indicates the typical magnitude of the difference in the water level at the three sites. During certain short-term events (e.g., on 16 January, 18–19 January and 22 January), the highest water levels at Pärnu and Daugavgriva exceeded those in the Baltic proper up to 50 cm. Some recorded water levels were apparently caused by local effects or may simply be erroneous. For example a sudden spike (for 4 hours, about 80 cm) on 14 January 1993 in the water level at Liepaja may reflect local water level in the vicinity of the Liepaja measurement site (Paper I). The tide gauge is situated in the canal between the Baltic Sea and the Lake of Liepaja where water may be trapped. However, instrumental errors cannot be excluded.

Significantly elevated water levels of the entire Baltic Sea usually take a few weeks to develop (Lehmann and Post, 2015) and may persist up to a few months (Soomere and Pindsoo, 2016). These time scales reflect the ratio of the surface area of the Baltic Sea (393,000 km^2) and the flow rate of water through the Danish straits (with the narrowest cross-sectional area of about 0.35 km^2). This ratio is much (about 20 times) smaller for the Gulf of Riga (17,913 km^2) and Irbe Strait (0.37 km^2). Therefore, it is likely that the strongly elevated water levels in the Gulf of Riga with respect to the Baltic Sea proper develop and relax relatively rapidly. It is therefore not unexpected that the courses of water level in the Baltic Sea and Gulf of Riga are usually very similar and that substantial deviations of water level in the gulf from these in the Baltic proper occur only in specific conditions and over relatively short time intervals.

To verify and quantify this conjecture, the technique of cross-spectrum calculations was applied to quantify the similarities and differences between the recordings at the three stations. This approach relies on the evaluation of covariance between Fourier transforms of the relevant time series (von Storch and Zwiers, 1999). This technique shows the coherence of, and reveals the phase shift between, different time series of water levels. As expected, the changes in the water level at weekly and longer time scales are highly coherent. However, the pairwise coherence between recordings at all three stations are completely lost on timescales shorter than about 10 h. This threshold can be interpreted as the characteristic timescale of the duration of single storms in the gulf.

3.2. Separation of components of water levels

The example presented in Section 3.1 (Figure 12) shows that the Gulf of Riga may often host short events of strongly elevated water levels compared to the level of the Baltic Sea, equivalently, a short-time increase in its water volume. This feature may be one of the reasons for the presence of extremely high water level outliers in this water body (Suursaar and Sooäär, 2007). To further investigate the impact of this mechanism on the water level, the components of water level at different time scales are separated in Paper II using an approach developed in Soomere et al. (2015b).

The idea is to distinguish two longer time-scale processes: one that governs the water level in the Baltic Sea at weekly and longer scales and another that reflects the water level fluctuations in the gulf with a time scale of about 12 h. This is done by applying once or twice the moving averaging procedure. It is performed once using time series from Liepaja to separate the proxy of water volume of the entire Baltic Sea from the proxy of local storm surges (Soomere et al., 2015b). This procedure is applied twice on time series from Daugavgriva and Pärnu to determine also the proxy of water volume of the Gulf of Riga. First, a running average with an averaging length T_1 of about one week is applied to all time series of water level. By subtracting the averaged time series $\overline{W}_{T1}$ from the original time series W_i, the first residual $W_i^{(R1)} = W_i - \overline{W}_{T1}$ is obtained. The averaged time series $\overline{W}_{T1}$ is interpreted as a proxy of the water volume of the entire Baltic Sea.

To establish the signal of excess water in the Gulf of Riga, a running average with an averaging length T_2 of about one day is applied to the first residual $W_i^{(R1)}$. The resulting average $\overline{W}_{T1T2}$ is interpreted as a proxy of the excess water in the gulf. The second residual $W_i^{(R2)} = W_i^{(R1)} - \overline{W}_{T1T2}$ characterises local storm surges in this context. The separation is not perfect. For example, for sequences of storms the values of the proxy $\overline{W}_{T1}$ contain a certain contribution from local storm surges and the residual $W_i^{(R1)}$ reflects only a part of the local surge height (Soomere et al., 2015b). This problem intrinsically persists in the procedure of the specification of $\overline{W}_{T1T2}$ and $W_i^{(R2)}$ (Paper II).

The optimal averaging lengths T_1 and T_2 are evidently site specific. In particular, the values of T_1 around one week used for the shores of the Baltic proper (Soomere et al., 2015b) are generally not necessarily applicable for the Gulf of Riga where the development of excess water volumes is much faster than in the entire Baltic Sea. In essence, the proper length of T_1 or T_2 can be interpreted as a natural scale for the separation of short-term (daily scale) fluctuations of water level from the changes in the water volume of the entire sea or its specific sub-basin.

The optimal values of T_1 and T_2 can be identified from the shape of the probability distribution of the residual time series. This conjecture is based on the observation that, for a specific value of T_1, the empirical distribution of the frequency of occurrence of different values of the (first) residual $W_i^{(R1)}$ (that reflects the magnitudes of local storm surges) almost exactly follows a classic exponential distribution (Soomere et al., 2015b) with a probability density function $\sim\exp(\lambda_1 x)$. This feature gives rise to the option of using the scale parameter $-1/\lambda_1$ of this distribution to characterise the vulnerability of a particular shore section with respect to the local storm surge (Soomere et al., 2015b). Its values for positive and negative surges are usually different.

The procedure for separating the components is as follows. Both branches of the empirical distribution of the frequency of occurrence of different values of the residual $W_i^{(R1)}$ are approximated with a quadratic polynomial $ax^2 + bx + c$, where x has the meaning of the empirical probability of occurrence of given water level in the time series. Following the analysis in Soomere et al. (2015b), it is assumed that for the optimum value of T_1 the coefficient $a(T_1)$ at the leading term of this polynomial vanishes. The resulting timescales T_1 are 10, 9.5 and 9 days for Liepaja, Daugavgriva and Pärnu, correspondingly. These values of T_1 are by 1–2 days longer than established in Soomere et al. (2015b) for the southern coast of the Gulf of Finland. The relevant value based on the modelled water

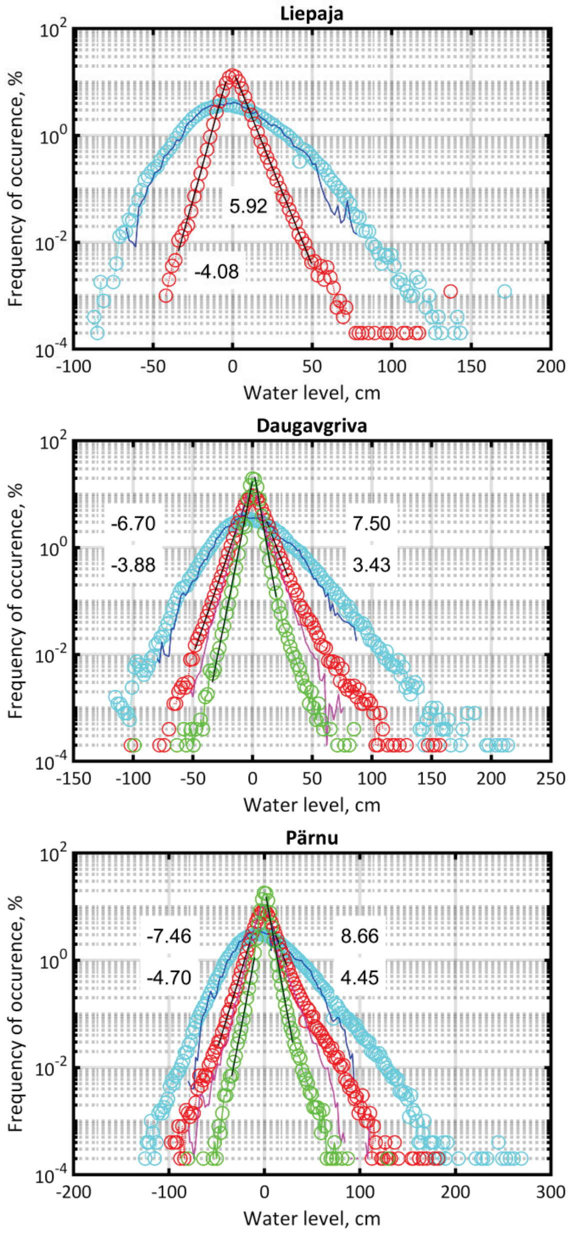


Figure 13. Empirical distributions of the frequency of occurrence of observed hourly water levels and first and second residuals 1961–2017 at Pärnu, Daugavgriva, and Liepaja. The second residual is not shown for Liepaja. Cyan, red and green markers show the distributions of the observed total water level and the first and second residuals, respectively. Blue and magenta lines show the similar distribution for the average water level for the total and first residual water levels, respectively. Black lines depict linear approximations of the residuals. Numbers on the figure indicate the values of the scale parameter $-1/\lambda_1$. The upper and lower values for the locations in the Gulf of Riga correspond to first (red) and second (green) residuals. From Paper II.

level time series in 1961–2005 from the Rossby Centre Ocean (RCO) model (Swedish Meteorological and Hydrological Institute) was $T_1 = 8.25$ days.

The scale parameters $-1/\lambda_1$ for the positive and negative branch of the residual $W_i^{(R1)}$ at Liepaja were 5.92 and –4.08, respectively (Figure 13). The similar values extracted from the output of the RCO model (Soomere et al., 2015b) were about 4.5 and –2.7, respectively. This difference indicates that the RCO model underestimates the probabilities of very low water levels near Liepaja. This conclusion applies also for Daugavgriva (where scale parameters retrieved from the observed and modelled data for the negative branch were –6.70 and –5.0, respectively) and Pärnu (–7.46 and –5.0, respectively).

The relevant values of the scale parameter $-1/\lambda_1$ extracted for the positive branch from the modelled data somewhat better match the similar values extracted from observed datasets at Daugavgriva (the values are 6.3 and 7.50, respectively) (Figure 13). The modelled and observed scale parameters for the positive branch of the data at Pärnu are 6.3 and 8.66, respectively.

A direct conjecture from this comparison is that the RCO model seems to underestimate the probability of very high and very low water levels at all study sites. The mismatches can be partially explained by the distance between the observation sites (e.g., in the city of Pärnu) and model grid points. The use of different time intervals (1961–2005 in the modelling) may also contribute to this mismatch. However, extensive mismatch of observation- and model-based estimates of certain statistical parameters of water levels seems to be quite usual in the study area (Soomere et al., 2018).

The observed water levels at all three sites generally follow a quasi-Gaussian distribution and contain a number of outliers (Figure 13). The quasi-Gaussian distribution is common in the nearshore of Finland (Johansson et al., 2001) and outliers are frequent on the Estonian (Suursaar and Sooäär, 2007) and Lithuanian coasts (Dailidienė et al., 2006). For the Pärnu measurement station, it is often assumed that the particular location of this tide gauge in the former water moat of the ancient fortification, kilometres away from open deep water, is the primary source of local effects and such outliers in the water level recordings (Eelsalu et al., 2014). The appearance of the relevant empirical distributions of water level at Daugavgriva suggests that such outliers are a common feature of the "climate" of water levels in the Gulf of Riga.

The tide gauge in Liepaja is located in the city centre, in the channel that connects the Liepaja harbour with Lake Liepaja. The location of the harbour is widely open to the Baltic Sea proper. The seabed near the harbour (and measurement site) deepens rapidly and water depth is 24 m at a distance of 1000 m of the shoreline. Thus it is likely that the first residual adequately quantifies the local effects. By applying an averaging interval of $T_1 = 10$ days, both (negative and positive) branches of the empirical probability distribution function of $W_i^{(R1)}$ become practically straight lines over several orders of magnitude in the log-linear representation. Similarly, the probabilities of negative surges follow an almost straight line for a particular value of T_1 in at Pärnu and also at Daugavgriva (Figure 13). This feature signals that both negative and positive branches of these distributions largely follow an exponential distribution.

The described procedure, if applied once, thus leads to a reasonable separation of the average water level from the signal of storm surges on the Baltic Sea shore of Latvia.

It determines acceptably (in terms of the above-mentioned criterion) the course of average water level during negative surges in the Gulf of Riga as well.

Notably, the positive branch of the first residual $W_i^{(R1)}$ (that represents positive surges) does not become almost straight for any value of T_1 at both Pärnu and Daugavgriva. This feature is interpreted in Paper II as an indication that elevated water levels in the interior of the Gulf of Riga are created by a more complicated mechanism and/or are affected by one further important driver, the impact of which can be possibly quantified by means of repetition of the described procedure.

To elaborate this idea, the analysis in Paper II relies on the assumption that high water levels in the gulf may occasionally contain another component that acts at an intermediate time scale longer than the duration of storms but shorter than about one week. A likely candidate for this mechanism is a two-step process of the formation of high water levels in the Gulf of Riga (Otsmann et al., 2001; Suursaar et al., 2002, 2003). The presence of this mechanism may cause mismatch in several statistical properties and trends of measured and modelled water levels at Pärnu (Soomere and Pindsoo, 2016).

To reveal the basic properties of this mechanism, the average $\overline{W}_{T1T2}$ of the first residual $W_i^{(R1)}$ is evaluated using running average over a time interval of T_2. A second residual $W_i^{(R2)} = W_i^{(R1)} - \overline{W}_{T1T2}$ of the course of water level at Daugavgriva and Pärnu is calculated using $\overline{W}_{T1T2}$. The use of the values $T_2 = 24$ and $T_2 = 22$ hours for Daugavgriva and Pärnu, respectively, leads to an almost straight line appearance of both branches of the empirical probability distribution of the second residual over at least two orders of magnitudes (Figure 13). The described procedure thus makes it possible to separate to some extent processes with a time scale of 1–2 days (including the events of large excess water volume in the Gulf of Riga) from the course of weekly average water level and from even shorter storm surge events.

As mentioned above, the separation of these three processes is not perfect. The resulting negative branches are almost straight over more than three orders of magnitude whereas the positive braches are almost straight over 1.2–2 orders of magnitude. Hence, the relevant distributions of short-term water level depressions may be adequately approximated with the exponential distribution $\sim\exp(\lambda_2 x)$. Similar to the above, the parameter λ_2 (or scale parameter $-1/\lambda_2$) could be used to characterise the vulnerability of the coastal areas with respect to locally elevated water levels created by relatively short processes (e.g., storm surges or seiches).

Figure 13 also reveals that multi-weekly changes in the water volume in the Baltic Sea alone may add up to 1 m to the average water level at Pärnu (considering differences the between observed water level and its first residual). As the monthly mean water level of the entire Baltic sea only very infrequently exceeds the long-term average by ≥0.5 m (Johansson and Kahma, 2016), events with the entire Baltic Sea water level ≥0.5 m usually last no longer than 2–3 weeks.

The data presented in Figures 12 and 13 suggest that mechanisms acting at shorter time scales may substantially add to the water level in the entire Gulf of Riga. A comparison of the empirical probability distributions of the first and second residual (Figure 13) signals that the excess water pushed into the gulf for 1–2 days may elevate the water level in the entire gulf by about 1 m compared to the water level in the Baltic proper (Paper II).

As the proxy of storm surges (the second residual for Daugavagriva and Pärnu data) often reflects only a part of the surge height, it is likely that the strongest local storm surges may push water level another 1 m higher as demonstrated by Suursaar et al. (2003).

Even though all three described mechanisms may be active simultaneously or subsequent to one another, it is not likely that they will provide their maximum possible contributions synchronously. However, their perfect synchronisation is also not excluded, as Suursaar et al. (2006) have estimated, the maximum water level at Pärnu in the worst case scenario may reach 3.5 m.

The multi-step method applied in Paper II for distinguishing the contribution of physical mechanisms with different typical time scales that influence water levels can also be applied for the analysis of similar processes in other water bodies. The derived parameters of the relevant exponential distributions can be used in various coastal management tasks.

3.3. Episodes with substantially different water levels

An important characteristic of the water level regime of the Gulf of Riga is the duration of situations when the local water level in the gulf is considerably lower or higher than in the Baltic proper. To analyse the related properties, a water level difference D within and outside the gulf is defined in Paper II as follows:

$$\begin{cases} D_D^{(t)} = W_D^{(t)} - W_L^{(t)}, \text{ if } \left|W_D^{(t)} - W_L^{(t)}\right| > D_{lim} \\ D_D^{(t)} = 0, \text{ if } \left|W_D^{(t)} - W_L^{(t)}\right| \le D_{lim} \end{cases}, \quad (1)$$

$$\begin{cases} D_P^{(t)} = W_P^{(t)} - W_L^{(t)}, \text{ if } \left|W_P^{(t)} - W_L^{(t)}\right| > D_{lim} \\ D_P^{(t)} = 0, \text{ if } \left|W_P^{(t)} - W_L^{(t)}\right| \le D_{lim} \end{cases}. \quad (2)$$

Here $W_D^{(t)}$ is the instantaneous water level at time instant t in at Daugavgriva, $W_P^{(t)}$ at Pärnu, $W_L^{(t)}$ at Liepaja, and D_{lim} is an arbitrarily chosen threshold. The quantity D is chosen to analyse the frequency and magnitude of systematic differences in water level in the Gulf of Riga and the Baltic Sea proper on scales from an hour up to 1–2 days. By using absolute values in expressions (1) and (2) it is possible to evaluate properties of both high and low water levels in the Gulf of Riga compared to the reference level at Liepaja.

The difference in the long-term average of measured data from the zero value is 2.1 cm at Liepaja, 5.2 cm at Pärnu and 9.4 cm at Daugavgriva (Paper II). The typical uncertainty of individual measurements is ~0.7 cm for the recordings at Daugavgriva, ~1.2 cm at Liepaja, and ~1.6 cm at Pärnu (Paper II). Therefore, a difference less than about 10 cm in readings of different tide gauges does not necessarily mean a different water level in the Gulf of Riga.

To reduce the impact of possible minor observational errors and described difference in the long-term average water levels on the results of the analysis, the minimum threshold D_{lim} was set to 10 cm. If this threshold D_{lim} was not reached, the relevant variable reflecting the presence of an episode of elevated or depressed water level in the gulf was set to zero. By varying the values of D_{lim}, it is possible to generate different sets of episodes of water level differences that correspond to thresholds beyond which specific threats will be realised on the shores of the Gulf of Riga.

Using a set of specific values of D_{lim}, events of different water levels in the Baltic Sea proper and in the Gulf of Riga are highlighted in Paper II. Each resulting episode of water level difference has a clearly defined starting instant (when the difference exceeds D_{lim}), duration, and course. This set of properties makes it possible to evaluate the basic characteristics (e.g., maximum, minimum, and mean difference) of such episodes for different thresholds and also to study temporal changes in the relevant sets.

The number of episodes and the parameters of single episodes of low or high relative water level for Pärnu and Daugavgriva are different. The distributions of the frequency of occurrence of episodes with different durations are also different for those two stations. Both relatively low and high water levels compared to the open Baltic Sea are more persistent at Pärnu (Figure 14). For example, the water level could be more than 50 cm higher for up to 1.5 days at Pärnu than at Liepaja, whereas at Daugavgriva, the corresponding length of time does not reach 1 day. This dissimilarity apparently reflects

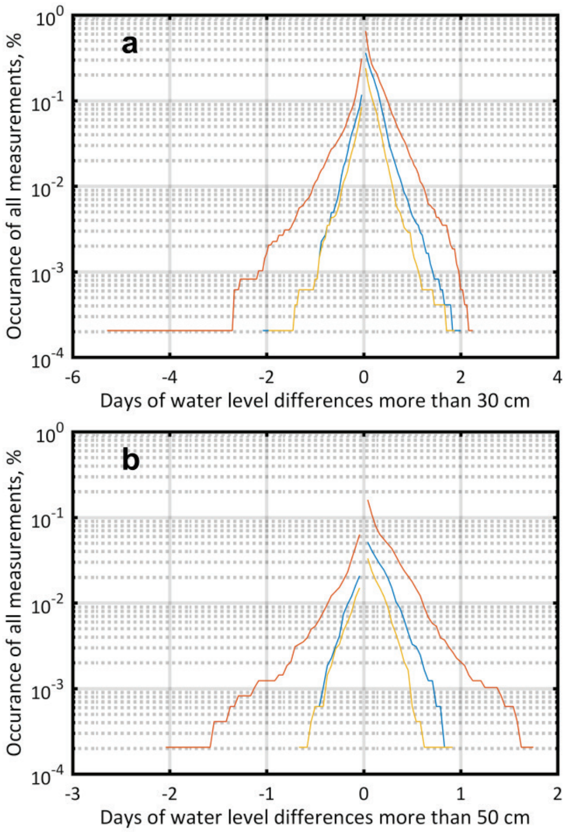


Figure 14. The frequency of occurrence of episodes of water level differences with a different duration between Liepaja and stations in the Gulf of Riga. a) episodes with water level difference $D_{lim} = 30$ *cm, b)* $D_{lim} = 50$ *cm. Red line: the probability of episodes when water level at Pärnu and Liepaja is different, blue: the same for Daugavgriva and Liepaja. The yellow line depicts the difference between the minimum/maximum value of the Gulf of Riga (Daugavgriva/Pärnu) and Liepaja. Negative values on the* x*-axis represent the duration of episodes when water levels in the Gulf of Riga are lower than at Liepaja. From Paper II.*

the difference in the location of these tide gauges. Pärnu Bay is open to the predominant south-west winds that often push water masses into the shallow-water bay for extended periods of time. The location at Daugavgriva is open to the north-west and the seabed in the vicinity of the measurement site deepens much more rapidly than in Pärnu Bay. However, water levels at both stations could be more than 50 cm higher than at Liepaja for more than half a day.

3.4. Changes in the properties of episodes of large water level differences

Large deviations of the water level in the Gulf Riga from the background water level in the Baltic proper are apparently created by relatively strong winds and usually occur during the comparatively windy months. It is therefore likely that changes to properties of these deviations are better expressed in quantities that are evaluated for stormy seasons as defined in Section 2.1 rather that in terms of such quantities evaluated for calendar years.

Based on this conjecture, the temporal changes in the water level differences between the gulf and open Baltic Sea are analysed in Paper II in terms of stormy seasons (from July to June of the subsequent year) for all three observation stations. For each stormy season the differences between water level at Pärnu and Liepaja, and between Daugavgriva and Liepaja, were evaluated using different thresholds D_{lim} in Paper II.

If the threshold is fairly small (10 cm), the number of episodes of water level difference is, on average, 300–400 during each stormy season (Figure 15). In other words, such events happen almost daily. It is likely that a large proportion of these episodes corresponds to local variations in the water level and does not reflect events of increased water volume in the gulf.

The temporal course of the number of such episodes is different for Dauvgavgriva and Pärnu. While the count of such episodes in records from Daugavgriva and Liepaja is almost constant over time, the count for Pärnu and Liepaja has decreased by a factor of two in the period 1961–2018.

A similar pattern of changes is evident in the number of episodes where the water level at a station of the Gulf of Riga exceeds that at Liepaja by >30 cm. The long-term annual average of episodes with this difference is 46 for Daugavgriva and 80 for Pärnu. While the count of such episodes is again almost constant at Daugavgriva (Figure 15b), the number of such events at Pärnu has decreased by a factor of 1.6. This decrease is statistically significant at a 95% level (Paper II).

The described dissimilarity in the temporal course of the number of episodes of higher water levels at the two measurement sites in the Gulf of Riga can be attributed to the properties of the locations of tide gauges at Daugavgriva and Liepaja. Substantially elevated water levels at Daugavgriva compared to Liepaja usually occur during relatively strong west and north-west winds. These winds may push additional water into the Gulf of Riga and may also create local surge in the vicinity of the Daugava River mouth. Theoretically, strong winds from the north-north-east could keep the water level high at Daugavgriva and lower it at Liepaja, but such winds are infrequent in the northern Baltic Sea (Soomere et al., 2008b).

Consequently, the persistent number of episodes of elevated relative water levels at Daugavgriva may signal that the annual average number of strong westerly and north-westerly winds has not significantly changed since the 1960s. This conjecture is consistent with the perception that storminess in the Baltic Sea region has not robustly changed during the 20th century (Bärring and von Storch, 2004).

The water level at Pärnu is very sensitive with respect to the wind direction (Suursaar et al., 2003). High water levels at Pärnu (including the occasions where water level is higher than at Liepaja) are mostly caused by south-westerly winds. Such winds push water into the relatively shallow Pärnu Bay but affect much less the water level along the open Baltic Sea coast of Latvia.

The substantial decrease in the number of episodes of large water level differences between Liepaja and Pärnu therefore signals that the annual average number of strong south-west wind episodes has considerably decreased since the 1960s. This change may be caused by systematic rotation of wind directions in the Baltic Sea region (e.g., Soomere et al., 2015a; Kudryavtseva and Soomere, 2017). This feature may reflect a shift in the typical trajectories of cyclones that cross this water body (Post and Kõuts, 2014).

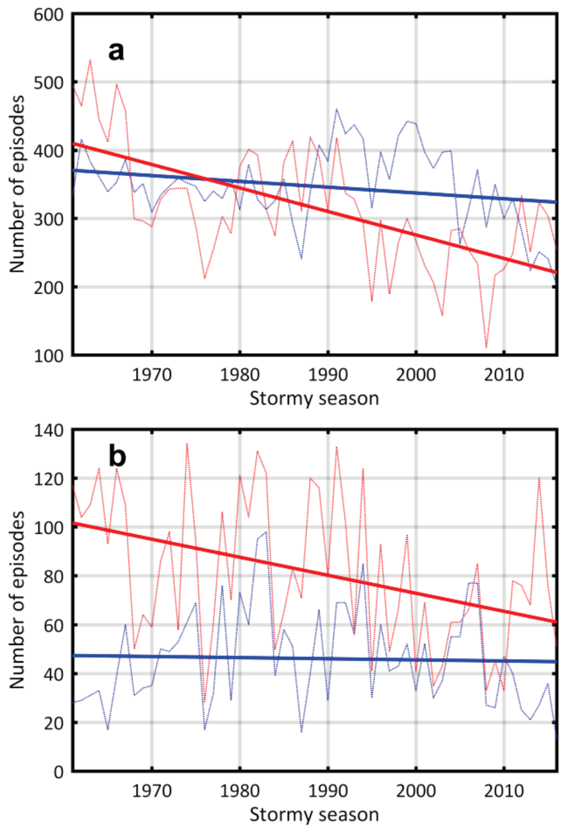


Figure 15. The number of episodes of differences between the water level at Liepaja and at stations in the Gulf of Riga from July to June of the subsequent year: a) $D_{lim} = 10$ cm, b) $D_{lim} = 30$ cm. Blue thin lines represent the number of such differences between the water level at Daugavgriva and Liepaja and red thin lines between Pärnu and Liepaja. Solid bold lines indicate the respective linear trends. From Paper II.

3.5. Magnitude of water level differences

The analysis in Section 3.4 only considers the count of episodes when the water level at stations in the Gulf of Riga exceeds the readings at Liepaja by a certain value, and does not take into account the duration of such events or the actual magnitude of the difference. Further information about such events is acquired in Paper II by means of the analysis of the sum M of all single (hourly) values of $D_D^{(t)}$ or $D_P^{(t)}$ over the entire duration of each event in Eq. (1) and (2). This quantity integrates in a simple manner, both the duration of the events and the actual difference in the water level between the Baltic Sea proper and the Gulf of Riga. The dimension of M is [s × m] whereas in Paper II, for simplicity, the unit [days × cm] is applied. As elevated water levels are created by west and north-west winds, the magnitude of water level differences M characterises the impact of atmospheric forcing on water levels in the Gulf of Riga.

For the threshold $D_{\text{lim}} = 30$ cm, the quantity M weakly decreases for both elevations and depressions of water level at Daugavgriva (Figure 16). The data set from Pärnu reveals

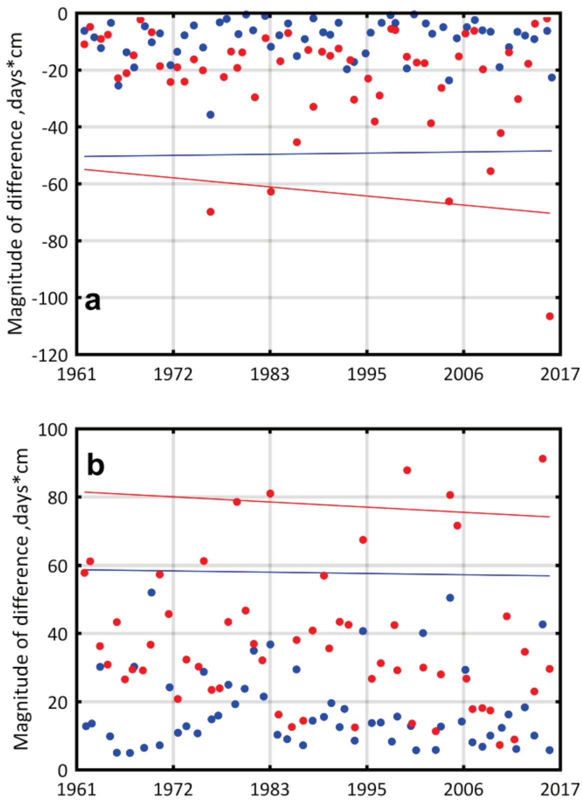


Figure 16. Maximum magnitudes of episodes of water level difference and their trendlines at Daugavgriva $D_D^{(t)}$ (blue) and Pärnu $D_P^{(t)}$ (red) for a) low water levels, b) high water levels during stormy seasons. The threshold for the difference between the observed values at Liepaja and at sites in the Gulf of Riga is for both cases $D_{lim} = 30$ cm. Trendlines are shifted vertically by 40 units for better readability. From Paper II.

a fast increase in the magnitude of depressions but a slight decrease for the "magnitude" of elevations. The trends are not statistically significant and the typical annual maximum magnitude of episodes of water level differences between the Gulf of Riga and the Baltic Sea proper has remained practically unchanged since the 1960s (Figure 16). Other choices of the threshold D_{lim} lead to the same qualitative pattern of temporal changes for the quantity M. These results hint that no substantial increase in (strong) wind speeds has occurred in the study area and in its vicinity. A slight decrease in the magnitude M of the episodes of water level differences at Pärnu and Liepaja may be also interpreted as reflecting an increase in the persistence of storm and weather patterns in the study area (Rutgersson et al., 2014).

The largest differences in the water level between Pärnu/Daugavgriva and Liepaja (Figure 17) within a single stormy season may extend from almost –120 cm (in 1991 and 1999) to at least 150 cm (in 1967) or >130 cm (in 2005). The data in Figure 17 also reveals that events that push very large amounts of water into the Gulf of Riga (so that its water level exceeds that at Liepaja by more than 100 cm) irregularly occur once in 5–10 years.

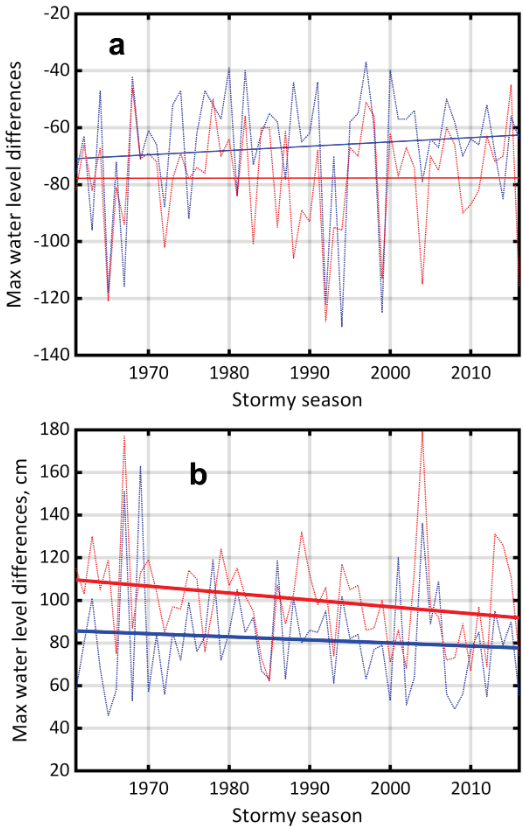


Figure 17. Largest water level differences during stormy seasons between Liepaja and Daugavgriva (blue) or Pärnu (red) shown as thin lines. Bold lines represent trends. a) low water levels in the Gulf of Riga, b) high water levels in the Gulf of Riga. The trendline for high water level differences (panel b) between Pärnu and Liepaja is significant at a 95% confidence level. From Paper II.

It is likely that such occasions correspond to situations presented in Figure 17 when high relative water levels are observed both at Daugavgriva and Pärnu.

The stormy season maxima of differences in the water levels have slightly decreased in the period 1961–2018 (Figure 17b). The relevant trends are statistically insignificant. Similarly, the stormy season absolute values of the minima of such differences (that is, the magnitudes of very low levels at both locations) have become smaller (Figure 17a). These features suggest that wind speed has not increased in storms that cause very high and low relative water levels in the Gulf of Riga.

4. Water-level-adjusted closure depth

This chapter explores some implications of the specific features of the dynamics of water level (in particular, the frequent co-presence of elevated water levels and strong waves) on the main properties of beaches in the eastern Baltic Sea. The analysis is based on modelled water level and wave properties and thus involves a shorter time interval (1970–2005) than the previous chapters. It addresses the possible dependence of closure depth on the properties of water level.

The closure depth (Nicholls et al., 1996) marks the location in the nearshore, down to which shoaling waves often move bottom sediments and continuously maintain a specific profile (often called the equilibrium beach profile; Dean, 1991). As the strength of the wave-seabed interaction depends on both wave properties and water depth (Dean and Dalrymple, 1991), changing water level owing to tides or during storm surge causes the surf zone to move land- or seaward. Tidal-driven changes in the water level usually do not affect the closure depth as high waves may reach the shore during any tidal phase. However, systematic synchronisation of elevated or depressed water level and high waves may to some extent modify the closure depth with respect to the long-term average water level on microtidal shores.

The analysis in this chapter focuses on the potential impact of such a synchronisation of waves and water level on the closure depth along sedimentary shores of the eastern Baltic proper, including two large semi-enclosed sub-basins – the Gulf of Riga and the Gulf of Finland (Figure 18). The study area covers about 1400 km from the Sambian (Samland) Peninsula (20°E, 55°N) to the eastern Gulf of Finland (28°E, 59°51′N). This stretch covers the entire nearshore of Lithuania, Latvia (including the Gulf of Riga) and Estonia, and includes part of the shores of Russia in the Kaliningrad District. The central idea is to calculate water-level-adjusted closure depth along this coastal stretch. The difference of this quantity from the classic closure depth indicates the areas in which strong waves systematically occur during high or low water levels. The analysis follows the material in Paper III.

4.1. Reconstruction of wave and water level properties

The hourly time series of significant wave height and peak period in the Baltic Sea for 1970–2007 were extracted for this analysis from calculations with the wave model WAM (Komen et al., 1994), undertaken by Dr. Andrus Räämet (Räämet and Soomere, 2010). The model used a regular grid with spatial resolution of $3' \times 6'$ (lat × long, about 3×3 nautical miles), a directional resolution of 15° and 42 wave frequencies ranging from 0.042 to 2.08 Hz and arranged in a geometric progression with an increment of 1.1 (that is, 0.042, 0.0462, 0.05082 Hz, etc.).

The simulations were forced with a wind data set extracted from the Swedish Meteorological and Hydrological Institute (SMHI) geostrophic wind database. To adjust geostrophic winds to standard height of 10 m, the wind speed was multiplied by 0.6 and wind direction was turned counter-clockwise by 15° (Bumke and Hasse, 1989). The presence of sea ice is ignored. The accuracy of the wind forcing and the reliability of the wave model output are discussed, e.g., in Soomere and Räämet (2011, 2014). The resulting wave heights were systematically underestimated by about 10%. This underestimation may to some extent affect the values of the water-level-adjusted closure depths but does not invalidate the main message of the analysis.

The study area was divided into 222 about 5.5–6.5 km long nearshore sections. The majority (154 out of 222, about 950 km) of the sections follow the shore of the Baltic proper and the Gulf of Finland. Another set of 68 sections covers the entire nearshore of the Gulf of Riga, with a length of about 450 km. The resulting spatial resolution of 5–6 km characterises acceptably the properties of waves in the nearshore along relatively straight sections of the study area in the nearshore of Latvia and Lithuania. The depths of the grid cells of the wave model (Figure 18) were chosen between 7 and 48 m, in order to avoid wave breaking in shallow water.

This resolution is insufficient in the locations dominated by smaller morphological elements such as the northern coast of Estonia where the typical spatial scales of straight sections of the shoreline are <1 km (Raukas and Hyvärinen, 1992; Soomere et al., 2008a). To examine the properties of spatial variation in the water-level-adjusted closure depth in

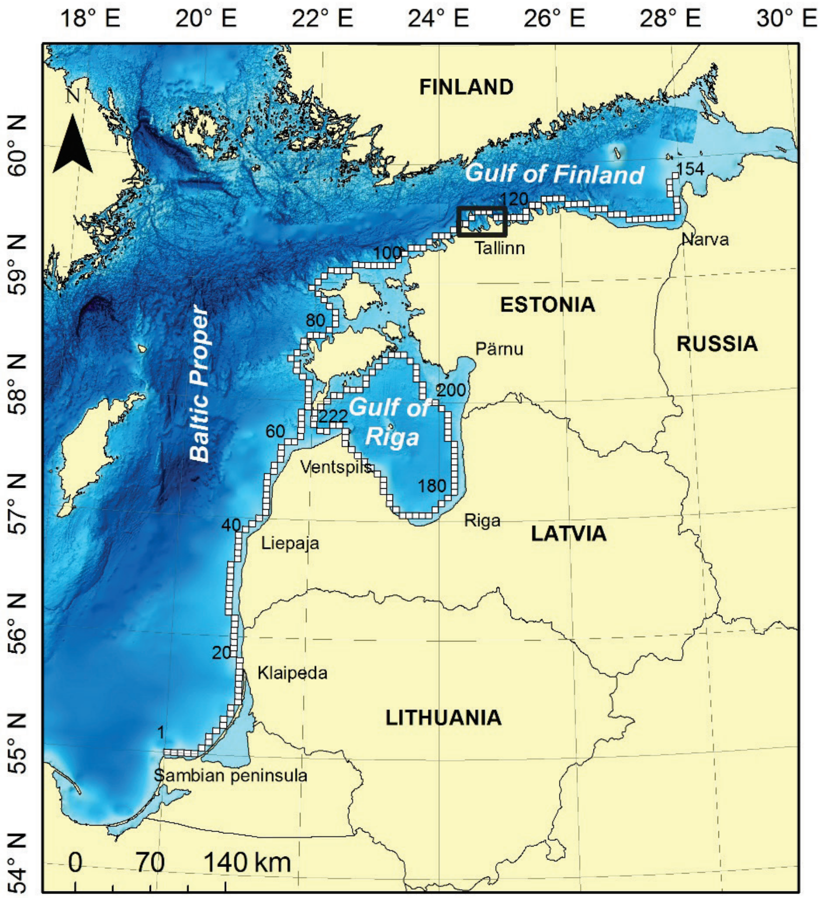


Figure 18. Grid points of the wave model used to evaluate the nearshore wave statistics and closure depth for relatively straight coastal sections and in locations open to the offshore. The box indicates the detailed study area in the vicinity of Tallinn Bay. From Paper III.

such areas with complicated geometry, an example of calculations with a higher resolution of about 0.5 km is performed for Tallinn Bay (Figure 18 and Figure 19). Wave properties in this area were estimated using a triple-nested version of the WAM model for the years of 1981–2014. The wave parameters were evaluated based on pre-computed maps of wave parameters (Soomere, 2005).

To develop such maps, a coarse version of the WAM model was first applied to the entire Baltic Sea. The output of this model served as an input to determine wave properties at the entrance to the Gulf of Finland. The WAM model was run with a grid step of about 1.8 km in the gulf. Finally, a higher-resolution (about 470 m) version of the WAM model resolved the major geometric and bathymetric features of the Tallinn Bay area.

The wave models for Tallinn Bay were forced with a spatially homogeneous wind field that followed measured wind properties from Kalbådagrund, a caisson lighthouse in the central part of the Gulf of Finland (59°59′N, 25°36′E). This measurement station was selected because the wind properties in this location are practically not affected by the presence of mainland. Since the measurement point lies at 32 m above the mean sea level, the wind speed values were corrected to standard height of 10 m by a factor 0.85 as recommended in (Launiainen and Laurila, 1984; Soomere, 2005).

The water level data for the entire nearshore of the study are were extracted from the output of the Rossby Centre Ocean (RCO) model. This model covers the entire Baltic Sea with a temporal resolution of 6 hours and for 45 years (May 1961–May 2005). Its horizontal and vertical resolution (2 × 2 nautical miles and 3–12 m for layer thickness, respectively) are commonly considered to be acceptable for the reproduction of the water levels in the

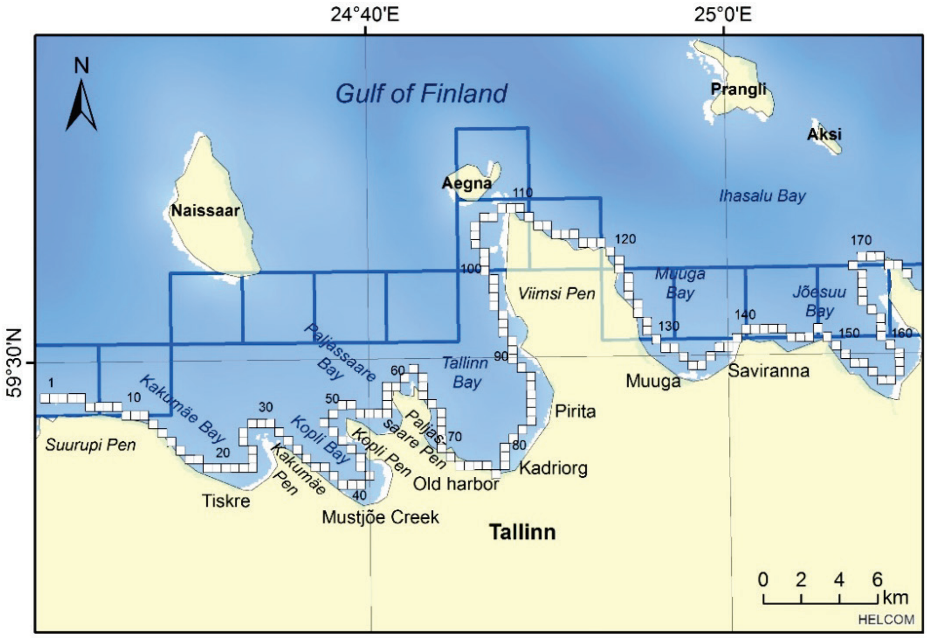


Figure 19. Grid cells of the fine-resolution version of the WAM model used for the evaluation of wave properties in the nearshore of Tallinn Bay (small white squares) and nearshore grid cells of the RCO model (large blue squares). From Paper III.

eastern Baltic Sea (Meier et al., 2004). Detailed descriptions of this model are presented in (Meier et al., 2003; Meier and Höglund, 2013). The model used a meteorological data set with a horizontal resolution of 22 km derived from the ERA-40 re-analysis (Samuelsson et al., 2011). For a particular segment of the nearshore the water levels were taken from the closest model cell for the time instant closest to the timeline of wave properties.

The spatial resolution of the RCO model (2 nautical miles) is better than the resolution of the WAM model (3 nautical miles) for Latvian and Lithuanian waters. For the Tallinn Bay area one cell of the RCO model provided water level information for 8–10 segments of the nearshore (Figure 19). As the interior of Tallinn Bay is not resolved in the RCO model, the values of water level in one of its cells in the outer region of Tallinn Bay were applied to about 40 segments of the nearshore of the WAM model.

4.2. Longshore variations in classic and adjusted closure depths

The core idea in Paper III is to take systematically into account the impact of high water levels during strong storms on the active part of beach profile. The values of closure depth are usually calculated from statistical properties of the roughest seas. Differently from this approach, a time series of instantaneous values of wave properties are used to evaluate closure depth in Paper III with respect of the long-term mean sea level. This quantity h_c (also called 'classic closure depth' below) is usually evaluated from the wave conditions that persist 12 hours a year (USACE, 2002):

$$h_c = p_1 H_{S,0.137} - p_2 \frac{H_{S,0.137}^2}{g T_S^2}. \tag{3}$$

Here $H_{S,0.137}$ is the threshold for the most severe significant wave height that occur 12 hours a year and T_S is the typical peak period of such seas. An application of expression (3) therefore only requires the information about the statistical properties of wave fields that are present in this expression. Two sets of values of coefficient in expression (3) are commonly used. The use of values $p_1 = 2.28$, $p_2 = 68.5$ (Hallermeier, 1981) is appropriate for the southern Baltic Sea (Cerkowniak et al., 2015a, b). The values $p_1 = 1.75$, $p_2 = 57.9$ (Birkemeier, 1985; Houston, 1996) tend to yield smaller closure depths than those obtained from the field data (Cerkowniak et al., 2015b).

The main idea of estimates of water-level-adjusted closure depths in Paper III relies on linking each entry of the time series of wave properties with the relevant entry of the water level time series. This link is introduced in Paper III by means of inclusion of the instantaneous deviation of the water level w_t from the long-term average into the calculation of closure depth. Formally, Eq. (3) is modified as follows:

$$h_{cwt} = p_1 H_{St} - p_2 \frac{H_S^2}{g T_t^2} - w_t, \tag{4}$$

where t indicates the particular time instant. The same formula without the influence of the water level would be:

$$h_{ct} = p_1 H_{St} - p_2 \frac{H_{St}^2}{g T_t^2}. \tag{5}$$

The formal difference of Eq. (5) from Eq. (3) is that H_{St} is the significant wave height at time instant t and T_t is the peak period at this time instant. A substantial difference in using Eq. (4) is that the values of the water-level-adjusted closure depth are evaluated as the threshold that is reached or exceeded by the values of h_{cwt} for 12 hours of the year. In other words, instead of application of a certain statistical property (12 hours' severest wave conditions used in Eq. (3)), the water-level-adjusted closure depth is found from the largest examples of the entire time series of h_{cwt} estimated using Eq. (4) based on instantaneous values of wave properties and water level. By construction, a comparison between the results of two approaches gives an indication of the effect of water level on closure depth.

The calculations were carried out as follows. First, the classic closure depths (without taking into account the instantaneous water level) were calculated with a time step of 1 hour for the Baltic proper, Gulf of Riga and Gulf of Finland, and with a time step of 3 hours for Tallinn Bay using Eq. (5). This procedure was followed by a calculation of the set of values of h_{cwt} with the same resolution and with application of the associated water level time series using Eq. (4). The water level information (once in 6 hours) was linearly interpolated in time to provide approximate instantaneous values for time instants of wave properties. An estimate for the adjusted closure depth for a typical year was found as the average of 0.137%-iles of h_{cwt} for single years of the simulation. Alternatively, an estimate of adjusted closure depth was derived as the 0.137%-ile of the entire set of h_{cwt} over all years.

The results presented here rely exclusively on numerical experiments. Their spatial resolution is evidently not sufficient for an exact representation of the processes in the immediate nearshore where local effects may play a significant role. Therefore, there is a

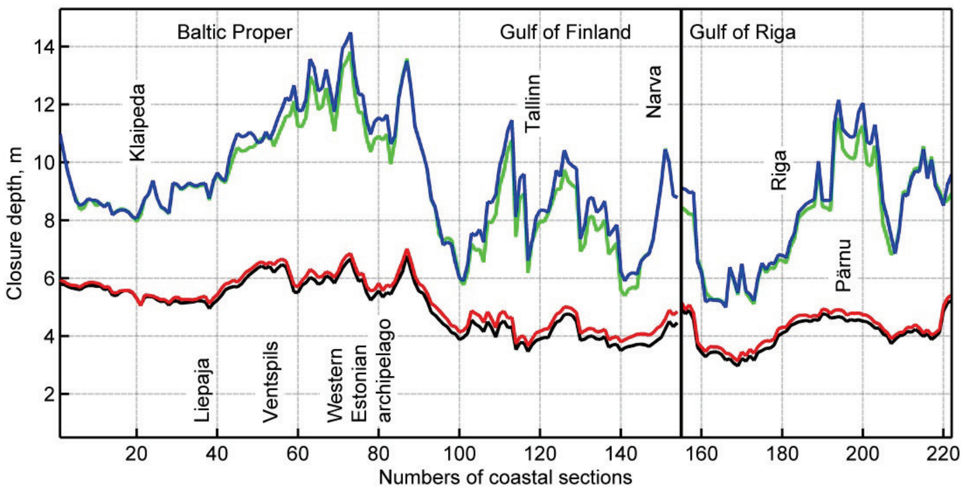


Figure 20. Closure depths evaluated using Eqs. (3), (4) and (5) with $p_1 = 1.75$, $p_2 = 57.9$ along the entire eastern coast of the Baltic Sea with a resolution of 3 nautical miles (left panel) and in the nearshore of the Gulf of Riga. Blue: maximum 'instantaneous' closure depth; Green: the same but adjusted with water level; red: closure depth from Eq. (3) based on the 0.137%-ile (12 hours a year) of wave height and the associated wave periods; black: closure depth from 0.137%-ile of the values of h_{cwt} in Eq. (4). From Paper III.

need to support the conjectures and evaluate the magnitude of local effects from actually measured data.

The largest closure depths (5–7 m) are along the open coasts of the Baltic Sea. The maxima are found at the coasts of the Western Estonian Archipelago and near Ventspils (Figure 20). The eastern shore of the Gulf of Riga and southern coast of the Gulf of Finland have clearly smaller values. The smallest closure depths are in the western Gulf of Riga (down to 3 m) and along those coastal segments of the Gulf of Finland that are open to the north-east or east (about 4 m).

The maxima of instantaneous values of h_{ct} in Eq. (5) have much larger variation along the study area. The difference between closure depths for a single coastal section and the maxima of h_{ct} are about 2.5 m along the northern coast of the Sambian Peninsula, the Lithuanian coast and near Liepaja (Figure 20). This difference increases further to the north near Ventspils, to almost 8 m for some segments of the shore of the Western Estonian Archipelago, and goes down to below 2 m for some segments of the southern shore of the Gulf of Finland but increases up to 7 m in some sections of this shore (Figure 20). This extensive variation signals that waves may strongly impact the seabed down to 14 m in specific segments of the shores of the Western Estonian Archipelago and down to 10–11 m in some sections of the southern shore of the Gulf of Finland. In some segments, the maxima h_{ct} in question by more than a factor of two exceed the estimate of the closure depth.

This large difference between the maxima of h_{ct} and the closure depth demonstrates that extreme wave conditions that impact deeper sections of the seabed only persist for a short time. In essence, it mirrors the infrequent presence of very severe seas with long wave periods during short time intervals. This conjecture is in line with the outcome of studies into wave energy potential of the eastern Baltic Sea, namely, that a significant amount of wave energy arrives to the shores of the study area over very short time intervals (Soomere and Eelsalu, 2014). This feature, however, also signals that strong wave-driven impacts to the seabed may sometimes occur at much deeper than the closure depth. In other words, this also signals that the closure depths calculated for the Baltic Sea using Eq. (3) should be interpreted as indicative, as very strong (albeit short) wave storms may move large sediment volumes in deeper areas than the classic closure depth suggests.

4.3. Impact of water levels on closure depths

The relative differences between classic and water-level-adjusted closure depths are almost zero on the Sambian Peninsula, along the Curonian Spit and on the mainland coast of Lithuania (Figure 21). This is because high waves often occur in these locations when the water level is close to (or even below) the long-term average.

This result is consistent with the presence of two-peak directional distribution of strong winds in the open Baltic Sea. Moreover, north-west storms do not necessarily produce high water levels along these coastal sections. Hence, high water levels and waves are not specifically synchronised in these coastal sections.

The difference between the classic and water-level-adjusted closure depth is between 2% and 8% along the Latvian coast and in the Gulf of Riga (Figure 21). The coasts in the open Baltic Sea area are predominantly straight and oriented in the North–South direction.

Strong winds usually blow from the south-west or north-north-west. Therefore it is not common to have storms that blow directly onshore to create very high water levels in these coastal sections.

The difference is slightly more pronounced in the Gulf of Riga but still leads to a generally insignificant decrease by no more than 8% from the classic closure depths to water-level-adjusted closure depths. Larger values of differences in the Gulf of Riga apparently reflect frequent situations when water is pushed into the gulf by west winds resulting in higher water levels than in the eastern Baltic proper, as described in Chapter 2.

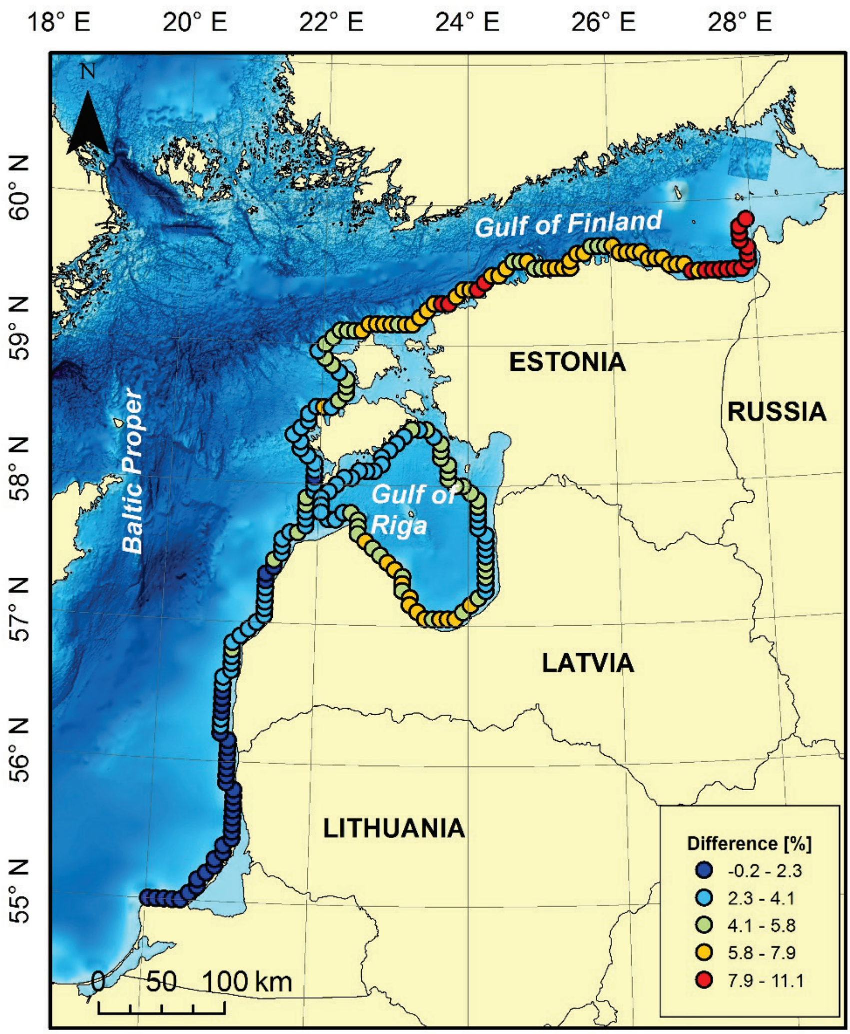


Figure 21. The relative difference (%) between the classic and adjusted closure depths along the eastern Baltic Sea coast evaluated using Eq. (3) and (4, 5) with $p_1 = 1.75$, $p_2 = 57.9$. The classic closure depths have been extracted from Soomere et al. (2013). From Paper III.

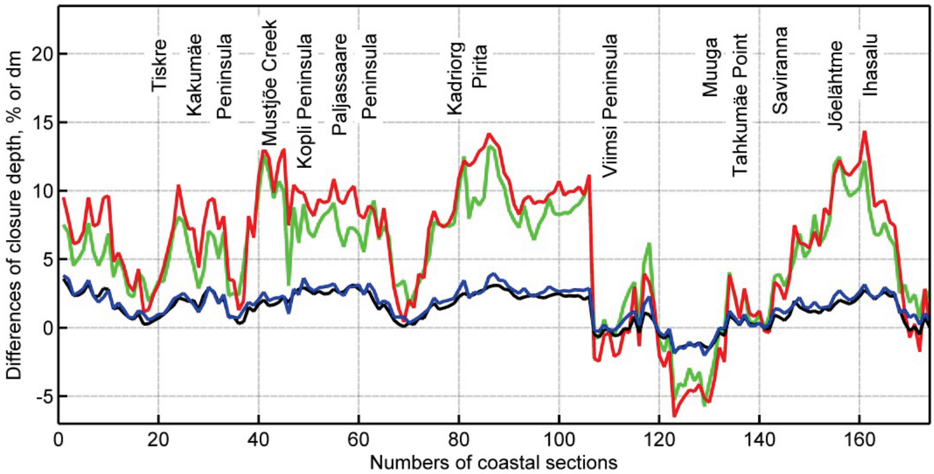


Figure 22. Relative (% of the adjusted closure depth) and actual (decimeters, dm) difference between classic and adjusted closure depths evaluated using Eqs. (3) and (4, 5) with $p_1 = 1.75$, $p_2 = 57.9$ in the vicinity of Tallinn. The classic closure depths have been extracted from Soomere et al. (2013). The notations are the same as for Figure 20. Note the characteristic jump from relatively large positive values in areas of the Viimsi Peninsula open to the west or northwest to negative values of the same magnitude in areas open to the east. From Paper III.

The widest relative differences between water-level-adjusted and classic closure depths in this spatial resolution are on the shores of the Gulf of Finland (up to 11% near Narva). These sections are therefore strongly affected by the frequent co-presence of high water levels and severe seas. Classic closure depths are considerably larger than the adjusted closure depths in sections that are open to the west or north-west.

Higher-resolution simulations demonstrate that the estimated differences may be significantly larger in single segments of the coast. Simulations in the Tallinn Bay area reveal that these relative differences may reach 15% at locations that are open to the west (Figure 22). In this area, it is characteristic that many bayheads are sheltered from predominant wind directions (Soomere et al., 2008a). Consequently, beach profiles are not necessarily fully developed in several sections that have not experienced severe waves over longer time periods. In other words, this effect implicitly damps the intensity of coastal erosion during time periods when this kind of synchronisation is effective. However, a strong storm from an unfavourable direction may lead to rapid deposition at their seaward ends and erosion of the coastal scarp.

The described fairly large difference between the classic and water-level-adjusted closure depths means that the probability of such events to widen the effective width of the underwater part of the beach profile is relatively small and less sediment is required to build it. Hence, the amount of sand fill for beach nourishment may be reduced by 20–30%. This reasoning applies also to other bays at the southern shore of Gulf of Finland where the lifetime of refills may be considereably longer than expected from the estimates of classical closure depth.

Conclusions

Summary of the results

The presented studies are focused on two aspects of the water levels dynamics and its implications in the eastern Baltic Sea: (i) overall properties of water level in the Gulf of Riga and Baltic proper shores of Latvia and (ii) the joint impact of high water level and strong waves in the entire eastern Baltic Sea. The analysis of water level in Latvian waters is based mostly on the previously unpublished data of Latvian measurements 1961−2018. For the joint impact analysis the modelled water levels and waves for the periods 1970−2005 and 1981−2005 are used.

The main objectives were to (i) establish the basic properties of water levels such as means, extremes and trends, (ii) examine their long-term and seasonal changes, (iii) separate components of water levels that act on different time scale, (iv) characterise situations where the water level in the gulf is considerably different from the rest of the Baltic Sea, (v) quantify the synchronisation of high waves and water levels for better coastal management.

The analysis confirmed that many well-known properties of the course and statistical features of the Baltic Sea water level (such as asymmetry of high and low water levels and a distinct annual cycle) exist in the Gulf of Riga and on the Baltic proper shores of Latvia. The widest range of water levels (311 cm between the all-time maximum and minimum) is at Daugavgriva in the southern bayhead of the Gulf of Riga. The range is about 60 cm smaller on the shores of the Baltic proper.

The water level empirical distributions have become narrower at Liepaja and Daugavgriva. The change is statistically significant at Liepaja at a 95% level. The probabilities of higher water levels have remained unchanged while very low water levels have become less frequent. This feature suggests that projections of water level extremes (e.g., Särkkä et al., 2017; Vousdoukas et al., 2017) may overestimate the rate of increase in the eastern Baltic Sea.

The land uplift-corrected annual mean water level on the Latvian coast increased by 0.14–1.18 mm/yr in the period 1961–2018, with larger rates of increase at Liepaja, Roja, Daugavgriva, and Salacgriva. This rate is slower than the signal of global sea level rise at the entrance of the Baltic Sea (1.63 mm/yr in Gräwe et al., 2019) and smaller than in Estonia and at Klaipėda. The fastest seasonal increase in the average water level (about 1.81–3.05 mm/yr) occurs from December to March.

The annual average water level shows no clear decadal-scale cyclic variations in the water level means and extremes. The increase rates of winter maxima are in the range of 1.28–4.73 mm/yr. These are substantially (up to 5.21 mm/yr) steeper than the similar values for stormy season (July–June) maxima. Most of these trends are statistically not significant and weaker than similar trends on the Estonian coast.

The seasonal course in the mean and extreme water level matches previous estimates of their annual variation in the Baltic Sea, with elevated water levels from July to February and lower than average in March–June. The typical range of weekly-scale average water level is 20–30 cm. The changes in this course for the two climatic periods (1961–1990 and 1991–2018) are in counterphase with the seasonal variations in the mean water level.

The monthly average water level has increased in January–June and decreased in July–November. The maximum magnitude of the changes is almost 30% of the amplitude of the seasonal course of the mean water level 1961–1990. A similar pattern is found for the monthly maxima and minima. This finding suggests that the overall tendency towards an increase in the magnitude of the annual cycle of the Baltic Sea water level (Ekman and Stigebrandt, 1990; Hünicke and Zorita, 2008) has been reversed in Latvian waters and in the Gulf of Riga and that the reaction of local phenomena to climate change may be substantially different in neighbouring sea areas.

The highest water levels in the interior of the Gulf of Riga are developed under the joint impact of three major drivers, each of which can add about 1 m to the resulting water level. These are the water volume of the entire Baltic Sea, water pushed by specific storms into the Gulf of Riga and surges caused by local storms. These components were separated using a moving average technique. The contribution of local storm surges at Daugavgriva and Pärnu almost precisely match an exponential distribution $\sim\exp(\lambda x)$. The approximate slopes of the negative and positive branches of this distribution for low and high water levels provide useful information for calculating the probability of coastal flooding. Very low water levels are more probable on the Estonian coast than on the Latvian shores of the Gulf of Riga.

Water level in the Gulf of Riga exceeds the level in the Baltic Sea proper by more than 100 cm irregularly once in 5–10 years. The development and relaxation timescales of such high elevations are about one day and thus much shorter compared to the time it takes for the entire Baltic Sea water volume to relax to its average value.

The impact of synchronisation of high water levels and strong wave storms was quantified in terms of water-level-adjusted closure depth. The difference between the classic and water-level-adjusted closure depth is between 2% and 8% along the relatively straight Latvian Baltic proper coast and in the Gulf of Riga, and up to 11% near Narva in the Gulf of Finland. Higher-resolution simulations demonstrate that this difference may reach up to 15% at certain locations in the Gulf of Finland that are open to the west. These sections are strongly affected by the frequent co-presence of high water level and severe seas. The difference between the classic and water-level-adjusted estimates may lead to considerable modification of estimates of the budget of underwater sediment volumes and, consequently, changes in possible costs of engineering works such as beach nourishment.

Main conclusions proposed to defend

1. The increase in average water level on Latvian shores is slower than the signal of global sea level rise at the entrance of the Baltic Sea. The rate of increase in the water level maxima is also slower than in Estonia and at Klaipėda.
2. The probability distribution of different water levels in Latvian waters has changed in the period 1961–2018 at a 95% level of statistical significance. Very low water levels have become less frequent whereas the statistical properties of very high levels have not substantially changed.
3. The amplitude of the seasonal course of water level has markedly decreased for the period 1961–2018. The average water level has decreased in July–November and increased in January–June.

4. The highest water levels in the Gulf of Riga are jointly influenced by three major drivers: the water volume of the entire Baltic Sea that changes on multi-weekly scale, water occasionally pushed by a sequence of cyclones into the gulf for 1–2 days and local storm surges with a duration of a few hours. Each of these drivers can contribute up to about 1 m to the resulting water level.
5. During events that cause large volumes of excess water in the Gulf of Riga, the water level in the gulf may exceed the Baltic Sea level by 1 m once in 5–10 years. The magnitudes of strongly elevated water levels show no changes since the 1960s. The annual average number of episodes of significant differences between the water level at Liepaja and Pärnu has decreased by a factor 1.6 whereas differences between Liepaja and Daugavgriva did not change. These results indicate an alteration of the directional structure of winds.
6. Synchronisation of severe seas and high water levels has insignificant impact on the closure depths on relatively straight coastal sections of the eastern coast of the Baltic proper. The impact is more pronounced in the Gulf of Riga where it leads to a decrease in the closure depths by up to 8%.
7. The closure depth is reduced up to 15% in several smaller bays in the Gulf of Finland by systematic co-presence of severe seas and high water levels.

Recommendations for further work

This study presented the extremes of observed Latvian water levels in a descriptive manner. A important step further would be a projection or forecast of values for different, longer return periods. This kind of information is a core input for the needs of coastal design and management. The foremost issue in this process is selecting the most suitable extreme value distribution. Although it is already a complicated task for the open ocean, because the data may be too short, inaccurate or non-stationary (Galiatsatou et al., 2019), it is further complicated in semi-enclosed seas like the Baltic Sea or the Gulf of Riga, where conventional methods for extreme value estimation seem to be not able to accommodate all observed and hindcast extremes (Suursaar and Sooäär, 2007; Eelsalu et al., 2014).

A possible way forward could be an ensemble approach (Eelsalu et al., 2014) for estimates of the properties of the distribution of different water levels, but it is still based on the assumption that the underlying processes that govern water level are statistically stationary. There is increasing evidence that these processes and their outcome in terms of extreme water level are non-stationary. This feature of changing climate may substantially modify projections of extreme water level, associated risks and methods for their mitigation.

The analysis of water levels at Latvian observation stations showed that there have been clear changes in the seasonal variations of mean and extreme water level between two climatic periods (1961–1990 and 1991–2018). These changes are in counterphase with the existing course of seasonal variations in the mean water level. The driver for this feature was not identified. It is likely that it might be a result of rotation of wind patterns. It is thus important to link the established changes with changes in the forcing patterns.

The estimates of water level driven variations in the closure depth in Paper III rely on numerical experiments. Their spatial resolution is evidently not sufficient for an exact representation of the processes in the immediate nearshore where local effects may play a significant role. Therefore, there is a need to support the conjectures of this part of the research and evaluate the magnitude of local effects for vulnerable coastal segments. This can be done by calculating wave parameters and water levels with higher resolution models which also cover the time period 2007–2020 combined with field measurements in the locations that are most affected by synchronisation of water level and wave properties.

Applying higher resolution wave models with a longer timespan and using water level measurements in the Gulf of Riga would make it possible to analyse more adequately the joint influence of water levels and wave heights in engineering applications. A natural extension of such analysis could be an improved estimate of the probability and magnitude of overtopping over various coastal engineering structures or more exact estimates of wave set-up and run-up heights depending on the background water level and instanteneous wave properties. This would be beneficial to coastal management and engineering as sea-induced loads and coastal erosion are highly dependent on the joint behaviour of waves and water level.

List of figures

Figure 1. Water level measurement sites in the Gulf of Riga and on the open coast of Latvia. Red squares show locations with the highest quality and coverage of observations (Table 1 and Table 2). Yellow circles depict stations where measurements were less frequent and/or had long gaps. Grey markers indicate some measurement stations outside Latvia. The blue square indicates measurement station Pärnu which is used in this thesis. The green square shows the Estonian meteorological station at the island of Vilsandi which serves as the source of wind information. Adapted from Paper I. 8

Figure 2. The temporal course of annual average water level and its trendline 1961–2018 at all Latvian stations listed in Table 1 and at Pärnu. The black lines mark the average evaluated for stormy seasons (the time intervals from 01 July to 30 June of the subsequent year) and cyan lines indicate the annual average for the calendar year. Note small, but important, differences between the lines depending on the definition of year. Adapted from Paper I. 21

Figure 3. Empirical probability distributions of occurrence of different water levels at Liepaja (a) and Daugavgriva (b) for the 30-year period of 1961–1990 (blue) and 28-year period of 1991–2018 (red). The horizontally aligned markers for high water levels at the frequency of ~0.0003% correspond to the recorded surge heights that happened exactly once in the period 1961–2018. The outlier at 174 cm for Liepaja corresponds to five equal entries on 18 October 1967. Adapted from Paper I. 22

Figure 4. Seasonal variation in the weekly water level at all 11 stations listed in Table 1 with respect to the long-term average at single measurement locations (thin lines) and in the average over nine stations (excluding Pavilosta and Andrejosta, thick red line). Differently from the rest of the analysis, de-meaned values of water level are used here for better comparison of data from different locations. The values of water level at single stations are first evaluated for each calendar day and then smoothed using a running average over seven days. The magenta line shows the variation at Pavilosta in 1961–2003, cyan lines represent other stations on the Baltic proper coast and green lines show other stations in the Gulf of Riga. Adapted from Paper I. 24

Figure 5. Seasonal variations in monthly water level properties 1961–2018. Lines from top: absolute maximum for a given month, average monthly maximum, mean, average monthly minimum, and absolute minimum for a given month. From Paper I. 26

Figure 6. Changes in the weekly average water level at single measurement locations (thin lines) and in the average over all locations (excluding Pavilosta and Andrejosta, thick red line) between the years 1961–1990 and 1991–2018. The variations at Pavilosta (magenta line) can be only evaluated for 1961–1990 and 1991–2003 and are thus ignored in the calculation of the average over all locations. Cyan lines represent the other stations on the Baltic proper coast (Liepaja and Ventspils) and green lines the other locations in the Gulf of Riga. Light red and yellow areas show the time interval for which the average water level has increased, or decreased, respectively. From Paper I. 27

Figure 7. Seasonal variations in monthly mean, maximum and minimum sea level at (a) Liepaja and (b) Daugavgriva for the 30-year periods 1961–1990 (blue lines) and 1991–2018

(red lines). Lines from top: average of monthly maxima, mean, and average of monthly minima of water level. From Paper I. 27

Figure 8. The count (numbers at markers) of annual extremes at all 11 stations listed in Table 1 in different months 1961–2018. Red: water level maxima, blue: water level minima. From Paper I. 28

Figure 9. Stormy season mean (middle lines), maximum (upper lines) and minimum (lower lines) water level and their 11-yr moving averages and trends, evaluated for time intervals from July to June subsequent year (a–d) and for winter (from December to March (e, f)). From Paper I. 29

Figure 10. Frequency of occurrence of all wind speeds and strong winds (>15 m/s) at Vilsandi 1961–2018. From Paper I. 32

Figure 11. Monthly variations in the correlation coefficient between the monthly mean water level and the NAO index (blue lines) and the monthly mean water level and the number of storm days at Vilsandi (red lines). From Paper I. 32

Figure 12. Water levels at Liepaja (blue), Daugavgriva (red) and Pärnu (yellow) in January 1993. The dashed black line shows the 8.25-day average of water levels at Liepaja. Small peaks (5–10 cm) with periods of several hours probably reflect different kinds of seiches in the Gulf of Riga. From Paper II. 34

Figure 13. Empirical distributions of the frequency of occurrence of observed hourly water levels and first and second residuals 1961–2017 at Pärnu, Daugavgriva, and Liepaja. The second residual is not shown for Liepaja. Cyan, red and green markers show the distributions of the observed total water level and the first and second residuals, respectively. Blue and magenta lines show the similar distribution for the average water level for the total and first residual water levels, respectively. Black lines depict linear approximations of the residuals. Numbers on the Figure indicate the values of the scale parameter $-1/\lambda_1$*. The upper and lower values for the locations in the Gulf of Riga correspond to first (red) and second (green) residuals. From Paper II.* 37

Figure 14. The frequency of occurrence of episodes of water level differences with a different duration between Liepaja and stations in the Gulf of Riga. a) episodes with water level difference $D_{lim} = 30$ *cm, b)* $D_{lim} = 50$ *cm. Red line: the probability of episodes when water level at Pärnu and Liepaja is different, blue: the same for Daugavgriva and Liepaja. The yellow line depicts the difference between the minimum/maximum value of the Gulf of Riga (Daugavgriva/Pärnu) and Liepaja. Negative values on the x-axis represent the duration of episodes when water levels in the Gulf of Riga are lower than at Liepaja. From Paper II.* 41

Figure 15. The number of episodes of differences between the water level at Liepaja and at stations in the Gulf of Riga from July to June of the subsequent year: a) $D_{lim} = 10$ *cm, b)* $D_{lim} = 30$ *cm. Blue thin lines represent the number of such differences between the water level at Daugavgriva and Liepaja and red thin lines between Pärnu and Liepaja. Solid bold lines indicate the respective linear trends. From Paper II.* 43

Figure 16. Maximum magnitudes of episodes of water level difference and their trendlines at Daugavgriva $D_D^{(t)}$ (blue) and Pärnu $D_P^{(t)}$ (red) for a) low water levels, b) high water levels during stormy seasons. The threshold for the difference between the observed values at Liepaja and at sites in the Gulf of Riga is for both cases $D_{lim} = 30$ cm. Trendlines are shifted vertically by 40 units for better readability. From Paper II. 44

Figure 17. Largest water level differences during stormy seasons between Liepaja and Daugavgriva (blue) or Pärnu (red) shown as thin lines. Bold lines represent trends. a) low water levels in the Gulf of Riga, b) high water levels in the Gulf of Riga. The trendline for high water level differences (panel b) between Pärnu and Liepaja is significant at a 95% confidence level. From Paper II. 45

Figure 18. Grid points of the wave model used to evaluate the nearshore wave statistics and closure depth for relatively straight coastal sections and in locations open to the offshore. The box indicates the detailed study area in the vicinity of Tallinn Bay. From Paper III. 48

Figure 19. Grid cells of the fine-resolution version of the WAM model used for the evaluation of wave properties in the nearshore of Tallinn Bay (small white squares) and nearshore grid cells of the RCO model (large blue squares). From Paper III. 49

Figure 20. Closure depths evaluated using Eqs. (3), (4) and (5) with $p_1 = 1.75$, $p_2 = 57.9$ along the entire eastern coast of the Baltic Sea with a resolution of 3 nautical miles (left panel) and in the nearshore of the Gulf of Riga. Blue: maximum 'instantaneous' closure depth; Green: the same but adjusted with water level; red: closure depth from Eq. (3) based on the 0.137%-ile (12 hours a year) of wave height and the associated wave periods; black: closure depth from 0.137%-ile of the values of hcwt in Eq. (4). From Paper III. 51

Figure 21. The relative difference (%) between the classic and adjusted closure depths along the eastern Baltic Sea coast evaluated using Eq. (3) and (4, 5) with $p_1 = 1.75$, $p_2 = 57.9$. The classic closure depths have been extracted from Soomere et al. (2013). From Paper III. 53

Figure 22. Relative (% of the adjusted closure depth) and actual (decimeters, dm) difference between classic and adjusted closure depths evaluated using Eqs. (3) and (4, 5) with $p_1 = 1.75$, $p_2 = 57.9$ in the vicinity of Tallinn. The classic closure depths have been extracted from Soomere et al. (2013). The notations are the same as for Figure 20. Note the characteristic jump from relatively large positive values in areas of the Viimsi Peninsula open to the west or northwest to negative values of the same magnitude in areas open to the east. From Paper III. 54

References

Averkiev, A.S., Klevannyy, K.A. 2010. A case study of the impact of cyclonic trajectories on sea-level extremes in the Gulf of Finland. *Continental Shelf Research*, 30(6), 707–714, doi: 10.1016/j.csr.2009.10.010.

Bärring, L., von Storch, H. 2004. Scandinavian storminess since about 1800. *Geophysical Research Letters*, 31, L20202, doi:101029/2004GL020441.

Birkemeier, W.A. 1985. Field data on seaward limit of profile change. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 111, 598–602, doi: 10.1061/(ASCE)0733-950X(1985)111:3(598).

Bosley, K.T., Hess, K.W. 2001. Comparison of statistical and model-based hindcasts of subtidal water levels in Chesapeake Bay. *Journal of Geophysical Research-Atmospheres*, 106(C8), 16869–16885, doi: 10.1029/2000JC000237.

Bumke, K., Hasse, L. 1989. An analysis scheme for determination of true surface winds at sea from ship synoptic wind and pressure observations. *Boundary-Layer Meteorology,* 47, 295–308, doi.org/10.1007/BF00122335.

Cerkowniak, G.R., Ostrowski, R., Stella, M. 2015a. Depth of closure in the multi-bar non-tidal nearshore zone of the Baltic Sea: Lubiatowo (Poland) case study. *Bulletin of the Maritime Institute Gdańsk*, 30, 180–188, doi:10.5604/12307424.1185577.

Cerkowniak, G.R., Ostrowski, R., Stella, M. 2015b. Wave-induced sediment motion beyond the surf zone: case study of Lubiatowo (Poland). *Archives of Hydro-Engineering and Environmental Mechanics*, 62(1–2), 27–39, doi:10.1515/heem-2015-00017.

[CIRIA, CUR, CETMEF 2007] *The Rock Manual. The use of rock in hydraulic engineering. 2nd edition*. *Publication C683.* CIRIA, London.

Coles, S. 2001. *An Introduction to Statistical Modeling of Extreme Values*. Springer, London.

Dailidienė, I., Davulienė, L., Tilickis, B., Stankevičius, A., Myrberg, K. 2006. Sea level variability at the Lithuanian coast of the Baltic Sea. *Boreal Environment Research*, 11(2), 109–121.

Dean, R.G. 1991. Equilibrium beach profiles: characteristics and applications. *Journal of Coastal Research,* 7(1), 53–84.

Dean, R.G., Dalrymple, R.A. 1991. *Water Wave Mechanics for Engineers and Scientists*. World Scientific, doi: 10.1142/1232.

Dean, R.G., Dalrymple, R.A. 2002. *Coastal Processes with Engineering Applications.* Cambridge University Press.

Dissanayake, P., Brown, J., Wisse, P., Karunarathna, H. 2015. Effects of storm clustering on beach/dune evolution. *Marine Geology*, 370, 63–75, doi: 10.1016/j.margeo.2015.10.010.

Eelsalu, M., Soomere, T., Pindsoo, K., Lagemaa, P. 2014. Ensemble approach for projections of return periods of extreme water levels in Estonian waters. *Continental Shelf Research*, 91, 201–210, doi: 10.1016/j.csr.2014.09.012.

Ekman, M. 1988. The worlds longest continued series of sea-level observations. *Pure And Applied Geophysics*, 127, 73–77, doi: 10.1007/bf00878691.

Ekman, M. 2003. The world's longest sea level series and winter oscillation index for Northern Europe 1774–2000. *Small Publications in Historical Geophysics*, 12, 1–31.

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 comparisons with oceanographic models. *Journal of Geophysical Research-Oceans*, 101(C5), 11993–11999, doi: 10.1029/96JC00318.

Ekman, M., Stigebrandt, A. 1990. Secular change of the seasonal variation in sea level and of the pole tide in the Baltic Sea. *Journal of Geophysical Research-Oceans*, 95(C4), 5379–5383, doi: 10.1029/JC095iC04p05379.

[EurOtop 2018] van der Meer, J.W., Allsop, N.W.H., Bruce, T., De Rouck, J., Kortenhaus, A., Pullen, T., Schüttrumpf, H., Troch, P., Zanuttigh, B. *Manual on Wave Overtopping of Sea Defences and Related Structures: An Overtopping Manual Largely Based on European Research, but for Worldwide Application*. University of Gent, Department of Civil Engineering, 2nd ed., http://www.overtopping-manual.com/assets/downloads/EurOtop_II_2018_Final_version.pdf.

Fernandez-Montblanc, T., Gomez-Enri, J., Ciavola, P. 2020. The role of mean sea level annual cycle on extreme water levels along European coastline. *Remote Sensing*, 12(20), art. no. 3419, doi: 10.3390/rs12203419.

Frison, T.W. 2000. Dynamics of the residuals in estuary water levels. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere*, 25(4), 359–364, doi: 10.1016/S1464-1909(00)00026-5.

Galiatsatou, P., Makris, C., Prinos, P., Kokkinos, D. 2019. Nonstationary joint probability analysis of extreme marine variables to assess design water levels at the shoreline in a changing climate. *Natural Hazards*, 98(3), 1051–1089, doi: 10.1007/s11069-019-03645-w.

Gräwe, U., Klingbeil, K., Kelln, J., Dangendorf, S. 2019. Decomposing mean sea level rise in a semi-enclosed basin, the Baltic Sea. *Journal of Climate,* 32(11), 3089–3108, doi: 10.1175/JCLI-D-18-0174.1.

Haigh, I.D., Nicholls, R., Wells, N. 2010. A comparison of the main methods for estimating probabilities of extreme still water levels. *Coastal Engineering*, 57(9), 838–849, doi: 10.1016/j.coastaleng.2010.04.002.

Hallermeier, R.J. 1978. Uses for a calculated limit depth to beach erosion. *Proceedings of 16th International Conference on Coastal Engineering, ASCE, Hamburg*, 1493–1512, doi: 10.1061/9780872621909.090.

Hallermeier, R.J. 1981. A profile zonation for seasonal sand beaches from wave climate. *Coastal Engineering*, 4, 253–277, doi: 10.1016/0378-3839(80)90022-8.

Hanson, H., Larson, M. 2008. Implications of extreme waves and water levels in the southern Baltic Sea. *Journal of Hydraulic Research*, 46(2), 292–302, doi: 10.1080/00221686.2008.9521962.

Harff, J., Deng, J., Dudzińska-Nowak, J., Fröhle, P., Groh, A., Hünicke, B., Soomere, T., Zhang, W. 2017. What determines the change of coastlines in the Baltic Sea? In: Harff, J., Furmańczyk, K., von Storch, H. (eds.), *Coastline Changes of the Baltic Sea from South to East. Past and Future Projection*, Coastal Research Library 19, Springer, Cham, 15–35, doi: 10.1007/978-3-319-49894-2_2.

Hawkes, P.J., Gouldby, B.P. Tawn, J.A., Owen, M.W. 2002. The joint probability of waves and water levels on coastal engineering design. *Journal of Hydraulic Research*, 40(3), 241–251, doi: 10.1080/00221680209499940.

Houston, J.R. 1996. Simplified Dean's method for beach-fill design. *Journal of Waterway*, *Port*, *Coastal*, *and Ocean Engineering*, 122(3), 143–146, doi: 10.1061/(ASCE)0733-950X(1996)122:3(143).

Howard, T., Pardaens, A.K., Bamber, J.L., Ridley, J., Spada, G., Hurkmans, R.T.W.L., Lowe, J.A., Vaughan, D. 2014. Sources of 21st century regional sea-level rise along the coast of northwest Europe. *Ocean Science*, 10(3), 473–483, doi: 10.5194/os-10-473-2014.

Hünicke, B., Zorita, E. 2008. Trends in the amplitude of Baltic Sea level annual cycle. *Tellus A*, 60(1), 154–164. doi: 10.1111/j.1600-0870.2007.00277.x.

Hünicke, B., Zorita, E., Soomere, T., Madsen, K.S., Johansson, M., Suursaar, Ü. 2015. Recent change – sea level and wind waves. In: The BACC II Author Team, *Second Assessment of Climate Change for the Baltic Sea Basin*, Regional Climate Studies. Springer, 155–185, doi:10.1007/978-3-319-16006-1_9.

Hurrell, J.W. 1995. Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science*, 269, 676–679, doi: 10.1126/science.269.5224.676.

Hurrell, J.W., Kushnir, Y., Ottersen, G., Visbeck, M. 2003. An overview of the North Atlantic Oscillation. In: *The North Atlantic Oscillation: Climatic Significance and Environmental Impact.* Geophysical Monograph, 134, American Geophysical Union, 1–35, doi: 10.1029/134GM01.

Iljina, J., Pastors, A. 1976, Surges and ebbs in Gulf of Riga. *Collection of Scientific Papers of Riga Hydrometeorological Observatory*, 15, 9–37 [in Russian].

[IPCC 2013] *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (eds.). Cambridge University Press.

Jaagus, J. 2006. Climatic changes in Estonia during the second half of the 20th century in relationship with changes in large-scale atmospheric circulation. *Theoretical and Applied Climatology*, 83, 77–88, doi: 10.1007/s00704-005-0161-0.

Jarmalavičius, D., Ilinskas, G., Dubra, V. 2007. Pattern of long-term seasonal sea level fluctuations in the Baltic Sea near the Lithuanian coast. *Baltica*, 20(1–2), 28–34.

Johansson, M., Boman, H., Kahma, K.K., Launiainen, J. 2001.Trends in sea level variability in the Baltic Sea. *Boreal Environment Research*, 6(3), 159–179.

Johansson, M., Kahma, K.K. 2016. On the statistical relationship between the geostrophic wind and sea level variations in the Baltic Sea. *Boreal Environment Research*, 21(1–2), 43–25.

Johansson, M., Kahma, K.K., Boman, H. 2003. An improved estimate for the long-term mean sea level on the Finnish coast. *Geophysica*, 39(1–2), 51–73.

Johansson, M., Kahma, K.K., Boman, H. 2004. Scenarios for sea level on the Finnish coast. *Boreal Environment Research*, 9, 153–166.

Jones, P.D., Jonsson, T., Wheeler, D. 1997. Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. *International Journal of Climatology*, 17, 1433–1450, doi: 10.1002/(SICI)1097-0088(19971115)17:13<1433::AID-JOC203>3.0.CO;2-P.

Jönsson, B., Döös, K., Nycander, J., Lundberg, P. 2008. Standing waves in the Gulf of Finland and their relationship to the basin-wide Baltic seiches. *Journal of Geophysical Research-Oceans*, 113(C3), Art. No. C03004, doi: 10.1029/2006JC003862.

Kamphuis, J.W. 2010. *Introduction to Coastal Engineering and Management*. World Scientific.

Karabil, S., Zorita, E., Hünicke, B. 2018. Contribution of atmospheric circulation to recent off-shore sea-level variations in the Baltic Sea and the North Sea. *Earth System Dynamics*, 9(1), 69–90. doi: 10.5194/esd-9-69-2018.

Kirezci, E., Young, I.R., Ranasinghe, R., Muis, S., Nicholls, R.J., Lincke, D., Hinkel, J. 2020. Projections of global-scale extreme sea levels and resulting episodic coastal flooding over the 21st century. *Scientific Reports*, 10(1), art. no. 11629, doi: 10.1038/s41598-020-67736-6.

Kollo, K., Ellmann, A. 2019. Geodetic reconciliation of tide gauge network in Estonia. *Geophysica*, 54(1), 27–38.

Koltsova, T., Belakova, J. 2007, Storm surges on the southern coast of Gulf of Riga. *BALTEX Newsletter*, 10, 15–18.

Koltsova, T., Belakova, J. 2009. Storm surges on the southern coast of Gulf of Riga: case study of the Lielupe River. In: Jones, J.A.A., Vardanian, T.G., Hakopian, C. (eds.). *Threats to Global Water Security*, NATO Advanced Research Workshop on Natural Disasters and Water Security, Yerevan, Armenia. NATO Science for Peace and Security Series C – Environmental Security, 91–97, doi: 10.1007/978-90-481-2344-5_10.

Komen, G.J., Cavaleri, L., Donelan, M., Hasselmann, K., Hasselmann, S., Janssen, P.A.E.M. 1994. *Dynamics and Modelling of Ocean Waves*. Cambridge University Press, doi: 10.1017/CBO9780511628955.

Kowalczyk, K. 2019. Changes in mean sea level on the Polish coast of the Baltic Sea based on tide gauge data from the years 1811–2015. *Acta Geodynamica et Geomaterialia*, 16(2), 195–209, doi: 10.13168/AGG.2019.0016.

Kudryavtseva, N., Soomere, T. 2017. Satellite altimetry reveals spatial patterns of variations in the Baltic Sea wave climate. *Earth System Dynamics*, 8(3), 697–706, doi: 10.5194/esd-8-697-2017.

Kudure, A. 2009. Typical synoptic situations causing extremely high water levels along the Latvian coast of the Baltic Sea and the Gulf of Riga. April 27–29, Delft, The Netherlands. http://www.meteo.lv/fs/files/CMSP_Static_Page_Attach/00/00/00/02/06/level.pdf (accessed 21 July 2019).

Kulikov, E.A., Medvedev, I.P. 2013. Variability of the Baltic Sea level and floods in the Gulf of Finland. *Oceanology*, 53(2), 145–151, doi: 10.1134/S0001437013020094.

Laiz, I., Ferrer, L., Plomaritis, T.A., Charria, G. 2014. Effect of river runoff on sea level from in-situ measurements and numerical models in the Bay of Biscay. *Deep Sea Research Part II: Topical Studies in Oceanography*, 106, 49–67, doi: 10.1016/j.dsr2.2013.12.013.

Launiainen, J., Laurila, T. 1984. Marine wind characteristics in the northern Baltic Sea. *Finnish Marine Research*, 250, 52–86.

Lazarenko, N.N. 1986. Variations of mean level and water volume of the Baltic Sea. In: *Proceedings of the Water Balance of the Baltic Sea Environment*, 16, 64–80 [in Russian].

Lehmann, A, Getzlaff, K, Harlaß, J. 2011 Detailed assessment of climate variability in the Baltic Sea area for the period 1958 to 2009. *Climate Research*, 46, 185–196. doi:10.3354/cr00876.

Lehmann, A., Höflich, K., Post, P., Myrberg, K. 2017. Pathways of deep cyclones associated with large volume changes (LVCs) and major Baltic inflows (MBIs). *Journal of Marine Systems*, 167, 11–18, doi:10.1016/j.jmarsys.2016.10.014.

Lehmann, A., Post, P. 2015. Variability of atmospheric circulation patterns associated with large volume changes of the Baltic Sea. *Advances in Science and Research*, 12, 219–225, doi:10.5194/asr-12-219-2015.

Leppäranta, M., Myrberg, K. 2009. *Physical Oceanography of the Baltic Sea*. Springer.

Liu, W., Beckheinrich, J., Semmling, M., Ramatschi, M., Vey, S., Wickert, J., Hobiger, T., Haas, R. 2017. Coastal sea-level measurements based on GNSS-R phase qltimetry: A case study at the Onsala Space Observatory, Sweden. *IEEE Transactions on Geoscience and Remote Sensing*, 55(10), 5625–5636, doi: 10.1109/TGRS.2017.2711012.

Losada, I.J., Reguero, B.G., Méndez, F.J., Castanedo, S., Abascal, A.J., Mínguez, R. 2013. Long-term changes in sea-level components in Latin America and the Caribbean. *Global Planetary Change*, 104, 34–50, doi:10.1016/j.gloplacha.2013.02.006.

Maritime Administration of Latvia, 2014. *Hydrography services, Baltijas jūras locija. Latvijas piekraste* (The Baltic Sea. Coast of Latvia), 3rd ed., Riga [in Latvian].

Medvedev, I. P., Rabinovich, A. B., Kulikov, E. A. 2017. The pole tide/14-month oscillations in the Baltic Sea during the 19th and 20th centuries: Spatial and temporal variations. *Continental Shelf Research*, 137, 117–130. doi: 10.1016/j.csr.2017.02.001.

Medvedev, I.P., Rabinovich, A.B., Kulikov, E.A., 2013. Tidal oscillations in the Baltic Sea. *Oceanology*, 53(5), 526–538, doi: 10.1134/S0001437013050123.

Medyna, P., Sobkowicz, P. 2017. Hydrographic and navigational analysis of Lower Oder shipping conditions – case study of the backflow occurrence. In: Kazmierczak, B., Kutylowska, M., Piekarska, K., TruszZdybek, A. (eds.), *9th Conference on Interdisciplinary Problems in Environmental Protection and Engineering* (EKO-DOK 2017). E3S Web of Conferences, 17, art. no. 00059, doi: 10.1051/e3sconf/20171700059.

Meier, H.E.M., Broman, B., Kjellström, E. 2004. Simulated sea level in past and future climates of the Baltic Sea. *Climate Research*, 27, 59–75. doi:10.3354/cr027059.

Meier, H.E.M., Döscher, R., Faxén, T. 2003. A multiprocessor coupled ice-ocean model for the Baltic Sea: application to salt inflow. *Journal of Geophysical Research-Oceans,* 108(C8), 32–73, doi: 10.1029/2000JC000521.

Meier, H.E.M., Höglund, A. 2013. Studying the Baltic Sea circulation with Eulerian tracers. In: Soomere, T., Quak, E. (eds.), *Preventive Methods for Coastal Protection*. Springer, 101–130, doi: 0.1007/978-3-319-00440-2_4.

Nicholls, R.J., Birkemeier, W.A., Hallermeier, R.J. 1996. Application of the depth of closure concept. In: *Proceedings of 25th International Conference on Coastal Engineering, Orlando*, 3874–3887. doi: 10.1061/9780784402429.299.

Nicholls, R.J. 2011. Planning for the impacts of sea level rise. *Oceanography*, 24(2), 144–157, doi: 10.5670/oceanog.2011.34.

Orviku, K., Jaagus, J., Kont, A., Ratas, U., Rivis, R. 2003. Increasing activity of coastal processes associated with climate change in Estonia. *Journal of Coastal Research*, 19, 364–375.

Otsmann, M., Suursaar, Ü., Kullas, T. 2001. The oscillatory nature of the flows in the system of straits and small semi enclosed basins of the Baltic Sea. *Continental Shelf Research*, 21(15), 1577–1603, doi: 10.1016/S0278-4343(01)00002-4.

Pajak, K., Kowalczyk, K. 2019. A comparison of seasonal variations of sea level in the southern Baltic Sea from altimetry and tide gauge data. *Advances in Space Research*, 63(5), 1768–1780. doi: 10.1016/j.asr.2018.11.022.

Pastors, A. 1965. Surges and ebbs in downstretch of Lielupe River. *Collection of Scientific Papers of LATNIIG & M*, 3, 279–308 [in Russian].

Post, P., Kõuts, T. 2014. Characteristics of cyclones causing extreme sea levels in the northern Baltic Sea. *Oceanologia,* 56(2), 241–258. doi: 10.5697/oc.56-2.241.

Pranzini, E., Williams, A. 2013. *Coastal Erosion and Protection in Europe*. Taylor and Francis.

Pruszak, Z., Zawadzka, E. 2008. Potential implications of sea-level rise for Poland. *Journal of Coastal Research*, 24(2), 410–422, doi: 10.2112/07A-0014.1.

Pugh, D.T., Vassie, J.M. 1978. Extreme sea levels from tide and surge probability. *16th International Conference on Coastal Engineering, August 27–September 3, 1978, Hamburg, Germany*, 911–930, doi: 10.1061/9780872621909.054.

Pugh, D.T., Vassie, J.M. 1980. Applications of the joint probability method for extreme sea-level computations. *Proceedings of the Institution of Civil Engineers Part 2-Research and Theory*, 69, 959–975, doi: 10.1680/iicep.1980.2179.

Räämet, A., Soomere, T. 2010. The wave climate and its seasonal variability in the northeastern Baltic Sea. *Estonian Journal of Earth Sciences*, 59(1), 100–113, doi: 10.3176/earth.2010.1.08.

Raudsepp, U., Toompuu, A., Kõuts, T. 1999. A stochastic model for the sea level in the Estonian coastal area. *Journal of Marine Systems*, 22(1), 69–87, doi: 10.1016/S0924-7963(99)00031-7.

Reiniks, M., Kalinka, M., Lazdans, J., Klive, J., Ratkus, B. 2010. Height system exit level and defining exit value. *Scientific Journal of Riga Technical University*, *Geomatics*, 7, 7–13 [in Latvian].

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 Anthrosphere 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. *Physics and Chemistry of the Earth*, 53–54, 43–53, doi: 10.1016/j.pce.2011.04.011.

Rutgersson, A., Jaagus, J., Schenk, F., Stendel, M. 2014. Observed changes and variability of atmospheric parameters in the Baltic Sea region during the last 200 years. *Climate Research*, 61(2), 177–190, doi: 10.3354/cr01244.

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 Environment Research*, 16 (Suppl. A), 117–137.

Samuelsson, P., Jones, C.G., Willén, U., Ullerstig, A., Gollovik, S., Hansson, U., Jansson, C., Kjellström, E., Nikulin, G., Wyser, K. 2011. The Rossby Centre Regional Climate Model RCA3: Model description and performance. *Tellus A*, 63, 4–23.

Särkkä, J., Kahma, K.K., Kämäräinen, M., Johansson, M.M., Saku, S. 2017. Simulated extreme sea levels at Helsinki. *Boreal Environment Research*, 22, 299–315.

Schmitt, F. G., Crapoulet, A., Hequette, A., Huang, Y. 2018. Nonlinear dynamics of the sea level time series in the eastern English Channel. *Natural Hazards*, 91(4), 267–285, doi: 10.1007/s11069-017-3125-7.

Soomere, T. 2005. Wind wave statistics in Tallinn Bay. *Boreal Environment Research*, 10(2), 103–118.

Soomere, T., Keevallik, S. 2001. Anisotropy of moderate and strong winds in the Baltic Proper. *Proceedings of Estonian Academy of Sciences. Engineering,* 7(1), 35–49.

Soomere, T., Räämet, A. 2011. Spatial patterns of the wave climate in the Baltic Proper and the Gulf of Finland. *Oceanologia,* 53(1-TI), 335–371, doi: 10.5697/oc.53-1-TI.335.

Soomere, T., Eelsalu, M. 2014. On the wave energy potential along the eastern Baltic Sea coast. *Renewable Energy*, 71, 221−233, doi: 10.1016/j.renene.2014.05.025.

Soomere, T., Räämet, A. 2014. Decadal changes in the Baltic Sea wave heights. *Journal of Marine Systems*, 129, 86–95, doi: 10.1016/j.jmarsys.2013.03.009.

Soomere, T., Pindsoo, K. 2016. Spatial variability in the trends in extreme storm surges and weekly-scale high water levels in the eastern Baltic Sea. *Continental Shelf Research*, 115, 53–64, doi: 10.1016/j.csr.2015.12.016.

Soomere, T., Kask, A., Kask, J., Healy, T.R. 2008a. Modelling of wave climate and sediment transport patterns at a tideless embayed beach, Pirita Beach, Estonia. *Journal of Marine Systems*, 74, 133–S146, doi: 10.1016/j.jmarsys.2008.03.024.

Soomere, T., Myrberg, K., Leppäranta, M., Nekrasov, A. 2008b. The progress in knowledge of physical oceanography of the Gulf of Finland: a review for 1997–2007. *Oceanologia,* 50(3), 287–362.

Soomere, T., Viška, M., Eelsalu, M. 2013. Spatial variations of wave loads and closure depth along the eastern Baltic Sea coast. *Estonian Journal of Engineering*, 19(2), 93–109, doi 10.3176/eng.2013.2.01.

Soomere, T., Bishop, S.R., Viška, M., Räämet, A. 2015a. An abrupt change in winds that may radically affect the coasts and deep sections of the Baltic Sea. *Climate Research*, 62, 163–171, doi: 10.3354/cr01269.

Soomere, T., Eelsalu, M., Kurkin, A., Rybin, A. 2015b. Separation of the Baltic Sea water level into daily and multi-weekly components. *Continental Shelf Research*, 103, 23–32, doi: 10.1016/j.csr.2015.04.018.

Soomere, T., Eelsalu, M., Pindsoo, K. 2018. Variations in parameters of extreme value distributions of water level along the eastern Baltic Sea coast. *Estuarine, Coastal and Shelf Science*, 215, 59–68, doi: 10.1016/j.ecss.2018.10.010.

Stephens, S.A., Bell, R.G., Haigh, I.D. 2020. Spatial and temporal analysis of extreme storm-tide and skew-surge events around the coastline of New Zealand. *Natural Hazards and Earth System Sciences*, 20, 783–796, doi: 10.5194/nhess-20-783-2020.

Stramska, M. 2013. Temporal variability of the Baltic Sea level based on satellite observations. *Estuarine, Coastal and Shelf Science*, 133, 244–250, doi: 10.1016/j.ecss.2013.09.002.

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(2), 249–260, doi: 10.1111/j.1600-0870.2006.00220.x.

Suursaar, Ü., Kullas, T., Otsmann, M. 2002. A model study of the sea level variations in the Gulf of Riga and the Väinameri Sea. *Continental Shelf Research*, 22(14), 2001–2019, doi: 10.1016/S0278-4343(02)00046-8.

Suursaar, Ü., Kullas, T, Otsmann, M., Kõuts, T. 2003. Extreme sea level events in the coastal waters of western Estonia. *Journal of Sea Research*, 49(4), 295–303, doi: 10.1016/S1385-1101(03)00022-4.

Suursaar, Ü., Jaagus, J., Kullas, T. 2006. Past and future changes in sea level near the Estonian coast in relation to changes in wind climate. *Boreal Environment Research*, 11, 123–142.

Talley, L.D., Pickard, G.L., Emery, W.J., Swift, J.H. 2011. *Descriptive Physical Oceanography: An Introduction*. 6th ed., Academic Press.

[USACE 2002] *Coastal Engineering Manual*. US Army Corps of Engineers. Manual No. 1110-2-1100 (CD).

Varbla, S., Ellmann, A., Delpeche-Ellmann, N. 2020. Utilizing airborne laser scanning and geoid model for near-coast improvements in sea surface height and marine dynamics. *Journal of Coastal Research*, Special Issue 95, 1339–1343, doi: 10.2112/SI95-257.1.

Viitak, M., Maljutenko, I., Alari, V., Suursaar, Ü., Rikka, S., Lagemaa, P. 2016. The impact of surface currents and sea level on the wave field evolution during St. Jude storm in the eastern Baltic Sea. *Oceanologia*, 58(3), 176–186, doi: 10.1016/j.oceano.2016.01.004.

von Storch, H., Zwiers, F.W. 1999. *Statistical Analysis in Climate Research*. Cambridge University Press.

Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Verlaan, M., Feyen, L. 2017. Extreme sea levels on the rise along Europe's coasts. *Earths Future,* 5(3), 304–323, doi: 10.1002/2016EF000505

Weisse, R., Bellafiore, D., Menendez, M., Mendez, F., Nicholls, R.J., Umgiesser, G., Willems, P. 2014. Changing extreme sea levels along European coasts. *Coastal Engineering*, 87, 4–14, doi: 10.1016/j.coastaleng.2013.10.017.

Weisse, R., Hünicke, B. 2019. Baltic Sea Level: Past, Present, and Future. In: *Oxford Research Encyclopedia, Climate Science*, 1–29, doi: 10.1093/acrefore/9780190228620.013.693.

Wigley, T.M.L. 2018. The Paris warming targets: emissions requirements and sea level consequences. *Climatic Change*, 147(1–2), 31–45, doi: 10.1007/s10584-017-2119-5.

Wikipedia, 2020. List of European windstorms. [WWW]. https://en.wikipedia.org/wiki/List_of_European_windstorms (accessed 30.12.2020).

Wisniewski, B., Wolski, T., Musielak, S. 2011. A long-term trend and temporal fluctuations of the sea level at the Polish Baltic coast. *Oceanological and Hydrobiological Studies*, 40(2), 96–107, doi: 10.2478/s13545-011-0020-9.

Zecchetto, S., Umgiesser, G., Brocchini, M. 1997. Hindcast of a storm surge induced by local real wind fields in the Venice Lagoon. *Continental Shelf Research*, 17(12), 1513–1538, doi: 10.1016/S0278-4343(97)00023-X.

Acknowledgements

First and foremost, I would like to thank my supervisor Prof. Tarmo Soomere who managed to bring me back to science. His profound guidance throughout the years spent in the Laboratory of Wave Engineering helped me to solve many difficult problems in work and research. I am also grateful for providing flexible working conditions and fruitful discussions. With his support and gained skills, my career as a coastal engineer has become more versatile and science oriented.

Secondly, I wish to thank my co-supervisor Prof. Kevin Ellis Parnell who has helped me with practical questions about the field work and coastal management. His view on my research and suggestions to it have helped to improve my work and outcome.

I am thankful for Latvian Environment, Geology and Meteorology Centre for publishing digitised water level data on their website and helping me with the site visits. I thank also the Estonian Weather Service for providing water level data and the Swedish Meteorological and Hydrological Institute for providing the water level data extracted from the Rossby Center Ocean (RCO) model. I am grateful for Dr. Andrus Räämet for modelled wave data for Paper III.

I am grateful to Katri Pindsoo and Maris Eelsalu who helped to compose maps for different purposes and showed the way on the PhD studies.

It has been pleasure to work among the staff of Laboratory of Wave Engineering. Their help and various discussions made many things easier. I would like to thank here Mojtaba Barzehkar, Dr. Nicole Delpeche-Ellmann, Dr. Andrea Giudici, Dr. Nadezhda Kudryavtseva, Fatemeh Najafzadeh, Margus Rätsep, Dr. Tomas Torsvik and Dr. Bert Viikmäe.

During more than 5 years I have experienced strong support from Estkonsult Ltd which provided me with flexible working conditions and an understanding environment. I would like to thank here my senior colleagues and supervisors Heiki Meos and Priit Põldre.

Last but not least I am very grateful to my family, especially my fiancée Kadri and son Kaspar. Without their support and understanding this work would not have been possible.

* * *

The studies were supported by Tallinn University of Technology, targeted financing (block grant SF0140007s11) and institutional block grant IUT33-3 of the Estonian Ministry of Education and Research, the Estonian Science Foundation (grant no. 9125), and the project “BalticCheckpoint” of the call MARE/2014/09 “Sea-basin check-points”. The final stage of the studies was also supported by the European Regional Development Fund program Mobilitas Plus, project MOBTT72, reg. no. 2014-2020.4.01.16-0024 and European Economic Area (EEA) Financial Instrument 2014–2021 Baltic Research Programme, project EMP480.

Abstract

Water level dynamics in the eastern Baltic Sea, 1961−2018

The thesis addresses water levels dynamics of the central part of the eastern Baltic Sea mostly based on *in situ* water level measurements in Latvian waters, 1961–2018, as well as implications of synchronisation of high water levels and strong wave storms in the entire eastern Baltic Sea based on numerically simulated time series of water level and wave properties in the nearshore.

The main properties of water level dynamics in Latvian waters are established in terms of mean, extremes, seasonal and cyclic variations, and long-term trends. The well-known properties of the course and statistical features of the Baltic Sea water level (such as a distinct annual cycle and an asymmetry of high and low water levels) are highlighted and quantified for both the Baltic proper shores of Latvia and in the Gulf of Riga.

The increase in average water level on Latvian shores is slower than the global sea level rise. The rate of increase in the water level maxima is also slower than in Estonia and at Klaipėda. The shape of the probability distribution of different water levels in Latvian waters has changed over the period 1960–2018 at a 95% level of statistical significance. While the probability of occurrence of elevated higher water levels and water level extremes have not substantially changed, very low water levels have become less frequent at Liepaja and Daugavgriva.

The properties of water levels on Latvian coast do not exhibit any clear decadal-scale cyclic variations. The predominant cyclic feature is the seasonal variation in the mean and extreme water levels. The weekly and monthly water level is above average in July–February and below average in March–June. June contains a minimum number of annual extremes. The amplitude of the seasonal course of water level has markedly decreased for the period 1991–2018 compared to 1961–1990. Water level has decreased in July–November and increased in January–June. This change has led to a shift of the high and low water "seasons" by several weeks.

The time scale and magnitude of three major drivers of highest water levels in the Gulf of Riga are established by means of separation of the total water level into three components with different time scale. The signal of water volume of the entire Baltic Sea drives changes on a multi-weekly scales. Water may be occasionally pushed by specific storms into the gulf for 1–2 days. The duration of local storm surges is usually a few hours. Each of these drivers may contribute up to about 1 m to the resulting water level. The excess water pushed into the Gulf of Riga may elevate the water level in the gulf by 1 m compared to the Baltic proper once in 5–10 years. Long-term changes in the magnitudes of such events may be caused by an alteration of the directional structure of winds.

The joint influence of waves and water levels were analysed from the viewpoint of closure depth. Synchronisation of severe seas and high water levels has insignificant impact on the closure depths and overall course of coastal processes on relatively straight coastal sections of the eastern coast of the Baltic Proper. The impact is more pronounced in the Gulf of Riga where it leads to a decrease in the estimate of closure depths by up to 8%. The closure depth is reduced up to 15% in several smaller bays in the Gulf of Finland by systematic co-presence of severe seas and high water levels.

Lühikokkuvõte

Läänemere idaranniku ja Liivi lahe veetaseme dünaamika 1961–2018

Doktoritöö käsitleb Läänemere idaranniku veetaseme dünaamikat peamiselt ajavahemikus 1961–2018 Läti rannikul ja Liivi lahes mõõdetud veetasemete alusel. Tugevate tormide ja kõrgete veetasemete ühismõju terves Läänemere idaosas analüüsitakse aastatel 1970–2005 modelleeritud lainete parameetrite ja veetasemete alusel.

Esitatakse veetasemete dünaamika peamiste parameetrite (aasta ja talveperioodi keskmised, ekstreemumid, sesoonsed ja tsüklilised kõikumised ning suhtelise ja absoluutse veetaseme pikaajalised trendid) kirjeldus nii Läti avamere ranniku kui ka Liivi lahe ranniku jaoks.

Keskmine veetase Läti rannikuil tõuseb aeglasemalt kui maailmameres, sh aeglasemalt kui Eestis ja Klaipėdas. Mõõdetud veetasemete empiirilise tõenäosusjaotuse kuju on muutunud asümmeetrilisemaks 95%-lise olulisusega. Keskmisest kõrgemate ja ekstreemsete veetasemete esinemise tõenäosus pole vähenenud, kuid Liepajas ja Daugavgrivas on kahanenud väga madalate veetasemete esinemise tõenäosus.

Mõõdetud veetasemetest ei ilmne aastakümneid hõlmavaid tsüklilisi kõikumisi. Tsükliliste nähtuste seas domineerib keskmiste ja ekstreemsete veetasemete sesoonne muutumine. Kuu ja nädala keskmised veetasemed on pikaajalisest keskmisest 5–15 cm kõrgemad juulist veebruarini ning 10–15 cm madalamad märtsist juunini. Kõige vähem veetasemete aastaseid maksimume on juunis. Sesoonne veetaseme kõikumise amplituud on aastail 1991–2018 oluliselt vähenenud võrreldes perioodiga 1961–1990. Juulist novembrini on 1991–2018 veetase olnud madalamal ning jaanuarist juunini kõrgemal kui 1961–1990. Sellega kaasneb kõrgete ja madalate veetasemete hooaegade nihkumine mitme nädala võrra.

Eristati Liivi lahe kõrgeid veetasemeid põhjustavate komponentide tüüpilised ajaskaalad. Vee hulga muutumine terves Läänemeres kestab mitmeid nädalaid. Üksikud teatud suunast puhuvad tormid võivad suruda Liivi lahte palju vett lisaks 1–2 päevaga. Kohalike tormide põhjustatud tormiaju mõju on tavaliselt mõni tund. Iga nimetatud komponendi panus veetasemesse võib olla ligikaudu 1 m. Ligikaudu üks kord 5–10 aasta tagant võib Liivi lahe veetase olla 1 meetri võrra kõrgem terve Läänemere omast.

Analüüsiti Liivi lahe suhteliselt kõrgete veetasemete esinemissagedust ja kestvust. Selliste sündmuste sagedus ja kestvus on pigem vähenenud. Täheldatud pikajalised muutused võivad olla põhjustatud puhuvate tuulte suundade muutumisest.

Veetasemete ja lainete ühismõju on analüüsitud sulgemissügavuse kontseptsiooni alusel. Kõrgete veetasemete ja lainete samaaegne esinemine avaldab vähest mõju sulgemissügavustele ja rannikuprotsesside üldisele iseloomule Läänemere idaranniku suhteliselt sirgetel rannalõikudel. See mõju on märgatav Liivi lahes, kus see põhjustab sulgemissügavuste hinnangu vähenemise kuni 8% võrra. Soome lahe põhjaranniku väikestes lahtedes võib kõrgete veetasemete ja tugevate lainete samaaegsus vähendada sulgemissügavust kuni 15%.

Appendix: Papers constituting the thesis

Paper I

Männikus, R., Soomere, T., Viška, M. 2020. Variations in the mean, seasonal and extreme water level on the Latvian coast, the eastern Baltic Sea, during 1961–2018. *Estuarine, Coastal and Shelf Science*, 245, art. no. 106827, doi: 10.1016/j.ecss.2020.106827.

Estuarine, Coastal and Shelf Science 245 (2020) 106827

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: http://www.elsevier.com/locate/ecss

Variations in the mean, seasonal and extreme water level on the Latvian coast, the eastern Baltic Sea, during 1961–2018

Rain Männikus [a,*], Tarmo Soomere [a,b], Maija Viška [c]

[a] Wave Engineering Laboratory, Department of Cybernetics, School of Science, Tallinn University of Technology, Tallinn, Estonia
[b] Estonian Academy of Sciences, Kohtu 6, Tallinn, 10130, Estonia
[c] Latvian Institute of Aquatic Ecology, University of Daugavpils, Riga, Latvia

ARTICLE INFO

Keywords:
Water level
Seasonal variability
Trends
Extreme water levels
Baltic Sea
Gulf of Riga
NAO index

ABSTRACT

High-resolution in situ water level data is one of the core sources for the identification and understanding the reaction of the sea to climate change. We analyse digitised recordings of water level measurements from all 10 currently functioning coastal tide gauges on the Latvian shores of the Baltic proper and in the Gulf of Riga for the period of 1961–2018. The frequency and temporal coverage of measurements vary greatly for these stations. The most complete hourly data are available from Liepaja on the Baltic proper coast and from Daugavgriva in the south-eastern bayhead of the Gulf of Riga. The water level regime is analysed from the viewpoint of (i) the entire range of water level variations, (ii) empirical probability distributions of different water levels, (iii) the seasonal course of water level, (iv) trends in the annual, seasonal, and monthly means and extremes of water level (in terms of the relative and uplift corrected absolute values), and (v) correlations of the main properties of water level with the North Atlantic Oscillation (NAO Gibraltar) index.

The empirical probability distributions of different water levels have become narrower in 1991–2018 compared to 1961–1990 whereas very low water levels are now less frequent. The amplitude of the seasonal course has greatly decreased over these time intervals. The annual mean and maxima of water level have increased in 1961–2018. The rate of increase is smaller than the rate of increase in the sea level in the North Atlantic suggesting that changes in the local drivers of water level mitigate the sea level rise in Latvian waters. Variations in the NAO index can explain 1/3 of the annual variability of the main properties of water level and up to 2/3 of this variability in wintertime (December–March). The changes in the statistical properties of water level are consistent with alterations to the directional structure of strong winds.

1. Introduction

Information about local water level is a crucial factor for coastal management and engineering. Long-term measurements and observations serve as the most reliable source of this information that could be used to analyse changes in the means, extremes, trends and various distributions of the water level in the past and future. Water level measurements on the Latvian coast in the central Baltic Sea have been carried out at Liepaja since 1865. As in many other locations, they were initially sporadic but have become systematic, frequent and accurate since the middle of the 20th century. As the amplitude of tides is just a few centimetres in the Baltic Sea (Leppäranta and Myrberg, 2009), their contribution to the observed water level is usually very small. The course and properties of water level have been thoroughly analysed in the neighbouring countries – Estonia (Suursaar and Sooäär, 2007), Finland (Johansson et al., 2001, 2004), Lithuania (Dailidienė et al., 2006), and Poland (Wisniewski et al., 2011; Hünicke et al., 2015; Kowalczyk, 2019). A systematic picture of the outcome of water level observations on Latvian shores is still missing (except for a few local case studies, e.g., Koltsova and Belakova, 2009).

This study makes an attempt to fill this gap in the description of water levels in the eastern Baltic Sea. The objectives are to (i) establish the basic properties of water level in the study area in terms of water level extremes, empirical probability distributions and the seasonal course of mean and maximum water levels, (ii) investigate long-term changes in these distributions, the seasonal course and annual mean and extreme water levels; (iii) check whether certain cyclic features may exist in the long-term course of water level, (iv) analyse relationships

* Corresponding author.
E-mail addresses: rain.mannikus@taltech.ee, rainm086@gmail.com (R. Männikus).

https://doi.org/10.1016/j.ecss.2020.106827
Received 18 October 2019; Received in revised form 27 April 2020; Accepted 6 May 2020
Available online 4 August 2020

between the course of water level and atmospheric circulation indices such as the NAO index; (v) establish connections between the identified changes and the wind regime in the study area. The analysis is performed from the retrospective viewpoint. The results serve as a direct contribution into better understanding of the properties and future of sea level in the entire Baltic Sea region.

The readings of water level observations and measurements used in this study reflect the relative sea level. This means that the three main factors influencing its variations (global sea level change, land uplift or subsidence, and changes in the water budget of the sea) are all reflected in the data set. According to (IPCC, 2013), global sea level rose by 1–2 mm/yr during the 20th century. The overall reason for this rise is climate warming with the main mechanisms acting via seawater thermal expansion and gradual melting of glaciers. As these mechanisms impact the whole ocean, their outcome is evidently manifested in the Baltic Sea as well, with or without a local temperature rise. The impact of changes in the water volume of the World Ocean becomes evident in the Baltic Sea via the sea level in the North Atlantic and specifically via sea level variations in the eastern North Sea. As demonstrated in (Mitrovica et al., 2001), this signal substantially depends on which part of the ice cap is melting. About 75% of the basin-average mean sea level change externally enters the Baltic Sea as a mass signal from the adjacent North Sea (Gräwe et al., 2019). The glacio-isostatic adjustment of the Baltic Sea region results in a decrease in the relative sea level in the northern Baltic Sea and in an increase in the southern Baltic Sea (see Harff et al., 2017 and references therein). The first two drivers therefore work against each other in the northern Baltic Sea but jointly enhance the water level rise in the southern regions of this water body. The study area is located in the region that has very small or almost zero vertical crust motion. The rate of the postglacial rebound varies along the Latvian coast from −0.3 to 1 mm/yr (Reiniks et al., 2010).

A regional (basin-wide) sea level component with typical duration of a few weeks reflects variations in the water volume of the whole Baltic Sea (Lehmann and Post, 2015; Lehmann et al., 2017). These variations are caused by water exchange through the Danish straits and by varying river discharge. Both drivers are largely controlled by atmospheric pressure patterns over the North Atlantic. Their variations can be expressed in terms of the North Atlantic Oscillation (NAO) index (Lehmann et al., 2002; Johansson et al., 2004). The water level in the Gulf of Riga (Fig. 1) may additionally experience substantial variations with an amplitude up to 1 m compared to the open part of the Baltic Sea and typical duration of about 1–2 days (Männikus et al., 2019). These variations are driven by storms from specific directions. Minor factors that may affect the Baltic Sea level are variations in salinity, temperature, precipitation and evaporation (e.g., Meier et al., 2004).

2. Data and methods

2.1. Study area

The coastline of Latvia consists of two major parts. The shores of the open Baltic Sea (Baltic proper) are from the border of Lithuania in the south to the Irbe Strait in the north (Fig. 1). This approximately 150 km long coastline section has two currently working water level gauges in the harbour cities of Liepaja and Ventspils, and one previously active measurement site at Pavilosta. The larger part, with a length of about 350 km, comprises the shore of the Gulf of Riga. Regular water level observations have been performed at seven observation stations (Kolka, Roja, Mersrags, Lielupes griva (the eastern part of Jurmala), Daugavgriva, Skulte and Salacgriva) in the Latvian part of the Gulf of Riga, and

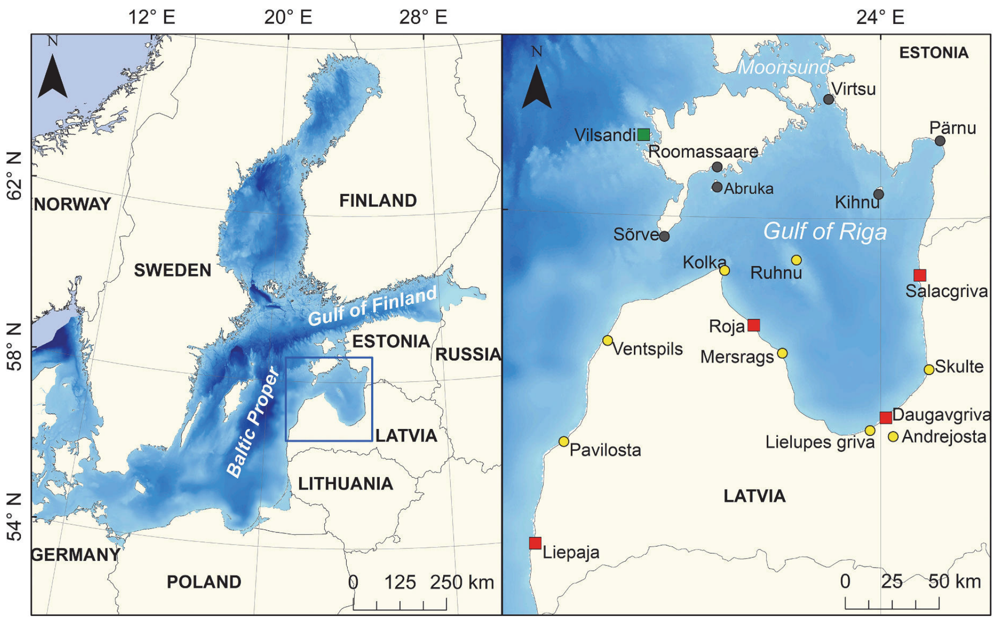


Fig. 1. Water level measurement sites in the Gulf of Riga and at the open coast of Latvia. Red squares show locations with the highest quality and coverage of observations (Tables 1 and 2). Yellow circles depict stations where measurements were less frequent and/or had long gaps. Grey markers indicate measurement stations outside Latvia. The green square shows the Estonian meteorological station which serves as the source of wind information. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

also at Andrejosta in the Port of Riga (Kudure, 2009). Water level observations have also been performed in Estonian waters at Pärnu, Sõrve, Roomassaare, Abruka, Virtsu, Kihnu and Ruhnu. Digitised data are available for all listed Latvian stations and from Pärnu in Estonia.

The Latvian nearshore of the Baltic proper is relatively shallow. The slope of the seabed increases rapidly from a certain distance from the shore. The 10 m isobath follows the shoreline about 7.5 km from the coast and the 20 m isobath is about 15 km away from the shoreline. The shallowest nearshore regions of this district are at the port of Liepaja (Maritime Administration of Latvia, 2014). It is therefore likely that the presence of an extensive shallow nearshore distinctly contributes to the formation of high water levels during strong onshore winds.

The Gulf of Riga is a semi-enclosed water body of generally regular size of about 130 × 140 km (Suursaar et al., 2002). Its main connection with the Baltic proper, the Irbe Strait, is 27 km wide. The water depth in the sill area is generally less than 10 m, except for a 20–22 m deep ravine in its northwestern part (Maritime Administration of Latvia, 2014). Another outlet of the Gulf of Riga goes through the Väinameri (Moonsund) subbasin. Its connection channel, the Suur Strait, is much narrower (4–5 km) and shallower (the sill depth is about 5 m) than the Irbe Strait. For this reason, most of the water exchange between the Gulf of Riga and northern Baltic proper usually occurs through the Irbe Strait.

The gulf is relatively shallow, with a maximum depth of 52 m and an average depth of about 23 m. However, the nearshore seabed deepens more rapidly than on the Latvian segment of the Baltic proper. The 10 m isobath is located approximately 2 km from shore and the 20 m isobath 3.5–8 km from the shore along almost the entire Latvian part of the gulf. Therefore, the contribution of local features (such as the presence of a shallow nearshore) to water level is generally smaller here than on the shores of the Baltic proper. A substantial contribution of local effects into the observed water levels is likely in selected locations on the northern shores of the gulf (Suursaar and Sooäär, 2007).

2.2. Water level data

The history of water level observation at selected locations on the Latvian coast extends over almost two centuries. Currently, automatic tide gauges at ten locations (including Andrejosta) are operated by the Latvian Environment, Geology and Meteorology Centre (LEGMC, http://www.meteo.lv). All water level measurements used in this paper are made from the "zero" datum of each station and are thus not been corrected against uplift rates. This local benchmark (see Kollo and Ellmann, 2019) is an individually selected horizontal plate with a constant absolute height that is linked to the tide gauge height staff.

The formal zero level of the gauge does not necessarily match the long-term water level in single locations (Table 1). The deviations are up

Table 2
Monthly and annual data coverage in the measurement locations in 1961–2018.

Location	Years with gaps (number of missing months in brackets)	Monthly data completeness	Annual data completeness
Liepaja	–	100%	100%
Pavilosta	1963 (1), 2004–2018 (12; station closed)	73.99%	74.14%
Ventspils	1971 (1), 1972 (5), 1973–1986 (12), 1987 (3), 1996–1999 (12), 2000 (9), 2003 (2)	66.09%	65.52%
Kolka	1966 (11), 1967 (9), 1968–1969 (12), 1980 (2), 1984 (3), 1989 (1), 1996 (2)	92.53%	93.10%
Roja	1973 (1), 1984 (1),	99.71%	100%
Mersrags	1961 (9), 1973 (1), 1988–2004 (12), 2005 (9)	67.96%	67.24%
Lielupes griva	1961 (8), 1968 (1), 1998 (1), 1999 (3), 2000 (4), 2001 (5), 2002 (11)	95.26%	93.10%
Andrejosta	–	100%	100%
Daugavgriva	–	100%	100%
Skulte	1972 (4), 1996 (4), 1998 (7), 1999 (2), 2000 (1), 2003 (2), 2004 (7), 2006 (1), 2008 (1)	95.83%	93.10%
Salacgriva	–	100%	100%

Table 1
The main parameters of the measurement locations, basic properties of water level (presented in the BK77 system) and hourly data completeness for 1961–2018. The maximum water level is represented by three values separated by a forward slash: (i) extracted from the current version of the official data, (ii) presented in (Kudure, 2009) and (iii) presented in (Averkiev and Klevannyy, 2010) in the national height system of this time (BK77).

Location	Measurements since	Co-ordinates	Mean level (cm)	Maximum level (cm) with date	Minimum level (cm) with date	Hourly data completeness 1961–2018
Liepaja	January 01, 1865	56°30′56″N, 20°59′58″E	2.0	174/174/174 October 18, 1967	−86 January 18, 1972	99.69%
Pavilosta	1930–December 12, 2003	56°53′N, 21°10′E	0.3	150/169/169 October 18, 1967	−87 December 31, 1978	12.28%
Ventspils	January 01, 1873	57°23′43″N, 21°32′4″E	0.9	141/148/148 October 18, 1967	−76 January 28, 2010	65.19%
Kolka	January 01, 1884	57°44′13″N, 22°35′34″E	1.2	161/134/134 January 09, 2005/ October 18, 1967	−113 November 03, 2000	35.25%
Roja	January 01, 1932/ November 01, 1949	57°30′24″N, 22°48′06″E	−1.0	167/160/160 January 09, 2005/ October 18, 1967	−89 January 28, 2010	30.28%
Mersrags	January 01, 1928	57°20′5″N, 23°7′58″E	0.9	166/183/183 November 02, 1969	−94 September 29, 1967	30.17%
Lielupes griva	January 01, 1946	56°59′1″N, 23°53′15″E	6.9	208/208/208 November 02, 1969	−107 October 14, 1976	96.46%
Andrejosta (Port Riga)	January 14, 1930	56°57′39″N, 24°5′38″E	11.4	225/229/229 November 02, 1969	−121 October 14, 1976	99.78%
Daugavgriva	January 01, 1875	57°3′34″N, 24°1′24″E	9.2	224/214/– November 02, 1969	−107 October 14, 1976	99.98%
Skulte	January 01, 1939	57°18′57″N, 24°24′34″E	6.1	231/247/247 November 02, 1969	−109 October 14, 1976	93.65%
Salacgriva	October 01, 1928	57°45′19″N, 24°21′13″E	5.8	215/228/228 March 28, 1968	−116 October 14, 1976	29.16%

to 11 cm at Andrejosta, around 6 cm at Lielupes griva, Skulte and Salacgriva, and less than 2 cm at other locations. In co-operation with the Latvian Geospatial Information Agency, the "zero" height marks of all Latvian tide gauge stations are levelled to the 1st class points of the national geodetic network with Level 1 precision levelling. The levelling is performed routinely once every two years. Extraordinary levelling is performed every time after a change or maintenance of the tide gauge or when there are reasons to suppose that the height mark has changed significantly.

The countries surrounding the Gulf of Riga used the Baltic Height System BK77 in the past. The reference level of BK77 is associated with the Kronstadt zero. In essence, this is a benchmark at Kronstadt near Saint Petersburg, defined as the average water level at this location in 1825–1840 (Lazarenko, 1986). This height system, which differs from the Scandinavian and Finnish tide gauge benchmarks (e.g., Lisitzin, 1966; Johansson et al., 2001), was used in Latvia until November 30, 2014 and in Estonia until the end of 2017 (Kollo and Ellmann, 2019). As the existing information about water levels in Estonia and Latvia published in the international literature until 2018–2019 and reflected in the synthesis papers (Averkiev and Klevannyy, 2010; Hünicke et al., 2015) is given in the BK77 system, we shall use water level data in this system as well.

From December 01, 2014 the BK77 system was replaced by the height system LAS200.5 (European Vertical Reference System, EVRS) in Latvia. A similar system associated with the Amsterdam Ordnance Datum was implemented in Estonia from January 01, 2018 (Kollo and Ellmann, 2019). The difference in the heights (and water levels) in the old and new system is mostly in the range of 15–24 cm. While the long-term formal average of water level at the observation sites of this region has been just a few centimetres in the BK77 system (Table 1), this average will be around 20–30 cm in the EVRS framework.

The readings of observations and measurements are digitally available for 11 Latvian stations (Table 1) and for Pärnu from 1961. Hence, we focus on time series of water level in the period 1961–2018. The properties of some of the available data sets, a description of several potentially erroneous recordings and an estimate of the level of uncertainties of the data at Daugavgriva, Liepaja, and Pärnu have been discussed in (Männikus et al., 2019) and we reconcile here only a few features. The sampling frequency, coverage and completeness of the recordings vary greatly between locations (Table 1). The sampling at several stations was only performed 2, 3 or 4 times a day, equivalently, once in 12, 8 or 6 h, until automatic hourly measurements were implemented in 2004–2006. While the older data has extensive gaps at some stations (Table 1), the automatic recordings contain only minor gaps with a length of a few hours. As the data were presented "as is", with no information about intercomparison of visually observed and instrumentally measured data, indirect methods were employed to estimate the level of uncertainties of recordings in (Männikus et al., 2019).

The sampling rate varied also over time. For example, water level recordings at Salacgriva are available three times a day in 1961–1981 and twice a day from 1982 until mid-October 2006. Thereafter, hourly data are available. The relevant dataset for Kolka contains four values a day until mid-September 2004. The data for two months in 1980, six months in 1996, and in 1968–1969 (Table 2) are missing entirely.

At Roja, water level observations were even less frequent (twice a day) until the end of 2004. The time series contains two gaps, each with duration of one month, in 1973 and 1984 (Table 2). After 2004 the measurements were carried out hourly, and the recordings have only minor gaps. At Mersrags, observations of water level were carried out 4 times a day until 1987. After that there is a long gap until 2004 when hourly automatic measurements started.

The Ventspils data set contains hourly recordings in 1961–1970. No data is available from 1970 until 1987. Hourly recordings exist again from April 1987 until 1995. The data set has large gaps that extend over months and entire years in the period 1996–2003. During some time intervals of this time period measurements were performed only four times a day. Almost complete hourly data are available from 2004. The presence of an almost 17 yr long gap in the Ventspils data set allows only a limited comparison of data from this station with other data sets, and suggests that trends evaluated for this station may have relatively large uncertainty. The water level recordings were performed at Pavilosta only a few times a day and ended in 2003. This data set is only used in the estimates of the seasonal course (Section 3.1) and the distribution of water level minima and maxima in different months (Section 3.2).

The most comprehensive data is available for Liepaja, Lielupes griva, Daugavgriva, Andrejosta, and Skulte (Table 1). Hourly observations with a very good coverage have been performed at these sites during the entire study period. The data set from Skulte has missing single observations in 1972, 1996, 1998 and 2004 (Tables 1 and 2). At Lielupes griva the gaps occur mostly at the turn of millennia (1998–2002) and during an 8 month period in 1961. Single gaps in the Liepaja and Daugavgriva data sets are mostly shorter than 8 h and only in a few cases extend to a few weeks (Männikus et al., 2019).

The water level course at Liepaja contains large and rapid changes. For example, the water level was 6 cm at Liepaja on January 14, 1993 at 05:00, increased to 144 cm at 10:00 and decreased to 60 cm at 14:00. On December 4, 1999 at 01:00 the water level was 51 cm, reached to 139 cm in 5 h and decreased back to 51 cm at 16:00. Both changes were accompanied by gentler water level variations at Pärnu and Daugavgriva with a lag of 4–8 h. A similar behaviour was observed at Liepaja on October 18, 1967 when the highest ever water level (174 cm) was recorded in this location. This value may be inaccurate (Männikus et al., 2019) but it mirrors very high water level at other stations.

Similar events of large and rapid variations in the water level have occurred at other stations in the Gulf of Riga. For example, water level rose in March 1968 at Salacgriva from 22 cm at 09:00 on March 27 to 215 cm at 15:00 on March 28, and decreased to 48 cm at 09:00 on the following day. As the observations were carried out 3 times day (once in 6 h except at 03:00 in the night), the changes may have been even faster. Although the rise and fall of water level seems realistic, measurement errors or failures to file the correct water level value cannot be ruled out because variations in the water level at other Latvian stations and at Pärnu were only around 50 cm on these days. As such occasions are very infrequent and do not affect the statistical properties of water level, we follow the recommendation of (Männikus et al., 2019) to keep the sensible outliers in the data sets.

2.3. *Inhomogeneity and local features*

From the presented material it follows that the observed water level time series are not fully homogeneous. The most massive inhomogeneity is introduced by an abrupt increase in the number of observations per day from a certain day within the calendar year of 2004 (Kolka and Roja) or 2006 (Salacgriva) when the automatic hourly measurements started. This feature strongly affects the estimates of annual and seasonal properties of water level. The gaps in the data from Kolka, Mersrags, Roja, Salacgriva, Pavilosta and Ventspils make the relevant data sets even less homogeneous. The changes in the frequency of observations additionally complicate the situation. Finally, the switch from visual observations to automatic water level measurements may also

Table 3
Annual and seasonal changes in the relative average water level in 1961–2018 (mm). The total changes are evaluated according to the linear trend. Three different descriptive periods for a year are used: calendar year (*A*), stormy season (from July to June of the subsequent year, *S*) and winter months (from December to March, *W*). Slopes of the relevant linear trendlines, local uplift rates *U*, and estimates of the slope of linear trendlines of the absolute average water level as $S+U$, $A+U$, or $W+U$ are presented in mm/yr. Statistically significant nonzero trends at a 95% and higher level are indicated in bold italics; and at a 90%–95% level in italics. The trends are evaluated based on monthly mean and extreme water levels. The estimates of similar trends based on all single measurements in each year differ from those presented by up to 0.02 mm/yr (see Appendix).

Locations		Change			Slope			*U*	Slope + *U*		
		A	S	W	A	S	W		A	S	W
Liepaja	mean	49	57	128	*0.85*	*0.98*	*2.20*	−0.10	0.76	0.89	2.10
	max	55	29	190	0.94	0.50	3.28		0.84	0.40	3.18
	min	25	35	46	0.43	0.61	0.80		0.33	0.51	0.70
Roja	mean	12	23	97	0.20	0.39	1.68	0.80	*1.00*	***1.18***	***2.46***
	max	46	13	229	0.80	0.23	3.95		1.59	1.01	*4.73*
	min	−60	−36	−19	−1.04	−0.62	−0.33		−0.25	0.16	0.45
Daugavgriva	mean	22	32	119	0.38	0.56	2.05	−0.25	0.14	0.31	1.81
	max	−97	−89	213	−1.67	−1.54	3.67		−1.91	−1.79	3.42
	min	5	19	−26	0.08	0.32	−0.44		−0.17	0.07	−0.68
Salacgriva	mean	57	68	168	0.98	*1.18*	*2.89*	0.20	*1.18*	***1.37***	***3.05***
	max	−5	−117	63	−0.08	−2.02	1.08		0.11	−1.82	1.28
	min	12	45	11	0.21	0.78	0.19		0.41	0.98	0.39

contribute to the level of inhomogeneity.

For the above-listed reasons, we employ several approaches for estimating the properties of water level and their long-term changes. We mostly use monthly mean and extreme values in the analysis of long-term trends. We employ two modifications of this approach. The calculation of statistical parameters of water level based on monthly values is straightforward for Liepaja, Daugavgriva, and Salacgriva where all months contain enough measurements (Table 2). This approach needs a certain modification for time series with longer gaps. To fill the gaps in monthly values, we use the feature that the water level recordings at neighbouring stations are strongly correlated. For example, the correlation coefficient between the simultaneous entries from Daugavgriva and Skulte (the distance between the stations is 37 km) is $R = 0.968$. This feature is useful when it is necessary to fill the gaps in the data set of a closely located station.

All results presented in Table 3 and in the text for Liepaja, Daugavgriva, and Salacgriva that have 100% coverage in terms of monthly properties are obtained using monthly values for these stations. The similar results for other stations also rely on a certain number of interpolated values. The recordings at Roja have a few gaps in the monthly values (Table 2). The missing values are filled with interpolated values from Mersrags and Kolka. The distance between these stations is about 20 km and the hydrometeorological conditions at both locations are fairly similar.

Water level observations or measurements have been performed hourly since 1961 at the stations presented in Table 3 (except for Roja). Therefore, the relevant data series are homogeneous in terms of the frequency of observations. The main source of inhomogeneity is the switch from visual observations to instrumental measurements in 2004–2006. It is natural to assume that the role of this kind of inhomogeneity is smaller than the overall uncertainty of water level measurements. According to (Männikus et al., 2019), the uncertainty of individual recordings is about 0.7 cm at Daugavgriva and about 1.2 cm at Liepaja. This level of uncertainty is negligible in the analysis presented below.

Alternatively to the estimates based on monthly values, we evaluated the main annual and seasonal parameters of water level time series at single sites using all available recordings at these locations during the relevant time intervals. The results are presented in the Appendix. To avoid unrepresentative data (when only a few entries per month are available), the months that contain less than 32 observations at Liepaja or at Kolka are ignored. Doing so guarantees that each month that is involved in the analysis is represented by at least 50% of routine observations. The difference between the resulting estimates is illustrated in terms of slopes of long-trends at the bottom of Table A1 of the Appendix. The results of all described methods coincide for stations with the highest coverage (Liepaja and Daugavgriva).

To estimate the influence of the change in the frequency of observations on the long-term properties and trends of water level, we also evaluated the main statistical parameters of water level time series based on a subset of water level recordings. This was only done for stations where the frequency of observations markedly changed over time. This subset contains the older low-frequency data and a selection from newer hourly data at the same time instants at which the observations exist in the older data. The difference of the slopes of trendlines evaluated using the resulting set of data and the above-described methods is generally smaller than the difference between similar values evaluated using all data and monthly means of water level in Table A1 (Appendix).

As the Andrejosta station is located about 10 km upstream of River Daugava, its water level recordings are strongly correlated with those at Daugavgriva ($R = 0.964$), located at the river mouth. We only partially use data from Andrejosta because since 1974 water level recordings at this location are at times substantially affected by the operational regime of the Riga hydroelectric power plant (see Section 3.2). This impact becomes evident as a specific shape of the annual course of water level. It affects the homogeneity of data and the nature and magnitude of changes to the water level statistics.

The correlation between the recordings made along the shores of the Baltic proper and in the Gulf of Riga is clearly weaker but still substantial. For example, the correlation coefficient of the hourly values at Liepaja and Daugavgriva is $R = 0.889$. This feature suggests that recordings in the Gulf of Riga to a large extent reflect the instantaneous water volume of the Baltic Sea. In other words, large excess water volumes of the Gulf of Riga (Männikus et al., 2019) do not substantially affect the long-term parameters of water level, except for extreme values.

2.4. Analysis of water level and land uplift

We use the highest quality data sets of water level (in terms of homogeneity and temporal coverage) from Daugavgriva and Liepaja (Table 1) to calculate empirical probability distributions of the occurrence of different water levels for different time periods. The changes in the shape of these distributions for different climatic periods (1961–1990 and 1991–2018) are highlighted using a standard Kolmogorov–Smirnov test as a significance test. This test is sensitive to differences in both location and shape of the empirical cumulative distribution functions of the two samples.

Extreme water levels in the Gulf of Riga (both water level maxima and minima, Table 1) are among the largest examples ever recorded in the Baltic Sea (Dailidienė et al., 2006; Averkiev and Klevannyy, 2010). Only on a very few occasions have even higher levels been observed at Saint Petersburg and in the south-western Baltic Sea. This feature is the result of pushing large amounts of water into the gulf during certain storms for a few days (Astok et al., 1999; Männikus et al., 2019) and stresses the importance of better understanding of how the water level extremes have varied in this region in the past. As the observation locations with the largest maxima are open to the predominant strong wind and wave directions (south-west or north-north-west, Soomere and Keevallik, 2001), local storm surge and wave-driven set-up may contribute to single water level readings at some stations (cf. Eelsalu et al., 2014).

Seasonal variations in the average and extreme water levels are studied in terms of their weekly and monthly properties. Slopes of trends are evaluated and their statistical significance (Table 3) is studied for monthly, seasonal, and annual means and extremes of water level over the period 1961–2018. We use standard linear regression techniques with a linear least squares method as realised in the default setup of functions 'fit' and 'fitlm' of Matlab R2019a Curve Fitting Toolbox. The slopes obtained in this manner also include the local land uplift rates.

To properly interpret the long-term changes in the water level at single stations in terms of (changes to) the absolute water level, it is necessary to take into account potential changes in the benchmark height of the measurement locations. The rate of vertical crust movements in the study area can be estimated from the total vertical movement (uplift/subsidence) rates in Latvia. These rates, evaluated using the data from the first state network leveling data of Latvia in 1929–1939 and Latvian State Class 1 leveling data from 2000 to 2010, are described in (Reiniks et al., 2010).

This comparison highlights the average rate of vertical changes in the geodetic points over a 70 yr period. The northwestern coast of Latvia exhibits uplift with a rate of approximately 1 mm/yr. The southeastern part of Latvia exhibits subsidence at an even greater rate, up to about 1.7 mm/yr. The zero line of the Earth's crust movement crosses the territory of Latvia from the vicinity of Liepaja towards Rujiena in the north-east of Latvia (Reiniks et al., 2010). The relevant measurements and modelling exercises suggest that Liepaja, Daugavgriva, and Salacgriva are located close to this zero line (Table 3). Liepaja, Lielupes griva, and Daugavgriva exhibit slow subsidence (0.1–0.25 mm/r) whereas other water level measurement sites used in this paper exhibit uplift from 0.2 mm/yr (Salacgriva) up to about 1 mm/yr at Kolka (Reiniks et al., 2010).

This analysis of the changes in the resulting absolute water levels is performed for monthly, seasonal and annual average, minimum and maximum water level under assumption that the land uplift rate has been constant during the entire study interval. This approach implies that the slopes of trends in the parameters of the absolute water level can be expressed as the sum of the relevant slope for the relative water level and the uplift or downlift rate (cf Table 3). As the uplift rates are fairly small, we focus on the behaviour of the relative water level and present the results for the trends in the absolute water level in terms of modifications in their level of statistical significance.

In order to examine the relationships between observed water levels and climate variations, we explore the correlations between the water level and the NAO index. This index, in essence, mirrors the difference in surface air pressure between Stykkisholmur, Iceland and Gibraltar (Jones et al., 1997) or Ponta Delgada, Portugal (Hurrel, 1995). As the NAO Gibraltar index offers slightly more consistent results in the analysis of the changes in the climate of Estonia next to the study area

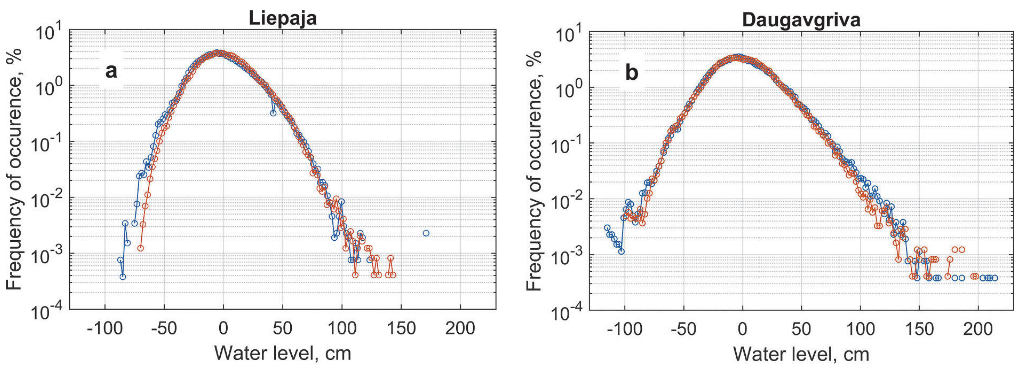


Fig. 2. Empirical probability distributions of occurrence of different water levels at Liepaja (a) and Daugavgriva (b) for the 30-year period of 1961–1990 (blue) and 28-year period of 1991–2018 (red). The horizontally aligned markers for high water levels at the lowest frequency of ~0.0003% correspond to the recorded surge heights that happened exactly once in the period 1961–2018. The outlier at 174 cm for Liepaja corresponds to five equal entries on October 18, 1967. See (Männikus et al., 2019) for comments on these values. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(Jaagus, 2006), we rely on this data (NAO Gibraltar) for the Latvian coast as well.

Additionally, we counted the number of storm days in every month based on recordings of wind properties at the Vilsandi meteorological station to the east of the island of Saaremaa in Estonia (Fig. 1). This count characterises to some extent possible changes in storminess in the Gulf of Riga. A storm day is defined in Orviku et al. (2003) as a day during which the wind speed is at least 15 m/s. The data from Vilsandi is used for this purpose because of its demonstrated quality in the representation of different wind properties in the northern Baltic proper. The wind data at Vilsandi is highly reliable except for easterly winds (Soomere and Keevallik, 2001) but these winds are generally less frequent and much weaker than south-western or north-north-western winds in this region.

3. Results

3.1. Probability distributions

The shape of empirical probability distributions of the occurrence of different water levels is analysed based on the most comprehensive Liepaja and Daugavgriva hourly data. Without loss of generality we consider here only relative water levels as recorded at the measurement sites. This approach is acceptable because the presence of weak land subsidence or uplift basically shifts such distributions built for different time intervals up or down but does not alter their shape. The overall shape of such distributions (Fig. 2) reflects a quasi-Gaussian appearance of similar distributions in the north-eastern Baltic Sea (Johansson et al., 2001). This shape substantially deviates from the shape of analogous distributions in the North Sea (e.g., Schmitt et al., 2018). The higher-value range of such distributions of the non-tidal residual water level usually approximately follows an exponential distribution (represented by a straight line in log-linear coordinates used in Fig. 2) that is characteristic for Poisson-type processes.

A quasi-Gaussian shape of these distributions in the Baltic Sea (Johansson et al., 2001; Soomere et al., 2015b) apparently reflects the joint impact of storm surges and the frequent presence of large volumes of excess water pumped into the Baltic Sea by certain sequences of atmospheric processes (Leppäranta and Myrberg, 2009). While the empirical probability distribution of short-term variations in the water level (with a time scale less than a week) is approximately exponential (Soomere et al., 2015b), the similar distribution for the background (weekly-scale) water level of the entire Baltic Sea usually has an almost Gaussian appearance (Soomere et al., 2015b).

The distributions in question are asymmetric at all measurement sites. Also, the similar distributions of the contributions of different components into the water level (not presented here; see Männikus et al., 2019 for details for Liepaja and Daugavgriva) are asymmetric in all considered locations. This shape of the distributions mirrors the well-known feature of this part of the Baltic Sea that elevated water levels are more likely than negative surges (Johansson et al., 2001; Suursaar and Sooäär, 2007). This conjecture is true for both storm surges and for the processes that reflect the water volume in the Baltic Sea and in the Gulf of Riga (Männikus et al., 2019). The magnitude of asymmetry (in terms of skewness of the distributions in question) is relatively large at Liepaja and Daugavgriva (1.431 and 1.674, respectively). This feature is consistent with the appearance of the relevant distributions that, visually, are more asymmetric than those at Tallinn (Soomere et al., 2015b) or Hanko (Johansson et al., 2001).

A comparison of the empirical probability distributions for the standard 30 years long climatological time interval 1961–1990 and for the years 1991–2018 indicates that these distributions have undergone certain changes. The largest alteration is that very low water levels (below −40 cm) have become less frequent at Liepaja (Fig. 2). The frequencies of occurrence of elevated water levels have remained practically unchanged. The number of entries exceeding 120 cm is also practically the same for the two intervals. The distribution has thus become narrower.

The changes are slightly different at Daugavgriva. A few occasions of very low water levels (below −100 cm) in 1961–1990 have not been repeated in 1991–2018 whereas the overall distribution of low water levels remains the same. A slight decrease has occurred in the frequency of relatively high water levels (around 100 cm). All very large recordings (around 200 cm) come from 1961 to 1990. The skewness parameter has decreased at both locations: from 1.425 to 1.159 at Liepaja and from 1.682 to 1.520 at Daugavgriva. These values are almost insensitive with respect to the choice of the time intervals. For example, for the 25 year long time intervals 1961–1985 and 1991–2015 the listed values are 1.465, 1.142, 1.684, and 1.515, respectively. The described pattern of changes indicates that the strong predominance of westerly winds over easterly winds in the entire Baltic Sea region (Omstedt et al., 2004) may have been modified to some extent over the last half century in the vicinity of the study area. The described feature can be caused, for example, by a shift of a part of strong wind direction from the west to the south-west (Bierstedt et al., 2015).

The changes are also relatively large in terms of kurtosis that to some extent characterises the probability of occurrence of very large absolute values of the quantity in question. The presence of a few positive outliers is typical for the water level regime in this region (Johansson et al., 2001; Soomere et al., 2015b). The kurtosis decreased from 3.576 to 2.826 at Liepaja and from 4.456 to 3.819 at Daugavgriva. The analogous values for 1961–1985 and 1991–2015 are 3.706, 2.775, 4.446, and 3.801, respectively. This change can be interpreted as showing a decrease in the probability of extremely low and extremely high water levels. A possible conjecture is that storms that produce the largest deviations of water level from the long-term average have not become stronger in the central Baltic Sea (cf. Rutgersson et al., 2014; Hünicke et al., 2015).

The changes in the shape of the distribution in question are clearly seen at Liepaja. The null hypothesis (that the distributions for different time periods are of the same form) was rejected by the Kolmogorov–Smirnov test at a 95% significance level at Liepaja. The changes at Daugavgriva are less pronounced and not statistically significant (74%). Interestingly, the level of significance of changes was much higher

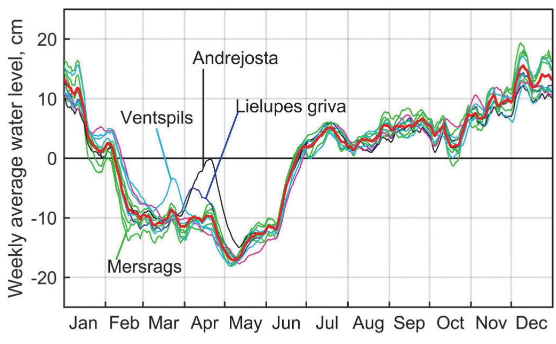


Fig. 3. Seasonal variation in the weekly water level at all 11 stations listed in Table 1 with respect to the long-term average at single measurement locations (thin lines) and in the average over nine stations (excluding Pavilosta and Andrejosta, thick red line). Differently from the rest of the analysis, we use here de-meaned values of water level for better comparison of data from different locations. The values of water level at single stations are first evaluated for each calendar day and then smoothed using a running average over seven days. The magenta line shows the variation at Pavilosta in 1961–2003, cyan lines represent other stations on the Baltic proper coast and green lines show other stations in the Gulf of Riga. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(87%) for time intervals 1961–1985 and 1991–2015 at Daugavgriva. This feature may be interpreted as signalling that certain changes to the water level regime occurred at the end of the 1980s (cf. Soomere et al., 2015a).

Further analysis of changes to the seasonal distributions of the occurrence of different water levels (for the sake of brevity not shown here) shows that the most pronounced variations to these distributions occurred for the windy autumn and winter season (understood as the period from October till March of the subsequent year). The changes to these distributions were much smaller in the relatively calm spring and summer season (from April to September). These results are in line with (Johansson et al., 2001).

3.2. Seasonal cycle

The seasonal cycle is a major component of sea level variability in micro-tidal water bodies such as the Baltic Sea (Passaro et al., 2015). Similar to the assumption employed in the analysis in Section 3.1, it is acceptable to consider the set of relative water level data in the analysis of seasonal variability because vertical crustal movements do not affect the properties of the seasonal course. It is well known that water level in the eastern Baltic Sea has extensive seasonal variability (Ekman and Stigebrandt, 1990; Jarmalavičius et al., 2007; Hünicke and Zorita, 2008; Karabil et al., 2018; Pajak and Kowalczyk, 2019). The seasonal cycle at all Latvian stations follows the classic perception that water level is generally below the long-term average during the relatively calm season (March–May) and well above average during the relatively windy autumn and winter. The average amplitude of the annual cycle is 30–35 cm at all stations. This amplitude is somewhat larger than that observed at Finnish stations (Johansson et al., 2001) and on the southern coast of the Gulf of Finland (Raudsepp et al., 1999). It is much larger than is witnessed on the Polish coast (Pajak and Kowalczyk, 2019).

The seasonal cycles of all stations, except for three sites (Fig. 3), follow each other almost exactly. The largest deviations of the weekly average at single stations from the average over all stations are less than ±6 cm for eight stations (Fig. 3). The deviation of up to 10 cm at Andrejosta in April apparently reflects the spring discharge maximum of River Daugava. This massive difference of the seasonal course of water level at Andrejosta from that in other stations signals that water level variations at this location are often strongly impacted by the river discharge. Therefore, changes in the water level regime at this location do not necessarily reflect processes in the Gulf of Riga. Moreover, the analysis in Passaro et al. (2015) suggests that the run-off from the River Daugava during warm winters with heavy precipitation could additionally raise the water level at the river mouth. For these reasons we exclude this data set from the detailed analysis of changes in the properties of water level. Similar spring maxima are also evident in the water level course at Ventspils in the Venta river mouth and at Lielupes griva about 3 km upstream of the Lielupe River. As their amplitude and duration are much smaller than at Andrejosta, we keep the relevant data sets in the further analysis.

The distinct maximum of water level from mid-November to mid-January is unusual in the older data from the western and southern Baltic Sea (Hünicke and Zorita, 2008). This maximum has frequently occurred (most notably in the eastern Baltic Sea) since the middle of the 20th century. For example, at Klaipėda a strong peak occurred in

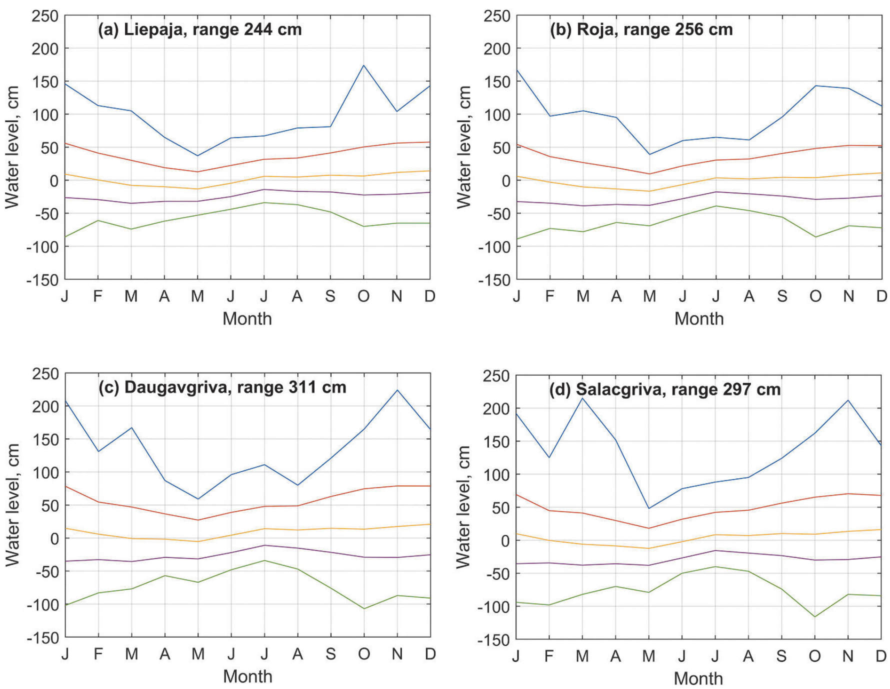


Fig. 4. Seasonal variations in monthly water level properties 1961–2018. Lines from top: absolute maximum for a given month, average monthly maximum, mean, average monthly minimum, and absolute minimum for a given month.

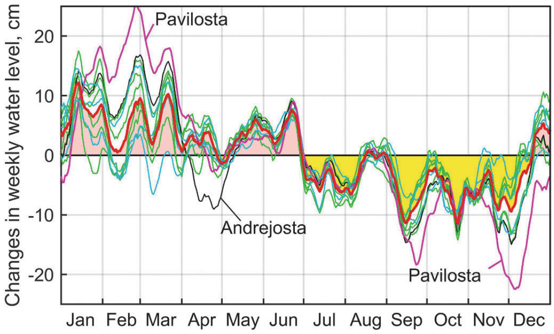


Fig. 5. Changes in the weekly average water level at single measurement locations (thin lines) and in the average over all locations (thick red line) between the years 1961–1990 and 1991–2018. The variations at Pavilosta (magenta line) can be only evaluated for 1961–1990 and 1991–2003 and are thus ignored in the calculation of the average over all locations. The steep decrease in water level at Andrejosta (black line) in April most likely represents the impact of the Riga hydroelectric power plant on the spring discharge of the Daugava River. As the level and timing of this impact is unclear, the data from Andrejosta has been also excluded from the calculation of the average over all locations. Cyan lines represent the other stations on the Baltic proper coast (Liepaja and Ventspils) and green lines the other locations in the Gulf of Riga. Light red and yellow areas show the time interval for which the average water level has increased, or decreased, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

July–September in 1898–1927 whereas a relatively weak peak was seen in January in 1976–2005 (Jarmalavičius et al., 2007). The winter maximum (Fig. 3) is separated from an equally distinct minimum in March–May by a rapid decrease in the water level in the second half of January and February. The spring minimum is followed by four summer and autumn months (July–October) during which the average water level slightly exceeds (by up to 6 cm) the long-term value (Fig. 3). The average water level during these months contains two minor maxima in July and in September, similar to the situation at several locations around the Baltic Sea (Hünicke and Zorita, 2008).

These maxima become evident at all Latvian stations, both on the shores of the Baltic proper and in the Gulf of Riga. Their presence is consistent with the results of the analysis of long-term spectra of the variability of Baltic Sea water levels. The presence of the midsummer maximum is apparently reflected as a strong semi-annual peak of the Baltic Sea seasonal variability (Stramska, 2013) whereas the peak in September may substantially contribute to the spectral peak that is interpreted as evidence of pole tide (Medvedev et al., 2017).

A qualitatively similar seasonal course is evident for other important parameters of water level such as water level extremes in terms of the absolute and average maximum and minimum for a given month. An analysis of seasonal variations in the parameters in question (Fig. 4) underlines seasonality as an important feature of water level variability.

The largest amplitude of water level in the entire study area exceeds 3 m at Daugavgriva in the southernmost bayhead of the Gulf of Riga. As the largest variations are characteristic to the months with the largest average water level, it is likely that this feature is mostly driven by wind stress (Karabil et al., 2018). This range is close to 3 m at Salacgriva on the eastern shore of the Gulf of Riga. The total range of variations is clearly smaller at Roja (256 cm) where the water level course seems to follow mostly that of the Baltic proper. The largest values of the extremes (highest ever and lowest ever water levels) in single months as well as the average monthly maxima and minima qualitatively follow the same seasonal course along the entire Latvian coast (Fig. 4).

Previous research has demonstrated that the amplitude of the seasonal cycle of water level (or its components) has increased in the Baltic

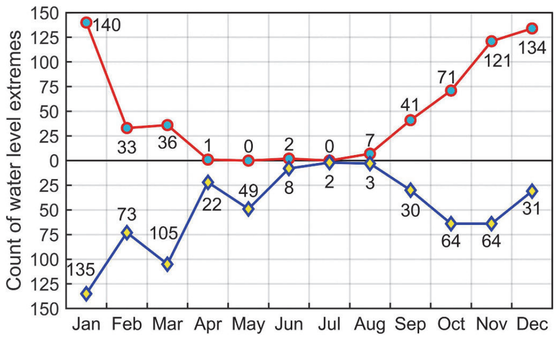


Fig. 7. The count (numbers at markers) of annual extremes at all 11 stations listed in Table 1 in different months 1961–2018. Red: water level maxima, blue: water level minima. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

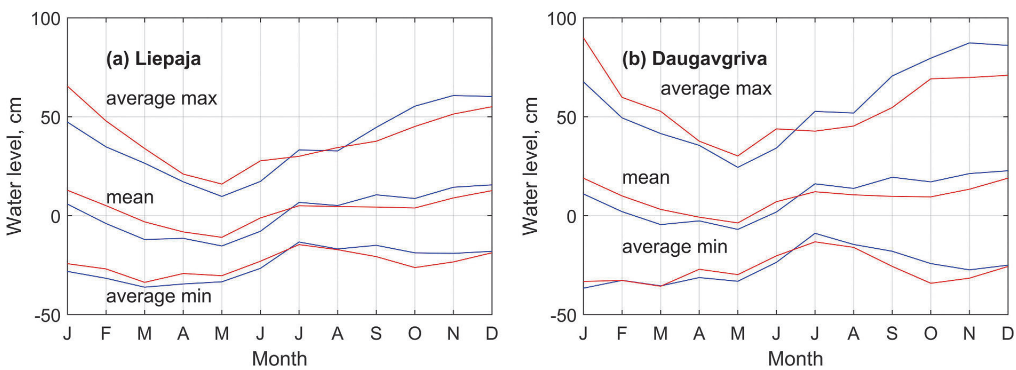


Fig. 6. Seasonal variations in monthly mean, maximum and minimum sea level at (a) Liepaja and (b) Daugavgriva for the 30-year periods of 1961–1990 (blue lines) and 1991–2018 (red lines). Lines from top: average of monthly maxima, mean, and average of monthly minima of water level. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Sea (Ekman and Stigebrandt, 1990; Hünicke and Zorita, 2008). Interestingly, for the Latvian waters the annual cycle shows the opposite behaviour. The changes in the seasonal average water level (Fig. 5) from 1961–1990 to 1991–2018 are almost exactly opposite to the seasonal course shown in Fig. 3. The average water level in months that had lower than average water levels in 1961–1990 (February–June) has increased substantially, on average by more than 5 cm. On the contrary, the average water level in months that had relatively high water levels in 1961–1990 (July–November) has decreased even more, by up to 8 cm in terms of monthly averages. The only exceptions are the second half of December and January.

This increase in the average water level in February–June and the decrease in July–November has apparently enhanced the winter maximum shown in Fig. 3. However, it has substantially suppressed the amplitude of the seasonal cycle. Importantly, this process is evident both on the Latvian shores of the Baltic proper and in the Gulf of Riga. Fig. 5 indicates that during a large part of the year the magnitudes of changes at all stations in the Gulf of Riga lie between those at Liepaja and Ventspils.

To further elaborate on the changes that have occurred in the seasonal course of various properties of water level, we address the monthly average minimum, mean and maximum water levels for single months for the time intervals of 1961–1990 and 1991–2018 (Fig. 6). The values of all listed parameters have substantially increased at the beginning of the year (from January to June) and decreased in autumn (from September to November). This feature is evident in all data sets and thus reflects changes in quite a large area of the Baltic Sea.

The reasons for such pattern of changes are unclear. The winter increase in the mean and maximum water levels in both the Baltic proper and in the interior of the Gulf of Riga may to some extent reflect a decrease in the extent of ice cover and an associated increase in the impact of wind on the water surface. A more probable driver of these changes is an alteration of the air pressure and wind patterns. While the sea level in the North Sea–Baltic Sea transitional zone is mostly driven by wind stress (Passaro et al., 2015), variations in the water level in the interior of the Baltic Sea are predominantly governed by atmospheric pressure (Karabil et al., 2018). Atmospheric pressure, ideally, can explain up to 88% of the water level variability in wintertime and 34% in summertime. The second most important driver is wind. Net energy flux at the surface explains up to 35% of the sea level variability in wintertime but a very small amount in summertime (Karabil et al., 2018). The changes in the summer part of the seasonal cycle therefore signal alterations in the large-scale pattern of atmospheric pressure whereas similar changes in wintertime apparently mirror modifications in the wind regime in the vicinity of the study area.

The described variability also provides *inter alia* a clue for the further analysis of long-term trends in water level in different seasons. For many purposes (e.g., for the evaluation of extreme water levels and their return periods using the block maximum method) it is important to ensure that water level extremes in successive time intervals are uncorrelated. Figure 7 demonstrates that the calendar year maxima of water level are concentrated in three months (November, December and January).

This feature means that the use of calendar years for extracting various extreme values (maxima or minima over certain time intervals) may lead to correlated values. Such correlated maxima may happen if a sequence of storms at the end of a year pushes a large amount of excess water into the Baltic Sea so that its water level remains high over a longer time period. For this reason it is recommended to use the maxima of the entire relatively windy season for the analysis of extreme water levels and their return periods in this water body (Soomere and Pindsoo, 2016). We follow this recommendation in the analysis of long-term behaviour, trends, and possible cycles in time series of extreme water levels.

The analysis presented in Fig. 7 suggests that it is sensible to use the time interval from July to the subsequent June (called stormy season below) for the evaluation of trends of various water level properties

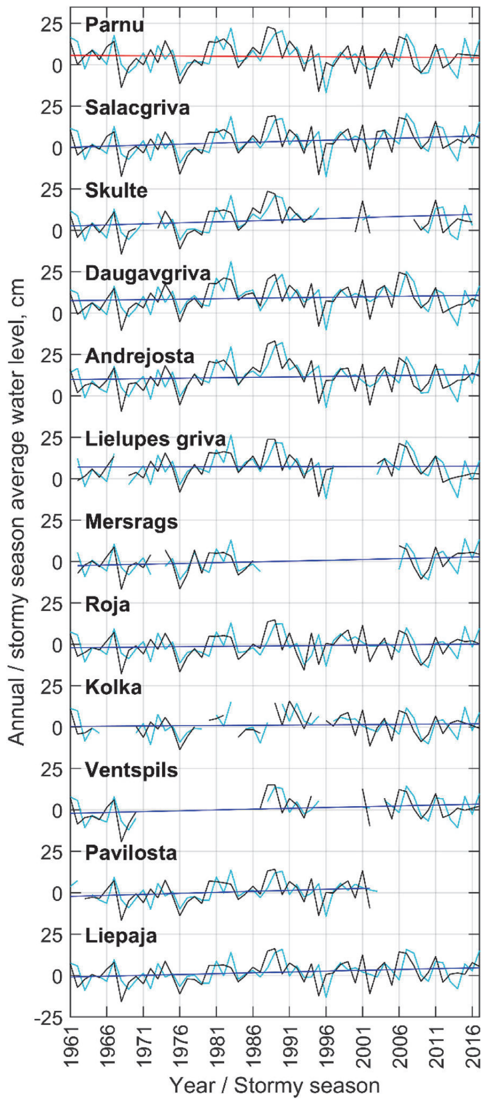


Fig. 8. The temporal course of annual average water level and its trendline in 1961–2018 at all Latvian stations listed in Table 1 and at Pärnu. The black lines mark the average evaluated for stormy seasons (the time intervals from 01 July to 30 June of the subsequent year) and cyan lines indicate the annual average. Note small, but important, differences between the two definitions of average water level (whether months from January to December or from July to the subsequent June are used to calculate the annual mean). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(especially trends of extreme values). This choice evidently leads to a more consistent interpretation of changes to the water level in wintertime (that otherwise may be split between two calendar years). In particular, it ensures that the selected water level maxima or minima are separated by a calm season and are maximally uncorrelated.

This approach also resolves the problem of the interpretation of a few unusual water level maxima, namely the annual maximum water levels at Liepaja (64 cm) and Skulte (98 cm). These values, recorded during a usually calm end of spring, on June 23, 1994, are abnormally low even for a typical calendar year. These recordings served as the maxima of this year only because the stormy season of autumn/winter 1993/1994 ended relatively early and the stormy season of autumn/winter 1994/1995 started relatively late. In all other respects these two stormy seasons were not exceptional. The presence of such extreme values because of the counting method potentially affects the projections of extreme values and thus management decisions. The use of the notion of stormy seasons leads also to a sensible separation of water level minima that are distributed much more evenly over different months (Fig. 7). For the listed reasons we consider in parallel, trends of the annual properties of water level and the same properties over stormy seasons that are defined as time intervals from July 01 to June 30 of the subsequent year.

3.3. Annual average water level

The times series of the annual average relative water level at all Latvian measurement sites (except for Lielupes griva) exhibit a gradual increase 1961–2018 (Fig. 8, Table 3). The rate of this increase varies from almost zero at Roja up to 0.98 mm/yr at Salacgriva. These rates are much smaller than in neighbouring countries and the data from Lielupes griva even shows a decrease at rate of −0.14 mm/yr. The increase in the annual and stormy season water level is statistically significant at a relatively low level of significance at some locations (Table 3). For example, the increase in the annual average is significant at a 90% level at Liepaja (91%), Skulte (92%) and Salacgriva (90%). The largest trends in the stormy season at Salacgriva (1.18 mm/yr) and Liepaja (0.98 mm/yr) are significant at a 93% level. No trend is statistically significant at a >95% level.

To estimate a proxy of the absolute average water level, we corrected the time series at single locations using the long-term crust uplift rate (Table 3). Technically, adding this rate to the slope of the relevant trendline of the relative water level results in the slope of the trendline of the absolute water level. This operation, however, modifies the estimates of confidence intervals of the resulting slope and thus also affects the level of statistical significance of the resulting trends.

The estimated rate of change in the absolute average water level varies from −0.39 mm/yr at Lielupes griva to 1.37 mm/yr at Salacgriva. These values are clearly less than in neighbouring areas. For example, the rate at Klaipėda is 1.3 mm/yr for 1898–2002, about 3 mm/yr since the 1970s and as high as 3.87 mm/yr for 1961–2002 (Dailidienė et al., 2006). The rates are from 1.5 mm/yr (at Ristna) to 2.3–2.7 mm/yr at Pärnu in the Estonian waters (Suursaar et al., 2006; Suursaar and Sooäär, 2007). The most intriguing is the difference in this rate at Sõrve (2.8 mm/yr) on the northern side of the entrance to the Gulf of Riga (Suursaar et al., 2006) and at Roja (1.00 mm/yr, Table 3) that is located only about 30 km to the southwest of the entrance on an almost straight coast. Somewhat smaller but still substantial is this difference between these rates at Pärnu and Salacgriva, both located on the eastern shore of the Gulf of Riga.

Interestingly, the discussed rates are much smaller than the signal of global ocean level rise at the entrance to the Baltic Sea (Gräwe et al., 2019) and different from similar rates in the neighbouring countries. In both Estonia and Lithuania, the average sea level has risen faster than in the global ocean (Dailidienė et al., 2006; Suursaar et al., 2006). About 60% of the observed local water level rise in Estonia is explained by global drivers while the rest (about 40%) is driven by regional and local factors (Suursaar et al., 2006).

The rates in question reflect the joint effect of (i) the global sea level rise, (ii) changes in the impact of (westerly) winds that fill the Baltic Sea with excess water, (iii) changes in the properties of drivers that create local storm surge and wave set-up. For the measurement locations in the Gulf of Riga (iv) changes in the impact of westerly winds that push extra water into this gulf may also play a role. A comparison of the outcome of the analysis in (Dailidienė et al., 2006; Suursaar et al., 2006; Suursaar and Sooäär, 2007) with Table 3 signals that changes in local drivers (ii)–(iv) have systematically mitigated the impact of global ocean level rise in Latvian waters during the time interval in question.

The pattern of long-term changes in the water level at Latvian measurement locations in single months (see Appendix) and seasons is qualitatively similar to the one in Estonia and Lithuania. The average relative water level generally decreases in all months from July to November at all measurement locations. None of the decreasing trends are statistically significant at any sensible level (~90%). The average water level increases relatively rapidly (1.96–4.16 mm/yr) in January. The increase is statistically significant at a >90% level at Liepaja, Skulte and Salacgriva. Consistently with Fig. 7, the increase is less pronounced but systematic at all locations in all months from February to June. It is statistically significant at a 95% level at seven stations in June and at a 90% level at five stations in April.

The presented analysis shows that trends of the relative water level in single months in summertime (June–August) have opposite signs at some stations. As a consequence, none of the trends for average water level during the summer season are statistically significant. This feature also compensates to some extent the trends for winter. Different studies assume different months for the winter season. Suursaar and Sooäär (2007) consider winter as a time period from January to March (JFM). We employ the viewpoint of Dailidienė et al. (2006) and assume that the time period from December to March (DJFM) represents winter in the study area. We only note that the trends found for JFM are generally steeper than those evaluated for DJFM.

The average relative water level in winter shows a much more rapid increase than in the summer months (Fig. 5, Table 3). The slopes of the relevant trendlines of the December–March average water level are mostly over 2.05 mm/yr, except for Roja and Lielupes griva where the increase is 1.68 and 1.20 mm/yr, respectively. This seasonal variation in the trends of average water level is similar in Lithuania and Estonia (Dailidienė et al., 2006; Suursaar and Sooäär, 2007). The trend of winter average water level is not statistically significant at a 95% or higher level at the considered stations. The closest p-values to this level ($p = 0.05$) for December–March are for Liepaja (0.065, 93% statistical significance), Daugavgriva (0.11, 89%) and Salacgriva (0.063, 93%). These relatively large p-values apparently reflect much stronger interannual variability of winter average water levels compared to the annual averages.

A clearer pattern is evident in the analysis of trends for the first (January–June) and second (July–November) half-years (see Table A1 in Appendix). We exclude water level recordings in December from this analysis as trends in different segments of this month have slopes with different sign. The average relative water level in January–June increases at all stations. The increase is statistically significant at a level of >95% at Salacgriva (2.08 mm/yr) and Liepaja, and at a level of >90% at Daugavgriva and Skulte. The average water level decreases at all stations in July–December. The decrease is statistically significant at a 95% level at Kolka and at a level slightly below 90% at Roja, Lielupes griva and Daugavgriva in July–November.

A correction of the water level time series by taking into account the crustal uplift or subsidence gives an absolute water level increase at Daugavgriva in January–June below the 90% level of statistical significance but does not affect the 95% level of significance of the increase at Liepaja. This correction increases the level of significance of the increase at all other stations (except for Lielupes griva). It results in a 95% level of significance of the increase in the absolute water level at Kolka, Roja, Mersrags, Skulte, and Salacgriva. On the contrary, none of the trends of the absolute water level in July–November is even close to being

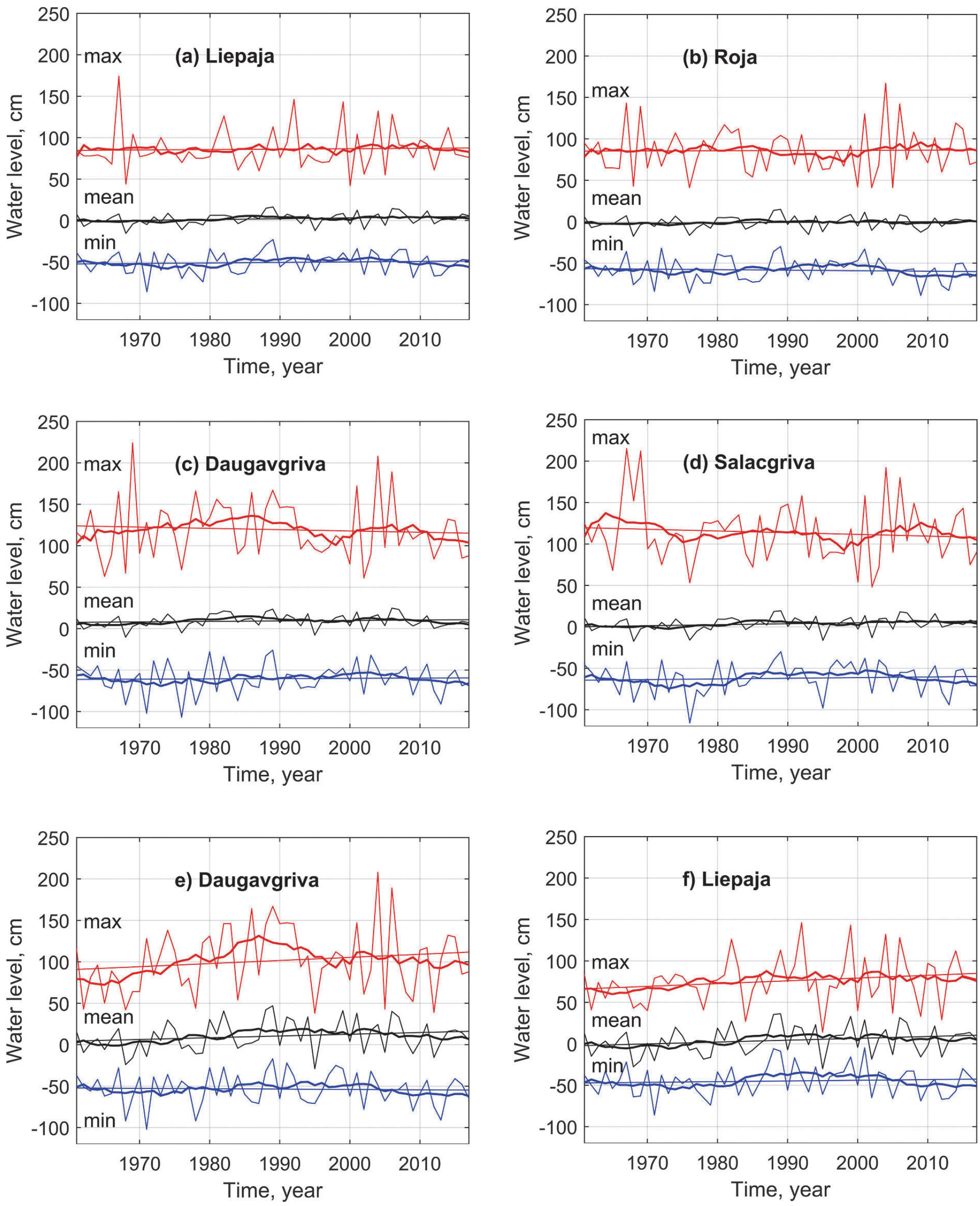


Fig. 9. Stormy season mean (middle lines), maximum (upper lines) and minimum (lower lines) water level and their 11-yr moving averages and trends, evaluated for time intervals from July to June of the subsequent year (a–d) and for winter (from December to March (e, f)).

statistically significant.

3.4. Water level maxima and minima

The trends of annual water level extremes (both maxima and minima) do not show any distinct pattern and even their signs vary at different stations (Table 3). The same is true for the maxima and minima over stormy seasons. The relevant trends are not statistically significant at any reasonable level. While the maxima generally increase, the magnitudes of the minima decrease at several measurement locations. As the water level minima in this region are usually driven by joint impact of high atmospheric pressure and persistent easterly winds, this feature signals that the intensity and/or duration of easterly winds may have decreased during the last half century in the study area.

The pattern of changes in monthly maxima and minima (see Appendix) is also highly variable. The maxima generally increase in January–June and decrease in July–November. The increase is strongest and statistically significant at a 90–95% level at several stations in January and, somewhat surprisingly, in June. As water level maxima in February–June usually do not serve as the annual maxima (Fig. 7), this increase, as well as the decrease in the magnitude of water level minima, apparently reflects the overall increase in water level in the entire study area in these months. Similarly, a generally occurring decrease in the monthly maxima in July–December at all stations apparently mirrors the overall decrease in the water level in these months.

An interesting nuance is provided by the analysis of seasonal water level extremes. The relevant pattern can be highlighted by looking at trends in the maximum water level over four winter months from December to March. The winter (DJFM) maxima exhibit relatively steep increase at almost all locations. The relevant trends differ from those evaluated for the annual maxima. For example, the annual maxima at Daugavgriva exhibit a strong decrease (−1.67 mm/yr) whereas the winter maxima have the second largest increase rate among the stations considered (3.67 mm/yr; Fig. 8). As the monthly maxima decrease in November and December and increase in January and February, the discussed increase in the winter (DJFM) maxima suggests that the season of strongest winds (in terms of their impact on the water level) is being gradually shifted from November–December to January–February.

Similar to the annual and stormy season minima, the winter water level minima possess no distinct trend. The annual and winter (DJFM) minima have become smaller at all stations (except for Roja where the annual minima have increased by −1.04 mm/yr). The changes are the smallest at Daugavgriva (0.08 and −0.44 mm/yr, respectively).

The discussed changes may partially reflect changes in the entire seasonal pattern of water level in this region. To some extent, these changes could be explained by a rotation of strong winds in the winter season. Daugavgriva and Lielupes griva are located in the shallow south-eastern bayhead of the Gulf of Riga. Differently from other stations, a growing number or increasing strength of storms from north-north-west may lead to an increase in both mean and extreme water level at these locations. The other measurement locations are apparently less sensitive to such changes in the wind pattern. The lowest trend slopes of the annual and winter maxima (−2.49 and 0.80 mm/yr, respectively) are found at Lielupes griva. The slopes of trends of annual maxima at Liepaja and Roja are positive (0.94 and 0.80 mm/yr) and relatively large in winter (over 3.28 mm/yr). This spatial variation suggests that the established set of trends of annual maxima in the interior of the Gulf of Riga is a local feature of the gulf and does not necessarily become evident in the Baltic proper.

3.5. Cyclic features

A moving average of some of the discussed quantities (stormy season mean, maximum, and minimum water level) evaluated using an 11-yr time window (Fig. 9) further highlights the presence of the trends described in Table 3. Differently from the situation at the Polish shores (Wisniewski et al., 2011), there is no evident cyclic behaviour of any of the quantities on Latvian shores. However, some cycles with an apparent period of ~30 years appear in the time series of maximum water levels at Daugavgriva and Salacgriva in the interior of the Gulf of Riga. Relatively strong positive anomalies (systematic deviations from the long-term average) in the 1980s and clearly smaller negative anomalies in the 1960s are evident at Daugavgriva. Large fluctuations of the values of annual extremes are characteristic at all stations in 2000–2010 and to a lesser extent at the end of the 1960s. However, these features do not show a regular pattern.

The deviations of the moving averages from the long-term mean values are much larger during winter months (from December to March) than in other seasons. Moreover, the trends for winter months (Table 3) are by more than 0.90 mm/y steeper (advancing to 5.86 mm/y at Daugavgriva) than those evaluated for the entire year or stormy season. This feature was also highlighted in the analysis of Lithuanian water levels (Dailidienė et al., 2006). It is apparently related to warm winters which are caused by more frequent advection of warm and wet air masses during the cold period. This process leads to rising temperature

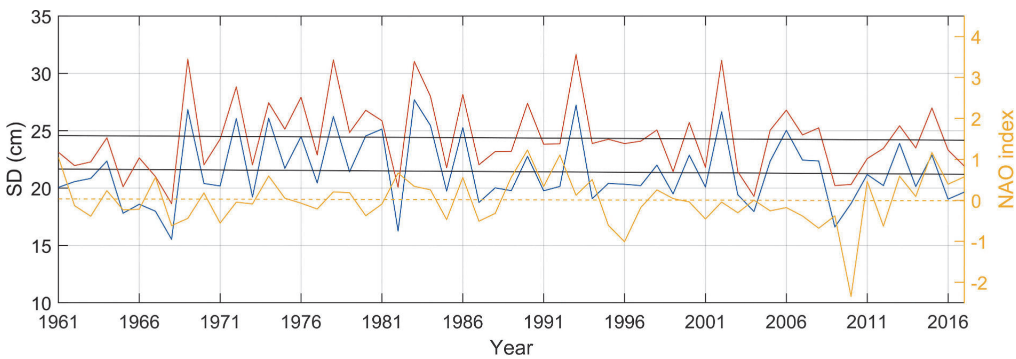


Fig. 10. Temporal course of the annual mean NAO (Gibraltar) index (orange) and water level standard deviations (SD, calculated from hourly data) at Liepaja (blue) and Daugavgriva (red). Straight lines are linear trendlines (starting from above: Daugavgriva, Liepaja, NAO index). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 4
Correlation coefficients between the annual NAO index and annual, minimum, mean, maximum, and standard deviation (SD) of water level, and the listed quantities in winter (from December to March). SD is calculated from hourly data that are available only for Liepaja and Daugavgriva.

	Min		Mean		Max		SD	
	all	winter	all	winter	all	winter	all	winter
Liepaja	0.32	0.72	0.33	0.68	0.29	0.51	0.16	0.32
Roja	0.38	0.73	0.43	0.70	0.38	0.55	–	–
Daugavgriva	0.34	0.72	0.32	0.68	0.27	0.48	0.22	0.40
Salacgriva	0.26	0.68	0.35	0.72	0.36	0.61	–	–

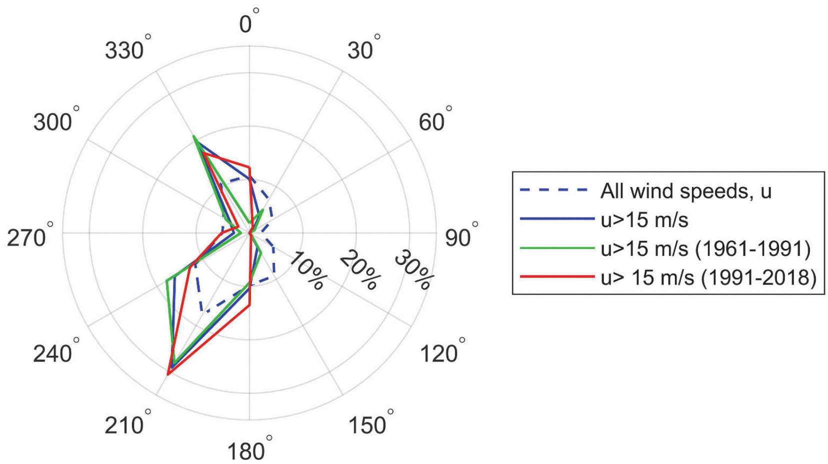


Fig. 11. Frequency of occurrence of all wind speeds and strong winds (>15 m/s) at Vilsandi 1961–2018.

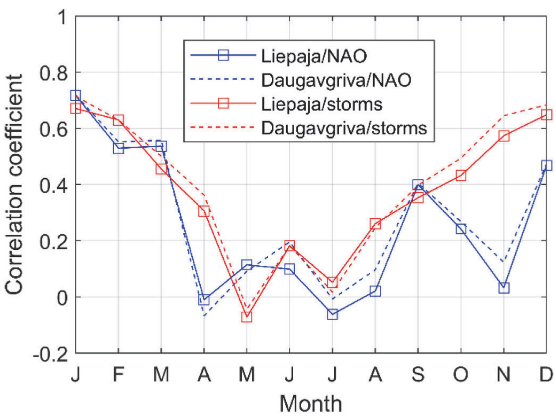


Fig. 12. Monthly variations in the correlation coefficient between the monthly mean water level and the NAO index (blue lines) and the monthly mean water level and the number of storm days at Vilsandi (red lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

and more intense movement of air from the west (Bukantis et al., 2001; Ekman, 2003, Hurrel et al., 2003).

3.6. Variability of water level and the NAO index

A convenient parameter to characterise the variability of the temporal course of water level is the annual standard deviation (SD) of the water level calculated on the basis of single measurements. It is natural that locations in the Gulf of Riga systematically exhibit larger water level variability (Fig. 10) than those in the Baltic proper. The average annual SD at Daugavgriva and Liepaja based on hourly data is 24.4 and 21.4 cm, respectively. Similarly to the Baltic proper shores of Lithuania (Dailidiene et al., 2006), the variability has not significantly altered in 1961–2018. The SD values for single years range between 15.5–27.7 cm and 18.6–31.6 cm, respectively (Fig. 10). These values are somewhat smaller than at Pärnu (27.7 and 20.6–35.9, respectively; Suursaar and Sooäär, 2007).

The temporal variations of this variability are different in different regions of the Baltic Sea. The Finnish data (Johansson et al., 2001) and recordings at Pärnu (Suursaar and Sooäär, 2007) indicate a clear increase in the variability of water level over many decades in the coastal waters of these countries. The data from the Baltic proper shores of Lithuania (Dailidienė et al., 2006) show no clear trend of this variability. The variability in question varies substantially (by up to ±30% from its long-term mean value) at Daugavgriva and Liepaja (Fig. 10). In terms of this quantity, the water level regime on the shores of Latvia thus is similar to this regime in Lithuania.

The annual water level minima, means and maxima are all positively correlated with the annual mean NAO index (Table 4). The correlation coefficients are mostly in the range of 0.3–0.4 and vary insignificantly at a single station (except for Salacgriva). The variations are larger for different stations. The quantities in winter (DJFM), especially the values of water level minima and mean, have much stronger correlation (the relevant coefficient >0.69) with the NAO index than those for other seasons. Notably, these correlations are even stronger than correlations between the winter NAO index and the annual mean sea level at Lithuanian tide gauges (e.g., 0.67 at Klaipėda; Dailidienė et al., 2006).

The correlation coefficients between the winter maxima and NAO index are somewhat lower, in the range of 0.52–0.63 for the four Latvian stations (Table 4). The correlation between the annual water level minima, mean and maxima and the annual/winter mean NAO index is statistically significant at a 99.9% level at all observation stations reflected in Table 4. This outcome is fully consistent with the conclusion of (Karabil et al., 2018) that some 88% of water level variations in the Baltic Sea can be explained by the pattern of atmospheric pressure over the Baltic Sea.

The SD of water level for both single years and winter seasons (DJFM) also correlates relatively strongly with the NAO index (Fig. 10). This correlation is weaker than the correlation between the annual water level minima, mean and maxima and the NAO index (Table 4). The correlation between the NAO index and water level SD at Liepaja and Daugavgriva is only significant at a 80% and 91% level, respectively. This difference apparently mirrors an almost total absence of correlation between the annual mean water level and water level standard deviation. These results are in line with the outcome of a similar analysis of the water level for the coast of Finland (Johansson et al., 2001).

The presented results are consistent with the general perception that changes to the statistical properties of the Baltic Sea water level fluctuations are largely driven by variations in the dynamics of air masses in the entire North Atlantic and, in particular, in the North Atlantic storm track. The water level in the Gulf of Riga, especially at stations in its southern and north-eastern bayheads (such as Pärnu, Suursaar et al., 2003), is particularly sensitive with respect to changes in the direction of strong winds. Many storms that cross the Baltic Sea travel from south-west or west, to north-east or east (Post and Kõuts, 2014). Changes to the trajectories of these storms or a decrease in the number of storms per unit area because of the lengthening of the North Atlantic storm track to the north-east (Lehmann et al., 2011) may affect water level statistics in the study area.

To shed some light on the changes in the local wind regime, we employ wind data from the island of Vilsandi. Measurements at this site adequately reflect the main properties of the wind regime in the north-eastern Baltic Sea such as extensive anisotropy of the wind field and the presence of two predominant directions of strong winds (Soomere, 2003). The empirical probability distribution of wind directions (wind rose) has two peaks at Vilsandi (Fig. 11). The most frequent winds blow from south-west. North-north-west winds are somewhat less frequent but in long term they may be even stronger. These features are more pronounced for moderate winds (10–15 m/s) and especially for strong winds (>15 m/s).

Wind data from Vilsandi 1961–2018 (Fig. 11) reveal an increase in the frequency of strong south-western winds and a decrease in the frequency of strong north-north-western winds. Moreover, no strong easterly and especially south-easterly winds have occurred at Vilsandi since 1991. These changes are consistent with the above-discussed decrease in the magnitude of low water levels (that are caused by strong easterly winds) and with the basically unchanging intensity of water level maxima in the Gulf of Riga (the formation of which is usually associated with strong north-north-western winds).

A quantitative measure that to some extent relates the occurrence of high water level and the overall pattern of atmospheric forcing is the number of storm days (defined as days with wind speed >15 m/s). The monthly count of storm days at Vilsandi has no correlation with the monthly mean water level for relatively calm months from April to August (Fig. 12). Similarly, the NAO index is almost uncorrelated with the mean water level for these months. Therefore, large-scale pressure differences expressed by the NAO index are a minor driver of the Baltic Sea water level in these months.

The correlation coefficients between the monthly count of storm days and the NAO index are relatively large (about 0.5–0.7) and have comparable magnitude for September and for the calendar winter months January, February, and March. It is thus likely that in these months the number of local high winds follows the large-scale pressure difference and that both this difference and local storms are the main drivers of the water level. Interestingly, the much higher correlation between the water level and the number of storm days than between the water level and the NAO index is characteristic for the calendar autumn months October, November, and December (Fig. 12). This feature can be interpreted as showing that local storms have much stronger impact on sea level than the large-scale pressure difference over the Northern Atlantic in these months. In essence, the described features confirm the conjecture of Karabil et al. (2018) that local winds are a major driver of water levels in the study area in the windy season.

4. Conclusions and discussion

We have performed, for the first time, a detailed analysis of observed and measured water level data from all functioning water level gauges in Latvian waters. The results fill the largest existing gap in the knowledge of water levels around the Baltic Sea. The analysis has first of all confirmed that many well-known properties of the course and statistical features of the Baltic Sea water level (such as a distinct annual cycle and asymmetry of high and low water levels) also exist on the Baltic proper shores of Latvia and in the Gulf of Riga. It is also expected that the widest range of water levels (311 cm between the all-time maximum and minimum) occurs at Daugavgriva in the southern corner of the Gulf of Riga. This range is about 250 cm on the shores of the Baltic proper and at the entrance to the Gulf of Riga.

We have also established several nontrivial or intriguing features. The empirical probability distributions of relative water level in Latvian waters follow the classic quasi-Gaussian shape that is characteristic for water level in the Baltic Sea. This shape is apparently created by the joint impact of variations in the water volume of the entire Baltic Sea (that have an almost Gaussian shape) and storm surges (that usually resemble a Poisson process). The shape of these distributions has changed at Liepaja at a 95% level of statistical significance. The data from Liepaja and Daugavgriva indicate that the distributions have become narrower. Very low water levels have become less frequent while the probabilities of higher levels have remained unchanged. The latter feature suggests that projections of water level extremes (e.g., Särkkä et al., 2017; Vousdoukas et al., 2017) may overestimate the rate of water level increase in the eastern Baltic Sea. Rapid increase in water level extremes is evidently applicable for certain coastal segments that are particularly affected by changes in the atmospheric forcing (Suursaar and Sooäär, 2007; Pindsoo and Soomere, 2020) or vulnerable with respect to wave set-up (Eelsalu et al., 2014). Long-term decrease in the magnitude of very low water levels is, in essence, an encouraging message for navigation in shallow waterways that are abundant in the eastern Baltic Sea (Gästgifvars et al., 2008) as well as for planning of specific constructions (such as sea outfalls that must be covered by water) in vulnerable areas (Opfermann, 2010).

As expected, the absolute (land uplift-corrected) water level increases at almost all Latvian measurement locations. The slopes of land uplift-corrected trends of annual mean water level on the Latvian coast (specifically at Liepaja, Roja, Daugavgriva and Salacgriva) during the period 1961–2018 were about 0.14–1.18 mm/yr. The fastest seasonal increase in the absolute average water level (about 1.68–2.89 mm/yr) occurs in winter months (from December to March). The rates of increase in both relative and absolute water level in Latvian waters are much smaller than the corresponding rates in Estonia and at Klaipėda and also smaller than the signal from global sea level rise at the entrance to the Baltic Sea. The relative water level has even slightly decreased (by 0.14 mm/yr) at Lielupes griva. It is therefore likely that the joint impact of local changes in the drivers of water level on the Latvian shores mitigates about one third of the impact of the global sea level rise. This feature prompts that local drivers of water level often have anisotropic nature (e.g., a predominant wind direction) and may strengthen or suppress the footprint of global processes in different regions of water bodies of complicated shape. This property gives rise to seemingly different reactions of various marine phenomena to climate change in different areas of the Baltic Sea (Kudryavtseva and Soomere, 2017) and thus makes the identification, quantification and forecast of climate changes in such water bodies an extremely complicated task.

Changes in the annual and stormy season (from July to subsequent June) water level maxima have a clearer pattern. Differently from, e.g., wave properties (Soomere and Räämet, 2014), the analysis reveals no clear decadal-scale cyclic variations in the water level means and extremes. The trends of winter maxima are in the range of 1.08–3.95 mm/yr and thus substantially (up to 5.34 mm/yr) steeper than the similar values for annual maxima. However, most of these trends are statistically not significant. Notably, the slopes of these trends are smaller than on the Estonian coast (where they are 3.5–11.2 mm/yr; Suursaar and Sooäär, 2007).

Not surprisingly, the properties of water level and its annual variability (in terms of standard deviations) correlate well with the values of the NAO (Gibraltar) index. The processes that govern the NAO index explain about 1/3 of the annual variability of the main properties of water level and up to 2/3 of this variability in winter (December–March). The overall pattern of changes is consistent with the decrease in the frequency of strong north-north-western and eastern winds in the region according to wind data from the island of Vilsandi.

The most substantial changes in the water level regime become evident from the analysis of its seasonal patterns. The seasonal course in the mean and extreme water level matches the general perception for their annual variation in the Baltic Sea. It has a distinct maximum in December–January, a deep minimum in March–June, and secondary maxima at the end of summer and in autumn. The changes in this course for the two climatic periods (1961–1990 and 1991–2018) are almost exactly in counterphase with the seasonal variations in the mean water level. The monthly average water level has decreased in July–November and increased in January–June. The magnitude of the changes is up to 30% of the amplitude of the seasonal course of the mean water level 1961–1990. A similar pattern of changes is found for the monthly maxima and minima. Therefore, the findings suggest that the overall tendency towards an increase in the magnitude of the annual cycle of the Baltic Sea water level (Ekman and Stigebrandt, 1990; Hünicke and Zorita, 2008) has been reversed in the study area.

We were not able to identify a clear physical driver for this feature; however, its presence once more signals that the reaction of local phenomena to climate change may be substantially different in neighbouring sea areas. On the one hand, both changes to this annual cycle and an increase in the average water level may considerably impact the functioning of beaches via an increase in the height where waves reach unprotected sediment above calm water level and thus the efficacy of wave impact on sedimentary beaches (Dean and Dalrymple, 2002). Long-term changes to this cycle during the windy season (when most massive wave energy attacks the shore) are at least equivalent or even more important in the context of coastal erosion (Pranzini and Williams, 2013) and transport of sediment than changes in the global sea level. On the other hand, a substantial decrease in the typical water level during strongest wave storms generally leads to an increase in the closure depth, that is, to a relocation of the place down to which waves maintain a certain underwater beach profile (Dean, 1991). As closure depth in the Baltic Sea is jointly governed by instantaneous water level and wave activity (Soomere et al., 2017), such changes may in long-term run undermine the stability of beaches with limited sand resources.

CRediT authorship contribution statement

Rain Männikus: Conceptualization, Methodology, Software, Resources, Visualization, Formal analysis, Data curation. **Tarmo Soomere:** Conceptualization, Methodology, Visualization, Formal analysis, Supervision, Funding acquisition, Formal analysis. **Maija Viška:** Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The research was supported by the Estonian Ministry of Education and Research (Estonian Research Council, institutional support IUT33-3) and co-supported by the Flag-ERA project FuturICT2.0, the Estonian Research Infrastructures Roadmap object "Infotechnological Mobility Observatory (IMO)", and the European Economic Area (EEA) Financial Instrument 2014–2021 Baltic Research Programme, project EMP480. The authors are deeply grateful to the Latvian Environment, Geology and Meteorology Centre and Estonian Weather Service for making the water level data publicly available. We would like to thank also Solvita Kalnina who arranged visits to Lielupes griva, Daugavgriva and Andrejosta.

Appendix

Table A1
Slopes of trends of monthly, seasonal and annual mean relative water level in 1961–2018. Bold italic: statistically significant increase/decrease at a 95% level, respectively, italic: increase or decrease at a 90% level. The *p*-values for single seasons are indicated in brackets. The data in months with less than 33 observations are excluded at Liepaja and Kolka, to avoid unrepresentative monthly means. The annual average is evaluated using all observations except for 2004 at Kolka and Roja, and for 2006 at Salacgriva. The average for these years and locations is calculated from the monthly means. The data is used "as is", with no attempt to fill missing values. Crustal uplift/subsidence has not been taken into account.

	Liepaja	Ventspils	Kolka	Roja	Mersrags	Lielupes griva	Daugav-griva	Skulte	Salacgriva
Jan	*3.21*	3.35	2.17	2.87	1.96	2.28	3.16	*4.16*	*4.10*
Feb	2.14	0.40	0.68	1.48	0.38	0.63	1.82	2.35	2.53
Mar	2.17	0.08	2.14	1.15	1.42	1.34	1.78	1.69	1.98
Apr	1.14	1.02	0.92	0.36	1.71	–0.03	0.85	1.74	0.82
May	***1.38***	1.01	0.93	0.74	*1.34*	0.89	*1.04*	1.36	1.28
Jun	***1.80***	***1.80***	1.01	*1.27*	***1.67***	***1.73***	***1.38***	***1.84***	***1.81***
Jul	–0.58	–0.67	*–1.44*	–1.29	–0.60	–0.95	–1.31	–1.11	–0.74
Aug	0.25	0.29	–0.82	–0.27	0.23	0.07	–0.42	0.07	0.40
Sep	–0.66	–0.11	–1.40	–1.37	–0.03	–1.33	–1.47	–0.65	–0.74
Oct	–0.40	–0.48	–1.05	–1.26	–0.59	–1.25	–1.42	–0.57	–0.64
Nov	–0.65	0.33	–1.39	–1.34	–0.39	–0.91	–1.19	–0.55	–0.325
Dec	0.62	2.49	–0.30	0.12	1.33	0.25	0.44	0.92	1.54
Jan–June	***1.98*** (0.024)	1.26 (0.21)	1.302 (0.18)	1.296 (0.16)	1.42 (0.115)	1.126 (0.26)	*1.67* (0.083)	*1.94* (0.063)	***2.08*** (0.038)
Jul–Nov	–0.41 (0.50)	–0.27 (0.65)	***–1.26*** (0.045)	–1.07 (0.107)	–0.31 (0.71)	–1.28 (0.108)	–1.16 (0.12)	–0.59 (0.42)	–0.41 (0.57)
Annual (all data)	*0.857* (0.095)	0.81 (0.18)	0.11 (0.83)	0.18 (0.74)	0.62 (0.27)	–0.17 (0.83)	0.39 (0.53)	*1.05* (0.082)	*0.997* (0.101)
Annual (monthly)	*0.869* (0.096	0.82 (0.18)	0.12 (0.83)	0.19 (0.73)	0.59 (0.30)	–0.14 (0.86)	0.39 (0.53)	*1.03* (0.085)	*0.997* (0.103)
Stormy season (all data)	*0.998* (0.071)	0.99 (0.13)	0.35 (0.55)	0.37 (0.54)	0.71 (0.23)	0.23 (0.73)	0.57 (0.37)	***1.245*** (0.046)	*1.25* (0.064)
Stormy season (monthly)	*1.002* (0.071)	0.99 (0.16)	0.28 (0.64)	0.41 (0.51)	0.97 (0.106)	0.10 (0.87)	0.57 (0.37)	1.08 (0.12)	*1.20* (0.07)

Table A2
Slopes of trends of monthly maximum water level. Notations are the same as in Table A1.

	Liepaja	Ventspils	Kolka	Roja	Mersrags	Lielupes griva	Daugavgriva	Skulte	Salacgriva
Jan	***5.66***	5.02	*5.42*	***6.14***	*5.46*	4.76	*6.49*	*7.63*	***7.88***
Feb	3.51	1.36	0.71	2.94	1.76	2.09	3.00	2.81	3.32
Mar	1.06	–0.16	2.29	1.36	1.88	–0.02	1.88	0.84	–1.37
Apr	1.23	0.91	1.16	–0.49	***3.71***	0.56	1.65	2.63	–0.85
May	1.55	1.25	0.94	0.91	0.69	0.63	1.12	1.00	1.10
Jun	***2.09***	1.79	*1.79*	***2.64***	***3.04***	1.92	1.90	*2.20*	***3.38***
Jul	–1.25	*–1.73*	***–2.65***	–1.73	–1.40	*–2.33*	***–3.21***	*–2.89*	–2.01
Aug	0.58	–0.06	–0.79	–0.16	0.99	–0.70	–1.09	–1.53	–0.01
Sep	–0.74	0.06	–0.97	–0.36	0.72	–2.37	–2.54	–2.64	–0.79
Oct	–2.13	–2.14	0.46	–0.38	0.11	–2.98	–2.78	–2.56	0.81
Nov	–1.91	–0.58	–2.24	–1.56	–0.85	–3.49	–4.08	–4.05	–2.37
Dec	0.03	2.87	–2.46	–0.64	0.81	–0.20	–0.99	–2.41	–0.96
Annual	0.95 (0.60)	0.66 (0.77)	2.42 (0.22)	0.82 (0.67)	0.76 (0.73)	–2.49 (0.37)	–1.70 (0.52)	–1.72 (0.56)	–0.09 (0.97)
Stormy season	0.5127 (0.797)	0.85 (0.73)	1.28 (0.56)	0.23 (0.92)	0.05 (0.98)	–1.39 (0.62)	–1.57 (0.59)	–2.475 (0.44)	–2.06 (0.48)

Table A3
Slopes of trends of monthly minimum water level. Notations are the same as in Table A1.

	Liepaja	Ventspils	Kolka	Roja	Mersrags	Lielupes griva	Daugavgriva	Skulte	Salacgriva
Jan	2.08	1.13	0.57	0.89	–1.01	0.66	1.31	2.58	2.08
Feb	1.21	–0.31	–1.56	–0.53	–1.68	–1.45	–0.39	0.45	0.04
Mar	1.06	–0.26	1.49	–0.13	0.34	–0.09	0.12	0.54	0.74
Apr	*1.78*	1.33	1.29	0.59	0.79	1.69	1.21	***2.30***	1.12
May	***1.35***	0.95	0.61	0.30	1.12	1.11	*1.38*	*1.75*	1.35
Jun	*1.17*	1.31	0.89	0.45	0.54	1.17	0.75	*1.58*	1.01
Jul	–0.70	–0.43	–0.06	***–1.74***	*–1.26*	–0.84	*–1.49*	–1.05	–1.23
Aug	0.45	0.39	–0.90	–0.25	–0.44	0.85	0.16	0.78	0.92
Sep	–0.05	1.00	***–2.19***	–1.36	0.05	–0.46	–0.40	0.61	–0.49
Oct	–1.72	–1.44	***–3.35***	***–3.27***	***–3.34***	–3.00	*–3.32*	–1.86	–1.84
Nov	–0.07	1.27	–0.44	–0.60	–0.56	1.03	0.13	1.01	1.526
Dec	0.74	2.19	–0.13	–0.49	–0.08	0.92	0.75	1.35	1.62
Annual	0.43 (0.65)	–0.12 (0.89)	–0.93 (0.50)	–1.06 (0.31)	–0.86 (0.49)	0.49 (0.72)	0.08 (0.95)	0.68 (0.63)	0.21 (0.88)
Stormy season	0.62 (0.55)	–0.43 (0.69)	–0.45 (0.75)	–0.74 (0.53)	–0.32 (0.80)	0.92 (0.53)	0.33 (0.82)	1.67 (0.31)	0.79 (0.58)

References

Astok, V., Otsmann, M., Suursaar, Ü., 1999. Water exchange as the main physical process in semi-enclosed marine systems: the Gulf of Riga case. Hydrobiologia 393, 11–18. https://doi.org/10.1023/A:1003517110726.

Averkiev, A.S., Klevannyy, K.A., 2010. A case study of the impact of cyclonic trajectories on sea-level extremes in the Gulf of Finland. Continent. Shelf Res. 30 (6), 707–714. https://doi.org/10.1016/j.csr.2009.10.010.

Bierstedt, S.E., Hünicke, B., Zorita, E., 2015. Variability of wind direction statistics of mean and extreme wind events over the Baltic Sea region. Tellus 67, 29073. https://doi.org/10.3402/tellusa.v67.29073.

Bukantis, A., Gulbinskas, Z., Kazakevicius, S., Kilkus, K., Mikelinskienė, A., Morkunaite, R., Rimkus, E., Samuila, M., Stankunavicius, G., Valiuskevicius, G., Zaromskis, R., 2001. The Influence of Climatic Variations on Physical Geographical Processes in Lithuania. Institute of Geography, Vilnius University ([In Lithuanian with English summary]).

Dailidienė, I., Davulienė, L., Tilickis, B., Stankevičius, A., Myrberg, K., 2006. Sea level variability at the Lithuanian coast of the Baltic Sea. Boreal Environ. Res. 11 (2), 109–121.

Dean, R.G., 1991. Equilibrium beach profiles: characteristics and applications. J. Coast Res. 7, 53–84.

Dean, R., Dalrymple, R., 2002. Coastal Processes with Engineering Applications. Cambridge University Press, Cambridge.

Eelsalu, M., Soomere, T., Pindsoo, K., Lagemaa, P., 2014. Ensemble approach for projections of return periods of extreme water levels in Estonian waters. Continent. Shelf Res. 91, 201–210. https://doi.org/10.1016/j.csr.2014.09.012.

Ekman, M., 2003. The world's longest sea level series and winter oscillation index for Northern Europe 1774–2000. Small publications in Historical Geophysics 12, 1–31.

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.-Oceans 95 (C4), C5379–C5383. https://doi.org/10.1029/JC095iC04p05379.

Gästgifvars, M., Müller-Navarra, S., Funkquist, L., Huess, V., 2008. Performance of operational systems with respect to water level forecasts in the Gulf of Finland. Ocean Dynam. 58 (2), 139–153. https://doi.org/10.1007/s10236-008-0137-6.

Gräwe, U., Klingbeil, K., Kelln, J., Dangendorf, S., 2019. Decomposing mean sea level rise in a semi-enclosed basin, the Baltic Sea. J. Clim. 32 (11), 3089–3108. https://doi.org/10.1175/JCLI-D-18-0174.1.

Harff, J., Deng, J., Dudzińska-Nowak, J., Fröhle, P., Groh, A., Hünicke, B., Soomere, T., Zhang, W., 2017. What determines the change of coastlines in the Baltic Sea?. In: Harff, J., Furmańczyk, K., von Storch, H. (Eds.), Coastline Changes of the Baltic Sea from South to East. Past and Future Projection, vol. 19. Springer, Cham, pp. 15–35. https://doi.org/10.1007/978-3-319-49894-2_2. Coastal Research Library.

Hünicke, B., Zorita, E., 2008. Trends in the amplitude of Baltic Sea level annual cycle. Tellus 60 (1), 154–164. https://doi.org/10.1111/j.1600-0870.2007.00277.x.

Hünicke, B., Zorita, E., Soomere, T., Madsen, K.S., Johansson, M., Suursaar, Ü., 2015. Recent change – sea level and wind waves. In: The BACC II Author Team, Second Assessment of Climate Change for the Baltic Sea Basin, Regional Climate Studies. Springer, pp. 155–185. https://doi.org/10.1007/978-3-319-16006-1_9.

Hurrel, J.W., 1995. Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. Science 269, 676–679. https://doi.org/10.1126/science.269.5224.676.

Hurrel, J.W., Kushnir, Y., Ottersen, G., Visbeck, M., 2003. An overview of the north Atlantic oscillation. In: The North Atlantic Oscillation: Climatic Significance and Environmental Impact. Geophysical Monograph, vol. 134. American Geophysical Union, pp. 1–35. https://doi.org/10.1029/134GM01.

Jaagus, J., 2006. Climatic changes in Estonia during the second half of the 20th century in relationship with changes in large-scale atmospheric circulation. Theor. Appl. Climatol. 83, 77–88. https://doi.org/10.1007/s00704-005-0161-0.

Jarmalavičius, D., Ilinskas, G., Dubra, V., 2007. Pattern of long-term seasonal sea level fluctuations in the Baltic Sea near the Lithuanian coast. Baltica 20 (1–2), 28–34.

Johansson, M., Boman, H., Kahma, K.K., Launiainen, J., 2001. Trends in sea level variability in the Baltic Sea. Boreal Environ. Res. 6 (3), 159–179.

Johansson, M., Kahma, K.K., Boman, H., 2004. Scenarios for sea level on the Finnish coast. Boreal Environ. Res. 9, 153–166.

Jones, P.D., Jonsson, T., Wheeler, D., 1997. Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. Int. J. Climatol. 17, 1433–1450. https://doi.org/10.1002/(SICI)1097-0088(19971115)17:13<1433::AID-JOC203>3.0.CO;2-P.

Karabil, S., Zorita, E., Hünicke, B., 2018. Contribution of atmospheric circulation to recent off-shore sea-level variations in the Baltic Sea and the North Sea. Earth Syst. Dyn. 9 (1), 69–90. https://doi.org/10.5194/esd-9-69-2018.

Kollo, K., Ellmann, A., 2019. Geodetic reconciliation of tide gauge network in Estonia. Geophysica 54 (1), 27–38.

Koltsova, T., Belakova, J., 2009. Storm surges on the southern coast of Gulf of Riga: case study of the Lielupe River. In: Jones, J.A.A., Vardanian, T.G., Hakopian, C., NATO Advanced Research Workshop on Natural Disasters and Water Security Yerevan Armenia (Eds.), Threats to Global Water Security. NATO Science for Peace and Security Series C – Environmental Security, pp. 91–97. https://doi.org/10.1007/978-90-481-2344-5_10.

Kowalczyk, K., 2019. Changes in mean sea level on the Polish coast of the Baltic Sea based on tide gauge data from the years 1811–2015. Acta Geodyn. Geomater. 16 (2), 195–209. https://doi.org/10.13168/AGG.2019.0016.

Kudryavtseva, N.A., Soomere, T., 2017. Satellite altimetry reveals spatial patterns of variations in the Baltic Sea wave climate. Earth Systems Dynamics 8, 697–706. https://doi.org/10.5194/esd-8-697-2017.

Kudure, A., 2009. Typical synoptic situations causing extremely high water levels along the Latvian coast of the Baltic Sea and the Gulf of Riga. April 27–29, Delft, The Netherlands. http://www.meteo.lv/fs/files/CMSP_Static_Page_Attach/00/00/00/02/06/level.pdf. (Accessed 21 July 2019).

Lazarenko, N.N., 1986. Variations of mean level and water volume of the Baltic Sea. In: Proceedings of the Water Balance of the Baltic Sea Environment, vol. 16, pp. 64–80.

Lehmann, A., Post, P., 2015. Variability of atmospheric circulation patterns associated with large volume changes of the Baltic Sea. Adv. Sci. Res. 12, 219–225. https://doi.org/10.5194/asr-12-219-2015.

Lehmann, A., Krauss, W., Hinrichsen, H.-H., 2002. Effects of remote and local atmospheric forcing on circulation and upwelling in the Baltic Sea. Tellus 54, 299–316. https://doi.org/10.1034/j.1600-0870.2002.00289.x.

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. https://doi.org/10.3354/cr00876.

Lehmann, A., Höflich, K., Post, P., Myrberg, K., 2017. Pathways of deep cyclones associated with large volume changes (LVCs) and major Baltic inflows (MBIs). J. Mar. Syst. 167, 11–18. https://doi.org/10.1016/j.jmarsys.2016.10.014.

Leppäranta, M., Myrberg, K., 2009. Physical Oceanography of the Baltic Sea. Springer, Berlin.

Lisitzin, E., 1966. Mean sea level heights and elevation systems in Finland. Commentationes Physico-Mathematica. Societas Scientiarum Fennica, 32 (4).

Männikus, R., Soomere, T., Kudryavtseva, N., 2019. Identification of mechanisms that drive water level extremes from in situ measurements in the Gulf of Riga during 1961–2017. Continent. Shelf Res. 182, 22–36. https://doi.org/10.1016/j.csr.2019.05.014.

Maritime Administration of Latvia, 2014. Hydrography Services, Baltijas Jūras Locija. Latvijas Piekraste, (The Baltic Sea. Coast of Latvia), third ed. Riga.

Medvedev, I.P., Rabinovich, A.B., Kulikov, E.A., 2017. The pole tide/14-month oscillations in the Baltic Sea during the 19th and 20th centuries: spatial and temporal variations. Continent. Shelf Res. 137, 117–130. https://doi.org/10.1016/j.csr.2017.02.001.

Meier, H.E.M., Broman, B., Kjellström, E., 2004. Simulated sea level in past and future climates of the Baltic Sea. Clim. Res. 27, 59–75. https://doi.org/10.3354/cr027059.

Mitrovica, J., Tamisiea, M., Davis, J., Milne, G.A., 2001. Recent mass balance of polar ice sheets inferred from patterns of global sea-level change. Nature 409, 1026–1029. https://doi.org/10.1038/35059054.

Omstedt, A., Pettersen, C., Rodhe, 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 (3), 205–216. https://doi.org/10.3354/cr025205.

Opfermann, B., 2010. Design and construction of a sea outfall in front of the seaside scenery of Binz on Rilgen Island. In: Wang, Y. (Ed.), Chinese-German Joint Symposium on Hydraulic and Ocean Engineering (CG JOINT 2010), pp. 531–535.

Orviku, K., Jaagus, J., Kont, A., Ratas, U., Rivis, R., 2003. Increasing activity of coastal processes associated with climate change in Estonia. J. Coast Res. 19, 364–375.

Pajak, K., Kowalczyk, K., 2019. A comparison of seasonal variations of sea level in the southern Baltic Sea from altimetry and tide gauge data. Adv. Space Res. 63 (5), 1768–1780. https://doi.org/10.1016/j.asr.2018.11.022.

Passaro, M., Cipollini, P., Benveniste, J., 2015. Annual sea level variability of the coastal ocean: the Baltic Sea–North Sea transition zone. J. Geophys. Res.-Oceans 120 (4), 3061–3078. https://doi.org/10.1002/2014JC010510.

Pindsoo, K., Soomere, T., 2020. Spatial variability in trends in water level extremes in the Baltic Sea. Continent. Shelf Res. 193, 104029 https://doi.org/10.1016/j.csr.2019.104029.

Post, P., Kõuts, T., 2014. Characteristics of cyclones causing extreme sea levels in the northern Baltic Sea. Oceanologia 56 (2), 241–258. https://doi.org/10.5697/oc.56-2.241.

Pranzini, E., Williams, A., 2013. Coastal Erosion and Protection in Europe. Routledge, Taylor and Francis, Abingdon-New York, p. 457.

Raudsepp, U., Toompuu, A., Kõuts, T., 1999. A stochastic model for the sea level in the Estonian coastal area. J. Mar. Syst. 22 (1), 69–87. https://doi.org/10.1016/S0924-7963(99)00031-7.

Reiniks, M., Kalinka, M., Lazdans, J., Klive, J., Ratkus, B., 2010. Valsts Augstuma Izejas Līmeņanoteikšana (Determining the State Height Level Output Data), vol. 7. Scientific Journal of Riga Technical University, Geomatics, pp. 7–13.

Rutgersson, A., Jaagus, J., Schenk, F., Stendel, M., 2014. Observed changes and variability of atmospheric parameters in the Baltic Sea region during the last 200 years. Clim. Res. 61, 177–190. https://doi.org/10.3354/cr01244.

Särkkä, J., Kahma, K.K., Kämäräinen, M., Johansson, M.M., Saku, S., 2017. Simulated extreme sea levels at Helsinki. Boreal Environ. Res. 22, 299–315.

Schmitt, F.G., Crapoulet, A., Hequette, A., Huang, Y., 2018. Nonlinear dynamics of the sea level time series in the eastern English Channel. Nat. Hazards 91, 267–285. https://doi.org/10.1007/s11069-017-3125-7.

Soomere, T., 2003. Anisotropy of wind and wave regimes in the Baltic Proper. J. Sea Res. 49 (4), 305–316. https://doi.org/10.1016/S1385-1101(03)00034-0.

Soomere, T., Keevallik, S., 2001. Anisotropy of moderate and strong winds in the Baltic Proper. Proc. Estonian Acad. Sci. Eng. 7 (1), 35–49.

Soomere, T., Räämet, A., 2014. Decadal changes in the Baltic Sea wave heights. J. Mar. Syst. 129, 86–95. https://doi.org/10.1016/j.jmarsys.2013.03.009.

Soomere, T., Pindsoo, K., 2016. Spatial variability in the trends in extreme storm surges and weekly-scale high water levels in the eastern Baltic Sea. Continent. Shelf Res. 115, 53–64. https://doi.org/10.1016/j.csr.2015.12.016.

Soomere, T., Bishop, S.R., Viška, M., Räämet, A., 2015a. An abrupt change in winds that may radically affect the coasts and deep sections of the Baltic Sea. Clim. Res. 62, 163–171. https://doi.org/10.3354/cr01269.

Soomere, T., Eelsalu, M., Kurkin, A., Rybin, A., 2015b. Separation of the Baltic Sea water level into daily and multi-weekly components. Continent. Shelf Res. 103, 23–32. https://doi.org/10.1016/j.csr.2015.04.018.

Soomere, T., Männikus, R., Pindsoo, K., Kudryavtseva, N., Eelsalu, M., 2017. Modification of closure depths by synchronisation of severe seas and high water levels. Geo Mar. Lett. 37 (1), 35–46. https://doi.org/10.1007/s00367-016-0471-5.

IPCC, 2013. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Stramska, M., 2013. Temporal variability of the Baltic Sea level based on satellite observations. Estuar. Coast Shelf Sci. 133, 244–250. https://doi.org/10.1016/j.ecss.2013.09.002.

Suursaar, Ü., Sooäär, J., 2007. Decadal variations in mean and extreme sea level values along the Estonian coast of the Baltic Sea. Tellus 59 (2), 249–260. https://doi.org/10.1111/j.1600-0870.2006.00220.x.

Suursaar, Ü., Kullas, T., Otsmann, M., 2002. A model study of the sea level variations in the Gulf of Riga and the Väinameri Sea. Continent. Shelf Res. 22 (14), 2001–2019. https://doi.org/10.1016/S0278-4343(02)00046-8.

Suursaar, Ü., Kullas, T., Otsmann, M., Kõuts, T., 2003. Extreme sea level events in the coastal waters of western Estonia. J. Sea Res. 49 (4), 295–303. https://doi.org/10.1016/S1385-1101(03)00022-4.

Suursaar, Ü., Jaagus, J., Kullas, T., 2006. Past and future changes in sea level near the Estonian coast in relation to changes in wind climate. Boreal Environ. Res. 11, 123–142.

Vousdoukas, M.I., Mentaschi, L., Voukouvalas, E., Verlaan, M., Feyen, L., 2017. Extreme sea levels on the rise along Europe's coasts. Earths Future 5 (3), 304–323. https://doi.org/10.1002/2016EF000505.

Wisniewski, B., Wolski, T., Musielak, S., 2011. A long-term trend and temporal fluctuations of the sea level at the Polish Baltic coast. Oceanol. Hydrobiol. Stud. 40 (2), 96–107. https://doi.org/10.2478/s13545-011-0020-9.

Paper II

Männikus, R., Soomere, T., Kudryavtseva, N. 2019. Identification of mechanisms that drive water level extremes from in situ measurements in the Gulf of Riga during 1961−2017. *Continental Shelf Research*, 182, 22−36, doi: 10.1016/j.csr.2019.05.014.

Continental Shelf Research 182 (2019) 22–36

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Identification of mechanisms that drive water level extremes from in situ measurements in the Gulf of Riga during 1961–2017

Rain Männikus[a,*], Tarmo Soomere[a,b], Nadezhda Kudryavtseva[a]

[a] Wave Engineering Laboratory, Department of Cybernetics, School of Science, Tallinn University of Technology, Akadeemia 21, Tallinn, 12618, Estonia
[b] Estonian Academy of Sciences, Kohtu 6, Tallinn, 10130, Estonia

ARTICLE INFO

Keywords:
Sea level
Water level measurements
Extreme water levels
Baltic sea
Gulf of Riga

ABSTRACT

We analyse a two-step mechanism for the formation of extremely high water levels in a semi-enclosed sub-basin of the Baltic Sea with the pumping of large amounts of water first into this sea and then into the Gulf of Riga. The analysis is based on hourly water level recordings at two observations sites in the gulf (Pärnu and Daugavgriva) and at one station (Liepaja) on the eastern shore of the Baltic Sea proper in the period 1961–2017. The empirical distributions of the probability of occurrence of different water levels have a classic quasi-Gaussian shape but are asymmetric: elevated water levels are more likely than negative surges. The highest recorded water levels in the interior of the Gulf of Riga exceed those on the open eastern coasts of the Baltic Sea proper by more than 1 m once in 5–10 years. The time scale of generation and relaxation of such elevated levels is about one day. There is no increase in the magnitude of episodes of strongly elevated water levels in the Gulf of Riga since the 1960s. The annual average number of episodes of significant differences between the water level at Liepaja and Pärnu has decreased by a factor of 1.6 whereas differences between Liepaja and Daugavgriva did not change. This pattern of changes indicates an alteration of the directional structure of winds in this area.

1. Introduction

An increase in sea level is one of the most significant threats to coastal communities (Nicholls, 2011). It may have severe consequences in terms of damage to property, and to loss of land and lives. It is likely that even if the targets of the Paris agreement are reached, (offshore) sea level will continue to rise at a substantial rate for centuries (Wigley, 2018). At a local scale, the course and statistics of water levels (understood in this paper as modelled or measured values at the coast) are the main inputs to all major coastal management and engineering projects. Long-term measurements are the most available and reliable source for extracting water level extremes, means, quantiles, trends and distributions. Extremes are projected to substantially increase on all European coasts by the end of this century (Vousdoukas et al., 2017). Estonian waters are one of "hot spots" in this context as the extreme water levels increase much faster than in the rest of the world's oceans (Soomere and Pindsoo, 2016). These warning signals call for more detailed analysis of the processes that drive changes in the water level extremes in semi-enclosed water bodies such as the Baltic Sea.

High water levels are usually generated by the collective impact of many factors. Tides, atmospheric pressure (inverted barometric effect), wind-driven surge and wave-induced set-up are usually the largest contributors to the total elevated water level (e.g., Talley et al., 2011). Traditionally, it has been assumed that, at least to a first approximation, these mechanisms impact the local water level independently of each other. This assumption is not always justified in the sense that the total water level (especially the residual after removing the tidal signal in shallow-water areas, Frison, 2000) often cannot be perfectly decoupled into a linear superposition of the contributing processes. For example the height of the local storm surge depends on the magnitude of the inverse barometric effect. We still rely, however, on this approximation that greatly simplifies the analysis and forecast of water levels. In essence, it makes it possible to at least approximately single out the signal of each mechanism from the overall course of water level, analyse separately its progression, timing and contribution to the total water level (e.g., Losada et al., 2013), and perform short-time forecasts and projections of extreme situations (e.g., Pellikka et al., 2018). It also allows in-depth analysis of gradual changes in the averages and extremes caused by a single driver (e.g., Soomere and Pindsoo, 2016; Vousdoukas et al., 2017).

The situation is more complicated in locations where substantial aperiodic variations in sea level occur at subtidal to intra-seasonal (daily to monthly) scales. These variations are an intrinsic component of the course of sea level in semi-enclosed water bodies such as

* Corresponding author. author.
E-mail address: rain.mannikus@taltech.ee (R. Männikus).

https://doi.org/10.1016/j.csr.2019.05.014
Received 22 November 2018; Received in revised form 15 April 2019; Accepted 16 May 2019
Available online 21 May 2019
0278-4343/

Chesapeake Bay (Bosley and Hess, 2001), the Venice lagoon (Zecchetto et al., 1997), water bodies with large rivers near their mouths (Buschman et al., 2009) or the Baltic Sea (Leppäranta and Myrberg, 2009) that are connected to the ocean via relatively shallow and narrow straits or (tidal) outlets. The associated fundamentally aperiodic variations in the water level have a typical timescale of a few weeks in the Baltic Sea. They are created by sequences of storm cyclones. Stormy winds that blow from particular directions over the Danish straits may bring substantial amounts of water into the Baltic Sea (Lehmann and Post, 2015; Lehmann et al., 2017). The large volume changes elevate the water surface of the entire sea by up to 1 m over its long-term level. The local impact of storms develops on the background of their high water level. This feature leads to the generation of extremely high outliers (called “statistically almost impossible water levels” by Suursaar and Sooäär, 2007) in certain parts of the sea. For this reason, the most devastating surges in the eastern part of the Baltic Sea occur when a strong storm approaches after a sequence of atmospheric conditions that have considerably increased the overall water volume of the Baltic Sea.

The overall properties and spatial patterns of water level in most of the Baltic Sea are relatively well understood (Hünicke et al., 2015). The largest storm surges in the eastern Baltic Sea occur in the northern extremity of the Bay of Bothnia, in the eastern end of the Gulf of Finland (Fig. 1) and on the eastern shores of the Gulf of Riga (Averkiev and Klevanny, 2010; Hünicke et al., 2015). The highest surges in the Baltic Sea may occur near Saint Petersburg (Averkiev and Klevanny, 2010). This is likely to persist in the future as the analysis in (Soomere and Pindsoo, 2016) revealed that the annual maxima of modelled water levels has increased rapidly (at a rate up to 10 mm/yr) in the eastern Gulf of Finland and Gulf of Riga in 1961–2004.

This increase is consistent with measurements made in the eastern Gulf of Finland. The match with in situ data is poor for the north-eastern Gulf of Riga (Soomere and Pindsoo, 2016). The mechanisms that may drive the highest surges in these two sub-basins are somewhat different. Extreme water levels in the eastern Gulf of Finland are attributed to deep cyclones that travel along a specific trajectory and with a particular velocity (Averkiev and Klevanny, 2010). When the storm ends, the release of the surge creates a gulf-scale seiche (or, more likely, a basin-scale seiche, Jönsson et al., 2008) that may endanger Saint Petersburg (Kulikov and Medvedev, 2013). However, excess water will not remain in the Gulf of Finland for a longer time because there is no sill between these sub-basins and the Baltic proper.

The situation is different in the Gulf of Riga (Fig. 1). It is a semi-enclosed gulf connected to the Baltic Sea by two relatively narrow and shallow straits. It is, therefore, possible that certain atmospheric conditions may push large volumes of water from the Baltic Sea into the gulf and additionally increase its water level (Astok et al., 1999; Suursaar et al., 2002, 2003). This conjecture is supported by the typical pattern of trajectories of cyclones in this area. Many storms that cross the Baltic Sea move from the south-west or west to the north-east or east (Post and Kõuts, 2014). The wind direction thus is from south-west or west at the beginning of the storm. This pattern creates a slope of the sea surface towards the north-east and leads to elevated water levels in the eastern and northern regions of the Baltic Sea, including the Gulf of Riga. Moreover, it is likely that westerly winds push additional water into the gulf by Ekman transport. When such a storm progresses to the east, the wind direction turns more to the north-west and north and prevents water from flowing out of the Gulf of Riga via Moonsund.

The water level time series from Pärnu station is used in a number of relevant studies (Medvedev et al., 2013, Soomere and Pindsoo, 2016, Suursaar and Sooäär, 2007; Suursaar et al., 2002, 2003, 2006, to mention a few). However, there are almost no studies of the water level in the rest of the Gulf of Riga or on the open Baltic Sea shores of Latvia in the literature (except for a few local case studies, e.g., Koltsova and Belakova, 2009).

To fill this gap, we address the course and statistics of water level in the Gulf of Riga. A particular focus is on the detection of episodes when the water level in this sub-basin is considerably higher than in the rest of the Baltic Sea for extended periods of time. Similarly to a recent analysis for the Baltic Sea proper and Gulf of Riga (Soomere et al., 2015), we make an attempt to separate the major components of the course of water level based on their typical timescales. We employ the classic technique of calculating the running average of water level time series with a properly designed length of the averaging interval. For better readability, we follow the tradition of using centimetres for the readings of water level (cf. Hünicke et al., 2015) and kilometres for surface and cross-sectional areas of water bodies in question.

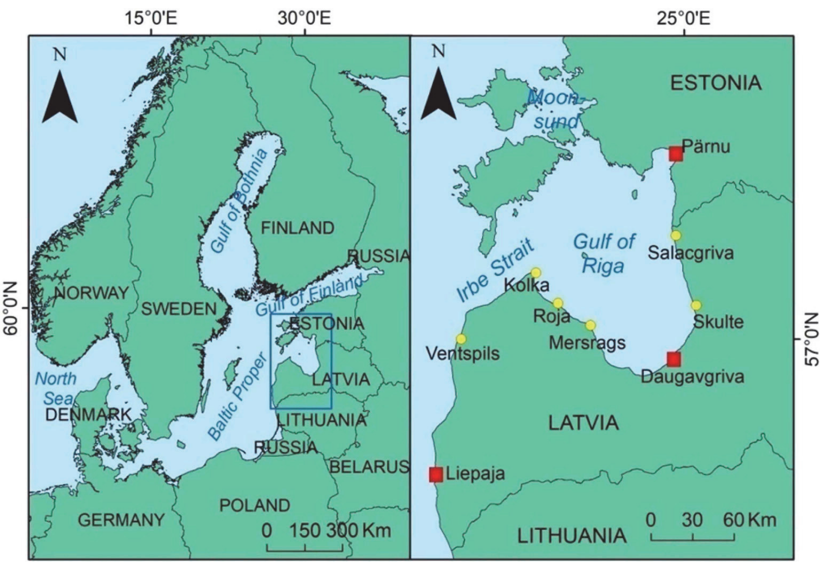


Fig. 1. Water level measurement sites in the Gulf of Riga and on the open coast of Latvia. Red rectangles show locations with the highest quality and coverage of observations that are analysed in this paper. Yellow circles depict stations where measurements were less frequent or had long gaps. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Coordinates of measurement stations, observed basic water level parameters (presented in the Baltic Height System BK77) and hourly data completeness for 01.01.1961–31.12.2017. Notice that according to (Averkiev and Klevanny, 2010), the maximum water level at Skulte was 247 cm and at Riga (Daugavgriva) 231 cm on 02 November 1969. Time series for Liepaja and Daugavgriva are from the Latvian Environment, Geology and Meteorology Centre. The data set for Pärnu from 01 January 1961 till 31 December 2017 was provided by the Estonian Weather Service.

Location	Measurements since	Co-ordinates	Mean level (cm)	Maximum level (cm)	Minimum level (cm)	Data completeness
Daugavgriva	01.01.1875	57°3′22″N, 24°1′40″E	9.4	224	−107	99.98%
Kolka	01.01.1884	57°44′13″N, 22°35′33″E	1.7	161	−113	34.11%
Liepaja	01.01.1865	56°29′7″N, 21°1′33″E	2.1	174	−86	99.69%
Mersrags	01.01.1928	57°20′5″N, 23°7′57″E	−0.1	166	−94	24.67%
Pärnu	(1893) 01.11.1949	58°22′55″N, 24°28′38″E	5.2	275	−121	99.54%
Roja	01.07.1932	57°30′27″N, 22°48′15″E	−1.1	167	−89	29.06%
Salacgriva	01.10.1928	57°45′18″N, 24°21′10″E	6.4	215	−116	27.92%
Skulte	01.01.1939	57°18′57″N, 24°24′34″E	6.4	231	−109	93.53%
Ventspils	01.01.1873	57°23′43″N, 21°32′3″E	1.1	141	−76	64.58%

2. Study area and data

The Gulf of Riga has a generally regular shape with an approximate size of 130 × 140 km (Suursaar et al., 2002). It has a surface area of 17,913 km^2, a volume of 406 km^3, maximal depth of 52 m and an average depth of about 23 m. The mean annual river inflow to the gulf is about 33 km^{3}yr^{-1}. The Daugava River and Pärnu River provide the largest discharge in the southern and north-eastern parts of the gulf, respectively. The main connection with the open part of the Baltic Sea is Irbe Strait, which has a width of 27 km, a sill depth of about 21 m and a cross-section area of 0.37 km^2. The Väinameri (Moonsund) sub basin can be considered as a second outlet of the Gulf of Riga. Its southernmost strait, Suur Strait, is the narrowest (4–5 km) section for north- and southward motions of water masses between the Gulf of Riga and northern part of the Baltic Sea proper. The sill depth is about 5 m.

Single recordings of water level in selected locations of the coasts of the Gulf of Riga and on the Baltic proper shore of Latvia have been documented for almost two centuries. Currently, there are several measurement sites on its shores that collect regular water level observations (Fig. 1, Table 1). The coverage and quality of the recordings vary greatly. Most stations had variable observation intervals and many gaps in the recordings. For example, water level measurements at Salacgriva were performed three times a day from 1961 to 1981. From 1982 until mid-October 2006 the water level was recorded twice a day and only since mid-October 2006 have the measurements been made hourly. At Kolka, measurements were taken four times a day until the middle of 2004. There are several long gaps in the time-series (e.g., two months in 1980 and six months in 1996) and values from 1968 to 1969 are missing entirely. Starting from the mid-September 2004, water level measurements are made hourly at Kolka but the recordings still contain minor gaps (with a length of a few hours). As the observation frequency has changed over the course of time, the observed time series at Kolka, Mersrags, Roja and Salacgriva are not entirely homogeneous.

The datasets suitable for our analysis are records of hourly observations from Skulte, Daugavgriva and Pärnu from 01 January 1961. Each of these datasets contains up to half million single entries. Because of its close distance (37 km) and strong correlation ($R = 0.967$) with sea levels at Daugavgriva, data from Skulte basically repeat the information that is contained in the Daugavgriva data. As the coverage of the Skulte data was clearly smaller than the Daugavgriva data, it was excluded from the analysis.

To identify deviations of water level in the Gulf of Riga from the Baltic Sea proper, we use measurements from the western coast of Latvia. There are two stations, Ventspils and Liepaja, in this region. However, the dataset from Ventspils has major coverage and resolution issues. The observations were carried out hourly from 1961 to 1970 at this site. After that, data were not available for many years. The recordings of hourly observations are available again from April 1987 to 1995. After that, until 2003, the data set has large gaps with entire years and months missing. The frequency of observations was also low; for example, at the end of 2000 measurements took place only four times a day. Hourly data are available after 2003. The presence of large gaps (e.g., up to 17 yr in the Ventspils dataset) makes the time series at some stations not directly comparable with others. For these reasons, the data sets from three sites – Liepaja, Daugavgriva and Pärnu – are chosen for the analysis.

The observed values in Latvia and Estonia are presented in the official height system used until 2017, the Baltic Height System BK77 with its reference to the Kronstadt zero. In essence, this is a zero-benchmark at Kronstadt near Saint Petersburg, defined as the average water level in Kronstadt in 1825–1840 (Lazarenko, 1986).

The percentage of meaningful hourly recordings at the three stations is from 99.54 to 99.98% (Table 1). The Daugavgriva data set has only a few short gaps. The recordings at Liepaja have gaps from 15 December 1994 to 06 January 1995 and from 02 to 31 December 2001. All values are missing on 13 June 2002, and 18 and 20 January 2012. A few values (1–2 h) are missing in almost every decade. The longest gaps in the Daugavgriva dataset are of 8 h duration. The water level values are missing in the Pärnu data set from 04 to 16 September 1990, 31 October–10 November 1990 and 14 September–20 October 2010.

It is likely that some recordings are erroneous. For example, the highest water level at Liepaja (174 cm) was recorded on 18 October 1967 at 14:00. Although this event can be attributed to a strong storm (Scandinavian storm Lena) on 17–18 October 1967, the course of recorded water levels is strange. Namely, the water level rose within 2 h from 60 cm to 174 cm, remained constant for 5 h and dropped to 100 cm in 1 h. This course can be explained by the location of the measurement site in a narrow canal between a coastal lake and the sea; however, measurement failure cannot be excluded as a reason. As this constant value persisted for a relatively long time and water levels were high at Pärnu and Daugavgriva also, the values are not excluded from the analysis.

As the data were presented “as is”, we employ indirect methods to estimate the level of uncertainties of recordings. The spectral density of water level time series in the Baltic Sea is flat (indicating random white noise properties) on timescales of approximately < 3 h (Medvedev et al., 2013). Using a running average with the window length of 3 h, we extracted the non-random signal and estimated measurement errors from the residuals. The resulting estimates of uncertainty of individual measurements are ~0.7 cm for the recordings at Daugavgriva, ~1.2 cm at Liepaja, and ~1.6 cm at Pärnu.

3. Results

3.1. Correlations of water levels and distributions of the frequency of occurrence

The overall shape of the empirical distributions of the probability of occurrence of different water levels (Fig. 2) reflects the classic quasi-Gaussian appearance of similar distributions in the north-eastern Baltic

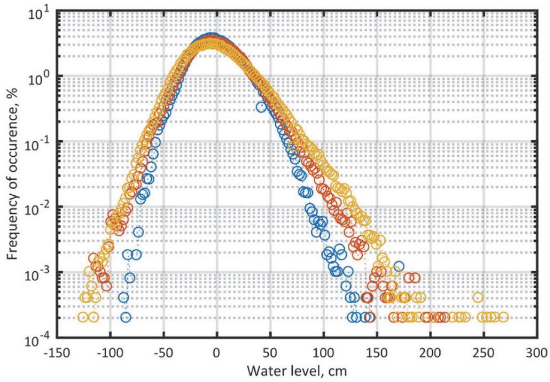


Fig. 2. Empirical distributions of the frequency of occurrence of different water levels at Liepaja (blue), Daugavgriva (red) and Pärnu (yellow). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Sea (Johansson et al., 2001). They all indicate a certain asymmetry: large elevated water levels are more likely than deep negative surges. The magnitude of asymmetry/skewness (for Liepaja, Daugavgriva and Pärnu 1.427, 1.673, 1.784, respectively) is higher than at Tallinn (Soomere et al., 2015) or Hanko (Johansson et al., 2001). The presence of a few positive outliers is also typical for the water level regime in this region (Johansson et al., 2001; Soomere et al., 2015).

It is natural that the recorded values in the three locations to a large extent reflect the instantaneous water volume of the Baltic Sea and thus are relatively strongly correlated. To evaluate the magnitude of correlations, we excluded the gaps. The readings at all stations showed a strong spatial correlation. The lowest correlations are observed for the sites at the ends of the Gulf of Riga. For example, for Liepaja and Daugavgriva/Pärnu the correlation coefficients are $R = 0.845$ and $R = 0.890$, respectively.

The highest recorded water levels in the interior of the Gulf of Riga (Table 1) considerably exceed those on the open eastern coasts of the Baltic Sea proper from Lithuania (Dailidienė et al., 2006) to the entrance to the Gulf of Riga (Averkiev and Klevanny, 2010). Even higher values have been recorded only at Saint Petersburg and on the south-western coast of the Baltic Sea. It is thus likely that such substantial water levels reflect certain specific features of the dynamics of the entire Gulf of Riga such as an excess water volume of the entire gulf. Alternatively, these maxima could be explained by local effects such as storm surge or high wave set-up on single sections of the coast. An example of the impact of such local effects is evident in the water level data at Ristna, Estonia, where a relatively large all-time water level maximum (209 cm) contains a substantial contribution from wave set-up (Eelsalu et al., 2014). Separation of the events of elevated water levels of the entire gulf from high local surges that occur simultaneously at Pärnu and Daugavgriva is to some extent possible by means of an analysis of the time scales of these events.

3.2. Elevated water levels in the Gulf of Riga

Strongly elevated water levels of the entire Baltic Sea usually take a few weeks to develop (Lehmann and Post, 2015) and persist up to a few months (Soomere and Pindsoo, 2016). These time scales evidently express the ratio of the surface area of the Baltic Sea (393,000 km^2) and the flow rate of water through the Danish straits (with the cross-sectional area of the three straits at their narrowest parts being about 0.35 km^2). This ratio is much smaller for the Gulf of Riga (17,913 km^2) and Irbe Strait (0.37 km^2). Therefore, the strongly elevated water levels in the Gulf of Riga with respect to the Baltic Sea proper should develop and relax relatively rapidly. It is thus likely that the course of water level in the Gulf of Riga is usually similar to that in the Baltic Sea proper and deviations only occur in specific conditions and over relatively short time intervals. To give some flavour of the course of such conditions, we present examples from two time intervals during which larger deviations of the water level between the Baltic Sea proper and the Gulf of Riga occurred.

The process of pushing large water volumes into the Baltic Sea does not necessarily lead to significant differences in the water level in the Baltic Sea proper and the Gulf of Riga. Fig. 3 presents the recordings from the three stations when water was continuously pushed into the Baltic Sea by a sequence of storms between 09 and 19 January 1993. The level of the entire sea (evaluated using the 8.25-day average of water levels at Liepaja as recommended in Soomere et al., 2015) and of the Gulf of Riga increased by 40 cm (Fig. 3). This process continued on 21–23 January and reached saturation on 24–26 January 1993, after which the entire Baltic Sea level started to decrease.

Fig. 3 demonstrates that the courses of water levels at the three sites, even though they follow each other in general, contain distinctly different local features (Fig. 3). The time series of the two stations in the Gulf of Riga are often phase-locked whereas the water level at Pärnu is usually higher than at Daugavgriva. As these two locations are open to different directions (south-east and north-west, respectively), very high local storm surges in these locations are normally created by winds from different directions. It is therefore likely that simultaneous occurrences of water levels at Pärnu and Daugavgriva higher than at Liepaja signal the excess water level in the entire Gulf of Riga.

Fig. 3 also reveals that the time series of water level at Pärnu and Daugavgriva maybe in antiphase over shorter time intervals. For example, on 23–30 January (Fig. 4) the water level at Daugavgriva was mostly higher than at Pärnu. This behaviour is consistent with the

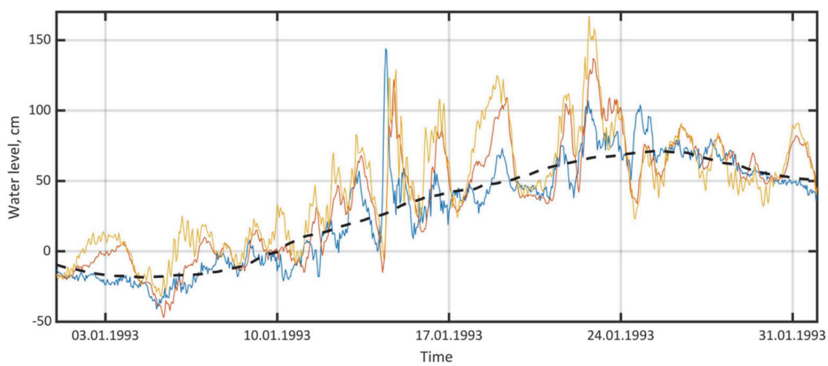


Fig. 3. Water levels at Liepaja (blue), Daugavgriva (red) and Pärnu (yellow) in January 1993. The dashed black line shows the 8.25-day average of water levels at Liepaja. Small peaks (5–10 cm) with periods of several hours probably reflect different kinds of seiches in the Gulf of Riga. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

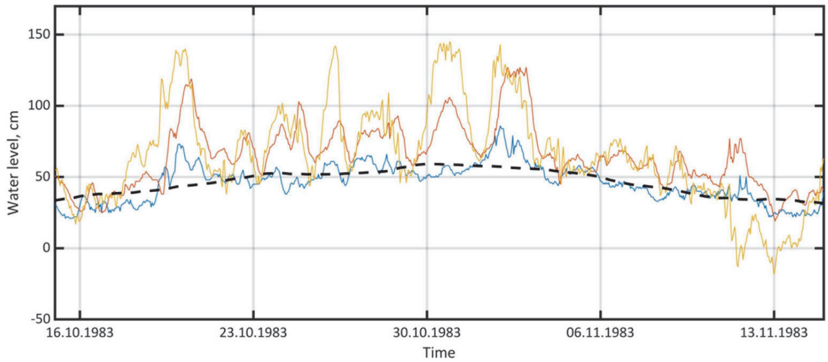


Fig. 4. Water levels at Liepaja (blue), Daugavgriva (red) and Pärnu (yellow) in autumn 1983. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

above remarks.

On 14 January 1993 there was a sudden spike (about 80 cm, for 4 h) in the water level at Liepaja. This phenomenon can be partly explained by the geographical configuration of the Liepaja measurement site. It is situated in the canal between the Baltic Sea and the Lake of Liepaja. Wind and topography may jointly trap water in the canal. However, instrumental errors cannot be ruled out.

Fig. 3 also provides an indication of the typical magnitude of differences in the water level at the three sites. The average water levels at all three sites closely followed each other. The highest water levels in the gulf exceeded those in the open sea by up to 50 cm during certain short-term events (e.g., on 16 January, 18–19 January and 22 January). The rapid relaxation of these events over a few hours signals that they most probably were not driven by an increase in the water volume of the entire Gulf of Riga.

The situation was different in October–November 1983. The entire Baltic Sea water level was elevated by about 50 cm (Fig. 4). The water level at both Daugavgriva and Pärnu was, by up to 70 cm, higher than at Liepaja during several events with duration of up to two days. Such large deviations of the water level in two fairly separated locations of the eastern Gulf of Riga from that near the entrance to the gulf probably indicate that the water volume of the entire Gulf of Riga increased for a certain period. The difference between the readings at Pärnu and Daugavgriva and the Baltic Sea proper took more than a day to level off. This persistence additionally suggests that the decrease probably reflected a flow of water out of the gulf.

The data in Fig. 4 make it possible to roughly estimate the time scales of the development and relaxation of events of elevated water levels in the Gulf of Riga. The elevation is mostly created and released with a rate of about 3–5 cm/h. This rate corresponds to the flow of about 1 km^3 of water an hour mainly through Irbe Strait. As the outflow embraces the entire cross-section of this strait, the estimated current speed (approximately 3 km/h or close to 1 m/s) is realistic.

To quantify further the similarities and differences between the recordings at the three stations, we applied the technique of cross-spectrum calculations which is essentially the covariance between Fourier transforms of time series (Von Storch and Zwiers, 1999). This technique highlights the coherency and phase shift between different time series of water levels. We applied the spec.pgram command from the *R* version 3.4.1 "stats" package. A few missing values in the time series were filled with the average values. A Fourier spectrum smoothing was applied, using Daniell smoothers with a width of 80. The cross-spectra were calculated for the pairs Liepaja–Daugavgriva, Liepaja–Pärnu, and Pärnu–Daugavgriva (Fig. 5).

The typical values of squared coherency for processes with time scales longer than about half a day (~ 12 h) are around 0.5 (except for Pärnu/Liepaja where the coherency for processes with a duration of a few days is only about 0.2). Slow processes (equivalently, changes in the water level on weekly and longer time scales) are highly coherent in the entire study area. All the stations show a complete loss of coherency on timescales shorter than 10 h, indicating the characteristic timescale of storminess in the Gulf of Riga. The phase plots show a phase shift (a delay) of 7 h between the processes at Liepaja and in the Gulf of Riga. A similar phase shift between the course of water level at Daugavgriva and Pärnu is less than 1 h.

3.3. Separation of components of water levels in the Gulf of Riga

The presented material has demonstrated that the water level in the Gulf of Riga may on certain occasions be strongly modified by a short-time increase in its water volume. This component of the water level may be one of the reasons why extremely high water level outliers occur (Suursaar and Sooäär, 2007). To further investigate the role of this mechanism on the water level, we make an attempt to separate the components of water level at different time scales using an approach developed in Soomere et al. (2015).

The above analysis suggests the need to single out two longer-scale processes: one that governs the water level in the entire Baltic Sea at weekly and longer scales and another that reflects coherent fluctuations in the entire gulf at time scales longer than about 12 h. As the duration of storm surges is usually < 12 h, a reasonable choice of the time scale for averaging eventually makes it possible to separate the processes at the "intermediate" time scale in the range of 0.5–7 days that are responsible for the water volume of the gulf from the local surges. Therefore, we apply the averaging procedure twice to the time series.

We first apply a running average with an averaging length T_1 of about one week (the exact values will be specified below). By subtracting the averaged water level $\bar{W}_{T1}$ from the observed (total) water level W_i, a first residual $W_i^{(R1)} = W_i - \bar{W}_{T1}$ is obtained. The average $\bar{W}_{T1}$ is a proxy of the water volume of the entire Baltic Sea. In the context of the Gulf of Riga the first residual $W_i^{(R1)}$ contains information about both excess water in the gulf and local storm surges. To single out the signal of excess water, a running average with another averaging length T_2 of about one day is applied to the first residual $W_i^{(R1)}$. The resulting average $\bar{W}_{T1T2}$ is a proxy of the excess water, and the second residual $W_i^{(R2)} = W_i^{(R1)} - \bar{W}_{T1T2}$ characterises storm surges.

Even though the first step of this procedure is straightforward and simple, it provides a sensible separation of the contribution of changing water volume of the entire sea into the observed water level time series (Soomere et al., 2015). The separation is, however, not perfect. For example, for sequences of storms the values of the average $\bar{W}_{T1}$ contain a certain contribution from local storm surges and the first residual reflects only a part of the surge height (Soomere et al., 2015). This

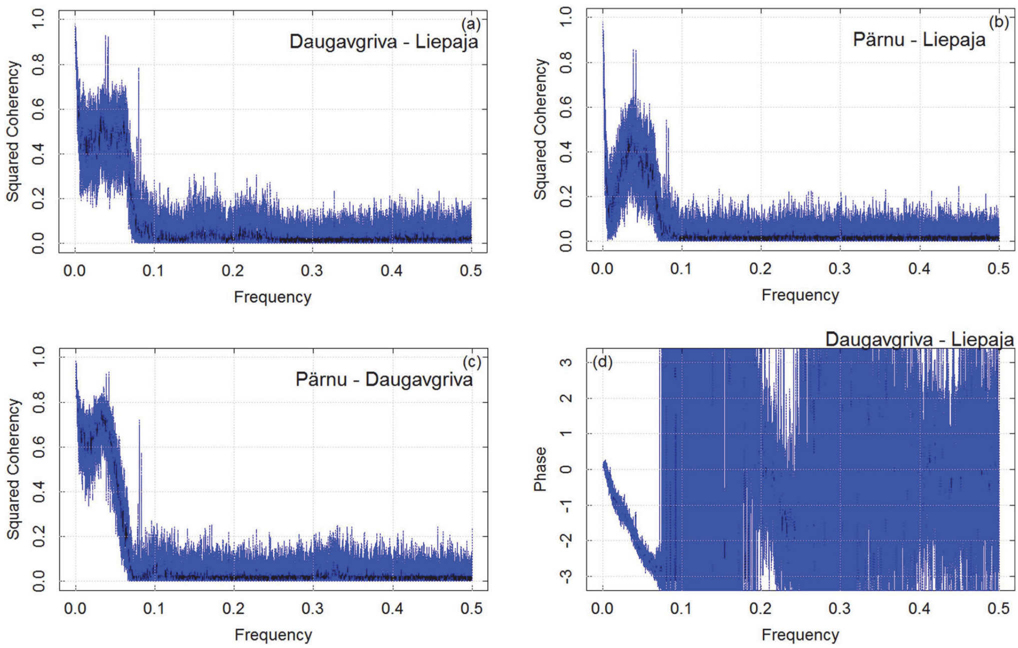


Fig. 5. Squared coherence of water level recordings at Liepaja, Pärnu and Daugavgriva (a, b, c). In these plots, the frequency is 1/(sampling frequency). In our case the sampling frequency is 1 h. The frequency of 0.1 translates to 10 h time scale. The method takes into account all the available data at the measurement stations; (d) phase plot of water level time series between Daugavgriva and Liepaja.

problem intrinsically persists in the procedure of the specification of $\bar{W}_{T1T2}$ and the second residual.

The optimal averaging lengths T_1 and T_2 are evidently site specific. In particular, the values of T_1 around one week identified for the shores of the Baltic proper (Soomere et al., 2015) are not necessarily applicable for the Gulf of Riga. The proper length of T_1 is a natural scale for the separation of short-term (daily scale) fluctuations of water level from the changes in the water volume of the entire sea. It can be identified from the shape of the probability distribution of the residual time series, namely, for a specific value of T_1, the empirical distribution of the frequency of occurrence of different values of the (first) residual $W_i^{(R1)}$ (that reflects the magnitudes of local storm surges) becomes a classic exponential distribution (Soomere et al., 2015) with a probability density function $\sim \exp(\lambda_1 x)$. Instead of slope λ_1, it is convenient to use the scale parameter $-1/\lambda_1$ (Soomere et al., 2015). It characterises the vulnerability of a particular shore section with respect to the local storm surge to some extent. Its values for positive and negative surges are usually different.

The procedure is as follows. Both branches of the empirical distribution of the frequency of occurrence of different values of the residual $W_i^{(R1)}$ are approximated using a quadratic function $ax^2 + bx + c$. For the optimum value of T_1 the coefficient $a(T_1)$ at the leading term vanishes. This approach was tested for the entire nearshore of Estonia and Latvia using the modelled water level time series in 1961–2005 from the Rossby Centre Ocean (RCO) Model (Swedish Meteorological and Hydrological Institute). It resulted in the typical value of the averaging interval $T_1 = 8.25$ days for the open shores of Estonia and on the southern coast of the Gulf of Finland (Soomere et al., 2015). The corresponding timescale T_1, evaluated from the measured data, is somewhat longer: 10 days (240 h) at Liepaja, 9.5 days (228 h) at Daugavgriva and 9 days (216 h) at Pärnu.

The scale parameters $-1/\lambda_1$ for the positive and negative branch of the residual $W_i^{(R1)}$ were about 4.5 and -2.7, respectively, for the modelled data (Soomere et al., 2015) and 5.92 and -4.08 for the observed data for Liepaja. The model thus underestimated the probabilities of very low water levels near Liepaja. This applies also for Daugavgriva (modelled and observed data scale parameters for the negative branch were -5.0 and -6.70, respectively) and Pärnu (values correspondingly -5.0 and -7.46). The relevant values of $-1/\lambda_1$ for the positive branch from the modelled data somewhat better match the similar values extracted from observed datasets at Daugavgriva (values respectively 6.3 and 7.50) (Fig. 6). The modelled and observed scale parameters for the positive branch of the data at Pärnu are 6.3 and 8.66, respectively. The RCO model seems to underestimate the probability of very high and very low water levels at all study sites. The mismatches can be partially explained by the distance between the observation sites (e.g., in the city of Pärnu) and model grid points. The use of different time intervals (1961–2005 in the modelling) may also contribute to this mismatch. However, extensive mismatch of model- and observation-based estimates of certain statistical parameters of water levels seems to be quite usual in the study area (Soomere et al., 2018).

The observed water levels at all three sites contain a large number of outliers (most notably the above-discussed recordings on 18 October 1967 at Liepaja) that clearly do not fit to the overall quasi-Gaussian distribution (Fig. 6). This feature is frequent on the Baltic Sea proper shores of Estonia and on the southern coast of the Gulf of Finland (Suursaar and Sooäär, 2007). It is often assumed that the particular location of the water measurement site at Pärnu (the former water moat of the ancient fortification, kilometres away from open deep water) is the primary source of local effects and such outliers in the water level recordings (Eelsalu et al., 2014). The appearance of distributions in Fig. 6, however, suggests that the presence of such outliers of water level is a common feature in the Gulf of Riga.

Similarly to the situation on the Estonian shores (Soomere et al., 2015), the distribution of this residual contains a few positive outliers at all three study sites that deviate from an exponential distribution. A

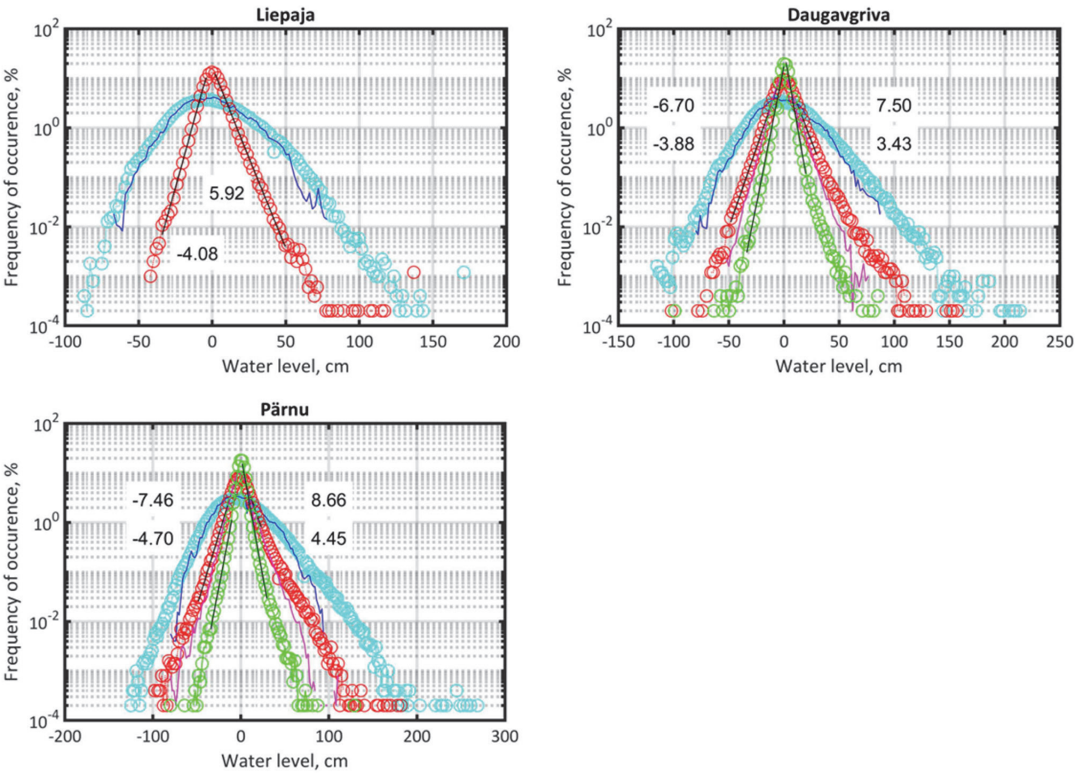


Fig. 6. Empirical distributions of the frequency of occurrence of observed hourly water levels and first and second residuals in 1961–2017. The second residual is not shown for Liepaja. Cyan, red and green markers show the distributions of the observed total water level and the first and second residuals, respectively. Blue and magenta lines show the similar distribution for the average water level for the total and first residual water levels, respectively. Black lines depict linear approximations ofthe residuals. Numbers on the figure indicate the scale parameters $-1/\lambda_1$. The upper and lower values for locations in the Gulf of Riga correspond to first (red) and second (green) residuals. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

very large positive outlier corresponds to a set of above-discussed recordings on 18 October 1967.

As Liepaja is widely open to the Baltic Sea proper and the seabed near the measurement site deepens rapidly (24 m in 1000 m), it is likely that the first residual adequately quantifies the local effects in this location. The described procedure leads to the results for this location that are similar to those in the Gulf of Finland and on the Estonian shores of the Baltic Sea. For the averaging interval of $T_1 = 10$ days, both (negative and positive) branches of the probability distribution function of $W_i^{(R1)}$ become practically straight lines over several orders of magnitude in the log-linear representation of the Liepaja data (Fig. 6). The probabilities of negative surges also follow an almost straight line for a particular value of T_1 at Pärnu and Daugavgriva (Fig. 6). The branch that represents positive surges does not become straight for any averaging length in these two locations.

This pattern may be interpreted as follows. On the one hand, the applied procedure leads to adequate values for the average water level of the Baltic Sea shores of Latvia and the Gulf of Riga. It also adequately singles out the course of water level during negative surges in the gulf. On the other hand, the first residual $W_i^{(R1)}$ seems to contain some other signal additionally to positive storm surges (that apparently represent a Poisson process).

An implicit conjecture is that high water levels in the Gulf of Riga may occasionally contain one more components that act at time scales longer than the duration of storms but shorter than about one week. The two-step process of the formation of high water levels in the Gulf of Riga (Astok et al., 1999; Suursaar et al., 2002, 2003) is a likely candidate for this component. Its impact may be responsible for the mismatch of several statistical properties and trends of measured and modelled water levels at Pärnu (Soomere and Pindsoo, 2016).

To highlight this component, we calculate the average $\bar{W}_{T1T2}$ of the first residual $W_i^{(R1)}$ using running average over a time interval of T_2 and a second residual $W_i^{(R2)} = W_i^{(R1)} - \bar{W}_{T1T2}$ of the course of water level at Daugavgriva and Pärnu. An appropriate averaging interval T_2 should be much shorter than T_1 but clearly longer than the time scale beyond which coherency in the water level at Daugavgriva and Pärnu is lost. Similarly to the above, this procedure to some extent separates processes with a time scale of 1–2 days (incl. the events of excess water volume in the Gulf of Riga) from even shorter storm surge events.

This procedure with the averaging lengths of $T_2 = 24$ hours for Daugavgriva and $T_2 = 22$ hours for Pärnu leads to an almost straight appearance of both branches of the distribution of the second residual over at least two orders of magnitudes (Fig. 6). The negative branch is almost straight over more than three orders of magnitude. The resulting distributions can thus be adequately approximated with the exponential distribution $\sim \exp(\lambda_2 x)$. The relevant parameters λ_2 (or scale parameters $-1/\lambda_2$) can be used to characterise the vulnerability of the coastal areas with respect to locally elevated water levels created by relatively short processes such as storm surges or seiches in the Gulf of Riga. The averaging interval T_2 can be interpreted as a natural scale for the separation of hourly scale fluctuations of water level.

The particular values of the second residual characterise to some

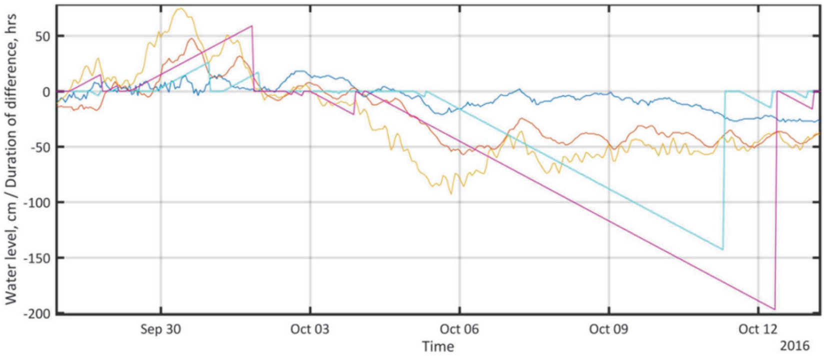


Fig. 7. An example of the quantification of episodes of substantial difference between observed water levels (cm) at Liepaja (blue), Daugavgriva (red) and Pärnu (yellow) in October 2016. Cyan line depicts the duration (in hours) of episodes of the water level difference > 10 cm between Daugavgriva and Liepaja; magenta between Pärnu and Liepaja. Each episode is highlighted as a right angle triangle. Its height shows the duration of the event (scale on the *y*-axis) and the side on the *x*-axis indicates the end instant of the episode. Positive heights indicate episodes when water level in the Gulf of Riga was higher than at Liepaja. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

extent the frequency of occurrence of medium-duration (about one day) events of difference of the water level at Pärnu or Daugavgriva from that in the Baltic Sea proper. Low water level situations are intrinsically slow events in this area (Suursaar and Sooäär, 2007) and do not necessarily mean unusually small water volumes of the Gulf of Riga. On the contrary, events of high water levels are relatively short (usually well below 12 h) at Pärnu (Suursaar et al., 2006) and apparently also at Daugavgriva. It is thus likely that large values of the difference between the first and second residual $W_i^{(R1)} - W_i^{(R2)}$ (equivalently, the average of the first residual $\bar{W}_{T1T2}$) represent events of substantial excess water volume in the Gulf of Riga. Such events often (with a probability of 10^{-3} or about 10 h a year, on average; Fig. 6) exceed 50 cm and have exceeded 1 m a few times during the last 57 years.

3.4. Episodes with the substantially different water levels in the Gulf of Riga

To analyse the frequency and magnitude of the systematic difference in water level in the Gulf of Riga and the Baltic Sea proper on scales from an hour up to 1–2 days, we first define variable D called water level difference:

$$\begin{cases} D_D^{(t)} = W_D^{(t)} - W_L^{(t)}, & \text{if} |W_D^{(t)} - W_L^{(t)}| > D_{lim} \\ D_D^{(t)} = 0, & \text{if } |W_D^{(t)} - W_L^{(t)}| \le D_{lim} \end{cases}, \quad (1)$$

$$\begin{cases} D_P^{(t)} = W_P^{(t)} - W_L^{(t)}, & \text{if } |W_P^{(t)} - W_L^{(t)}| > D_{lim} \\ D_P^{(t)} = 0, & \text{if} |W_P^{(t)} - W_L^{(t)}| \le D_{lim} \end{cases}, \quad (2)$$

where $W_D^{(t)}$ is the instantaneous water level at time instant t at Daugavgriva, $W_P^{(t)}$ at Pärnu, $W_L^{(t)}$ at Liepaja and D_{lim} is an arbitrarily chosen threshold. By using absolute values in the formulae, it is possible to evaluate both high and low water levels in the Gulf of Riga compared to Liepaja. As the recordings are taken hourly, it is natural to assume that the possible mismatch in the exact observation time is less than 30 min.

As discussed earlier, the typical uncertainty in water level recordings is up to 1.7 cm at Liepaja and in the order of 1 cm at the other stations. However, the average water levels at stations differ even more, by 9 cm (Table 1). To reduce the impact of possible minor observational errors and this difference on the long-term average water levels and on the results of the analysis, the minimum threshold D_{lim} was set to 10 cm in the analysis of water level differences.

For more detailed analysis of the properties of single events of clearly different water levels in the Baltic Sea proper and the Gulf of Riga and statistical properties of the set of such events, we employ different (basically arbitrary) thresholds D_{lim} for the absolute values of water level differences. If this threshold D_{lim} is not reached, the relevant variable is set to zero. This approach is, in essence, a straightforward generalisation of the classic method for highlighting single events in time series of natural phenomena (e.g., wave storms in the Mediterranean) (Boccotti, 2000). Doing so creates a natural separation of events of different water levels in the Baltic Sea proper and in the Gulf of Riga. Each resulting episode of water level difference has a clearly defined starting instant, duration and course.

This set of properties makes it possible to evaluate the basic characteristics (e.g., maximum, minimum, and mean difference) of such episodes for different thresholds. The selected threshold D_{lim} should not be too small (because events with a small difference in water levels could contaminate the entire picture) and also not too high (as the number of occurrences should be large enough to make reasonable conclusions). By varying the threshold D_{lim} it is also possible to generate different sets of episodes of water level differences that correspond, for example, to thresholds beyond which specific threats will be realised on the shores of the Gulf of Riga.

We first quantify the duration of episodes of water level differences with respect to the instantaneous water level at Liepaja as the reference value. Fig. 7 shows how the procedure works for the threshold $D_{lim} = 10$ cm. An episode starts when the water level at Pärnu or Daugavgriva exceeds Liepaja by 10 cm and ends when this difference drops below 10 cm.

The number of episodes and the parameters of single episodes for Pärnu and Daugavgriva are generally different (Fig. 7). The distributions of the frequency of occurrence of episodes with different durations are also dissimilar for these two observation sites. Both relatively high and low water levels compared to the open Baltic Sea are more persistent at Pärnu than at Daugavgriva (Fig. 8). This can be explained by the locations of observation stations. Pärnu Bay is open to the predominant south-westerly winds that often pile up water masses into this shallow-water bay with typical depths around 5 m. Daugavgriva is open to the north-west and the seabed in the vicinity of the measurement site deepens much more rapidly than in Pärnu Bay.

3.5. Temporal changes in properties of the episodes of large water level differences

Even though the number of episodes of water level differences and the starting point and duration of each episode described in the previous subsection depend on the applied thresholds, it is natural to expect that for a reasonable set of thresholds the temporal pattern of the magnitude of such episodes also provides information about changes in the system. In particular, it is likely that most of the episodes of strongly elevated water levels in the Gulf of Riga reflect westerly and north-westerly storms. As these storms usually occur in the autumn and early winter months (Leppäranta and Myrberg, 2009), the properties of such a series of storms evaluated on an annual basis may be deceptive.

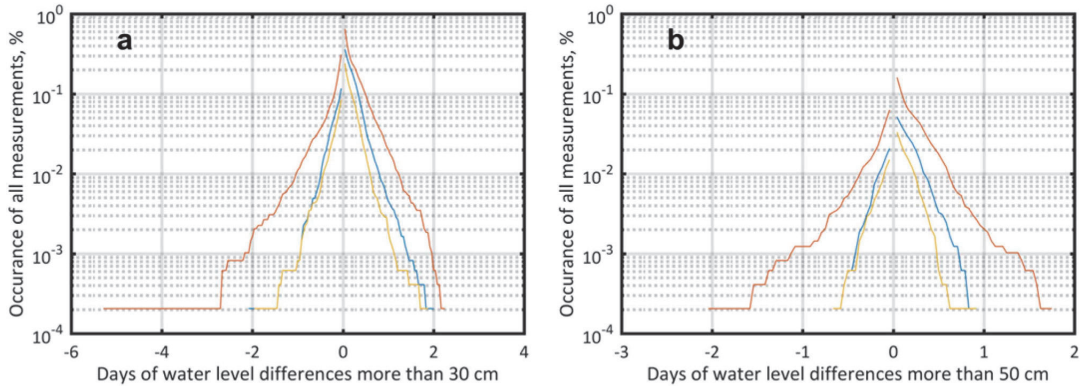


Fig. 8. The frequency of occurrence of episodes of water level differences with a different duration between Liepaja and stations in the Gulf of Riga. a) episodes with water level difference D_{lim}=30 cm, b) D_{lim}=50 cm. Red line: the probability of episodes when water level at Pärnu and Liepaja is different, blue: the same for Daugavgriva and Liepaja. The yellow line depicts the difference between the minimum/maximum value of the Gulf of Riga (Daugavgriva/Pärnu) and Liepaja. Negative values on the *x*-axis represent the duration of episodes when water levels in the Gulf of Riga are lower than at Liepaja. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Moreover, very high water levels in different calendar years are not necessarily independent in the Baltic Sea basin (Johansson et al., 2001; Soomere and Pindsoo, 2016). As the strongly elevated water levels of the entire Baltic Sea may persist for a few months (Leppäranta and Myrberg, 2009), a sequence of storms in December of a particular year may significantly affect the course of water level in sub-basins of the sea in January of the subsequent year. To avoid this problem, we split the data set into segments that have the duration of one year and extend from July until June of the subsequent year. Each such segment fully covers one autumn-winter stormy season.

The number of episodes when the water level at Pärnu or Daugavgriva is only slightly (by at least 10 cm) higher than in the Baltic proper is, on average, 300–400 each year (Fig. 9). Therefore, such events occur almost daily. It is likely that on many occasions such episodes correspond to seiches or other local drivers and do not reflect the events of the increased water volume of the gulf. The number of such episodes based on records from Daugavgriva and Liepaja is almost constant over the half-century of observations whereas the similar number based on records from Pärnu and Liepaja has decreased by a factor of two (Fig. 9a).

A similar pattern of changes is evident in the number of episodes during which the water level in the Gulf of Riga exceeds that at Liepaja by at least 30 cm. The long-term annual average of such episodes is 80 for Pärnu and 46 for Daugavgriva. Similarly to the above, some such episodes may reflect local effects in the measurement sites in the Gulf of Riga. It is, however, likely that those in which the water level at both Pärnu and Daugavgriva is higher than at Liepaja (e.g., in October and November 1983, Fig. 4) correspond to strongly increased water volumes in the gulf. Fig. 9b reveals no clear trend in the number of such events at Daugavgriva but indicates that the number of such events for Pärnu has decreased by a factor of 1.6. This decreasing trend is statistically significant at a 95% level.

The geometry of the Gulf of Riga and eastern Baltic Sea is such that substantially elevated water levels at Daugavgriva compared to Liepaja usually occur during relatively strong westerly and north-westerly winds. These winds may push excess water into the Gulf of Riga and/or create local surge in the vicinity of the Daugava river mouth. Technically, strong winds from north-north-east could lower the water level at Liepaja and keep it high at Daugavgriva but such winds are infrequent in the northern Baltic Sea (Soomere et al., 2008). In this context, the persistent number of the episodes of elevated water levels at Daugavgriva may be interpreted as showing that the annual average number of strong westerly and north-westerly winds has not significantly changed since the 1960s. This conjecture is consistent with the understanding that storminess in the Baltic Sea region has not substantially changed during the 20th century (Bärring and von Storch, 2004).

The water level at Pärnu is very sensitive with respect to the wind direction (Suursaar et al., 2003). High water levels at Pärnu compared to those at Liepaja are mostly caused by south-westerly winds. Such winds push water into the relatively shallow Pärnu Bay but much less affect the water level along the open Baltic Sea coast of Latvia. The substantial decrease in the number of episodes of large water level differences between Liepaja and Pärnu therefore signals that the annual average number of such strong wind episodes has considerably decreased since the 1960s.

3.6. *Magnitude of water level differences*

Further information about potential changes in the processes that occur in the study area may be extracted from the combination of the height and duration of both high and low water level episodes. Fig. 8 shows how frequent events can be with a certain water level difference and duration. As wave fields in the Baltic Sea and especially in the Gulf of Riga have relatively short memory and rapidly react to changing wind patterns, waves are more likely to pose increased risks when they occur at times of high water level. Such events are frequently associated with strong erosion of the shores, problems with accessibility for low-lying households or infrastructure, and damage to coastal engineering structures. Effects will be more serious when conditions persist for a longer time. It is thus important to estimate whether events of substantially elevated water levels in the Gulf of Riga compared to the Baltic Sea proper have become longer or more powerful.

To quantify the potential joint impact of the height of the water level difference and the duration of a relevant event, we introduce the quantity M, the magnitude of an event of substantial water level difference between the Baltic Sea proper and the Gulf of Riga. A simple way to do this is to associate with each such event the integral of the values of this difference throughout the event. For hourly water level recordings, this is equivalent to the sum of single values of $D_D^{(t)}$ or $D_P^{(t)}$ in each event. The unit for M is days × centimetres. This quantity to some extent characterises the properties of atmospheric forcing that creates an elevated water level or depression in the Gulf of Riga. Elevated water levels are created by westerly and north-westerly winds. Temporal changes in the magnitude M therefore may reflect changes in the "magnitude" (strength, duration and match with the geometry of the

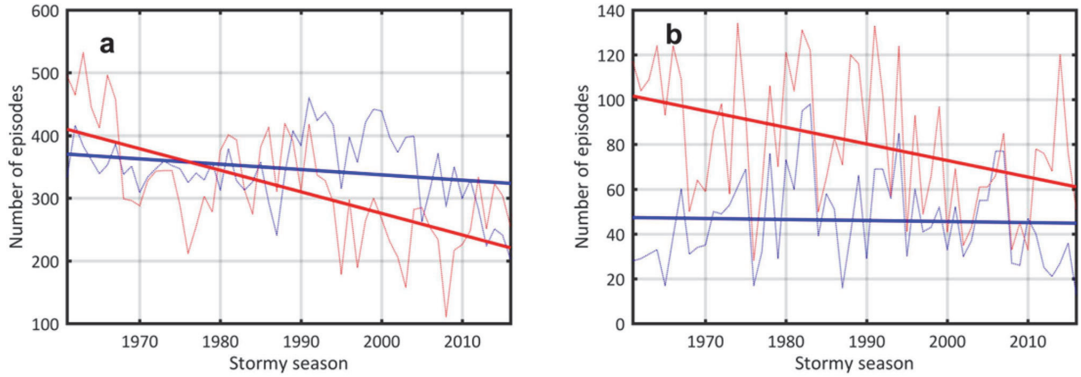


Fig. 9. The number of episodes of significant differences between the water level at Liepaja and at stations in the Gulf of Riga from July to June of the subsequent year: a) D_{lim} = 10 cm, b) D_{lim} = 30 cm. Blue thin lines represent the number of such differences between the water level at Daugavgriva and Liepaja and red thin lines between Pärnu and Liepaja. Solid bold lines indicate the respective linear trends. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Gulf of Riga) of a certain subset of storms in the Baltic Sea region that is able to produce substantial differences in the water level between the Baltic Sea proper and the Gulf of Riga.

As a few of the strongest storms often generate the most of the damage to the shores and coastal engineering structures (Kamphuis, 2010), we address the changes in the maxima of M during single stormy seasons for the threshold D_{lim} = 30 cm. These maxima have a weak decreasing trend for both relative elevations and depressions of water level at Daugavgriva (Fig. 10a). The data set from Pärnu reveals a slight decrease for the “magnitude” of elevations but much faster increase in the magnitude of depressions. None of the trends is statistically significant.

Therefore, the typical annual maximum “magnitude” of episodes of water level differences between the Baltic Sea proper and the Gulf of Riga has remained practically unchanged since the 1960s. It is however intriguing that the “magnitude” of the largest low and elevated water level episodes (that appear once in 4–5 years) shows, at least visually, an apparent increase for Pärnu (Fig. 10). The absolute values of the maxima of this quantity in 1995–2017 are by a factor of about 1.7–1.8 larger than in the 1960s. It is however likely that this feature indicates an increase in the variability of the quantity M rather than an increase in its multi-annual maxima.

The discussed feature may also be interpreted as showing that the population of storms in the Baltic Sea basin contains a few examples that support high and prolonged episodes of elevated and low water levels in the Gulf of Riga around 1980 and since the mid-1990s. These storms are not necessarily stronger as the quantity M also depends on the duration of the episode. However, the gradual increase in the “magnitude” of a few long events with elevated water levels in the Gulf of Riga compared to the water level in the rest of the Baltic Sea carries the potential for an increase in the risk of flooding of low-lying areas, wave-induced damage to the shores and intense episodes of wave-driven alongshore sediment transport in the gulf.

The particular values of magnitudes M depend heavily on the threshold D_{lim} chosen to detect the episodes of large differences in the water level. To highlight the role of this threshold in the changes in M we repeated the calculations of the annual maxima of these magnitudes with various thresholds and evaluated the slopes of the associated trendlines (Fig. 11). There are practically no changes in the magnitude of annual strongest episodes of negative water level differences between Liepaja and Daugavgriva. This quantity for Pärnu rapidly decreases for all thresholds whereas the decrease is faster for small differences. A rapid increase of this quantity for small thresholds (D_{lim} = 10–15 cm) in the context of Daugavgriva water level being higher than at Liepaja

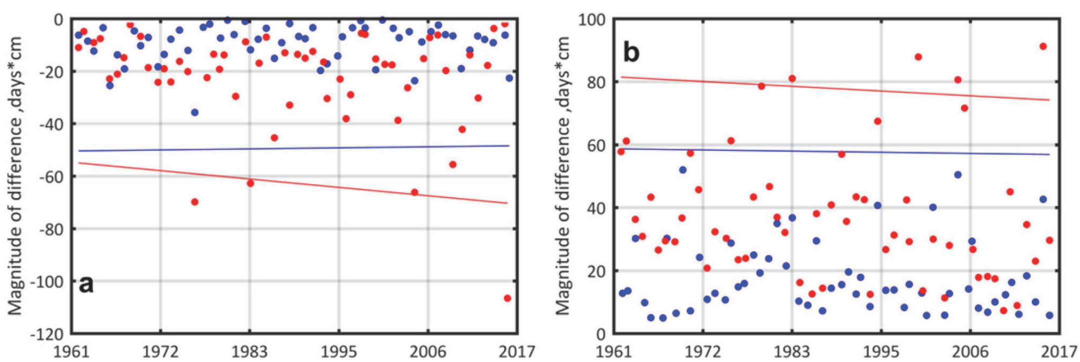


Fig. 10. Annual maximum magnitudes of episodes of water level difference and their trendlines at Daugavgriva $D_D^{(t)}$ (blue) and Pärnu $D_P^{(t)}$ (red) for a) low water levels, b) high water levels. The threshold for the difference between the observed values at Liepaja and in sites in the Gulf of Riga is for both cases D_{lim} = 30 cm. Trendlines are shifted vertically by 40 units for better readability. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

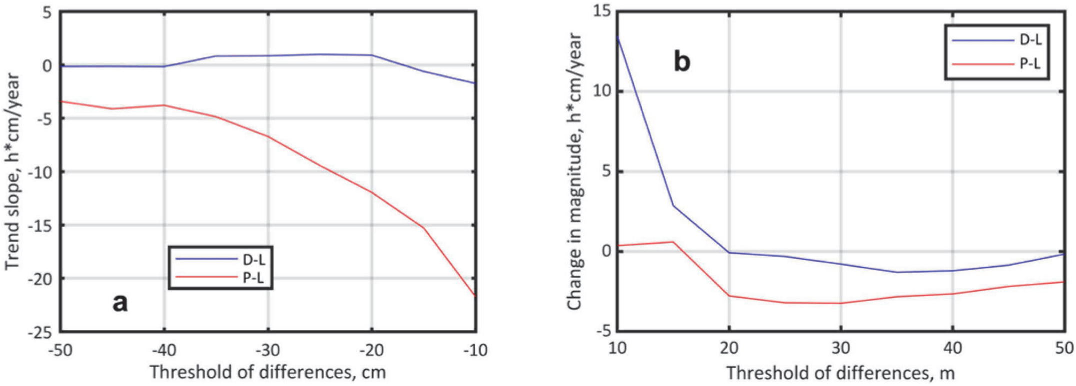


Fig. 11. The dependence of the slopes of trendlines of annual extremes of the magnitude of episodes of water level differences between Liepaja and Daugavgriva (blue) and Liepaja and Pärnu (red) on various thresholds in 1961–2017: a) low water levels in the Gulf of Riga, b) high water levels in the Gulf of Riga. All underlying trends were statistically insignificant. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

most likely reflects the process of merging of neighbouring episodes into longer ones that have larger magnitudes in these metrics. Essentially no changes have occurred for Pärnu.

To identify whether an increase in the water level difference or the duration of single events generates large "magnitudes" of episodes of elevated water levels, we also evaluated the maximum water level difference at Pärnu and Daugavgriva compared to the values in Liepaja. Very low or high water levels in the Gulf of Riga occur when the recordings both at Daugavgriva and Pärnu substantially deviate from those at Liepaja. Fig. 12 indicates that this difference may reach from almost -120 cm (in 1991 and 1999) to at least 150 cm (in 1967) or > 130 cm (in 2005).

Several very low water levels that occurred in the 1990s in the Gulf of Riga were apparently associated with strong easterly winds. The all-time highest water levels at Pärnu were recorded in 1967 (253 cm) and in 2005 (274 cm) (Suursaar et al., 2006). Importantly, there is definitely no increasing trend of the annual maxima of differences in the water levels. Instead, Fig. 12a shows a slight (and statistically insignificant) decrease in the relevant magnitudes of very low levels at Daugavgriva and a similar (also statistically insignificant) decrease in the relative elevations at Pärnu. This feature suggests that wind speed has not increased in storms that create very large relative elevations and very low relative water levels in the Gulf of Riga.

3.7. The largest relative elevations and depressions in the Gulf of Riga

To illustrate the potential consequences of large water level differences we describe here some single events. Fig. 10 indicates that exceptionally powerful events of elevated or depressed water levels in the Gulf of Riga (compared to the Baltic Sea proper) occur irregularly, on average once in five years. Some of them develop on the background of moderate or close to average water levels of the entire Baltic Sea. Such events usually do not lead to dangerous situations on the shores of the Gulf of Riga. However, they may create problems for navigation in shallow river mouths.

For example, the most powerful event in the terms of "magnitude" M was a low water level at the beginning of October 2016. The water level difference between Pärnu and Liepaja exceeded 60 cm for more than one day. The water level at Liepaja was slightly below the long-term average (between -20 and 0 cm). The water level at Daugavgriva was between -57 and -20 cm and at Pärnu between -88 and -50 cm.

An exceptionally powerful storm Gudrun (Erwin) in January 2005 (Suursaar et al., 2006) produced the fourth largest example of magnitude M of water level differences (with respect to the threshold of $D_{lim} =$ 30 cm) for Pärnu (81 days × cm) and the second highest (50 days × cm) for Daugavgriva. The courses of observed water levels at

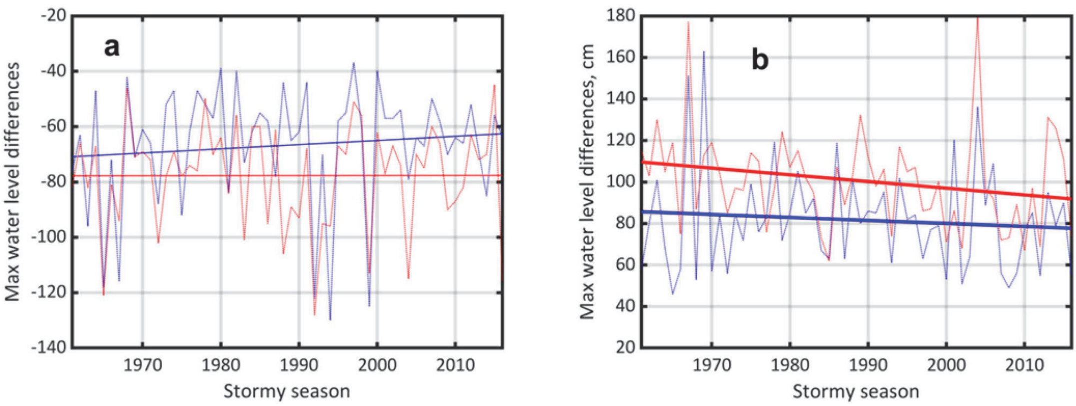


Fig. 12. Annual largest water level differences between Liepaja and Daugavgriva (blue) or Pärnu (red) shown as thin lines. Bold lines represent trends. a) low water levels in the Gulf of Riga, b) high water levels in the Gulf of Riga. The trendline for high water level differences (panel b) between Pärnu and Liepaja is significant at a 95% confidence level.

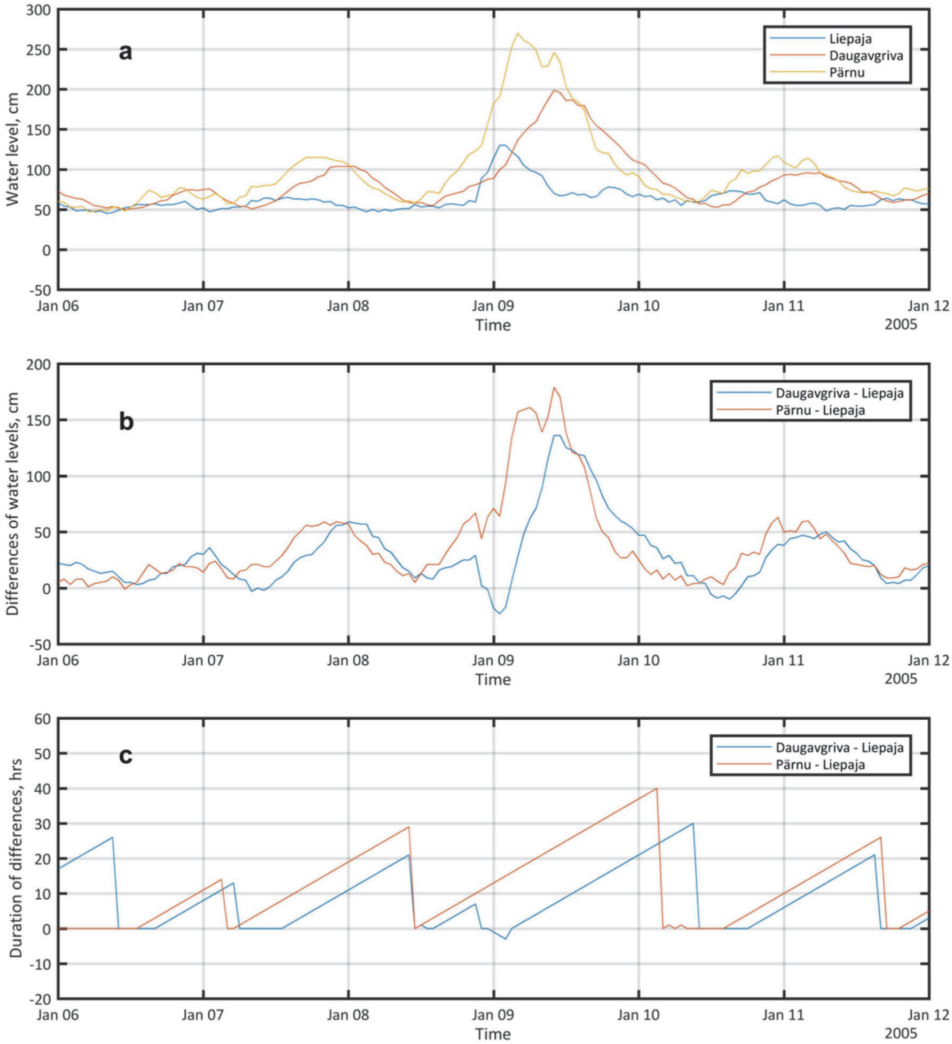


Fig. 13. Temporal course of a) water level at Liepaja, Daugavgriva and Pärnu, b) the difference of water level in the Gulf of Riga from that at Liepaja, c) single episodes of high water levels in the Gulf of Riga for the threshold $D_{lim} =$ 10 cm in January 2005.

every station, their difference from the recordings at Liepaja and durations of the episodes of differences are shown in Fig. 13. The water level at Pärnu was up to 180 cm and at Daugavgriva up to 135 cm higher than at Liepaja. As the water level in the entire Baltic Sea (including Liepaja) was 70–80 cm higher than the long-term average (Suursaar et al., 2006) this storm created a particularly dangerous water level. Even though it is not possible to exactly separate the excess water volume from the storm surge, it is likely that the average water level in the Gulf of Riga was up to 1 m above the Baltic Sea average.

The event with the largest magnitude M of water level elevations in the Gulf of Riga occurred during the storm Uwe (6.–11.12.2015, Wikipedia, 2018) at the beginning of December 2015. The relevant values reached $M = 91$ days × cm at Pärnu and $M = 43$ days × cm at Daugavgriva (Fig. 14). The maximum water levels at Daugavgriva and Pärnu reached 117 and 152 cm, respectively, on 07 December 2015. The maximum water level differences between these sites and Liepaja were 85 and 101 cm, respectively. As the water level at Liepaja (and in the rest of the Baltic Sea) was much less elevated (by about 50 cm with respect to the long-term average) than in January 2005, this storm did not lead to any serious consequences.

On some occasions, it is not clear whether or not substantial changes to the water volume of the Gulf of Riga have occurred. For example, on 27 February 1990, the water level at Liepaja increased rapidly from 26 cm to 111 cm within 9 h. The water level at Pärnu lagged behind this increase for several hours but then also increased rapidly (by almost 160 cm within 24 h) and reached its maximum (178 cm) 9 h later than Liepaja. The maximum difference between recordings at Pärnu and Liepaja was 115 cm. The background water level in the Baltic Sea proper was about 30–40 cm above long-term average; thus much lower than, e.g., during windstorm Gudrun and no serious consequences were reported.

Very large relative water level elevations usually occur more or less synchronously at Pärnu and Daugavgriva. The recordings contain examples where very high water levels were observed on only one of these

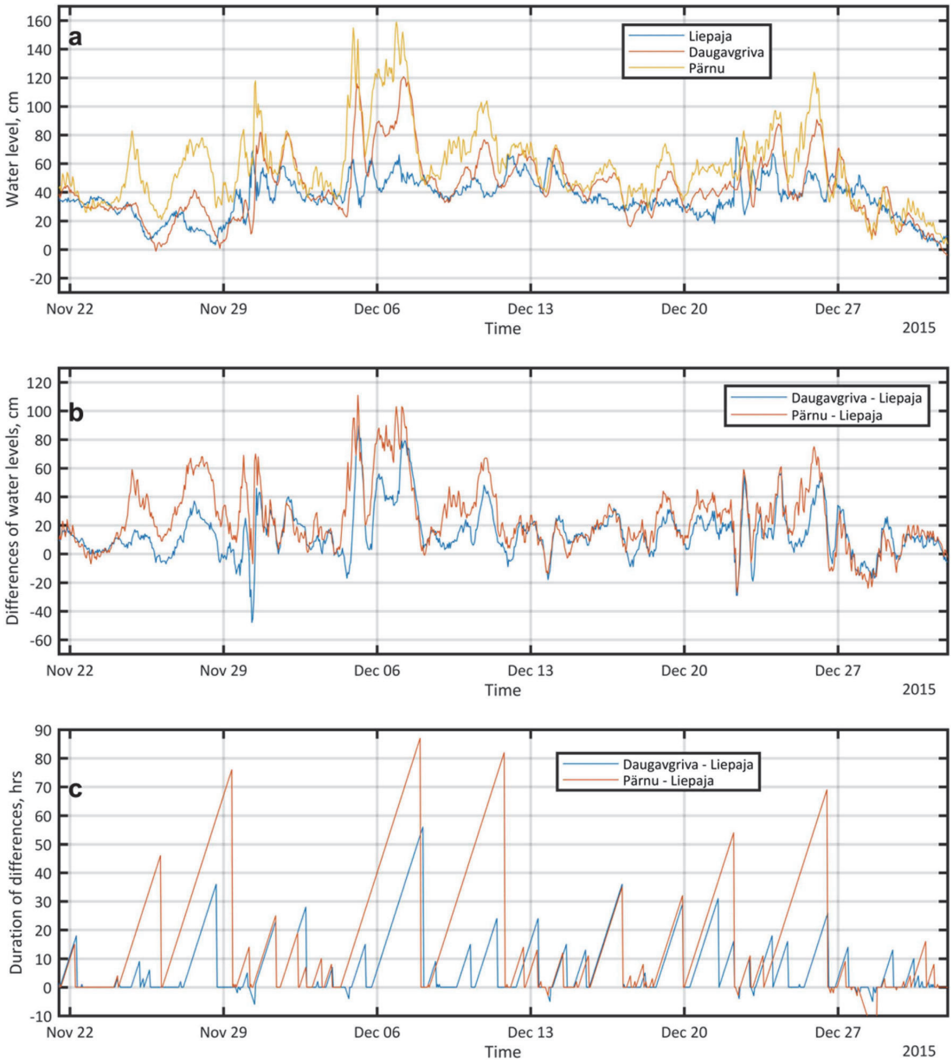


Fig. 14. Temporal course of a) water levels at Liepaja, Daugavgriva and Pärnu, b) the difference of water level in the Gulf of Riga from that at Liepaja, c) single episodes of high water level for the threshold D_{lim} = 10 cm in November–December 2015. Note the sequence of two events of water level elevations by almost 1 m in the Gulf of Riga compared to that in Liepaja on 05–07 December.

locations. For example, on 05 November 1979 water level at Pärnu rose rapidly. At a certain time instant it was almost 1 m above that at Liepaja. In Daugavgriva the difference remained less than 20 cm. It is likely that this situation was created by a local storm from a specific direction to which the water masses in Pärnu Bay are the most sensitive (cf. Suursaar et al., 2003). As the water level in the Baltic Proper was about 40 cm below the long-term average, this event was basically unnoticed. Another event with M = 79 days × cm on 27 November 1979 developed on the background of about 30 cm elevated Baltic Sea proper water level. It produced a water level difference up to 120 cm in the Gulf of Riga and the total water level over 150 cm at Pärnu.

4. Conclusions

The main aim of this paper was to diagnose and quantify the situations in which the water level in the Gulf of Riga considerably exceeds the water level in the Baltic Sea proper. Such occasions are particularly dangerous when the Baltic Sea water level is already substantially elevated. The analysis focuses on two differently located stations (Daugavgriva and Pärnu) for which high-quality, long-term water level recordings are available. The recordings at the reference station in Liepaja reflect the water level in the open Baltic Sea.

The main hypothesis is that the highest water levels in the interior of the Gulf of Riga are developed under the joint impact of three major drivers: water volume of the entire Baltic Sea that changes on multi-weekly scale, water occasionally pushed by a sequence of cyclones into the Gulf of Riga for 1–2 days and local storm surges with a typical duration of a few hours. Each of these drivers may add about 1 m to the resulting water level.

The analysis reveals that the water level in the Gulf of Riga (estimated using the two differently located stations) exceeds that in the Baltic Sea proper by more than 100 cm irregularly once in 5–10 years. The development and relaxation time of such events are governed by the ratio of the surface area of the Gulf of Riga and the cross-section of straits that connect this water body to the adjacent sub basins. Both the development and relaxation timescales are about one day and are thus much shorter compared to the time it takes for the entire Baltic Sea water volume to relax to its average value.

The technique used to separate the total water level into weekly-scale and more rapidly changing components (Soomere et al., 2015) is modified to single out events of increased water volume in the Gulf of Riga. The component that acts on the time scale of a few days is separated from the impact of storm surges and seiches by another averaging process over approximately one day. This separation leads to distributions of local storm surges at Daugavgriva and Pärnu that almost precisely match an exponential distribution ~ exp (λx). The approximate slopes of their positive and negative branches (or the associated scale parameters $-1/\lambda$) for low and high water levels provide useful information for calculating the probability of coastal flooding.

The scale parameters for the positive branch of the first residual at Liepaja and Daugavgriva match well the modelled results in (Soomere et al., 2015). For Pärnu, the modelled scale parameter is smaller than that extracted from observations. The scale parameters for the negative branch are larger than the typical values along the open coast of Estonia. This indicates that very low water levels are more probable on the Latvian coast than on the Estonian shores.

The performance of this approach depends on whether the typical time scales of the major processes that govern the water level in the Gulf of Riga are sufficiently different. While this is the case for the changes to the water volume of the entire Baltic Sea on (multi-)week scales (Post and Kõuts, 2014) and the impact of single storms over about one day, the separation of events of increased or decreased water volume of the Gulf of Riga and single storms is less strict and seems to be more reliable for low water levels.

The typical annual average number of episodes during which the water level in the Gulf of Riga exceeds that at Liepaja by > 30 cm is about 80 for Pärnu and about 46 for Daugavgriva. The number of such events has been constant at Daugavgriva but has decreased by a factor of 1.6 at Pärnu. The decreasing trend is statistically significant at a 95% level. The properties of the strongest events of this kind have not significantly changed since the 1960s and are almost insensitive with respect to the particular thresholds of water level difference used in the analysis.

We have introduced a scalar quantity that characterises the "magnitude" of episodes of water level differences in the Baltic Proper and in the interior of the Gulf of Riga in terms of an integral of their value and duration. There are also no changes in the annual maxima of this quantity for events of water level differences between the Gulf of Riga and the Baltic Sea proper. However, it seems that rare (once in about five years) single events with very large "magnitudes" have been added to the system starting from the 1980s.

5. Discussion

The improved knowledge of several parameters of the relative elevations and depressions of the water level in the Gulf of Riga has obvious significance in various tasks of coastal management and crisis regulation systems. The extended method for singling out the contribution of different physical mechanisms that drive very high water levels can be applied for the analysis of such processes in other water bodies where the relevant time scales are sufficiently different.

The data sets used in this study cover 57 years 1961–2017 during which a multitude of changes in the atmospheric forcing factors of the Baltic Sea have been observed (Hünicke et al., 2015). It is, however, not straightforward to draw conclusions about persistence and changes in the background processes that drive the water level in the study area as the relevant arguments are mostly circumstantial.

First of all, the long-term persistence of "magnitudes" of episodes of water level differences at differently located observation sites may be interpreted as showing that no substantial increase in (strong) wind speeds has occurred in the study area and in its vicinity. Similarly, the persistent number of the episodes of elevated water levels at Daugavgriva may be interpreted as showing that the annual average number of strong western and north-western winds (that usually drive such episodes) has not significantly changed since the 1960s. Even though this conjecture only applies to selected wind directions, it is consistent with the understanding that storminess in the Baltic Sea region did not substantially change during the 20th century (Bärring and von Storch, 2004) and indirectly supports the view about an increase in the persistence of storm and weather patterns in the study area (Rutgersson et al., 2014).

It is likely that the substantial and statistically significant decrease in the number of episodes of large water level differences between Liepaja and Pärnu reflects certain more subtle changes in the wind forcing. In essence, this indicates that the annual average frequency of relatively strong south-westerly winds over the Gulf of Riga (that mostly drive these differences) has considerably decreased since the 1960s. Technically, this means a modification of the directional structure of relatively strong winds in the study area. This change may stem from various alterations of the large-scale pattern of atmospheric processes such as a systematic rotation of wind directions in the Baltic Sea region (e.g., Soomere et al., 2015; Kudryavtseva and Soomere, 2017). In the context of the Baltic Sea, it may result from a shift in the typical trajectories of cyclones that cross this water body (Post and Kõuts, 2014).

Acknowledgements

The research was supported by the Estonian Ministry of Education and Research (Estonian Research Council, institutional support IUT33-3) and co-supported by the ERA-NET+ RUS project EXOSYSTEM and Flag-ERA project FuturICT2.0. The authors are deeply grateful to the Latvian Environment, Geology and Meteorology Centre and Estonian Weather Service for making the water level data publicly available.

References

Astok, V., Otsmann, M., Suursaar, Ü., 1999. Water exchange as the main physical process in semi-enclosed marine systems: the Gulf of Riga case. Hydrobiologia 393, 11–18. https://doi.org/10.1023/A:1003517110726.

Averkiev, A.S., Klevanny, K.A., 2010. A case study of the impact of cyclonic trajectories on sea-level extremes in the Gulf of Finland. Cont. Shelf Res. 30 (6), 707–714. https://doi.org/10.1016/j.csr.2009.10.010.

Bärring, L., von Storch, H., 2004. Scandinavian storminess since about 1800. Geophys. Res. Lett. 31, L20202 doi:101029/2004GL020441.

Boccotti, P., 2000. Wave Mechanics for Ocean Engineering. Elsevier Oceanography Series, vol. 64 Elsevier B.V., Amsterdam.

Bosley, K.T., Hess, K.W., 2001. Comparison of statistical and model-based hindcasts of subtidal water levels in Chesapeake Bay. J. Geophys. Res. – Oceans 106 (C8), 16869–16885.

Buschman, F.A., Hoitink, A.J.F., van der Vegt, M., Hoekstra, P., 2009. Subtidal water level variation controlled by river flow and tides. Water Resour. Res. 45 (10), W10420. https://doi.org/10.1029/2009WR008167.

Dailidienė, I., Davulienė, L., Tilickis, B., Stankevičius, A., Myrberg, K., 2006. Sea level variability at the Lithuanian coast of the Baltic Sea. Boreal Environ. Res. 11 (2), 109–121.

Eelsalu, M., Soomere, T., Pindsoo, K., Lagemaa, P., 2014. Ensemble approach for projections of return periods of extreme water levels in Estonian waters. Cont. Shelf Res. 91, 201–210. https://doi.org/10.1016/j.csr.2014.09.012.

Frison, T.W., 2000. Dynamics of the residuals in estuary water levels. Phys. Chem. Earth B Hydrol. Oceans Atmosph. 25 (4), 359–364. https://doi.org/10.1016/S1464-1909(00)00026-5.

Hünicke, B., Zorita, E., Soomere, T., Madsen, K.S., Johansson, M., Suursaar, Ü., 2015. Recent change – sea level and wind waves. In: The BACC II Author Team, Second Assessment of Climate Change for the Baltic Sea Basin, Regional Climate Studies. Springer, pp. 155–185.

Johansson, M., Boman, H., Kahma, K.K., Launiainen, J., 2001. Trends in sea level variability in the Baltic Sea. Boreal Environ. Res. 6 (3), 159–179.

Jönsson, B., Döös, K., Nycander, J., Lundberg, P., 2008. Standing waves in the Gulf of

Finland and their relationship to the basin-wide Baltic seiches. J. Geophys. Res. – Oceans 113 (C3), C03004. https://doi.org/10.1029/2006JC003862.
Kamphuis, J.W., 2010. Introduction to Coastal Engineering and Management. World Scientific.
Koltsova, T., Belakova, J., 2009. Storm surges on the southern coast of Gulf of Riga: case study of the Lielupe River. In: Jones, J.A.A., Vardanian, T.G., Hakopian, C. (Eds.), Threats to Global Water Security. NATO Advanced Research Workshop on Natural Disasters and Water Security, Yerevan, Armenia, pp. 91–97. https://doi.org/10.1007/978-90-481-2344-5_10. NATO Science for Peace and Security Series C – Environmental Security.
Kudryavtseva, N., Soomere, T., 2017. Satellite altimetry reveals spatial patterns of variations in the Baltic Sea wave climate. Earth Syst. Dyn. 8 (3), 697–706. https://doi.org/10.5194/esd-8-697-2017.
Kulikov, E.A., Medvedev, I.P., 2013. Variability of the Baltic Sea level and floods in the gulf of Finland. Oceanology 53 (2), 145–151. https://doi.org/10.1134/S0001437013020094.
Lazarenko, N.N., 1986. Variations of mean level and water volume of the Baltic Sea. Proceedings of the Water Balance of the Baltic Sea Environment, vol. 16. pp. 64–80.
Lehmann, A., Post, P., 2015. Variability of atmospheric circulation patterns associated with large volume changes of the Baltic Sea. Adv. Sci. Res. 12, 219–225. https://doi.org/10.5194/asr-12-219-2015.
Lehmann, A., Höflich, K., Post, P., Myrberg, K., 2017. Pathways of deep cyclones associated with large volume changes (LVCs) and major Baltic inflows (MBIs). J. Mar. Syst. 167, 11–18. https://doi.org/10.1016/j.jmarsys.2016.10.014.
Leppäranta, M., Myrberg, K., 2009. Physical Oceanography of the Baltic Sea. Springer, Berlin.
Losada, I.J., Reguero, B.G., Méndez, F.J., Castanedo, S., Abascal, A.J., Mínguez, R., 2013. Long-term changes in sea-level components in Latin America and the Caribbean. Glob. Planet. Chang. 104, 34–50. https://doi.org/10.1016/j.gloplacha.2013.02.006.
Medvedev, I.P., Rabinovich, A.B., Kulikov, E.A., 2013. Tidal oscillations in the Baltic Sea. Oceanology 53 (5), 526–538. https://doi.org/10.1134/S0001437013050123.
Nicholls, R.J., 2011. Planning for the impacts of sea level rise. Oceanography 24 (2), 144–157. https://doi.org/10.5670/oceanog.2011.34.
Pellikka, H., Leijala, U., Johansson, M.M., Leinonen, K., Kahma, K.K., 2018. Future probabilities of coastal floods in Finland. Cont. Shelf Res. 157, 32–42. https://doi.org/10.1016/j.csr.2018.02.006.
Post, P., Kõuts, T., 2014. Characteristics of cyclones causing extreme sea levels in the northern Baltic Sea. Oceanologia 56 (2), 241–258. https://doi.org/10.5697/oc.56-2.241.
Rutgersson, A., Jaagus, J., Schenk, F., Stendel, M., 2014. Observed changes and variability of atmospheric parameters in the Baltic Sea region during the last 200 years. Clim. Res. 61 (2), 177–190. https://doi.org/10.3354/cr01244.
Soomere, T., Pindsoo, K., 2016. Spatial variability in the trends in extreme storm surges and weekly-scale high water levels in the eastern Baltic Sea. Cont. Shelf Res. 115, 53–64. https://doi.org/10.1016/j.csr.2015.12.016.
Soomere, T., Myrberg, K., Leppäranta, M., Nekrasov, A., 2008. The progress in knowledge of physical oceanography of the Gulf of Finland: a review for 1997–2007. Oceanologia 50 (3), 287–362.
Soomere, T., Eelsalu, M., Kurkin, A., Rybin, A., 2015. Separation of the Baltic Sea water level into daily and multi-weekly components. Cont. Shelf Res. 103, 23–32. https://doi.org/10.1016/j.csr.2015.04.018.
Soomere, T., Eelsalu, M., Pindsoo, K., 2018. Variations in parameters of extreme value distributions of water level along the eastern Baltic Sea coast. Estuar. Coast Shelf Sci. 215, 59–68. https://doi.org/10.1016/j.ecss.2018.10.010.
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 (2), 249–260. https://doi.org/10.1111/j.1600-0870.2006.00220.x.
Suursaar, Ü., Kullas, T., Otsmann, M., 2002. A model study of the sea level variations in the Gulf of Riga and the Väinameri Sea. Cont. Shelf Res. 22 (14), 2001–2019. https://doi.org/10.1016/S0278-4343(02)00046-8.
Suursaar, Ü., Kullas, T., Otsmann, M., Kõuts, T., 2003. Extreme sea level events in the coastal waters of western Estonia. J. Sea Res. 49 (4), 295–303. https://doi.org/10.1016/S1385-1101(03)00022-4.
Suursaar, Ü., Kullas, K., Otsmann, M., Saaremäe, I., Kuik, J., Merilain, M., 2006. Cyclone Gudrun in January 2005 and modelling its hydrodynamic consequences in the Estonian coastal waters. Boreal Environ. Res. 11 (2), 143–159.
Talley, L.D., Pickard, G.L., Emery, W.J., Swift, J.H., 2011. Descriptive Physical Oceanography: an Introduction, sixth ed. Academic Press, London, pp. 560.
Von Storch, H., Zwiers, F.W., 1999. Statistical Analysis in Climate Research. Cambridge Univ. Press, New York, pp. 484.
Vousdoukas, M.I., Mentaschi, L., Voukouvalas, E., Verlaan, M., Feyen, L., 2017. Extreme sea levels on the rise along Europe's coasts. Earths Future 5 (3), 304–323. https://doi.org/10.1002/2016EF000505.
Wigley, T.M.L., 2018. The Paris warming targets: emissions requirements and sea level consequences. Clim. Change 147 (1–2), 31–45. https://doi.org/10.1007/s10584-017-2119-5.
Wikipedia, 2018. List of European Windstorms. [WWW]. https://en.wikipedia.org/wiki/List_of_European_windstorms, Accessed date: 12 October 2018.
Zecchetto, S., Umgiesser, G., Brocchini, M., 1997. Hindcast of a storm surge induced by local real wind fields in the Venice Lagoon. Cont. Shelf Res. 17 (12), 1513–1538. https://doi.org/10.1016/S0278-4343(97)00023-X.

Paper III

Soomere, T., **Männikus, R.**, Pindsoo, K., Kudryavtseva, N., Eelsalu, M. 2017. Modification of closure depths by synchronisation of severe seas and high water levels. *Geo-Marine Letters*, 37(1), 35−46, doi: 10.1007/s00367-016-0471-5.

Geo-Mar Lett (2017) 37:35–46
DOI 10.1007/s00367-016-0471-5

ORIGINAL

Modification of closure depths by synchronisation of severe seas and high water levels

Tarmo Soomere[1,2] · Rain Männikus[1] · Katri Pindsoo[1] · Nadezhda Kudryavtseva[1] · Maris Eelsalu[1]

Received: 2 July 2016 / Accepted: 21 September 2016 / Published online: 3 October 2016

Abstract The closure depth indicates the depth down to which storm waves maintain a universal shape of the coastal profile. It is thus a key parameter of the coastal zones for a variety of engineering and ecosystem applications. Its values are commonly estimated with respect to the long-term mean water level. The present study re-evaluates closure depths for microtidal water bodies where the wave loads are highly correlated with the course of the water level. The test area is the eastern Baltic Sea. The closure depth is calculated for the eastern Baltic Sea coast with a resolution of 5.5 km and the vicinity of Tallinn Bay with a resolution of 0.5 km. While the classic values of closure depth are extracted from statistics of the roughest seas, the present analysis is based on single values of a proxy of the instantaneous closure depth. These values are evaluated from numerically simulated time series of wave properties and water levels. The water level-adjusted closure depths are almost equal to the classic values at the coasts of Lithuania but are up to 10% smaller at the Baltic Proper coasts of Latvia and Estonia. The difference is up to 20% in bayheads of the Gulf of Finland.

Introduction

Even though different coastal stretches of the World Ocean host extremely different wave conditions and sediment properties, the basic shapes and properties of cross-sections (coastal profiles) of virtually all sedimentary coasts are extremely persistent. This persistence is quantified in terms of so-called equilibrium beach profiles (EBP; Dean 1991). The concept of EBP is often used for approximate solutions to various engineering problems (Dean and Dalrymple 2002), such as quantification of the changes to the shoreline position owing to sea level change (Bruun 1962), estimates of lifetime of beach nourishment (Dean 2002) or extracting variations in the sediment volume from shoreline relocation (Kask et al. 2009; Kartau et al. 2011; Eelsalu et al. 2015).

The shape of an EBP is frequently approximated using a power law that expresses the water depth $h(y)$ along the profile in terms of the distance y from the shoreline:

$$h(y) = Ay^b \quad (1)$$

This approximation contains three basic parameters: scale factor A, exponent b and closure depth h_c down to which such a profile exists. This simplification, even if it overlooks several important processes such as the dynamics of sand bars (Cerkowniak et al. 2015a, 2016), makes it possible to identify and forecast major changes to the beach based on fairly limited information about the local wave climate and sediment properties.

The scale factor A mirrors the grain size of the beach sediment (Dean and Dalrymple 2002). The exponent b is often close to $b = 2/3$ (Dean 1991) but may vary in quite a large range (Dean et al. 1993) and even reach levels $b > 1$ (Kit and Pelinovsky 1998; Didenkulova and Soomere 2011). The closure depth h_c is defined as the maximum depth at which the breaking waves effectively adjust the whole profile (Hallermeier 1978, 1981). In practice, it is understood as the depth where survey profiles recorded at different time instants pinch out to a common line (Kraus 1992). In other words, seawards from this depth waves occasionally move bottom

✉ Tarmo Soomere
soomere@cs.ioc.ee

[1] Institute of Cybernetics at Tallinn University of Technology, Akadeemia tee 21, 12618 Tallinn, Estonia

[2] Estonian Academy of Sciences, Kohtu 6, 10130 Tallinn, Estonia

sediments but are not able to continuously maintain a specific profile.

The major simplification from the EBP concept is that many properties of the beach can be easily evaluated or forecast based on the knowledge of only two fundamental quantities for each beach segment. These are the typical grain size (that determines the parameter A) and the closure depth h_c that is mostly a function of the local wave climate. Both may vary along the shoreline.

Another commonly used simplification is that the scale factor and closure depth are almost independent of each other. They reflect very different physical factors—sediment properties on the beach and parameters of the largest waves that approach the beach respectively. This feature is, however, only true for a certain range of the grain size for which a breaking wave mobilises substantial volumes of sediment (so that a sequence of waves can effectively shape the profile) for a short time interval (so that the impact of transport of suspended sediment by various types of wave-driven currents on this profile is minor). In classic studies (Hallermeier 1981) the typical sediment diameters ranged between 0.16 and 0.42 mm. It is generally thought that the described feature is applicable for most of the sandy beaches (Dean and Dalrymple 2002). For variable sediment grain size or for beaches with much larger typical grain size (e.g. gravel beaches), the closure depth is commonly specified from morphological and sedimentological criteria (e.g. Larson 1991; Phillips and Williams 2007).

The described split of the closure depth from several other features of beaches makes it possible to replace time-consuming and costly profiling of beaches by certain properties of waves (Houston 1996; Nicholls et al. 1996). These attempts are particularly useful in studies of coasts where the extraction of the limits of an EBP is nontrivial. For example, the surf zone substantially varies over the tidal cycle at macrotidal coasts (Phillips and Williams 2007), the presence of gently sloping underwater platforms in the nearshore often distorts the shape of the profiles (Simm 1996), the impact of strong nearshore currents on finer sediments may additionally modify the seaward end of the profile (Cerkowniak et al. 2015b), the EBP of sinking coasts may be masked by flooded coastal features, and Arctic coasts may exhibit specific features (Are and Reimnitz 2008; Are et al. 2008). Also, such attempts may give a better description of coasts that are occasionally modified by very strong storms that tend to prolong the EBP towards the offshore (Nicholls et al. 1996).

The original idea to evaluate the closure depth relied on the roughest wave conditions that persist for 12 h in a row once a year (Hallermeier 1981). It is now commonly accepted to use the parameters of severest seas of any 12 h in a year. The closure depth is often approximated as a quadratic function of the wave height (USACE 2002):

$$h_c = p_1 H_{S,0.137} - p_2 \frac{H_{S,0.137}^2}{g T_S^2} \quad (2)$$

Here $H_{S,0.137}$ is the significant wave height that occurs 12 h a year and T_S is the typical peak period of such seas. This approach has been applied to evaluate closure depths along sedimentary shores of the eastern and southern Baltic Sea (Soomere et al. 2013; Cerkowniak et al. 2015a, b). The use of values $p_1 = 2.28$, $p_2 = 68.5$ (Hallermeier 1981) leads to a fairly good match of closure depths estimated from Eq. 2 and from field studies in the southern Baltic Sea. Application of the values $p_1 = 1.75$, $p_2 = 57.9$ (Birkemeier 1985; Houston 1996) yields clearly smaller closure depths than those obtained from the field data (Cerkowniak et al. 2015b).

Equation 2 can be simplified in cases when the ratio of certain measures characterising the roughest waves and the mean wave height varies insignificantly (Nicholls et al. 1996). For example, along many US coasts, the majority of wave fields approximately follow a Pierson–Moskowitz spectrum. For such wave fields, $H_{S,0.137} \approx 4.5 H_{Smean}$ and

$$h_c \approx q_1 H_{S,0.137\%} \approx q_2 H_{Smean} \quad (3)$$

where H_{Smean} is the average significant wave height (Houston 1996), $q_1 = 1.5$ (Birkemeier 1985; often a value of $q_1 = 1.57$ is used, Hallermeier 1981) and $q_2 = 6.75$.

The combinations of wave heights and periods in strong storms are not necessarily the same in other parts of the world ocean. Many smaller-size water bodies host mainly unsaturated (JONSWAP-type) wave fields for which the relationship $H_{S,0.137} \approx 4.5 H_{Smean}$ is not applicable (Soomere et al. 2013). For example, the difference between estimates using Eqs. 2 and 3 may reach 30% in selected sections of the eastern Baltic Sea where commonly $H_{S,0.137} \approx 5.5 H_{Smean}$ and $\tilde{q}_2 = 8.25$ gives reasonable estimates of the closure depth.

The specific timing of severe seas and water levels may significantly modify the wave–bottom interaction in semi-sheltered microtidal water bodies. For example, high waves typically attack the eastern coast of the Baltic Sea (Fig. 1) when the water level is at least 0.6–1 m above average. These values are up to 30% of closure depths in semi-sheltered bays of the Gulf of Finland (Soomere et al. 2008). In extreme cases (e.g. in Pärnu Bay in south-western Estonia), the surge heights (up to 2.74 m, Suursaar and Sooäär 2007) are comparable with the closure depths. This means that the strongest storms (that are expected to govern the closure depth) may have relatively small impact on the seaward end of the equilibrium beach profile. Therefore, the closure depth may be governed by weaker wave storms, during which water levels are close to the long-term average one.

In this paper, the closure depths are recalculated for the eastern Baltic Sea coast from the Sambian (Samland) Peninsula until the eastern Gulf of Finland (incl. the Gulf of Riga) using information about water level during wave storms. The analysis is performed in high resolution (0.5 km) for the Tallinn area where possible modifications of the closure depth may have a marked influence on the estimates of sediment budgets (Soomere et al.

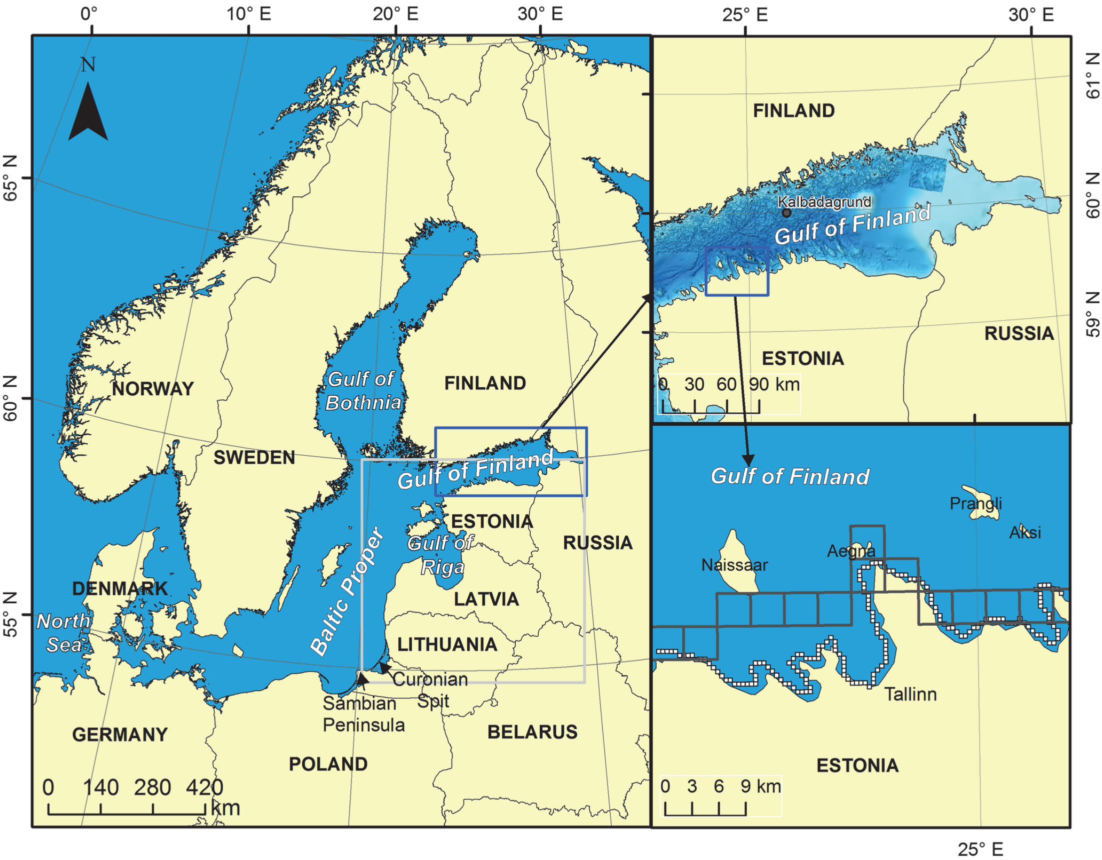


Fig. 1 Location scheme of the Baltic Sea and study area (*grey box*). The box in the left panel and panels at the right present computational areas of the triple-nested wave model applied to the Tallinn Bay area

2008) and the lifetime of beach nourishment activities. The paper is structured as follows. It starts with a description of the study area, modelled datasets used in the calculations and the method of evaluation of modified (adjusted to the water level) closure depths. This is followed by a presentation of adjusted closure depths for the open Baltic Sea coast, Gulf of Riga and the vicinity of Tallinn as well as their alongshore variability. The concluding sections discuss the possible implications of the results and shortly formulate the main conclusions.

Study area and method

Simulated wave properties

The focus is on sedimentary shores of the eastern Baltic Proper and two large semi-enclosed sub-basins—the Gulf of Riga and Gulf of Finland. The study area (Fig. 1) covers an about 1,400 km long coastal stretch from the Sambian Peninsula (20°E, 55°N) up to the eastern Gulf of Finland (28°E, 59°51′N). This stretch involves the entire nearshore of Lithuania, Latvia and Estonia, and part of the shores of Russia in the Kaliningrad District (Fig. 2).

The hourly time series of significant wave height and peak period were extracted from numerical simulations of the Baltic Sea wave fields for 1970–2007. The wave model WAM (Komen et al. 1994) was run for a regular grid with a spatial resolution of 3′×6′ (lat.×long., about 3×3 nautical miles), and a directional resolution of 15° (Räämet and Soomere 2010) using 42 wave frequencies ranging from 0.042 to 2.08 Hz with an increment of 1.1. The forcing wind data at the standard height of 10 m were constructed from the Swedish Meteorological and Hydrological Institute (SMHI) geostrophic wind database by reducing the wind speed by 40% and turning the wind direction counter-clockwise by 15°. The presence of sea ice is ignored. The accuracy of the wind forcing and the reliability of the wave model output are discussed by, for example, Soomere and Räämet (2011, 2014). The main features of the numerically reconstructed wave climate

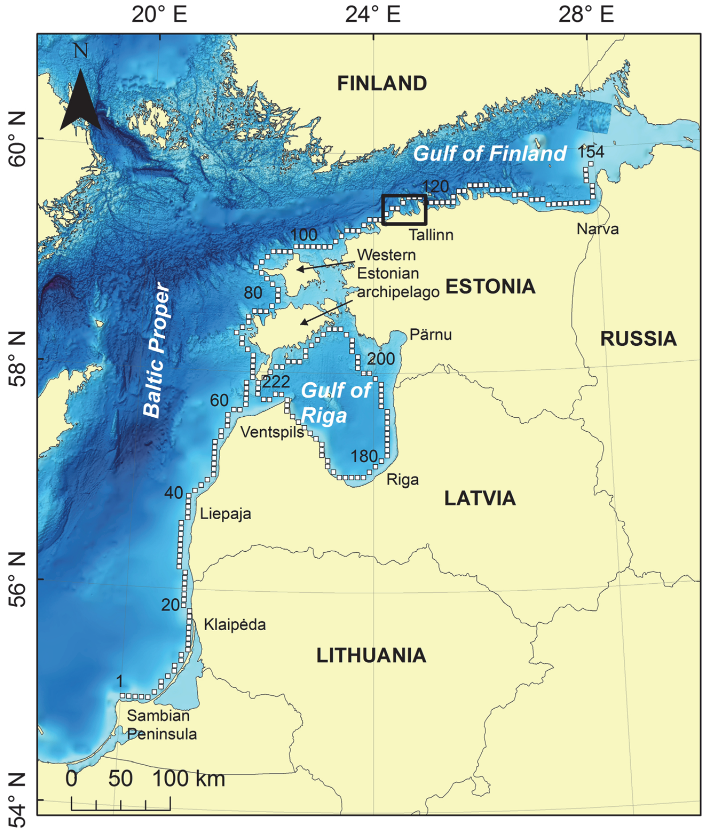


Fig. 2 Grid points of the wave model used to evaluate the nearshore wave properties and closure depths at the eastern Baltic Sea coast. *Box* Detailed study area in the vicinity of Tallinn Bay

and their comparison with available instrumental measurements and visual observations are presented in Soomere (2016).

The study area is divided into 222 about 5.5–6.5 km long nearshore sections, out of which 154 (950 km) follow the shores of the Baltic Proper and the Gulf of Finland and 68 sections (450 km) cover the Gulf of Riga. Although it is possible to reconstruct the wave properties until the surf zone (Lopez-Ruiz et al. 2015), variations in the water level may substantially relocate the seaward border of the surf zone, and the reliability of such calculations is low because of insufficient information about the geometry of the seabed. For this reason, the present study uses the grid cells of the wave model (Fig. 2) at depths from 7 to 48 m (the average of 18 m) where the WAM model adequately replicates the wave properties. For the same reason, the wave model grid cells in the eastern Gulf of Riga are chosen outside Pärnu Bay.

Estimates with a resolution of 5–6 km usually characterise acceptably the properties of waves and the nearshore along relatively straight sections of the study area. They are unreliable at several locations of the Baltic Sea such as the northern coast of Estonia where the typical morphological elements have spatial scales <1 km. This coast is almost straight at scales of few 100s of meters but contains large peninsulas and bays on scales from a few km (Raukas and Hyvärinen 1992). As the bays are open to different directions, wave loads markedly vary along the coast (Pindsoo and Soomere 2015). As an example of a shore segment with complicated geometry, the present study considers an about 50 km long nearshore section in the vicinity of Tallinn in a resolution of about 0.5 km (Figs. 1 and 2).

Significant wave height and peak period were calculated in the vicinity of Tallinn Bay with a spatial resolution of about 470 m using a triple-nested version of the WAM model for the years 1981–2014 (Figs. 1 and 3). In a simplified scheme, long-term calculations of sea state were replaced by an analysis of pre-computed maps of wave parameters (Soomere 2005). A coarse model was first applied to the entire Baltic Sea as described above. Information from this model was used to determine wave properties at the entrance to the Gulf of Finland. A medium-resolution version of the model was run with a grid step of about 1.8 km in this gulf. Finally, a higher-resolution (about 470 m) model resolved the major geometric and bathymetric features of the Tallinn Bay area.

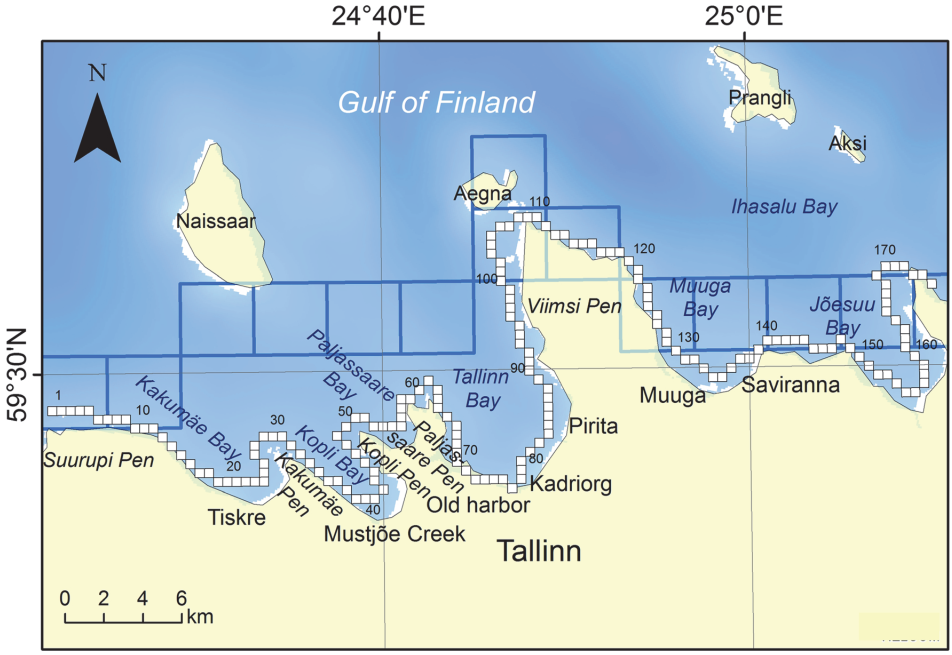


Fig. 3 Grid cells of the fine-resolution version of the WAM model (*small squares*) and nearshore grid cells of the RCO model (*large squares*)

This hierarchy of models was forced with a spatially homogeneous wind field, constructed from high-quality records of wind properties at Kalbådagrund, a caisson lighthouse in the central part of the Gulf of Finland (Fig. 2, 59°59′N, 25°36′ E). This is the only location in the gulf that is not affected by the presence of mainland. As the wind measurements are performed at Kalbådagrund at the height of 32 m above the mean sea level, the height correction factor 0.85 was used to reduce the recorded wind speed to the standard height of 10 m. The reader is referred to Soomere (2005), Soomere et al. (2013), Pindsoo and Soomere (2015) and references therein for a description of the wave model and a discussion of the quality of wind information and the reliability of the model output.

Modelled water levels

The information about water level was extracted from the output of the Rossby Centre Ocean Model (RCO). The relevant dataset with a temporal resolution of 6 h for May 1961–May 2005 was produced by the SMHI and provided in the framework of BONUS BalticWay cooperation (Soomere et al. 2014). Detailed descriptions of this ocean circulation model are presented in a number of publications (e.g. Meier et al. 2003; Meier and Höglund 2013), and here only its major features are shortly depicted. The horizontal and vertical resolutions of this model (2×2 nautical miles and 3–12 m respectively) are commonly considered to be acceptable for the reproduction of the water levels in the eastern Baltic Sea whereas a certain deviation of the modelled storm surges from the observed values exists in the western Baltic Sea (Meier et al. 2004). The model was forced with a meteorological dataset with a horizontal resolution of 22 km derived from the ERA-40 re-analysis (Samuelsson et al. 2011). The water levels for a particular segment of the nearshore were taken from the closest circulation model cell for the time instants closest to the timeline of wave properties. The water level data mostly match the wave data in the open Baltic Sea but one circulation model cell provides water level information for almost 60 segments of the nearshore in Tallinn Bay (Fig. 3).

The simulated datasets have different temporal coverages. The coverage of wave properties with a resolution of 5–6 km is limited by the availability of geostrophic winds (1970–2007). Wind properties at Kalbådagrund are only available since 1981, and the RCO model simulation covers the time interval of May 1961–May 2005. The closure depths with a resolution of 3 nautical miles are thus evaluated based on 35 years of data (1970–2005). The estimates for the Tallinn Bay area rely on 25 years of data (1981–2005).

Estimates of water level-adjusted closure depth

The approximate values of classic and adjusted (to the water level) closure depths can be evaluated from Eq. 2 using several slightly different approaches that represent the response of the beach to processes on different timescales (Nicholls et al. 1998). For shorter (e.g. annual) timescales, an estimate can be derived using the threshold $H_{S,0.137}$ for each year and the typical period T_S for wave fields that exceed this threshold. An average of the resulting estimates characterises the lower limit of closure depth. This approximation can be used to estimate, for example, the lifetime of small beach nourishment activities during years with an average wave climate.

The use of threshold $H_{S,0.137}$ and the typical peak period of such severe seas for the entire simulation interval 1970–2007 provides a conservative estimate of closure depth for years with largest wave activity, equivalently, the width of the EBP that is created during a longer time interval. The experience in the Baltic Sea conditions suggests that the values $p_1 = 1.75$, $p_2 = 57.9$ in Eq. 2 lead to a certain underestimation of the closure depth (that is, to its values that are valid during relatively short time intervals that do not contain strong storms) whereas the values $p_1 = 2.28$, $p_2 = 68.5$ also characterise the reaction of the beach profile to strong storms that infrequently occur during longer time intervals (Cerkowniak et al. 2015a, b).

Estimates of water level-adjusted closure depths require different handling because each entry of the time series of wave properties should be associated with the relevant entry of the water level time series. The role of single wave events in the formation of the EBP can be quantified using a proxy for the 'instantaneous' water level-adjusted closure depth $\tilde{h}_{cwt}$ for each entry of the time series of wave properties:

$$\tilde{h}_{cwt} \approx h_{ct} - w_t \tag{4}$$

Here w_t is the deviation of the water level from the long-term mean at time instant t and h_{ct} is the 'instantaneous' closure depth with respect to the long-term average water level evaluated from the following modification of Eq. 2:

$$h_{ct} = p_1 H_{St} - p_2 \frac{H_{St}^2}{g T_t^2} \tag{5}$$

The only difference from Eq. 2 is that here H_{St} is the significant wave height and T_t is the peak period at time instant t.

First calculated were the values of $\tilde{h}_{cwt}$ for each time instant of wave time series (hourly for the open Baltic Sea coast and once in 3 h for the Tallinn Bay area). The results reflect the approximate water depths (with respect to the long-term average water level), seawards of which breaking waves of the particular sea state are not able to massively relocate bottom sediment. As modelled water levels are available only once in 6 h, a total of 51,313 single values of wave properties and water heights are employed in calculations with a resolution of 3 nautical miles.

An approximation of the water level-adjusted closure depth (called adjusted closure depth below) for a single year is estimated as the threshold that is reached or exceeded by the values of $\tilde{h}_{cwt}$ during 12 h of this year. An estimate for the adjusted closure depth for a typical year is found as the average of such 0.137%-iles of $\tilde{h}_{cwt}$ for all years of the simulation. The similar percentile of $\tilde{h}_{cwt}$ for the entire simulation interval (35 years for the open Baltic Sea coast, 25 years for the Tallinn Bay area) represents the possible extension of the EBP during sequences of (or long-lasting) very strong storms. Alternatively, rough approximations of the adjusted closure depth were found using Eq. 4 and the described procedure, with the instantaneous closure depths provided by Eq. 3 with $\tilde{q}_2 = 8.25$.

Results

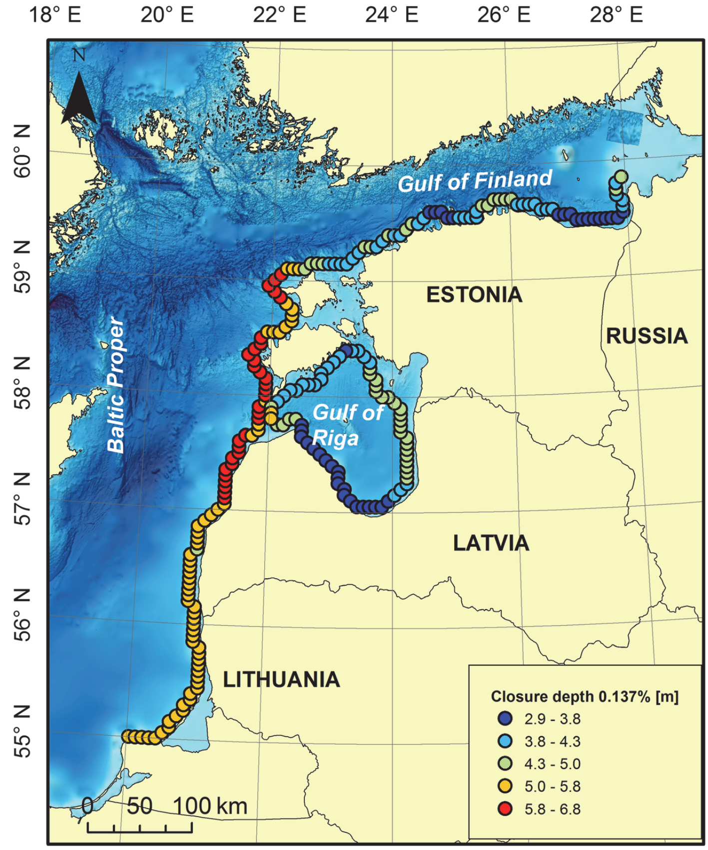
Longshore variations in classic and water level-adjusted closure depths

It is natural that all approximations of the adjusted closure depths closely follow the similar pattern of classic closure depths established in Soomere et al. (2013). The alongshore variations of the difference between the classic and adjusted versions of all these measures are also fairly similar. For this reason, the present study reports only the results for the averages of the 0.137%-iles of $\tilde{h}_{cwt}$ for each year and the similar estimate for the classic closure depth using $p_1 = 1.75$, $p_2 = 57.9$ in Eqs. 2, 4, 5 (Figs. 4 and 5). As the analysis is performed based on single values of instantaneous closure depths, some features of these time series are also described.

The largest values of the adjusted closure depths (5–7 m) are found along the open coasts of the Baltic Proper, with maxima at the Sambian Peninsula, near Ventspils and at the coasts of the Western Estonian archipelago (Fig. 5). The closure depths are clearly smaller in the eastern Gulf of Riga and along the entire southern coast of the Gulf of Finland. The smallest values occur in the western Gulf of Riga and along those coastal segments of the Gulf of Finland that are open to the northeast or east.

The estimates of the classic and adjusted closure depths almost coincide along the northern coast of the Sambian Peninsula and the Lithuanian coast (Fig. 5). The frequent copresence of increased water levels and high waves noticeably modifies the closure depth to the north of the Lithuanian–Latvian border (Figs. 5 and 6). The maximum values of $\tilde{h}_{cwt}$ for single coastal segments markedly (on average by a factor of two in the entire study area) exceed the classic closure depths h_c evaluated from Eq. 2. This difference reflects the occasional presence of very severe seas during short time intervals. It basically mirrors the well-known substantial variation in the properties of the largest waves in the nearshore (Babanin et al. 2011). The marked difference also signals that

Fig. 4 Adjusted closure depths along the eastern Baltic Sea coast evaluated as the 0.137%-iles of the relevant instantaneous closure depths $\tilde{h}_{cwt}$ defined in Eq. 4 with $p_1 = 1.75$, $p_2 = 57.9$



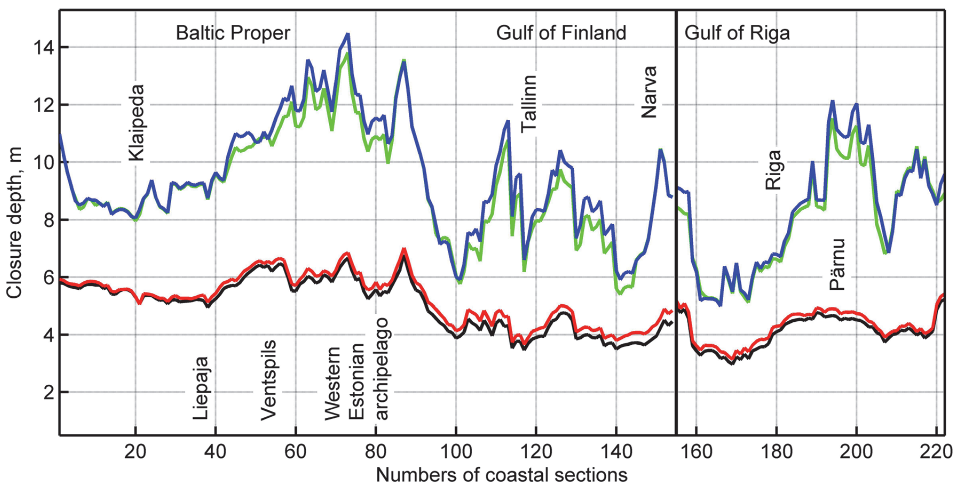


Fig. 5 Closure depths evaluated using Eqs. 2 and 4, 5 with $p_1 = 1.75$, $p_2 = 57.9$ for the eastern coast of the Baltic Sea with a resolution of 3 nautical miles. *Blue* Maximum 'instantaneous' closure depth h_{ct}, *green* the same but adjusted with water level $\tilde{h}_{cwt}$, *red* the classic closure depth from Eq. 2, *black* the adjusted closure depth from Eqs. 4, 5; *both red and black* evaluated as 0.137%-iles of the relevant single values over the entire study interval

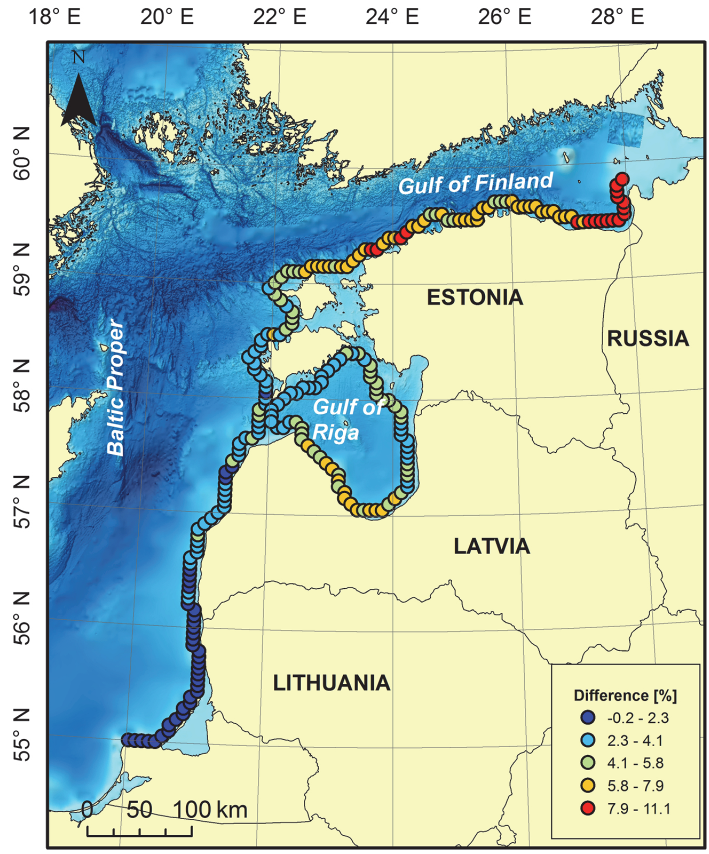


Fig. 6 The relative difference (%) between the classic and adjusted closure depths along the eastern Baltic Sea coast evaluated using Eq. 2 and Eqs. 4, 5 with, $p_1 = 1.75$, $p_2 = 57.9$. The classic closure depths have been extracted from Soomere et al. (2013)

the closure depths evaluated for the Baltic Sea using Eq. 2 should be interpreted as indicative ones. In other words, very strong storms may relocate massive sediment volumes at much larger depths than the formal closure depth for this water body (Cerkowniak et al. 2015a, b).

Impact of water level on closure depth

The relative difference of the quantities evaluated from Eq. 2 and Eqs. 4, 5 is almost zero at the Sambian Peninsula, along the Curonian Spit and at the mainland coast of Lithuania (Fig. 6). The adjusted closure depth is even slightly larger than the classic one in the vicinity of Klaipėda (Fig. 7). Consequently, severe seas often occur in these coastal segments when the water level is close to (or even below) the long-term average. This outcome is consistent with the two-peak directional distribution of strong winds in the open Baltic Sea. North-western storms do not necessarily produce an increased water level along these coastal sections, and high waves approach in such storms often during water levels that match the long-term average.

The difference increases to 3–4% near Liepaja and persists at this level along the north-western coast of Latvia and the nearshore of the Western Estonian archipelago (Figs. 6 and 7). The coasts in these areas are predominantly straight and oriented in the north–south direction. Stormy winds usually blow from the southeast or north-northwest. Thus, storms that blow exactly onshore and create very high water levels are infrequent in this region. The difference in question is somewhat larger (4–6%, in selected locations up to 8%) in the Gulf of Riga. Such large values apparently reflect a common situation during westerly winds that push water level in this semi-enclosed gulf even higher than in the eastern Baltic Proper.

The shores of the Gulf of Finland are even more strongly affected by the frequent co-presence of high water level and severe seas. The adjusted closure depths are considerably larger than the classic ones in sections that are open to the west or northwest. The relative difference between these two quantities reaches 11% in Narva Bay (Figs. 6 and 7) and is also fairly large in the western part of the gulf.

This difference may be substantially larger in single segments of the coast. Higher-resolution simulations reveal

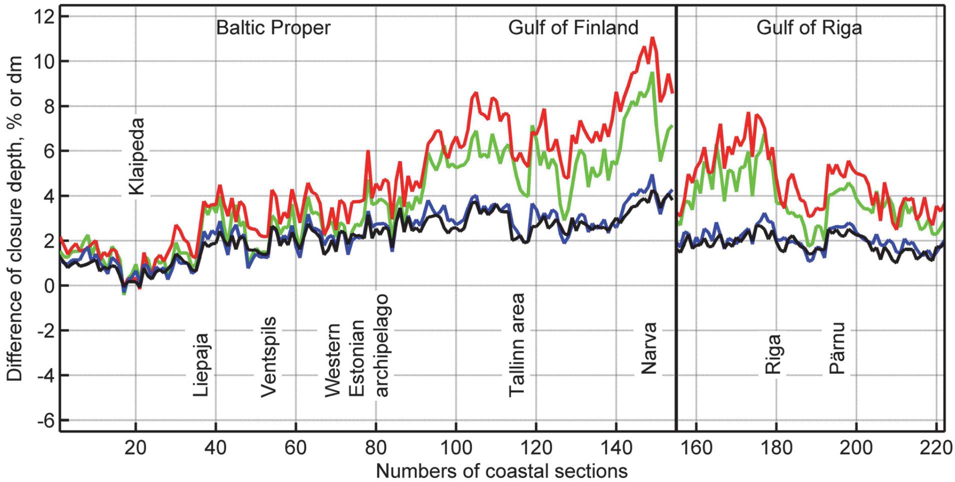


Fig. 7 The relative (% of the adjusted closure depth) and actual (dm) difference between classic and adjusted closure depths along the eastern coast of the Baltic Sea. The classic closure depths have been extracted from Soomere et al. (2013). *Green and blue* Relative and actual difference between the classic (h_{ct}) and adjusted ($\tilde{h}_{cwt}$) maximum instantaneous closure depths respectively, evaluated using $p_1 = 2.28$, $p_2 = 68.5$; *red and black* the same for values found from Eq. 2 and Eqs. 4, 5 with $p_1 = 1.75$, $p_2 = 57.9$ as 0.137%-iles of the relevant single values over the entire study interval

that it reaches 15–20% at locations of the Tallinn Bay area that are open to the west (Figs. 8 and 9). This area is characterised by relatively rapid postglacial uplift and an overall sediment deficit (Raukas and Hyvärinen 1992). Many bayheads are geometrically sheltered from predominant wind directions (Soomere et al. 2008). Consequently, beach profiles at several locations are not fully developed. This means that occasional strong storms may rapidly fill their seaward ends. This process may lead to unexpectedly rapid erosion of the coastal scarp. The described fairly large difference between the classic and adjusted closure depths considerably decreases the probability of such events and thus implicitly diminishes the associated marine hazards in the affected coastal sections. This property may play an important role in the functioning of the nearshore environment in this region because the seabed generally deepens rapidly and substantial amounts of finer sediment are necessary to fill the entire EBP. Also, the described feature may reduce the amount of sand fill for beach nourishment by 20–30%.

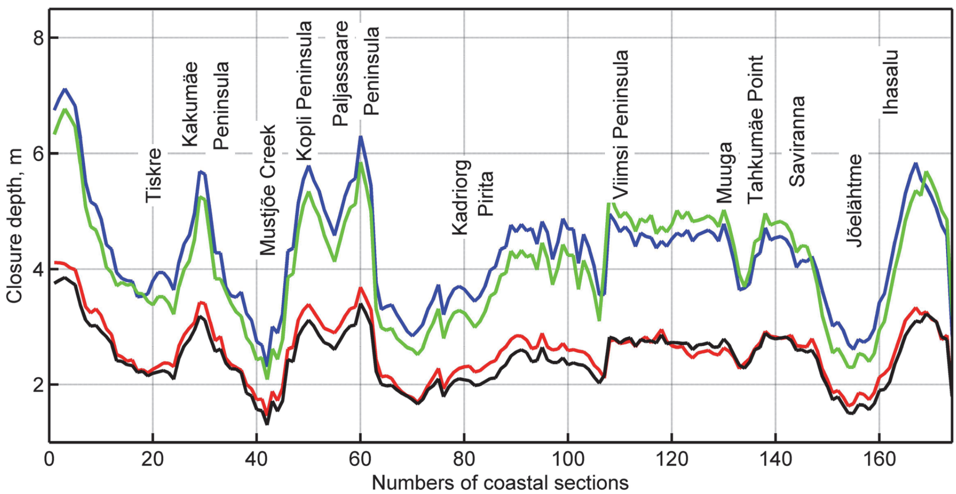


Fig. 8 Closure depths evaluated using Eqs. 2 and 4, 5 with $p_1 = 1.75$, $p_2 = 57.9$ for the Tallinn Bay area with a resolution of 1/4 nautical miles. The classic closure depths have been extracted from Soomere et al. (2013). The notations are the same as for Fig. 5

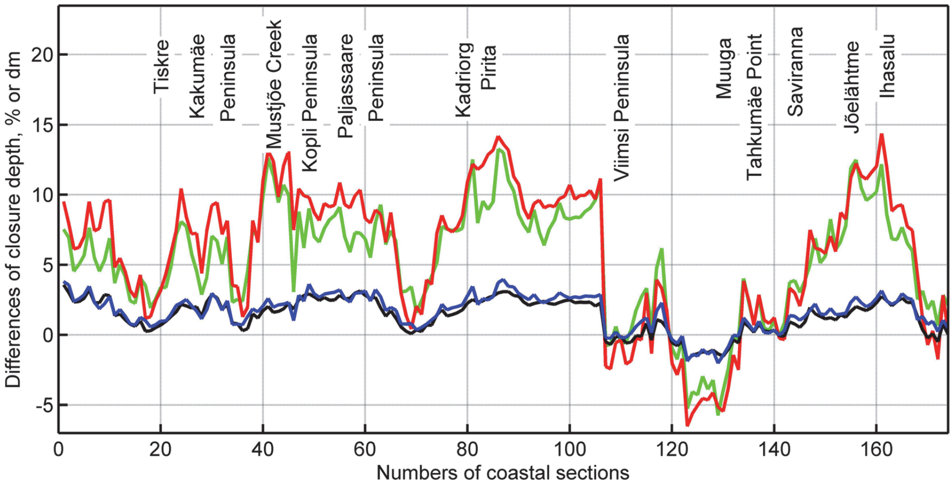


Fig. 9 Relative (% of the adjusted closure depth) and actual (dm) difference between classic and adjusted closure depths evaluated using Eqs. 2 and 4, 5 with $p_1 = 1.75$, $p_2 = 57.9$ in the vicinity of Tallinn. The classic closure depths have been extracted from Soomere et al. (2013). The notations are the same as for Fig. 7. Note the characteristic jump from relatively large positive values in areas of the Viimsi Peninsula open to the west or northwest to negative values of the same magnitude in areas open to the east

Discussion

The core new feature of the present approach is an attempt to take systematically into account the impact of elevated water levels during strong wave storms on the properties of the active part of the underwater beach profile. A more technical change is in how the adjusted closure depth is evaluated. The classic values of closure depth are extracted from statistical properties of the roughest seas (optionally including information about wave periods). The analysis in this paper additionally includes water level, and the necessary statistical properties are extracted from a time series of a proxy of the instantaneous closure depth. The main outcome is that in some segments of the eastern Baltic Sea the classic estimates of closure depth may considerably overestimate the dimensions of the active part of beaches. This conjecture partially explains why some beaches of the study area with very limited sand volume are still relatively stable (e.g. Kartau et al. 2011).

The presented results rely exclusively on numerical experiments. As contemporary models adequately reconstruct not only statistical properties but also most of the course of wave properties and water level, it is likely that the order of magnitude of adjustments is captured correctly. However, the spatial resolution of the models is evidently not sufficient for an exact representation of the processes in the immediate nearshore where local effects may play a significant role. For example, modelled and extreme water levels may deviate almost by a factor of two at certain locations of the Estonian coast (Eelsalu et al. 2014), and strong storms may mobilise significant volumes of sand at much larger depths than the closure depth in the southern Baltic Sea (Cerkowniak et al. 2015b). Consequently, there is a clear need for field evidence to support these conjectures and to evaluate the magnitude of local effects.

The possibilities of detection of this feature evidently vary along the Baltic Sea coast. The northern part of the study area experiences postglacial uplift (that today overrides the global sea level rise) whereas a weak subsidence and a gradual increase in the water level is characteristic in the southern part (Leppäranta and Myrberg 2009). Several subsiding sections of the study area (e.g. the Curonian Spit) have comparatively large amounts of fine sediment and gentle underwater slopes in the nearshore. Consequently, a separation of the contemporary EBP is not always possible, and the detection of the discussed effect is complicated. The same applies to the southern and eastern coasts of the Gulf of Riga.

The entire concept of EBP is not applicable for several stretches of limestone coasts of Estonia that host very limited amounts of fine sediment. This region, however, contains numerous sandy beaches (formed from ancient sand deposits) and some sections of active gravel coast. As the slope of the seabed is relatively large along the North Estonian coast (Orviku 1974), the characteristic 'bend' at the seaward end of the EBP is often clearly visible (Soomere et al. 2008). This bend apparently moves seawards in response to the land uplift. It is thus likely that the best evidence of the described effect could be gathered from profiles of sandy beaches of the uplifting Northern Estonia.

The probability of occurrence and possible implications of the described feature are apparently minor at open ocean coasts where breaking waves can be very high, and the presence of large waves is not necessarily related to a high storm surge. The consequences may be relatively strong in many pocket beaches (cf. Frihy et al. 2004) or longer coastal sections of microtidal seas (Anfuso et al. 2011) where severe wave fields are often associated with increased water levels. The established difference between the classic estimates of the closure depth and the actual depth of the seaward end of the EBP feature may lead to considerable modification of estimates of the budget of underwater sediment volumes—e.g. after engineering works when the full EBP has not been built up yet. It is also likely that the presence and magnitude of the onshore sand transport from beyond closure depth (Houston and Dean 2014; Houston 2015) first of all depend on the adjusted closure depth.

Conclusions

The presented numerical simulations of the potential influence of frequent synchronisation of severe seas and increased water levels in the eastern Baltic Sea lead to the following conclusions:

- This kind of synchronisation has an insignificant impact on the closure depths and overall course of coastal processes in relatively straight coastal sections of the eastern coast of the Baltic Proper. Strong storms occasionally create increased water levels in such sections but high waves also often approach during water levels that are close to the long-term average. The synchronisation is slightly more pronounced in the Gulf of Riga but still leads to a generally insignificant decrease in the closure depths.

- Systematic co-presence of severe seas and high water levels in the Gulf of Finland may reduce the closure depth by up to 20% in several parts of this water body. This feature implicitly suppresses the intensity of coastal erosion because the effective width of the coastal profile (counted from the shoreline) is smaller and less sediment is needed to build it. Consequently, much less sand may be needed for the nourishment of such beaches. Equivalently, the lifetime of beach refills may be considerably longer than expected based on classic estimates of closure depth.

Acknowledgements This study was initiated by the Small Grants Scheme Project "Effects of climate changes on biodiversity in the coastal shelves of the Baltic Sea" 2015–2016 (EEA grant No. 2/EEZLV02/14/GS/022) financed by European Economic Area Financial Instrument 2009–2014 Programme "National Climate Policy". The research was partially supported by the institutional support of the Estonian Ministry of Education and Research (IUT33-3) and by the project "Sebastian Checkpoints – Lot 3 Baltic" of the call MARE/2014/09. Also acknowledged are constructive assessments by J. Deng and J. Harff.

Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest with third parties.

References

Anfuso G, Pranzini E, Vitale G (2011) An integrated approach to coastal erosion problems in northern Tuscany (Italy): littoral morphological evolution and cell distribution. Geomorphology 129:204–214. doi:10.1016/j.geomorph.2011.01.023

Are F, Reimnitz E (2008) The *A* and *m* coefficients in the Bruun/Dean Equilibrium Profile equation seen from the Arctic. J Coast Res 24: 243–249. doi:10.2112/05-0572.1

Are F, Reimnitz E, Grigoriev M, Hubberten HW, Rachold V (2008) The influence of cryogenic processes on the erosional arctic shoreface. J Coast Res 24:110–121. doi:10.2112/05-0573.1

Babanin AV, Hsu T-W, Roland A, Ou S-H, Doong D-J, Kao CC (2011) Spectral wave modelling of Typhoon Krosa. Nat Hazards Earth Syst Sci 11:501–511. doi:10.5194/nhess-11-501-2011

Birkemeier WA (1985) Field data on seaward limit of profile change. J Waterw Port C Div 111:598–602

Bruun P (1962) Sea level rise as a cause of shore erosion. J Waterw Harbours Div ASCE 88:117–133

Cerkowniak GR, Ostrowski R, Stella M (2015a) Depth of closure in the multi-bar non-tidal nearshore zone of the Baltic Sea: Lubiatowo (Poland) case study. Bull Maritime Inst Gdańsk 30:180–188. doi:10.5604/12307424.1185577

Cerkowniak GR, Ostrowski R, Stella M (2015b) Wave-induced sediment motion beyond the surf zone: case study of Lubiatowo (Poland). Arch Hydro Eng Environ Mech 62:27–39. doi:10.1515/heem-2015-00017

Cerkowniak GR, Ostrowski R, Pruszak Z (2016) Application of Dean's curve to investigation of a long-term evolution of the southern Baltic multi-bar shore profile. Oceanologia. doi:10.1016/j.oceano.2016.06.001

Dean RG (1991) Equilibrium beach profiles: characteristics and applications. J Coast Res 7:53–84

Dean RG (2002) Beach nourishment. Theory and practice. World Scientific, River Edge, NJ

Dean RG, Dalrymple RA (2002) Coastal processes with engineering applications. Cambridge University Press, New York

Dean RG, Healy TR, Dommerholt AA (1993) A "blind-folded" test of equilibrium beach profile concepts with New Zealand data. Mar Geol 109:253–266. doi:10.1016/0025-3227(93)90064-3

Didenkulova I, Soomere T (2011) Formation of two-section cross-shore profile under joint influence of random short waves and groups of long waves. Mar Geol 289:29–33. doi:10.1016/j.margeo.2011.09.011

Eelsalu M, Soomere T, Pindsoo K, Lagemaa P (2014) Ensemble approach for projections of return periods of extreme water levels in Estonian waters. Cont Shelf Res 91:201–210. doi:10.1016/j.csr.2014.09.012

Eelsalu M, Soomere T, Julge K (2015) Quantification of changes in the beach volume by the application of an inverse of the Bruun Rule and laser scanning technology. Proc Est Acad Sci 64:240–248. doi:10.3176/proc.2015.3.06

Frihy OE, Iskander MM, Badr AEMA (2004) Effects of shoreline and bedrock irregularities on the morphodynamics of the Alexandria coast littoral cell, Egypt. Geo-Mar Lett 24:195–211. doi:10.1007/s00367-004-0178-x

Hallermeier RJ (1978) Uses for a calculated limit depth to beach erosion. In: Proc 16th Int Conf Coast Eng. ASCE, Hamburg, p 1493–1512
Hallermeier RJ (1981) A profile zonation for seasonal sand beaches from wave climate. Coast Eng 4:253–277
Houston JR (1996) Simplified Dean's method for beach-fill design. J Waterw Port C Div 122:143–146. doi:10.1061/(ASCE)0733-950X(1996)122:3(143)
Houston JR (2015) Shoreline response to sea-level rise on the southwest coast of Florida. J Coast Res 31:777–789. doi:10.2112/JCOASTRES-D-14-00161.1
Houston JR, Dean RG (2014) Shoreline change on the east coast of Florida. J Coast Res 30:647–660. doi:10.2112/JCOASTRES-D-14-00028.1
Kartau K, Soomere T, Tõnisson H (2011) Quantification of sediment loss from semi-sheltered beaches: a case study of Valgerand Beach, Pärnu Bay, the Baltic Sea. J Coast Res SI 64:100–104
Kask A, Soomere T, Healy TR, Delpeche N (2009) Rapid estimate of sediment loss for "almost equilibrium" beaches. J Coast Res SI 56: 971–975
Kit E, Pelinovsky E (1998) Dynamical models for cross-shore transport and equilibrium bottom profiles. J Waterw Port Coast Ocean Eng 124:138–146. doi:10.1061/(ASCE)0733-950X(1998)124:3(138)
Komen GJ, Cavaleri L, Donelan M, Hasselmann K, Hasselmann S, Janssen PAEM (1994) Dynamics and modelling of ocean waves. Cambridge University Press, Cambridge
Kraus NC (1992) Engineering approaches to cross-shore sediment processes. In: Lamberti A (ed) Proc short course, Design and reliability of coastal structures. In: 23rd Int Conf Coast Eng (ICCE), 1–3 October 1992, Venice, p 175–209
Larson M (1991) Equilibrium profile of a beach with varying grain size. In: Proc Coastal Sediments 1991, Seattle, Washington. ASCE, p 905–919
Leppäranta M, Myrberg K (2009) Physical oceanography of the Baltic Sea. Springer Praxis, Berlin
Lopez-Ruiz A, Solari S, Ortega-Sanchez M, Losada M (2015) A simple approximation for wave refraction - Application to the assessment of the nearshore wave directionality. Ocean Model 96:324–333. doi:10.1016/j.ocemod.2015.09.007
Meier HEM, Höglund A (2013) Studying the Baltic Sea circulation with Eulerian tracers. In: Soomere T, Quak E (eds) Preventive methods for coastal protection. Springer, Cham, pp 101–130. doi:10.1007/978-3-319-00440-2_4
Meier HEM, Döscher R, Faxén T (2003) A multiprocessor coupled ice-ocean model for the Baltic Sea: application to salt inflow. J Geophys Res Oceans 108(C8):3273. doi:10.1029/2000JC000521
Meier HEM, Broman B, Kjellström E (2004) Simulated sea level in past and future climates of the Baltic Sea. Clim Res 27:59–75. doi:10.3354/cr027059
Nicholls RJ, Birkemeier WA, Hallermeier RJ (1996) Application of the depth of closure concept. In: Proc 25th Int Conf Coast Eng. ASCE, Orlando, p 3874–3887
Nicholls JR, Larson M, Capobianco M, Birkemeier WA (1998) Depth of closure: improving understanding and prediction. Coast Eng 1998: 2888–2901. doi:10.1061/9780784404119.219
Orviku K (1974) Estonian seacoasts (in Russian). Estonian Academy of Sciences Publishers, Tallinn
Phillips MR, Williams AT (2007) Depth of closure and shoreline indicators: empirical formulae for beach management. J Coast Res 23: 487–500. doi:10.2112/05-0593.1
Pindsoo K, Soomere T (2015) Contribution of wave set-up into the total water level in the Tallinn area. Proc Est Acad Sci 64(3S):338–348. doi:10.3176/proc.2015.3S.03
Räämet A, Soomere T (2010) The wave climate and its seasonal variability in the northeastern Baltic Sea. Estonian J Earth Sci 59:100–113. doi:10.3176/earth.2010.1.08
Raukas A, Hyvärinen H (eds) (1992) Geology of the Gulf of Finland (in Russian). Valgus, Tallinn
Samuelsson P, Jones CG, Willén U, Ullerstig A, Gollovik S, Hansson U, Jansson C, Kjellström E, Nikulin G, Wyser K (2011) The Rossby Centre Regional Climate Model RCA3: model description and performance. Tellus A 63:4–23. doi:10.1111/j.1600-0870.2010.00478.x
Simm JD (ed) (1996) Beach management manual. CIRIA Report 153, London
Soomere T (2005) Wind wave statistics in Tallinn Bay. Boreal Environ Res 10:103–118
Soomere T (2016) Extremes and decadal variations in the Baltic Sea wave conditions. In: Pelinovsky E, Kharif C (eds) Extreme ocean waves, 2nd edn. Springer, Cham, pp 107–140. doi:10.1007/978-3-319-21575-4_7
Soomere T, Räämet A (2011) Spatial patterns of the wave climate in the Baltic Proper and the Gulf of Finland. Oceanologia 53(1-TI):335–371
Soomere T, Räämet A (2014) Decadal changes in the Baltic Sea wave heights. J Mar Syst 129:86–95. doi:10.1016/j.jmarsys.2013.03.009
Soomere T, Kask A, Kask J, Healy TR (2008) Modelling of wave climate and sediment transport patterns at a tideless embayed beach, Pirita Beach, Estonia. J Mar Syst 74:S133–S146. doi:10.1016/j.jmarsys.2008.03.024
Soomere T, Viška M, Eelsalu M (2013) Spatial variations of wave loads and closure depth along the coast of the eastern Baltic Sea. Est J Eng 19:93–109. doi:10.3176/eng.2013.2.01
Soomere T, Döös K, Lehmann A, Meier HEM, Murawski J, Myrberg K, Stanev E (2014) The potential of current- and wind-driven transport for environmental management of the Baltic Sea. Ambio 43:94–104. doi:10.1007/s13280-013-0486-3
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. doi:10.1111/j.1600-0870.2006.00220.x
USACE (2002) Coastal Engineering Manual. US Army Corps of Engineers, Washington, DC, Manual No. 1110-2-1100 (CD)

Curriculum Vitae

1. Personal data

Name	Rain Männikus
Date and place of birth	29.11.1986, Tallinn, Estonia
Address	Akadeemia tee 21, 12618 Tallinn
Phone	(+372) 58 400 274
E-mail	rain.mannikus@taltech.ee

2. Education

Educational institution	Graduation year	Education (field of study / degree)
Tallinn University of Technology	2012	Civil Engineering / Master's Degree

3. Language competence/skills

Language	Level
Estonian	C2
English	C1
German	C1
Russian	B1

4. Special courses and further training

Period	Educational or other organisation
November 2019	Course "Generation and Analysis of Waves in Physical Models" (1 week) in Aalborg, Denmark
June 2017	CoastTools summer school (1 week) in Faro, Portugal
September 2016	Baltic Earth summer course (1 week) on "Climate of the Baltic Sea region" in Askö, Sweden
February 2016	Short course (3 weeks) on Coastal Systems in UNESCO-IHE in Delft, the Netherlands
September 2015	Short course (1 week) on Morphological modelling in Delft3D in UNESCO-IHE in Delft, the Netherlands

5. Professional employment

Period	Organisation	Position
July 2016–to date	Lainemudel Ltd	Coastal engineer
April 2015–to date	Tallinn University of Technology, Institute of Cybernetics	Early stage researcher
August 2013–to date	Estkonsult Ltd	Structural and coastal engineer
June 2012–August 2013	Nordecon Plc	Site manager / Superintendent

6. Research activity

6.1. Publications

Research papers indexed by the Web of Science and SCOPUS database (1.1):

Dreier, N., **Männikus, R.**, Fröhle, P. 2020. Long-term changes of waves at the German Baltic Sea coast: Are there trends from the past? *Journal of Coastal Research*, Special Issue 95, 1416−1416, doi: 10.2112/SI95-274.1.

Männikus, R., Soomere, T., Viška, M. 2020. Variations in the mean, seasonal and extreme water level on the Latvian coast, the eastern Baltic Sea, during 1961–2018. *Estuarine*, *Coastal and Shelf Science*, 245, art. no. 106827, doi: 10.1016/j. ecss.2020.106827.

Männikus, R., Soomere, T., Kudryavtseva, N. 2019. Identification of mechanisms that drive water level extremes from in situ measurements in the Gulf of Riga during 1961−2017. *Continental Shelf Research*, 182, 22−36, doi: 10.1016/j.csr.2019.05.014.

Soomere, T., **Männikus, R.**, Pindsoo, K., Kudryavtseva, N., Eelsalu, M. 2017. Modification of closure depths by synchronisation of severe seas and high water levels. *Geo-Marine Letters*, 37(1), 35−46, doi: 10.1007/s00367-016-0471-5.

Peer-reviewed articles in other international journals (1.2) and collections (3.1):

Kääard, A., Valdmann, A., Eelsalu, M., Pindsoo, K., **Männikus, R.**, Soomere, T. 2016. Preventive management of undesired changes in alongshore sediment transport in planning of waterfront infrastructure. In: Galiano-Garrigos, A., Brebbia, C.A. (eds.), *The Sustainable City XI. Proceedings of the 11th International Conference on Urban Regeneration and Sustainability (SC 2016), Alicante, Spain*, WIT Press, Ashurst, Southampton, 419−430. (WIT Transactions on Ecology and the Environment; 204), doi: 10.2495/SC160361

Männikus, R., Soomere, T., Torsvik, T. 2012. Optimizing breakwater configuration for vessel wakes and wind waves. *IEEE/OES Baltic 2012 International Symposium, 8–11 May 2012, Klaipėda,* Proceedings, 1−8, doi: 10.1109/BALTIC.2012.6249201.

Articles published in other conference proceedings (3.4):

Männikus, R., Soomere, T., Kudryavtseva, N. 2016. On the water level measurements in the Gulf of Riga during 1961−2016. In: Reckermann, M., Köppen, S. (eds.), *2nd Baltic Earth Conference Multiple Drivers for Earth System Changes in the Baltic Sea Region*: *11–15 June 2018, Helsingor, Denmark*, *Conference Proceedings*. International Baltic Earth Secretariat Publication No 13. Geesthacht, Germany, 130−131.

Abstracts of conference presentations (5.2):

Eelsalu, M., **Männikus, R.**, Pindsoo, K., Soomere, T. 2018. In search for management options of shores of the City of Tallinn, Estonia. *7th IEEE/OES Baltic Symposium Clean and Safe Baltic Sea and Energy Security for the Baltic Countries, 12–15 June 2018, Klaipėda, Lithuania, Abstract book*, 27.

Männikus, R., Soomere, T., Kudryavtseva, N. 2018. Superelevations of water level in the Gulf of Riga. In: *Baltic Earth Workshop on Multiple Drivers for Earth System Changes in the Baltic Sea Region. Tallinn, Estonia, 26–27 November 2018, Programme, Abstracts, Participants.* Geesthacht, Germany: Helmholtz-Zentrum Geesthacht, 38. (International Baltic Earth Secretariat Publication; 14).

Other creative activities (6.7):

Parnell, K.E., Soomere, T., **Männikus, R.**, Tõnisson, H. 2020. Raudne rannakaitse hävitab randa [Seawalls destroy beaches]. *Postimee*s, 90(7101), 15 April 2020, 20. [In Estonian].

Männikus, R., Eelsalu, M. 2020. Häädemeeste valla korduva üleujutusega ala piiri määramise ja ehituskeeluvööndi täpsustamise uuring. [Study of heights of coastal flooding in Häädemeeste county]. Research report. Tallinn: Lainemudel Ltd. [In Estonian].

Männikus, R., Soomere, T. 2020. Lainetuse analüüs Tallinki uue sadama olude hindamiseks. [Analysis of wave climate and its interaction with ships for a new harbour of Tallink]. Research report. Lainemudel Ltd. [In Estonian].

Männikus, R. 2019. Lainetuse ja veetasemete analüüs Väike-Pakri sadama projekteerimiseks. [Wave and water level analysis for the design of marina in Väike-Pakri]. Research report. Lainemudel Ltd. [In Estonian].

Männikus, R., Pindsoo, K. 2018. Lainetuse ja veetasemete analüüs Reidi tee rannakindlustuse projekteerimiseks. [Wave and water level analysis for the design of coastal protection of Reidi tee in Tallinn]. Research report. Lainemudel Ltd. [In Estonian].

Männikus, R., Pindsoo, K. 2017. Kelnase sadama hüdrodünaamiline modelleerimine. [Hydrodynamical simulations in Port of Kelnase]. Research report. Lainemudel Ltd. [In Estonian].

Männikus, R., Pindsoo, K. 2017. Leppneeme sadama hüdrodünaamiline modelleerimine. [Hydrodynamical simulations in Port of Leppneeme]. Research report. Lainemudel Ltd. [In Estonian].

Männikus, R., Soomere, T. 2016. Setete transpordi hindamine ning heljumi leviku modelleerimine Merirahu sadama lähistel. [Assessing and modelling suspended sediment transport in Merirahu marina]. Research report. Institute of Cybernetics at Tallinn University of Technology. [In Estonian].

Männikus, R., Pindsoo, T. 2016. Kihnu sadama kaitsemuuli mõju analüüs. [Influence of a breakwater on Port of Kihnu]. Research report. Institute of Cybernetics at Tallinn University of Technology. [In Estonian].

Männikus, R., Torsvik, T., Soomere, T. 2015. Sõru sadama kai nr 1 pikendamise mõju setete transpordile. [Influence of the length of quay no 1 on sediment transport in Port of Sõru]. Research report. Institute of Cybernetics at Tallinn University of Technology. [In Estonian].

Elulookirjeldus

1. Isikuandmed

Ees- ja perekonnanimi	Rain Männikus
Sünniaeg ja -koht	29.11.1986, Tallinn, Estonia
Aadress	Akadeemia tee 21, 12618 Tallinn
Telefon	(+372) 58 400 274
E-mail	rain.mannikus@taltech.ee

2. Hariduskäik

Õppeasutus	Lõpetamise aeg	Haridus (eriala / kraad)
Tallinna Tehnikaülikool	2012	Tööstus- ja tsiviilehitus / tehnikateaduste magister

3. Keeleoskus

Keel	Tase
eesti	emakeel
inglise	C1
saksa	C1
vene	B1

4. Täiendõpe

Õppimise aeg	Täiendõppe nimi ja läbiviija
November 2019	Kursus „Generation and Analysis of Waves in Physical Models” (1 nädal). Aalborg, Taani
Juuni 2017	Suveülikool „CoastTools” (1 nädal). Faro, Portugal
September 2016	Baltic Earth suveülikool (1 nädal) „Climate of the Baltic Sea region”. Askö, Rootsi
Veebruar 2016	Lühikursus (3 weeks) „Coastal Systems” UNESCO-IHE. Delft, Holland
September 2015	Lühikursus (1 nädal) „Morphological modelling in Delft3D” UNESCO-IHE. Delft, Holland

5. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
Juuli 2016–tänaseni	Lainemudel OÜ	Rannikuinsener
Aprill 2015–tänaseni	Tallinna Tehnikaülikool, Küberneetika Instituut	Nooremteadur
August 2013–tänaseni	Estkonsult OÜ	Projekteerija
Juuni 2012–August 2013	Nordecon AS	Objektijuht / Töödejuhataja

6. Teadustegevus

Avaldatud teadusartiklite, muude publikatsioonide ning peetud konverentsiettekannete loetelu on toodud ingliskeelse elulookirjelduse juures.

ISSN 2585-6901 (PDF)
ISBN 978-9949-83-667-3 (PDF)