

Reply to Referee #1

We thank the referee for careful reading the manuscript, critical assessment of the analysis and useful and professional comments which helped to improve the paper. Please find below the detailed replies to all the questions.

1) Please clarify the study area. In L. 83-85 it is said that the study focusses on Gulf of Riga. A bit later (line 97) it said that “The study area – the shores of Latvia with a total length of about 500 km...” I think that neither is fully correct: Besides Gulf of Riga, also Latvian coasts in the Baltic Proper are considered. Secondly, large part of the discussed Gulf of Riga actually belongs to Estonia, including one station where the data come from (Pärnu). Also the paper title says that the study area is “Latvian waters”. I understand that it is difficult to conveniently introduce such details in the title. But the fact about Pärnu and Estonia should be stated possibly earlier in the paper. Currently it is hidden to far quarters of the manuscript.

- Thank you for this observation. The study area involves all Latvian waters, but we also use data from one Estonian tide gauge. We state now this fact earlier in the paper.

2) L.110 “...may increase the average sea level in the entire Baltic Sea by almost 1 m for several months (Soomere and Pindsoo, 2016)”. I believe this 1 m is exaggerated for the entire Baltic. Soomere and Pindsoo (2016) said “...raise the average sea level by almost 1 m for a few weeks”. Weeks - and it was probably for the eastern part of the sea. But then, sea level must be lower in other parts. Johansson and Kahma (Boreal Env Res, 2016, 21), say on p.34 with monthly-based analysis: “The Baltic Sea average level Hd ranged from –43 to +51 cm in 1933–2012”. One month 51 cm, one month 45-50 cm. L.118 Considering the above-said, also this 1+1+1 m quantification does not quite hold.

- Thank you, this was an inexact formulation. We had in mind that large water volumes may increase the water level by 1 m within a few weeks. This increase usually starts from a lower than average water level. Still, Pindsoo and Soomere 2016 have shown that water levels elevated by 60–80 cm over long-term average have persisted for several weeks in the eastern Baltic Sea. We have formulated this aspect carefully now in the manuscript. The increase in water level in the eastern Gulf of Riga by more than 1 m compared to the water level at the Baltic proper shores of Latvia has occurred several times since the 1960s (Männikus et al., 2019). It is natural that the 1+1+1 m process does not work as a simple sum as conditions favourable for one mechanism are not perfect for others.

3) L.130, Table 1. I wonder, in three stations the hourly data completeness is 30% and in other three 99%. Please ensure shortly that it does not influence the statistics (distribution parameters) – particularly considering the potential completeness changes over years in these 30% stations.

- Although some of the tide gauges had lower completeness, it was uniformly low except for the period after 2005 there was an increase in a number of measurements. None of the stations showed a change in completeness during the years of the abrupt shift. We performed a test to check how low completeness could have affected the results. For that, we took one of the most complete stations, Pärnu, randomly removed 70% of the data and applied precisely the same method of the extreme value analysis. The resulted data had 30% completeness, which is characteristic for the less complete stations, such as Roja and Salacgriva. Running 100 times the same analysis,

we found that the same abrupt change in the shape parameter was observed even with only 30% completeness in 85% of the cases. This indicates that in case of the less complete stations, we do see the abrupt shift at an 85% confidence level. However, the tests showed that lower completeness leads to the location parameter being significantly underestimated. An explanation about how the completeness of the data could affect the extreme value distribution fitting is added to the paper.

4) *Were the data 1961-2018 detrended before analysis, or perhaps, it is not a problem? I.e., is there a possible influence of local uplift/subsidence or global sea level rise to e.g. variations in location parameter?*

- The signal of the mean sea level variations was removed from the extremes. This removes all slowly varying sea level changes, and the analysis focuses only on the storm surges. Therefore, the influence of the local uplift or global sea level rise can not affect the results of the manuscript.

5) *L.320- Major regime shift in the Baltic region in 1989/90 is well known indeed. However, how to explain this odd shift in the form of “dent” in the shape parameter inside the Gulf of Riga in 1984-90? Seems like an artefact. In L.430- it is shortly discussed on the basis of changes in average air flow speed (Keevallik and Soomere 2014), possibly including regime shifts in 1987 (up) and 1993 (down) above the Gulf of Finland. How about changes in wind direction? For instance, Fig.7e,g,h by Suursaar (<http://dx.doi.org/10.3176/earth.2013.05>) shows variations in annual resulting wind direction at stations near Gulf of Riga. In 1985-94, the direction was quite stable 230-250 deg (good direction for inflow through Irbe Strait), while before and after it fluctuated plus-minus off that direction. Just a guess.*

- The problem is that interrelations between wind properties at a single location and extreme water levels are not straightforward. Extreme water levels in this part of the world are created by long sequences of “events” that affect water surface at different locations. The background for the largest extremes (elevated water level of the entire sea) is created by specific atmospheric forcing in the southwestern Baltic Sea. Pumping of water into the Gulf of Riga requires another subsequent forcing pattern and high local surge, possibly the third pattern. The analysis of (Männikus et al., 2019) reveals a recognizable change in the directional structure of strong winds at Vilsandi. We hope to look in more detail into the local wind patterns in the future, but it is currently out of the scope of this manuscript. However, we added a section to the revised version of the manuscript describing the connection between the extreme water levels in the Latvian waters with multiple climatic indices (please check the reply to the referee 2). This shows that the observed phenomenon has a weak relation to the local wind and stronger connection to the global atmospheric circulation.

6) *Fig.8. If the numbers in brackets mark the range in centimetres (134,141), why not express it 136-141? What does this range mean anyway - neither explained in the text nor in legend. What does Pärnu 50-yr return value 211,220 mean? Pärnu had measurements 253 cm and 275 cm within 39 years.*

- Thank you, the numbers in brackets were changed to the range as advised. The 50-yr return value of Parnu in the range 211-220 cm was obtained by removing the slowly varying components from the data, then the generalized extreme value distribution (stationary in case of Fig. 8) was fitted to all the yearly maxima, and the return value was calculated. These measurements indeed showed a maximum of 275 cm in Parnu on 9th of January 2005. After removing the mean variation from this extreme, it is only 269 cm. However, this extreme event was only one of a kind. Fitting a distribution considers all the extremes and underestimated this outlier. The outliers are discussed in detail in section 2.3. The corresponding explanation was added to the text.

Minor/technical comments

L.23 too many (9) keywords, some repeating title words

80 - We reduced the number of keywords.

L.31 This highlight “Best fit in terms of step-like approximation for shape parameter established” makes no sense as a highlight. Also the third highlight misses something.

- We modified the formulation of this highlight

L.39 Mudersbach and Jensen

85 - We corrected the typo

L.58 easternmost Baltic Sea – feels weird

- We changed to “eastern subbasins of the Baltic Sea.”

L.78 open coast of Latvia – feels weird

- We changed to “Baltic proper shores of Latvia.”

90 *L.105 (100, etc) Väinameri (Moonsund) sub-basin in the Western Estonian archipelago → West Estonian Archipelago Sea*

- We added this change

Please unify units in the Fig. axes (commas, parentheses): Water level, cm; Return period, year; Time [yr]; Time [yrs] etc.

95 - The units are unified

L.205 hrs – not much shorter than hours

- The notation for hours is written in a unified way now

L.443 Klevanny -> Klevanny

- Thank you; this name appears differently in different sources.

100 **Reply to Referee #2**

General comment

105 *Despite I operate outside this study area, it seems like many efforts have already been done in the literature to explain changes in mean sea level, extreme sea levels, and distribution parameters in the Baltic Sea and the Gulf of Riga. For instance, changes in extreme events as well as changes in extreme value distributions have been studied at Pärnu (Suursaar 2007, Eelsalu 2014, Ekman 1996, among others). Also, spatial variations in extreme sea level distributions have been studied along the eastern coast of the Baltic Sea (Soomere 2018, Ekman 1996). I, therefore, believe that the paper would require more work to create additional value to the existing literature,*

for example, by extending the study to the possible causes of the temporal changes in the tail distribution of the extreme water levels. For instance, previous works have found significant correlations between winter months sea level changes and changes in wind and pressure changes as well as with the North Atlantic Oscillation index in the Baltic Sea and at Pärnu (Anderson 2002, Suursaar 2007, among others). Although in a different study area, Tsimplis et al. (2005) found that NAO contributes both to changes in the mean and extreme water levels in the North Sea. Correlation between climate indexes and GEV distribution parameters were previously assessed in other areas (for instance, Méndez et al 2006).

Reply: We thank the referee for careful reading the manuscript, critical assessment of the analysis and useful and professional comments which helped to improve the paper. We fully agree with this observation and recommendations. There are many studies into water level extremes in the Baltic Sea in general. Also, many issues of the water level regime have been addressed in the context of Estonian, Russian (Gulf of Finland) and Finnish waters. Strangely, such studies are missing for the Latvian waters (except for a recent one by ourselves [Männikus et al., 2019]). For this reason, it seemed to us that the almost unexplored Latvian water level data deserve focused attention.

Most of the existing studies into extreme water levels in the Baltic Sea basin have been performed under the assumption of stationarity of the underlying extreme value distributions. Only Suursaar and Sooäär (2007) ask the question of possible changes in the parameters of the GEV distribution. However, they choose basically the same data set (1923-2005) and exclude the maximum in 2005 and then also the maximum in 1967. Eelsalu et al. (2014) address the possibilities of ensemble approach for the construction of a better projection of extreme water levels and their return periods, and for the identification of locations with a substantial magnitude of local effects. Ekman (1996) provides an analysis of the extremes of the water volume of the Baltic Sea. Soomere et al. (2018) study spatial variations in the parameters of extreme value distributions. All this research is, to some extent, relevant in the context of our study and has been mentioned in the original submission. We have extended the Introduction towards more precise coverage of the listed items and added (Ekman, 1996) into the list of references.

We also agree that much more research is necessary to attribute the changes and patterns we highlight with the possible forcing factors. Thank you for reminding this issue and providing the relevant references. The link between the NAO and the Baltic Sea level is spatially very heterogeneous (even in wintertime) and has also displayed substantial decadal variations in the last two centuries (e.g. Andersson, 2002; Jevrejeva et al., 2005; Hünicke et al., 2015, Karabil et al., 2017). We would like to mention also that although the relation between the NAO and the mean water level was addressed in a multitude of papers, the relation to the sea level extremes is not studied in detail.

Following the suggestion, we added a section to the paper describing the connection between the extreme water levels in the Latvian waters with the main driving climatic indices in the region. Overall, the relation between the sea level extremes in the Gulf of Riga and the climatic indices is highly unstable and significantly variable in time. The figure below shows the running correlation results (only the correlations with more than 95% confidence) of Daugavgrīva water level extremes with NAO, SCAND, and PNA, which showed the strongest relation. The Arctic Oscillation showed the same results as the NAO and is not shown here. The other locations in the Gulf of Riga showed the same results. Using the running correlation analysis, we found that the relation with NAO was the weakest during the 1984-1988 period.

Moreover, during that period, a shift in the months most affected by NAO is observed. Before 1984, the NAO index showed the highest correlation in January. However, after 1988, there is an abrupt shift, and after that, the largest correlation coefficients were observed in March.

Multiple teleconnections were studied using the correlation analysis, such as SCAND, AO, AAO, EA, EATL-WRUS, Poleur, EP-NP, PNA, PT, THN, WP and tested which one had shown the highest correlation during the 1985-1990 period. The highest (negative) correlation during that period is observed with the SCAND index. In the Baltic Sea region, the positive phase of NAO is associated with the westerly winds and negative phase with more frequent winds from the east and north-east (e.g., Trigo, Osborn and Corte-Real 2002). The SCAND mode, on the other hand, is responsible for the south-easterly winds in the positive phase and north-westerly winds in the negative phase (Bueh and Nakamura 2007; Gao, Yu and Paek 2017). This indicates that the change in the running correlation coefficients from positive correlation with NAO to negative correlation with SCAND is most likely caused by the short-term change in the prevailing wind direction.

Interestingly, the second-highest correlation (corr. coefficient ~ 0.55) during 1985-1990 is found between the water level extremes and PNA index (see the bottom panel of the figure below). The PNA pattern is well known as the most influential climate patterns in the Northern Hemisphere mid-latitudes beyond the tropics and is strongly influenced by the El Niño-Southern Oscillation phenomenon. However, it was never considered to be influencing the sea level variability in the Baltic Sea (except for some discussed influence on the Baltic Sea ice, Jevrejeva, Moore, and Grinsted 2003). Our analysis showed for the first time that PNA could affect the Baltic Sea extreme sea levels in intermittent periods. This can occur during the transition period of the regime shifts when the relationship with NAO is weak.

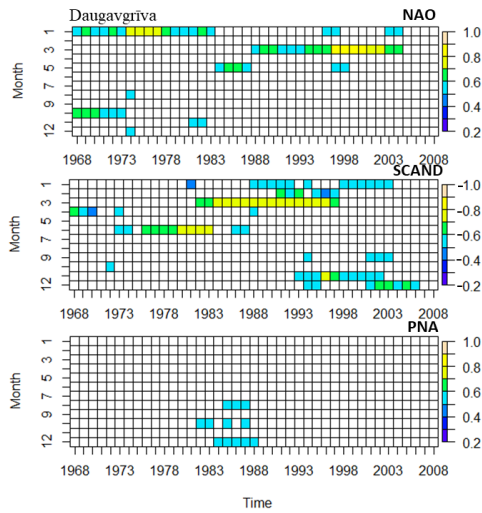


Figure 1 Sliding correlation results for Daugavgrīva and NAO, SCAND, and PNA climatic indices. The correlation is calculated for the water level monthly maxima with a window of 15 years. Only the correlation coefficients with the significance of more than 95% are shown.

1. Sometimes in the text, Fig and Figure are used indistinctly.
 - The names of the figures were unified
2. Line 190. Figure 4 is called before figure 3 in the main text.
 - In the new version of the manuscript, it is corrected
3. Line 220/225. In order to assure reproducibility, I would recommend indicating the equations, functions, or tools used in Matlab as well as a quick description of Hydrognomon, for those who are not familiar with it.
 - Thank you, we added the description in the manuscript
4. In the same sense, I recommend an extension of the explanation about the water level data processing before performing the distribution fitting. By doing so, the reader can reproduce and understand how the data have been processed to obtain the extreme water level from the tide gauge records.
 - The additional description was added to the manuscript
5. Figures. The overall quality of the figures should be improved, for instance, by matching the font size and font name with the main text.
 - The figures were improved
6. Line 260. I would recall here, as the authors do in section 2.3, that changes in the shape parameter have consequences in the tail of the distribution, determining the behavior of the events with very low frequency.

- We added the additional description of the consequences of the tail distribution

7. Line 270, figure 5. It would be good to see results for all other locations, as in figure 7. Same for the results of scale parameters (figure 6).

- The figures for the other locations are added

8. Line 290. “As the 95% confidence intervals of estimates of this parameter for single years mostly overlap, it is safe to say that the location parameter of the GEV distribution of water level extremes has not experienced any substantial changes in Latvian waters since the 1960s”. I’m curious about changes in the location parameter at Skulte, these changes appear significant when comparing the location parameter obtained by ~2000 vs ~1975. Also, including a grid in the figures would improve the comparison across years. I recommend also to further explain how the statistical significance has been calculated.

- What we meant is that although visually there is a change in the location parameter, the uncertainties in Fig.5 are rather large. Considering the uncertainties, the location parameter could have been ~98 (lower level) in 1975 and ~99 (upper level) in 2001. The uncertainties (95% conf. intervals) were obtained during the GEV fitting. We added a more detailed explanation about it.

9. Line 415. “... observed and measured water maxima in...”. Aren’t they the same?

- The typo was corrected

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230 **Non-stationary analysis of water level extremes in Latvian waters,
Baltic Sea, during 1961–2018.**

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Abstract. Analysis and prediction of water level extremes in the eastern Baltic Sea is a difficult task because of the contribution of various drivers to the water level, the presence of outliers in time series and possibly non-stationarity of the extremes owing to the changes in the atmospheric forcing. Non-stationary modelling of extremes was performed to the block maxima of water level derived from the time series at six locations in the Gulf of Riga and one location in the Baltic proper, 240 Baltic Sea, during 1961–2018. Several parameters of the ~~Generalised~~Generalized Extreme Value distribution of the measured water maxima both in the Baltic proper and in the interior of the Gulf of Riga exhibit statistically significant changes over these years. The most considerable changes occur to the shape parameter ξ . All stations in the interior of the Gulf of Riga experienced a regime shift: a drastic abrupt drop of the shape parameter from $\xi \approx 0.03 \pm 0.02$ to $\xi \approx -0.36 \pm 0.04$ around 1986 followed by an increase of a similar magnitude around 1990. This means a sudden switch from a Fréchet 245 distribution to a three-parameter Weibull distribution and back. ~~The water level extremes at Liepāja~~The period of an abrupt shift (1986–1990) in the shape parameters of GEV distribution in the interior of the Gulf of Riga coincides with the significant weakening of correlation between the water level extremes and the North Atlantic Oscillation (NAO). The water level extremes at Liepāja in the Baltic proper and Kolka at the entrance to the Gulf of Riga reveal significant linear trends in the location and scale parameters. This pattern indicates a different course of the water level extremes in the Baltic proper 250 and the interior of the Gulf of Riga. The described changes may lead to greatly different projections for long-term behaviour of water level extremes and their return periods based on data from different intervals.

Key words

Water level, block maximum, extreme ~~values, Generalised Extreme Value distribution~~value distributions, non-stationary 255 analysis, regime shift, ~~Baltic Sea~~, Gulf of Riga

Highlights

- Water level extremes in the eastern Baltic Sea and the Gulf of Riga ~~analysed~~analyzed for 1961–2018
 - Significant changes in parameters of ~~Generalised~~Generalized Extreme Value distribution identified
 - Significant linear trends in the location and scale parameters the Baltic proper ~~established~~
 - ~~The shape parameter changes in a step-like manner~~
- 260

- The shape parameter of GEV has regime shifts around 1986 and 1990 in the gulf
- ~~Best fit in terms of step-like approximation for shape parameter established~~

1 Introduction

Extreme values are the most common input for coastal design and management (Coles, 2004). Observed or measured time-series of water level usually serve as the most reliable source of information. However, a sophisticated approach to a problem (extent of a flood, height of a structure ~~ete-)and so forth~~) requires not only the values of extremes but also their frequency (e.g., return periods of different heights) and the duration of extreme events. As time-series of observed water level are commonly not longer than 100 years, there have been attempts to find suitable theoretical statistical distributions of extreme values which could be used to find reliable values for return periods. This is a complicated issue since the data may be too short, inaccurate or non-stationary (Mudersbach ~~and~~ Jensen, 2010; Galiatsatou et al., 2019). Moreover, there could be different populations of storms which result in extreme values which do not follow the chosen distribution (Suursaar and Sooäär, 2007).

The situation is even more complicated in estuarine-type environments where a multitude of drivers may contribute to the formation of high water levels (Del-Rosal-Salido et al., 2019). In the Baltic Sea, the frequent presence of long-term aperiodic high water levels in the entire sea (Lehmann and Post, 2015; Lehmann et al., 2017) may contribute to storm surges depending on the location, openness and orientation of single coastal sections. For example, in the eastern regions of the Baltic Sea, the largest storm surges are caused by strong westerly winds that often also push large volumes of water into this sea (Lehmann et al., 2017).

Depending on the method in use, set of data and regional differences in the storm surge heights, the estimates of water level extremes commonly reveal the disparity between different models and observations (Bardet et al., 2011). This feature was thoroughly ~~analysed~~analyzed in (Meier et al., ~~2004~~) using two different circulation models and two sea-level scenarios. Dieterich et al. (2019) demonstrated that the estimates of water level extremes for several areas of the Baltic Sea such as the Skagerrak, Gulf of Finland and Gulf of Riga are sensitive to the choice of the particular regional climate (circulation) model even if forced by the same external drivers. The uncertainties of projections of extreme water levels can be made smaller by an increase in the model resolution (Kowalewski and Kowalewska-Kalkowska, 2017). This approach inter alia makes it possible to resolve the nonlinear response of the water level extremes to the increase in the mean water level in shallow regions (Gräwe and Burchard, 2012). Different drivers of extreme water levels interact in a nonlinear manner so that their joint impact may be more significant than the sum of effects of single drivers (Hieronymus et al., 2017). The most complicated dynamics seem to occur in the ~~easternmost~~eastern subbasins of the Baltic Sea, where conventional methods for extreme value estimation are not able to accommodate all observed and hindcast extremes (Suursaar and Sooäär, 2007;

Eelsalu et al., 2014). Moreover, the spread among different methods can be substantial in areas that may have extensive wave set-up.

The large-scale atmospheric teleconnections characterizing the North Atlantic, such as the North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) exhibit a well-known correlation with the mean sea level of the Baltic Sea (e.g., Andersson, 2002; Lehmann et al., 2002; Dailidienė et al. 2006; Suursaar and Sooäär 2007) and its eastern subbasins (Männikus et al., 2020). Specifically, some 88% of water level variations in the Baltic Sea can be explained by the pattern of atmospheric pressure over the Baltic Sea (Karabil et al., 2018). This correlation is the highest in winter (DJFM) and is most likely caused by a strong impact of the wind conditions over the North Sea on the Baltic Sea mean sea level. The positive phases of NAO are characterized by stronger westerly winds and more frequent storms, which push the water from the North Sea to the Baltic Sea through the Danish straits.

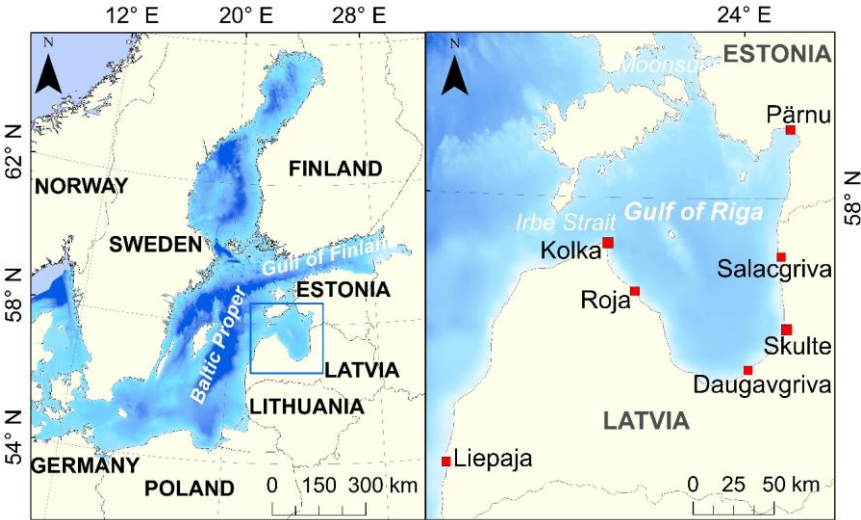
The correlation between the sea level and NAO exhibits a remarkable variability with time, which became stronger in the 20th century (e.g., Andersson, 2002; Jevrejeva et al. 2005). One possible explanation is drifting of the actual Icelandic low-pressure centre with time, which is not visible in the NAO index time series since it is measured between two fixed locations (e.g., Andersson, 2002). The drift will result in a change of the regional wind and time-variable correlation with the fixed NAO index. It is also possible that an interplay of several large-scale atmospheric teleconnections is driving the sea-level variability in the Baltic Sea region.

The relation between the extreme sea levels and the teleconnections, however, is not widely studied in the Baltic Sea region, especially in terms of its time variability. Jaagus and Suursaar (2013) show that there is a positive correlation between the NAO, AO indices and water level monthly maxima along the Estonian coast and a negative correlation with the Scandinavia index (SCAND). The East Atlantic, East Atlantic/Western Russia and Polar indices, on the other hand, do not show any significant correlations. Marcos and Woodworth (2017) demonstrate that the 99th percentile of the sea level is related to the NAO index along the Swedish and Finnish coasts, and it is independent of the mean sea level variations. Männikus et al. (2020) discuss that there is a significant correlation between the NAO annual index and the annual sea level maxima, minima and standard deviations observed in the Gulf of Riga. The correlation is different during the seasons and is most pronounced in winter (DJFM).

The analysis of Weisse et al. (2014) signals an increase in the Baltic Sea water level extremes in the past 100 years. The main contributor to this process is the increase in the mean sea level. This is consistent with the outcome of the analysis of the water volume extremes of the Baltic Sea over two centuries (Ekman, 1996). An increase in wind speed will lead to a stronger reaction of the water level in areas such as the Gulf of Finland, where extremes are already high (Hieronymus et al., 2018). A specific feature of the Baltic Sea is that extreme water levels may increase faster than the mean water level even without an increase in the wind speed (Meier, 2006; Soomere and Pindsoo, 2016). This property seems to be distinctive to

the eastern sub-basins such as the Gulf of Finland, Western Estonian archipelago and the Gulf of Riga (Fig. 1), and to the south-eastern segments of the sea (Pindsoo and Soomere, 2020).

A natural reflection of this difference in the increase in water extremes is the extensive spatial variation in the parameters of the General Extreme Value (GEV) distribution for water level extremes along the north-eastern Baltic Sea shore (Soomere et al., 2018). This variation includes alongshore changes in the sign of the GEV shape parameter. It signals the necessity of using different particular cases (three-parameter Weibull, Gumbel or Fréchet) distribution for adequate projections of extreme water levels and their return periods in different coastal segments. The situation is even more complicated in changing climates where the background process of formation of high water levels is not necessarily statistically stationary, and the parameters of the GEV distribution of extreme water levels may change in time (Kudryavtseva et al., 2018). Such variations of these parameters may lead to great variations in projections of the resulting water level for ~~longer~~more extended return periods.



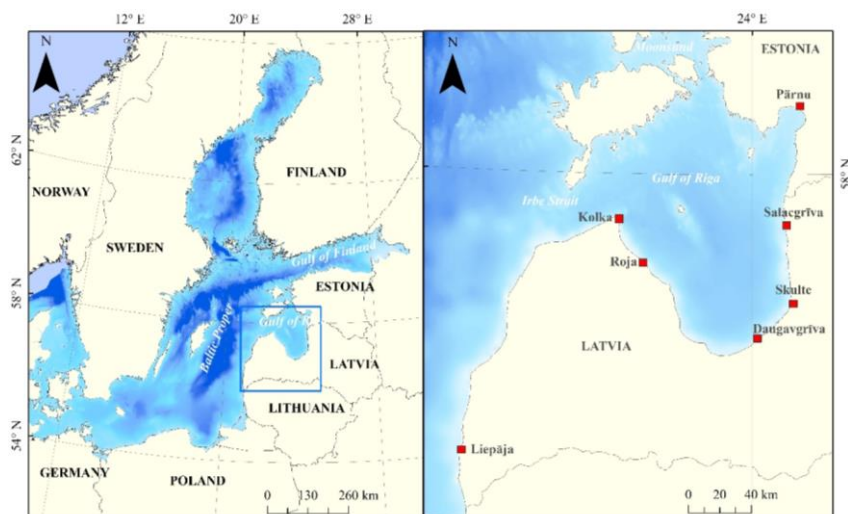


Figure 2: Analysed/Analyzed water level measurement sites (red rectangles) in the Gulf of Riga and on the open-coast/Baltic proper shores of Latvia.

Spatio-temporal variations in the parameters of the GEV distribution in the Baltic Sea basin have been so far analysed-based on modelled water levels (e.g., Kudryavtseva et al., 2018; Soomere et al., 2018)-analyzed based on modelled water levels (e.g., Kudryavtseva et al., 2018; Soomere et al., 2018). Most of the existing studies into extreme water levels in the eastern Baltic Sea have been performed under the assumption of stationarity of the underlying extreme value distributions. Only Suursaar and Sooäär (2007) address possible changes in the parameters of the GEV distribution for different periods in Pärnu for 1923–2005. A comparison of projections of extreme water levels and their return periods for modelled and measured data indicates that local effects may substantially contribute into the extreme water levels in specific locations (Eelsalu et al. 2014). This outcome motivates more detailed research into long-term data sets of water level. The availability of high-quality long-term observed or measured water level data sets from the shore of the central Baltic Sea region makes it possible to extend this analysis to in situ data.

In this paper, we focus on the temporal behaviour of the parameters of distributions of extreme water levels in the Gulf of Riga (Fig. 1)-Latvian waters (Fig. 1). The most interesting and less studied from the viewpoint of water level extremes part of the study area is the Gulf of Riga. Extreme water levels in this sub-basin are, historically, the third-highest in the entire Baltic Sea after the eastern Gulf of Finland and south-western Baltic Sea (Dailidienė et al., 2006; Averkiev and KlevannyKlevanny, 2010). This feature reflects a specific pattern of the formation of water levels in this semi-enclosed water body (Astok et al., 1999; Männikus et al., 2019). For completeness, we include a comparison with the properties of

extreme water levels at one tide gauge (Pärnu) in Estonian waters. The data from Pärnu until 2005 have been analyzed in Suursaar and Sooäär (2007).

The main objective of this study is to ~~characterise~~characterize the temporal course and quantify the magnitude of temporal changes to the parameters of the GEV at selected observation sites. We start from a description of the study area, data and methods for the analysis of extreme water levels in ~~Section~~Sect. 2. The analysis is based on block maxima of water levels over the windy autumn and winter season. Differently from annual maxima, such maxima are not serially correlated. The nature of changes to various parameters of the GEV is ~~analysed~~analyzed in ~~Section~~Sect. 3. We also test different approximations which could describe the patterns of change of in GEV parameters and roughly estimate the role of non-stationarity of the data in the formation of the values of parameters of GEV.

2 Data and methods

2.1 Observed data in the study area

The study area – the shores of Latvia with a total length of about 500 km – consists of two major segments. About half of the study area on the western coast of Latvia is open to the Baltic proper (Fig. 1). The water level regime and the behaviour of water level maxima in this segment, represented by the Liepāja and Kolka tide gauges, are ~~largely~~mostly similar to the relevant features in Lithuania (Dailidienė et al., 2006) and the western shores of the Western Estonian archipelago (Suursaar and Sooäär, 2007; Eelsalu et al., 2014; Soomere et al., 2018). Another half of the study area is located on the western, southern and eastern shores of the Gulf of Riga (Fig. 1). The tide gauge at Pärnu is located about 70 km to the north of the border between Latvia and Estonia. This gulf has a generally regular size with dimensions about 130×140 km (Suursaar et al., 2002) and is connected with the Baltic proper via relatively narrow and shallow (systems of) straits. The ~~main~~primary connection, Irbe Strait, is 27 km wide but with water depth in the sill area mostly <10 m (Maritime Administration of Latvia, 2014). The connections of another outlet via the Väinameri (Moonsund) sub-basin in the ~~Western~~West Estonian ~~archipelago~~Archipelago Sea are much narrower (the width of, e.g., Suur Strait is 4–5 km) and shallower, with the sill depth of about 5 m.

Irbe Strait is open towards the Baltic proper to the south-west, that is, to one of the predominant wind directions (Soomere, 2003). This configuration of the Gulf of Riga supports a two-step mechanism of formation of extreme water levels (Astok et al., 1999). As mentioned above, specific patterns of atmospheric forcing may drive a large volume of water into the Baltic Sea on weekly scales (Post and Köuts, 2014; Lehmann et al., 2017). Such ~~large~~massive volume changes may increase the average sea level in the entire Baltic Sea ~~by almost 1 m so much that the sea level in the eastern Baltic Sea may persist by 60–80 cm over the long-term mean for several months~~many weeks (Soomere and Pindsoo, 2016). A similar process may additionally increase the average sea level in the entire Gulf of Riga ~~so that water level in its eastern and southern parts exceeds the sea level at the Baltic proper shores of Latvia~~ by another 1 m (Männikus et al., 2019). Even though such highly

385 elevated water levels usually persist only a few days in this gulf, they are usually driven by strong westerly winds over Irbe Strait. Therefore, they are often associated with high local storm surges in the western parts of the gulf.

Extremely high water levels in the Gulf of Riga are thus developed under the joint impact of three major drivers: water volume of the entire Baltic Sea with a characteristic timescale of weeks, water occasionally pushed by a sequence of cyclones into the Gulf of Riga for 1–2 days (Suursaar et al., 2002), 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 (Männikus et al., 2019). The joint impact of these processes has likely led to extreme water levels from 2.47 m at Skulte to 2.75 m at Pärnu (Averkiev and Klevanny, 2010).

Water level observations have been carried out at various locations on the Latvian coast over almost two centuries. Currently, Latvian Environment, Geology and Meteorology Centre (LEGMC) operates tide gauges at ten sites. The readings of observations and measurements are available on their website (<http://www.meteo.lv>) from 1961. The sampling frequency, coverage and completeness of recordings vary greatly between the locations. Hourly records started mostly in the middle of 395 2000s when automatic devices were installed. The properties and quality of these time-series are presented in (Männikus et al., 2020). In this study, time-series from seven stations (Liepāja, Kolka, Roja, Daugavgrīva, Skulte and Salacgrīva in Latvian waters and Pärnu in Estonian waters, Figure 2; Table 1) are used as these are most reliable in terms of monthly completeness. The Estonian Weather Service provided the data set for Pärnu.

Table 1. The main parameters of the observation locations, basic properties of water level (presented in the BK77 system) and hourly data completeness for 01.01.1961–31.12.2018 in these locations. The maximum water level is extracted from the current version of the official data (Männikus et al., 2020). The data set for Pärnu from 01 January 1961 till 31 December 2018 was provided by the Estonian Weather Service.

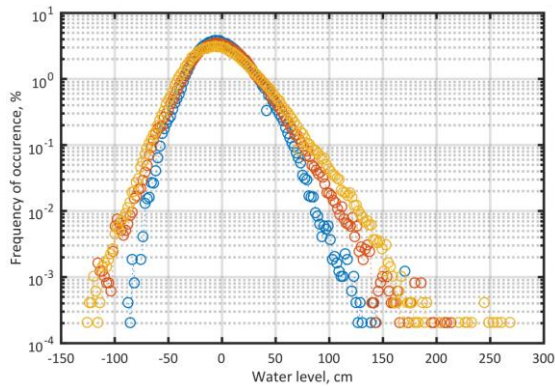
Location	Measure- mentsMeasure ments since	Co- ordinatesCoo rdinates	Mean level (cm)	Maximum level (cm) with date	Minimum level (cm) with date	Hourly data completeness 1961–2018
Liepāja	01.01.1865	56°30'56"N, 20°59'58"E	2.0	174 (18.10.1967)	–86 (18.01.1972)	99.69%
Kolka	01.01.1884	57°44'13"N, 22°35'34"E	1.2	161/134/134 (09.01.2005/ 18.10.1967)	–113 (03.11.2000)	35.25%
Roja	01.01.1932 01.11.1949	57°30'24"N, 22°48'06"E	–1.0	167 (09.01.2005/ 18.10.1967)	–89 (28.01.2010)	30.28%
Daugavgrīva	01.01.1875	57°3'34"N, 24°1'24"E	9.2	224 (02.11.1969)	–107 (14.10.1976)	99.98%
Skulte	01.01.1939	57°18'57"N, 24°24'34"E	6.1	231/247/247 (02.11.1969)	–109 (14.10.1976)	93.65%
Salacgrīva	01.10.1928	57°45'19"N, 24°21'13"E	5.8	215 (28.03.1968)	–116 (14.10.1976)	29.16%
Pärnu	(1893) 01.11.1949	58°22'55"N, 24°28'38"E	5.2	275 (09.01.2005)	–121 (14.10.1976)	99.54%

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From 01 December 2014 the height system LAS200.5 (European Vertical Reference System, EVRS) is used in Latvia. Before that, the official height system BK77 with reference level associated with the Kronstadt zero was used. This zero was defined as the average water level at this location in 1825–1840 (Lazarenko, 1986). As the information about water levels in Latvia and neighbouring Baltic countries published in the international literature until 2019 is given in the BK77 system, we shall use water level data in this system as well. Moreover, other authors (Averkiev and KlevannyKlevanny, 2010) have also given results in the BK77.

The quality of data in these stations is analysedanalyzed in detail in Männikus et al. (2019, 2020). The interplay of the water masses in the lake of Liepāja and the canal connecting the lake with the sea may inon some occasions greatly affect the readings of extreme water levels. Seasonal course of water level at Daugavgrīva is influenced by the hydroelectric plant about 20 km upstream of the river; however, this impact does not affect annual maxima of water levels at this site.

The shapes of empirical probability distributions of the occurrence of different water levels at Liepāja, Daugavgrīva and Pärnu (Fig. 2) were analysedanalyzed in Männikus et al. (2019). The completeness of the dataset of hourly observations is ≥99.54%. The recordings at Liepāja represent water levels at the eastern shore of the Baltic proper. The site at Kolka is also strongly influenced by the water level in the Baltic proper. However, the Daugavgrīva and Pärnu data characterisecharacterize water level in the southern and north-eastern bayhead of the Gulf of Rīga, respectively.



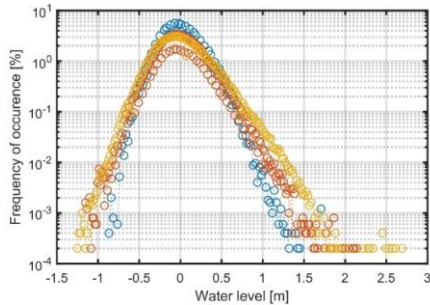


Figure 3: Empirical distributions of the frequency of occurrence of different water levels at Liepāja (blue), Daugavgrīva (red) and Pärnu (yellow). Adapted from Männikus et al. (2019).

Both empirical probability distributions have a quasi-Gaussian appearance which is characteristic in the north-eastern Baltic Sea (Johansson et al., 2001). This shape of the probabilities reflects the joint impact of storm surges (that follow a Poisson distribution on open ocean shores, Schmitt et al., 2018) and frequently existing large volumes of excess water. The excess water is pumped into the Baltic Sea by ~~certain~~^{specific} sequences of atmospheric processes (Leppäranta and Myrberg, 2009) and exhibit a Gaussian distribution (Soomere et al., 2015a). The skewed shapes of the distributions for Liepāja and Daugavgrīva (skewness 1.431 and 1.674, respectively) indicate a well-known property of eastern Baltic Sea that elevated water levels are more likely than negative surges (Johansson et al., 2001; Suursaar and Sooäär, 2007; Männikus et al., 2019).

2.2 Projections based on block maxima

Long-term water level time-series can be ~~analysed~~^{analyzed} and interpreted using ~~the~~ results of the extreme-value theory if certain fundamental conditions are fulfilled. The essential requirements are that the selected maximum or minimum values in the time series to be used, e.g., for the block maximum method (Coles, 2004) must be (i) statistically independent and (ii) identically distributed. In other words, each value should be an independent, random sample from the same population.

To achieve statistical independence and remove possible serial correlation, one should consider only values that are sufficiently separated in time. Monthly water level maxima are often correlated because there is a significant time lag between the impact of large-scale atmospheric patterns and the reaction of water level (Johansson et al., 2014). As the events of elevated water level of the entire Baltic Sea (Post and Kōuts, 2014; Samuelsson and Stigebrandt, 1996) may last a few months (Pindsoo and Soomere, 2016), often annual maximum or minimum values at every observation station are considered in the analysis of extremes: (e.g., Méndez et al., 2006). However, sometimes annual extremes may be correlated as well. The same cluster of storms may be reflected by two subsequent annual maxima (one in December, another in January of the next year).

Männikus et al. (2020) highlighted the well-known seasonal variability in water level course in the eastern Baltic Sea. It was shown that the most reliable way to select uncorrelated water level extremes is to use the maxima of the entire relatively windy season starting from late spring or early summer (e.g., in July) and ending in June of next year. This extended windy season is called the stormy season for brevity. The set of water level maxima for stormy seasons is suitable for the analysis of extreme water levels and their return periods in the eastern Baltic Sea (Soomere and Pindsoo, 2016).

The difference between the two sets of block maxima (annual and stormy season) is generally insignificant. However, substantial differences are seen in the projections of extreme water levels and their return periods. Eelsalu et al. (2014) reported about 10 cm differences for the observed data in Estonian coastal waters whereas high water levels projected using the maxima of stormy seasons were usually higher than those based on the annual maxima. For above-listed reasons, we employed block maxima for stormy seasons defined as time periods from 01 July until 30 June of the subsequent year.

2.3 Extreme value distributions

The water level data from tide gauges listed in Table 1 were used “as is” as presented on the LEGMC website. To avoid the impact of nonzero average water level on the outcome of the analysis of extremes of water level (Coles, 2004), the time series were de-meaned. The water level maxima for each stormy season were found directly from the de-meaned time series. Projections of extreme water levels and their return periods were constructed based on the theoretical extreme value distributions (Coles, 2004). These are Generalized Extreme Value (GEV) distribution and its particular cases Gumbel, Fréchet and Weibull distributions. The use of these distributions is justified if samples are independent and identically distributed random variables. The Gumbel and Weibull distributions are, in fact, particular cases of a GEV distribution:

$$G_{st}(x; \mu, \sigma, \xi) = \exp \left\{ - \left[1 + \xi \left(\frac{x - \mu}{\sigma} \right) \right]^{-1/\xi} \right\}. \quad (1)$$

The GEV distribution is characterized by a location parameter $\mu \in \mathbb{R}$, scale parameter $\sigma \in \mathbb{R}$, and shape parameter $\xi \in \mathbb{R}$ (Coles, 2004). Here x has the meaning of block maxima (e.g., maximum water level for each stormy season). The return period $T(\hat{x})$ for a particular value $x_{\hat{x}}$ is given by the $1/[1 - T(\hat{x})]$ -th percentile of $G(x)$

$$T(\hat{x}) = \frac{1}{1 - G(\hat{x})}. \quad (2)$$

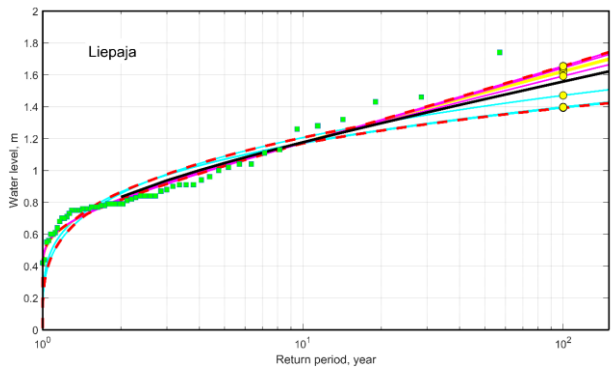
For the shape parameter $\xi \rightarrow 0$, the GEV distribution reduces to a Gumbel distribution. If $\xi < 0$, the GEV distribution is equivalent to a three-parameter Weibull distribution, and for $\xi > 0$ to a Fréchet distribution (Fig. 4f3f). A Gumbel distribution is best suitable for the description of extremes of populations described by distributions with an exponential tail such as the Gaussian distribution. A Weibull distribution matches extremes of populations with so-called light-tailed (very rapidly decaying) distributions. The Fréchet distributions have a strong positive tail.

The shapes of empirical water level distributions at Liepāja and Daugavgrīva resemble a Gaussian distribution but are skewed towards high water levels (the skewness is 1.431 and 1.674, respectively). Their kurtosis (3.3 and 4.2 for Liepāja and

Daugavgrīva, respectively) is slightly different from the value of kurtosis of a Gaussian distribution (Eq. 3). Therefore, the probability of very high water level values differs from their expectation for a Gaussian-distributed data set.

A typical feature of the north-eastern Baltic Sea coastal waters is the presence of outliers in the water level recordings that do not follow the classic extreme value distributions (Fig. 34). The threshold for defining the outliers could be evaluated from the difference between the first and third quartile of the sample (Suursaar and Sooäär, 2007). The difference is multiplied by 1.5 and added to the third quartile to reach the threshold. These outliers could be created, for example, by a sequence of storms that first raised water level considerably in the entire Baltic Sea and then created a “usual” surge in single locations on the background of strongly elevated offshore water level. In this sense, these outliers may represent a different population of water level extremes. In some occasions, the outliers could be explained by local effects, for example, by substantial river discharge or even by reading or measurement error (cf. Männikus et al., 2019). For example, the highest water level at Liepāja (174 cm) was recorded on 18 October 1967 at 14:00 during an event when the water level rose within 2 hours from 60 cm to 174 cm, remained constant for 5 hours and then dropped to 100 cm in one hour. The water level was likely very high this day at Liepāja; however, it is unlikely that water level was constant for five hours.

The presence of a few outliers typically insignificantly impacts the integral parameters of the entire distribution but may have an impact on the parameters of the associated extreme value distributions and projections of return periods of very high water levels (Suursaar and Sooäär, 2007). For example, using a Gumbel distribution would eventually underestimate the importance of positive outliers and lead to underestimation of values of higher return periods. The opposite bias can be expected from the use of a Weibull distribution. Hence, it would be reasonable to consider various distributions for long-term projections.



495 ~~Figure 3: Return periods of extreme water levels in Liepāja evaluated using a two-parameter Weibull (cyan), Gumbel (yellow) and GEV (magenta) distributions. Green squares indicate block maxima and yellow circles show different values for a return period of 100 years. Bold dashed red lines show limits of minima and maxima of the ensemble of projections. The bold black line indicates the mean of projections. There are six positive outliers at Liepāja.~~

500 To evaluate the parameters of the GEV (including ~~(3-parameter) Weibull, Fréchet and Gumbel distributions, and the 2-parameter Weibull and Fréchet~~) and ~~Gumbel distributions~~, distribution we used built-in ~~procedures~~procedure of maximum likelihood estimation ‘gevfit’ and ‘wblfit’ in *Matlab* ~~were used~~. As it is not possible to decide beforehand which theoretical distribution at best describes water levels and their extremes on the Latvian coast, we also employed other methods for calculating the parameters of these extreme value distributions. We used a method of moments which resulted in unbiased and biased estimates of parameters. Finally, we used free software Hydrognomon (<http://hydrognomon.org/>) for the processing and analysis of water level data. This application runs on standard Microsoft Windows. Its statistical module ~~was employed~~of Hydrognomon, a freely available general-purpose software tool to evaluate the parameters of the GEV and

505 Gumbel distributions (<http://hydrognomon.org/>). It is an open-source application (<http://hydrognomon.org/>) running on standard Microsoft Windows platforms, and also part of the openmeteo.org framework. This software employs typical hydrological applications, such as homogeneity tests, stage-discharge analysis, areal integration of point data, hydrometric data processing, evapotranspiration modelling, and lumped hydrological modelling.

2.4 Non-stationary extreme value analysis

510 To get an estimate of the level of non-stationarity of the extreme value distribution, a sliding window approach was used. The time series was separated into 30-year long consecutive windows. In each window, a stationary GEV distribution (Eq. 1) was fitted to the block maxima x with a fixed location parameter μ , scale parameter σ , and shape parameter ξ . Before the fit, the background non-stationarity of the time series caused by the joint impact of global sea-level rise and local postglacial uplift is removed subtracting the annual mean from the block maxima.

515 If the results of the sliding GEV test revealed that the parameters of the distribution are time-variable, a non-stationary GEV analysis described below was performed. In such a case, it is assumed that the parameters are functions of time $\mu = M(t)$, $\sigma = \Sigma(t)$, and $\xi = \Xi(t)$. With this hypothesis, a non-stationary GEV distribution is fitted with one parameter changing with time (either location, scale or shape parameter). An illustration of the method is shown in Fig. 43.

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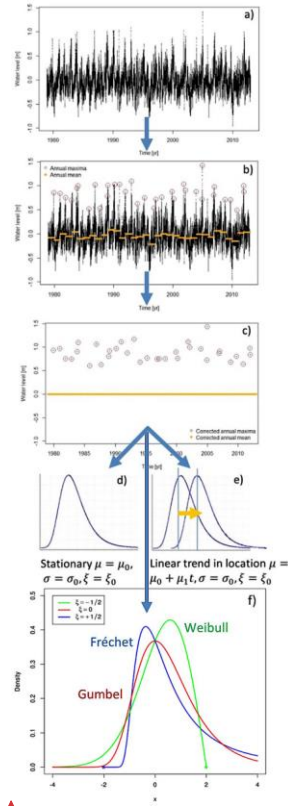


Figure 4:3: The sequence of operations applied to the water level time series: a) the time series is extracted from the model; b) background non-stationarity is removed by subtracting the annual mean from the data; c) a series of maxima of different stormy seasons is created, d) stationary and non-stationary GEV distributions with changing location (e), scale, or shape (f) parameters are fitted to the data.

For example, to test if the shape parameter is changing with time (Fig. 4:3f), the following distribution is fitted:

$$G_{nonst}(x; \mu, \sigma, t) = \exp \left\{ - \left[1 + \xi \left(\frac{x - \mu}{\sigma} \right) \right]^{\frac{1}{\xi(t)}} \right\} \quad (3)$$

For the non-stationary GEV fit, we used the *ismev* package (version 1.42) in *R* programming language (version 3.6.1). Various functions describing the time variability of the parameters were applied, including a linear dependence

$$M(t) = \mu_0 + \mu_1 t, \quad \Sigma(t) = \sigma_0 + \sigma_1 t, \quad \text{or} \quad \Xi(t) = \xi_0 + \xi_1 t, \quad (4)$$

quadratic dependence

$$M(t) = \mu_0 + \mu_1 t + \mu_2 t^2, \Sigma(t) = \sigma_0 + \sigma_1 t + \sigma_2 t^2, \Xi(t) = \xi_0 + \xi_1 t + \xi_2 t^2, \quad (5)$$

530 and a piecewise constant step-function

$$M(t) = \begin{cases} 0, & t < t_0 - \Delta t \\ a, & t \geq t_0 - \Delta t, t \leq t_0 + \Delta t. \\ 0, & t < t_0 + \Delta t \end{cases} \quad (6)$$

Equation (6) defines a simple model of an abrupt change in the parameter of interest with an amplitude a at time instant t_0 and the event duration Δt . To test whether a particular time dependence of the water level extremes is better than a stationary GEV fit, a likelihood ratio test is applied.

535 An increase in the location parameter μ with time represents the case when the whole GEV distribution is shifted to the right, towards higher values. This means that all extremes, from the most severe ones down to ~~the~~ “medium-range” and “low-range” ones are getting higher (e.g., Kudryavtseva et al., 2018). A decrease in this parameter would lead to changes in the opposite direction. The scale parameter σ is responsible for the width of the distribution. An increase in the scale parameter indicates that “medium-range” extremes are getting more frequent, whereas a decrease corresponds to less frequent
540 “medium-range” extremes.

Changes to the shape parameter ξ may have more complicated consequences. This parameter of a GEV distribution defines the overall type (shape) of the extreme value distribution. In particular, a change in the sign of the shape parameter corresponds to a switch between the radically different types of extreme value distribution. For example, if the negative values of the shape parameter shift towards values close to zero, the extremes that are initially ~~characterised~~ characterized by
545 a Weibull distribution with an upper limit start to follow a Gumbel distribution gradually. Further increase in this parameter means a switch to a Fréchet distribution that has a lower limit (Fig. 4):
A Gumbel distribution describes best the extremes following distributions with an exponential tail such as the Gaussian distribution. A Weibull distribution matches extremes of populations with very rapidly decaying distributions. The Fréchet distributions are characterized by a strong positive tail.

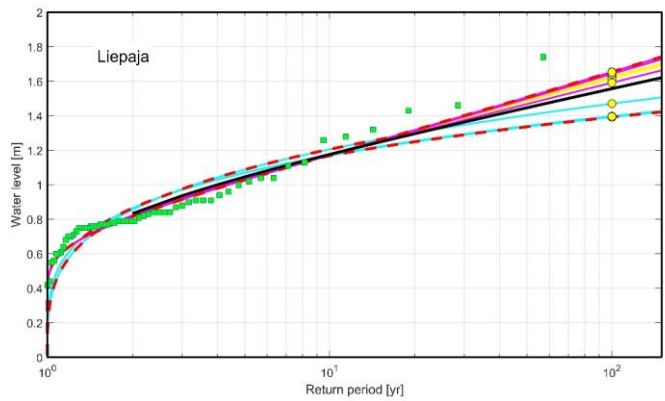


Figure 4: Return periods of extreme water levels in Liepāja evaluated using a two-parameter Weibull (cyan), Gumbel (yellow) and GEV (magenta) distributions. Green squares indicate block maxima and yellow circles show different values for a return period of 100 years. Bold dashed red lines show limits of minima and maxima of the ensemble of projections. The bold black line indicates the mean of projections. There are six positive outliers at Liepāja.

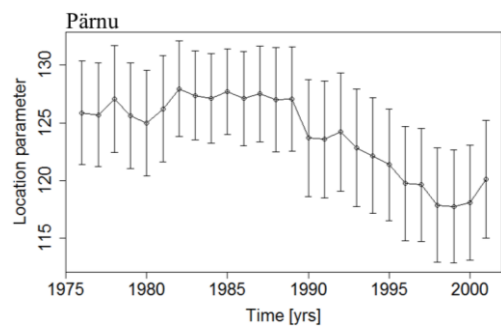
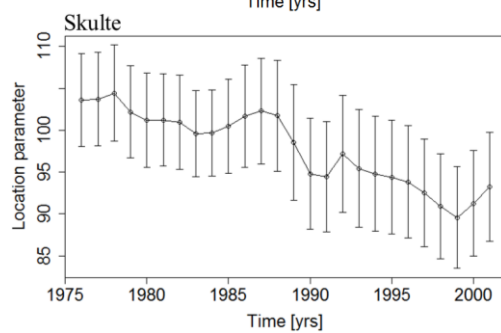
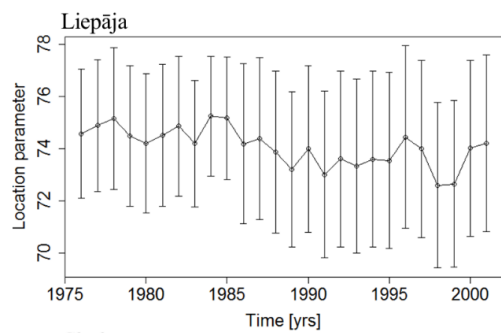
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3 Results

3.1 Temporal changes in the parameters of the GEV distribution

To estimate the magnitude of changes to the parameters of the GEV at selected observation sites (equivalently, to reveal whether extreme water levels may follow a non-stationary process), a sliding GEV fit was performed. The time series of stormy season maxima of water levels (Fig. 4b3b) for all seven measurement sites were divided into consecutive intervals (windows) with a constant width. A stationary GEV (Eq. 1) fit was performed for each time interval. The window size was thoroughly tested, and the optimal value of 30 years was selected as it provided the lower noise level.



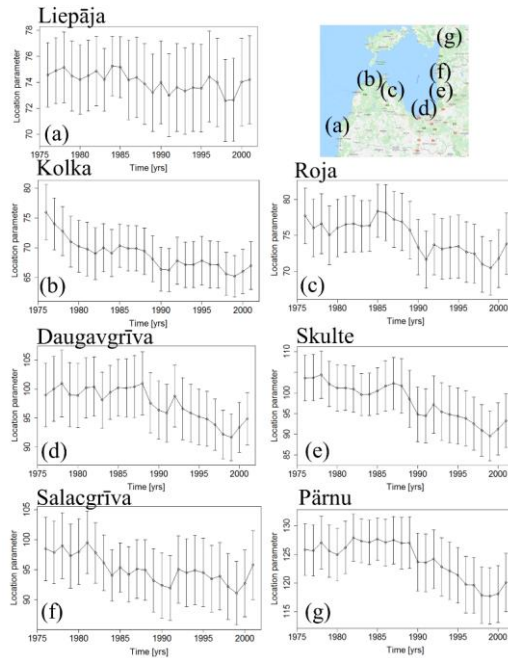
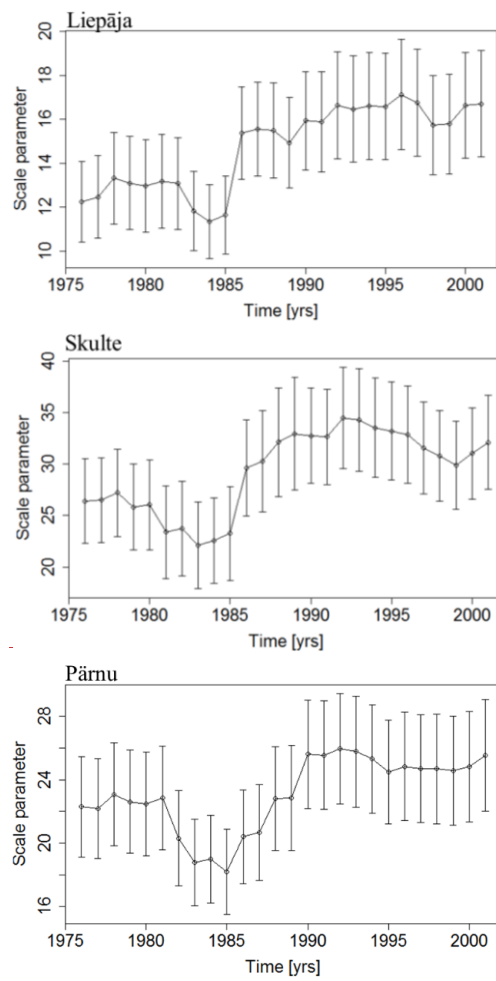


Figure 4: Location parameter μ as a function of time for **Liepāja (top) and Skulte (middle), and Pärnu (bottom)** tide gauges and 95% confidence intervals of its estimates. The presented estimates were derived using a sliding GEV fit with the window of 30 years. The time on the plots corresponds to the time in the middle of this window.

The location parameter μ did not show significant changes at most of the measurement sites. Its values remained almost constant at some locations on the Baltic proper shore (e.g., Liepāja, Fig. 55a) as well as at some places of the eastern Gulf of Riga such as Daugavgrīva, and Salacgrīva. At the other sites (Skulte, Pärnu, Roja, and Kolka), this parameter slightly decreased by about 10% (Fig. 5). The data from the Skulte tide gauge on the eastern shore of the Gulf of Riga exhibited the most substantial drop in the location parameter from 104 to 90 cm (Fig. 5).



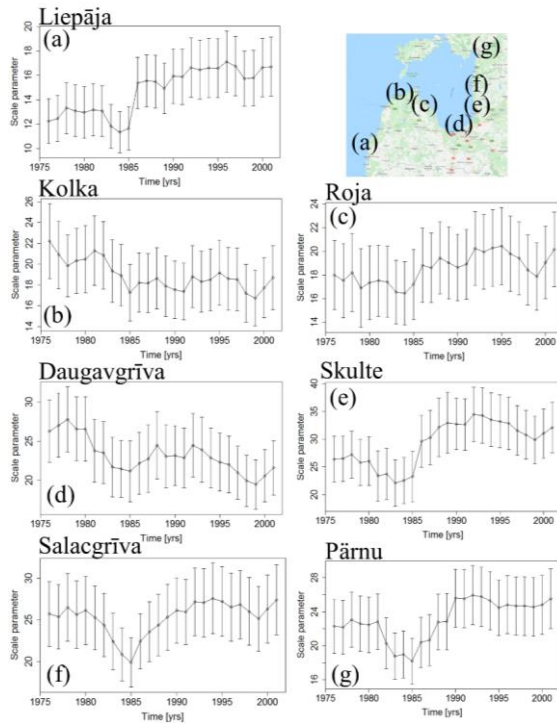


Figure 5: Scale parameter σ as a function of time for Liepāja (top) and Skulte (middle), and Pärnu (bottom) tide gauges. The presented estimates were derived using a sliding GEV fit with the window of 30 years. The time on the plots corresponds to the time in the middle of this window.

From these measurement locations, Kolka is primarily affected by the water level in the Baltic proper, Roja is located at the western shore of the Gulf of Riga and Pärnu in the north-eastern bayhead of the Gulf of Riga. ~~As the~~The 95% confidence intervals of estimates of this parameter obtained from the GEV fitting are rather large and overlap for single years—mostly overlap. For example, considering the uncertainties in the location parameter at Skulte can be ~98 (lower level) in 1975 and ~99 (upper level) in 2001 (Fig. 5). Therefore, it is safe to say that the location parameter of the GEV distribution of water level extremes has not experienced any substantial changes in Latvian waters since the 1960s.

Contrarily, the analysis of the time series using the sliding GEV fit revealed ~~large~~considerable changes in the scale parameter σ at some locations and spatially variable pattern of its variations. Its values experienced a slight decrease of ~20% during

1981–1990 at Pärnu (Fig. 6, ~~bottom6g~~), Salacgrīva (Fig. 6f), and Skulte (Fig. 6, ~~middle6e~~). Even more substantial increase of 25% was observed at Liepāja (Fig. 6, ~~top6a~~). However, other tide gauges did not show significant variability in this parameter.

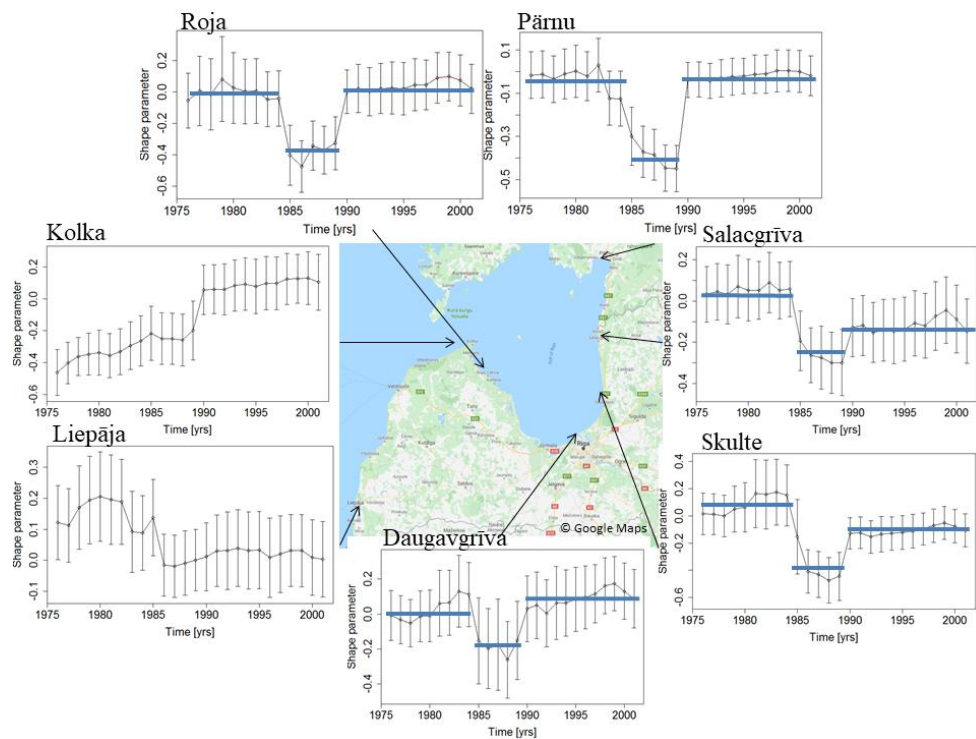
595 **3.2 Regime shifts in terms of the shape parameter**

The most dramatic changes of >50% were observed in the shape parameter ξ (Fig. 7). This feature indicates significant non-stationarity of stormy season maxima in terms of the shape of the GEV distribution. The temporal course of the shape parameter obtained with the sliding GEV fit is different at different stations. At Liepāja, the shape parameter was between 0.1 and 0.2 until the mid-1980s and dropped almost zero from 1985. In other words, a Fréchet distribution was replaced by a Gumbel one. This parameter was negative (between -0.4 and -0.2) at Kolka until the end of the 1980s and then rapidly increased to about 0.1. Therefore, a Weibull distribution of water level extremes was replaced by a Fréchet distribution at this location.

The values of the shape parameter at all other stations experience a regime shift: a drastic abrupt drop around 1985 followed by an increase of a similar magnitude around 1990. Before and after this drop the shape parameter was close to zero in most stations. At Skulte and Salacgrīva it ~~stabilised~~stabilized on the level of -0.1 whereas it increased to about 0.1 at Daugavgrīva. During the years 1985–1990, it was from about -0.2 (~~at~~Salacgrīva and Daugavgrīva) down to about -0.4 at Roja, Pärnu, and Skulte (Fig. 7, Table 2).

Importantly, Fig. 7 demonstrates that the features of temporal changes in the shape parameter ξ of the relevant GEV are different at the locations reflecting (or strongly affected by) water levels in the Baltic proper (see above) and in the interior of the Gulf of Riga. The properties of water level at all measurement sites in the interior of the Gulf of Riga show consistent behaviour. Before 1985, the shape parameter is consistently close to zero in the sense that its difference from zero is less than the level of uncertainty (95% confidence intervals) of its evaluation. Thus, differently from the Baltic proper, the GEV distribution follows a Gumbel one in the Gulf of Riga.

During the regime shift in 1985–1989, all stations (except for Daugavgrīva) show consistently negative values of the shape parameter with the average value over all stations $\xi \approx -0.36 \pm 0.04$. Therefore, the extreme values of water level followed a three-parameter Weibull distribution. Only the data from Daugavgrīva reveal a considerable uncertainty in the sense that 95% confidence limits involve the zero value for most of the years in 1985–1989. Therefore, its switch to negative values is not as clear as for other sites.



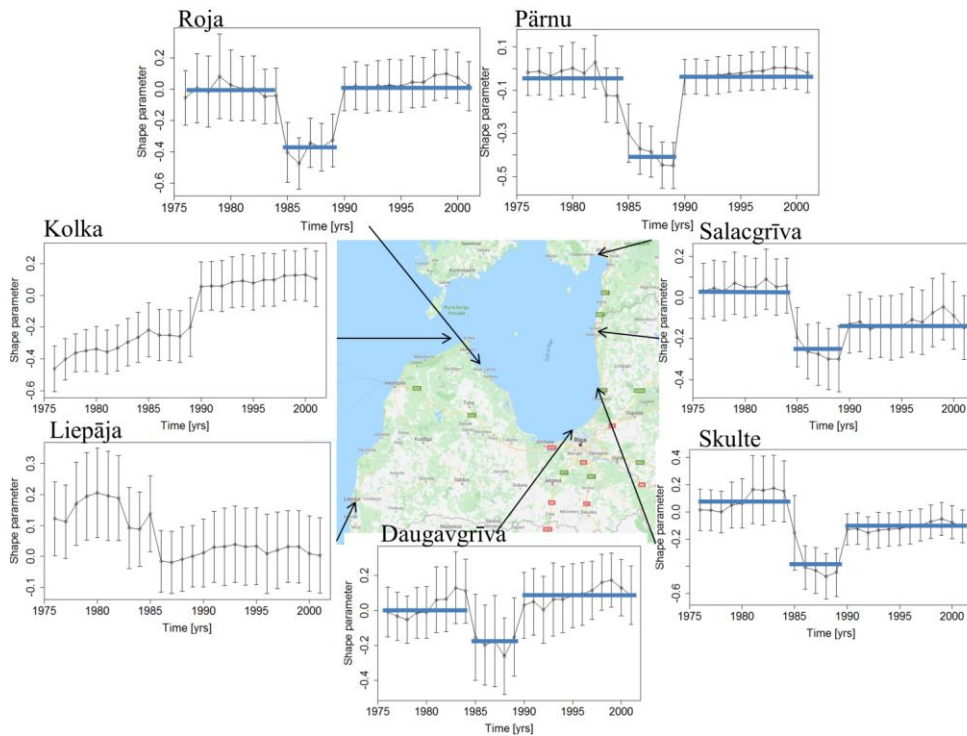


Figure 6: Shape parameter ξ as a function of time for six tide gauge locations in Latvian waters and Pärnu in the north-eastern Gulf of Riga. The presented estimates of the shape parameter were derived using a sliding GEV fit with the window of 30 years. The time on the plots corresponds to the time in the middle of the sliding window. The blue lines show average values of the shape parameter for three time periods: before 1985, 1985–1989, and after 1989 (Table 2).

After 1989, the recordings show a higher discrepancy in ξ . At Daugavgrīva, Pärnu, and Roja $\xi \approx -0.0 \pm 0.02$ within the uncertainties and thus a Gumbel distribution is acceptable again. The estimates for the shape parameter of the GEV distribution for Salacgrīva and Skulte return to a negative (but smaller) value $\xi \approx -0.12 \pm 0.04$.

The test for non-stationarity employs a sliding window of 30 years. For example, the GEV parameters listed for the year 1985 are evaluated using the extreme water level data from 1970 to 2000. Therefore, the abrupt changes in the shape parameter do not necessarily occur specifically in 1985 or 1989. As the reported values of the parameters

characterise the GEV fit of extreme water levels over 30 years, using 15 years before and after the listed “central” year of the fit, the regime shift may have occurred at a somewhat different time instant.

To more consistently estimate the relative magnitude of the identified step-like changes with respect to the typical level of variations in the shape parameter, we make use of the overall appearance of the course of the shape parameter of the GEV distribution that resembles a step-like behaviour with two instants of a regime shift. Using the estimated uncertainties σ_e , we can assess the statistical significance of these variations. The abrupt changes range in significance from $2\sigma_e$ (Daugavgrīva) to $7.8\sigma_e$ (Pärnu). The magnitude of the change at other stations is in the range of $4\text{--}5\sigma_e$. This shows a high significance of the shift at all stations except for Daugavgrīva. The described significant change in the shape parameter ξ indicates a dramatic shift in the overall appearance of the extreme value distribution from an approximately Gumbel one to a Weibull-like shape in 1985 and the back to a Gumbel distribution in 1989.

Out of five locations which exhibit an abrupt shift in the shape parameter (Fig. 7), two tide gauges (Roja and Salacgrīva), exhibit a low level of completeness of about 30% (Table 1). To test how this might affect the results of the extreme value analysis, we introduced gaps to the sea level time series of one of the most complete stations, Pärnu. For that, 70% of the data were randomly removed from the Pärnu data 100 times, and then precisely the same method of the non-stationary extreme value analysis was applied, and the presence of the step-function in the shape parameter was assessed. The test showed that lower completeness leads to an underestimation of the location parameter. However, in 85% of the cases, the same abrupt shift in the shape parameter was observed. This indicates that in case of the less complete stations, we do see the abrupt shift at an 85% confidence level.

Table 2. The average value of shape parameter ξ as a result of sliding GEV fit with a window of 30 years before 1985, 1985–1989, and after 1989 (Fig. 7).

Measurement site	ξ (until 1985)	ξ (1985–1989)	ξ (from 1989)
Daugavgrīva	0.03 ± 0.06	-0.2 ± 0.1	0.09 ± 0.05
Pärnu	-0.03 ± 0.06	-0.39 ± 0.05	-0.02 ± 0.03
Roja	-0.01 ± 0.07	-0.38 ± 0.07	0.04 ± 0.05
Salacgrīva	0.05 ± 0.06	-0.27 ± 0.06	-0.12 ± 0.05
Skulte	0.09 ± 0.07	-0.38 ± 0.09	-0.11 ± 0.04

3.3 Non-stationary extreme value analysis

To model the non-stationary extreme values, we tested the following hypotheses:

- (a) The GEV location, scale, and shape parameters follow a linear trend (Eq. 4)

(b) The GEV shape parameter follows a quadratic trend (Eq. 5)

(c) The GEV shape parameter follows a step-function (Eq. 6).

These model functions Eqs. (4–6) were used to describe, to a first approximation, the possible course of time variability of parameters in non-stationary GEV fit (Eq. 3). The linear trends (case a) are commonly used to describe the impact of climate change on the ocean or atmosphere conditions. The hypotheses (b) and (c) were chosen to reach a better description of the detected features of the variability of the shape parameter (Fig. 7).

The use of the assumption of the presence of a linear trend in all GEV parameters (case a) showed that only tide gauges located in the Baltic proper (Liepāja) or locations in the Gulf of Riga that are largely affected by the water level in the Baltic proper (Kolka) follow a significant trend in at least one of the parameters (Fig. 8). The data from Kolka revealed a linear trend in the location parameter at a significance level of 89% and in the shape parameter at a significance level of 94%. The parameters of the GEV distribution for water level maxima at Liepāja tide gauge revealed weaker linear trends in the location parameter (81% significance level) and scale parameter (84% significance level) were observed. However, no significant linear trends (at least an 80% significance level) were detected in any of the GEV parameters at all sites in the interior of the Gulf of Riga. Even though the ~~above-trends as~~ mentioned ~~trendsearlier~~ at Liepāja and Kolka are not statistically significant at a commonly accepted 95% level, the presented features indicate an intrinsic difference in the behaviour of water level extremes in the inner area of the Gulf of Riga compared to the stations that reflect water level in the Baltic proper.

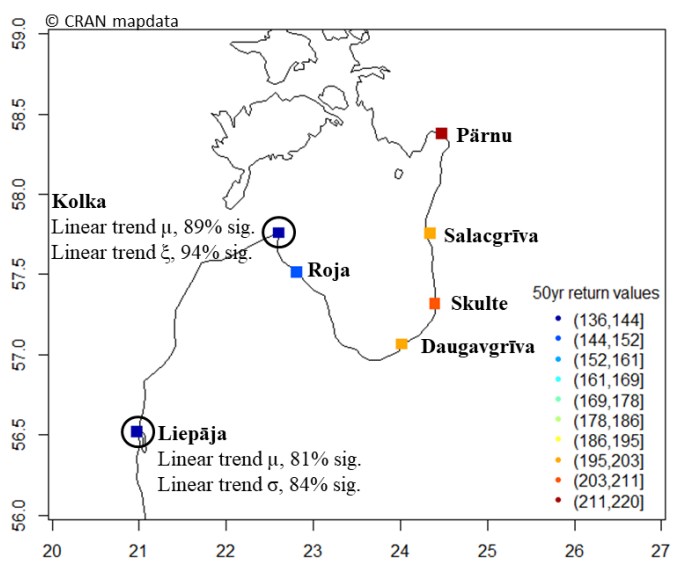
Interestingly, results presented in ~~Section~~Sect. 3.1 demonstrate that the sliding GEV fit (with the assumption that the parameters of the GEV are constant within each single time window) showed almost no changes in the parameters of GEV at Liepāja. This confirms that sliding GEV can be used in assessing whether the extremes behave in a non-stationary manner. However, to accurately model the time variability of GEV, a more elaborate approach such as non-stationary GEV fit, should be performed. A likely reason for this difference is that the sliding GEV fit involves a smaller number of years within each window, whereas the non-stationary GEV fit considers all available data.

The shape of temporal changes in various parameters (Figs. 5–7) suggests that even if a clear linear trend is missing, fittings using the more complicated functional shape of approximations may reveal further information about changes in these parameters. A quadratic function is a natural choice to highlight acceleration of changes as well as to identify the presence of cycles with periods longer than the entire time series if some of the parameters have a clearly defined minimum or maximum within the observation time interval. Fitting a quadratic trend to the shape parameter at all locations (case b) showed a significant fit only for the Skulte water level extremes with a minimum in 1988 (at a significance level of 93%). However, the fit did not follow well the observed change. Therefore, it is unlikely that the observed changes had a cyclic manner.

Finally, a step-like function was used to model the changes in the shape parameter following the sliding GEV analysis that showed that the fitted shape parameters exhibit an abrupt shift (Fig. 7). To find a suitable approximation of such changes

(case c, Eq. 6) which best describes the change and to specify when did it happen and how long did it last, we tested various settings of a step function (Eq. 6). The parameter Δt was varied from 1 to 15 years. The corresponding total duration of the event ($2\Delta t$) was in the range of 2 to 30 yrs, correspondingly. The parameter t_0 corresponds to the time in the middle of the event. It was modified in the range of 1981–1991 with a step of one year. The amplitude of both regime shifts was assumed to be the same. It was changed from -0.2 to -1 incrementally with a step of 0.2 . The constructed step functions were used to model the time variability of the GEV shape parameter at all locations. These functions were fitted to the set of block maxima of water levels using a non-stationary GEV fit (Eq. 3).

The properties Δt and t_0 of the best approximation using step-function for the course of the shape parameter, vary largely for individual stations. This not necessarily means a large discrepancy of the properties of the relevant extreme value distributions because recordings at different sites may be affected by several local features. To obtain the best fit for all stations, we used a collective location approach, where a sum of the goodness of fit for all stations was used as a measure of the quality of the fitted non-stationary distribution (e.g., Votier et al., 2008). This approach provided more consistent results. In some cases, however, it showed lower formal statistical significance compared to the tests performed for individual sites. The negative log-likelihood value of the non-stationary GEV fit was used as a measure of the goodness of fit.



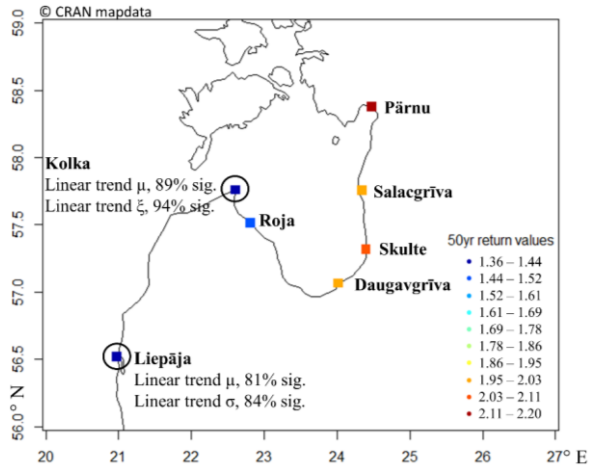


Figure 7: 50-year return values (colour scale; numbers in brackets indicate the range in centimetres) obtained with a stationary GEV function fit (squares). The tide gauges with a significant linear trend in one of the GEV parameters are marked with large black circles.

A sensitivity test was performed to check what parameters affected the fit the most. The goodness of fit was significantly affected by the change in Δt and t_0 . However, it was less sensitive to the amplitude of regime shift a of the fitted step function in Eq. (6). Therefore, it was fixed to the value $a = 0.36$ that was averaged over all seven stations in Table 2. This feature indicates that the existing data are consistent in terms of the magnitude of the regime shift in the middle and end of the 1980s.

For the stations located in the interior of the Gulf of Riga (that is, excluding Kolka), the best fit for the shape parameter was $\Delta t = 2$, $t_0 = 1988$. The corresponding abrupt shift therefore formally started in 1986 and lasted until 1990. The likelihood ratio test showed that the non-stationary GEV fit with the shape parameter following a step-function with $\Delta t = 2$, $t_0 = 1988$ described extreme values better than the stationary fit. This claim is valid with statistical significance of 99.9% at Roja and Salacgrīva, 98% at Daugavgrīva, 85% at Skulte, and 80% at Pärnu. The identified step function is consistent with the results obtained with the sliding GEV fit (Fig. 7, Table 2). However, the formal statistical significance of the presence of an abrupt change depends on the method in use. In case of the sliding GEV, the most significant change was obtained at Pärnu, and the least significant one occurred at Daugavgrīva.

3.4 Links with large-scale climate indices

To study if the observed abrupt regime shift in the distribution of sea-level extremes coincides with changes in the large-scale atmospheric circulation, we performed a correlation analysis between the sea level extremes and multiple teleconnections, such as Atlantic multidecadal Oscillation (AMO), Atlantic Meridional Mode (AMM), Antarctic Oscillation (AAO), Arctic Oscillation (AO), East Atlantic (EA), East Atlantic/Western Russia (EATL-WRUS), North Atlantic Oscillation (NAO), Pacific/North American (PNA), Polar/Eurasia (Poleur), Scandinavia (SCAND), Baltic Winter index (WIBIX) and compared the level of the correlation during the 1985–1990 period.

The WIBIX index (Hagen and Feistel, 2005) was obtained from the Leibniz Institute for Baltic Sea Research, Warnemünde (<https://www.io-warnemuende.de/wibix.html>, accessed on 01.09.2020). The other climatic indices were obtained from the National Oceanic and Atmospheric Administration (NOAA). The EA, EATL-WRUS, Poleur, PNA, SCAND were downloaded from <https://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml>, and the others from <https://psl.noaa.gov/data/climateindices/list/>, all links accessed on 01.09.2020.

Due to previously reported strong seasonality of correlations between the Baltic Sea water levels and NAO (e.g., Jaagus and Suursaar, 2013), the correlation analysis was performed for both annual and monthly maxima. The monthly mean was subtracted from the monthly maxima and yearly mean from the annual maxima to create stationary time series in a statistical sense. Pearson's correlation was employed for the correlation analysis below. We also used the non-parametric Kendall's and Spearman's correlation coefficients to test if it affects the results. Although Kendall's correlation resulted in approximately ~30% lower values, the time variability of the correlation stayed exactly the same, therefore, not affected the results of this paper. For some indices, such as WIBIX, only the total correlation was calculated, since only yearly values of the index were available.

In general, the total correlation coefficients, calculated between the annual maxima and annual climatic indices exhibited low values. The AAO index had a negative correlation of -0.4 ± 0.2 at Daugavgrīva (99% significance level, below denoted as sign. 1.) and -0.3 ± 0.2 at Skulte (94% sign. 1.). The extreme water levels at Līpāja showed a low but significant positive correlation of 0.3 ± 0.2 with both NAO (99% sign. 1.) and AO (97% sign. 1.) indices. The other locations did not show any significant total correlations with any other studied indices. However, a sliding correlation approach applied to the monthly sea level maxima and the climatic indices revealed significant changes in the correlation coefficients in time and with seasons. Fig. 9 shows running correlation results with a window of 15 years (only the correlations with $>95^{\text{th}}$ percentile confidence levels are shown) of Daugavgrīva water level extremes with NAO, SCAND and PNA teleconnections. The indices in Fig. 9 revealed a significant change in the correlation during the 1986–1990 period of the abrupt regime shift. The Arctic Oscillation showed practically the same results as the NAO, which was typical for the Baltic Sea region (Jaagus and Suursaar, 2013).

755 The sliding correlation analysis revealed that the NAO, AO, and SCAND indices showed remarkably similar results for all
the stations in the interior of the Gulf of Riga (Daugavgrīva, Roja, Pärnu, Salacgrīva, and Skulte). For all these locations, the
NAO index was characterized by weakening of the correlation during the 1985–1990 period and shift in seasonality (Fig.
10). Before 1984, the NAO index showed the highest correlation in January. However, after 1988, the highest correlation
coefficients were observed in March (Fig. 10) exhibiting an abrupt change in seasonal correlation with the NAO. Therefore,
the non-stationarity of sea-level extremes in the area is most likely caused by the severe time variability of the NAO signal in
760 the sea level extremes.

The SCAND index, from the other hand, revealed the strongest negative correlation in March during 1982–1990,
consistently for all the interior of the Gulf of Riga stations. However, the Liepāja and Kolka tide gauges exhibited different
dynamics of the sliding correlation with these teleconnections. The correlation with NAO revealed a gradual positive trend in
Liepāja and a negative trend in Kolka (Fig.10). This change in correlation with NAO can explain the observed reversed
765 changes in the GEV shape parameters in Liepāja and Kolka (Fig. 7) since a stronger correlation with NAO corresponds to
more frequent and powerful storms.

Interestingly, the time series from Daugavgrīva and Skulte tide gauges showed a significant correlation with the PNA
teleconnection in December and October (Fig. 11, Fig. 9). The correlation coefficients reached 0.6 ± 0.3 (December) and
 0.5 ± 0.3 (October) at Daugavgrīva during 1984–1988. Since the El Niño and PNA can in principle affect the European
770 climate intermittently and in a non-stationary way (e.g., Brönnimann, 2007), it is possible that during the weakening of the
correlation with the NAO, a faint signal from the other factors affecting the European climate was detected in this study.
However, a more detailed analysis is required to study the effects of the Pacific region on the Baltic Sea climate.

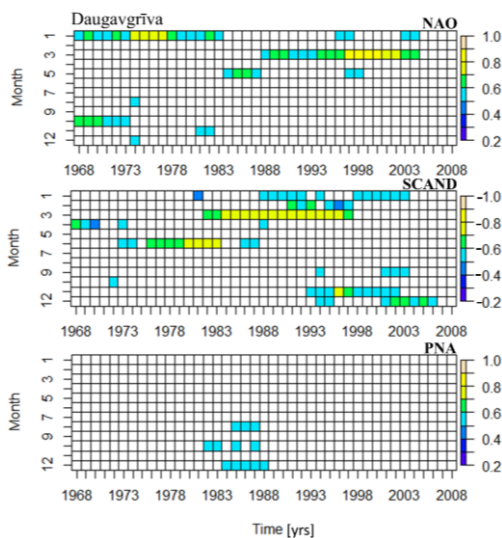


Figure 9: Sliding correlation results for Daugavgrīva and NAO, SCAND, and PNA climatic indices. The correlation is calculated for the water level monthly maxima with a window of 15 years. Only the correlation coefficients with the significance of more than 95% are shown.

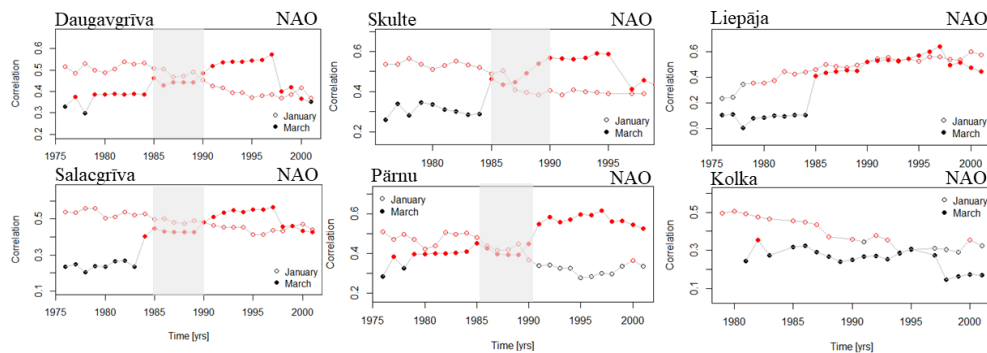


Figure 10: Sliding correlation results between the water level maxima in January (open circles) and March (solid circles) with the NAO index. The correlation is calculated using a window of 30 years. The correlation coefficients with the significance of more than 95% are marked in red. The grey rectangle highlights the period of the abrupt regime shift.

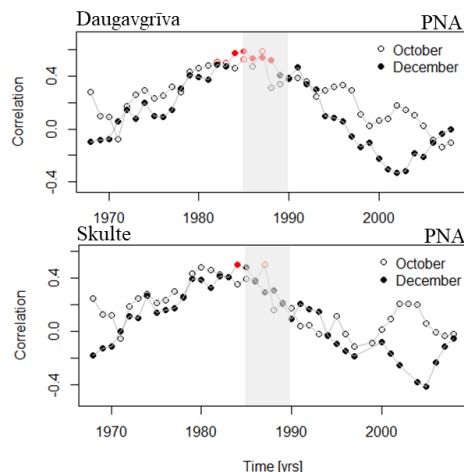


Figure 11: Sliding correlation results between the water level maxima in October (open circles) and December (solid circles) with the PNA index. The correlation is calculated using a window of 15 years. The correlation coefficients with the significance of more than 95% are marked in red. The grey rectangle highlights the period of the abrupt regime shift.

4 Conclusions and discussion

The core conclusion from the performed analysis is that the parameters of theoretical extreme value distributions of the observed ~~and measured~~ water maxima in Latvian waters, both on the shore of the Baltic Proper and in the interior of the Gulf of Riga exhibit statistically significant changes over the last 60 years. The ~~greatest~~most remarkable changes occur ~~to~~in the shape parameter of the GEV distribution. These changes may cause fundamentally different projections for long-term behaviour of water level extremes and their return periods as the underlying extreme value distribution changes from a three-parameter (reversed) Weibull distribution to a Gumbel one. While the reversed Weibull distribution has a finite upper limit, any water level height may occur according to Gumbel distributions.

Surprisingly, the nature of changes in the shape parameter of the GEV distribution for water level maxima is substantially different on the shores of the Baltic proper and in the interior of the Gulf of Riga. This parameter changes more gradually and mostly in one direction at sites directly affected by the water level regime of the Baltic proper. The direction of changes is different at different locations: the shape parameter decreases on the open shore of the Baltic proper at Liepāja but increases at Kolka.

Interestingly, the temporal course of the shape parameter has a pair of regime shifts at all measurement sites in the interior of the Gulf of Riga. During most of the time, this parameter is close to zero and, therefore, the GEV distribution can be

800 approximated well by a Gumbel distribution. The shape parameter becomes negative (and thus a reversed three-parameter Weibull distribution governs the water level maxima) around the year 1986. In contrast, its value jumps back to a level close to zero in around the year 1990. This regime shift may reflect abrupt changes in geostrophic winds in 1987/1988 (Soomere et al., 2015b) and surface-level winds in the 1980s (Keevallik and Soomere, 2014). The described process may also mirror massive evidence of regime shift in various abiotic variables in Estonia in 1989–1990 in biotic time series of bogs and
805 marine ecosystems in 1990 (Kotta et al., 2018).

We demonstrate that the period of an abrupt shift (1986–1990) in the shape parameters of the GEV distribution in the interior of the Gulf of Riga coincides with the weakening of the correlation with NAO. However, the tide gauges at the Latvian shore of the Baltic proper showed completely different time variability of the link with the NAO, showing a positive increase in case of Liepāja, and a decrease in Kolka (Fig. 10). The different appearance of changes to the shape parameter and nature of correlation with NAO in the interior of the Gulf of Riga and at the Latvian shore of the Baltic proper suggests that there is a strong relationship between the shape parameter of the GEV distribution and correlation with NAO in the Baltic Sea. The difference in the temporal course of the shape parameter in the two basins may stem from the very nature of the formation of extreme water levels in the Gulf of Riga. It is a multi-step process that is possibly only effective under a specific sequence of atmospheric events. The probability of occurrence of such events is evidently correlated with the values of the NAO index.

810 Many previous works have found significant correlations between winter sea-level changes (that usually are responsible for the extreme water levels) and changes in wind and air pressure as well as with the North Atlantic Oscillation (NAO) index in the Baltic Sea in general (e.g., Anderson, 2002), and in Pärnu in the Gulf of Riga in particular (Suursaar and Sooäär, 2007). Similar links have been established for the neighbouring areas. For example, the NAO contributes to changes in the mean and extreme water levels in the North Sea (Tsimplis et al., 2005). The link between the NAO and the Baltic Sea level has displayed substantial decadal variations in the last two centuries; however, the link was perceived as spatially heterogeneous, even in wintertime (e.g., Andersson, 2002; Jevrejeva et al., 2005; Hünicke et al., 2015; Karabil et al., 2017). In this paper, we demonstrated that there is a significant spatial difference in the link between the Baltic Sea extreme water levels and NAO. The established connection between the time variable link with the NAO and the non-stationary behaviour of the GEV parameters of extreme water levels implies that if the other regions in the world exhibit time-variable link with atmospheric teleconnections it can result in non-stationary behaviour of the sea level extremes, and under- or overestimation of the risks.

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