Simulating sea level extremes from synthetic low-pressure systems

Jani Särkkä[1], Jani Räihä[1], Mika Rantanen[1], and Matti Kämäräinen[1]

[1] Finnish Meteorological Institute, P.O.Box 503 , FI-00101 Helsinki, Finland

Correspondence: Jani Särkkä (Jani.Sarkka@fmi.fi)

Abstract. In this article we present a method for numerical simulations of extreme sea levels using synthetic low-pressure systems as atmospheric forcing. Our simulations can be considered as estimates of the high sea levels that may be reached when a low-pressure system of high intensity and optimal track passes the studied region. We test the method using sites located along the Baltic Sea coast and simulate synthetic cyclones with various intensities and tracks. To model the effects of the cyclone properties on sea level, we simulate internal Baltic Sea water level variations with a numerical two-dimensional hydrodynamic model, forced by an ensemble of time-dependent wind and air-pressure fields from synthetic cyclones. The storm surges caused by the synthetic cyclones come on top of the mean water level of the Baltic Sea, for which we used a fixed upper estimate of 100 cm. We find high extremes in the northern Bothnian Bay and in the eastern Gulf of Finland, where the sea level extreme due to the synthetic cyclone reach up to 3.5 meters. In the event that the mean water level of the Baltic Sea has a maximal value (1 meter) during the cyclone, highest sea levels of 4.5 meters could thus be reached. We find our method to be suitable for use in further studies of sea level extremes.

1 Introduction

A large part of the population and infrastructure in the Baltic Sea region is concentrated in the vicinity of the coastline. The potential for extreme sea level conditions must be accounted for when considering the safety of citizens and the need for coastal flood protection. A comprehensive investigation of the present-day sea level variability and of the possible scenarios for mean sea level in the future is essential for the determination of coastal flooding risks (Pellikka et al., 2018; Leijala et al., 2018; Pellikka et al., 2023). The impact of atmospheric conditions on sea level extremes is an important research topic within this context.

Sea level is measured by tide gauges situated on the coastline. Tide gauge records are available for many locations on the Baltic Sea coast only for the past 100-200 years, but several historical floods can be reconstructed from other sources, e.g., historical records or studies of coastal sediments (Rutgersson et al., 2022). Nonetheless, it may be assumed that many sea level extremes during the past 1000 years have left no traces in historical records, especially in historically sparsely populated coastal areas such as around the coast of the Bothnian Bay. In the northern Baltic Sea, the coastline has retreated due to land uplift, and the coastal strip affected by flooding in the past is now further away from the shoreline. Therefore the effects of high sea levels have been reduced by the relative decline in the mean sea level with respect to the shoreline.

The Baltic Sea is a shallow semi-enclosed sea, connected to the Atlantic Ocean through the narrow and shallow Danish Straits. The local short-term sea level variations are due to winds, air pressure, currents, tides, and internal oscillations (seiches). Long-term changes are caused by global mean sea level variations, postglacial land uplift and the water flow between the North Sea and the Baltic Sea through the Danish Straits (Leppäranta and Myrberg, 2009; Johansson et al., 2014). The sea level

30 extremes in the Baltic Sea are highest during winter months, most commonly in November, December and January (Wolski and Wiśniewski, 2023). The short-term sea level extremes (on hourly or daily timescales) are usually caused by moving extratropical cyclones which in favorable atmospheric conditions can strengthen to powerful windstorms (Della-Marta et al., 2009). The annual number of extratropical cyclones and windstorms in the Baltic Sea region has a large inter-annual variability and no significant trends were observed during 1980–2019 (Laurila et al., 2021). The effects of short-term sea level fluctuations

35 are largest in the narrow bays of the Baltic Sea. In particular, the narrow Gulf of Finland is vulnerable to coastal flooding due to windstorms, such as Storm Gudrun, which caused damages in 2005 (Tõnisson et al., 2008; Averkiev and Klevannyy, 2010). Major coastal flooding occurred in St. Petersburg in 1777, 1824, and 1924 (Kulikov and Medvedev, 2017), of which the flood in 1824 was the most extreme, with maximum sea level height 4.21 m. Even in cases where in situ sea level measurements are not available, traces of extreme sea level events can be found in sediment studies (Piotrowski et al., 2017; Leszczyńska et al.,

40 2022). More information on sea level extremes in the Baltic Sea can be found in recent reviews considering the region (Weisse et al., 2021; Rutgersson et al., 2022).

In this study, we simulate extreme sea levels exceeding the values found in tide gauge observations. We reconstruct idealised cyclones storms that are physically realistic, but which have not occurred during the era of tide gauge observations. We model the cyclones by describing a pressure field with a spatially varying time-dependent function that reproduces the typical cyclone

45 characteristics. This method has been used to study extreme sea levels in the Gulf of Finland (Averkiev and Klevannyy, 2010; Kalyuzhnaya et al., 2015; Apukhtin et al., 2017), and in the Bothnian Bay (Gordeeva and Klevannyy, 2020). In a recent study (Andrée et al., 2022), synthetic uniform wind fields were used in extreme sea levels simulations and an empirical-statistical method was used to model the site-specific relations between wind and extreme sea level. In addition, synthetic cyclones have been used to assess hazards caused by high sea level and waves in tropical regions (Leijnse et al., 2022).

50 In this study, we simulate sea levels at three locations on the Baltic coast using synthetic cyclones as an atmospheric input for the sea level model. We choose these locations on the basis of where particularly high sea levels are expected, representing different sub-basins of the Baltic Sea: Oulu for the Bothnian Bay, St. Petersburg for the Gulf of Finland, and Riga for the Bay of Riga.

2 Data and methods

2.1 Synthetic atmospheric forcing

To model the sea levels associated with our synthetic cyclones, we need information on the atmospheric conditions for the forcing of the sea level model. To this end, we use a method where the mean sea level pressure and surface winds of the
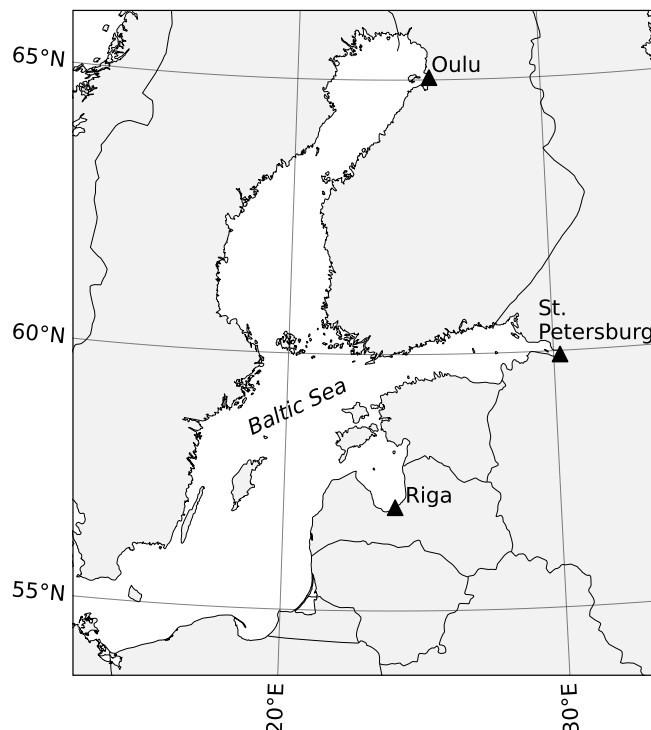
Figure 1. The Baltic Sea and locations (Oulu, St. Petersburg and Riga) where high sea levels were studied.

cyclone are calculated from the pressure field of a cyclone propagating with a constant velocity. The pressure field has the form of a Gaussian function

$$P_{x,y} = P_0 + \Delta P \exp\{-\frac{(x-x_0)^2}{2\sigma^2} - \frac{(y-y_0)^2}{2\sigma^2}\}, \tag{1}$$

where P_0 is the air pressure sufficiently far from the cyclone center, ΔP is the pressure anomaly in the cyclone center, x_0 and y_0 are the time-dependent coordinates of the cyclone center, and σ, the width of the pressure anomaly, is related to the radius R of the cyclone via $\sigma = 0.25R$. 10-metre geostrophic wind components (u_g, v_g) are calculated from the pressure field using the geostrophic balance as

$$u_g = -\frac{1}{f\rho}\frac{\partial P}{\partial y}, v_g = \frac{1}{f\rho}\frac{\partial P}{\partial x}, \tag{2}$$

where u_g (m s^{-1}) is the zonal geostrophic wind component, v_g (m s^{-1}) is the meridional geostrophic wind component, $f = 2\Omega\sin(\phi)$ is the Coriolis parameter (Ω is the rotation rate of the Earth and ϕ is the latitude) and ρ is the density of air (1.3 kg m^{-3}). An example of the pressure and wind field of a synthetic cyclone is shown in Fig. 2.
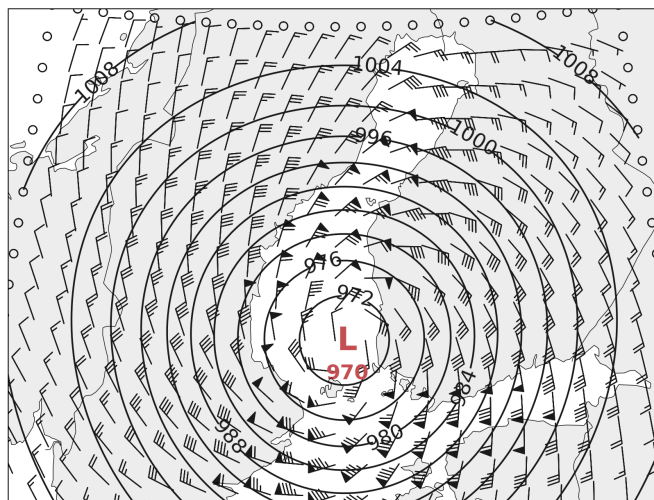
Figure 2. Example of synthetic cyclone and induced winds. Contours represent sea level pressure (hPa) and wind barbs represent 10 m winds (knots).

Actual wind components (u, v) differ from the geostrophic winds (u_g, v_g), especially near the surface where friction acts
70 to slow winds down, leading to winds turning anticlockwise in the Northern Hemisphere, and where curvature effects (the centrifugal force) are important. We study this difference between the theoretical geostrophic and the actual near-surface wind by using the analysis previously applied by Särkkä et al. (2017), with linear regression applied separately for wind speed and direction in the ERA-Interim reanalysis dataset (Dee et al., 2011) over the period 1979–2012. We obtain spatially varying coefficients for wind speed and direction change by comparing the actual 10-metre winds of the reanalysis dataset
75 with geostrophic winds that we calculate from the mean sea level pressure field. We then modify the geostrophic winds in the cyclone generator with coefficients from Särkkä et al. (2017) to achieve more realistic wind fields. Finally we save these wind fields and pressure fields in a numerical grid and use them as the input of the sea level model.

2.2 Cyclone parameters

The depth and horizontal extent of the synthetic cyclone, related to ΔP and radius R, must be limited by physical considera-
80 tions. We set the maximum value of the pressure anomaly ΔP to -40 hPa and the minimum radius R to 1000 km. With these values, the maximum surface wind speeds reach 40 m s^{-1} over the Baltic Sea. For larger pressure anomalies and smaller radii, even higher wind speeds are generated in the simulations, but such high speeds are not realistic in the Baltic Sea. The numerical sea level model describes how surface winds cause water flow through the wind friction component in the Navier-Stokes equations. The dependence of the wind friction on velocity is quadratic in our model, but in reality this dependence is likely
85 different for extreme wind speeds (over 50 m s^{-1}). This is an additional argument for limiting the surface wind speeds to 40 m s^{-1} for the synthetic cyclones. We vary only four parameters in the simulations: the latitude and longitude of cyclone origin,
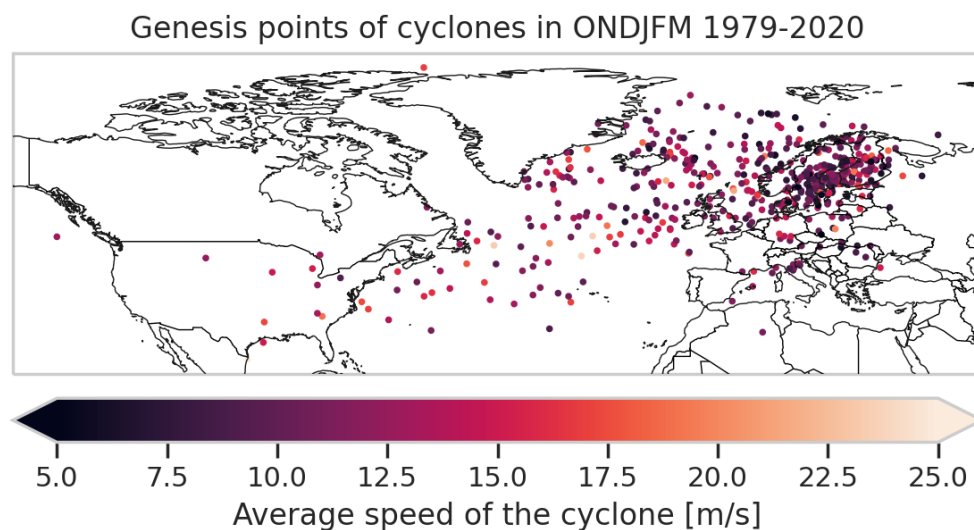
Figure 3. Genesis points of cyclones that pass the Baltic Sea region in October-March 1979-2020 in ERA5 reanalysis.

plus the speed and direction of cyclone propagation (cyclone velocity and direction given by zonal speed u and meridional speed v). We estimate the distribution of mean cyclone velocities for storms that pass the Baltic Sea region during October-March 1979-2020 based on ERA5 reanalysis data (Hersbach et al., 2020) using the same cyclone track dataset as was used in Laurila et al. (2021). The smallest velocities from this analysis are around 5 m s^{-1} (Fig. 4). Even smaller velocities of the cyclone lead to situations where the cyclone is almost stationary, with cyclone winds piling water towards the coast. As this scenario is likely unrealistic, we limit the minimum velocity of the cyclone to 5 m s^{-1}.

2.3 Numerical sea level simulation

In our numerical simulations we use a sea level model which describes the internal (intra-basin) fluctuations of the Baltic Sea with a set of two-dimensional hydrodynamic equations (Häkkinen, 1980) based on the Hansen sea level model (Hansen, 1956). We treat the Baltic Sea as a closed basin, with no connection through the Danish Straits to the North Sea. This one-layer sea level model is derived from the Navier-Stokes equations, and uses surface winds and surface pressure as atmospheric forcing. The spacing of the numerical grid is 0.1 degrees in the meridional direction and 0.2 degrees in the zonal direction. The model has previously been validated with Finnish tide gauge data and with ERA-Interim forcing 1979-2012 (Särkkä et al., 2017). The correlation was between 0.91 and 0.94 for all 13 Finnish tide gauge sites. The details of the sea level model were explained in Särkkä et al. (2017).

The variations in the water volume of the Baltic Sea are mainly caused by the flow of the water in and out of the Baltic Sea through the Danish Straits. The contribution of the water volume to the local sea level (also called preconditioning) is termed the water balance component. This component can be estimated with a statistical model, based on wind speeds at a single
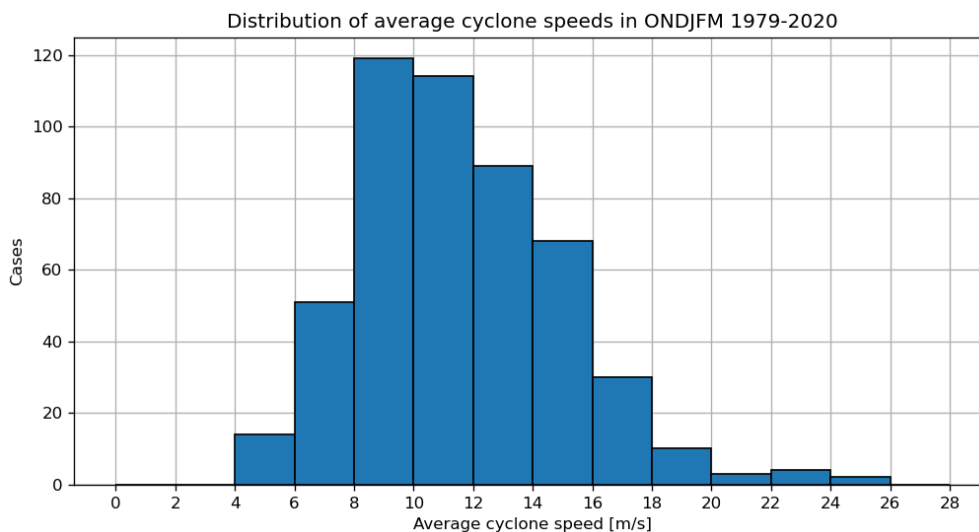
Figure 4. Distribution of mean speeds of cyclones that pass the Baltic Sea region in October-March 1979-2020 in ERA5 reanalysis.

coordinate point at (55° N, 15° E) (Johansson et al., 2014; Särkkä et al., 2017). The progression of a cyclone over the Baltic Sea region in the high sea level cases takes only one or two days, and the change in the water balance within this time is small (less than 10 cm). Thus we do not include changes in the water balance in our simulations. Instead, we estimate the extreme value of the water balance component to be 100 cm (Särkkä et al., 2017) and add it to the simulated local sea level maximum. This describes the situation when preceding weather conditions have raised the water volume in the Baltic Sea, and then the arriving cyclone causes fluctuations on top of the high mean sea level.

The tides are small in the Baltic Sea, with largest tidal ranges (over 20 cm) at the eastern end of the Gulf of Finland and near the Danish Straits in the southwestern Baltic Sea. For a large part of the Baltic coast, the tidal range is only a few cm (Medvedev et al., 2016), and thus we do not include tides in the model.

2.4 Simulation parameters

We select three sites to represent different bay areas of the Baltic Sea, including coastal cities where the sea level variability is large and where the effects of flooding are significant - the latter due to dense inhabitation with substantial infrastructure on low-lying coastlines. As the predominant direction of the cyclone tracks is from the west (Fig. 3), we choose to study sites at the ends of bays, on the eastern coast of the Baltic Sea. At these locations, the effect of wind-driven water transport is largest, as the water piles towards the coastline. We select the locations so that the Gulf of Bothnia is represented by Oulu, situated at its northern end (Fig. 1). The Gulf of Finland is represented by St. Petersburg, situated at its eastern end. The smaller sub-basin, the Bay of Riga is represented by Riga. In the Gulf of Bothnia, we also simulated sea levels at Kemi, but found that the highest simulated sea levels at Oulu exceeded the ones found at Kemi.

We use the surface wind and pressure fields of synthetic cyclones as atmospheric forcing for the sea level model. We compare simulation results with the observed extremes in tide gauge data from Fig. 1 of Averkiev and Klevannyy (2010). 125 As we calculate only short-term sea level changes, our results represent the sea level fluctuation with respect to the sea level preceding the arrival of the cyclone. In Table 1 we give the parameters that yield the highest sea levels at each of the three sites. The highest sea levels are reached, as expected, for the cyclones with the maximal values of the pressure anomaly (40 hPa) and cyclone radius (1000 km). A common factor for the cyclone tracks of these maxima was that the propagation speeds were close to the minimum speed limit 5.0 m s^{-1} : 5.7 m s^{-1} for Oulu, 5.4 m s^{-1} for St. Petersburg and 5.0 m s^{-1} for Riga. Due to 130 the low propagation speed, high wind speeds prevail for a longer time over the Baltic Sea, enhancing the water flow towards the ends of bays. For even lower propagation speeds, the extreme sea levels at the studied sites would likely be still higher.

Location	Origin	Press. anomaly	Radius (km)	zonal vel.	meridional vel.	total velocity (m s^{-1})	Max. sea level (cm)
Oulu	(61.0, 10.0)	-40	1000	4.3	3.7	5.7	294
St. Petersburg	(57.5, 10.0)	-40	1000	4.8	2.5	5.4	346
Riga	(67.0, 10.0)	-40	1000	3.3	-3.7	5.0	265

Table 1. Cyclone parameters for the highest simulated sea levels at Oulu, St. Petersburg and Riga.

3 Results

The differences in vertical reference systems between different countries complicate our comparison of simulated extremes against observed extremes. As our aim is only to estimate the extremes to an accuracy of tens of centimeters, we use a fixed 135 value of 100 cm for the water balance component, even where this value differs between the reference systems.
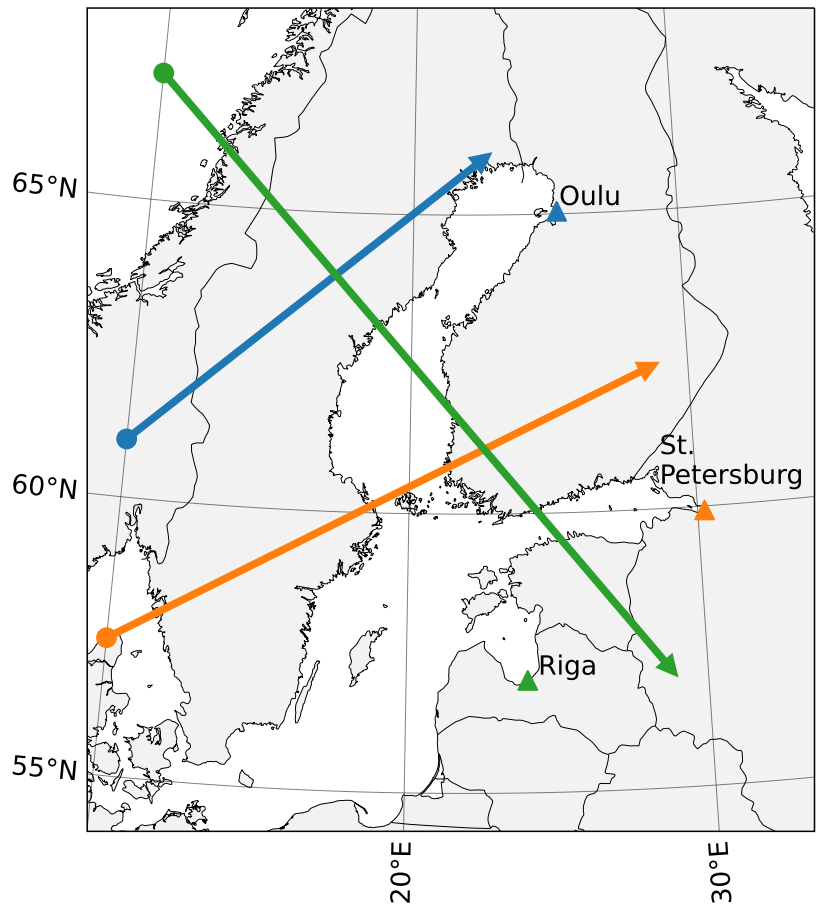
Figure 5. Cyclone tracks of the highest simulated sea levels at Oulu, St.Petersburg and Riga.
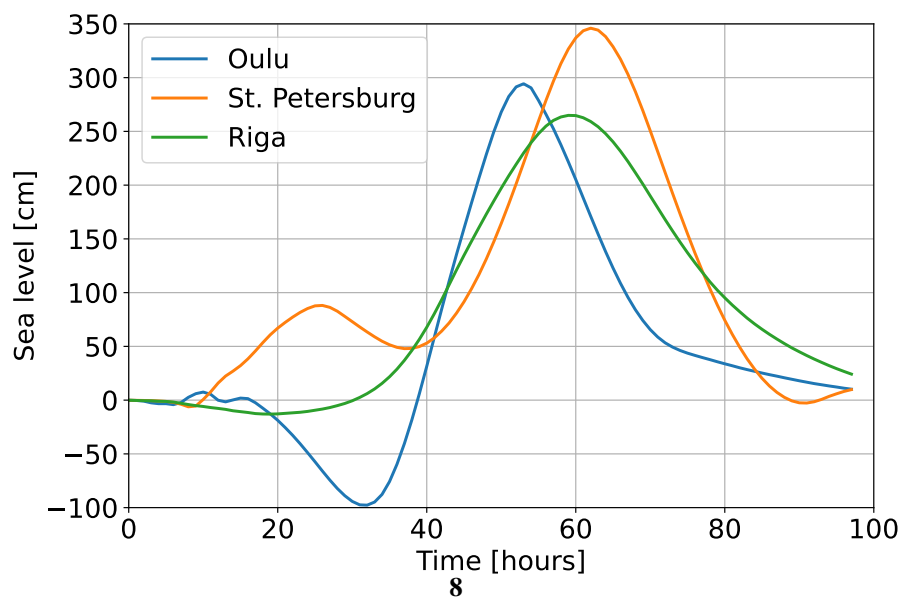

Figure 6. Highest simulated sea levels at Oulu, St.Petersburg and Riga.

The simulated sea level extreme at **Oulu** is caused by a cyclone progressing northeastwards from southern Norway towards Finnish Lapland (Fig. 5). The strong winds on the right hand side of the propagation direction generate water flow from the central Baltic Sea towards the northern end of the Bothnian Bay. At first, the wind direction in front of the cyclone center is towards the northwest in the Bothnian Bay, moving water away from Oulu and causing a decrease in sea level down to -100

140 cm. Then, as the cyclone center moves northwest of the Bothnian Bay, the wind direction is towards the northeast, piling water towards the northeastern end of the bay, which causes a rapid increase in sea level at Oulu. Finally, when the cyclone is north of the Bothnian Bay, the wind direction is from west to east over the northern Bothnian Bay. This pushes yet more water towards the Oulu coastal region, leading to a very high sea level maximum of 294 cm (Fig. 6). The highest observed sea level at Oulu is 183 cm from January 1984. Taking into account the maximum water balance component (100 cm), a sea level at Oulu of

145 394 cm could be reached, which is significantly higher than the observed maximum value. In the study of Andrée et al. (2022) with uniform wind fields (wind speed 22 m s^{-1}), the highest simulated sea levels in the Bothnian Bay were at Kalix and Kemi (both situated west of Oulu), where extreme sea levels between 275 and 300 cm were obtained. These levels are of the same magnitude as our result for the extreme sea level at Oulu without the water balance component.

Räty et al. (2022) used Bayesian hierarchical modeling to analyse return level estimates and theoretical upper limits for

150 the sea level on the Finnish coast from tide gauge data. At Oulu, the 1000-year return level is approximately 200 cm and the theoretical upper limit for the sea level using Bayesian modeling is approximately 250 cm. These estimates include the water balance component, and are considerably lower than the nearly 4 meters estimate in our analysis. This indicates that the high values that we obtain from our synthetic cyclones method can not always be derived from the statistical extreme value analysis.

The cyclone track that causes the highest simulated sea level extreme at **St. Petersburg** (346 cm, Fig. 5) is interesting.

155 The cyclone originates from northern Denmark and moves over southern Finland. Winds cause water to flow from the central Baltic Sea to the Gulf of Finland, which accumulates water at its eastern end. The highest observed sea level occurred in 1824, reaching 421 cm at St. Petersburg. The simulated sea level at St. Petersburg by Averkiev and Klevannyy (2010) was 590 cm. Taking into account the maximum water balance component of 100 cm, the highest estimated sea level in our simulations at St. Petersburg is 446 cm. The higher spatial resolution Averkiev and Klevannyy (2010) use near St. Petersburg is likely the

160 reason for the 1.5 meter difference between their simulated maximum and our result. The narrow shape of the Gulf of Finland and its west-east orientation leave the eastern end of the Gulf of Finland especially vulnerable to sea flooding when weather conditions induce water transport towards St. Petersburg.

The highest simulated sea level maximum at **Riga** is due to a cyclone originating in central Norway, then moving to the southeast over the Bothnian Sea and southwestern Finland (Fig. 5). Northerly winds push water from the Bothnian Sea and

165 central Baltic Sea towards the Bay of Riga. As the cyclone moves over the Gulf of Finland and Estonia to Russia, the north-westerly winds cause water accumulation in the vicinity of Riga. The simulated maximum at Riga is 265 cm. The highest observed sea level is 229 cm from November 1969. By adding the water balance component of 100 cm, the highest estimated sea level is 365 cm, considerably higher than the observed maximum.

In summary, the simulated extremes clearly exceed the observed ones at Oulu and Riga, even accounting for a tens of
170 centimeters ambiguity in the value of the water balance component from the reference level of the tide gauge location. At St.
Petersburg, however, the simulated extreme is of similar height to the observed extreme in 1824.

4   Conclusions

The results of our study show that a numerical sea level model combined with synthetic cyclones can be used to study the
characteristics of those cyclones that induce extreme sea levels on the Baltic coast. Comparing the three studied sites, we find
175 the highest simulated sea levels at St. Petersburg, - around 3.5 meters, - so that, adding the water balance component, sea levels
over 4 meters are possible. These values are comparable with the values observed during the extreme flood of 1824 (421 cm
in St. Petersburg). As the flood in 1824 was the highest in the 300-year history of St. Petersburg, the simulated case could
correspond to the extreme weather conditions that contributed to the sea levels observed in 1824.

The high sea level at Oulu, approximately 4.0 meters, is due to a cyclone causing water flow from the entire Gulf of Bothnia
180 towards the northern Bothnian Bay, and finally the change in wind direction from westwards to eastwards in the Bothnian Bay.
One could expect that an even higher sea level would be found in Kemi, situated at the northern end of the Bothnian Bay,
as the highest sea level in Finland (201 cm in 1982) was observed there. In our simulations at Kemi (results not discussed in
this publication), the highest maxima are all under 4.0 meters. The shape of the coastline and bathymetry in the Bothnian Bay
apparently favor high sea levels at Oulu more than at Kemi. Our simulation results indicate that there is potential for a flood
185 exceeding four meters at Oulu, far surpassing the observed maximum in 1984 (183 cm).

At Riga, the highest simulated sea level is obtained with a cyclone passing the Baltic Sea with a track from central Sweden
towards northwestern Russia. The simulated extreme of 265 cm (with 1 m added to include the water balance component) is
considerably higher than the observed maximum (229 cm) in 1969. The cyclone related to the maximum in 1969 had a similar
track compared to the one used in our simulation. This indicates that a similar storm track can occur and that a cyclone with
190 such a track and slow velocity could cause high sea levels in the Riga region.

Our method has certain limitations. The spatial description of the simulated cyclone (Fig. 2) is not completely realistic, as
the cyclone is symmetrical and lacks frontal structures which are typical for extratropical cyclones. The pressure anomaly of
the simulated cyclone is not time-dependent, neglecting the deepening and filling of the cyclone. Comparing to the description
of the synthetic cyclone in (Averkiev and Klevannyy, 2010), we find that the deviation from the symmetric structure is not
195 large in their model. The value of the pressure anomaly affects the simulated sea level mainly when the cyclone moves over
the sea. Therefore including the deepening and filling of the pressure anomaly would have only a small effect on the simulated
sea levels on the coast, as the simulated cyclones move in a short time over the sea.

Our results indicate that synthetic cyclones are a useful tool for studying the sea level response to cyclones with different
characteristics. In particular, our method offers the opportunity to study those extreme sea levels which can be expected on the
200 Baltic Sea coast if all the components that raise the water level are present, namely a high water balance paired with a slow and

deep cyclone moving along an optimal track. Our simulations of extreme sea levels reveal those areas of the Baltic Sea which, due to shoreline geometry and coastal bathymetry, are especially prone to extreme coastal flooding.

Author contributions. All authors contributed to the design of the study. JR and MK implemented the method for the generation of synthetic cyclones. JS implemented the numerical sea level model. MR studied the properties of cyclones from reanalysis data. JS performed the sea

205 level simulations with synthetic cyclones and conducted the analysis presented in the paper, and wrote the manuscript with critical comments from the other authors.

Competing interests. The authors declare that they have no conflict of interest.

References

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Andrée, E., Drews, M., Su, J., Larsen, M. A. D., Drønen, N., and Madsen, K. S.: Simulating wind-driven extreme sea levels: Sensitivity to wind speed and direction, Weather and Climate Extremes, 36, 100 422, https://doi.org/https://doi.org/10.1016/j.wace.2022.100422, 2022.

Apukhtin, A., Bessan, G., Gordeeva, S., Klevannaya, M., and Klevannyy, K.: Simulation of the probable maximum flood in the area of the Leningrad Nuclear Power Plant with account of wind waves, Russian Meteorology and Hydrology, 42, 113–120, 2017.

215 Averkiev, A. S. and Klevannyy, K. A.: A case study of the impact of cyclonic trajectories on sea-level extremes in the Gulf of Finland, Continental Shelf Research, 30, 707 – 714, https://doi.org/10.1016/j.csr.2009.10.010, tides in Marginal Seas - A special issue in memory of Prof. Alexei Nekrasov, 2010.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haim-

220 berger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N., and Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Quarterly Journal of the Royal Meteorological Society, 137, 553–597, https://doi.org/10.1002/qj.828, 2011.

Della-Marta, P. M., Mathis, H., Frei, C., Liniger, M. A., Kleinn, J., and Appenzeller, C.: The return period of wind storms over Europe,

225 International Journal of Climatology, 29, 437–459, https://doi.org/10.1002/joc.1794, 2009.

Gordeeva, S. M. and Klevannyy, K. A.: Estimation of the maximum and minimum surge levels at the Hanhikivi peninsula, Gulf of Bothnia, Boreal Environment Research, 25, 51–63, 2020.

Häkkinen, S.: Computation of sea level variations during December 1975 and 1 to 17 September 1977 using numerical models of the Baltic Sea, Deutsche Hydrographische Zeitschrift, 33, 158–175, 1980.

230 Hansen, W.: Theorie zur Errechnung des Wasserstandes und der Strömungen in Randmeeren nebst Anwendungen, Tellus, 8, 287–300, 1956.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Vil-

235 laume, S., and Thépaut, J.-N.: The ERA5 global reanalysis, Quarterly Journal of the Royal Meteorological Society, 146, 1999–2049, https://doi.org/10.1002/qj.3803, 2020.

Johansson, M. M., Pellikka, H., Kahma, K. K., and Ruosteenoja, K.: Global sea level rise scenarios adapted to the Finnish coast, Journal of Marine Systems, 129, 35–46, https://doi.org/10.1016/j.jmarsys.2012.08.007, 2014.

Kalyuzhnaya, A. V., Visheratin, A. A., Dudko, A., Nasonov, D., and Boukhanovsky, A. V.: Synthetic storms reconstruction for coastal floods

240 risks assessment, Journal of Computational Science, 9, 112–117, https://doi.org/10.1016/j.jocs.2015.04.029, 2015.

Kulikov, E. A. and Medvedev, I. P.: Extreme Statistics of Storm Surges in the Baltic Sea, Oceanology, 57, 772–783, https://doi.org/10.1134/S0001437017060078, 2017.

Laurila, T. K., Gregow, H., Cornér, J., and Sinclair, V. A.: Characteristics of extratropical cyclones and precursors to windstorms in northern Europe, Weather and Climate Dynamics, 2, 1111–1130, https://doi.org/10.5194/wcd-2-1111-2021, 2021.

245   Leijala, U., Björkqvist, J.-V., Johansson, M. M., Pellikka, H., Laakso, L., and Kahma, K. K.: Combining probability distributions of sea level variations and wave run-up to evaluate coastal flooding risks, Natural Hazards and Earth System Sciences, 18, 2785–2799, https://doi.org/10.5194/nhess-18-2785-2018, 2018.

Leijnse, T. W. B., Giardino, A., Nederhoff, K., and Caires, S.: Generating reliable estimates of tropical-cyclone-induced coastal hazards along the Bay of Bengal for current and future climates using synthetic tracks, Natural Hazards and Earth System Sciences, 22, 1863–

250   1891, https://doi.org/10.5194/nhess-22-1863-2022, 2022.

Leppäranta, M. and Myrberg, K.: Physical Oceanography of the Baltic Sea, Springer, https://doi.org/10.1007/978-3-540-79703-6, 2009.

Leszczyńska, K., Stattegger, K., Moskalewicz, D., Jagodziński, R., Kokociński, M., Niedzielski, P., and Szczuciński, W.: Controls on coastal flooding in the southern Baltic Sea revealed from the late Holocene sedimentary records, Scientific Reports, 12, 9710, https://doi.org/10.1038/s41598-022-13860-4, 2022.

255   Medvedev, I. P., Rabinovich, A. B., and Kulikov, E. A.: Tides in Three Enclosed Basins: The Baltic, Black, and Caspian Seas, Frontiers in Marine Science, 3, 46, https://doi.org/10.3389/fmars.2016.00046, 2016.

Pellikka, H., Leijala, U., Johansson, M. M., Leinonen, K., and Kahma, K. K.: Future probabilities of coastal floods in Finland, Continental Shelf Research, 157, 32 – 42, https://doi.org/10.1016/j.csr.2018.02.006, 2018.

Pellikka, H., Johansson, M. M., Nordman, M., and Ruosteenoja, K.: Probabilistic projections and past trends of sea level rise in Finland,

260   Natural Hazards and Earth System Sciences, 23, 1613–1630, https://doi.org/10.5194/nhess-23-1613-2023, 2023.

Piotrowski, A., Szczuciński, W., Sydor, P., Kotrys, B., Rzodkiewicz, M., and Krzymińska, J.: Sedimentary evidence of extreme storm surge or tsunami events in the southern Baltic Sea (Rogowo area, NW Poland), Geological Quarterly, 61, 973–986, https://doi.org/10.7306/gq.1385, 2017.

Räty, O., Laine, M., Leijala, U., Särkkä, J., and Johansson, M. M.: Bayesian hierarchical modeling of sea level extremes in the Finnish coastal

265   region, Natural Hazards and Earth System Sciences Discussions, 2022, 1–23, https://doi.org/10.5194/nhess-2021-410, 2022.

Rutgersson, A., Kjellström, E., Haapala, J., Stendel, M., Danilovich, I., Drews, M., Jylhä, K., Kujala, P., Larsén, X. G., Halsnæs, K., Lehtonen, I., Luomaranta, A., Nilsson, E., Olsson, T., Särkkä, J., Tuomi, L., and Wasmund, N.: Natural hazards and extreme events in the Baltic Sea region, Earth System Dynamics, 13, 251–301, https://doi.org/10.5194/esd-13-251-2022, 2022.

Särkkä, J., Kahma, K. K., Kämäräinen, M., Johansson, M. M., and Saku, S.: Simulated extreme sea levels at Helsinki, Boreal Environment

270   Research, 22, 299–315, 2017.

Tõnisson, H., Orviku, K., Jaagus, J., Suursaar, Ü., Kont, A., and Rivis, R.: Coastal Damages on Saaremaa Island, Estonia, Caused by the Extreme Storm and Flooding on January 9, 2005, Journal of Coastal Research, 24, 602–614, https://doi.org/10.2112/06-0631.1, 2008.

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

275   871-2021, 2021.

Wolski, T. and Wiśniewski, B.: Characteristics of seasonal changes of the Baltic Sea extreme sea levels, Oceanologia, 65, 151–170, https://doi.org/https://doi.org/10.1016/j.oceano.2022.02.006, 2023.