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The Impact of Serial Cyclone Clustering on Extremely High Sea Levels in the Baltic Sea

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Key Points:

- Serial cyclone clustering (SCC) commonly causes elevated sea levels in the Baltic Sea
- Peak storm surges during SCC are on average 2–2.7 times (25–48 cm) higher than during single cyclones
- The intensity of the cyclones within the SCC modulates the storm surge levels, with deeper cyclones more likely to induce higher surges

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract In the Baltic Sea, sea level variations are often very pronounced. During the winter season, storm surges caused by strong extratropical cyclones (ETCs) can have major societal impacts on coastal cities. In this study, using reanalysis-based cyclone tracks and in-situ tide gauge records, we show that serial cyclone clustering (SCC) leads to higher sea levels in the Baltic Sea than situations where only one ETC passes the tide gauge. Consequently, almost half of extreme sea level events in the Baltic Sea are associated with cyclone clustering periods. For example, in Helsinki, 45% of the extreme sea level events coincided with SCC periods of three or more ETCs, while only 6% of the events coincided with a single ETC. Our study represents a significant advance in the understanding of the factors influencing sea level variations in the Baltic Sea.

Plain Language Summary Sea levels in the Baltic Sea can vary a lot. In winter, powerful storms can lead to storm surges that seriously affect coastal towns. Our research studied storm paths and sea level observations. We found that multiple consecutive storms within a week raise sea levels in the Baltic Sea more than when only one storm passes the same location. As a result, most of the high sea level events in the Baltic Sea are linked to periods when several storms pass the region. In Helsinki, for instance, almost half of all analyzed high sea level events co-occurred with periods when at least three storms occurred, while only 6% of high sea level events occurred due to a single storm. Our analysis is a significant progression in understanding the reasons that impact the Baltic Sea water levels. Hence, these results could aid in preparing for possible coastal floods.

1. Introduction

Extratropical cyclones (ETCs) are prevalent weather systems throughout mid and high latitudes. In northern Europe and the Baltic Sea region, an average of 10–15 ETCs occur each month, with the strongest ETCs primarily happening during the winter season (Laurila et al., 2021). Powerful ETCs can bring heavy precipitation and strong winds which in turn can cause extensive damage to society. In the Baltic Sea, storm surges and the resulting coastal flooding events are the major impacts associated with the passage of strong ETCs (Rutgersson et al., 2022).

In the exit region of the North Atlantic storm track, ETCs typically occur in clusters rather than at regular intervals (Mailier et al., 2006). The passage of several high-intensity ETCs over a particular, fixed location within a relatively short period of time is defined as serial cyclone clustering (SCC; Dacre & Pinto, 2020). SCC, its impacts on society and its connection to the large-scale circulation have been extensively studied in western Europe (Economou et al., 2015; Hauser et al., 2023; Pinto et al., 2014; Priestley et al., 2017a, 2017b, 2018), but the studies on SCC in the Baltic Sea region are comparatively limited.

The Baltic Sea is a shallow, semi-enclosed sea with generally weak tides. Even so, the sea level variations in the Baltic Sea are often quite pronounced. The most extreme sea levels are usually observed along the eastern coast of the Baltic Sea, namely in the coasts of Finland, Russia, Estonia and Latvia, where the amplitude of sea level variations can exceed 3 m (Rutgersson et al., 2022; Wolski et al., 2014). These countries are often exposed to strong ETCs coming from the west or south-west and causing sea-level rise due to the strong winds and low pressure associated with them.

Extremely high sea levels caused by the passage of strong ETCs in the Baltic Sea have been investigated in several previous studies. A well-documented case is Storm Gudrun in January 2005. The storm was one of the strongest storms ever recorded in northern Europe (Bengtsson & Nilsson, 2007; Soomere et al., 2008). During the passage

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of Storm Gudrun, record high sea levels were observed in Estonia and Finland (Soomere et al., 2008; Suursaar et al., 2006). In Helsinki, the sea level rose to +151 cm above the mean sea level, causing losses of 12 million euros to society along the Finnish coast (Pellikka et al., 2018).

Previous studies have shown that extreme storm surges in the Baltic Sea depend mainly on three components: (a) the initial water volume in the Baltic Sea prior to the storm, (b) the characteristics of the storm, and (c) basin-wide standing waves in the water level caused by winds and atmospheric pressure variations (i.e., seiches) (Pellikka et al., 2018; Wiśniewski & Wolski, 2011; Wolski & Wiśniewski, 2020). Although previous studies have investigated the characteristics of ETCs causing extreme sea levels in the Baltic Sea (Suursaar et al., 2009, 2018; Wolski & Wiśniewski, 2021), there is some evidence that a single ETC is not sufficient to cause extremely high sea levels, but that a series of ETCs is required (Post & Kõuts, 2014; Soomere & Pindsoo, 2016; Suursaar et al., 2018). However, a comprehensive analysis of the role of cyclone clustering for the extreme sea levels in the Baltic Sea is lacking.

In this study, we use objectively tracked ETCs to investigate the impact of SCC on high sea levels in the Baltic Sea. In particular, the question we aim to address is: are extremely high sea level events along the Baltic Sea coasts typically caused by the passage of single ETCs, or are several successive ETCs required? In addition to this primary focus, we also explore how cyclone intensity affects elevated sea levels, to clarify whether the strength of cyclones within a cluster leads to higher sea level anomalies.

2. Data and Methods

Our study is based on ERA5 reanalysis (Hersbach et al., 2020) and in-situ sea level observations from Baltic Sea tide gauges. We focus on the extended cold season, that is, October–March (ONDJFM) period from 1979/1980 to 2021/2022, as this is the season when the strongest ETCs typically occur in northern Europe (Laurila et al., 2021).

2.1. Cyclone Tracks and Defining Serial Cyclone Clustering

To identify the tracks of individual ETCs, a tracking algorithm called TRACK (Hodges, 1995, 1999) is applied to ERA5 reanalysis data. Following the methodology of Laurila et al. (2021), the tracking is based on 3-hourly mean sea level pressure (MSLP) fields which were filtered to T63 resolution to remove small-scale noise in the MSLP fields. In addition, wavenumbers less than five were excluded to remove the large planetary-scale waves from the tracking. In order to focus on large ETCs, ETCs traveling less than 500 km and lasting less than 24 hr were excluded from the analysis.

A circular area with a radius of 700 km is defined for each tide gauge location (Figure 1). The choice of radius was somewhat subjective, but 700 km is close to the mean value for deep (<980 hPa) ETCs over the Euro-Atlantic region (Rudeva & Gulev, 2007) and is consistent with previous clustering studies (Hauser et al., 2023; Pinto et al., 2014; Priestley et al., 2017b). ETCs with at least one point of their track inside the circle are included in the analysis. Because weak ETCs are unlikely to have a significant effect on sea level, we select only the strongest 50% of ETCs at each tide gauge. Intensity thresholds are defined locally based on the minimum MSLP distributions of ETCs when located within a 700 km radius. These thresholds (i.e., the median ETC intensities) are 985.5 hPa for Kemi, 989.1 hPa for Helsinki, 987.7 hPa for Landsort and 990.0 hPa for Pärnu. Note, however, that the ETCs in our analysis were not selected according to the sea levels they caused.

SCC is defined according to an absolute frequency metric previously used, for example, in Hauser et al. (2023). Each ETC passing the tide gauge is assigned to a calendar day when the ETC reaches its minimum MSLP within the area. Time series of daily ETCs and the 7-day running sum of ETCs are then obtained for the entire ONDJFM period 1980–2022. Based on the 7-day running sum of ETCs, we identify periods when only one ETC (referred to as ETC1), two, or at least three ETCs (referred to as SCC2 and SCC3+, respectively) pass the tide gauge within a 7-day time frame. Preliminary SCC periods are defined by finding the dates of the first and last ETC in the SCC periods, and final SCC periods are defined by adding ±1 day around each preliminary SCC period. For Helsinki we found 149 ETC1, 121 SCC2 and 94 SCC3+ periods for the 43 ONDJFM seasons considered here. The typical duration of SCC3+ periods is 9 days and has 4 ETCs (Figure S1 in Supporting Information S1). Note that SCC2 periods can contain more than 2 ETCs in total (Figure S2 in Supporting Information S1), but their frequency cannot exceed 2 ETCs per 7 days.

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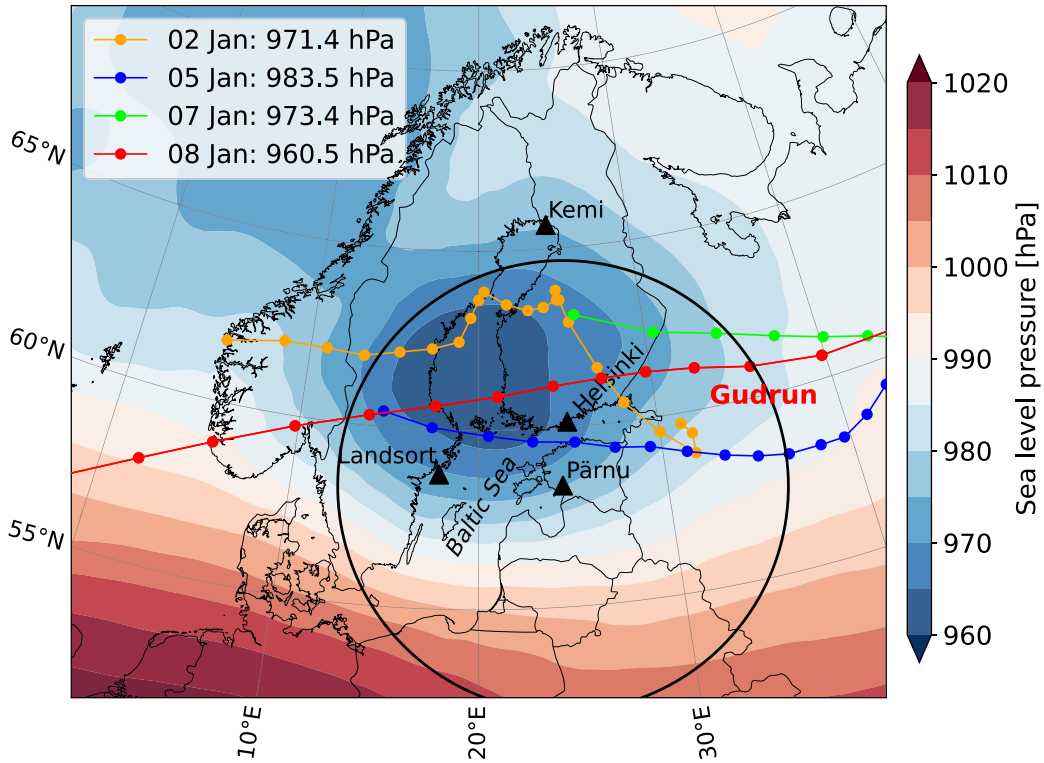

Figure 1. Location of the tide gauges used in the study. The black circle shows the 700 km radius used to define SCC in Pärnu. Background shading depicts MSLP on 9 January 2005 at 00 UTC when Storm Gudrun hit the Baltic Sea. Dotted lines indicate the tracks of the four ETCs preceding the January 2005 flooding with the track of Storm Gudrun colored with red. The legend shows minimum MSLP of the ETCs and the dots of the tracks indicate the location of the ETC center every 3 hours.

2.2. Sea Level Observations and Extreme Sea Level Events

We use hourly sea level observations from tide gauges located in Kemi and Helsinki (Finland), Landsort (Sweden), and Pärnu (Estonia) for ONDJFM 1980–2022 (Figure 1). In Supporting Information S1, some results are also shown for four additional tide gauges situated in the Baltic Sea. The time series were detrended to eliminate the decreasing trend in relative sea level due to post-glacial crustal uplift. Detrending was performed by fitting a linear trend to the annual mean sea level time series and then removing this trend from the hourly values.

To investigate how ETCs affect the local sea level and the total water volume of the Baltic Sea, we separate the sea level into short-term and weekly-scale components. The short-term component describes the ETC-driven variations in the sea level while the weekly-scale component reflects the volumetric changes of the entire Baltic Sea. For the weekly-scale component, we use the 8-day moving average of hourly sea level, as the 8-day moving average has been shown to be a good proxy for the overall water volume of the Baltic Sea (Männikus et al., 2019; Pindsoo & Soomere, 2020; Soomere et al., 2015). The short-term component is then defined as the residual between the hourly sea level and its 8-day moving average.

Extreme sea level events (ESL98) are defined as time periods when the daily maximum sea level exceeds the local 98th percentile of the respective sea level climatology at the tide gauge during the ONDJFM 1980–2022. These thresholds were 100.5 cm in Kemi, 82.3 cm in Helsinki, 57.0 cm in Landsort and 108.8 cm in Pärnu. ESL98 was allowed to continue until the sea level was below the threshold value for 7 consecutive days. Thus, if two threshold crossings occur consecutively, they are considered as separate events if there is at least 7 days between them. For the 43 ONDJFM seasons considered here, we found 81 ESL98s in Kemi, 51 in Helsinki, 32 in Landsort and 71 in Pärnu. The median duration of ESL98s at the tide gauges ranged from 1 to 3 days (Figure S3 in Supporting Information S1).

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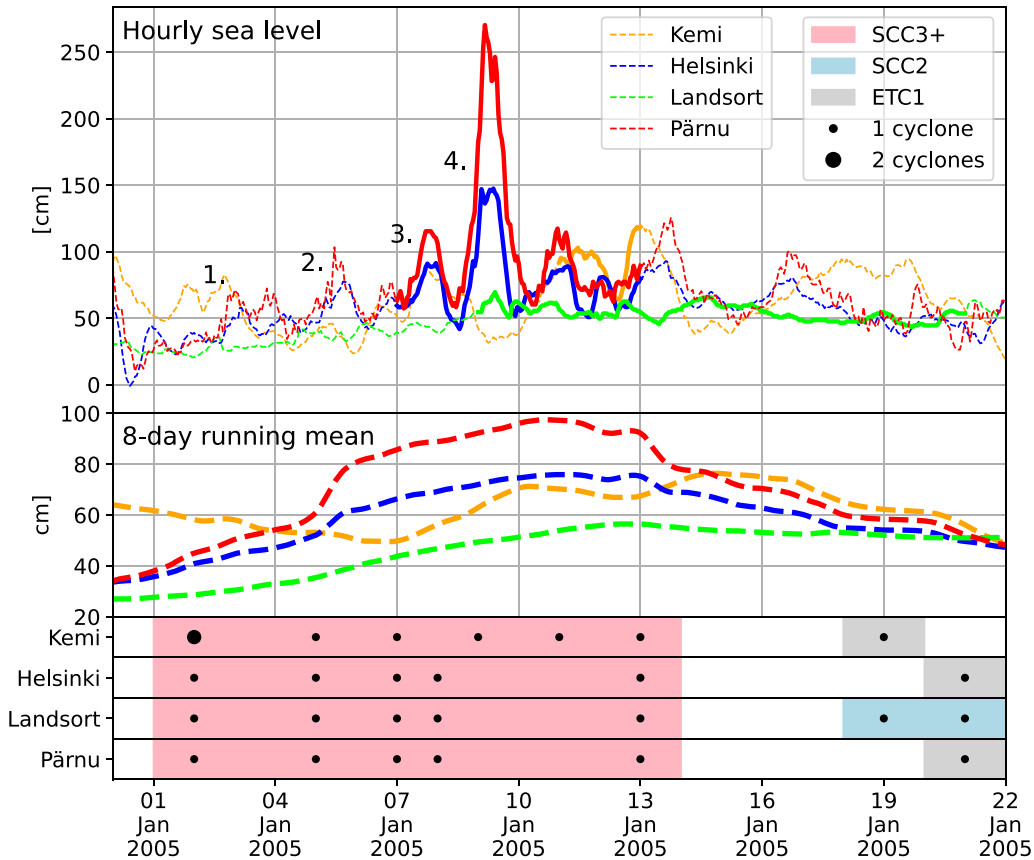

Figure 2. Time series of hourly sea level at the four tide gauges on 31 Dec 2004–22 Jan 2005 (top), the 8-day running mean of the sea level (center), and serial cyclone clustering periods (bottom). Thickenings of the colored lines in the top panel depict the time range of extreme sea level events. Black circles in the bottom panel mark the number of passing ETCs, and the shading represents the magnitude of SCC periods.

We calculate composite sea level anomalies centered around each SCC onset date. In this context, lagged sea level anomaly refers to the lag with respect to the onset date of each SCC period. Sea level anomalies are calculated iteratively, taking into account the intraseasonal variability of the sea level height (see Supporting Information).

3. Results

3.1. January 2005 Flooding

We begin with a short case study by analyzing January 2005 record-breaking flooding event. The beginning of January 2005 was characterized by high ETC activity as four ETCs (all with minimum MSLP values below 985 hPa) crossed the Baltic Sea region between 1 and 8 January 2005 (Figure 1). The last one of these four ETCs was Storm Gudrun which caused the highest sea levels in recorded history at practically all coastal locations in Estonia and southern Finland (Averkiev & Klevannyy, 2010), including Pärnu and Helsinki (Figure 2).

The extremely high sea levels on 9 January co-occurred with the SCC3+ period (Figure 2). Particularly for Pärnu and Helsinki, the fingerprints of individual ETCs can be seen in the sea levels. However, the most interesting observation is that instead of each ETC causing a flood of approximately the same intensity, the peaks always rose higher than the previous one. In Pärnu, the first peak was 71 cm, the second 103 cm, the third 115 cm and finally the fourth peak, induced by Storm Gudrun, was 270 cm (Figure 2). A similar increase in storm surge intensity can be seen in Helsinki and Landsort, but not in Kemi.

A potential explanation for amplified flooding during the SCC period is demonstrated in the central panel of Figure 2. A series of sequential ETCs, each following the same trajectory (Figure 1), generated westerly winds

near the Danish Straits, resulting in a rise in the water volume of the Baltic Sea. The background water level component, estimated here with the 8-day running mean, shows a 30 cm rise in Pärnu between 1 and 5 January (Figure 2, central panel). This result highlights the importance of several successive ETCs in significantly raising the water level prior to the arrival of the final storm in the SCC period.

The co-occurrence of SCC and extreme sea levels in January 2005 in the Baltic Sea provides preliminary evidence that SCC may be an important mechanism in the amplification of extreme sea levels. Although Storm Gudrun stands out as a remarkably exceptional meteorological event (Suursaar et al., 2006), with a storm surge that would have potentially achieved record-breaking level even in the absence of prior ETCs, its storm surge was likely further intensified by the cumulative elevated water levels induced by the preceding ETCs.

3.2. Composite Sea Level Around Single Cyclones and Clustering Periods

To understand how the number of ETCs affects the sea level at the tide gauges, the top row of Figure 3 shows a lagged sea level anomaly around all SCC3+, SCC2 and ETC1 onset dates. The day 0 on the *x*-axis of Figures 3a–3d corresponds to the onset date of each SCC period, which in turn is one day before the first ETC in the cluster or, in the case of ETC1, one day before the only ETC. It can be seen that for all tide gauges the clustering of several ETCs leads to systematically higher sea levels on average than a single ETC.

Furthermore, sea levels higher than usual persist for an extended period during SCC3+ periods compared to SCC2 or ETC1 periods. For the ETC1 composite, higher than normal sea levels usually last for a duration of 2–4 days. For the SCC2 composite, such a deviation persists for roughly 20 days; however, for the SCC3+ composite, increased sea levels persist for over 20 days. It should be noted, however, that the solid lines in Figures 3a–3d represent averages over all cases and that sea levels following individual SCC events (shading around the lines) rarely behave as the average. For example, if two short SCC3+ periods occur consecutively within a 20-day period, the 20-day lag in Figures 3a–3d may include the effect of both events. Although Figure 3 only displays four tide gauges, the findings are of a similar nature across four other tide gauges situated within the Baltic Sea (Figure S4 in Supporting Information S1).

There are subtle differences in the composite mean sea level anomalies between the tide gauges. In Kemi (Figure 3a) and Pärnu (Figure 3d), the peaks of ETC1 mean are the highest (16 cm in both), indicating that single ETCs induce typically higher storm surges in Kemi and Pärnu than in Helsinki or Landsort. For SCC3+ mean, the peaks are 31 cm in Kemi, 30 cm in Helsinki, 23 cm in Landsort and 34 cm in Pärnu. In contrast to Helsinki and Landsort, Kemi and Pärnu are located at the end of bays, which may explain the higher importance of individual ETC surges compared to cluster situations, which in turn have a greater impact on the total volume of water in the Baltic Sea. We found that in Helsinki, Landsort and Pärnu, approximately 80% of all SCC3+ events has led to statistically higher sea level than the climatology 6–12 days after the onset date of the SCC period (Figure S5 in Supporting Information S1).

The maximum in the composite mean also tends to occur later the more ETCs there are in the SCC periods. In Landsort (Figure 3c), the maximum occurs on day 2 in ETC1, on day 5 in SCC2 and on day 6 in SCC3+. As Landsort is located in the central Baltic Sea and represents the variation in the total water volume of the Baltic Sea (Lehmann & Post, 2015), the delayed occurrence of maximum sea level corresponding to the increasing number of ETCs is most likely attributed to the gradual filling of the Baltic Sea basin through the cumulative water level contributions of successive ETCs.

It is also worth noting that for many tide gauges, the water level of the SCC3+ time series is slightly higher than that of SCC2 or ETC1 even before day 0. This may be due to autocorrelation of SCC3+ periods, that is, many SCC3+ periods are preceded by an earlier SCC3+ period within the previous 20 days, the effect of which is effectively reflected in the composite mean.

By separating the sea level into short-term (Figure S6 in Supporting Information S1) and weekly-scale (Figure S7 in Supporting Information S1) components, we found that cyclone clustering affects primarily the weekly-scale component. For example, the composite mean in Landsort shows on average 19 cm of higher weekly-scale component during SCC3+ than during ETC1 periods (Figure S7c in Supporting Information S1).

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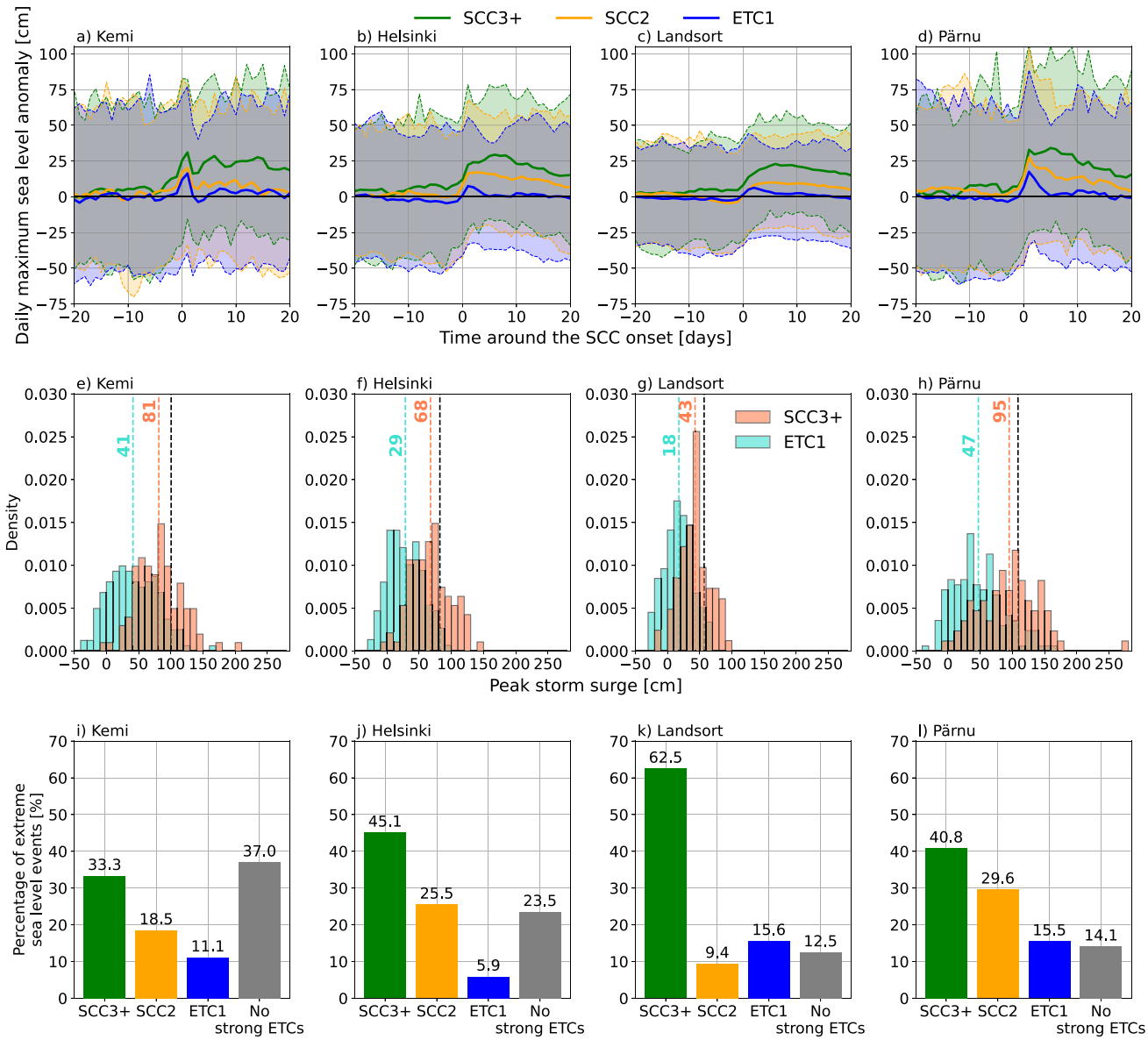

Figure 3. Top row (a–d): composite lagged sea level anomaly centered around serial cyclone clustering (SCC) onsets at Kemi, Helsinki, Landsort, and Pärnu tide gauges. The green line indicates the composite mean of SCC3+ periods, the orange line SCC2 periods, and the blue line ETC1 periods. The shading around the lines presents 5–95 percentile interval of the sea level composite. Middle row (e–h): frequency distributions of daily maximum sea level measured at the tide gauge during SCC3+ (red) and ETC1 periods (blue). The colored lines and values indicate the means of the distributions. Black vertical line show the threshold of extreme sea level. Bottom row (i–l): percentages of extreme sea level events co-occurring with different SCC periods.

3.3. Extreme Sea Level Events During Serial Cyclone Clustering

We compared the frequency distributions of peak storm surges for all SCC3+ and ETC1 periods. These distributions are shown in the middle row of Figure 3 and Figure S4 in Supporting Information S1. Depending on the tide gauge, the mean maximum sea level in SCC3+ periods is 2.0–2.7 times (25–48 cm) higher than in ETC1 periods. For example, in Pärnu (Figure 3h), the peak storm surge during ETC1 situations has a mean of 46 cm, while the clustering of at least three ETCs leads to an average surge of 95 cm.

Figures 3e–3h also shows that it is very rare for the maximum sea level to remain negative during the SCC3+ period. This happened only in February 1986 (Kemi), January 2010 (Helsinki and Landsort), and February 2010 (Pärnu and Landsort). Interestingly, all of these 3 months were exceptionally cold in Finland with a negative

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North Atlantic Oscillation (NAO) index (Osborn, 2011). This suggests that the storm track was shifted southward during these cases, inducing thus more frequently easterly and northerly winds during the passage of the ETCs.

According to the two-sided Kolmogorov-Smirnov test, the SCC3+ and ETC1 distributions (Figure 3, middle row) at all four gauges are statistically different (p-value <0.01) from each other. This provides further evidence that clustering of at least three ETCs leads to higher sea levels than only a single ETC.

In the previous section, we provided evidence that the more ETCs there are in the clustering periods, the higher the sea level typically rises. However, in order to prepare for coastal flooding, it is important to quantify the probability of ESL98s in different cyclone clustering periods. Therefore, we examined all ESL98s from all the tide gauges and determined whether they occurred in SCC3+, SCC2, ETC1 periods or in periods without strong ETCs (Figure 3, bottom row).

The largest fraction, also a clear majority (62.5%) of ESL98s in SCC3+ periods, occurs in Landsort (Figure 3k). In Helsinki and Pärnu, slightly less than half of the ESL98s (45% and 41%, respectively) occurred during SCC3+. In Kemi, most of the ESL98s occur in situations where there are no strong ETCs nearby, although the proportion is quite close to that caused by SCC3+ (Figure 3i).

The blue bars in Figures 3i-3l indicate the proportion of ESL98s where only a single ETC passes the tide gauge. This probability is lowest in Helsinki (5.9%) and highest in Landsort (15.6%). Summing the values of SCC3+ and SCC2 periods, about 70% of all extremely high sea levels elsewhere than in Kemi are associated with the passage of at least two ETCs. Thus, less than a third of historical coastal flooding events have occurred with the passage of only one strong ETC or zero ETCs. The class of no strong ETCs (gray bars in Figures 3i–3l) include situations where no ETCs is located within 700 km of the tide gauge or the ETC is weaker than the median ETC and therefore not captured by our analysis.

We found that the probability of SCC3+ to occur simultaneously with extreme sea levels $P(SCC3+|ESL98)$ was 33%–63% (green bars in Figures 3i–3l). However, it is important to note that the inverse probability $P(ESL98|SCC3+)$ is lower; that extreme sea levels occur with SCC3+ with a smaller percentage. The extreme sea level thresholds correspond to percentile ranks of 73% in Kemi, 71% in Helsinki, 73% in Landsort and 60% in Pärnu in the SCC3+ distributions (black dashed lines Figures 3e–3h). This implies, for example, that 71% of SCC3+ events have not led to extreme sea levels in Helsinki. In other words, 27%–40% of SCC3+ periods have led to ESL98s. For ETC1, these percentages are only 3%–6%, suggesting that the likelihood of ESL98 increases significantly when multiple ETCs occur in a row.

3.4. The Impact of Cyclone Intensity on Sea Level

Despite the fact that most extreme sea levels tend to occur during clustering periods, there is still large case-to-case variability in sea levels within the different SCC groups. This raises the question of whether other characteristics of cyclone clusters, such as ETC intensity, contribute to sea level rise.

Analysis of the average minimum MSLP of each ETC in the cluster, visualized in Figure 4, shows that the strength of ETCs (lower MSLP) indeed correlates relatively strongly with sea level. More specifically, clusters of ETCs or single ETCs with lower MSLP tend to result in higher sea levels. The larger slope of the linear fit for all regions except Kemi in SCC3+ (Figures 4e–4h) compared to ETC1 (Figures 4a and 4b) indicates a larger importance of cyclone strength on the sea level within the cluster than in cases of single ETC. The higher values of the Pearson correlation coefficient for all regions except Kemi increase the statistical validity of these relationships.

These results suggest that, especially within the group of clustered ETCs, stronger ETCs further enhance the risk of high sea levels. In other words, if there is a strong ETC, higher sea levels are more likely in the clustered case than if the ETC occurs in isolation. Other variables, such as a higher number of ETCs within a cluster (shown by the colors of the dots), are also positively correlated with sea level height, however, these relationships are less pronounced.

4. Discussion and Conclusions

In this paper, we have combined objectively tracked ETCs and sea level observations from 43 extended cold seasons and examined how SCC affects the occurrence of extremely high sea levels in the Baltic Sea. The research question of our study was whether high sea levels along the Baltic Sea coasts are typically caused by the passage

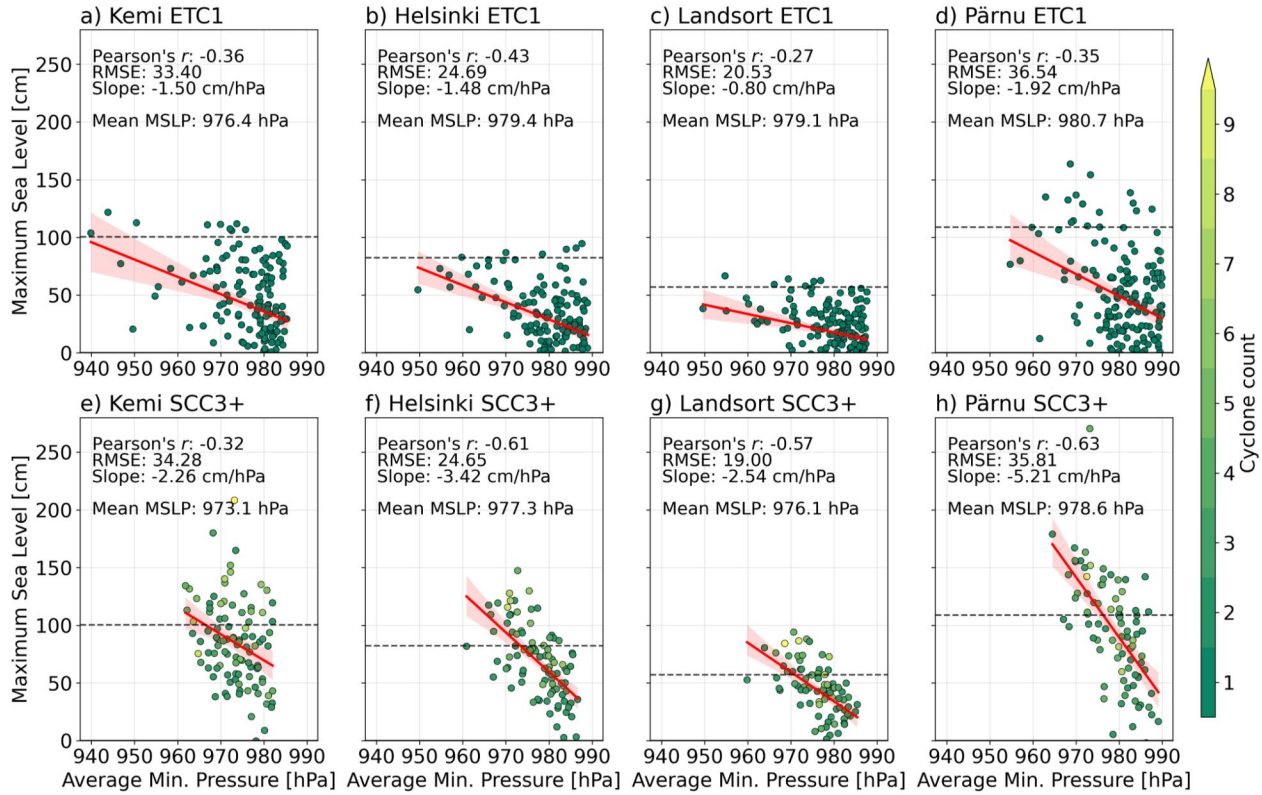

Figure 4. The maximum sea level and average minimum MSLP for all cyclones in the cluster for ETC1 (a–d) and SCC3+ (e–h). The red line shows the linear regression fitted to the data points and the shading represents 95% confidence interval of the fit. Horizontal dashed line marks the threshold of extremely high sea level. The colors of the data points indicate the number of ETCs in the cluster; for ETC1, this is one for all data points. Annotated are Pearson's correlation coefficient, the root mean squared error, the slope of the linear fit, and the average minimum MSLP of the ETCs.

of single ETCs or whether several successive ETCs are required. According to our results, almost half of all extreme sea level events (ESL98s) are associated with the clustering of at least three ETCs, and only 10% of ESL98s are caused by single ETCs (Figures 3i-3l).

Building on previous research attributing increased sea levels to atmospheric circulation patterns (Andersson, 2002; Bednorz & Tomczyk, 2021) or prevailing westerly winds (Johansson & Kahma, 2016; Lehmann & Post, 2015), our investigation introduces a novel perspective by focusing on the clustering of multiple ETCs. While it is well known that ETC activity and large-scale atmospheric circulation patterns are linked (Sepp, 2009), previous studies have not investigated the sea level variations from the standpoint of ETC clustering.

The main novelty of this study not accounted for in the previous research comes from the large sample size of ETCs. We tracked all strong ETCs over the last 43 cold seasons, resulting in a total of 750–861 analyzed ETCs per tide gauge (in total 1,349 different ETCs). This allowed us to robustly quantify the impact of cyclone clustering on extremely high sea levels. Previous research has only focused on those ETCs that caused the most extreme storm surges (Post & Kõuts, 2014; Suursaar et al., 2018); however, we consider all strong ETCs, regardless of how much flooding they caused.

It is important to stress that the clustering of several ETCs does not always lead to ESL98s. For example, in Landsort, we found that 27% of the SCC3+ periods have induced extremely high sea levels, which means that 73% of all SCC3+ periods did not result in extremely high sea levels (Figure 3g). An important factor that modulates the water level height within the clustering is the intensity of the ETCs. We found that more intense ETCs tend to further enhance the risk of high sea levels, specifically if stronger ETCs occur in a cluster (Figure 4).

One limitation of this study is that we did not consider the track orientation of the ETCs. For example, on 9 January 2005, the highest storm surges were recorded at tide gauges south of the storm tracks, while no extreme sea levels were recorded at Kemi (Figures 1 and 2). Thus, a cluster situation where the ETCs pass to the south of

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the tide gauge is probably more likely to produce low sea levels because the wind at the tide gauge is blowing from the east or north. Indeed, the lowest sea levels in SCC3+ periods were associated with particularly cold winters (not shown), when the storm track was probably located further south than normal due to negative NAO.

In summary, we found that high sea level extremes in the Baltic Sea, especially along coastlines in the central part of the sea, are typically associated with not one, but multiple passing ETCs within a week. Previous studies have emphasized that destructive storm surges, such as the one in January 2005, require high initial water volume in the Baltic Sea to occur (Pellikka et al., 2018; Weisse et al., 2021; Wolski & Wiśniewski, 2020). Our results do not contradict this, but we found that this pre-existing high initial water volume is often a consequence of the preceding ETCs. These antecedent ETCs increase the water volume in the Baltic Sea by forcing the water through the Danish Strait, thus "preconditioning" the water level for the actual storm that causes the highest surge.

Acronyms

ESL98	Extreme sea level event
ETC	Extratropical cyclone
ETC1	Only 1 ETC in a 7-day period
MSLP	Mean sea level pressure
NAO	North Atlantic Oscillation
ONDJFM	October-March
SCC	Serial cyclone clustering
SCC2	Serial cyclone clustering with 2 ETCs in a 7-day period
SCC3+	Serial cyclone clustering with at least 3 ETCs in a 7-day period

Data Availability Statement

Tide gauge observations from Finland are available through Finnish Meteorological Institute's open data portal at https://en.ilmatieteenlaitos.fi/download-observations. Tide gauge observations from Sweden are available from Swedish Meteorological and Hydrological Institute webpage at https://www.smhi.se/data/oceanografi/ladda-ner-oceanografiska-observationer. ERA5 reanalysis data is available from Copernicus Climate Data Store in Hersbach et al. (2023).

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