Impact and response of storm Babet from a Swedish perspective

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Summary

In October 2023, storm Babet led to the most severe erosion in decades along the Swedish South coast. In this study we approach the affected coastal landscape as a coupled social-ecological system where environmental components (e.g. geology, bathymetry, waves) interact with social components (e.g. infrastructure, management, economic activities) to influence the outcome of an extreme event. We use observational data to analyse the meteorological and oceanographic conditions prior to and during Babet, and numerical modelling to create hindcast wave data covering 1959–2023. To understand Babet relative to other events we compare sea levels and waves during Babet to normal conditions and other extremes, especially focusing on the joint occurrence of high sea levels and large waves. Using LiDAR data, we quantify the morphological changes between 2019 and 2023 along approximately 220 km of coast. By interviewing stakeholders from municipal, regional and national level and from private and public sector, we analyse how Babet impacted coastal societies and how key authorities responded to the event. We also analyse how relevant stakeholders received, understood and acted on weather warnings issued by authorities.

Our findings show Babet to be an unusual but not unprecedented event. The high sea levels were caused by westerly winds pushing large amounts of water in to the Baltic basin prior to the event and wind setup during the event. We show the combination of high sea levels and large onshore waves seen during Babet to be unusual, explaining why Babet was more impactful than other events of similar sea levels. Weather warnings were available from October 17th, but many struggled to understand the combined risks associated to forecast high sea levels and easterly winds. Affected municipalities were differently organized before and during Babet, but mostly managed to deal with the event well. The larger organisational challenges were identified in the aftermath due to increased workloads and new types of tasks. As for the morphological changes they are in places significant. The total erosion is close to 1.3 million m^3 and the total accretion close to 760 000 m^3, resulting in a net loss of 510 000 m^3. Expressed as normalized values in the longshore direction changes range from erosion surpassing 150 m^3/m to accretion reaching almost 50 m^3/m. We identify parts along the coast where we believe most of the erosion between 2019 and 2023 stems from Babet, but also stretches where changes can only partially be attributed to Babet. We see that societal impacts during Babet were dictated more by coastal assets' type and proximity to the sea then by the magnitude of morphological change.

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Keywords

Erosion, morphological evolution, storm surge, LiDAR, wave modelling, weather warnings, crisis management, Scania, Baltic Sea

Zusammenfassung

Im Oktober 2023 führte der Sturm Babet an der schwedischen Südküste zur stärksten Erosion seit Jahrzehnten. In dieser Studie betrachten wir die betroffene Küstenlandschaft als ein gekoppeltes sozial-ökologisches System, in dem Umweltkomponenten (z. B. Geologie, Bathymetrie, Wellen) mit sozialen Komponenten (z. B. Infrastruktur, Management, wirtschaftliche Aktivitäten) zusammenwirken, um die Auswirkungen eines Extremereignisses zu bestimmen.

Wir verwenden Beobachtungsdaten, um die meteorologischen und ozeanografischen Bedingungen vor und während Babet zu analysieren, und numerische Modellierung zur Erstellung von Hindcast-Daten für den Zeitraum 1959-2023.

Um Babet im Verhältnis zu anderen Ereignissen zu verstehen, vergleichen wir Wasserstände und Seegang während Babet mit normalen Bedingungen und mit anderen Extremereignissen, wobei wir uns insbesondere auf das zeitgleiche Auftreten von hohen Wasserständen und großen Wellen fokussieren. Mithilfe von LiDAR-Daten quantifizieren wir die morphologischen Veränderungen zwischen 2019 und 2023 entlang eines Küstenabschnitts von etwa 220 km Länge. Durch die Befragung von Stakeholdern auf kommunaler, regionaler und nationaler Ebene sowie aus dem privaten und öffentlichen Sektor analysieren wir die Bedeutung von Babet für die Gesellschaft im küstennahen Raum, und wie die maßgebenden Behörden auf das Ereignis reagierten. Wir analysieren auch, wie die relevanten Interessengruppen die von den Behörden herausgegebenen Wetterwarnungen aufgenommen, verstanden und darauf reagiert haben.

Unsere Ergebnisse zeigen, dass Babet ein ungewöhnliches, aber nicht beispielloses Ereignis war. Die hohen Wasserstände wurden durch Westwinde verursacht, die vor dem Ereignis große Wassermengen in das Ostseebecken drückten, sowie durch Windstau während des Ereignisses. Wir zeigen, dass die Kombination aus hohen Wasserständen und großen auflandigen Wellen während Babet ungewöhnlich war, was erklärt, warum Babet größere Auswirkungen hatte als andere Ereignisse mit ähnlichen Wasserständen. Wetterwarnungen wurden ab dem 17. Oktober ausgegeben, aber viele Empfänger hatten Schwierigkeiten, die kombinierten Risiken zu verstehen, die mit vorhergesagten hohen Wasserständen und Ostwinden verbunden waren. Die betroffenen Gemeinden waren vor und während des Babet-Ereignisses unterschiedlich organisiert, konnten das Ereignis aber meist gut bewältigen. Die größeren organisatorischen Herausforderungen wurden im Anschluss an das Ereignis aufgrund der erhöhten Arbeitsbelastung und neuen Arten von Aufgaben festgestellt. Was die morphologischen Veränderungen betrifft, so sind sie zum Teil erheblich. Die Gesamterosion beläuft sich auf fast 1,3 Mio. m³ und die Gesamtdeposition auf fast 760 000 m³, was zu einem Nettoverlust von 510 000 m³ führt. Ausgedrückt als normalisierte Werte in Richtung entlang der Küste reichen die Veränderungen von einer Erosion von mehr als 150 m³/m bis zu einer Deposition von bis zu 50 m³/m. Wir identifizieren Abschnitte entlang der Küste, an denen wir annehmen, dass der größte Teil der Erosion zwischen 2019 und 2023 von Babet herrührt, aber auch Abschnitte, in denen die Veränderungen nur teilweise auf Babet zurückzuführen sind. Wir sehen, dass die gesellschaftlichen Auswirkungen während Babet eher durch den Typ der Küsten-Assets und deren Nähe zum Meer als durch das Ausmaß der morphologischen Veränderungen bestimmt wurden.

Schlagwörter

Erosion, morphologische Entwicklung, Sturmflut, LiDAR, Wellenmodellierung, Wetterwarnung, Krisenmanagement, Scania, Ostsee

1 Introduction

The Swedish Geotechnical Institute (SGI) and the Swedish Civil Contingencies Agency (MSB) have identified ten Swedish regions at particular risk of negative impacts from floods, landslides or erosion as the climate changes (SGI and MSB 2021). The Swedish South coast is one such region. Parts of the coast already suffer from erosion in today's climate (Malmberg-Persson et al. 2016), and due to a high presence of coastal settlements, erodible soils and low-lying coastal landscapes, flood and erosion risks are expected to multiply manifold with sea level rise (SGI and MSB 2021).

The South coast of Sweden undergoes both morphological (Malmberg-Persson et al. 2016) and societal changes (Blomberg 2001). Many simpler summer houses have been converted to all-year residential homes, leading to a more permanent human presence and increased investments in societal services along the coast. Such societal growth can affect the coastal morphology, just as the morphological evolution can affect the growth or decline of coastal societies.

In October 2023, storm Babet impacted the coast of Sweden at a scale not seen for decades. The storm impacted the physical landscape through erosion and accretion, but it also impacted societies along the coast. It highlighted coastal vulnerabilities and tested stakeholders' ability to prepare for, and deal with the aftermath of, the event under current management systems and distribution of responsibilities. In this study, we adopt a multidisciplinary approach to analysing storm Babet and its impacts from a Swedish perspective. We approach the coastal landscape as a coupled social-ecological system (Walker et al. 2004) where environmental components (e.g. geology, bathymetry or waves) interact with social components (e.g. infrastructure, economic activities or management) to influence the outcome of an extreme event (Malvarez et al. 2021). We ask what the meteorological, oceanographic and hydrodynamic conditions were prior to and during Babet, how they compare to normal conditions and other extremes, how Babet impacted societies along the coast and how key authorities responded to the event. We also investigate the morphological evolution between 2019 and 2023 and how the severity of the societal impacts seen after Babet correspond to the magnitude of morphological change 2019–2023.

2 Study area

In Sweden, storm Babet mainly impacted the South and East coasts of Scania County (see Figure 1A), Sweden's southernmost and third largest region with a population of approximately 1.4 million. It consists of 33 municipalities, of which six were foremost affected by Babet and are the focus of this study; Vellinge, Trelleborg, Skurup, Ystad, Simrishamn and Kristianstad (see Figure 1B). The coastline is complex and irregular in shape. Its geological composition has been surveyed from land and from sea by the Swedish Geological Survey (SGU), result shown in Figure 2A (Malmberg-Persson et al. 2016). The survey shows sand and gravel beaches to dominate the area, followed by glacial till deposits with boulders and eroding bluffs. There are also sections of hard material like cobbles or bedrock headlands, especially to the South-east. Long-term morphological evolution was studied by (Malmberg-Persson et al. 2016) by analysing aerial photos from the mid-20th century and comparing to 2010 (see Figure 2B). In (Stelzer and Philipson 2023) the coastline evolution between 2015 and 2022 was studied in eastern Ystad municipality using Sentinel 2 satellite scenes. While the long-term morphological evolution is generally slow in the study area there are exception. East of Löderup Strandbad the coast has eroded at rates of up to 5–10 m/year (Malmberg-Persson et al. 2016, Stelzer and Philipson 2023) which is exceptionally high for Swedish conditions. Further East a pivoting point between erosion and accretion can be seen at Sandhammaren (see Figure 2B), and accretion rates of 3–5 m/year or more are not uncommon (Malmberg-Persson et al. 2016, Stelzer and Philipson 2023).

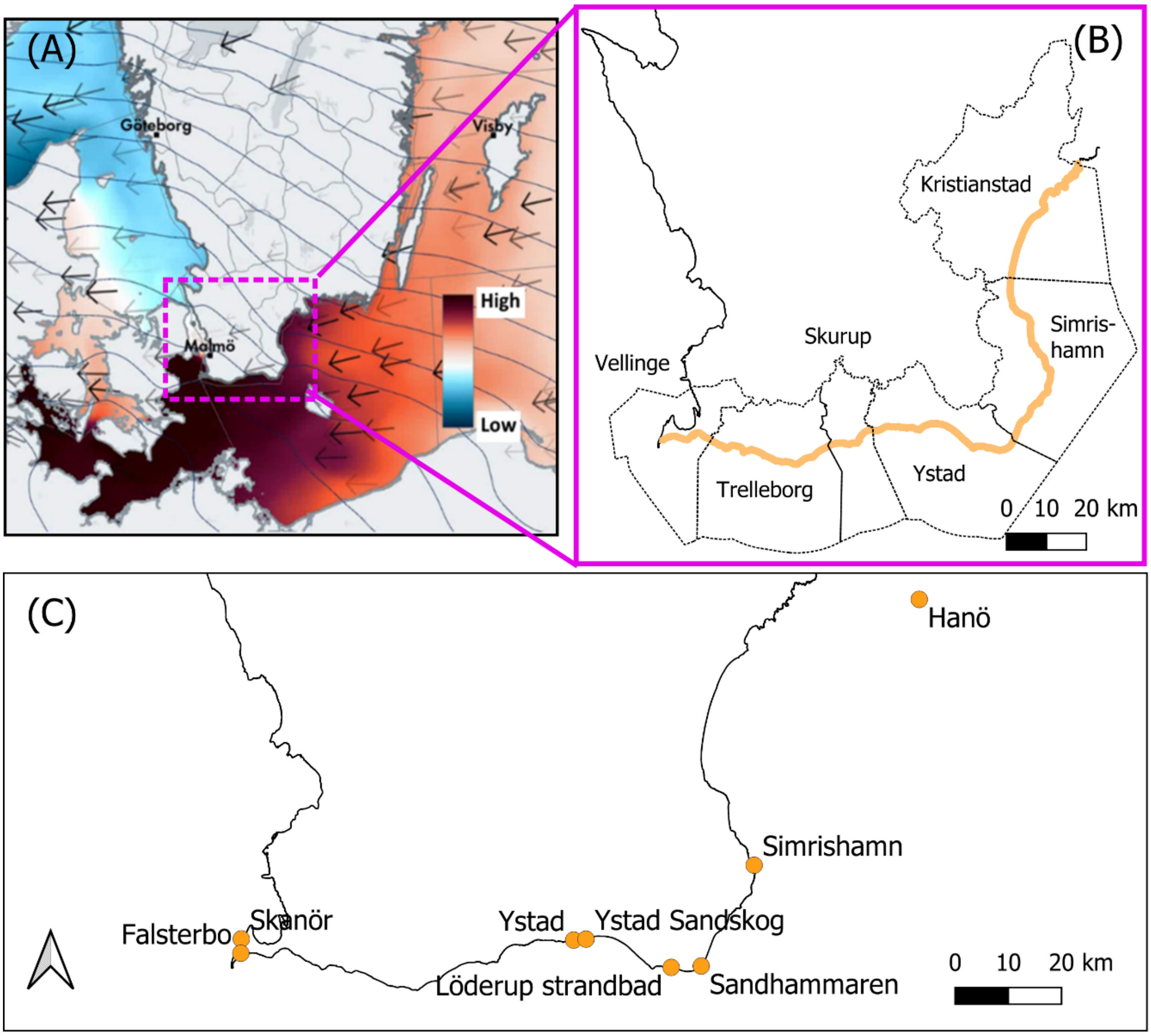

Figure 1: (A) Wind direction (arrows) and sea levels (colors) during night towards October 21st, showing the coast of the study area to be the most affected in Sweden by Babet. (B) The coastline included in the study (orange) along with borders and names of affected municipalities. (C) Locations of interest that are referenced in the study.

Active coastal management is uncommon and mostly limited to hard structures. A noteworthy exception is Ystad municipality who after decades of unsuccessful attempts to combat erosion using hard structures started a nourishment program in 2011. Since then, Ystad Sandskog and Löderups Strandbad (see Figure 1C) have been nourished on four occasions

(2011, 2014, 2017, 2020). The total volumes of added sand amounts to 245 000 m³ for Ystad Sandskog and 91 000 m³ for Löderups Strandbad. These are the only recurring beach nourishments operations of scale in Sweden, but at least two other municipalities (Trelleborg and Kristianstad) are planning nourishments in the coming years.

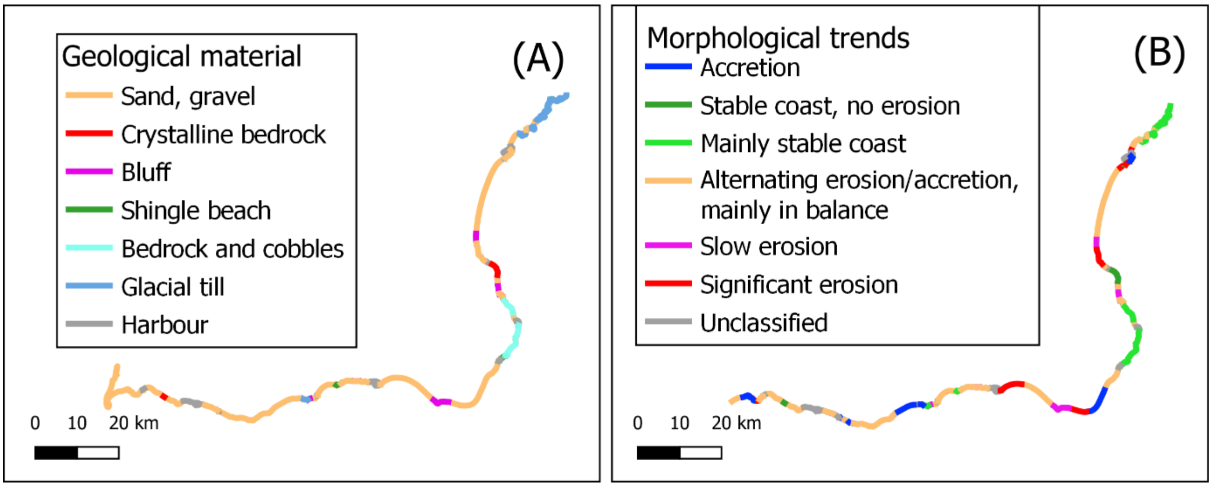

Figure 2: (A) The material along the coast is dominated by sand and gravel, followed by glacial till and eroding bluffs. (B) Morphological trends, based on analysis of aerial photos between mid-20th century and 2010. Both (A) and (B) are adapted from (Malmberg-Persson et al. 2016).

3 Governance and crises management in Sweden

Municipalities in Sweden are self-governing units with an elected council. All municipalities have equal obligations towards their inhabitants, but factors like size, demography, taxpayer collective and population density vary between municipalities. Municipalities' de facto capacity to engage with issues such as coastal management and climate change adaptation varies in terms of human and financial resources, leading to differences in how and to what extent municipalities organize themselves (Storbjörk and Uggla 2015).

The Swedish Planning and Building Act gives municipalities extensive power to decide how land and water within their jurisdiction should be used. Municipalities must ensure that new development does not take place in areas exposed to natural hazards, but do not hold the same responsibility to protect existing buildings. This responsibility lies with the individual property owner.

The regional governance relevant to this study is the County Administrative Board of Scania (CAB), a non-elected extension of the government. CAB is responsible for coordinating crisis management within Scania and plays a role in legal permitting processes related to water or coastal management.

Managing extreme weather events falls under the Swedish system of crisis management, hinged on the principle that an extraordinary event should as far as possible be managed locally (Law 2006:544). There are three geographical levels of responsibility: local, regional and national. Municipalities are responsible at the local level, CAB at the regional level and the Swedish Civil Contingencies Agency at the national level.

In cases of extreme weather events, the Swedish Meteorological and Hydrological Institute (SMHI) play a critical role to the crisis management system as they issue weather forecasts and weather warnings. Since 2021, the Swedish warning system is impact based, meaning warnings are based on the potential level of impact that an expected weather event may cause. Warning thresholds (i.e. weather intensity such as expected wind speed or sea level) and interacting risk factors are adapted to regional conditions and prerequisites. Most types of warnings are issued with integrated collaboration, meaning that when forecast models indicate that a regional threshold might be surpassed, SMHI initiates a collaboration chain and decision-making process involving relevant regional and local stakeholders. Based on the forecast and pre-existing thresholds, SMHI will draft a proposal for a weather warning and discuss it with the CAB of the relevant region. If needed CAB will initiate further cooperation at local levels with municipalities and other relevant stakeholders, and report back to SMHI. Based on the input received through this process, SMHI will finalize and release a weather warning. This process commonly takes a few hours from warning proposal to issued warning but factors such as the severity of the weather situation and the foresight with which the warnings have been proposed play a role for the urgency of the process. Most collaboration is conducted during office hours, but the operation is maintained 24/7 if necessary. When local stakeholders have been informed of an upcoming weather event, they should implement necessary action at a local level. The timescale of this varies depending on the type of action required (e.g. dissemination of information to residents or physical barriers) and the resources and preparedness at the relevant municipality. The purpose of the collaboration is to make the weather warning system as precise as possible by combining forecasts with a contextualised understanding of potential impacts. Warnings are designated as yellow, orange or red according to the expected level of consequence, with red being the most serious.

It is up to the municipalities to interpret if an event should be considered extraordinary, and if so whether to enter an elevated state of emergency preparedness. According to (Becker and Bynander 2018), it is unusual that an event is formally declared extraordinary.

4 Available data and methodology

Elevation data, sea level data and wind data are collected regularly by state agencies, but they do not feed into any monitoring aimed at coastal morphology. Sporadic measurement campaigns, mainly transect measurements, have been done by municipalities, researchers, consultants or others, but they have largely been project-specific and uncoordinated.

4.1 Meteorological, oceanographic and hydrodynamic data

4.1.1 Wind and sea level observations

The meteorological and oceanographic conditions prior to and during Babet are investigated using SMHI wind and sea level observational data. Sea level data is obtained from three SMHI tide gauges within the study area; Skanör, Ystad and Simrishamn (see Figure 3). The operational period of each gauge is presented in Table 1, Sect. 5.1, along with the station's max recorded sea level and the max recorded sea level during Babet. Figure 6A, Sect. 5.1, shows observed sea levels between October 12th and 24th.

Wind observational data including wind speed, gust wind speed and wind direction is available at several locations, e.g. close to the tide gauges in Skanör or Simrishamn. In spite of this, wind station Hanö located in the North-east of the study area (see Figure 3) is used as it is deemed more representative of the general conditions leading to wind setup and wave generation (see Sect. 5.1 for more details). Figure 6B, Sect. 5.1, shows observed wind data at Hanö between October 12th and 24th. By comparing wind data to sea levels, we investigate how wind patterns influenced the sea levels prior to and during Babet.

To investigate if Babet is an outlier event, sea levels during Babet are compared to other events from the tide gauge records. To further understand Babet relative to other events, we compare the joint occurrence of high waves and high sea levels seen during Babet to the joint occurrence of these factors during other events by plotting observational sea level data against hindcast wave data (see Sect. 4.1.2). We also compare the simulated wave conditions during Babet to the simulated wave conditions during the 1872 November storm.

4.1.2 Simulated wave data

There are no operating wave buoys in the study area, but wave data simulated using a SWAN (Booij et al. 1999) regional hindcast wave model is available, initially formulated and validated in a study by (Adell et al. 2023). The model is forced with wind data from ERA5 global reanalysis dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al. 2020). The existing hindcast data covers the period 1959–2021. It has been calibrated and validated against wave observations in the Baltic Sea and indicate robust results for both offshore and nearshore performance (Adell et al. 2023). The model uses an unstructured grid. For layout and bathymetry, see Figure 3. Simulated wave conditions include significant wave height (H_s), peak wave period (T_p) and wave direction (θ). The same model configuration has been used in (Sukchaiwan et al. 2024) to simulate wave conditions during the 1872 November storm, using reconstructed wind conditions from (Rosenhangen and Bork 2009) as forcing.

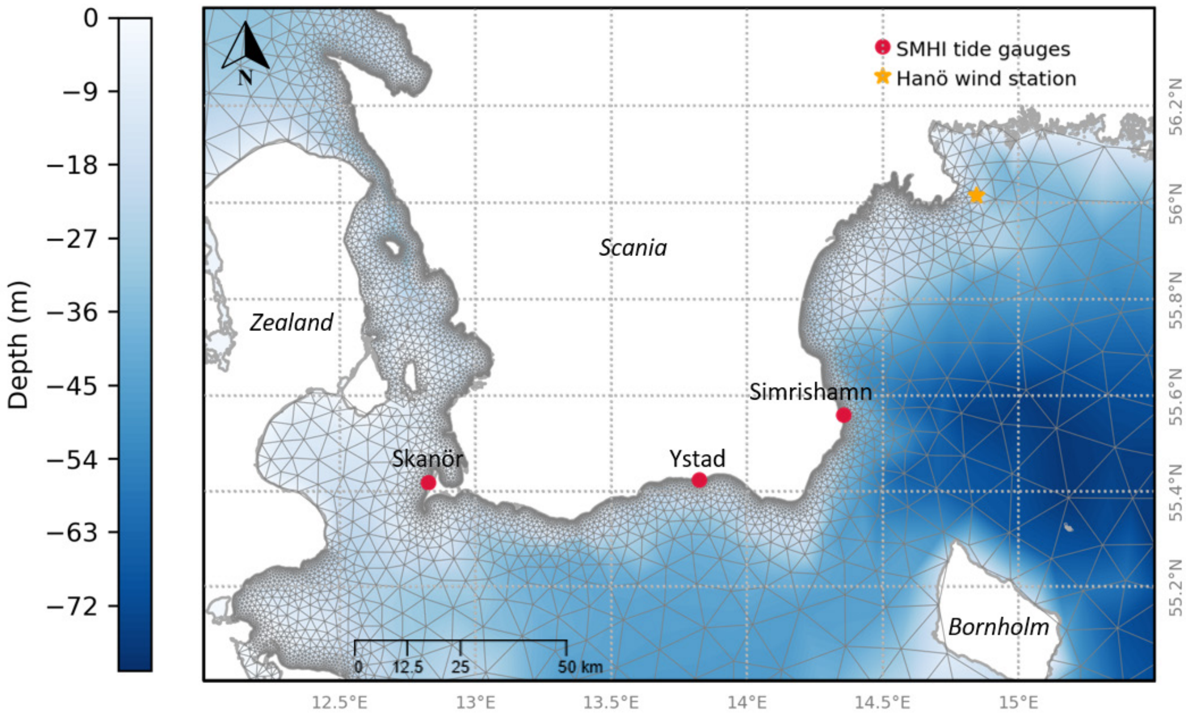

Figure 3 Setup of the SWAN regional hindcast model, showing the layout of the unstructured model grid and the bathymetry for the study area. The locations of tide gauges operated by SMHI are indicated with red points and the location of Hanö wind station is indicated with the orange star.

In this study we produce new hindcast wave data through a similar modelling procedure, using the same model setup as (Adell et al. 2023), but with input data extended to December 2023 to include Babet. This renders a hindcast wave data set covering 1959–2023. The wave conditions during Babet are compared to the overall wave conditions during 1959–2023 and to the 1872 November storm at three locations close to SMHI tide gauge stations. Wave conditions during Babet are also compared to coastal morphological evolutions seen between 2019 and 2023 (see Sect. 5.4) to qualitatively assess Babet's contribution to the changes between 2019 and 2023.

4.2 Elevation data

4.2.1 Digital terrain models (DTM)

There are high-resolution (1x1 m) digital terrain models available from February 2019 (DTM_{2019}) and December 2023 (DTM_{2023}), based on LiDAR data from the Swedish Land Survey. Subtracting DTM_{2019} from DTM_{2023} gives a difference raster ($DTM_{2023-2019}$) showing changes in elevation in every raster cell between 2019 and 2023 (see Figure 4A). By multiplying the elevational change of a raster cell by its area, we obtain the volumetric change of the cell. The cell area is 1 m^2, so the elevational change per cell equals the volumetric change per cell. To normalise the data in the longshore direction, we split the coast into 100 m long segments by introducing equidistant transects perpendicular to the coast (see Figure 4A). Next, we introduce a boundary to limit the landward extension of the analysis to areas exhibiting actual elevational change between 2019 and 2023, and a seaward boundary to exclude water (see Figure 4A). Using the transects and boundary lines we create polygons of varying cross-sectional width but equal longshore length (see Figure 4B), and use the polygons to summarise raster cell values within each polygon. The sum of all cell values within a polygon equals the volumetric change within that polygon. We summarise negative, positive and all raster values separately to separate total erosion, total accretion and net volumetric change within each polygon. We divide the obtained volumes by the longshore length of each polygon, i.e. 100 m, to express erosion, accretion and net volumetric changes between 2019 and 2023 as a normalized m^3/m value in the longshore direction (see Figure 4C). The normalized values allow analysis along hundreds of kilometres of coast, while still utilising all the information in the underlaying dataset (see Figure 4D).

The landward extent of areas experiencing change in elevation between 2019 and 2023 is generally clear in $DTM_{2023-2019}$ (see Figure 4A), and coincides with a clear and sharp crest line in DTM_{2023}. As our landward boundary we use a manual digitization of crest lines from DTM_{2023}, following a methodology described in (Tremasova 2024).

The seaward boundary used to exclude water from $DTM_{2023-2019}$ is a national water polygon supplied by the Swedish Land Survey. The polygon does not mimic conditions during any specific LiDAR scan, it is a generalized water line over time, so if sea levels are elevated during a LiDAR scan sea water can extend further inland than the polygon. During the 2023 scan sea levels where elevated 20–40 cm above MSL. This creates some risk of false accretion since water surfaces not excluded by the water polygon will be interpreted as increased terrain, i.e. accretion. Methods of identifying water directly from the LiDAR or DTM data were tested, e.g. slope or aspect analysis of terrain data or intensity analysis of LiDAR data. At first glance all methods seemed promising, but in the end the amount of data noise led the automated processes to generate greater errors than utilizing the Land Survey's polygon. Results from slope, aspect and intensity analysis were still used to manually cross-check the water polygon's coverage at several locations along the coast to qualitatively understand the risk of false accretion in the results. The overall effect of false accretion is deemed small but not negligible, and most pronounced along the East coast.

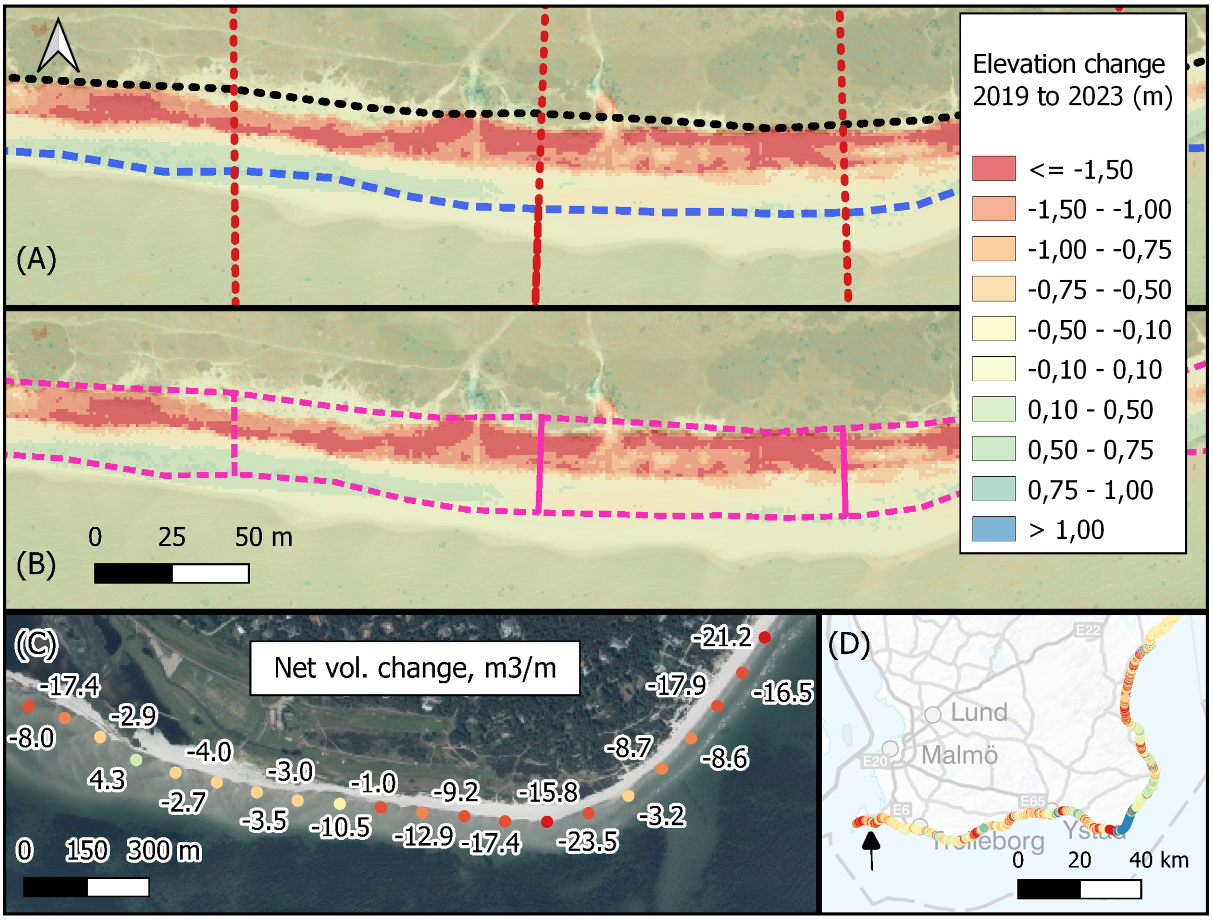

Figure 4: (A) Raster showing change in elevation per raster cell. Black line – crest line, blue line – waterline, red lines – transects every 100 m, perpendicular to the coastline. (B) Crest, water and transect lines merged to polygons for summarizing raster values. (C) Normalized net volumetric change presented as m^3/m in the longshore direction. (D) Same information as (C), but presented at regional scale. Arrow shows location of (A), (B) and (C).

4.2.2 GNSS-GPS (transect measurements)

Terrain transect measurements can show the morphological evolution of a coast, especially if done consecutively along the same transect. There are some transects measurements within the study area, both pre- and post-Babet, collected by municipalities, academia, state or private sector using high precision GNSS-GPS (see Figure 5). The data is from 2021, 2022 and 2023 (pre- and post-Babet). The measurements do not cover a sufficient portion of the coast for a regional analysis of morphological change, but they supplement the DTM analysis by offering local insight into the morphological evolution between 2021 and 2023. The measurements are used as part of the qualitative analysis of Babet's contributing to the morphological changes observed between 2019 and 2023.

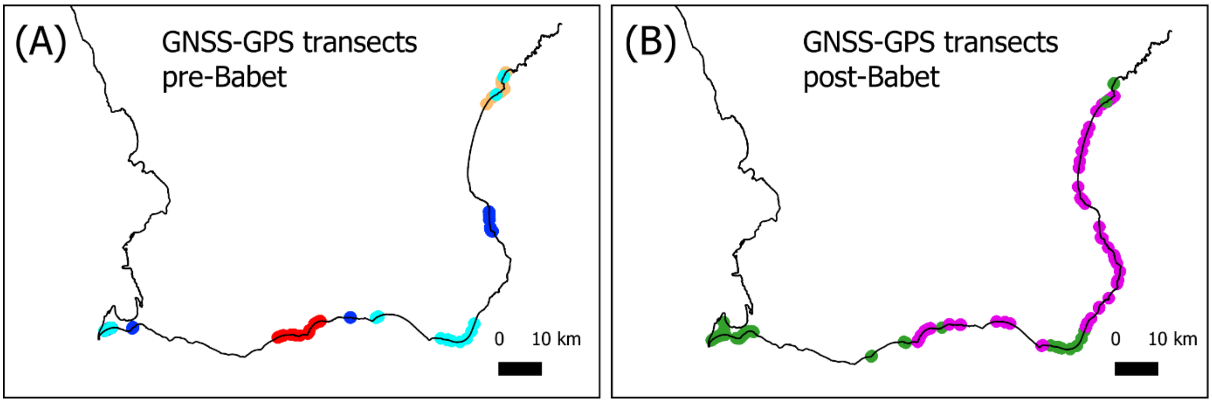

Figure 5: A) GNSS-GPS transect measurements available pre-Babet (red=2021, orange=2022, blue=2023, cyan=Oct 2023, pre-Babet. Sometimes there are measurements from multiple years in the same area, this cannot be seen due to the scale). (B) GNSS-GPS measurements post-Babet (magenta=collected by SGI, green=collected by other parties).

4.3 Societal impact and response

To capture the relevant authorities' response to Babet, along with main damages and lessons learnt, 22 semi-structured interviews were conducted. All the interviews were conducted over Zoom between April and July 2024 and lasted between 35 and 70 minutes. Two informants were interviewed at the same time in three interviews. The interviews were based on a dynamic interview guide encompassing themes including previous experiences of extreme coastal storms and erosion, existing routines, plans and strategies related to crisis management and climate adaptation, preparations and actions before, during and after Babet, and their overall view of lessons learnt from Babet.

Relevant informants were first identified through the network "Regional coastal cooperation" with the aim to include informants from the affected municipalities, CAB Scania, the Swedish Transport Administration (STA) and SMHI. Additional informants were located through a snowballing approach, where one informant recommends additional people to interview. The roles and titles of the municipal informants ranged from head of municipal administrations, climate and environmental strategists to more technical and operative roles. The interviews were recorded through detailed note taken and imported and analysed in NVivo.

5 Results

5.1 Sea levels and winds prior to and during Babet

Figure 6A and B show sea levels and wind measurements prior to, during and after Babet. In the time series it is possible to identify two key characteristics 1) the sea level is elevated in the days before Babet and 2) the further increase in sea level during Babet corresponds to a shift from westerly to easterly winds followed by a build-up of easterly wind speeds.

The first point is a consequence of dense low-pressure traffic during the first haft of October leading to sustained and predominantly South-westerly winds pushing large volumes of water to the Baltic Sea through Öresund. Figure 7A shows outflow (negative inflow) of water from the Baltic Sea through Öresund to be the norm during 2023, but during the first half of October the flow direction is reversed and an accumulated inflow of approximately 20 km³ can be seen (see Figure 7B). The large inflow of water led to increased sea levels throughout the study area.

Regarding the second point, the increase in sea level starting on the 18th coincides with westerly winds decreasing in speed, allowing water previously pushed to the East of the basin to flow back towards the West. As the wind shifts rapidly from West to East and increases in speed during the 18th, the semi-enclosed nature of the basin along with the unusually large volume of water in the Baltic Sea caused significant wind setup in the study area. The dips in sea levels around the 12th and 15th are related to westerly winds first pushing water from the West to the East, lowering levels in the western Baltic Sea, and water then running back and elevating sea levels as the westerly wind speeds decrease.

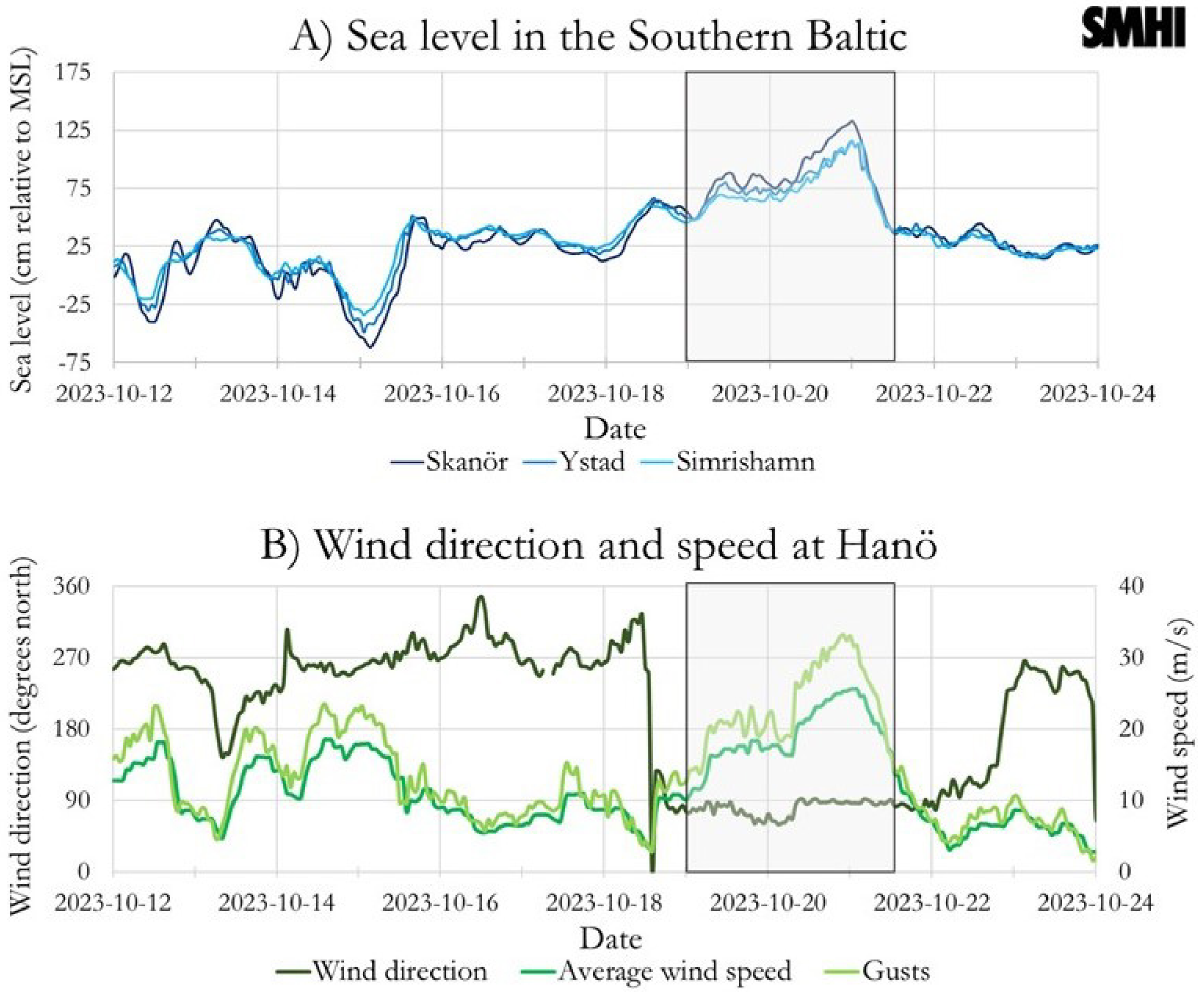

Figure 6: (A) Observed sea levels in the study area, note the increased sea levels in the days before Babet. (B) Wind speed and wind direction at Hanö. Note how the increased sea levels during Babet coincide with a sharp turn in wind direction. This is due to wind setup caused by easterly winds.

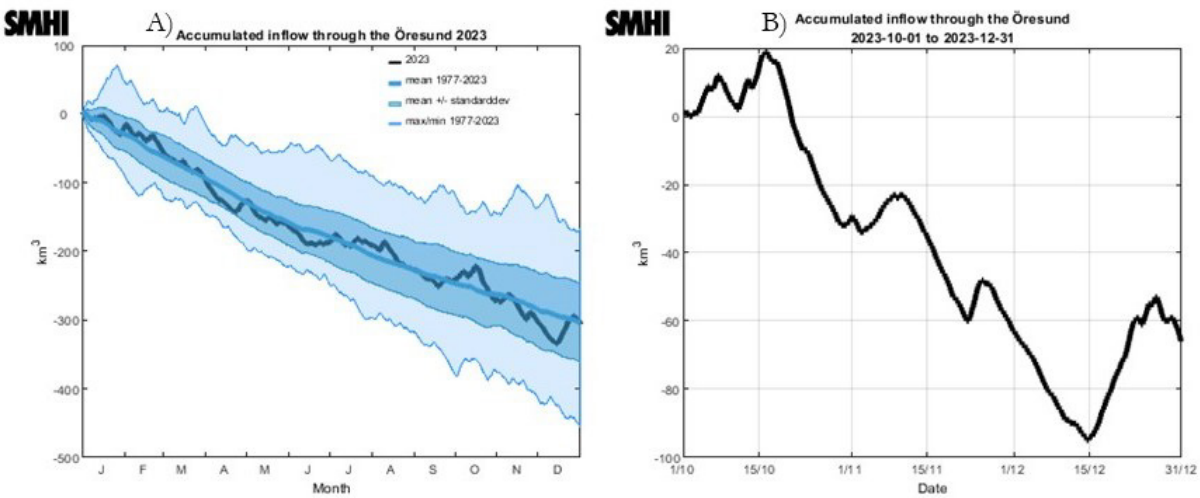

Figure 7: (A) Accumulated inflow through the Sound during 2023 (black line), mean and max/min for the period 1977–2023 (different shades of blue). (B) Accumulated inflow through the Sound 2023-10-01 to 2023-12-31, showing an accumulated inflow of 20 km^3 prior to Babet.

5.2 Waves during Babet

Figure 8 shows simulated significant wave height (*Hs*) at the peak of the event, white arrows show wave directions. Waves were higher along the East coast, especially in the South-east around Simrishamn (location c), where *Hs* reached >6 m offshore with directly incident wave attack. The South coast was more sheltered than the East, but still experienced *Hs* in the order of 2–3 m. Sections of the South coast that are South-east facing were hit more head-on by waves compared to sections that are South-west facing (see Figure 8).

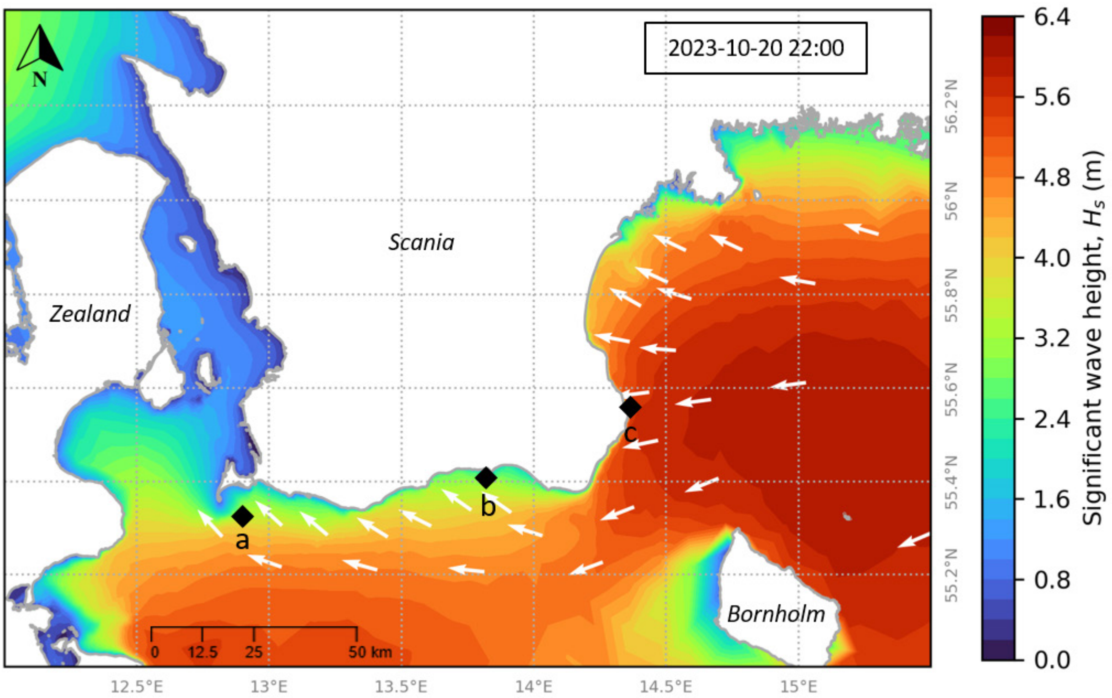

Figure 8: Map showing the simulated significant wave height during the storm peak, the arrows represent wave direction. Locations a, b and c correspond to locations at approximately 10 m depth where time series of wave conditions is extracted from the model and approximately correspond to locations of the tide gauges.

5.3 Babet compared to other events

Table 1 shows data from the SMHI tide gauges in the study area. The table shows that sea levels during Babet were high but not extreme compared to other recorded events. An event in January 2017 led to similar or higher levels at Skanör and Simrishamn, and at Ystad the New Year's Eve storm of 1904 led to considerably higher levels, 167 cm relative MSL compared to 121 cm relative MSL for Babet.

Table 1: Tide gauge records available within the study area, including operational period, maximum recorded level and maximum level recorded during Babet. The stations are operated by SMHI and data is available open-access at www.smhi.se/data.

Station	Operational period	Max recorded level *	Max level* Babet
Skanör	1992 – ongoing	154 (2017-01-04)	135
Ystad	1886 – 1987 and 2014 – ongoing	167 (1904-12-31)	121
Simrishamn	1982 – ongoing	126 (2023-10-21)**	126

* cm, relative to mean sea level, MSL
** max level prior to Babet was 121 cm, relative MSL, 2017-01-04

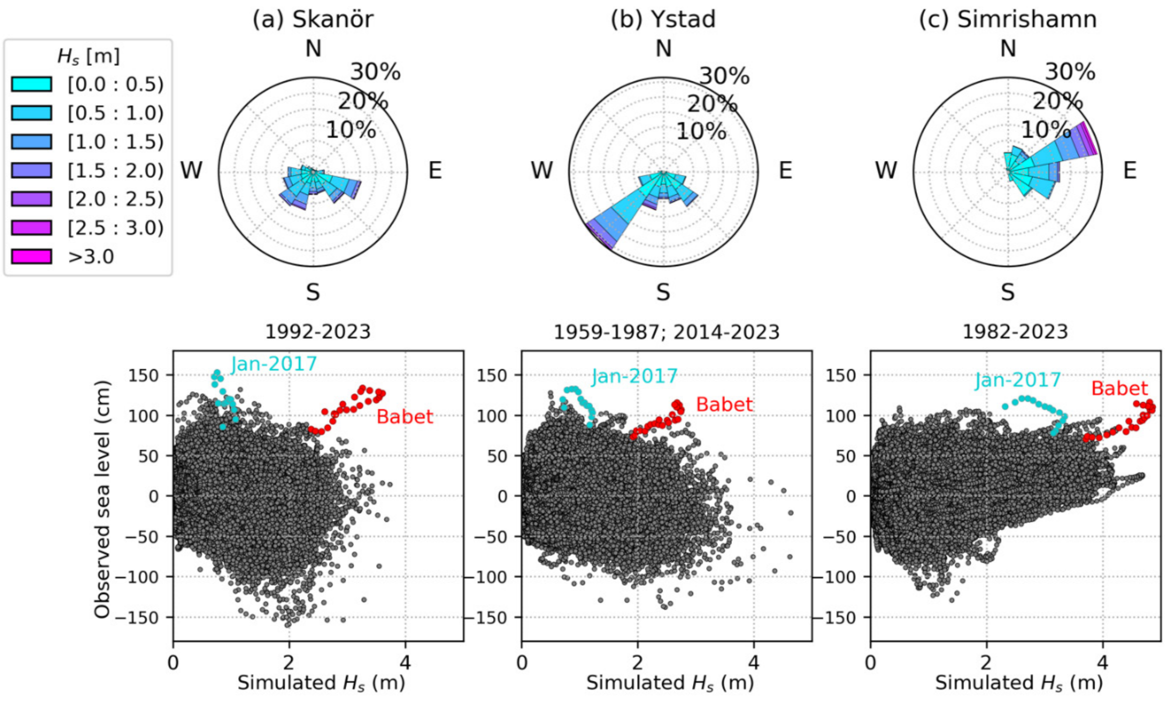

Figure 9: Wave roses with data extracted at 10 m depth (see Figure 8 locations a-c) covering the period 1959–2023 to illustrate the typical wave climate conditions. The scatter plots show the joint occurrence of wave heights and observed sea level for the overlapping periods of available data. Observed sea levels is in relation to MSL.

Even though January 2017 and Babet are comparable events in terms of sea level, damages seen along the coast were more severe during Babet than in 2017. This is due to Babet being a rare occasion of high sea levels coinciding with high onshore waves. The top panel of Figure 9 shows wave roses at locations close to the tide gauges (see Figure 8 for locations), data extracted at approximately 10 m depth. The roses show large waves from East to South-east (i.e., the conditions during Babet) to be unusual, especially at Skanör and

Ystad on the South coast. The bottom panel of Figure 9 shows the joint occurrence of wave heights and observed sea level for the overlapping periods of available data. Data points from 12 h on either side of Babet's peak are indicated with red points to set the storm in context to available historic data. The January 2017 event is shown in turquoise. Although sea levels in January 2017 were similar or higher when compared to Babet, wave heights were much lower, making Babet a different and more energetic event with more erosive potential. At all three locations Babet represents an outlier, but for partially different reasons. At Skanör Babet is a clear outlier both in terms of sea level and Hs. At Ystad, Babet is not as clearly an outlier in terms of Hs, but Hs >2 m in combination with sea levels >1 m is an outlier, especially when considering that the wave direction was from the South-east instead of the South-west. In Simrishamn high waves in combination with high sea levels is more frequent, but here it is Hs >4 m in combination with sea levels >1 m that makes Babet an outlier.

While Babet is an outlier in modern times, historical events like the 1904 New Year's Eve storm or the 1872 November storm (Andrée et al. 2023) followed a similar but more severe development as Babet. Figure 10 shows wave conditions during Babet compared to wave conditions during the 1872 storm (Sukchaiwan et al. 2024). The two events are largely similar, but the 1872 storm is more extreme. Simulated wave heights are approximately 0.5–1 m higher during the 24 hours leading up to the peak. Sea levels were also considerably higher during the 1872 storm (Sukchaiwan et al. 2024) due to the stronger winds. Comparing Babet to other events shows Babet to be an unusual, but not unique, event.

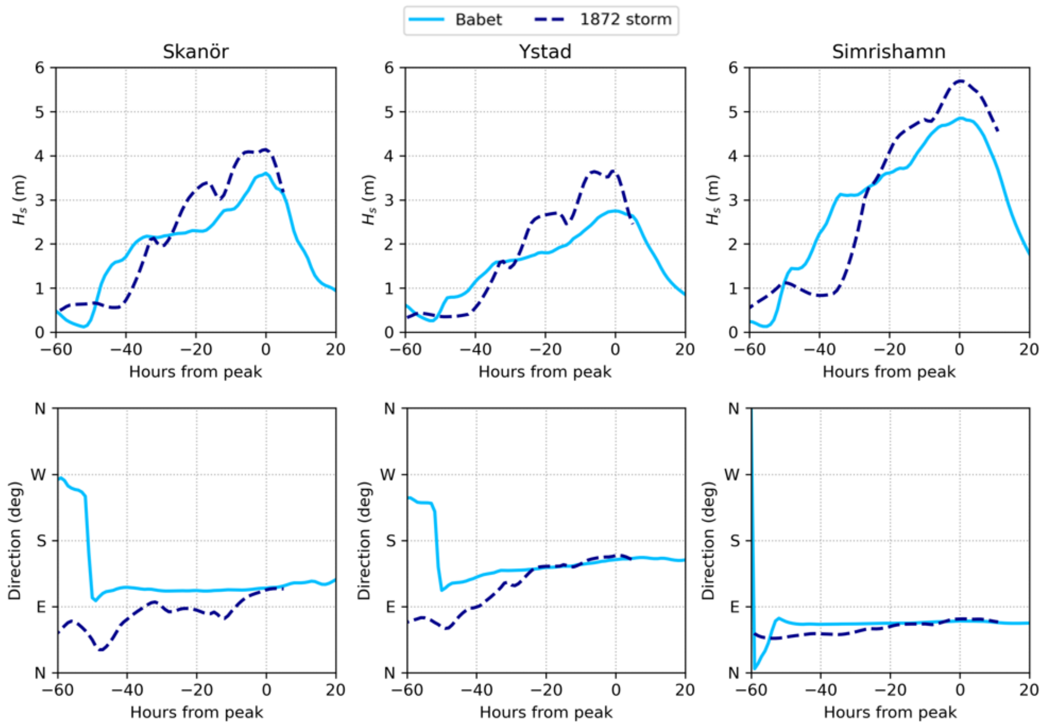

Figure 10: Simulated significant wave height (H_s) and wave direction during the 1872 November storm (dashed line) and Babet (solid line). The locations match those of the scatter plots and wave roses in Figure 9. The two events show similarities, but 1872 led to larger waves.

5.4 Morphological change

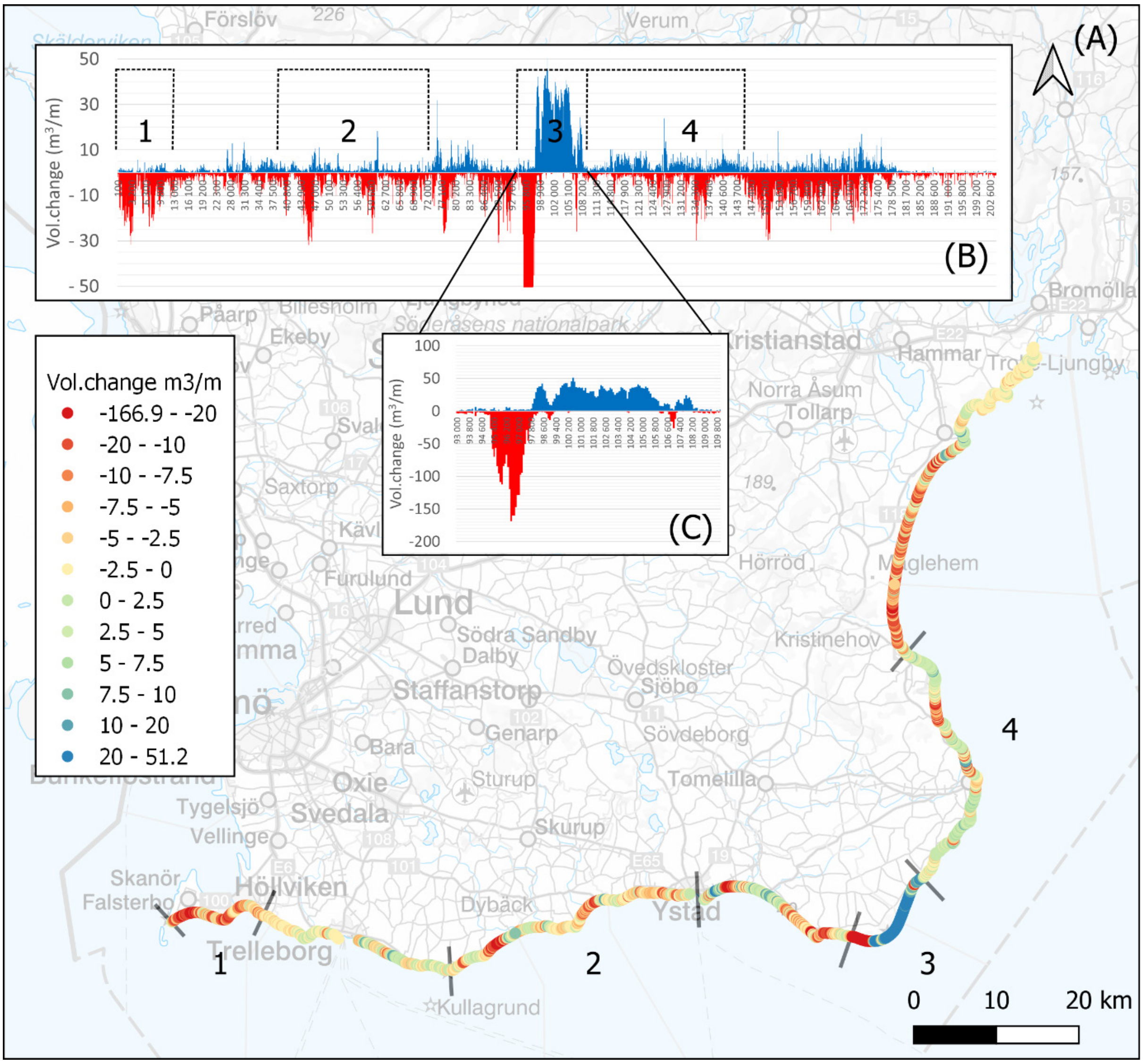

Figure 11: Volumetric changes between 2019 and 2023, expressed as normalized m^3/m in the longshore direction. (A) Net volumetric change plotted on a map. Segments 1–4 are discussed further in Sect. 6.1. (B) Erosion and accretion as a bar chart. Segment numbers are the same as in (A) to facilitate orientation. The Y-axis is cut at +/−50 m^3/m for increased readability. (C) A subset of (B) requiring a larger Y-axis span to read results.

Figure 11 shows morphological change between 2019 and 2023, expressed as a normalized m^3/m value in the longshore direction. (A) shows net volumetric change on a map, facilitating orientation and offering geographical context. (B) shows the components erosion and accretion separated and presented as bar charts, offering understating of magnitudes and hotspots. The x-axis of (B) is distance in meters along the coast, starting in the South-west and finishing in the North-east. The y-axis of (B) is cut at +50/−50 m^3/m to facilitate reading. (C) is a subset of (B) that requires a larger y-axis span. Segments 1–4 are areas that are discussed further in Sect. 6.1. Figure 11 shows that most of the coast experienced morphological changes between 2019 and 2023, but the type and magnitude varies along the coast. The subset (C) in Figure 11 shows changes that are exceptional in a Swedish context, with erosion reaching >150 m^3/m and accretion close to 50 m^3/m. The pattern follows a long-term trend in the area (see Figure 2B). Total erosion in the study area is close to 1.3 million m^3, total accretion close to 760 000 m^3, resulting in a net loss of 510 000 m^3 between 2019 and 2023. As stated in Sect. 4.2.1 results contain some false accretion, so accretion is likely slightly lower and the net loss slightly higher.

5.5 Impacts and damages from Babet

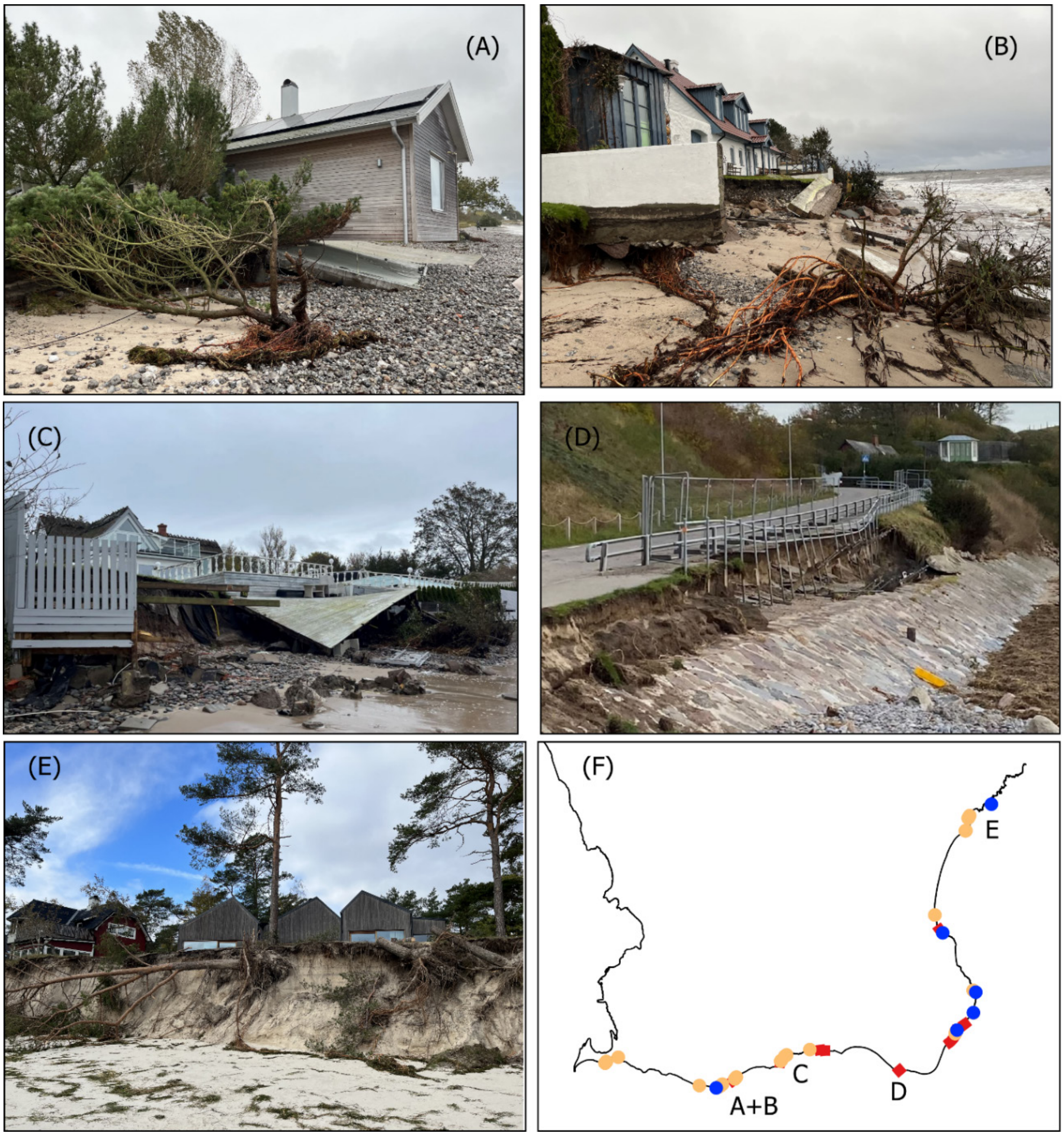

Figure 12: Examples of damages occurred during Babet. (A), (B) and (C) shows residential houses that suffered damages. (D) shows an undermined access road to a harbour and (E) shows residential houses that were not damaged by the storm, but where there is a risk that subsequent landslides in the unstable slope will lead to damages. (F) Some of the recorded damages along the coast. Orange=buildings, red=roads, blue=harbours.

Impacts and damages to coastal societies caused by Babet can be found throughout the study area (see Figure 12F), but the type and severity of the impacts vary and the highest levels of erosion in $DTM_{2023-2019}$ do not coincide with the highest societal impacts post-Babet. E.g., segment 1 in Figure 11 (Vellinge) suffered more widespread erosion than segment 2 (Trelleborg/Skurup), yet the societal impacts were greater in segment 2 due to residential houses being located very close to the sea (see Figure 12A, B, C). Figure 12F shows buildings were also damages in segment 1, but these were small and simple beach huts with limited societal impacts. Around Simrishamn (segment 4) the erosion was more limited due to the geology of the segment (see Figure 2A), yet Simrishamn experienced significant damages to their harbours due to high waves, e.g., 3000 kg stone blocks were pushed off the crest of a harbour pier. In Kristianstad the steep cliff faces left by Babet led to fear amongst some property owners that their buildings would be damaged by subsequent landslides (see Figure 12E). Coastal roads were also damaged, e.g. in Ystad municipality where an access road to Kåseberga harbour was undermined (see Figure 12D). Several roads also had to temporarily close due to overwashed debris and sand blocking the road. Beyond the initial damages, Babet also led to secondary impacts such as delayed investments and delayed development projects when municipal units had to reorganise their funds toward damage repairs.

5.6 Interpretation of warnings and preparations

On October 17th, SMHI published an orange warning for very high sea-levels along Scania's coast, as well as a warning for easterly wind up to 24 m/s. On the morning of the 19th, the severity increased and yellow warnings for wind over land were also issued, describing persistent eastern storm guts up to 30 m/s from the evening of the 20th over southern parts of Scania. The warnings were preceded by a collaboration between SMHI and CAB Scania. CAB's crisis management unit also arranged regional coordination conferences on October 19th and 20th, where municipalities and SMHI participated.

All interviewed informants had noted the weather warnings, and some had participated at the coordination conferences. Many referenced the 1872 storm, but several interviewed municipal officials still found it difficult to fully understand the combined risks of the forecast high sea levels and easterly winds.

In SMHI's warning, coastal erosion was listed as a potential impact of high sea levels, but this was communicated as one of several possible risks. For some municipal officers in Ystad and Vellinge, the severity of the situation was only realised after a consultant with specific expertise in coastal processes contacted them, explicitly warning them of the potential erosion risk. Like this consultant who had spent a lot of time in the coastal landscape, it appears as those with specific and experiential knowledge of the sea and shoreline combined with the ability to read forecasts could best interpret the severity of the warnings.

Once the warnings were received within the different organisations, the preparations mainly followed the same patterns. For the municipalities, it involved clearing manholes, in- and outlets, pulling up jetties, mooring boats and securing marinas. For the STA, it involved closing off and monitoring roads. In Vellinge, temporary flood defences were erected according to pre-existing plans, the municipality also established a secondary defence line and had trucks with gravel on standby should there be a breach.

No interviewed organisation formally elevated their emergency preparedness and declared an extraordinary event, but the municipalities of Trelleborg, Ystad and Vellinge elevated their preparedness within relevant administrative units such as the technical and communication unit. In Simrishamn and Skurup, a form of informal preparedness took place with select staff members working extra hours over the weekend.

5.7 Dealing with the aftermath

In the immediate aftermath of Babet, the municipalities and the STA focused on clearing rubble from roads and public areas as well as conducting acute repairs on critical infrastructure such as roads, harbour, sewers and securing public areas. While the immediate phase appears to have worked well, more challenging aspects included communication with property owners and how to interpret the existing legislation. At the core of the problem was a misconception on behalf of the public that the municipality held a responsibility to help repair or protect private property, a responsibility that lies on the property owner (see Sect. 3). Another issue was informing property owners of the need for adequate legal processing before repair or protective measures were implemented along the coast. The erosion caused by Babet left some property owners with a sense of urgency and a perceived need to build protective measures immediately.

Municipal informants as well as the STA had difficulties interpreting what legal permits were required during repairs and reconstructions of coastal defences. More readily available information on the necessary legal processing at different stages of erosion damage, for example in urgent situations when facilities needed immediate repairs, were therefore called for by informants.

Babet's aftermath also proved challenging for the CAB's water unit as the number and size of cases associated to Babet was unprecedented. The workload limited the unit's possibilities to pursue reports of coastal defences being built without the proper permits. Babet triggered internal discussions on where to draw the line on what a property owner may or may not do without first seeking legal permits. To facilitate the legal interpretation the officers at the unit also engaged in outreach and information to municipalities and property owners.

5.8 A window of opportunity? Lessons learnt and moving forward

Babet was by informants interpreted as a precursor of anticipated climate change effects that manifested earlier than expected and the event was seen to have created a greater awareness of extreme events, climate change and the need for adequate response and adaptation. As such, Babet strengthened commitments to existing or planned strategies related to coastal preparedness and climate change adaptation. For example, informants in Vellinge said that the support for the ongoing development of a large coastal defence had increased after Babet. In Ystad and Simrishamn, insights gained from Babet led to plans to revise their action plans for the coast. An informant from Skurup also stated that the event had put more weight behind arguments to restrict development in coastal zones and vulnerable locations. The extreme event was by informants deemed as an eye-opener for local politicians, which they hoped could provide more resources for risk reduction and spur further discussion on sustainable coastal development. In Simrishamn, a heightened political awareness had already been noticed as the municipal unit received the funds requested for repairs and climate change adaptation. Still, some cautioned that the public memory is short and the attention Babet received might diminish as other new pressing issues emerge.

Within the area of emergency preparedness, informants generally praised the immediate response to Babet regardless of how the preparedness was set-up. Within the municipalities, units were described as having pulled together as a team with an overwhelming commitment and engagement from the involved staff members. Babet also catalysed learning and reflections within the organisations with the potential to change existing routines and practices. One such reflection that informants from both Trelleborg and Ystad made was the need for an overarching coordinator between the different municipal units during the operations and responses to an emergency.

In Simrishamn, informants said they would assess the possibility to elevate the level of preparedness within one municipal unit to ensure sufficient staff and resources during an emergency response. Officials from Skurup expressed the most vocal need to strengthen their emergency preparedness and argued that Babet had showed the necessity for a more formalised preparedness procedure including clearer routines, mandates and funds for preparedness.

6 Discussion and conclusion

6.1 Morphology evolution and the importance of Babet

In Sect. 5.4 we show morphological changes between 2019 and 2023. If the effect of Babet could be isolated it would yield new insights into storm erosion during an outlier event. Due to the four-year gap in the LiDAR data, we cannot quantitatively isolate Babet, but the supplementary data (e.g. geological conditions, long-term trends, transect measurements, stakeholder testimonies) gives us site-specific contextual understandings that allow us to qualitatively estimate if Babet is the main driver of change along different parts of the coast. Below we show four examples of segments along the coast where we have done this.

Segment 1 in Figure 11 (Vellinge). Mostly high erosion values in $DTM_{2023-2019}$, 15–20 m^3/m or more not being uncommon. Sandy beaches with a long-term trend of *mainly in balance* or *accreting* along most of the segment (Figure 2B). Comparing GNSS-GPS data from March and (pre-storm) October 2023 to DTM_{2019} shows generally good agreement, indicating limited change in elevation between 2019 and 2023 pre-storm. Available data suggest limited to no erosion between 2019 and 2023 pre-storm, leading us to the conclusion that most of the erosion in $DTM_{2023-2019}$ can be attributed to Babet.

Segment 2 in Figure 11 (Eastern Trelleborg and Skurup). General net erosion in $DTM_{2023-2019}$ along most of the segment, with some pockets of net accretion. Higher erosion numbers, in the order of 15–25 m3/m, are found at coastal segments facing SSE and located in the western parts of bay-shapes. A long-term morphological trend of *mainly in balance* or *accreting* (Figure 2B) can be seen, and (Ziolkowska 2024) indicate mostly stable or growing dunes 2019–2023 pre-storm, however one of the erosion hotspots shows slight dune retreat in the years before Babet. Available data suggests some morphological activity prior to Babet, but at a limited scale. We therefore conclude most of the changes seen in $DTM_{2023-2019}$ to stem from Babet.

Segment 3 in Figure 11 (East of Löderup strandbad). The coast shows very high morphological activity, erosion reaching >150 m^3/m and accretion >40 m^3/m. The coastal segment has for decades been one of the morphologically most active in Sweden, and we can conclusively say that not all changes seen in $DTM_{2023-2019}$ stem from Babet.

Segment 4 in Figure 11 (Simrishamn). Erosion is comparatively low in $DTM_{2023-2019}$ and limited to a few hotspots, even though the coast likely experienced the largest waves during Babet (see Figure 8). The low erosion is likely due to the geology of the coast being mainly *bedrock and cobbles* (see Figure 2A). The erosion hotspots correspond well to stretches classified as *sand/gravel* or *bluff coast*. The dominating long-term morphological trend is *mainly stable*, but there is a stretch of *slow erosion* (Figure 2B). Based on available data we conclude Babet to be an important driver of change along the segment, likely the main driver along most stretches.

We recommend continued research into isolating Babet's impact on the morphology of the coast. The Swedish Land Survey have LiDAR data of the study area from 2010 and from 2025. Extending the analysis to 2010–2025 would be one way of quantitatively comparing the 2019–2023 period to the years before and after, creating relevant context for the changes seen between 2019 and 2023.

6.2 Societal impact and response

Already on October 17th it was possible to identify Babet as an upcoming event with the potential to alter the coastal landscape at region scale, but understanding the full severity required specialized skills and knowledge of coastal processes as well as local conditions. SMHI correctly forecast and issued warnings for high sea levels and strong easterly winds, but many recipients of the warnings did at first not grasp the potential severity of the upcoming weather. One way of conveying the severity might have been to point out similarities between the forecast and the 1872 storm, as this storm is well understood in the region as an extreme. At the same time, it is unattainable for a national authority to have insight into all relevant regional and local contexts in Sweden, and it can be argued that since the 1872 storm is well-known then a forecast of high sea levels and strong easterly winds should set off alarms with stakeholders at regional and local levels. The initial struggle to grasp the severity showcases the need for clear and explicit warnings from SMHI, but also the need for regional and local authorities to analyse weather warnings through a lens of local contexts and consequences.

The municipalities' right to self-organise their emergency preparedness is reflected in the differences in municipal responses to Babet, but preparations and the immediate responses to Babet seem to have worked well irrespective of how it was formally organized. The aftermath however proved more challenging, revealing organisational difficulties of sustainably coping with drastically increased workloads and new types of tasks over periods of weeks or months. This is true both for the municipalities and for CAB.

In the absence of a national or regional actor with a strong mandate for cross-organisational coordination, coastal professionals within and between organisations still found ways of coordinating efforts prior to, during and after Babet, sharing data and knowledge and drawing upon each-other's strengths and opportunities. This led to extensive documentation of Babet, laying the ground for a better understanding of the event through continued research. The Swedish experiences show that with well-established and cross-organisational connections between a variety of stakeholders prior to an event, significant self-organization can take place. This shows the importance of not working in silos, and having good dialogue between public sector, private sector, academia and local stakeholders.

Babet can be considered a focusing event that exposed existing challenges. The event illustrated ongoing tensions, knowledge gaps and uncertainties related to the roles and responsibilities between municipalities and property owners in developing and financing coastal management and adaptation, and it shed light on the need to bring more clarity into the division of responsibility on how to develop and fund preventive measures and coastal defences. Related to this was a request for more expert and government support and funding on how to plan and adapt coastal areas to climate change including the contentious issue of managed retreat. This ties in to overarching questions on the capacity of individual municipalities to respond to current and future extreme weather events and whether responses should be taken at a regional rather than municipal level. Despite these challenges stakeholders such as the municipalities and CAB pulled together and engaged in information and dialog with property owners. Still, the findings show that these questions need further clarification from the government. Babet also catalysed learning and reflections within the organisations both in terms of how to best organise emergency preparedness and the direction of climate change adaptation, which has the potential to change existing routines, practices and policy directions. From a Swedish perspective, Babet serves as a warning and a reminder of how severely our coasts can be hit by individual storms, without having to experience the full effects of historical extremes such as the 1872 November Storm. In this sense Babet offers a window of opportunity for learning and building coastal awareness, capacity and resilience in Sweden, both for the next storm under present conditions and for the challenges ahead due to climate change.

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