EESTI MEREAKADEEMIA
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Merehariduskeskus

Siret Räämet

SPATIAL REMOTE SENSING DATA ANALYSIS FOR MAPPING EXTREME EVENTS IN THE EASTERN BALTIC SEA

Diploma thesis

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Hereby I declare, that I have written this thesis independently.

No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

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Contents

Annotation

The thesis's general objective was to map the Eastern Baltic Sea's sea surface temperature, sea surface height and significant wave height extremes (extent, frequency, intensity).

The data products used in the study were obtained from Copernicus Marine Environment Monitoring Service and analysed with MATLAB. The study period for marine heatwave (MHW) analysis was 1989-2020, and the study period for analysing the extreme sea levels (ESL) and extreme wave heights (EWH) was 1993-2021.

The results of the analysis revealed that MHW days were most frequent in the Gulf of Riga (1200 MHW days) and the most intense in the coastal areas of the Gulf of Finland and in the Pärnu Bay (2,9-3,2°C). The entrance of the Gulf of Finland had the most ESL days (+1180 ESL days) and ESL was the most intense in the Gulf of Riga (0,3 m). EWH days were most frequent in the coastal areas of north-western Estonia and in the entrance of the Gulf of Finland (60-80 EWH days) and the most intense in the entrance of the Gulf of Finland (1,6 m). All the statistically significant extreme trends increased over the study period.

There has not been this kind of comprehensive study on extreme events in the Eastern Baltic Sea, therefore the results are unique. The results can be used for coastal and offshore planning or for research purposes to investigate more in detail certain extremes of interest.

Keywords: Geospatial data, Copernicus CMEMS, extreme events, climate change, Eastern Baltic Sea

Abbreviations

CMEMS	Copernicus Marine Environment Monitoring Service
EGoF	Eastern Gulf of Finland
ENSO	El Niño-Southern Oscillation
Ent-GoF	Entrance to the Gulf of Finland
GoF	Gulf of Finland
GoR	Gulf of Riga
IPCC	Intergovernmental Panel on Climate Change
NaN	Not a Number
NAO	North Atlantic Oscillation
SSH	Sea surface height
SST	Sea surface temperature
SWH	Significant wave height
WGoF	Western Gulf of Finland

1 Introduction

1.1 Physical oceanography and climate dynamics

The climate of the Earth is a complex system impacted by many elements, including the physical features and dynamics of the oceans. Understanding the function of physical oceanography in climate dynamics is essential for forecasting and mitigating climate change consequences.

Understanding climate changes in the marine environment is important because it affects the surrounding environment on different levels, both people and the environment around them, as well as biodiversity and ecosystems. In order to detect changes, they must be observed. The most important parameters monitored in the marine environment, which are also examined in Intergovernmental Panel on Climate Change's (IPCC) reports, are sea temperature, sea ice, ice sheets, sea level, tides, waves, and chemical properties. (IPCC, 2021)

The general objective of the thesis is to map sea surface temperature (SST), sea surface height (SSH) and significant wave height (SWH) extremes (extent, frequency, intensity) in the Eastern Baltic Sea.

1.1.1 Sea surface temperature

Sea surface temperature (SST), which refers to the temperature of the ocean's top layer, is one of the main factors that can reveal climate change. It is possible to use various methods to measure and monitor SST, including satellite remote sensing, in-situ measurements and numerical modelling. (Talley et al., 2011)

The climate system could be significantly impacted by changes in SST because warmer seas can intensify tropical cyclones and other extreme weather events. Furthermore, variations in temperature can also have a considerable influence on marine ecosystems, impacting the number and distribution of various species as well as the ecosystem processes that control the ocean's carbon and nutrient cycles. (Hoegh-Guldberg & Bruno, 2010)

Moreover, the oceans have a significant role in climate regulation by functioning as a heat sink, collecting and storing heat from the atmosphere. SST changes can therefore have a considerable influence on heat transport and storage by the oceans, impacting regional and global temperature changes. SST is considered one of the essential climate variables. (Talley et al., 2011)

1.1.2 Sea level

Physical oceanography also considers sea level as a key parameter because variations in sea level may have a significant impact on people and coastal areas. Changes in ocean currents, melting ice caps and glaciers, and thermal expansion of saltwater due to warming can all cause sea level to rise or fall. Rising sea levels can cause floods, erosion, and infrastructure destruction, with serious economic and societal consequences. (Nicholls & Cazenave, 2010)

Changes in sea level are also related to the dynamics of the climate system. Shifts in ocean circulation patterns can have an impact on the distribution of heat and carbon across the ocean, affecting sea level. Melting ice caps and glaciers, for example, can contribute to global sea level rise, affecting ocean circulation patterns and causing changes in regional and global climate patterns. Studying these complex processes is crucial for forecasting future sea level rise and developing mitigation plans for coastal areas. (Alexander et al., 2013)

1.1.3 Wave height

Another key characteristic used for describing the physical state of oceans and seas is wave height. Wave height data is used, for instance, in the construction of offshore structures like oil platforms, wind farms, and coastal defence systems. (Talley et al., 2011). Additionally, it provides information on the energy exchange between the ocean and atmosphere. Waves are generated by wind and are an important mechanism by which momentum is transferred between the ocean and atmosphere. Wave energy can influence the temperature and density of the ocean, as well as the nature of ocean currents. This, in turn, has the potential to have a significant impact on Earth's climate, including changes in regional and global temperature, ocean circulation, and weather patterns. (Young et al., 2011a)

By including wave height data into models, it is possible to understand how the oceans and atmosphere interact and how these interactions affect global climate patterns (Vanem, 2016).

1.2 Global climate extremes

Climate extremes refer to unusual or severe weather conditions that deviate from typical weather patterns. These extremes can include heatwaves, droughts, floods, hurricanes, as well as wildfires. Climate extremes have been on the rise in recent years, and their extent, intensity, duration, and frequency are expected to continue to increase as global temperatures rise due to anthropogenic greenhouse gas emissions. (Albeverio et al., 2006)

According to the IPCC Fifth Assessment Report, there is high confidence that the frequency and intensity of extreme heatwaves have increased globally since the mid-20th century, and it is likely that the frequency of heavy precipitation events has increased in many regions (IPCC, 2014). It also noted that it is very likely that human influence has contributed to the observed changes in frequency and intensity of extreme weather events.

In addition, the increasing frequency and intensity of hurricanes, wildfires, and droughts have been highlighted. Frequency of hurricanes reaching Category 3 or higher has increased over the past four decades, with the strongest hurricanes becoming even stronger. In total, climate extremes are becoming more frequent and intense because of climate change. These trends have significant impacts on human health, agriculture, infrastructure, and ecosystems. (Kossin et al. 2019)

Given the significance of extreme occurrences, it is critical to study and comprehend them in order to better foresee and prepare for their possible consequences.

1.2.1 Marine Heatwaves

Marine heatwaves (MHW) are prolonged periods of abnormally warm SSTs that can last for days to months and have severe consequences for marine ecosystems and organisms. Temperatures that are above the local historical average for a certain area and time of year by a certain threshold, are considered as MHWs. (Hobday et al., 2016)

Study by Hobday et al. (2016) suggests to use the 90th percentile threshold for detecting MHWs. Length of the event should be at least five consecutive days. This kind of threshold identifies events that exceed the upper range of what is considered as “normal” and duration requirement ensures that short spikes, which do not have significant impact on marine ecosystems, are not considered as MHWs.

MHWs intensity has raised globally 0,04°C per decade during the period between 1982-2016 and yearly MHW days between 1987-2016 has increased 54% compared to the period of 1925-1954 (IPCC, 2021). The Baltic Sea has a warming trend in general, average SST has risen 0.62 ± 0.41°C per decade, which also affects MHW occurrences (Jamali et al., 2022). In addition, MHWs in the Baltic Sea have been shown to have a relationship with large-scale climatic oscillations such as the El Niño-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) (Lehmann et al. 2021; Smoliński et al. 2019).

Climate changes have made MHWs more frequent, and they can have a significant effect on marine ecosystems. These events have the potential to impact nutrient cycles, ocean currents, as well as the distribution and abundance of marine animals. Moreover, MHWs can result in mass fatalities, especially in species that are not suited to rapid temperature variations (Harvey et al., 2022). It has been reported that MHWs have caused mass mortality of seagrass, invertebrates and fish, but on the other hand accelerated the growth of invasive species populations (Smith et al., 2021). Likewise, the MHWs could lead to harmful algal blooms and anoxia, which impact individuals more than just variances in temperature (Gruber et al., 2021).

1.2.2 Extreme Sea Level

Extreme sea level (ESL) refers to the high-water level that occurs during extreme weather events. It is an important characteristic for coastal planners and engineers to consider because it has a direct influence on the design and construction of coastal infrastructure such as sea walls, breakwaters, and flood control systems. (Muis et al., 2016; Resio & Westerink, 2008)

The ESL is defined with the same criteria as for MHW. The ESL is defined as a high water level that exceeds the 90th percentile threshold for a specific location and with a duration of at least five consecutive days. This definition ensures that ESL events are identified only when they exceed the upper range of what is considered "normal" for that location and events lasting a considerable amount of time are considered.

It is claimed that the overall number of storm surges are correlated with ESL occurrences. As a result, when storm season occurs from fall to winter, then ESLs mainly occur at this time. According to a study by Stramska & Chudziak (2013), the average sea level in the Baltic Sea has an estimated trend of 3,3 mm per year. This rise is higher than the global average sea level rise, which is estimated to be around 1.8 mm per year. Therefore, ESL events globally are predicted to occur more often in the future (IPCC, 2021). It is expected that ESL occurrences happening once in 100 years, will occur once in 1 year due to global warming (Tebaldi et al., 2021). Also, it is expected that ESL events will occur 20-30 times more frequently by 2050 (IPCC, 2019). Also, ESLs in the Baltic Sea have been rising 3-4 mm a year due to increase in water volume maxima during the period of 1965-2005 (Pindsoo & Soomere, 2020).

As mentioned earlier, ESLs occur during extreme weather events, such as storms, and hurricanes. These events can result in a temporary rise in sea level, which can cause floods and other coastal dangers, especially in populated coastal regions. It is also vital to accurately characterise the frequency and intensity of ESL height occurrences to estimate future flood risk in a changing climate. (Resio & Westerink, 2008)

1.2.3 Extreme Significant Wave Height

Extreme significant wave height (EWH) is defined as significant wave height (SWH), which exceeds specified threshold (Gao et al., 2022; Li et al., 2022). As mentioning SWH, it refers to the average height of the highest one-third of waves in a specific location. These waves have an impact with a greater force and intensity on the beach than regular waves, which significantly accelerate coastal erosion (Van Rijn, 2011). It is a crucial parameter for ocean engineers, maritime and coastal planners, and other stakeholders involved in designing, constructing, and maintaining coastal and offshore infrastructure. (Talley et al., 2011)

To define EWH in this thesis, the same criteria as for MHW and ESL is followed. Meaning, EWH is a SWH that exceeds the 90th percentile for a given location for a period of at least five consecutive days.

The global trends for SWH suggests it is influenced by wind speed, and it varies seasonally (Young et al., 2011b). For the Baltic Sea, the spatial average of SWH had a not significant trend from -2.5 mm up to +3 mm per year during 1970-2007 (Soomere, 2023). According to the IPCC (2019) EWHs have increased in the Southern and North Atlantic oceans 8-10 mm per year during 1985-2018. The occurrences of EWHs are expected to rise similarly to the ESL, in some locations EWHs occurring once in 100 years, in future it is expected to occur once or even more in a year (IPCC, 2019).

Therefore, understanding these are fundamental for constructing safe and resistant coastal and offshore infrastructure, also for designing vessels. Extreme waves have the potential to cause considerable damage and even failure in structures that are not designed to withstand them (Teena et al., 2012).

1.3 Study area - Eastern Baltic Sea

The thesis focused on the eastern Baltic Sea surrounding Estonia, which includes the Gulf of Finland (GoF) and Gulf of Riga. For analysis, the area was divided into four subregions: Entrance to the Gulf of Finland (Ent-GoF), Eastern Gulf of Finland (EGoF), Western Gulf of Finland (WGoF) and Gulf of Riga (GoR) (Figure 1).

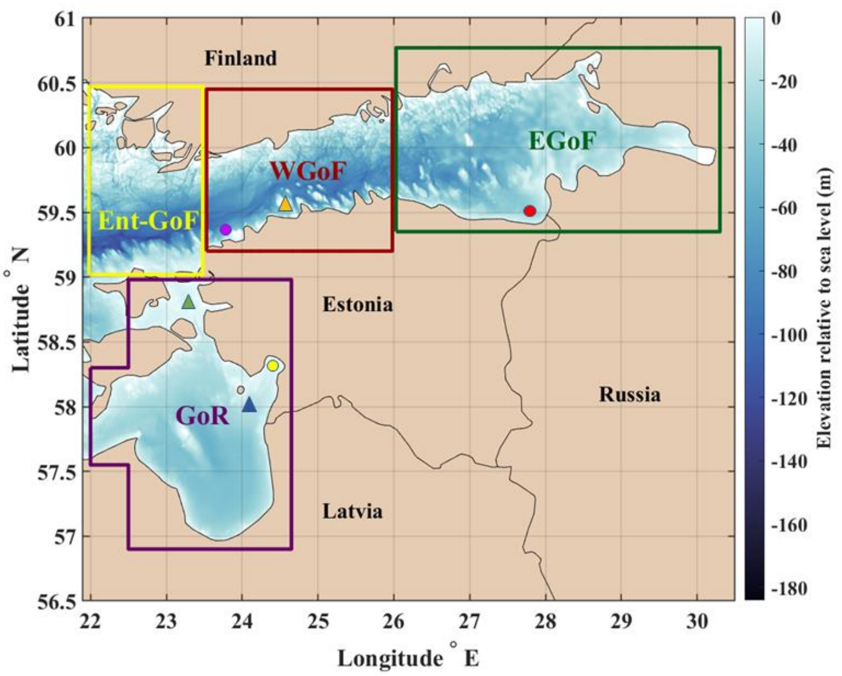

Figure 1. Map of Eastern Baltic Sea with subregions. Hotspot locations (circles): Pärnu Bay (yellow), NW coast of Estonia (purple) and Narva Bay (red). Areas of interest (triangles): GoR wind farm (blue), Väinameri (green) and Bay of Tallinn (orange).

The GoF is located in the north-eastern Baltic Sea and the western boundary is considered as a line between Osmussaar and Hanko peninsula. The mean temperature of the water ranges from 0°C in the winter to 20°C in the summer near coastal areas. The GoF has a maximum depth of 123 metres and an average depth of 37 metres. The water circulation is mostly driven by wind and slightly by density (Alenius et al., 1998). The water from Ent-GoF flows to GoF along the Estonian coast and outflows along the Finnish coast, but there are seasonal differences in the flow strength (Laanemets et al., 1997). The GoR has positive freshwater input mainly from the east, Neva River, with a mean runoff 114 km^3 per year. The mean surface salinity varies between 0‰-7‰, being higher in the west and lower in the east. The Ent-GoF separates the saline Baltic Proper water from less saline GoF water. The sea level varies in the GoF region, but it has the highest variability in January and is lowest in July. Wave height is highest in autumn and winter and lowest in summer, in the middle of the GoF the mean SWH has been 0,5 m in spring to 1,3 m in winter. (Alenius et al., 1998)

The Ent-GoF and GoR are connected through the Väinameri (Moonsund) in the north and south-west, relatively. It is around 50 km long and wide. The Väinameri is very shallow, the average depth is 4,7 m (Suursaar & Kullas, 2006). The GoR is located between Latvia to the south and Estonia to the northeast. The GoR is around 240 kilometres long and 120 kilometres broad at its widest point. The gulf is shallow, the average depth is around 23 metres, and the maximum depth is approximately 52 metres. The climate of the GoR is comparable to the GoF, there’s cold winters and warm summers. (Bergström et al., 2018) Water level in the GoR is mainly impacted by overall water volume of the Baltic Sea, cyclones consistently pushing water to GoR and storm surges. There is also a significant input of freshwater from the Daugava River and Pärnu River, mean inflow of 33 km^3 per year. (Männikus et al., 2019). The freshwater from the Daugava River causes lower salinity in the northern part of the gulf, while the southern part has higher salinity due to the influence of the Baltic Sea. (Feistel et al., 2010)

1.4 Previous studies on the Eastern Baltic Sea

The Baltic Sea region experiences a maritime climate, characterised by mild temperatures and high levels of precipitation. However, climate change is affecting the region by leading to changes in sea surface temperature, wave height, and sea level height. This section aims to give a brief overview of prior studies in order to gain a better understanding of previous knowledge.

Climate change is affecting the SSTs and MHWs in the Eastern Baltic Sea. A study by Meier et al. (2018) found that the SST in the Baltic Sea has increased by 0,6°C per decade over the past century. The decadal SST trend in the GoF and GoR during 1982-2021 has been 0,36 ± 0,41°C and 0,45 ± 0,31°C, relatively (Jamali et al., 2022). Moreover, study by Suursaar (2020) has shown that under certain wind circumstances, MHW may cover a very large region, including the whole GoF. In the summer of 2021 a MHW occurred in the GoF and the daily mean at its peak was 26,3°C (Suursaar, 2022).

Sea level rise is one of the most significant results of climate change in the Baltic Sea region. Study by Suursaar & Sooäär (2007) indicated to sea level trend of 1,5-1,7 mm per year in Tallinn (EGoF), 1,7-2,1 mm per year in Narva (WGoF) and 2,3-2,7 mm per year in Pärnu during the period of 1925-2005. This rise is mostly higher than the global average sea level rise, which is estimated to be around 1.8 mm/year (Church & White, 2011). The ESLs occur mostly in the EGoF and in the eastern part GoR (Wolski & Wiśniewski, 2023).

Long-term SWHs in the Baltic Sea are examined in study by (Soomere & Räämet, 2011). According to it, SWH has risen approximately 20 mm during a 48-year period in the Ent-GoF and EGoF, and 10-20 mm in the WGoF and GoR. EWHs are found to have increased in the northern and north-eastern parts of the GoF since 1970, because of strengthening of south-westerly winds at the expense of others. Also, it is important to know that average SWH variances around 15% during a 10-year period (Soomere & Räämet, 2014). The maximum SWH measured in the GoF was 5,2 m in November of 2001 (Tuomi et al., 2011).

Generally, the effects of climate change and extreme events in the ocean systems can be better understood by investigating the spatial and temporal distribution of extreme events in recent decades.

1.5 Objectives of the study

The general objective of the thesis is to map SST, SWH and SSH extremes (extent, frequency, intensity) in the Eastern Baltic Sea. The specific objectives of this study are to:

- map the location and extent of extreme events, such as MHWs, EWHs and ESLs, in the eastern Baltic Sea region;
- quantify the nature of extreme events, including their intensity and duration, through the data analysis;
- analyse the long-term variability of extreme events (trend analysis);
- describe the potential impacts of extreme events on coastal and offshore activities/construction.

2 Data and Method

The objective of this section is to provide a thorough explanation of the data and methodology used in current study. There are three main methods for obtaining ocean data. The first and most reliable method is direct measurement from the sea, which provides accurate data at a specific time and location. However, the inability to provide data on a larger spatial scale is one of the method's limitations.

To get over this restriction, there is access to two different methods for obtaining ocean data. The first alternative is the utilisation of satellite remote sensing data and the second alternative is outputs of numerical models. While numerical modelling and remote sensing techniques both have limitations and potential errors, advancements in computer and data science have significantly increased the accuracy and reliability of both methods. As a result, they are very useful methods in ocean-related scientific research as well as in operational services and have been widely used in various studies.

2.1 Data

The three main data products used in this study are SST, SSH, and SWH, which are discussed in more detail below. These products were used to investigate MHWs, ESLs, and EWHs (Table 1).

Validation of used data is essential to ensure the accuracy and reliability of the results. In this thesis, it is done by referencing previous studies, where the same dataset has been utilised and validated. The quality information document provided by Copernicus Marine Environment Monitoring Service (CMEMS) is used as the main source of information for validation.

Table 1. Overview of used SST, SSH and SWH products.

Product name	Input parameter	Output parameter	Spatial resolution	Temporal resolution	Time period
SST_BAL_SST_L4_REP_OBSERVATIONS_010_016	SST	MHW	0.02° x 0.02°	Daily	1982-2020 (1989-2020)
SEALEVEL_EUR_PHY_L4_MY_008_068	SSH	ESL	0.125° x 0.125°	Daily	1993-2021
BALTICSEA_REANALYSIS_WAV_003_015	SWH	EWH	0.018° x 0.018°	Hourly converted to daily	1993-2021

2.1.1 Sea Surface Temperature Product

For the SST, the Baltic Sea Sea Surface Temperature Reprocessed (SST_BAL_SST_L4_REP_OBSERVATIONS_010_016) dataset from the CMEMS is used in the thesis. The SST product has been used also in other studies (Goebeler et al., 2022; Liblik et al., 2022; Liblik & Lips, 2019; Schwegmann & Holfort, 2021). This dataset has been gathered using a variety of satellite instruments. The data is processed and reanalysed using advanced algorithms to ensure reliability and consistency across all time periods. The product has a spatial resolution of 0.02° x 0.02° and daily temporal resolution. The time range for the data is from 1 January 1982 to 31 December 2020. (CMEMS, 2022a)

Validation results from CMEMS quality information document indicates that the product is consistent with the in-situ measurements. The mean bias in the Baltic Sea region is 0.16°C and 0.12°C for drifting and moored buoys, indicating that the SST product is slightly warmer than in-situ measurements. Standard deviation for drifting buoys was 0.55 and for moored buoys 0.43. (CMEMS, 2022a). Also, the data has been validated by another study where the regression slope, correlation, absolute average error and bias, which were 0,96, 0,98, 0,62°C and -0,28°C, relatively (Liblik & Lips, 2019).

The time series of mean SST of the subregions during the period from 1982 to 2020 indicated an anomaly during the winters in the first 7 years of data analysis (Figure 2). As a result, only the years 1989-2020 were used in the analysis to exclude the differences caused by artificial anomalies from earlier years.

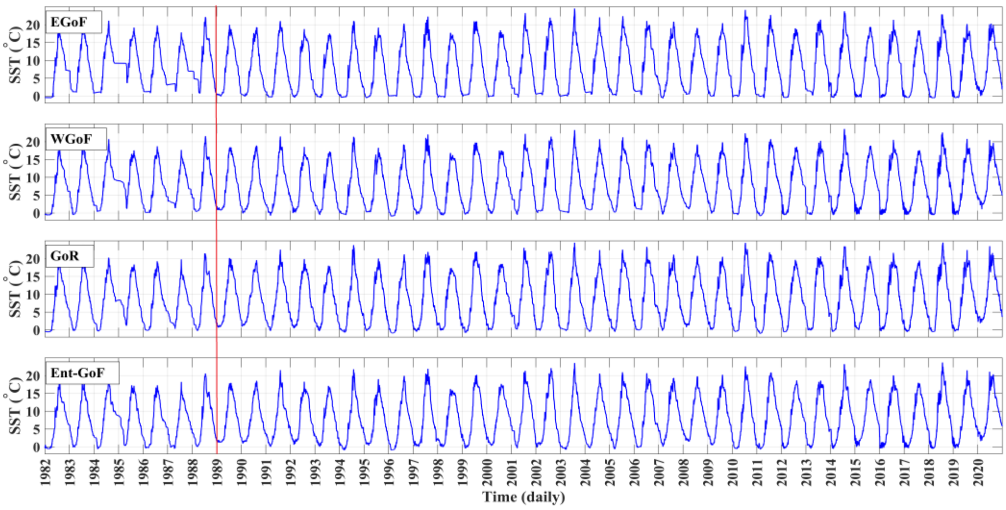

Figure 2. The time series of mean SST during the period 1982-2020. Red line indicating the year of 1989.

2.1.2 Sea Surface Height Product

For the SSH European Seas Gridded L4 Sea Surface Heights And Derived Variables Reprocessed 1993 Ongoing (SEALEVEL_EUR_PHY_L4_MY_008_068) dataset from CMEMS was used, which has been used also in other studies (Menna et al., 2023; Michael & Kies, 2022). The product collects information on sea level from multiple satellite altimeter types. The data is afterwards processed and reanalysed in a manner similar to the SST data. Spatial resolution of the product is 0.125° x 0.125°, and daily temporal resolution. The time range for the data used in the thesis is from 1 January 1993 to 31 December 2021. (CMEMS, 2022c)

The SSH product errors in the Eastern Baltic Sea area are estimated to be 1 cm in open sea and 7 cm near coastal areas, and even larger values in coastal regions with high variability (CMEMS, 2022c). Compared to in-situ measurements of two tidal gauge stations, it was found that correlation coefficient between data and in-situ measurements was 0,51-0,52 (Michael & Kies, 2022)

2.1.3 Significant Wave Height Product

Baltic Sea Wave Hindcast (BALTICSEA_REANALYSIS_WAV_003_015) model dataset from CMEMS was used for the SWH analysis. The product has been used previously in the study by Björkqvist et al. (2021). The product is based on a numerical model that simulates the behaviour of ocean waves while taking into consideration several different environmental variables, such as wind and bathymetry. The SWH hindcast is provided with spatial resolution of 2 x 2 km (approx. 0.018° x 0.018°) and with hourly temporal resolution that later was converted to a daily temporal resolution. The data used in the thesis is from 1 January 1993 to 31 December 2021. (CMEMS, 2022b)

The hindcast model's overall accuracy is regarded as good after being validated against 9 measurement sites. The SWH hindcast's bias is at highest -0.12 m, which shows that the model primarily underestimates SWH. The statistics indicate that SWHs are typically overestimated in coastal regions and underestimated in open areas. (CMEMS, 2022b). Also, in the study by Björkqvist et al. (2021), CMEMS data validation was used.

2.2 Method

The objective of the thesis was to map extreme events in the Eastern Baltic Sea. To achieve this, spatial data analysis was used as a quantitative research method, which involved analysing SST, SSH and SWH data to find extreme event statistics at the specified location (Figure 3).

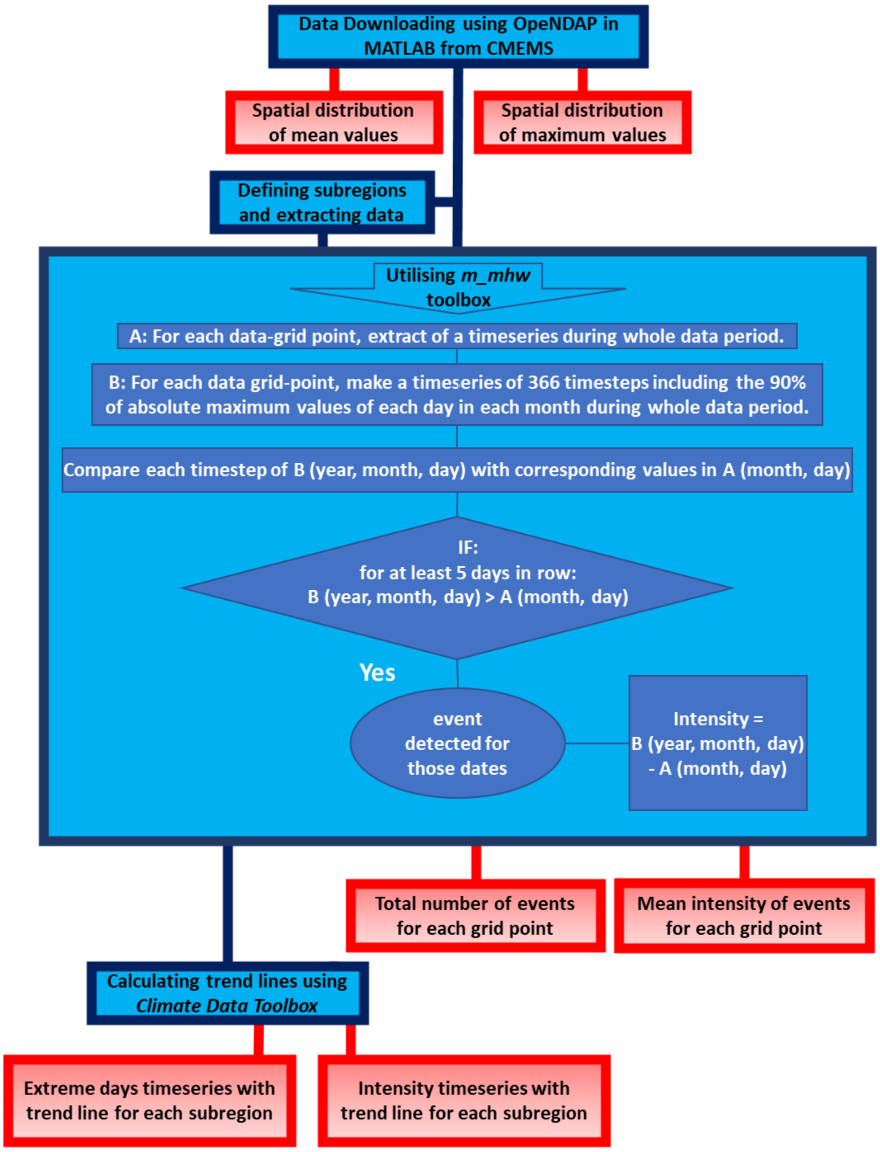

Figure 3. A flow chart showing the sequence of data processing steps for each parameter - SST, SLH and SWH. Red boxes indicate the output parameters (maps, timeseries) of the analysis.

Data analysis was conducted with MATLAB which is a combination of programming language and an interactive platform. It is widely used in different scientific and engineering fields, finance, energy, electronics, physics, and earth sciences. MATLAB offers a variety of built-in functions, tools, and toolboxes, which make it simpler to carry out difficult mathematical operations and visualise large datasets. (MathWorks, 2023)

The SST, SLH and SWH datasets were downloaded from CMEMS using MATLAB scripts due to the large data volume, which was caused by data's high resolution and long observation period. The download of required datasets was a straightforward process thanks to MATLAB's ability to link with external databases such as CMEMS. Defining the data type, time period and region of interest was required, and MATLAB would automatically detect and download the relevant data.

Maps of the spatial distribution of mean and maximum values for each dataset in the study area were generated after data download. The mean was calculated for each grid point by calculating the sum of all the values and dividing it with the number of days. The maximum values for each grid point were also picked over the course of the whole study period. These maps provided a good understanding of the data's variability in time and space.

The *m_mhw* toolbox was utilised to detect extreme events in each dataset (Zhao & Marin, 2019). This algorithm sorted the data values in ascending order for each grid point and determined the threshold as the number corresponding to 90% of these values. The threshold value for each grid point was compared to the value of each point at every timestep. Extreme event was identified and stored, if a point contained more than 5 consecutive days of a value greater than the threshold. These extreme events were then considered for each parameter (SST, SSH, and SWH), in the order of MHW, ESL, and EWH.

The mean intensity of an extreme event was calculated separately for each grid point and for each subregion as a daily mean. In this thesis, mean intensity was determined by dividing the cumulative intensity of extreme events by their duration in days. The cumulative intensity is the sum of intensity over the duration of the extreme event by computing intensity, a value was obtained that showed how much greater the mean extreme event was than the climatological mean over the entire period the data was gathered.

$$mean\ intensity = \frac{cumulative\ intensity}{duration}$$

By calculating the mean intensity for each grid point, it was possible to determine the areas in the Eastern Baltic Sea region where extreme events were most intense and had the potential to have the biggest threat on the surrounding environment.

For the subregions time series each parameter (MHW, ESL and EWH) extreme days were counted and totalled yearly. To determine trends and trend statistical significance p-values in subregions' time series (intensity and extreme days), *Climate Data Toolbox* was utilised (Greene et al., 2019). Trend lines for intensity time series were calculated without considering the Not a Number (NaN) values and trend was considered statistically significant if the p-value was less than 0,05.

3 Results

3.1 Sea Surface Temperature and Marine Heatwave statistics

The mean and daily mean of maximum SST maps (Figure 4) provide a visual representation of the spatial distribution of mean and maximum SST values over the Eastern Baltic Sea from January 1989 to December 2020. Long-term satellite-derived SST data was used to create the maps.

The mean SST values vary spatially over the study's region, ranging from 7,5°C to 9°C. In general, the northern section of the study area had lower mean SST with values close to 7,5°C, while the southern part of the GoF had mean values close to 8,2°C. Additionally, the GoR, located in the study area's southwestern corner, stands out as a location with relatively higher mean SST values, especially in the southern and eastern part of the gulf, where the mean SST values were close to 9°C.

During the 32-year study period, the daily mean of maximum SST values ranged from 22°C to 29°C. Maximum SST values were generally higher in coastal areas compared to offshore areas. The values were highest in the EGoF, where the SST reached 28-29°C in agreement with (Jamali et al., 2022). Also, the GoR had significantly higher maximum SST values compared to the Ent-GoF and WGoF, with SSTs reaching 27°C in the southern and eastern areas. In contrast, the maximum SSTs in the WGoF and Ent-GoF ranged from 23°C to 24°C, with slightly higher values observed in the northern part of the Ent-GoF.

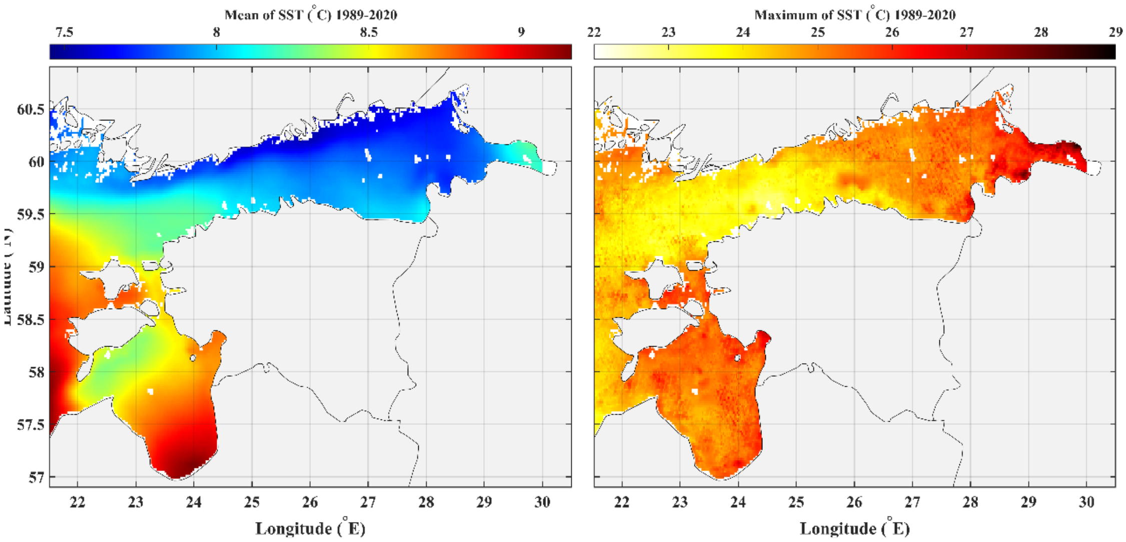

Figure 4. Mean (left) and maximum (right) SST 1989-2020.

The number of days that MHWs have occurred, and the mean intensity map (Figure 5) provide an overview of the frequency and intensity of MHWs in the Eastern Baltic Sea during the study period.

The highest frequency of MHW days was in the GoR, with up to 1200 MHW days in the western part of the gulf. Slightly less MHW days, around 950, occurred in the eastern part of the GoR. The Ent-GoF had between 900 to 1000 MHW days and the WGoF had even less occurrences, between 800-900 MHW days. The EGoF had between 700 to 900 MHW days, with less occurrences in the north-eastern coast and more in the middle part and in the most eastern part of the GoF.

The mean intensity of MHWs was highest in the GoF coastal areas, especially in the north and east, where the intensity varied from 2,9°C to 3,2°C. Additionally, the Pärnu Bay, in the northeastern part of the GoR, had high mean MHW intensity up to 3,1°C. In comparison, the WGoF and the Ent-GoF witnessed lower MHW intensity, which ranged from 2,3°C to 2,8°C, which was less intense than the eastern area. Mean MHW intensity for the whole study area was significantly higher in the coastal areas compared to the offshore areas.

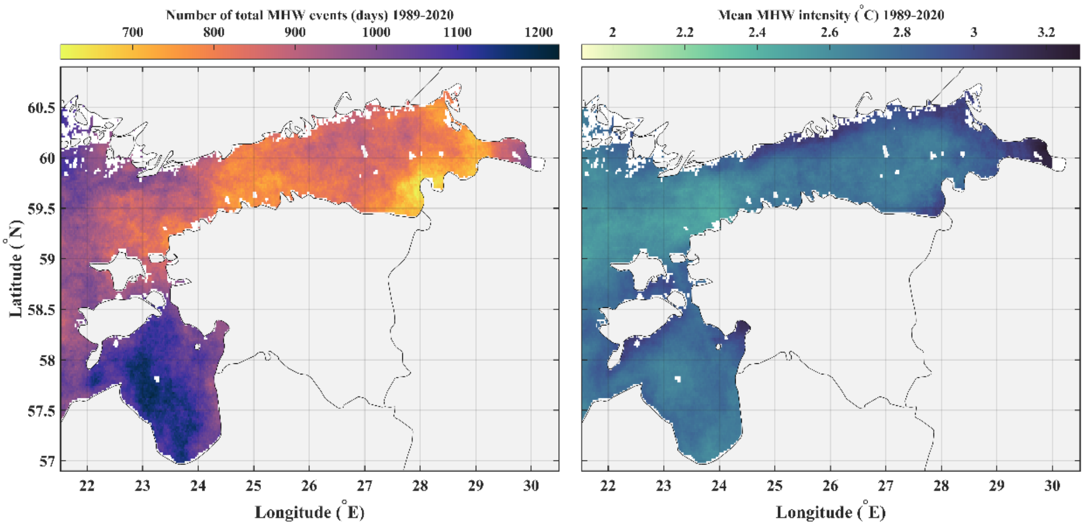

Figure 5. Number of total MHW days that have occurred (left) and mean intensity of MHWs (right) from 1989 to 2020.

The time series of MHW days for subregions with trend lines (Figure 6) gives an overview of frequency and decadal trend of MHW days during the period of 1989-2020.

The EGoF had the highest number of MHW days in a single year during the study period, with 333 MHW days. In contrast, the WGoF, GoR, and Ent-GoF had the most MHW days in 2020, with 233, 261 and 260 MHW days, respectively, which is significantly less than the EGoF MHW days in 2011.

The trend lines for the MHW days time series indicate a decadal increase in MHW days. Particularly, an increasing trend is present in the EGoF, WGoF, GoR, and Ent-GoF subregions, with increases of 30, 32, 30, and 36 MHW days per decade, respectively. Meaning the MHW events have been becoming longer during the study period.

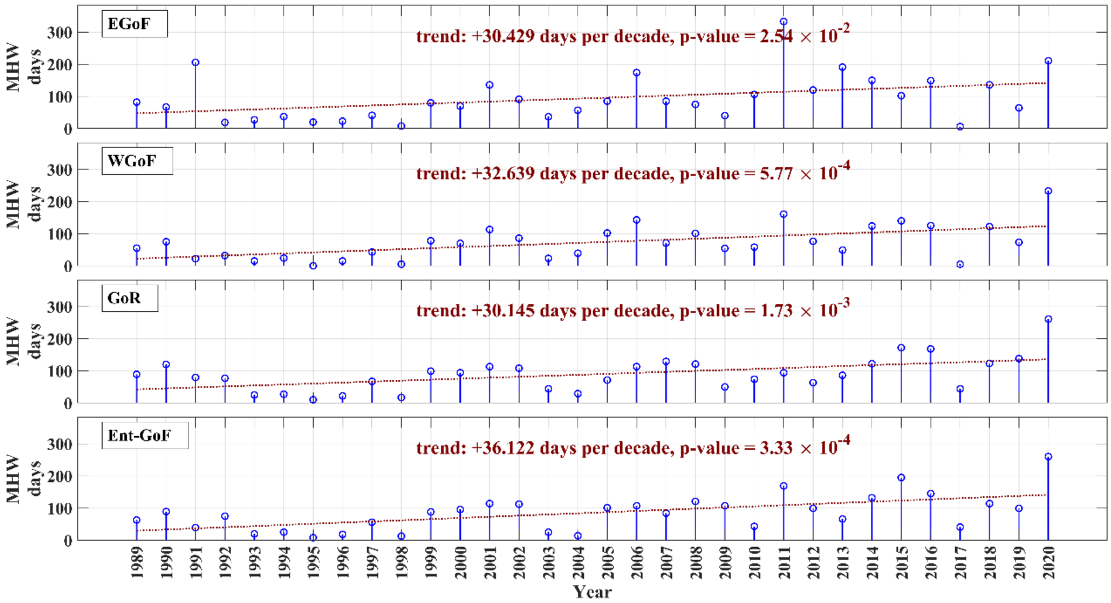

Figure 6. Mean MHW days time series for subregions with trend line 1989-2020.

The time series of mean MHW intensity for each subregion with trend line (Figure 7) provides information about MHWs intensity during the whole study period. The mean MHW intensity values for each subregion were shown on the time series graphs only when the MHW events had occurred.

The most intensive MHWs in the EGoF, GoR, and Ent-GoF occurred in the spring of 2018, with intensity values of 9°C, 7.3°C, and 6.6°C, respectively. In the spring of 2016, the western GoR had the most intense MHW, with an intensity of 7.5°C. The intensity of MHWs was often highest in the spring and summer, and with lower intensity but longer duration occurrences in the winter.

Overall, the analysis of the mean MHW intensity time series for each subregion indicated an upward trend in MHW intensity for the study period. All the subregions had the same mean intensity trend, 0,12°C per decade. The intensity is expected to rise the same amount in each subregion, and it is not affected by the frequency or intensity of MHWs.

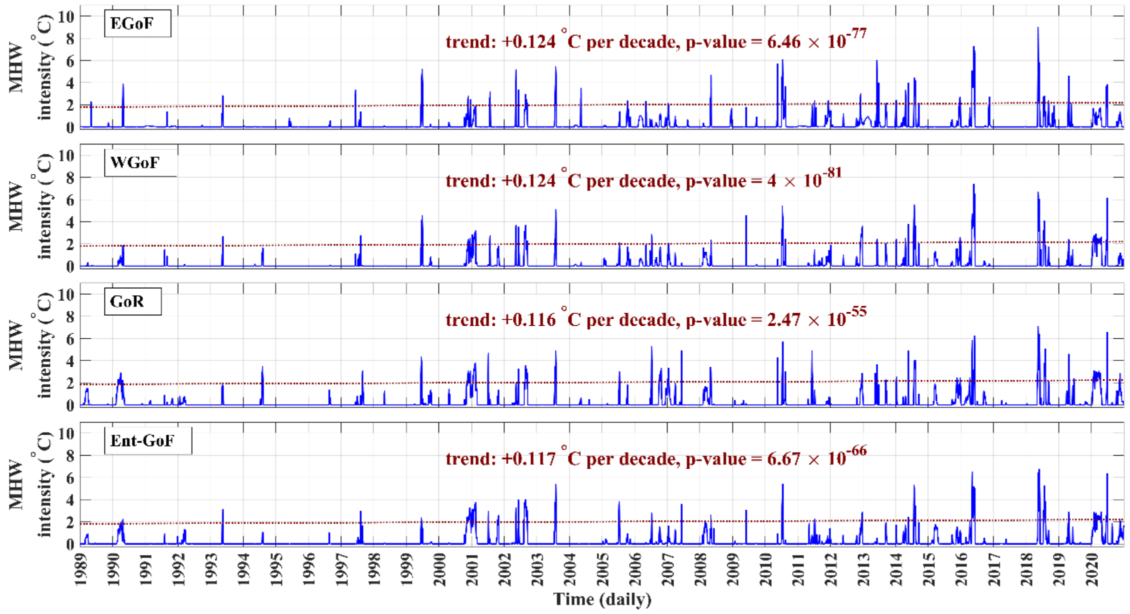

Figure 7. Mean MHW intensity time series for subregions with trend line 1989-2020.

3.2 Sea Surface Height and Extreme Sea Level statistics

The SSH mean and maximum maps (Figure 8) provide an overview of the mean and daily mean of maximum values for the study period of 1993–2021. The maps were produced using data from altimeters (satellites).

The mean SSH values varied spatially over the study region. The mean SSH in the GoF increased from west to east. In the Ent-GoF, it ranged from 0,36 to 0,37 m, in the WGoF it was between 0,37 m and 0,41 m and was highest in the eastern part of the gulf, over 0,41 m. In contrast, the GoR had the lowest mean SSH, which varied from 0,35 to 0,36 m.

Similar to the mean SSH, the daily mean of maximum SSH in the GoF throughout the study period rised from west to east. The maximum SSH values ranged from 1 m to 1,05 m in the western area of the gulf and above 1,1 m in the eastern part. The southern coastal areas of the Ent-GoF had the greatest SSH, with highest of 1,05 m. However, the majority of the open sea had maximum values between 0,95 m and 1 m. The daily mean of maximum values in the GoR increased in the north-eastern region and reduced toward the south-west. Despite this, the maximum SSH for the whole GoR ranged from 1 m on the south-west coast to over 1,1 m in the north-east. Daily mean of maximum SSHs were highest in specific coastal areas, in the north-eastern of GoR and EGoF.

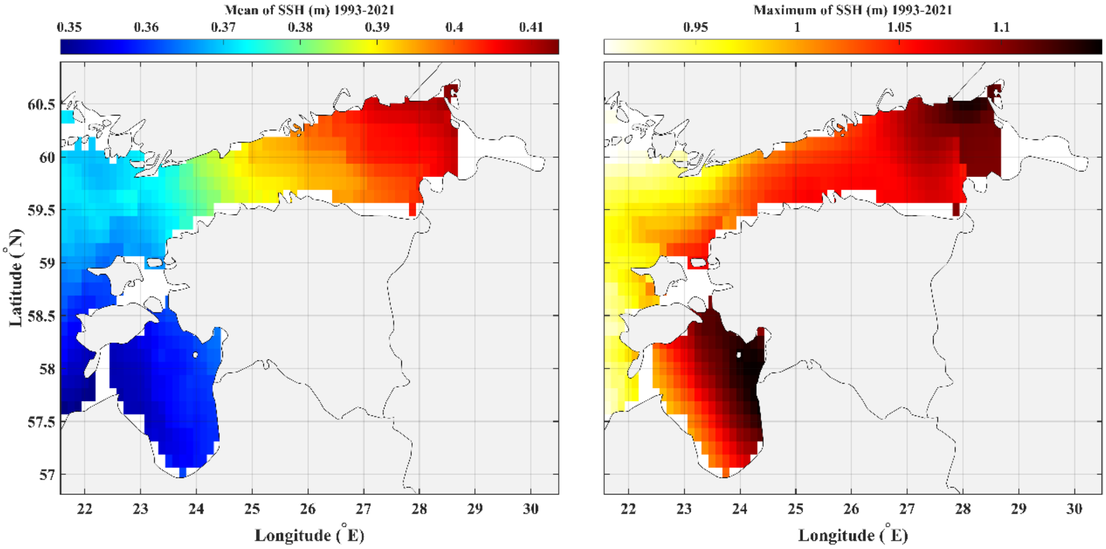

Figure 8. Mean (left) and maximum (right) SSH 1993-2021.

The spatial distribution of ESL frequency and intensity during the length of the 29-year study period is shown in the map of total days that ESL has occurred and mean intensity of ESL occurrences (Figure 9).

ESL days were prevalent in the Ent-GoF and WGoF, where extreme days occurred over 1180 days in 29 years. Moving further to the EGoF, the frequency of extreme days reduced to 980-1000 days. The number of ESL days in the GoR was higher in the northern part of the gulf, ranging between 1120 and 1160 days. In the rest of the gulf, there were extreme days commonly around 1080. ESL days occurred more in coastal areas, which were closer to the Open Baltic Sea.

The mean intensity of ESL occurrences in the GoF were between 0,26 m and 0,28 m intensifying towards the eastern part of the gulf. Ent-GoF had higher intensity in east and south, but when moving more towards the open sea, the intensity decreased to 0,25 m. ESLs were the most intense in the semi-closed area, the GoR, where the mean intensity was higher in the eastern part of the gulf, reaching 0,3 m. The GoR, which is a more enclosed gulf, had a greater ESL intensity than the more open and larger GoF.

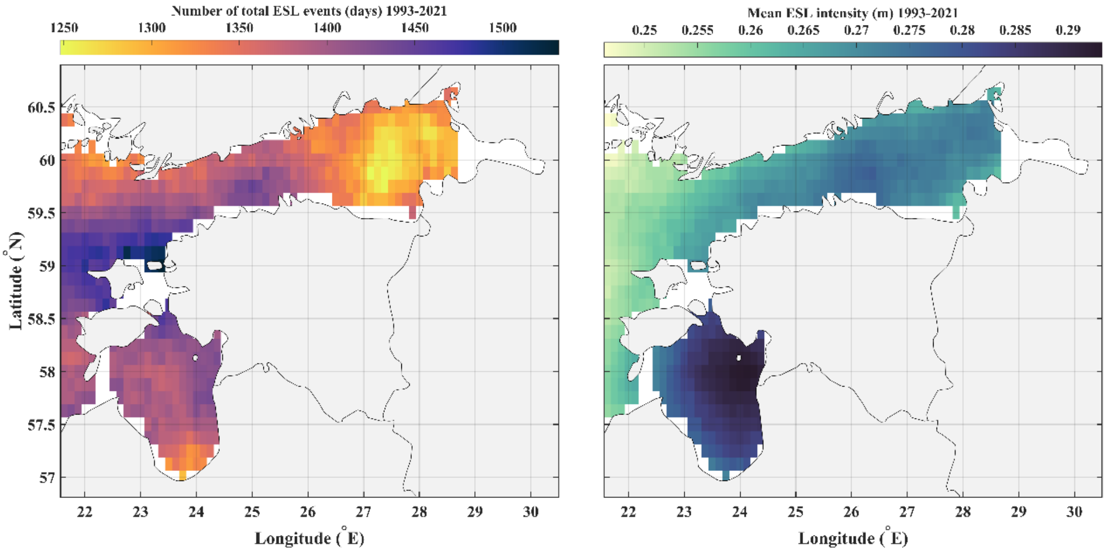

Figure 9. Number of total ESL events that have occurred (left) and mean intensity of ESLs (right) from 1993 to 2021.

The frequency and decadal trend of ESL days through the period of 1993–2021 are shown in the time series of ESL days for subregions with trend lines (Figure 10).

In 2020 all the subregions had their highest number of ESL days during the period of 1993-2021. In that year most ESL days occurred in the EGoF, 239 days. The WGoF, GoR and Ent-GoF had 216, 221 and 210 ESL days, respectively.

All subregions observed a noticeable rise in the frequency of ESL occurrences, according to the trend analysis of ESL days time series data. The GoR had the highest trend value, 35 days per decade. The EGoF and Ent-GoF ESL days trend lines had slightly lower values, 33 days, and the WGoF trend indicated 32 days per decade increase. In conclusion, trend lines indicate that ESL days are expected to increase in every subregion.

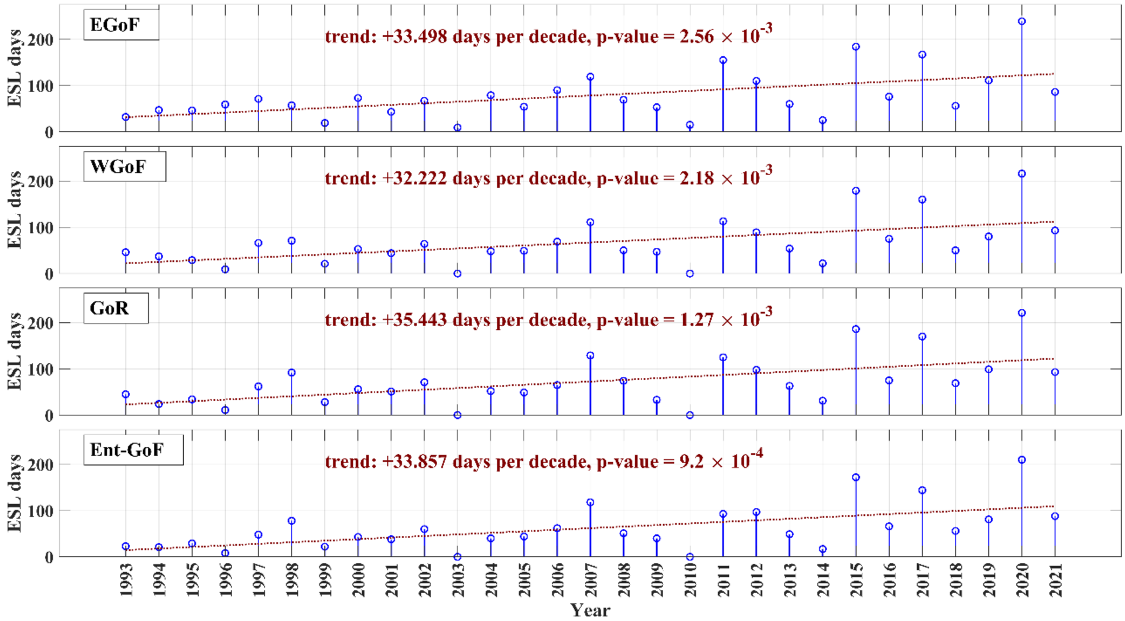

Figure 10. Mean ESL days time series for subregions with trend line 1993-2021.

The time series of ESL mean intensity for each subregion (Figure 11) provides data about variances in ESL intensity and each subregion's trend from 1993 to 2021.

Each subregion's most intense ESL events took place in December 2015. The intensity in the EGoF and WGoF was 0,61 m, while the Ent-GoF had a mean intensity of 0,55 m. The GoR experienced the highest intensity, with a mean intensity of 0,69 m.

Overall, the trend lines indicate that ESL occurrences have increased over time. In the early years of the study period, there were few low intensity events per year, or even years without any extremes. However, ESL occurrences occurred regularly with higher and lower peaks in the last decade of the study. The trend lines show 0,02 m intensity increase per decade for each subregion (Ent-GoF, WGoF, EGoF and GoR).

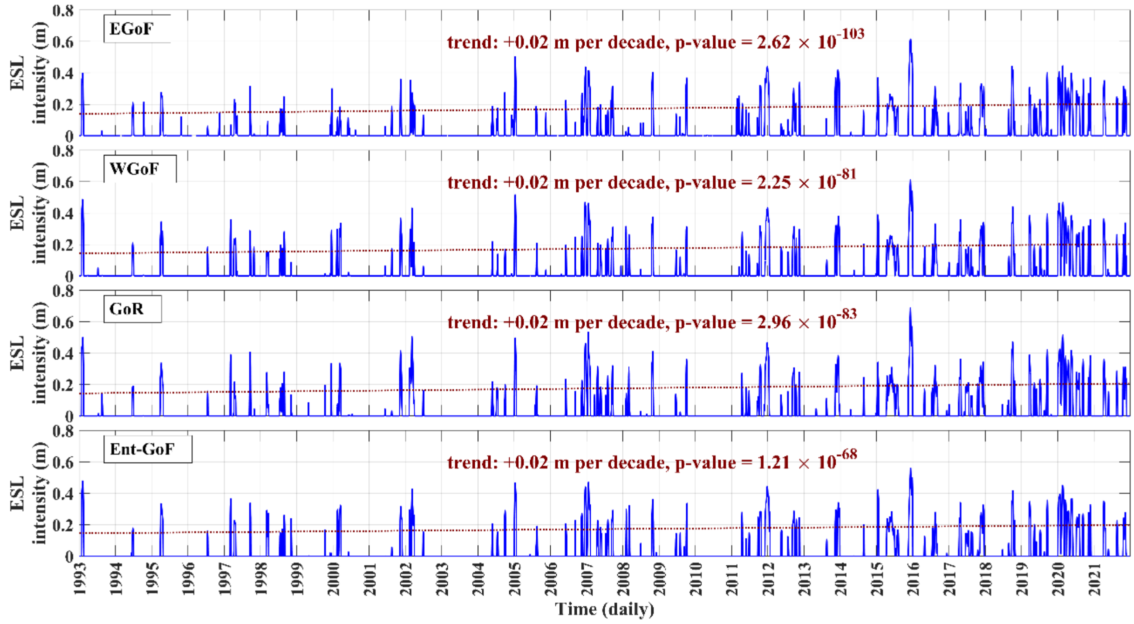

Figure 11. Mean ESLs intensity time series for subregions with trend line 1993-2021.

3.3 Significant Wave Height and Extreme Wave Height statistics

The spatial distribution of mean and daily mean of maximum SWHs from 1993 to 2021 is shown in the SWH mean and maximum map (Figure 12). The hindcast model was used to create the map.

Mean SWHs were the highest in the Ent-GoF, reaching to 1 m or even more. In the middle part of the entire GoF, the wave height was around 0.8 m, while in the coastal areas the wave height was 0.4 m. Also, in the middle part of the GoR the mean SWH was higher than the coastal area, respectively 0,8 m and 0,4-0,6 m.

The daily mean of maximum SWHs were almost the same height across the entire GoF. The Ent-GoF had slightly higher SWHs, up to 5 m. In the WGoF, the daily mean of maximum SWHs had highest values in the middle part of the gulf, and in the EGoF SWHs were slightly lower in the southern part compared to the northern part. In the GoR the SWHs were consistently the same height, around 4 m, only in the Gulf of Pärnu SWHs were lower, 2 m or below. Overall, daily mean of maximum values for the entire study area were similar, even when the mean values were significantly different.

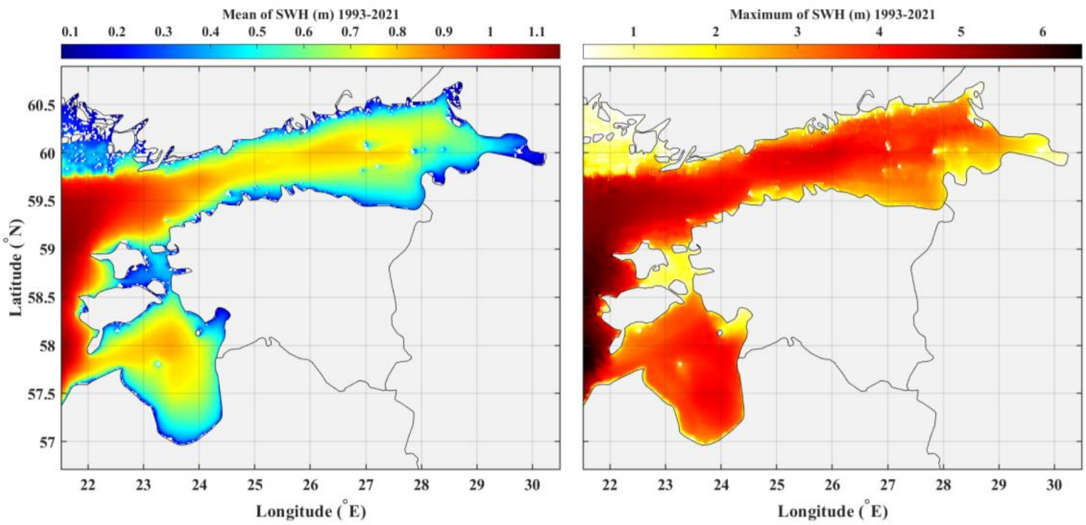

Figure 12. Mean (left) and maximum (right) SWH 1993-2021.

The map showing the total EWH days that have occurred and the mean intensity of EWHs (Figure 13) provides a spatial distribution of SWH extreme days and an intensity of extreme SWHs throughout the duration of the 29-year study period.

The coastal areas had the most EWH days. EWH occurrences were more frequent in the south-west, as well as in the eastern and south-eastern parts of the GoF. These locations had at least 60 days of extreme occurrences. Ent-GoF had 50-60 extreme days during the 29-year period, which is slightly higher than in the middle part of the GoF, where extreme days occurred in 20-50 days. EWH events happened most often in the coastal regions of the GoF, totalling 60 to 80 days. There were 30 to 50 extreme days in the centre of the gulf.

The Ent-GoF had mean intensity of EWH events reaching heights of 1,6 m. The intensity in the centre of the GoF ranged from 0,9 to 1,2 m, while it was lower towards the shore at roughly 0,2-0,4 m. Furthermore, the mean EWH intensity in the GoR was greater in the middle of the gulf (0,8-1,2 m) than in the coastline regions (0,4-0,6 m).

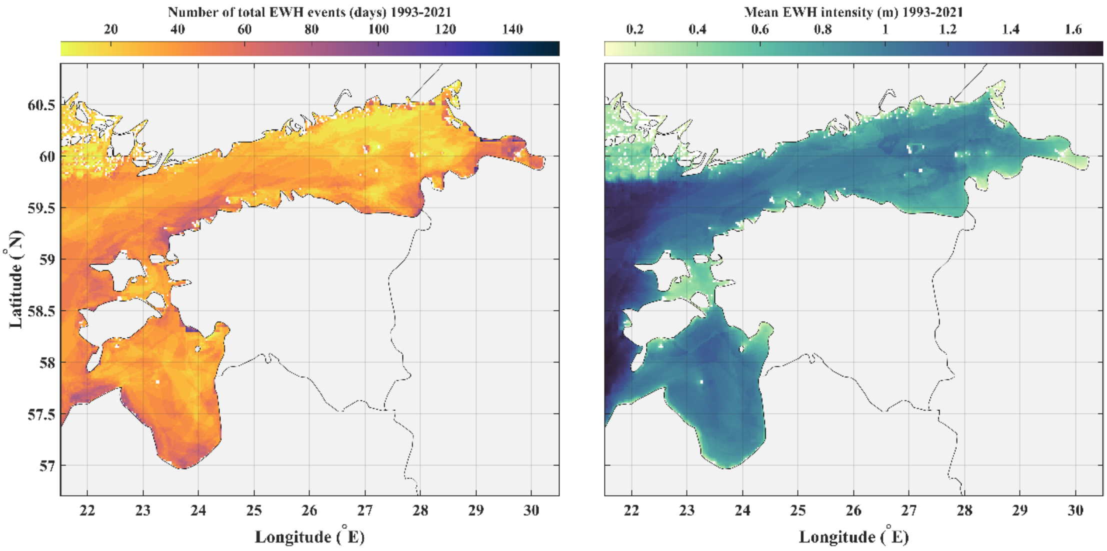

Figure 13. Number of total EWH events (left) and mean intensity of EWHs from 1993 to 2021.

The time series of mean EWH days for subregions with trend line (Figure 14) provides information about EWH day occurrences in every year during the study period.

Over the period of 1993-2021, yearly EWH days have varied in each subregion. The Ent-GoF had the lowest EWH days and variation during the study period in comparison to the EGoF, WGoF and GoR. All the subregions had the highest number of EWH days in 2020, when EGoF, WGoF, GoR and Ent-GoF had 107, 76, 66 and 52 EWH days, respectively.

The trend lines indicated an increasing number of EWH days in EGoF, WGoF and GoR, with 11, 4 and 1 day per decade, respectively. On the other hand, the Ent-GoF has a slightly decreasing trend value. But only EGoF out of 4 subregions had a statistically significant trend, which means other subregions might have a random variability in EWH days.

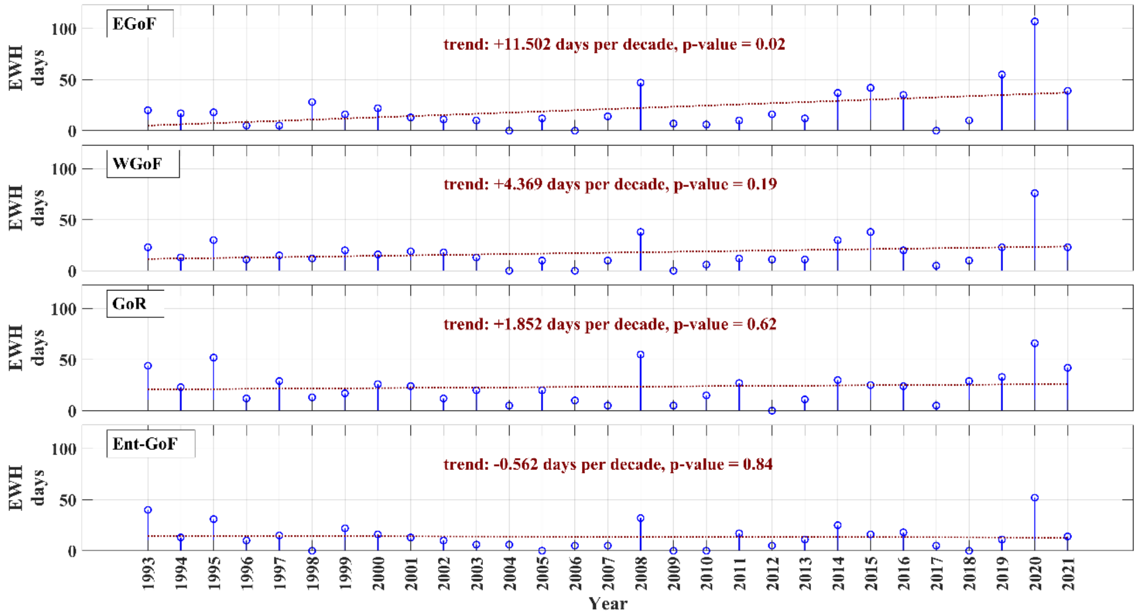

Figure 14. Mean EWH days time series for subregions with trend line 1993-2021.

An overview of the intensity of EWH during the duration of the whole study period is presented by the time series of EWH mean intensity for each subregion with trend line (Figure 15).

In the last decade of the study period the frequency of higher intensity events had increased compared to the period preceding the last decade. In addition, compared to the Ent-GoF and WGoF, the intensity of EWH events had been lower in the EGoF and the GoR.

The WGoF and the Ent-GoF had the highest intensity of EWH in the last ten years of the study period in the summer of 2020, with intensities of 1.09 m and 1.02 m, respectively. EWH events with intensities of 0.55 m and 0.82 m, respectively, occurred in the EGoF in the summer of 2016 and in the GoR in the summer of 2013.

The trend analysis of the subregions' EWH intensities does not indicate a noticeable increasing intensity trend of EWH between 0,001 m to 0,002 m per decade during the period of 1993-2021. It reveals that during the study period, the intensity of EWHs in the Baltic Sea subregions remained stable.

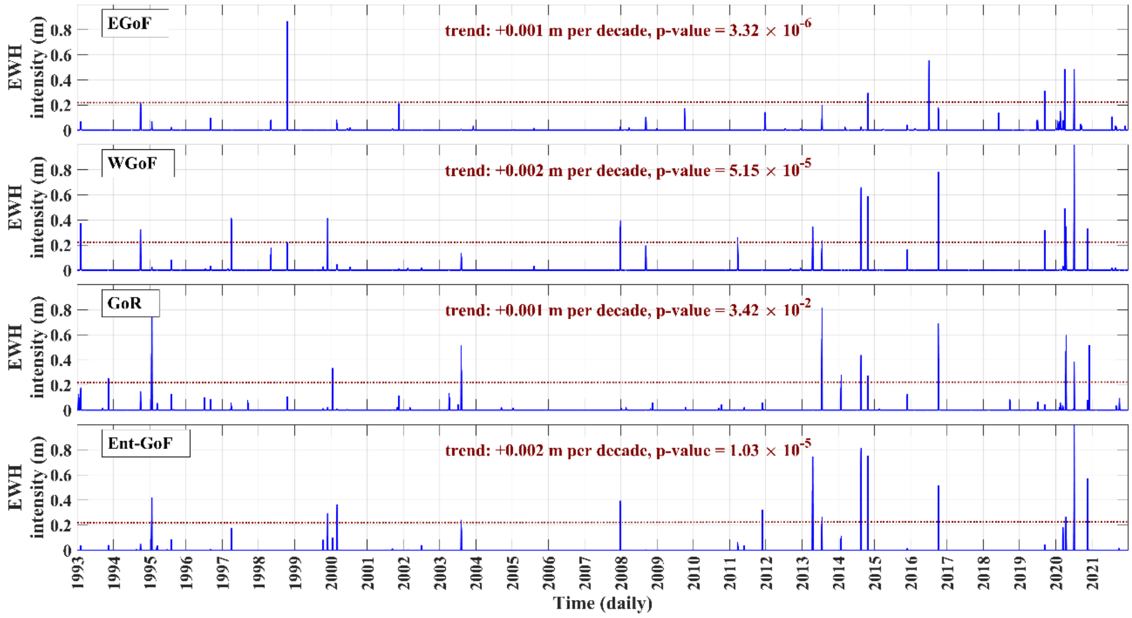

Figure 15. Mean EWH intensity of subregions with trend line 1993-2021.

4 Discussion

4.1 Temporal trends

This chapter focuses on discussing the differences and similarities of subregions' spatial mean trends of SST, SSH and SWH, extreme event days and extreme event intensities. The temporal trends for each subregion parameter were calculated and shown with the time series in the results section. Also, the trend for each subregion spatial mean SST, SSH and SWH was calculated separately and added to the table, which all were statistically significant (Table 2).

Table 2. Table of decadal trends of each parameter for subregions. Red colour indicates a not significant trend with p-value >0,05.

			Subregions			
			EGoF	WGoF	GoR	Ent-GoF
Trends (per decade)	1989-2020	SST (°C)	0.55	0.56	0.50	0.54
		MHW days	30.43	32.64	30.15	36.12
		MHW intensity (°C)	0.12	0.12	0.12	0.12
	1993-2021	SSH (m)	0.05	0.05	0.05	0.04
		ESL days	33.50	32.22	35.44	33.86
		ESL intensity (m)	0.02	0.02	0.02	0.02
	1993-2021	SWH (m)	0.03	0.02	0.01	0.01
		EWH days	11.50	4.37	1.85	-0.56
		EWH intensity (m)	0.001	0.002	0.001	0.002

The mean SST decadal trend indicates increases in the SST in the GoF. The values were similar in the EGoF, WGoF and Ent-GoF (0,54°C to 0,56°C per decade). It means that SST in the whole GoF area has been increasing at the same rate. Additionally, the GoR's SST trend was in the same magnitude as in the GoF, 0,50°C. The trend values for SST are similar to study by Jamali et al. (2022), where the trend for the GoF was 0,36 ± 0,41°C and for GoR it was 0,45 ± 0,31°C. The Ent-GoF's MHW days trend was the highest of all subregions, increasing 36 days per decade. The trends in the GoF decreased from the west to east. Meaning, the MHW days trend was higher in the GoF's area where MHW days occurred more frequently, according to Figure 5. In contrast, the GoR behaves differently, it had the lowest trend of MHW days, 30 days per decade, but it had the highest number of MHW days in the whole study area. The MHW intensity trend is the same in every subregion, 0,12°C per decade. Meaning, the MHWs intensity rise is predicted to be the same in the whole study area.

The SSH has risen in all subregions, the most in the GoR, EGoF and WGoF, 0,05 m per decade. However, in the Ent-GoF SSH has risen only 0,01 m per decade less, which means that SSH has a similar increase trend in each subregion. Mean SSH trends from other studies have shown a slightly smaller increase in the GoR, 0,01-0,04 m per decade, depending on the exact location of measurement (Männikus et al., 2020; Suursaar & Jaagus, 2006). In the WGoF and EGoF, a study by Suursaar & Sooäär (2007) indicated a mean SSH trend between 0,01-0,02 m per decade. Also, the ESL days trend is similar in each subregion, highest in the GoR with an increase of 35 days per decade, 33 day increase is in the Ent-GoF and EGoF, and in the WGoF it is 32 days per decade. The ESL intensity trend indicates the same rise per decade for each subregion, 0,02 m.

The mean SWHs had a considerable positive trend in the EGoF and WGoF, 0,03 m and 0,02 m per decade. In the Ent-GoF, which is open to the Baltic Sea, and in the GoR were the trends relatively lower, 0,01 m per decade. Meaning the SWHs are expected to rise more in the GoF, rather than the area open to the Baltic Sea or the GoR, which is also mentioned in the study by Soomere & Räämet (2011). In addition, the trend of EWH days indicates a significant upward trend in the EGoF, 11 days per decade. Other subregions' trends were not statistically significant, meaning they did not have sufficient reliability. The EWH intensity trends reveal a very minor rise in each sub-region, which has little to no long-term impact. Additionally, a low trend on EWH indicates decadal variability in EWH, which is mentioned in the study by Soomere & Räämet (2014).

4.2 Extreme event hotspots

Extreme event hotspots based on the extreme event maps are in the Pärnu Bay, north-western coastal area of Estonia and Narva Bay in the WGoF. The locations of the hotspots are shown in Figure 1.

Pärnu Bay is a hotspot for the MHW and ESL. The Pärnu Bay is very shallow, meaning the water in general warms up faster and MHW occurrences are frequent and very intensive. ESL occurrences in the Pärnu Bay are not as frequent as in the north-western coastal area of Estonia, but these are very intensive. The ESL is mostly caused by strong west and south-western winds, which push the water into Pärnu Bay and cause the water level to rise (Suursaar et al., 2003).

In the north-western coast of Estonia there is a hotspot for EWHs. Both, the number of extreme event days and intensity were high in this area. Meaning that extreme events occurred there more often than in the nearby areas and SWHs intensities were significantly higher compared to nearby areas.

In addition to the Pärnu Bay, Narva Bay was an MHW hotspot. In comparison to the centre of WGoF, Narva Bay is also a shallower area. The MHWs were very intense there, however the extreme events were less frequent compared to the Pärnu Bay.

4.3 Socio-economic impact on areas of interest

Based on the analysis of extreme events, three areas of increased interest are discussed in this chapter and the locations of the areas of interest are shown in Figure 1.

The coastal areas of the Bay of Tallinn are heavily populated and there are several minor and larger ports along the coastline, therefore it is an area with elevated interest. According to the results, there were around 800 MWH, 1400 ESL and 60 EWH days and the mean intensity was 2,5°C, 0,27 m and 0,4-0,6 m, respectively. The ESL and EWH are important extremes in the area because they have the potential to damage ports, coastal infrastructure, and buildings. The algal bloom, which could affect people's quality of life, can be accelerated by increased SST values, which MHWs indicate to.

In the GoR there is an area planned for wind farms, which is 40 km away from the Pärnu coast (Liivi Lahe Meretuulepark). Operating vessels in this area must be resistant to the extreme conditions in the sea, which is why it is important to know the statistics of high waves and sea level in this area. According to the results, the daily mean of maximum SSH has been in this area over 1,1 m and the daily mean of maximum SWH was 4 m, a total number of 1400 ESL and 40 EWH days occurred, and the mean intensity was 0,29 m and 1 m, respectively. The SSH and SWH maximum show how high values should be considered when building and operating wind farms. These extremes can cause problems for navigation and operating/servicing the wind farm.

Väinameri is a shallow sea area, located between the GoR and Ent-GoF. There is relatively intense ship traffic between the mainland and the islands. Furthermore, due to its low depth, there is rich bottom flora and fauna. Extremes, such as MHW, EWH and ESL could have an influence on the area by reducing seabed life, limiting navigability and affecting the coastal ecosystems. According to the results, the highest SST was 25-26°C, there were 900-1000 MHW days, and the mean intensity was around 2,8°C. Because of the poor resolution of the data, there is no relevant information for SSH. However, there is data on SWH. In the Väinameri, the daily mean of maximum SWH was 2 m. A total of 20-40 EWH days occurred, with a mean intensity of around 0.4 m.

5 Conclusions

Based on the CMEMS data (SSH, SWH, SST) analysis (spatial maps and temporal trends) the extremes in the Eastern Baltic Sea were mapped. The main findings are:

1. MHW events occurred most frequently in the GoR (1200 MHW days), and the intensity was highest in the coastal areas of GoF and Pärnu Bay (2,9-3,2°C). ESL events had the highest frequency in the Ent-GoF (+1180 ESL days) and were most intense in the GoR (0,3 m). EWH events occurred most frequently in the NW Estonia’s and EGoF’s coastal area (60-80 EWH days) and the intensity was the highest in Ent-GoF (1,6 m).

2. All parameters, which had a statistically significant trend, had an upward increase in all values. The MHW and ESL day trends had noticeable increase in all subregions (30-36 MHW days and 32-35 ESL days per decade), also EWH days in EGoF had significant increase (11 EWH days per decade). Extreme intensity trends were in large scale the same in every subregion for MHWs (0,12°C per decade), ESLs (0,02 m per decade) and EWHs (0,001-0,002 m per decade).

3. Regions which are impacted the most by the extremes in the Eastern Baltic Sea are:
   a. Pärnu Bay with frequent MHWs and intensive ESLs;
   b. north-western coast of Estonia with frequent and intense EWHs;
   c. Narva bay with intense MHWs, but not as frequent as in the Pärnu bay.

4. Areas in interest with socio-economic impact are:
   a. Bay of Tallinn, where extremes have potential to damage ports, coastal infrastructure and buildings. Also, floods and algal blooms can affect health of humans and animals, as well as have impact on ecosystem functioning;
   b. Vessels operating in the GoR's wind farming area must withstand extreme conditions caused by ESL and EWH, which can cause problems for navigation;

c. Väinameri, with its shallow depth, is influenced by MHW, ESL and EWHs. These extremes could affect bottom flora and fauna, navigability and coastal ecosystems.

Summary

Earth's climate system is impacted by dynamics of the oceans. Therefore, it is important to understand changes and extremes in the marine environment to be able to forecast and mitigate the climate change consequences. The thesis's general objective was to study SST, SWH and SSH extremes (extent, frequency, intensity) in the Eastern Baltic Sea, which are respectively MHW, EWH and ESL.

The study area was divided into four subregions: Ent-GoF, EGoF, WGoF and GoR, which made it possible to study each region separately. All data used in the thesis was downloaded from CMEMS. Satellite data covering the time period of 1989-2020 was used for the sea surface temperature analysis. A satellite altimetry product from the time period of 1993-2021 was used for sea level height analysis and for wave height analysis model hindcast product was used with time range of 1993-2021.

All the extremes (MHWs, EWHs and ESLs) were identified using the same criteria. To consider an event as an extreme event, it had to exceed the 90% threshold of absolute maximum value for at least 5 days in a row. The *m_mhw* toolbox was used in MATLAB to detect extremes for each parameter. Maps and time series with trend lines were generated based on the data and extreme event analysis.

After analysing the data, results were obtained for SST, SSH, and SWH and their extreme events. The SST and MHW results showed that mean SST ranged from 7,5-9°C, increasing from north to south and daily mean of maximum values were highest in the EGoF and GoR, 27-29°C. MHW days occurred most often in the GoR, up to 1200 days during 32 year period. The mean intensity of MHWs was highest in Pärnu Bay (3,1°C). MHW intensity was generally higher in the coastal areas when compared to offshore areas.

The SSH and ESL results indicated that mean SSH was higher in the GoF and increased from west to east (0,36-0,41 m). The daily mean of maximum values showed the same spatial distribution pattern to the mean values in the GoF (0,95-1,1 m). Maximum values were highest in the north-east of GoR and EGoF (+1,1 m). The ESL days were most frequent in the Ent-GoF and WGoF (+1180 ESL days). The mean intensity in the GoF

had a similar pattern to the maximum values, increasing from west to east (0,26-0,28 m). Mean ESL intensity was highest in the GoR (0,3 m).

The SWH and EWH results showed that mean SWH was higher in the Ent-GoF (1 m) and in the middle of the GoF and GoR (0,8 m). In the coastal areas mean SWH were relatively lower (0,4 m). The daily mean of maximum SWH was in the GoF and GoR around 4-5 m, similar across the whole study area. The EWH days were most frequent in coastal areas GoF and GoR (60-80 EWH days). The mean intensity of EWHs were highest in the Ent-GoF (1,6 m), in the GoF between 0,9-1,2 m and in the GoF around 0,8-1,2 m.

The trends were calculated for SST, SSH, SWH and for their extreme (MHW,ESL and EWH) days and intensity, and the similarities and differences among the subregions were discussed. Most noticeable were MHW and ESL days trends, which increased in all subregions (30-36 MHW days and 32-35 ESL days per decade). Additionally, the EWH days trend in the EGoF had a noticeable increase, 11 EWH days per year. The MHW and ESL mean intensity trends were the same in each subregion, 0,12°C and 0,02 m per decade, respectively.

The extreme event hotspots based on the results were Pärnu Bay with both frequent and intensive MHWs and intensive ESL events, the north-western coast of Estonia with frequent and intensive EWHs and Narva Bay with intense MHWs. The areas of interest with socio-economic impact are Bay of Tallinn, GoR’s wind farming area and Väinameri. The Bay of Tallinn is a highly populated coastal area, where ESLs and EWHs could cause damage to infrastructure and MHWs accelerate the algal blooms, affecting humans and ecosystems. In the GoR’s wind farming area SSH and EWH could cause navigation issues to operate the wind farm. Väinameri is a shallow sea area with rich bottom flora and fauna, where MHWs and ESLs could affect seabed life, navigability and coastal ecosystem.

Based on the thesis objectives and results, all objectives were achieved fully. The thesis' findings may be applied to coastal and offshore planning, for research purposes to study how extreme events have impacted the marine environment, and to get a comprehensive understanding of marine extreme event occurrences in the Eastern Baltic Sea. Furthermore, based on the findings of this thesis, it is possible to improve the study by focusing more specifically on the extreme event of interest.

Lühikokkuvõte

Kaugseire ruumiandmete analüüs ekstreemsete loodusnähtuste kaardistamiseks Läänemere idaosas

Siret Räämet

Maa kliima süsteem on mõjutatud ookeanite dünaamikast ning nende protsesside mõistmine on oluline prognooside tegemiseks ning kliimamuutuse tagajärgede kohanemisega valmistumiseks. Muutused merekeskkonnas mõjutavad nii inimesi kui ka ümbritsevat keskkonda, looduslikku mitmekesisust ja ökosüsteeme. Muutuste tuvastamiseks on vaja neid eelnevalt jälgida ning seejärel analüüsida.

Käesoleva lõputöö üldiseks eesmärgiks oli kaardistada Läänemere idaosas merevee pinnatemperatuuri, merevee taseme ning olulise lainekõrguse ekstreemseid sündmuseid. Nendeks sündmusteks on vastavalt merekuumalaine, ekstreemne merevee tase ning ekstreemne lainekõrgus. Uuritav ala, Läänemere idaosa (Soome laht ja Liivi laht), jagati neljaks piirkonnaks, milleks olid: Soome lahe suudmeala, lääne- ja idaosa ning Liivi laht.

Analüüsis kasutati Copernicus merekeskkonna seire teenuse (CMEMS) produkte. Merevee pinnatemperatuuri produkti andmed olid kogutud ajavahemikus 1989-2020 ning merevee taseme ja olulise lainekõrguse produktide ajavahemik oli 1993-2021. Kasutati keskmistatud päevaseid väärtuseid. Ekstreemsete sündmuste tuvastamiseks kasutati samasid kriteeriume, s.t. keskkonna parameetri (merevee temperatuur, merevee tase, oluline lainekõrgus) väärtus pidi ületama 90% lävendit maksimaalsest väärtusest vastavas asukohas vähemalt 5 järjestikusel päeval.

Tulemuste kohaselt esines kõige rohkem merekuumalaine päevi Liivi lahes (1200 päeva) ning merekuumalainete keskmine intensiivsus oli kõrgeim rannikuäärsetel aladel Soome ja Pärnu lahes (2,9-3,2°C). Ekstreemse merevee taseme päevi esines enim Soome lahe suudmes, üle 1180 päeva ning antud sündmused olid kõrgeima keskmise intensiivsusega Liivi lahes (0,3 m). Ekstreemse lainekõrguse päevi esines enim Eesti looderannikul ja Soome lahe idaosa rannikualadel (60-80 päeva) ning intensiivsemad olid need Soome lahe suudmes.

Trendide analüüsi tulemuste põhjal olid kõikidel ekstreemsete sündmuste parameetritel, mis olid statistiliselt olulised, positiivne trend. Merekuumalaine ja ekstreemse merevee taseme päevade trend näitas märkimisväärset kasvu kõikides piirkondades (30-36 merekuumalaine päeva ja 32-35 ekstreemse merevee taseme päeva kümnendi kohta) ning lisaks osutas ka ekstreemsete lainekõrguste päevade trend Soome lahe idaosas 11 päevasele kasvule kümnendi kohta. Ekstreemsete sündmuste intensiivsuse trendid olid üldiselt sarnased kõikides piirkondades. Merekuumalaine, ekstreemse merevee taseme ja ekstreemse lainekõrguse keskmine intensiivsus oli kõikides piirkondades vastavalt 0,12°C, 0,02 m ja 0,001-0,002 m kümnendi kohta.

Koostatud kaartide põhjal olid ekstreemsete sündmuste koondumispaikadeks Pärnu laht sagedaste merekuumalainete ja intensiivsete ekstreemsete merevee tasemetega, Eesti looderannik sagedaste ja intensiivsete ekstreemsete lainekõrgustega ning Narva laht intensiivsete merekuumalainetega. Lisaks kirjeldati töös ekstreemsete sündmuste potentsiaalset mõju sotsiaalmajanduslikult huvipakkuvatele piirkondadele. Esimeseks piirkonnaks oli Tallinna laht, kus ekstreemsed sündmused võivad potensiaalselt kahjustada sadamaid ja rannikuäärseid ehitisi. Samuti võivad üleujutused ja vetikate õitsemine mõjutada inimesi, loomi ning ökosüsteemide toimimist. Teine piirkond oli planeeritav Liivi lahe tuulepark, kus ekstreemsed nähtused võivad tekitada navigatsiooni probleeme piirkonnas töötavatele laevadele. Kolmandaks piirkonnaks oli Väinameri, mis on madal, rikkaliku põhjaelustiku ning tiheda laevaliiklusega piirkond. Ekstreemsed olud võivad potensiaalselt mõjutada põhjaelustikku, laevatatavust ning ranniku ökosüsteeme.

Märksõnad: Ruumiandmed, Copernicus CMEMS, ekstreemsed sündmused merel, kliimamuutus, Läänemere idaosa

Resources

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