Natural Hazards and Extreme Events in the Baltic Sea Region

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Abstract

A natural hazard is a naturally occurring extreme event that has a negative effect on people and society or the environment. Natural hazards may have severe implications for human life and they can potentially generate economic losses and damage ecosystems. A better understanding of their major causes, probability of occurrence, and consequences enables society to be better prepared to save human lives, and to invest in adaptation options. Natural hazards related to climate change are identified as one of the Grand Challenges in the Baltic Sea region. We here summarize existing knowledge about extreme events in the Baltic Sea region with the focus on the past 200 years, as well as future climate scenarios. The events considered here are the major hydro-meteorological events in the region and include wind storms, extreme waves, high and low sea level, ice ridging, heavy precipitation, sea-effect snowfall, river floods, heat waves, ice seasons, and drought. We also address some ecological extremes and implications of extreme events for society (phytoplankton blooms, forest fires, coastal flooding, offshore infrastructures, and shipping). Significant knowledge gaps are identified, including the response of large-scale atmospheric circulation to climate change and also concerning specific events, for example, occurrences of marine heat waves and small-scale variability of precipitation. Suggestions for future research include further development of high-resolution Earth System Models and the potential use of methodologies for data analysis (statistical methods and machine learning). With respect to expected impacts of climate change, changes are expected for sea level, extreme precipitation, heat waves and phytoplankton blooms (increase), and cold spells and severe ice winters (decrease). For some extremes (drying, river flooding, and extreme waves), the change depends on the area and time period studied.

1 Introduction

Natural hazards and extreme events may have severe implications for society, including threats to human life, economic losses, and damage to ecosystems. A better understanding of their major causes and implications enables society to be better prepared, to save human lives, and to mitigate economic losses. Many natural hazards are of hydro-meteorological origin (storms, storm surges, flooding, droughts), and impacts can sometimes be due to a mixture of several factors (e.g. a storm surge in combination with heavy precipitation and river discharge).

In Europe in 2018, four severe storms caused almost 8bn$ in losses (Munich Re, 2018), while a heat wave and drought caused roughly 3.9bn$ in losses. According to the European Environment Agency (EEA), increases in frequency and/or magnitude of extreme events such as floods, droughts, wind storms, or heat waves will be among the most important consequences of climate change (EEA, 2010). Although climate change has received considerable scientific attention, knowledge about changing extremes and their impacts is still somewhat fragmented, in particular when it comes to compound events (Zscheischler et al., 2018). While confidence in knowledge about the relation between global warming and hot extremes is high, it is only medium with respect to knowledge about global warming's relation to heavy precipitation/drought (IPCC, 2018). Furthermore, the confidence level decreases when approaching the local scale (IPCC, 2014). Significant advances have occurred, but the understanding of mechanistic drivers of extremes and how they may change under anthropogenic forcing is still incomplete.

What is defined as "extreme" depends on the parameter and the application in relation to thresholds of the extreme to generate extreme consequences in society or ecosystems. A large amount of the available scientific literature is based on extreme indices, which are either based on the probability of occurrence of given quantities or on threshold exceedances. Typical indices include the number, percentage, or fraction of days of occurrence below the 1st, 5th, or 10th percentile, or above the 90th, 95th, or 99th percentile, generally defined for given timeframes (days, month, season, annual) with respect to the 1961–1990 reference time period (Seneviratne et al., 2012). Using predefined extreme indices allows for comparability across modelling and observational studies and across regions. Peterson and Manton (2008) discuss collaborative international monitoring efforts employing extreme indices. Extreme indices often reflect relatively moderate extremes, for example, events occurring during 5 or 10 % of the time. For more rare extremes, extreme value theory (EVT) is often used due to sampling issues. EVT (e.g., Coles, 2001) aims at deriving a probability distribution of events from the upper or lower tail of a probability distribution (typically occurring less frequently than once per year or per period of interest). Some literature has used other approaches for evaluating characteristics of extremes or changes in extremes, for instance, analysing trends in record events or investigating whether records in observed time series are being set more or less frequently than would be expected in an unperturbed climate (Benestad, 2003, 2006; Zorita et al., 2008; Meehl et al., 2009; Trewin and Vermont, 2010). Besides the actual magnitude of extremes (quantified in terms of probability/return frequency or absolute threshold), other relevant aspects from an impact perspective include the duration, the spatial area affected, timing, frequency, onset date, and continuity (i.e., whether there are "breaks" within a spell). There is thus no precise definition of an extreme (e.g. Stephenson et al., 2008). In particular, there are limitations in the definition of both probability-based and threshold-based extremes and their relations to impacts. In the reviewed literature, a variety of definitions are used.

The Baltic Sea watershed drains nearly 20 % of European land areas (see Fig.1). It ranges from the highly populated south, with a temperate climate and intensive agriculture and industry, to the north, where the landscape is boreal and rural. Changes in the recent climate as well as probable future climate change of mean parameters in the Baltic Sea region are relatively well described (e.g. BACC I, 2008; BACC II 2015; Rutgersson et al., 2014), but the uncertainty is greater for extreme events due to larger statistical uncertainties for rare events. Natural hazards and extreme events have been identified as one of the grand scientific challenges for the Baltic Sea research community (Meier et al., 2014).

Changes in extreme events can be caused by a combination of changes in local/regional conditions and changes of a larger scale; atmospheric circulation patterns are thus of crucial importance. Extreme events occur over a wide range of scales in time and space; short-term events range from sub-daily to a few days (basically meso-scale and synoptic-scale events) while long-lasting events range from a few days to several months. There is no clear separation between short-term and long-term events, and sometimes the presence of a long-term event may intensify the impact of a short-term one. We here summarize existing knowledge of extreme events in the Baltic Sea region. We focus on past and present states, as well as future climate scenarios and expected changes when possible.

The events considered here include wind storms, high and low sea level, heat waves, drought, ice seasons, heavy precipitation, sea-effect snowfall, river floods, ice ridging, and extreme waves. We also address some ecological extremes and some implications of extreme events for society (phytoplankton blooms, forest fires, coastal flooding, offshore infrastructures, and shipping). It should be noted that this is not a comprehensive summary but a selected number of aspects with implications for society. The text focuses on the current base of knowledge but also identifies knowledge gaps and research needs.

For almost three decades, knowledge about the Baltic Sea ecosystem has been systematically assessed, initially by BALTEX and, since 2013, by its successor, Baltic Earth. As a result, two comprehensive assessment reports have been released: BACC I (2008) and BACC II (2015). The present study is one of the thematic Baltic Earth Assessment Reports (BEARs), which comprises a series of review papers that summarize and assess the available published scientific knowledge on climatic, environmental, and human-induced changes in the Baltic Sea region (including its catchment). As such, the series of BEARs constitutes a follow-up of the previous BACC assessments. BEARs are constructed around the Grand Challenges and scientific topics of Baltic Earth (baltic.earth/grandchallenges) with a general summary (Meier et al., 2021).

1.1 Methods, past and present conditions

For the past and present conditions, we focus on time periods covering up to the last 200 years, to rely on robust in situ measurements only (not proxy data). The Baltic Sea area is relatively unique in terms of long-term data, with a dense observational network (compared to most regions) covering an extended time period, although many national (sub-) daily observations still await digitization and homogenization. The network of stations with continuous and relatively accurate measurements has been developed since the middle of the 19th century (a few stations were established in the middle of the 18th century). The period since about 1950 is relatively well covered by observational data. For some applications (e.g. heavy precipitation), the relatively low frequency of sampling is a limitation; this was improved with the establishment of automatic stations at the end of the 20th century. In spite of the relatively good observational coverage over a long time, lack of observations is a major obstacle for assessing long-term trends and past extreme events and for climate model evaluation. The density of the observational network is high compared to many regions, but still low compared to the resolution required for evaluation of today's most fine-scale climate models.

Despite shortcomings, a number of high-resolution gridded data sets derived from point-based observations exist at resolutions as high as a few kilometres for parts of the Baltic Sea region.

The inclusion of satellite data since 1979 added to the spatial information, particularly over data-sparse regions. However, data that span extended periods cannot be expected to be homogeneous in time. This is particularly important for the increasing number of reanalysis products that are available for the region. In a reanalysis, all available observations are integrated as increments into a numerical model by means of data assimilation in space and time. This works fine if the overall structure of the observing system does not change dramatically over time; however, when completely new observing systems (for example, observations from satellites) are introduced, this structure changes. Making use of all available observations, a frozen scheme for the data assimilation of observations into state-of-the-art climate models is used to minimize inhomogeneities caused by changes in the observational record over time. However, studies indicate that these inhomogeneities cannot be fully eliminated (e.g., Stendel et al., 2016). In addition, systematic differences between the underlying forecast models, such as due to their different spatial resolutions (Trigo, 2006; Raible et al., 2008) and differences in detection and tracking algorithms (Xia et al., 2012) may affect parameters such as cyclone statistics (for example, changes in their intensity, number, and position). Reanalysis products include NCEP/NCAR (from 1948 onwards; Kalnay et al., 1996; Kistler et al., 2001), ERA-Interim, starting in 1979 (Dee et al., 2011), and more recently, CERRA (Schimanke et al., 2019) and ERA5 (Hersbach et al., 2020). Other reanalyses use a limited data assimilation scheme to go further back in time, such as the 20th Century Reanalysis 20CR (from 1871 onwards; Compo et al., 2011). On the regional scale, detailed regional reanalysis products with higher-resolution models and more observations have been developed (e.g. Dahlgren et al., 2016; Kaspar et al., 2020).

1.2 Methods, future scenarios

The development of general circulation models (GCMs) has created a useful tool for projecting how climate may change in the future. Such models describe the climate at a set of grid points, regularly distributed in space and time. In some cases, dynamical downscaling with regional models or empirical-statistical downscaling using statistical models are also used. A large multi-model co-ordinated climate model experiment, CMIP Project Phase, was initiated; currently version 5 (CMIP5, Taylor et al., 2012) is the main source of information, while the next phase, CMIP6 (Eyring et al., 2016), is increasingly being used. Co-ordinated downscaling activities including regional climate models (RCMs) include those of the European research projects PRUDENCE (Déqué et al., 2007) and ENSEMBLES (Kjellström et al., 2013) as well as the WCRP-supported international CORDEX project with its European branch EURO-CORDEX (Jacob et al., 2014).

Projections of climate change depend inherently on scenario assumptions of future human activities. Widely used are the representative concentration pathways (RCPs) (van Vuuren et al., 2011). An RCP represents a climate-forcing scenario trajectory (e.g. including changes in greenhouse gas emissions, aerosols, land use, etc.) adopted by the IPCC for its Fifth Assessment Report (AR5) in 2014. RCPs describe different climate futures, all of which are considered possible depending on how strong the forcing of the climate system is. The four RCPs used for AR5, namely RCP2.6, RCP4.5, RCP6, and RCP8.5, are labelled after their associated radiative forcing values in the year 2100 (2.6, 4.5, 6.0, and 8.5 W/m^2, respectively (Moss et al., 2008; Weyant et al., 2009), relative to that in pre-industrial times, (e.g. 1750). RCP4.5 is used in many studies assuming increasing carbon dioxide emissions until 2040 and after that decreasing. RCP8.5 assumes a rapidly increasing carbon dioxide and methane emissions and is increasingly seen as an unlikely worst-case scenario (Hausfather and Peters, 2020). Prior to the RCPs, scenarios from the Special Report on Emission Scenarios (Nakicenovic et al., 2000) were widely used. The main scenario families included were: A1, representing an integrated world with rapid economic growth; A2, a more divided world with regional and local focus; B1, an integrated and more ecologically friendly world; and B2, a divided but more ecologically friendly world.

2 Current state of knowledge

2.1 Changes in circulation patterns

The atmospheric circulation in the European/Atlantic sector plays an important role for the regional climate of the Baltic Sea basin and the surrounding areas (e.g., Hurrell, 1995; Slonosky et al., 2000; 2001). Large-scale flow characteristics are among the main drivers of the connection between local processes and global variability and change. It is therefore essential to investigate the changes in large-scale flow. The main driver is the NAO (Hurrell et al., 2003); with quasi-stationary centres of action, the Icelandic Low and the Azores High, it is a measure of the zonality of the atmospheric flow. The dominant flow is westerly, but due to the large variability, other wind directions are also frequently observed.

The strength of the westerlies is controlled by the pressure difference between the Azores High and the Icelandic Low (Wanner et al., 2001; Hurrell et al., 2003; Budikova, 2009) and is expressed by the NAO index, which is the normalized pressure difference between these two regions. The NAO index varies from days to decades. The long-term (1899–2018) temporal behaviour of the NAO (Fig. 2) is essentially irregular, and there is large interannual to interdecadal variability, reflecting interactions with and changes in surface properties, including sea surface temperature (SST) and sea ice content (SIC). While it is not clear whether there is a trend in the NAO, for the past five decades, specific periods are apparent. Beginning in the mid-1960s, a positive trend towards more zonal circulation with mild and wet winters and increased storminess in Central and Northern Europe, including the Baltic Sea area, has been observed (Hurrell et al., 2003; Gillett et al., 2013). After the mid-1990s, however, there was a tendency towards more negative NAO indices, in other words, a more meridional circulation and more cold spells in winter, which can only occur with winds from an easterly or a northerly direction (see Sect. 2.2.3). Other studies (e.g., Deser et al., 2017; Marshall et al., 2020) do not find a significant long-term trend. It has been speculated that NAO changes are due to a shift of the Atlantic multidecadal variability (AMO) into the warm phase (Gastineau and Frankignoul, 2015).

Most of the state-of-the-art climate models reproduce the structure and magnitude of the NAO reasonably well (e.g. Davini and Cagnazzo, 2014; Ning and Bradley, 2016; Deser et al., 2017; Gong et al., 2017).

There is no consensus on how large a fraction of the interannual NAO variability is forced externally (Stephenson et al., 2000; Feldstein, 2002; Rennert and Wallace, 2009). Several such external forcing mechanisms have been proposed, including SST (Rodwell et al., 1999; Marshall et al., 2001), volcanoes (Fischer et al., 2007), solar activity (Shindell et al., 2001; Spangehl et al., 2010; Ineson et al., 2011), and stratospheric influences (Blessing et al., 2005; Scaife et al., 2005), including the quasi-biennial oscillation (Marshall and Scaife, 2009) and stratospheric water vapour trends (Joshi et al., 2006). Remote SST forcing of the NAO originating from as far as the Indian Ocean was proposed by Hoerling et al. (2001) and Kucharski et al. (2006), while Cassou (2008) proposed an influence of the Madden–Julian Oscillation. In addition, Blackport and Screen (2020) showed that recent observations suggest that the observed correlation between surface temperature gradients and circulation anomalies in the middle troposphere have changed in recent years.

Regarding sea ice, many authors have found an effect of sea ice decline on the NAO (Strong and Magnusdottir, 2011; Peings and Magnusdottir, 2016; Kim et al., 2014; Nakamura et al., 2015), while others (Screen et al., 2013; Sun et al., 2016; Boland et al., 2017) do not identify any dependence on changing sea ice extent. Furthermore, the interaction of changes in the Arctic on midlatitude dynamics is still under debate (Dethloff et al., 2006; Francis and Vavrus, 2012; Barnes, 2013; Cattiaux and Cassou, 2013; Vihma, 2017).

Atmospheric blocking refers to persistent, quasi-stationary weather patterns characterized by a high-pressure (anticyclonic) anomaly that interrupts the westerly flow in the mid-latitudes. By redirecting the pathways of mid-latitude cyclones, blockings lead to negative precipitation anomalies in the region of the blocking anticyclone and positive anomalies in the surrounding areas (Sousa et al., 2017). In this way, blockings can also be associated with extreme events such as heavy precipitation (Lenggenhager et al., 2018) and drought (Schubert et al., 2014).

A weakening of the zonal wind, eddy kinetic energy, and amplitude of Rossby waves in summer (Coumou et al., 2015) as well as an increased waviness of the jet stream associated with Arctic warming (Francis and Vavrus, 2015) in winter have been identified, which may be linked to an increase in blocking frequencies. Blackport and Screen (2020) argue that observed correlations between surface temperature gradients and the amplitude of Rossby waves have broken in recent years. Therefore, previously observed correlations may simply have been internal variability. On the other hand, it has been shown that observed trends in blocking are sensitive to the choice of the blocking index, and that there is a huge natural variability that complicates the detection of forced trends (Woollings et al., 2018), compromising the robustness of observed changes in blocking. A review by Overland et al. (2015) concluded that mechanisms remain uncertain as there are many dynamical processes involved, and considerable internal variability masks any signals in the observation record. There is weak evidence that stationary wave amplitude has increased over the North Atlantic region (Overland et al., 2015), possibly as a result of weakening of the North Atlantic storm track and transfer of energy to the mean flow and stationary waves (Wang et al., 2017).

The decrease of the poleward temperature gradient will lead to a weakening of westerlies and increase the likelihood of blockings. On the other hand, maximum warming (compared to other tropospheric levels) will occur just below the tropical tropopause due to the enhanced release of latent heat, which tends to increase the poleward gradient, strengthen upper-level westerlies, and affect the vertical stability, thus altering the vertical shear in mid-latitudes. It is not clear which of these two factors has the largest effect on the jet streams (Stendel et al., 2020).

State-of-the-art models are generally able to capture the general characteristics of extratropical cyclones and storm tracks, although many of them underestimate cyclone intensity and still exhibit comparatively large biases in the Atlantic/European sector (Davini and d'Andrea, 2016; Mitchell et al., 2017). IPCC has already stated that this is resolution-related (IPCC, 2013; Zappa et al., 2013). In addition, there is evidence for a correlation of the quality of simulations of cyclones and of blockings (Zappa et al., 2014).

There is significant natural variability of the atmospheric circulation over Europe on decadal time scales (Dong et al., 2017; Ravestein et al., 2018). Drivers of circulation changes have been proposed, including polar and tropical amplification, stratospheric dynamics, and the Atlantic meridional overturning circulation (AMOC) (Haarsma et al., 2015; Shepherd et al., 2018; Zappa and Shepherd, 2017). For more local changes, the attribution is more straightforward, where one example is the soil moisture feedback, for which an enhancement of heat waves due to a lack of soil moisture has been demonstrated (Seneviratne et al., 2013; Teuling, 2018; Whan et al., 2015).

Räisänen (2019) finds only a small impact of circulation changes on the observed annual mean temperature trends in Finland, but circulation changes have considerably modified the trends in individual months. In particular, changes in circulation explain the lack of observed warming in June, the very modest warming in October in southern Finland, and about a half of the very significant warming in December.

On a more global scale, CMIP5 simulations suggest enhanced drying and consequently an increase of summer temperatures due to more meridional circulation which would result in extra drying, particularly in spring. If that is the case, the summer soil moisture feedback would be enhanced (van der Linden et al., 2019; van Haren et al., 2015). Soil drying, for example, under extended blocking situations, would lead to non-linear interactions between atmosphere and land resulting in further temperature increase (Douville et al., 2016; Douville and Plazzotta, 2017; Seneviratne et al., 2013; Teuling, 2018; van den Hurk et al., 2016).

2.2 Extreme conditions (current knowledge, and potential future change)

2.2.1 Wind storms

In situ observations allow direct analysis of winds, in particular over sea (e.g., Woodruff et al., 2011). However, in situ information, especially over land, is often locally influenced, and inhomogeneities make the straightforward use of these data difficult, even for recent decades. Examples include an increase in roughness length over time due to growing vegetation or building activities, inhomogeneous wind data over the German Bight from 1952 onwards (Lindenberg et al., 2012), and “atmospheric stilling” in continental surface wind speeds due to widespread changes in land use (Vautard et al., 2010). Many studies turn down direct wind observations and instead rely on reanalysis products (see Sect. 1.1). However, analysis of storm track activity for longer periods using reanalysis data suffers from uncertainties associated with changing data assimilation and observations before and after the introduction of satellites, resulting in large variations across assessments of storm track changes (Chang and Yau, 2016; Wang et al., 2016).

Owing to the large climate variability in the Baltic Sea region, it is unclear whether there is a trend in wind speed. Results regarding changes or trends in the wind climate are thus strongly dependent on the period and region considered (Feser et al., 2015a, 2015b). Through the strong link to large-scale atmospheric variability over the North Atlantic, conclusions about changes over the Baltic Sea region are best understood in a wider spatial context, considering the NAO. The positioning of the jet stream and storm tracks and the strength of the north–south pressure gradient in the North Atlantic can largely explain the decadal changes in 10-m wind speeds in Northern Europe, with low windiness in winters of the 1980s and 2010s and high windiness of the 1990s (Laurila et al., 2021).

Recent trend estimates of the total number of cyclones over the northern hemisphere extra tropics during 1979–2010 reveal a large spread across the reanalysis product, strong seasonal differences, and decadal-scale variability (Tilinina et al., 2013; Wang et al., 2016; Chang et al., 2016; Matthews et al., 2016; Gregow et al., 2020). Common to all reanalysis data sets is a weak upward trend in the number of moderately deep and shallow cyclones (7 to 11 % per decade for both winter and summer), but a decrease in the number of deep cyclones in particular for the period 1989–2010. Chang et al. (2016) have reported a minor reduction in cyclone activity in northern hemisphere summer due to a decrease in baroclinic instability as a consequence of Arctic temperatures rising faster than at low latitudes. Chang and Yau et al. (2016) also notice that state-of-the art models (CMIP5) generally underestimate this trend. In northern hemisphere winter, recent studies claim an increase in storm track activity related to Arctic warming. Recent research (Feser et al., 2021) reveals no clear trend but reports an increasing similarity over time in reanalyses, observations, and dynamically downscaled model data.

Despite large decadal variations, there is still a positive trend in the number of deep cyclones over the last six decades, which is consistent with results based on NCEP reanalyses between 1958 and 2009 over the northern North Atlantic Ocean (Lehmann et al., 2011). Using an analogue-based field reconstruction of daily pressure fields over Central to Northern Europe (Schenk and Zorita, 2012), the increase in deep lows over the region might be unprecedented since 1850 (Schenk, 2015). For limited areas, the conclusions are rather uncertain. Past trends in homogenized wind speed time series (1959–2015), in both mean and maximum, have been generally negative in Finland (Laapas and Venäläinen, 2017).

The role of differential temperature trends on storm tracks has been recently addressed, both in terms of upper tropospheric tropical warming (Zappa and Shepherd, 2017) and lower tropospheric Arctic amplification (Wang et al., 2017), including the direct role of Arctic sea ice loss (Zappa et al., 2018), and a possible interaction of these factors (Shaw et al., 2016). The remote and local SST influence has been further examined by Ciasto et al. (2016), who further confirmed sensitivity of the storm tracks to the SST trends generated by the models and suggested that the primary greenhouse gas influence on storm track changes was indirect, acting through the greenhouse gas influence on SSTs. The importance of the stratospheric polar vortex in storm track changes has received more attention (Zappa and Shepherd, 2017). In an aqua-planet simulation, Sinclair et al. (2020) find a decrease in the number of extratropical cyclones and a poleward and downstream displacement due to an increase in diabatic heating.

A projection of future behaviour of extratropical cyclones is impeded by the fact that several drivers of change interact in opposing ways. With global warming, the temperature gradient between low and high latitudes in the lower troposphere is decreasing due to polar amplification. Near the tropopause and in the lower stratosphere, the opposite is true, thus implying changes in baroclinicity (Grise and Polvani, 2014; Shaw et al., 2016; Stendel et al., 2020). An increase in water vapour enhances diabatic heating and tends to increase the intensity of extratropical cyclones (Willison et al., 2015; Shaw et al., 2016) and contribute to a propagation further poleward (Tamarin and Kaspi, 2017). The opposite is also true in parts of the North Atlantic region, for example, south of Greenland. For this region, the N–S gradient is increasing as the weakest warming in the entire northern hemisphere is over ocean areas south of Greenland. North of this local minima the opposite is true. The increase in the N-S gradient over the North Atlantic may be responsible for some GCMs showing an intensification of the low-pressure activity and thereby high wind speed over a region from the British Isles and through parts of north-central Europe (Leckebusch and Ulbrich, 2004).

So, in summary, there is no clear consensus in climate change projections as the extent to which changes in frequency and/or intensity of extratropical cyclones have an effect on the Baltic Sea region.

Wind storms can also be accompanied by wind gusts (downbursts), potentially causing severe damage. Wind gusts driven by convective downdrafts or turbulent mixing can also occur during larger-scale wind storms, like Mauri in 1982 (Laurila et al., 2019). There is limited information on past or future trends concerning occurrence of wind gusts.

2.2.2 Extreme sea level

The rising global mean sea level poses a major hazard for the population living in the vicinity of the coast and will compound the risk of coastal floods. The effects of climate change on wind climate and tidal extremes may lead to further increases in the frequency and intensity of extreme sea levels on top of the mean sea level rise. Even if the sea level extremes only last a limited time, they are capable of causing severe damage to the coastal infrastructure and endangering human lives. Likewise, extreme sea levels are a major threat to coastal areas along the Baltic Sea coast due to flooding and erosion. Hence, sand dunes may experience large deformations during a single storm.

In the Baltic Sea, extreme sea levels are caused by wind, air pressure (inverse barometric effect), and seiche. The Danish straits prevent the entrance of tidal waves into the Baltic Sea, and the amplitude of the internal tides is only a few centimetres. The only exceptions are the south-western Baltic Sea and the eastern Gulf of Finland, where tides can reach 20 cm (Medvedev et al., 2016). The water exchange between the North Sea and the Baltic Sea causes about a maximum 1 m variation in monthly mean sea levels (Leppäranta and Myrberg, 2009). Due to the shape of the Baltic Sea, the highest and lowest sea levels are found at the ends of the bays, as in the eastern end of the Gulf of Finland, northern end of the Gulf of Bothnia, and in the Gulf of Riga, whereas the amplitude of variation is smallest in the central Baltic Sea. The Baltic Sea areas with the largest sea level variations, based on tide gauge data from the period 1960–2010, are shown in Fig. 4 (from Wolski et al., 2014).

In the studies of observed extreme sea levels, no significant trends in extremes exceeding mean sea level rise have been found, excepting the Gulf of Bothnia. The frequency of extremes has been observed to increase for some locations. The observed maxima and minima on the Baltic Sea coast along with 100-year return levels based on interpolated coastal tide gauge observations from the period 1960–2010 were studied by Wolski et al. (2014). They observed an increase in the yearly number of storm surges (defined as sea levels 70 cm above zero level of the European Vertical Reference Frame or local mean sea level in Finland and Sweden). The increase was largest in the Gulf of Finland (Hamina and Narva) and in the Gulf of Riga (Pärnu). Ribeiro et al. (2014) investigated the changes in extreme sea levels in 1916–2005 from daily tide gauge records of seven stations in Denmark and Sweden on the Baltic Sea coast, using generalized extreme value (GEV) and quantile regression methods. The mean sea level rise was removed from the observations. They observed a statistically significant trend in annual sea level maxima in the Gulf of Bothnia (1.9 mm/year for Ratan and 2.6 mm/year for Furuögrund). For other locations, the maxima could be considered stationary. Marcos and Woodworth (2017) studied the tide gauge data, concluding that the changes in the 100-year return levels after 1960 in the Baltic Sea were explained by the mean sea level rise.

There are only few published projections of extreme sea levels in the Baltic Sea. As they are based on a limited set of climate projections, the extreme values can only be considered preliminary estimates which will be complemented by other sea level projections in the future. Projected extreme sea levels for the Baltic Sea coast in 2100 were calculated by Vousdoukas et al. (2016) considering only the effect of the atmosphere on the sea level (storm surges) while omitting global mean sea level rise and land uplift. The Delft3D sea level model was forced with eight global climate models from CMIP5 database, and the projected changes were calculated from ensemble means of model simulations. In 2100, the present-day 100-year storm surge was projected to take place every 72 years under RCP4.5 and every 44 years under RCP8.5. The ensemble means of storm surges (return periods from 5 to 100 years) increase along the northern Baltic Sea coast with time for both RCPs. The increase is largest in the Bothnian Bay and in the Gulf of Finland, reaching about 0.5 m. Along the southern Baltic Sea coast, there is a smaller or no increase in most scenarios. When the storm surges are averaged over the Baltic Sea coast, the increase in the storm surges of return periods from 5 to 500 years is only 10–20 cm for different scenarios. By 2100, the inter-annual variation in the seasonal maxima, indicated by the standard deviation, increased by 6 % in RCP4.5 and by 15 % in RCP 8.5. This indicated that the variations in the maxima might increase more than the 30-year mean, suggesting that the maxima could have a higher increasing trend than the mean sea level has. The extreme sea levels along Europe's coasts, caused by the combined effect of mean sea level, tides, waves, and storm surges, were studied by Vousdoukas et al. (2017). In the Baltic Sea, the 100-year sea level due to waves and storm surges was projected to rise 35 cm (average over the Baltic coast) by 2100 in RCP8.5. The rise is largest in the eastern coast of the Baltic Sea, and the intra-model variation of the 100-year level increases up to 0.6 m in 2100. To increase the confidence in the future projections of storm surges in the Baltic Sea, we must rely on future research where a larger set of regional and global climate models is used with refined sea level models. The dependence between extreme sea levels and wind waves has to be assessed when the joint effect of storm surge and wave setup on the coast is studied. For the Baltic Sea, this dependence should be included when joint probabilities of compound events of high sea levels and waves are calculated, as is done in Kudryavtseva et al. (2020). Sea levels are discussed extensively by Weisse et al. (2021).

2.2.3 Warm and cold spells in the atmosphere

Extreme events related to climate change include extended periods with high (or low) temperatures. The Baltic Sea area is generally less exposed to severe heat spells compared to, for example, southern parts of Europe. During the last decade, however, record-breaking heat waves have hit the region, namely, those in 2010, 2014, and 2018 (Sinclair et al., 2019; Liu et al., 2020; Baker-Austin et al., 2016; Wilcke et al., 2020). Because people living in the Baltic Sea region are adapted to a relatively cool climate, high summertime temperatures pose a significant risk to health in the current climate (e.g., Kollanus and Lanki, 2014; Åström et al., 2016; Ruuhela et al., 2018, 2021), highlighting the need for measures against overheating of residential buildings (Velashjerdi Farahani et al., 2021).

The interannual variability and trends in the magnitude, temporal and spatial extent, and frequency of heat waves in the Baltic Sea drainage basin are mainly driven by large-scale fluctuations in atmospheric circulation (Sect. 2.1), anthropogenic climate change, and associated regional increases in mean temperature that exceed the global average warming (BACC I, 2008; BACC II, 2015; Rutgersson et al., 2014; Jaagus et al., 2014, 2017; Irannezhad et al., 2015; Owczarek and Filipiak, 2016; Aalto et al., 2016; Räisänen, 2017; SMHI, 2019; Meier et al., 2021). While of particular importance are fluctuations in the occurrence of blockings and other circulation patterns (Horton et al., 2015; Brunner et al., 2017), other factors such as local soil moisture feedbacks (Brulebois et al., 2015; Miralles et al., 2014; Whan et al., 2015; Cahynová and Huth, 2014; see also Sect. 2.2.5) and solar radiation also play a role. For example, Tomczyk and Bednorz (2014) showed a clear link between heat waves along the southern coast of the Baltic Sea and circulation patterns. Furthermore, the 2018 heat wave in Finland was strongly affected by abundant incoming short-wave radiation due to unusually clear skies (Sinclair et al., 2019; Liu et al., 2020). Regarding the local/regional amplitude of a heat wave, land cover use may also play a role. For example, several factors besides the very warm air mass likely contributed to the record high temperature in Finland in 2010 (37.2 °C) (Saku et al., 2011), and in a recent simulation study it was found that replacing a dense urban layout by a suburban type of land use resulted in small but systematic decreases in air temperatures in July (Saranko et al., 2020).

A widely used heat wave indicator is the warm spell duration index (WSDI), defined as the annual (or seasonal) count of days with at least 6 consecutive days when the daily maximum temperature exceeds the corresponding 90th percentile. If using the period 1961–1990 as a baseline when calculating the 90th percentiles, as done in Fig. 8 (top left), a statistically highly significant increasing trend across the period 1950–2018 can be found in annual WSDI, when averaged over land areas of the Baltic Sea region (with a Theil-Sen's slope of 1.7 per decade). In southern Sweden, the Baltic states, and southern and western Finland, 30-year averages of annual WSDI were about 14 days per year or more during a recent time span (1989–2018) (Fig. 8, bottom left), while during the baseline period the annual count there had been about 6–8 on average. Similar results have been obtained by Irannezhad et al. (2019) and Matthes et al. (2015). The former detected statistically significant increases in annual WSDI near the western coast of Finland for the period 1961–2011, changes of both positive and negative signs in northern and eastern parts of the country, and not statistically significant increases elsewhere. The latter considered WSDI in 1979–2013 separately in winter and summer and reported statistically significant increases in summer at several Swedish and Norwegian weather stations and, in winter, also at Finnish stations.

In the future, heat waves are projected to occur more often and to become longer and more intense. Today's warm spells tend to be increasingly frequent, but also increasingly "normal" from a statistical point of view (Rey et al., 2020). Accordingly, quantitative estimates of the rates of future changes strongly depend on the selected definition of "heat wave" (Jacob et al., 2014). The mean length and number of heat waves where the 20 °C daily mean temperature is exceeded have been projected to increase by about one and a half times in southern Finland under RCP4.5 between the periods 1900–2005 and 2006–2100 (Kim et al., 2018). A bias-adjusted median estimate for changes in WSDI in Scandinavia for the period 2071–2100, with respect to 1981–2010, is about 15 days under RCP8.5, with an uncertainty range of about 5–20 days (Dosio, 2016).

Accompanying more frequent and longer warm spells are decreases in the frequency, duration, and severity of cold spells, based on both observations (Easterling et al., 2016) and model projections (Sillmann et al., 2013; Jacob et al., 2014). Cold winter weather in the Baltic Sea region is closely associated with a negative phase of NAO and warm conditions in the Greenland region, and this statistical relationship has strengthened during the recent period of rapid Arctic warming (1998–2015), suggesting that Arctic influences might intensify in the future, perhaps leading to more unusual and persistent weather events (Vihma et al., 2020). On the other hand, northerly winds from the Arctic are milder than before (Screen, 2014). A cold winter, with unusually low temperatures like those in southern parts of the Baltic Sea area in the winter of 2009/10, has become less likely because of anthropogenic changes (Christiansen et al., 2018).

The role of changes in circulation remains remarkable; they explain about one half of the very significant warming in December in Finland during the period in 1979–2018 (Räisänen, 2019).

Analogous to WSDI, the cold spell duration index (CSDI) is defined as the annual or seasonal count of days with at least 6 consecutive days during which the daily minimum temperature is below the corresponding 10th percentile. Because of statistically significant decreases in spatially averaged CSDI over land areas of the Baltic Sea region during the period 1950–2018 (with a Theil-Sen's slope of -0.4 per decade), CSDI is nowadays typically clearly smaller than WSDI (Fig. 8, right). There are regional and seasonal differences, however. Statistically significant decreases in winter CSDI across the period 1979–2013 have been widespread in Norway and Sweden, but less prevalent in eastern Finland, while changes in summer have been small in general (Matthes et al., 2015). It is also worth noting that because of extremely cold weather in January-February 1985 and particularly in January 1987 (Twardosz et al., 2016) and owing to cold winters also more recently, results from trend analyses for the occurrence of cold spells can be strongly affected by the selection of a time period.

The cold spell duration index in the northern subregion of Europe is projected to decrease in the future with a likely range of from 5 to 8 days fewer per year by 2071–2100 with respect to 1971–2000 (Jacob et al., 2014).

2.2.4 Marine Heat Waves

Marine heat waves are becoming globally more common (Frölicher et al, 2018), and their intensity and occurrence are projected to increase further in the near future (Oliver et al., 2019). A first documented marine heat wave event in the Baltic Sea occurred in the summer of 2018, when the surface mixed layer became extraordinarily warm in many locations. Due to this and an accompanying atmospheric heat wave in the summer of 2018, large parts of the Baltic Sea were anomalously warm from mid-June to August. According to the satellite data, SST at the warming peak were up to 27 °C from the Bornholm Sea to the central eastern and western Gotland Sea, 22–25 °C in the Gulf of Bothnia, and 23–25 °C in the western parts (Naumann et al., 2018). For the entire Baltic Sea, May to August showed a positive SST anomaly of 4–5 °C.

In the coastal regions, the exceptional warming extended down to the bottom layer and had a significant impact on marine biogeochemistry (Humborg et al., 2019). According to the long-term measurement at the coastal region of the Gulf of Finland, the temperature at the bottom (31 m) was higher than 20 °C. That was the all-time record since 1926. Humborg et al. (2019) showed also that the warming elevated CO_2 and CH_4 concentration at the bottom considerably. After the actual heat wave event, bottom greenhouse-gas-rich waters were exposed to the surface due to storm-induced upwelling and, as a final consequence, CO_2 and CH_4 fluxes from sea to atmosphere were enhanced.

Knowledge about occurrence and impact of marine heat waves in the Baltic in the future is limited. Instead of directly analysing changes of marine heat waves, Meier et al. (2019) used climate projections to estimate how the number of warm SST days and the record-breaking anomalies of summer will change SST in the future. According to their study, both of these indicators will become more common in the future, but more important findings are that SST extremes exhibit large variability in time scales of decades and the changes are manifested in a more pronounced way in open sea areas than coastal regions.

2.2.5 Drought

The Baltic Sea basin is a region that, in general, has sufficient water resources to support natural ecosystems and societal needs. Despite this, dry conditions occur from time to time in different parts of the region and cause meteorological, soil moisture, and hydrological droughts. The main driver of any kind of drought is a long-term precipitation deficit that might be strengthened by high temperature, winds, low humidity, and intense water consumption. In the Baltic Sea basin, droughts are strongly connected with blocking processes in the atmospheric circulation over the Atlantic–European sector (see Sect. 2.1). Drying conditions frequently connected with extreme temperatures are referred to in Sect. 2.2.3. Change in precipitation during the 20th century in the Baltic Sea basin has been variable and characterized by an increase in its extreme characters, also reflected in the river flow regime (see Sect. 2.2.7 and 2.2.9).

There are some tendencies characterizing changes in dry conditions in recent decades. Drought frequency has increased since 1950 across Southern Europe and most parts of Central Europe with a corresponding decrease in low runoff. In many parts of Northern Europe, drought frequency has decreased, with an increase in winter minimum runoff, while in spring and summer months, strong negative trends were found (decreasing streamflow, shift towards drier conditions) (Stahl et al., 2010; 2012; Poljanšek et al., 2017; Gudmundsson et al., 2017). There are local and regional studies generally supporting this broader picture (Valiukas 2011; Przybylak et al., 2007; Stonevičius et al., 2018; Danilovich et al., 2019). However, Bordi et al. (2009) describe a negative trend of droughts since 2000.

Future projections show that the number of dry days in the southern and central parts of the Baltic Sea basin will increase in summer (Lehtonen et al., 2014a). The time average near-surface soil moisture in the Baltic Sea basin during March–May under the RCP8.5 scenario for the period 2070–2099, relative to 1971–2000, averaged over 26 GCMs will decrease by up to 8 % in the north and up to 4 % in the south part of the basin (Ruosteenoja et al., 2018). According to Spinoni et al. (2018), the meteorological droughts are projected to become more frequent and severe by 2041–2070 and 2071–2100 in summer and autumn in the Mediterranean area, Western Europe, and northern Scandinavia according to RCP4.5, and in the whole European continent (except Iceland) under RCP8.5 scenario.

The studies of soil moisture droughts showed drought projections ranging between strong drying and wetting conditions in Central Europe (Orlowsky and Seneviratne, 2013).

In hydrological regime streamflow, droughts will become more severe and persistent in many parts of Europe due to climate change, except for northern and north-eastern parts of Europe. In north-eastern Europe, including the Baltic countries, flow deficits in the non-frost season show a declining trend, with reductions in deficit volumes of up to 60 % and more by the end of current century (Forzieri et al., 2014). The decrease of drought magnitude and duration is expected for Central and Northern Europe (except southern Sweden) according to Roudier et al. (2016). This reduction of low flow duration and magnitude is mainly caused by less snowfall and more precipitation for areas with low flows in winter and by a general increase of rainfall for areas with low flows in summer (Vautard et al., 2014).

On the other hand, Prudhomme et al. (2014), using several climate and hydrological models, find a general increase of hydrological droughts over Europe, but they focus on less extreme droughts, and use RCP 8.5, at the end of the century. The runoff in late spring and summer is likely to decrease (thus an increase of probability of hydrological droughts) in most of the basin, due to earlier snowmelt, increased evapotranspiration, and possibly, particularly in the southern parts, reduced summer precipitation (Räisänen, 2017). Increasingly severe river flow droughts are projected for most European regions, except central-eastern and north-eastern Europe (Cammalleri et al., 2020). Climate change scenarios project on average a small decrease in the lowest water levels during droughts in Finland (Veijalainen et al., 2019).

2.2.6 Sea ice seasons

Maximum Ice extent of the Baltic Sea (MIB) is one of the essential variables describing climate change and variability in the Baltic Sea. In an average winter, the maximum annual ice extent is 165,000 km^2, indicating that the Bay of Bothnia, coastal areas of the Bothnian Sea, the Archipelago Sea, the Eastern Gulf of Finland, and the Bay of Riga are ice covered (BACC II, 2015; Meier et al., 2021). During extreme cold conditions, all the Baltic Sea sub-basins can be partly ice covered, and during the mildest winter, only the Bay of Bothnia is ice covered. Based on the MIB time series, which dates back to 1720, Seinä and Palosuo (1996) classified ice winters according to ice extent. Years with MIB less than 81,000 km^2 were classified as extremely mild ice winters, and MIB larger than 383,000 km^2 as extremely severe ice winters. Here we discuss the drivers of ice winter extremes and their observed and expected changes. In the parallel BEAR report by Meier et al. (2021), an analysis of observed and projected sea ice changes more broadly is provided.

Annual maximum ice extent is a cumulative indicator of the severity of a winter. It is largely driven by the large-scale atmospheric circulation, and its inter-annual variability is well correlated with the NAO index (Omstedt and Chen, 2001; Vihma and Haapala, 2009). During winters with NAO index > + 0.5, the average MIB is 121,000 km^2, with a range from 45,000 to 337,000 km^2, while during winters with NAO index < -0.5, the average MIB is 259,000 km^2, with a range from 150,000 to 405,000 km^2. Extremely mild ice winters (MIB < 60,000 km^2) have occurred in 1930, 1961, 1989, 2008, 2015, and 2020. According to Uotila et al. (2015), the winter of 2015 was the first winter when the Bay of Bothnia was definitely only partly ice covered. That winter was dominated by strong south-westerlies associated with a record high NAO index. This enhanced the atmospheric large-scale transport of warm Atlantic air masses to the Baltic Sea region. In addition, anomalous low ice extent was partly due to higher than average downward long-wave radiation because of increased cloudiness which decreased heat loss and cooling of the ocean surface layer. Also, episodes of warm Foehn winds due to cyclones passing over the Scandinavian mountains were observed in that winter. Uotila et al. (2015) concluded that extremely mild winters were more common during the 1985–2015 period than in any other 30-year period since 1720. After 2015, only one winter has been average in terms of MIB. The others are classified as mild or extremely mild ice winters. The winter of 2020 was an all-time record low ice winter. In that winter, central parts of the Bay of Bothnia were again ice free and the MIB was only 37,000 km^2. Extremely severe winters (MIB > 383,000 km^2) have not been observed since 1987. During the last 30 years, the most severe winter occurred in 2011, which caused major problems and economic losses for marine traffic (see Sect. 2.3.4).

Ongoing changes towards a milder climate demand a revision of the Seinä and Palosuo (1996) definition of extremely mild and severe ice winters. They choose to classify 11 % of the lowest MIBs as extremely mild winters. Correspondingly, 11 % of the largest MIBs were counted as an extremely severe winter. If we are utilizing the same thresholds for the last 30 years' data, limits for the extremely mild and severe winters would be ~ 50,000 km^2 and ~ 240,000 km^2, respectively.

According to climate projections, the Baltic Sea ice will experience considerable shrinking and thinning on average in the future (BACC I, 2008; BACC II, 2015). This is particularly clear for the Bothnian Sea, Bothnian Bay, and Gulf of Finland. Changes in mean sea ice conditions will also reflect on sea ice extremes. In general, present severe ice seasons will become rare and present extreme mild ice season more common but changes in sea ice extremes have not been examined in details yet.

2.2.7 Precipitation

Precipitation extremes in the Baltic Sea region are mainly related to i) synoptic-scale mid-latitude low-pressure systems and ii) convective precipitation events associated with meso-scale convective systems or resulting from single intense cloudbursts. Additionally, sea-effect snowfall events can generate large amounts of snow in coastal areas downstream from the Baltic Sea (Sect. 2.2.8). Climatologically, summer is the season with the strongest convective activity, and this is also the season with the strongest cloudbursts. Precipitation extremes associated with low-pressure systems are most frequent in fall and winter when the large-scale atmospheric circulation is favourable for bringing low-pressure systems towards Northern Europe.

High-resolution gridded data sets that may be used for evaluation of climate model performance for precipitation include: PTHBV covering Sweden at 4 km grid (Johansson and Chen, 2005); the Finnish data set at 1 km and 10 km grid by Aalto et al. (2016); the REGNIE data set at 1 km grid covering Germany (Rauthe et al., 2013); CPLFD-GDPT5 for Poland at 5 km (Berezowski et al., 2016); and seNorge2 for Norway at 1 km grid (Lussana et al., 2019). Another recent data set is the joint product consisting of PTHBV data in combination with precipitation estimates from radar data over Sweden resulting in the 4x4 km, 1 hourly resolution HIPRAD (HIgh-resolution Precipitation from gauge-adjusted weather RADar) data set covering 2009–2014 (Berg et al., 2016). Finally, it is noted that these national data sets are derived using slightly different methods, implying that they cannot directly be compiled and used as one high-resolution data set for the entire Baltic Sea region.

Representing the strong spatial and temporal variability of precipitation constitutes a true challenge for climate models, and careful evaluation against observations is key before the models can be applied. Typically, large-scale features such as the total precipitation volume over the Baltic Sea region are relatively well captured by climate models even at coarser resolution, as shown for a regional climate model at 50 km resolution by Lind and Kjellström (2009). However, such coarse-scale climate models are limited in their ability to reproduce fine-scale details of the observed precipitation climate. Higher resolution, for instance in the EURO-CORDEX ensemble (12.5km grid spacing), improves this (e.g. Prein et al., 2016), but spatial details are still too coarsely represented to adequately address precipitation over complex topography (e.g. Pontoppidan et al., 2017). In addition to spatial details, the simulation of the diurnal cycle is also often flawed in coarse-scale models (e.g. Walther et al., 2013). With even higher horizontal resolution, so-called convection-permitting models with grid spacing of a few kilometres are found to improve the simulation of both spatial and temporal features of precipitation (e.g. Belušić et al., 2020). Importantly, this also involves the representation of extreme events as they are much more capable of representing high-intensity rainfall than their coarser-scale counterparts (e.g. Kendon et al., 2012; Lenderink et al., 2019; Lind et al., 2020). For an example see Fig. 5, which shows how a convection-permitting model improves the representation of precipitation over Sweden.

According to BACC I (2008) and BACC II (2015), precipitation trends in the Baltic Sea basin over the past 100 years have varied in time and space. Examples exist of both increasing and decreasing trends in different areas for different periods and seasons. Positive trends were detected for the cold part of the year for Fennoscandia by Benestad et al. (2007), and Estonia, Latvia, and Lithuania by Jaagus et al. (2018). Along with warming it is also noted that the fraction of snowfall in relation to total precipitation is decreasing with time (Hynčica and Huth, 2019; Luomaranta et al., 2019).

Increasing intensity of precipitation events resulting from the larger water-holding capacity of a warmer atmosphere is an expected impact of climate change (Bengtsson, 2010). Based on European E-OBS data, Fischer and Knutti (2016) demonstrate that heavy daily precipitation, defined as the 99.9th percentile that roughly corresponds to a 1 in 3 years event, has become 45 % more frequent comparing the last 30 years with the preceding 30 years. For even more extreme precipitation events like 1 in 10, 20, or even 50 years, the large variability makes it difficult to draw any firm conclusions about changes, especially for small areas with only a few observation stations. For example, Olsson et al. (2017a) found no significant trend in annual maxima based on Swedish gauge data from 1880 to 2017, even when data from gauges across the whole country were used. For less intense events such as the 90th, 95th and 99th percentiles of daily precipitation or the total number of days with more than 10 mm of precipitation, a number of studies have reported on increasing trends in Europe (e.g. Donat et al. 2016) or parts of the Baltic Sea region for different seasons (e.g. BACC I (2008) and BACC II (2015) and references therein).

Climate projections of future climate show increasing precipitation in Northern Europe, including the Baltic Sea region (IPCC, 2013; BACC I; BACC II, 2015). Southern Europe, on the other hand, is projected to receive less precipitation, and as the border line between increasing and decreasing precipitation moves from the south in winter to the north in summer, there are some models that project less precipitation in parts of the Baltic Sea region in summer (Christensen and Kjellström, 2018). In addition to changes in mean precipitation, projections show a similar north–south pattern of changes in wet-day frequency with increases in the north and decreases in the south (Rajczak et al., 2013). Regardless of the sign of change in seasonal mean precipitation, heavy rainfall is projected to increase in intensity for most of Europe, including the Baltic Sea region (Nikulin et al., 2011; Rajczak et al., 2013; Christensen and Kjellström, 2018), as illustrated in Fig. 6. Snowfall is projected to decrease on an annual mean basis, but in winter, daily snowfall amounts and extreme events may increase (Danco et al., 2016). Precipitation intensities are projected to increase at durations ranging from sub-daily to weekly. Martel et al. (2020), based on three large ensembles, including one with a high-resolution regional climate model, concludes that increases in 100-year return values of annual maximum precipitation are stronger at sub-daily time scales than for 1-day or 5-day events. Newly developed convection-permitting regional climate models have been shown to sometimes yield different climate change signals for extreme precipitation events compared to coarser scale models (> 10 km grid spacing). For instance, Kendon et al. (2012) showed stronger increases in summertime intense precipitation in a 1.5 km model compared to a 12 km one for the southern UK. Similarly, Lenderink et al. (2019) showed a stronger increase for intense precipitation in a number of summer months when applying a synthetic warming signal of 2 °C to the large-scale boundary conditions. Until now, such models have not been applied for climate change studies of the Baltic Sea region and it is not clear what the response to warming would be.

Stronger precipitation extremes associated with a warmer climate can have major impacts on society. Large amounts of precipitation are closely associated with flooding, which is common in the Baltic Sea region.

More intense cloud bursts are closely associated with urban flooding but also with adverse effects on agriculture and infrastructure in rural areas. Stronger climate change signals in recently developed convection-permitting models compared to previous state-of-the-art models can have major impacts on the provision of climate services and advice in the context of climate change adaptation.

2.2.8 Sea-effect snowfall

The sea-effect snowfall is typically generated in the early winter when thick cold air masses flow over the relatively warm open water basin. The warm water heats the cold air above the water and acts as a constant source of heat and moisture leading to convection. The rising air generates bands of clouds, which quickly grow into snow clouds. Snowfall is enhanced when the moving air mass is uplifted by the orographic effect on the shores or by the convergence of air near the coast as it packs air and forces it to rise, inflating convection (Savijärvi, 2012). The highest precipitation levels occur over the sea close to the coast (Andersson and Nilsson, 1990). With suitable wind direction, these snowbands can bring heavy snowfalls to the coastal land area.

The sea-effect snowfall is very sensitive to the wind direction because a long fetch over the water body is required (Laird et al., 2003). On the Baltic Sea, the most favourable wind directions vary from north to north-east (Jeworrek et al., 2017) due to the cold air outbreaks from the north-eastern continent. Nevertheless, for the two major bays (the Gulf of Bothnia and the Gulf of Finland), the sea-effect snowfall can occur on any coast with cold air outbreaks. Favourable conditions for the development of convective snowbands include an optimum strong wind, large air-sea temperature difference, low vertical wind shear, high atmospheric boundary layer height, and favourable wind directions (Jeworrek et al., 2017; Olsson et al., 2020).

Sea-effect (lake- or bay-effect) snowstorms may disrupt several sectors of society and can cause damage costing millions of euros (Juga et al., 2014). Intense and prolonged sea-effect snow events can produce tens of centimetres of snow accumulation and last for days. In Northern Europe, the transport systems are most impacted by winter extremes, such as snowfall, cold spells, and winter storms, by increasing the number of vehicle accidents, injuries, and other damage as well as greatly increasing travel times (Vajda et al., 2014; Groenemeijer et al., 2016). Critical infrastructures are affected by disturbances in the emergency and rescue services as well as roof and tree damage and failures in power transmission due to heavy snow loading. Road maintenance and transportation of snow to disposal sites if there is not enough space for snow storage along the streets can be costly (Keskinen, 2012).

The impacts of a sea-effect snowfall event depend on its intensity and duration as well as on the location. In Stockholm (November 2016, ~40 cm of snow accumulation) and Gävle (December 1998, ~100 cm) in Sweden, public transport was affected; buses, trains and flights were late or cancelled and cars were trapped on roads. Also, the Danish island of Bornholm was overwhelmed by ~140 cm deep snowdrifts in December 2010. As the snowfall lasted for several days, the island ran out of places to move the snow. A sea-effect snowfall in the Helsinki metropolitan area in Finland in February 2012 (~5–10 cm, Juga et al., 2014) caused severe pile-ups on the main roads, with hundreds of car accidents and dozens of injured persons. On the other hand, no damage or accidents were reported due to a much larger snowfall accumulation, 73 cm of new snow in less than 24 hours, in a small municipality of Merikarvia, on the western coast of Finland, in January 2016 (Fig. 7, Olsson et al., 2017b, 2018).

Our current knowledge is mainly based on studies from the Great Lakes in North America (Wright et al., 2013; Cordeira and Laird, 2008; Laird et al., 2009, 2003; Niziol et al., 1995; Hjelmfelt, 1990). For the Baltic Sea there is an increasing number of studies concerning the formation (Olsson et al., 2017b; Mazon et al., 2015; Savijärvi, 2015; Savijärvi, 2012; Andersson and Nilsson, 1990; Gustafsson et al., 1998) and statistical analysis (Jeworrek et al., 2017; Olsson et al., 2020) of sea-effect snowfalls, as well as the effects of excess snowfall on society (Juga et al., 2014; Vajda et al., 2014).

Using simulations conducted with the regional climate model RCA4 for the period 2000–2010, 4 to 7 days a year showed favourable conditions for snowband formation in the western Baltic Sea area and 3 days per year in the eastern Baltic Sea area (Jeworrek et al., 2017; Olsson et al., 2020). A good physical understanding is essential if we want to assess potential changes in frequency and intensity in the future. Based on simple physical reasoning, the probability of the events might increase or decrease due to climate change. The ice-cover season is becoming shorter in different parts of the Baltic Sea, and the annual maximum ice extent is projected to decrease (BACC II, 2015; Luomaranta et al., 2014, Höglund et al., 2017; see also Sect. 2.2.6), extending the time period when convective snowbands can form. In addition, wintertime precipitation amounts are increasing (Sect. 2.2.7). On the other hand, on an annual mean basis, conditions might become less favourable for sea-effect snowfall due to a shorter thermal winter (Ruosteenoja et al., 2020) and a smaller share of snowfall compared to rain in the warming climate (Sect. 2.2.7).

The sea-effect snowfall events typically have smaller temporal and spatial scales than what is covered by the observational network and resolved by climate models. The high-resolution ERA5 data were used in a case study for January 2016. The preliminary results were promising towards the use of reanalysis data over sea, but the data cannot produce intensive enough convective snowfall over land (Olsson et al., 2018). Newly developed convection-permitting regional climate models (see Sect. 2.2.7), in turn, open up new possibilities to assess the future evolution of the probability of the occurrence.

2.2.9 River floods

River flooding affects more people worldwide than any other natural hazard. River floods often result in inundations, which means that the water level in the river exceeds the safe line and water floods to the adjacent territories. The flood risks are affected by global warming and large-scale and regional changes in the water cycle. In the Baltic Sea basin, the scale of spring floods is affected by precipitation, snow-water accumulation prior to freshet, depth of frozen soil, soil wetness since the previous autumn, the presence of ice crust before flooding, and the combination of flood waves, among other things.

A detailed assessment of climate change of river floods for Northern Europe was provided in BACC I (2008) and BACC II (2015). Estimates of *annual* streamflow in the Baltic Sea basin showed trends towards increase (Hisdal et al., 2010; Wilson et al., 2010). This has been confirmed for Latvian rivers; the trend was statistically significant for many rivers, including Daugava (Klaviņš et al., 2008; Kļaviņš and Rodinov, 2008). However, some studies show a tendency for a decrease in annual discharge, particularly in the southern catchments (Hansson et al., 2011; Gailiuš et al., 2011).

Most studies have detected positive trends with increasing streamflow in winter months in most catchments of the Baltic Sea basin (Stahl et al., 2010; Hisdal et al., 2010; Reihan et al., 2007). A tendency of *spring* *streamflow* decreasing has been reported for the east Baltic states (excluding Russia and Belarus) by Reihan et al. (2007). Trends in the annual maximum and minimum discharges for the major rivers Daugava, Lielupe, Venta, Gauja, and Salaca indicate a statistically significant decrease in maximum discharge (Klaviņš et al., 2008; Kļaviņš and Rodinov, 2008). The same tendencies were found for the Daugava and Neman rivers in the Belarussian part of the Baltic Sea basin (Danilovich et al., 2007).

After the last BACC publication in 2015 there are only a few studies devoted to the past hydrological regime changes. Arheimer and Lindström (2015) concluded that the observed anomalies in annual maximum daily flow for Sweden were normally within 30 % deviation from the mean of the reference period. There were no obvious trends in the magnitude of high flow events over the past 100 years. There was a slight decrease in flood frequency, although in a shorter perspective it seems that autumn floods have increased over the last 30 years. The flood decrease is connected with seasonality change in the study region. Changes in flood time occurrence in Europe were also established by Blöschl et al. (2017). In the Baltic Sea region, they detected floods shifting from late March to February due to the earlier snow-melting, driven by temperature increases in the region and a decreasing frequency of Arctic air mass advection (see Sect. 2.1).

The number of severe floods has increased significantly since the 1980s in the Nemunas River delta. The floods occur often in spring and winter, but the lifetime of individual floods has become shorter (Valiuškevičius et al., 2018). No significant long-term trends in annual streamflow have been found in north-west Russia (Nasonova et al., 2018; Frolova et al., 2017) or Belarus (Partasenok, 2014). Meanwhile, the intra-annual distribution of runoff has changed significantly during the last decades. In particular, runoff during winter low-flow periods has increased significantly while spring runoff and floods during snow-melt have been decreasing due to the exhausted water supply in snow before spring. However, the general pattern of described changes in water regime varies from year to year due to the increasing and decreasing frequency of extreme flow events.

For future climate, a decrease of annual mean (Latvia, Lithuania, and Poland) and seasonal streamflow according to the SRES scenario A1B, A2, and B2 was projected for the rivers in Norway and Finland (Beldring et al., 2008; Veijalainen et al., 2010; Apsīte et al., 2011; Kriaučiūnienė et al., 2008; Szwed et al., 2010), and an annual streamflow increase by 9–34 % has been projected for Denmark (Thodsen et al., 2008; Jeppesen et al., 2009). Large uncertainties in the future hydrological regime were reported for Sweden (Yang et al., 2010; Olsson et al., 2011). Alfieri et al. (2015) showed positive changes in mean flow in Northern and Eastern Europe.

Significant negative changes in maximum flow are mainly located in north-eastern Europe, including the Baltic countries, Scandinavia, and north-western Russia. According to Thober et al. (2018), in Northern Europe, floods will decrease by up to 5 % under 3 °C global warming and high flows increase up to 12 %. A decrease of floods in this region has been projected in several studies (Arheimer and Lindström, 2015; Alfieri et al., 2015; Roudier et al., 2016).

According to Olsson et al. (2015), moderate changes in annual mean flow and a significant decrease of early spring discharge peaks by 2051–2090 are expected in Finland. A significant decrease in the magnitude of spring floods and a significant increase in autumn floods are shown for Sweden (Arheimer and Lindström, 2015). For spring floods, the trend obtained using two climate projections indicates a 10–20 % reduction by the end of the century compared to the 1970s. For autumn floods, the trend was in the opposite direction, with 10–20 % higher magnitudes by the end of the century. Roudier et al. (2016) established the relatively strong decrease in flood magnitude in parts of Finland, north-west Russia and northern Sweden, whereas in southern Sweden and some coastal areas in Norway, increases in floods are projected. Northern streams in Finland are predicted to lose much of the seasonality of their flow regimes by 2070 to 2100, which is explained by projected air temperature increase and maximal flow decrease (Mustonen et al., 2018). The increase of winter and decrease of spring streamflow has been projected for four main river basins in Belarus (Western Dvina, Neman, Dnepr, and Pripyat` rivers) by Volchek et al. (2017). The streamflow in the east of the Baltic Sea basin (the Western Dvina River within Russia and Belarus) will be characterized mostly by a decrease of mean streamflow in the upper stream and an increase in the lower part of the river basin. The projected maximal streamflow is expected to decrease, with the largest changes in the lower part of the river basin up to 25 % (Danilovich et al., 2019).

However, there are studies opposing this finding. There are slight increases of floods in some parts of Sweden and Norway and in north-eastern Europe, according to Donnelly et al. (2017). High runoff levels are found to increase over large parts of continental Europe, increasing in intensity, robustness, and spatial extent with increasing warming.

The increase of winter runoff and peak discharges was projected by Kasvi et al. (2019); the most significant changes are expected in wintertime – by 20–40 % to 2050–2079 in south-western Finland. The increases in floods are projected by Roudier et al. (2016) in southern Sweden and some coastal areas in Norway. Almost everywhere, the increase in 100-year floods (QRP100) is stronger than the 10-year floods (QPR10).

2.2.10 Extreme waves

It is important to better understand extreme ocean waves as a natural hazard in the Baltic Sea so that society can adapt and implement safety measures. Vertical motions on the ocean surface consist of an extensive spectrum of frequencies and periods (Munk, 1950; Holthuijsen, 2007). Here we focus on the wind-generated waves and mainly on the significant wave height representing the average height of the highest third of the waves. Significant wave height serves as an indicator when discussing extreme waves; however, the highest individual wave in a wave record is 1.6–2.0 times higher than significant wave height (Björkqvist et al., 2018; Pettersson et al., 2018). Some ambiguity exists when it comes to which sea states can be called extreme (Hansom et al., 2015) because locally higher wave heights in not particularly stormy conditions can lead to damage and fatalities and may become labelled in the media as extreme, giant, freak, monster, or rogue waves. Rogue waves are typically defined as a maximum wave height of more than twice the significant wave height.

The main drivers of extreme wave conditions are high-wind-speed events and circulation patterns leading to sustained wind direction over a fetch of water that varies depending on the location. On 12 January 2017, an intensive low-pressure system generated a wave in the northern Baltic Sea referred to in the media as a "monster wave" more than 14 m high, equalling or exceeding the previous record from 22 December 2004 (EUMETSAT, 2017; Björkqvist et al., 2018). Significant wave heights measured around 8 m according to the Finnish Meteorological Institute (FMI). Even higher waves with significant wave heights up to 9.5 m have been estimated to occur in the northern Baltic Proper during the wind storm Gudrun in January 2005 (Soomere et al., 2008; Björkqvist et al., 2018). A high-resolution numerical model study for the time period 1965 to 2005 (Björkqvist et al., 2018) showed a 99.9th percentile for significant wave height in the Baltic

Sea of 6.9 m. They found 45 unique extreme wave events with modelled significant wave height above 7 m during the 41-year simulation. Twelve of them had a maximum above 8 m, six exceeded 9 m, and one event showed significant wave height over 10 m. Extreme waves in the Baltic Sea can have a significant impact on sea level dynamics and coastal erosion, which is also discussed further in Weisse et al. (2021).

Many studies have been conducted to characterize the present-day variations in the wave fields using measurements (e.g. Kahma et al., 2003; Pettersson and Jönsson, 2005; Broman et al., 2006) and using modelling (e.g. Jönsson et al., 2003; Räämet and Soomere, 2010; Björkqvist et al., 2018) also describing the seasonal dependence (e.g. Soomere, 2008; Räämet and Soomere; 2010). Björkqvist et al. (2018) showed that 84 % of wave events with significant wave heights above 7 m occurred during November through January. The areas of highest significant wave heights are found in the southern and eastern Baltic Proper (Björkqvist et al., 2018). This is consistent with the typical synoptic weather pattern of middle latitudes but modulated by bathymetry and fetch conditions, as well as meso-scale weather effects (Soomere, 2003, Nilsson et al., 2019). The pattern of 100-year return-value estimates of significant wave height, based on 10 km resolution simulations for 1958–2009, is represented here by the 99.9th percentile significant wave height in Fig. 3 (in agreement with Aarnes et al., 2012; Björkqvist et al., 2018; Nilsson et al., 2020). The northern basins typically experience reduced wave heights, both due to the shorter fetch conditions and to the occurrence of sea ice limiting the wave growth during the season when the highest waves otherwise can be expected to occur (e.g. Tuomi et al., 2019; Nilsson et al., 2019).

Only a few studies have also been conducted on near-shore extreme waves; for example, Gayer et al. (1995), Paprota et al. (2003), and Sulisz et al. (2016) discussed the formation of extreme waves and wave events along Polish and German coasts and reported a large number of freak-type waves. Although significant progress has been made in understanding and predicting ocean extremes and freak waves (e.g. Cavaleri et al., 2017; Janssen et al., 2019), a practical definition using usually more well-predicted parameters, such as significant wave height, is presently used in warnings (Björkqvist et al., 2018) based on high-resolution wave modelling. The horizontal resolution of wave modelling hindcast studies for the Baltic Sea has varied from about 1.1–1.85 km to about 22 km (Nilsson et al., 2019; Björkqvist et al., 2018; Jönsson et al., 2003). The small-scale spatial and time variations are often missed by the models, and coarse resolution (6–11 km) may not provide sufficient accuracy to study extremes (Larsén et al. 2015; Björkqvist et al., 2018).

Present-day trends from long-term in situ observations and wave modelling are inconclusive and possibly site-specific (e.g. Soomere and Räämet, 2011b). From reviewing multiple studies discussing changes and trends in significant wave heights at Baltic Sea sites across time periods of more than 30 years, there is often no clear trend in severe wave heights, or the trends are small and explained by the large natural variability in the wind climate (Sect. 2.1 and 2.2.1) (e.g. Räämet et al., 2010, Soomere et al., 2012; Soomere and Räämet, 2011a). Trends in mean wave height are small but statistically significant (0.005 m/year for 1993–2015) from satellite altimetry (Kudryatseva and Soomere, 2017), but higher quantiles behaved less predictably. A spatial pattern with an increase in the central and western parts of the sea and a decrease in the east was observed.

Future changes to the Baltic Sea extreme wave characteristics are found to be uncertain and only a few studies exist. For the wave field in a future climate, Mentaschi et al. (2017) reported an increase of extreme wave energy flux (on average 20 %, with maxima up to 30 %). They used a global wave model (approximately 1.5-degree resolution) driven by an ensemble of global coupled models from the CMIP5 under the high emission RCP scenario 8.5. They suggest that the changes are caused by changes in the NAO index. Groll et al. (2017) analysed wave conditions under two IPCC AR4 emission scenarios (A1B and B1) by running a higher-resolution wave model and implementing effects of sea ice through ice-covered grid cells if ice thickness was larger than 5 cm. They found higher significant wave height in the future for most regions and simulations. Median wave results showed temporally and spatially consistent changes (sometimes larger than 5 % and 10 %), whereas extreme waves (99th percentile) showed more variability in space and among the simulations, and these changes were smaller (mostly less than 5 % or 10 %) and more uncertain. The changes reported were attributed to higher wind speeds and also to a shift to more westerly winds. The sea ice was clearly reduced in the Bothnian Sea, Bothnian Bay, and Gulf of Finland in the simulations, but changes in the 30-year mean of annual wind speed maximum showed a decrease in the northern Baltic Sea. Multi-decadal and the inter-simulation variability illustrated the uncertainty in the estimation of a climate change signal (Dreier et al., 2015; Groll et al., 2017).

Simulations of sea ice variations in a warmer climate may be one of the most important factors determining the future wave field. If significant reduction of ice in the northern Baltic Sea basin occurs, changes to the wave field are likely unless compensated for by changing wind patterns (Groll et al., 2017). Zaitseva-Pärnaste and Soomere (2013) showed significant correlation between energy flux and ice season. Comparing ice-free and ice-time included statistics, ice-free conditions increased significant wave heights on the order of about 0.3 m both for mean values and 99th percentile values (Tuomi et al. 2011, Björkqvist et al., 2018). Fairly small anthropogenic effects for the wave fields are expected for the next century, but results are uncertain and depend on changes in both wind climate (Sect. 2.1 and 2.2.1) and ice conditions (Sect. 2.2.6 and 2.2.11).

2.2.11 Ice ridging

Sea ice extremes depend on the temporal and spatial scale under consideration, but more importantly on geographical location and climate conditions – 5 m thick pressure ridges are common off the Hailuoto island in the Bay of Bothnia every winter, but rarely present in the southern Baltic Sea. The society's capacity to manage sea-ice-related hazards also depends on the likelihood of occurrence of sea ice. In some regions, even a thin ice cover can cause large economic losses to society if the sea ice freezing occurs in a region where marine traffic is operated by non-ice-class vessels. On a local scale, the predominant feature of drift ice is its large variation in thickness. Due to the differential ice motion, pack ice experiences opening, closing, rafting, and ridging. In the Baltic Sea, the thickest ice, that is, pressure ridges, can be 30 m thick, but typically they are 2–5 m thick (Leppäranta and Myrberg, 2009; Ronkainen et al., 2018). After initial formation of ridges, they remain in the pack ice as obstacles for shipping. Ridges are formed when pack ice experiences convergent motion. In the Baltic Sea, this is common when pack ice is drifting against the fast ice. In those coastal boundary zones (Oikkonen et al., 2016), mean ice thickness can be half a metre thicker than in the pure thermodynamically grown level ice in the fast ice zone (Ronkainen et al., 2018).

During the convergent motion, pack ice experiences compression and its internal stress increases. Internal stress, also called ice pressure or ice compression, depends on the strength of wind and currents but also on ice thickness, floe geometry, and cumulative area of coherent ice region in motion (Leppäranta, 2011). Ice motion, concentration, thickness, and internal stress of pack ice are strongly coupled. Internal stress of pack ice, which reduces ice motion, increases non-linearly with ice concentration and thickness. In an ultimate situation, very thick ice can be stationary even under strong winds.

For shipping, ridges are well observed obstacles using radar and visual methods. They mainly impact the duration of time at sea, but sea ice compression is more difficult to observe and can cause total stoppage or even damage to ships and vessels. Sea ice compression can be directly observed by in situ sea ice stress measurements, but those measurements are rare in the Baltic Sea (Lensu et al., 2013). Implicitly, ice compression events have been observed by ships navigating in ice.

The most severe ice winters during the last 10 years occurred in 2010 and 2011 due to negative NAO (Cattiaux et al., 2010). In the winter of 2011, 14 ship accidents occurred due to harsh ice conditions (Hänninen, 2018). For a comparison, during the average winters there are only one to five accidents. Several compression events were also reported during the winter of 2011. The most hazardous one occurred at the end of February, when marine traffic was totally halted for a few days. Below, we provide an anatomy of this extreme event.

January and February 2011 were characterized by cold and calm weather in the northern Baltic Sea. Consequently, the Gulf of Bothnia became totally ice covered by early February. Because of the weak winds, the Bothnian Sea was mainly covered by 15–30 cm thick undeformed ice (Fig. 9). This situation created favourable preconditions for an intensive ice compression and ridging event. After a cold and calm period, a change in weather pattern occurred on 24 February, when a cyclone arrived in the Bothnian Sea region. The wind speed increased up to 18 m/s, and strong south-westerly winds prevailed for the following five days. Consequently, pack ice drifted towards the north-eastern sector of the Bothnian Sea. The ice field experienced compression and strong deformations, and the undeformed level ice field was redistributed to a heavily deformed ice field. In the south-west area of the Bothnian Sea, a coastal lead was generated due to divergent ice motion (Fig. 9). According to helicopter electromagnetic measurements (Ronkainen et al., 2018), the mean sea ice thickness along ~100 km transects in the heavily deformed areas increased up to 1.6 m. Thickness of individual ridges was 4–8 m (Fig. 9). Sea ice compression, or internal stress of ice, has not been regularly measured in the Baltic Sea, but ice-breaker and merchant vessel crews have been reporting observations of ice pressure from their bridges. Indications of the ice pressure include closing of ship channels, reduction of ship speed, besetting in ice, and compression of ice against ships' hulls. During the period from 24 February to 7 March 2011, 142 ice compression cases were reported in the Gulf of Bothnia. Of these, 25 reported severe compressions, or 3–4 on a scale of 4 (FMI ice service; Lensu et al., 2013). Compression and thick ice caused a total close-down of marine traffic for several days. Even the largest merchant vessels needed assistance from the ice-breakers. In many cases, the ice-breakers needed to assist the merchant vessels one at a time as traditional assistance in convoys was not possible.

Sea ice extent and thickness are projected to decrease markedly in the Baltic (Meier et al., 2021). It is also expected that occurrence of severe ice winters will decrease and consequently heavy ice ridging and compression events will become rare if wind conditions remain the same in the future.

2.2.12 Phytoplankton blooms

One component of the marine ecosystem here considered as an extreme event is phytoplankton blooms (for the marine ecosystem in general, see Viitasalo et al., 2021). Blooms are visible mass occurrences of phytoplankton after excessive growth. They become visible with increased water turbidity, sometimes even discoloration (red tides) or surface scums. The mass occurrence of toxic species (harmful algal blooms) may have a detrimental impact on the environmental components, lead to toxic incidents, and may also cause economic harm, for example, by constraining the touristic use of the coastal waters (Wasmund, 2002). Phytoplankton (algae and cyanobacteria) undergoes typical annual successions, induced by the regular changes of abiotic (solar radiation, temperature, nutrient concentrations) and biotic (feeding, infections, competition, allelopathy) factors. Under favourable conditions, including sufficient nutrient (N, P, Si) concentrations and solar radiation as well as low wind that allows stratification in the upper water layers, massive phytoplankton growth may occur, leading to blooms. Phytoplankton forms the basis of the pelagic food web and, after sedimentation, feeds the benthos also. Its blooms are natural phenomena and a vital component of the ecosystem. Only the excessive blooms caused by anthropogenic eutrophication may be considered a nuisance, and phytoplankton blooms should be reduced to natural occurrences (HELCOM, 2007). The natural level of occurrence has not yet been achieved in most areas of the Baltic Sea (HELCOM, 2018).

Eutrophication was identified as a major problem in the Baltic Sea in the 1960s and 1970s, leading to the foundation of the Helsinki Commission (HELCOM) in 1974 and the induction of complex monitoring in the Baltic Sea since 1979. Meanwhile, the concentrations of growth-limiting macronutrients, dissolved inorganic nitrogen (DIN), and dissolved inorganic phosphorus (DIP) are decreasing (Andersen et al., 2017). Major Baltic inflows (MBI) are rare events which lead to reoxygenation of deep waters and fixation of phosphorus in the sediment. The latest MBI occurred in December 2014 (Mohrholz et al., 2015). Its effect on oxygen concentrations in deep waters was only of short duration and DIP concentrations were increasing again by 2015, both in deep and surface waters of the Gotland Deep (Naumann et al., 2018). It had no clear effect on phytoplankton biomass, and it did not introduce new phytoplankton species into the Baltic Sea. The originally dominating diatoms in the spring blooms have decreased since the end of the 1980s in the Baltic Proper (Wasmund et al., 2013) and have been replaced by dinoflagellates (Klais et al., 2011). The ratio of diatoms and dinoflagellates may be a sensitive indicator for changes in the ecosystem, including the food web. It was used to develop the Dia/Dino index as an indicator for the implementation of the Marine Strategy Framework Directive (Wasmund et al., 2017).

The summer blooms of cyanobacteria are the most massive ones in the Baltic Proper and the Gulfs of Finland, Riga, and Gdańsk. Long-term analyses including historical data revealed that cyanobacterial blooms became a common phenomenon as of the 1960s (Finni et al., 2001). Cyanobacteria seem to increase on a worldwide scale due to global warming (Karlberg and Wulff, 2013). Cyanobacterial species tend to have higher growth rates at high temperatures than other phytoplankton species and they are favoured in thermally stratified waters (O'Neil et al., 2012). Also, increased freshwater inflow, as projected mainly in the north of the Baltic area (BACC II, 2015), will intensify stratification and support cyanobacteria blooms. However, wind-induced upwelling in early summer may induce blooms, which is primarily an effect of phosphorus input into the surface water (Wasmund et al., 2012). If stratification is disrupted by wind, established cyanobacteria blooms may collapse (Wasmund, 1997). As the bloom-forming buoyant cyanobacteria have a patchy occurrence, representative sampling is difficult and the amount of data may be insufficient for a reliable trend analysis. The development of cyanobacteria blooms has been reported annually in HELCOM Environment Fact Sheets since 1990 (Öberg, 2017; Kownacka et al., 2020), but general trends could not be identified in these three decades. However, in specific regions, trends may occur which may even be in opposite directions (Olofsson et al., 2020). A few recent extreme blooms are mentioned here.

On 20 July 2017, cyanobacteria warnings were issued for eight beaches in the area of the Gulf of Gdańsk, and on 22–24 July 2017, three bathing sites were closed due to the decreased water transparency. In 2018, all the bathing sites of the Gulf of Gdańsk and Puck Bay were closed for 12 days owing to the formation of toxic scums. In the Gulf of Finland, the exceptionally warm summer of 2018 (see also marine heat waves, Sect. 2.2.4) caused the strongest cyanobacterial bloom of the 2010s (SYKE, 2018) . Remarkably, the typical cyanobacteria genus of the summer blooms was also abundant in winter under the ice on the western and eastern Finnish coasts, as identified for example on 7 January 2019 (SYKE, 2019).

In the past decade, blooms of toxic dinoflagellates have increasingly been observed in shallow coastal waters of the Baltic Sea. Neurotoxic *A. ostenfeldii* now regularly forms dense bioluminescent summer blooms in the Åland archipelago and the Gulf of Gdańsk (Hakanen et al., 2012). The highest cell concentrations so far recorded for this species were measured in the Åland area in August 2015 (Savela et al., 2016). In July 2015, a dense bloom of *Karlodinium veneficum,* killing fish in a shallow bay at the south-west coast of Finland, captured the attention of regional authorities (SYKE, 2016).

Global warming is generally becoming a threat that may influence the phytoplankton strongly (Cloern et al., 2016; Reusch et al., 2018). Future changes in eutrophication as well as a changing climate will influence the occurrence of harmful algal blooms. If the Baltic Sea Action Plan is implemented successfully, it is suggested that record-breaking cyanobacteria blooms will not occur in the Baltic Sea in the future (Meier et al., 2019).

A phenomenon worth mentioning is the extension of the growing season of phytoplankton in the oceans (Gobler et al., 2017), and also in the Baltic Sea (Groetsch et al., 2016). The period with satellite-estimated chlorophyll *a* (chl *a*) concentrations of at least 3 mg m^{-3} has doubled from approximately 110 days in 1998 to 220 days in 2013 in the central Baltic Sea (Kahru et al., 2016). Based on weekly measurements of phytoplankton biomass and chl *a* concentrations at a coastal station in the Bay of Mecklenburg from 1988 to 2017, Wasmund et al. (2019) found an earlier start of the spring bloom with a rate of 1.4 days/year and a later end of the autumn bloom with 3.1 days/year and a corresponding extension of the growing season (Fig. 10). The earlier start of the growing season was correlated with a slight increase in sunshine duration during spring, whereas the later end of the growing season was correlated with a strong increase in water temperature in autumn. As the growing season has extended recently from February to December at the investigated site, a further extension is practically not possible. However, this process may be still ongoing in other regions of the Baltic Sea.

2.3 Possible implications for society

Extreme events and projected changes caused by global warming or changes in the atmospheric circulation could have significant and potentially disastrous consequences for Baltic societies. This section examines the potential implications of extremes and changes of extremes on forest fires, coastal flooding, offshore wind activities, and shipping in the Baltic Sea area, all of which are linked to key economic sectors. These are also linked to the multiple drivers of the Baltic Sea systems (Reckerman et al., 2021).

2.3.1 Forest fires

Fires play a key role in the natural succession and maintain biological diversity in boreal forests. They also pose a threat to property, infrastructure, and people's lives (e.g., Rowe and Scotter, 1973; Zackrisson, 1977; Esseen et al., 1997; Virkkala and Toivonen, 1999; Ruokolainen and Salo, 2006). Moreover, fires have a deteriorating impact on air quality (Konovalov et al., 2011; R'Honi et al., 2013; Popovicheva et al., 2014), in extreme cases even in regions hundreds of kilometres away from the actual fire (Mei et al., 2011; Mielonen et al., 2012; Vinogradova et al., 2016). The emissions of gases and aerosols through fires as well as changes in surface albedo also have impacts on climate. Due to increasing fire activity, boreal forests may even shift from carbon sink to a net source of carbon to the atmosphere, resulting in a positive climate feedback (Oris et al., 2014; Walker et al., 2019). The impact of aerosols is more complex, yet it is generally short-lived. However, heat-trapping soot from large conflagrations can enter into the stratosphere and persist there for months (Ditas et al., 2018; Yu et al., 2019). Changes in surface albedo due to fires tend to decrease radiative forcing in the long term (e.g., Randerson et al., 2006; Lyons et al., 2008).

Large forest fires are often associated with long-lasting drought and heat waves. Recently, during the exceptionally warm and dry summer of 2018, numerous large fires burned a total of more than 20,000 hectares of forest in Sweden (Sjöström and Granström, 2020; Krikken et al., 2021). According to an analysis performed by Krikken et al. (2021), climate change has so far increased the probability of such events roughly by 10 %. Also, during the heat wave of 2014, a single conflagration in Västmanland burned nearly 15,000 hectares. In Russia, the persistent heat wave of 2010 resulted in devastating forest fires (Bondur, 2011; Witte et al., 2011; Vinogradova et al., 2016).

The natural source of fire in boreal forests is lightning. Nowadays lightning strikes ignite about 10 % of fires in Sweden and Finland (Granström, 1993; Larjavaara et al., 2005b). In Northern Europe, the distribution of lightning-ignited fires follows approximately the thunderstorm climatology with fewer ignitions in the north (Granström, 1993; Larjavaara et al., 2005a). In recent years, many of the largest fires have been caused by forest machinery operations (Sjöström et al., 2019).

Irrespective of the ignition source, weather influences the conditions for the spreading of fires. In Northern European boreal forests, climate, and particularly precipitation variability, has been an important decadal-scale driver of fires even during recent centuries with strong human influence on fire occurrence (Aakala et al., 2018). In boreal forests in general, interannual variability in burned area can largely be explained by fluctuations in lightning activity (Veraverbeke et al., 2017) and also by variations in large-scale atmospheric circulation patterns (Milenković et al., 2019). Usually, only a few years with large forest fires account for the majority of burned area from decadal to centennial time scales (Stocks et al., 2002).

In recent decades, burned area in Northern European forests has mainly remained low (Lindberg et al., 2021). This is because fires in the area tend to be small compared to other boreal regions, mainly thanks to effective fire suppression. There are still some distinct differences in the fire activity between different countries in the area. Most noteworthy, in recent years relatively large fires have been much more common in Sweden than in Finland, though large fires are still much more common in Russia, Canada, and Alaska (e.g., Stocks et al., 2002; Vivchar, 2011; Smirnov et al., 2015). However, large fires were not uncommon in Fennoscandia before the cultural transition to modern agriculture and forestry led to a steep decline in annual burned area by the end of the 19th century (Parviainen, 1996; Wallenius, 2011). In response to global warming, the forest-fire danger is generally projected to increase across the circumboreal region (e.g., Flannigan et al., 2009; Wotton et al., 2010; Shvidenko and Schepaschenko, 2013; Sherstyukov and

Sherstyukov, 2014). This is particularly due to enhanced evaporation in a warmer climate. Already, within recent decades, long-lasting drought events have become more intense throughout Europe (see Sect. 2.2.9), increasing temperatures having been the main driver of the change (Manning et al., 2019). According to the most extreme warming scenarios, summer months with anomalously low soil moisture that occurred recently in Northern Europe once in a decade may occur more often than twice in a decade in the late 21st century (Ruosteenoja et al., 2018). However, fire regimes in northern and mid-boreal forests have appeared to be more sensitive to climate variations compared to fire regimes in southern boreal forests (Drobyshev et al., 2014). Hence, Drobyshev et al. (2014) concluded that fire regimes across Scandinavia might even show an asynchronous response to future climate changes. Moreover, years with large forest fires in northern Scandinavia have historically tended to occur more frequently during cooler rather than warmer climate periods (Drobyshev et al., 2016), yet these large-fire years have mainly occurred in association with individual warm and dry summers. In Finland, the climate change impact on forest-fire risk has been evaluated in several studies (Kilpeläinen et al., 2010; Mäkelä et al., 2014; Lehtonen et al., 2014b, 2016). In these studies, the projected decrease in soil moisture content has been reflected as a projected increase in fire risk. Assuming the current relationship between weather and the occurrence of forest fires, Lehtonen et al. (2016) estimated that in Finland, the number of fires larger than 10 ha may double or even triple during the present century. Nevertheless, there is considerable uncertainty regarding the rate of the change, largely due to the uncertainty of precipitation projections. Yang et al. (2015) predicted that in northern Sweden, the fire risk could even decrease in the future, whereas considering a projected decrease in population density, Backman et al. (2021) predicted that in the Republic of Karelia, the number of fires would decrease in the future and it is uncertain whether the burned area would increase or decrease.

In addition to meteorological conditions, fire potential is largely determined by the availability of flammable fuels in forests. In Southern Europe, the biomass availability may become a limiting factor for increasing fire activity (Migliavacca et al., 2013). However, in Northern Europe this is unlikely, as forest productivity and biomass stock are projected to increase under a warming climate (Kellomäki et al., 2008; Dury et al., 2011).

2.3.2 Coastal flooding

The projected regional sea level rise (e.g. Grinsted et al., 2015) coupled with the expected intensification of sea level extremes (e.g. Vousdoukas et al., 2018) discussed in Sect. 2.2.2 will widely affect both natural and human systems along the Baltic Sea.

In the past, several major floods have occurred on the Baltic Sea coast. While there are few surviving sea level measurements or other historical records dated before the 19th century, traces of extreme floods are found from sand layers. Studies of coastal sediments, compared with historical records, imply that the 1497 flood, which damaged cities on the southern Baltic coast, was the largest storm surge on the Polish coast in 2000 years (Piotrowski et al., 2017). St. Petersburg has also proved vulnerable to coastal and fluvial flooding, and the highest documented surge occurred in 1824, when the water level rose to 367 cm at Kronstadt, and possibly even to 410 cm at St. Petersburg (Bogdanov and Malova, 2009) over local mean sea level. In the era of tide gauges, the most severe flood along the southern Baltic coast happened in 1872. This storm caused severe damage at the German and Danish coasts, and 271 lives were reported lost (Rosenhagen and Bork, 2008). At Travemünde, Germany, the sea level rose to 340 cm (Jensen and Müller-Navarra, 2008); at Skanör, along the southern Swedish coast, the sea level reached approximately 240 cm

(Fredriksson et al., 2016). For the Gulf of Finland and the Gulf of Riga, the most severe flooding on record was caused by the Gudrun wind storm in 2005, when the observed sea level reached 197 cm in Hamina (Finland), 230 cm in St. Petersburg (Russia), 207 cm in Ristna (Estonia), and 275 cm in Pärnu (Estonia) (Suursaar et al., 2006).

In a European perspective, the uncertain influence of climate change on the frequency and intensity of waves and wind as a predictor of future damage costs due to coastal flooding is of limited importance relative to the observed and projected influence of sea level rise on storm surge heights. Hence, Vousdoukas et al. (2018) find that the indirect effect of mean sea level rise, uplifting high sea levels under extreme weather conditions, serves as the main driver of the increased coastal flood damage in the future and accounts for 88–98 % of the total damage. Interestingly, the highest relative contribution from changes in cyclones is projected along the Baltic Sea coast. This stems from a combination of low relative sea level rise along the Baltic Sea catchment that is due to the land uplift and intensifying waves and storm surges due to climate change based on the projections used by Vousdoukas et al. (2017). In general, there is no consensus as to whether the wind storms are expected to become more frequent (Sect. 2.2.1). For Finland and Sweden in particular, due to land uplift, the physical footprint of sea level rise in future damage estimates is weakened. Conversely, socio-economic development along the coast is likely to be a main driver and modulate the intensification of coastal hazards amongst Baltic Sea countries.

In the absence of improved coastal management practices and coastal adaptation, the expected population exposed to coastal flooding along the Baltic Sea coastline annually as well as the expected annual damage (EAD) due to coastal flooding are both likely to increase by orders of magnitude (e.g. Forzieri et al., 2016; Vousdoukas et al., 2018; Mokrech et al., 2014; Brown et al., 2018). While the impacts on managed as well as natural coastal and near-coastal terrestrial ecosystems may be significant, Baltic coastal cities are likely to be mainly responsible for future coastal flood losses due to their high concentration of people, infrastructure, and valuable assets. To keep future coastal flood losses low, climate change adaptation measures urgently need to be installed or reinforced (Vousdoukas et al., 2020; Abadie et al., 2019) to withstand extreme sea levels (see Sect. 2.2.2).

Apart from recent work by Paprotny and Terefenko (2017) for Poland, environmental and economic impact assessments from the regional to the national level generally belong to the grey literature. Similarly, impact assessments at the local (city) level have so far been mainly carried out by engineering consultancies to facilitate the development of local adaptation strategies (Thorarinsdottir et al., 2017). Due to local constraints and a lack of best practices, the methodologies behind such detailed assessments often vary greatly and are not comparable.

Figure 11 shows different damage estimates related to coastal flooding, including for some of the most exposed cities along the Baltic Sea. Prahl et al. (2017) have calculated a set of macroscale damage cost curves (Fig. 11, main part), that is, damage cost as a function of flood height, for the 600 largest cities in Europe, including all of the major cities along the Baltic Sea. Land-use information is being used rather than population coupled with GDP per capita as the basis for approximating the location of assets; this ensures that flooded assets are inherently co-located with the city. For the hydrological modelling, a high-resolution digital elevation model for Europe is used together with a simple static-inundation model that only accounts for hydraulic connectivity. While this approach readily allows for estimation of the damage costs associated with flooding for any European coastal city, the "coarseness" of the methodology (including the underlying empirical and categorical information on land-use and flood defences, which goes into the calculations) can lead to overestimation of the damage cost curves, especially for low-lying urban and high-value areas. This is particularly found to be the case for (but not restricted to) Copenhagen (Fig. 11, main part).

For comparison, Abadie et al. (2016) have carried out a set of economic impact assessments for Copenhagen, Helsinki, and Stockholm in 2050 based on an improved version of the same large-scale modelling framework (cf. the insert of Fig. 11, lower rows). Using the same input as Prahl et al. (2017), Abadie et al. (2016) have developed a European-scale assessment framework, where a continuous stochastic diffusion model is used to describe local sea level rise, and Monte Carlo simulations yield estimates of the (risk) damage caused by the modelled sea level rise. This is paired with an economic damage function developed for each city and point in time. The results found by Abadie et al. for the RCP8.5 scenario are shown in Fig. 11. For Copenhagen and Stockholm, the damage cost estimates of Prahl et al. (2017) are largely consistent with those of Abadie et al. (2016).

Vousdoukas et al. (2018, 2019, 2020) have estimated the EAD from coastal flooding for all countries in Europe (excluding adaptation) by combining future climate model projections with a set of gridded projections of gross domestic product, population dynamics, and exposed assets based on selected shared socio-economic pathways. Flood defences are considered to be recorded in the FLOPROS database (Scussolini et al., 2015). As seen in the table in Fig. 11 (upper rows), at the end of the century, Denmark is expected to suffer the most severe damage from increased coastal flooding resulting from climate change due to its long coastline, followed by Germany, Poland, and Sweden.

The large observed variation in cost estimates related to future coastal flooding in the Baltic Sea may easily be ascribed to the different approaches, data, and scales used for impact modelling, including key assumptions, in particular relating to economics. To improve confidence in impact assessments, a comparable assessment of methods, models, and assumptions is needed in order to establish more solid evidence within the area. Likewise, impacts due to compound events where, for example, extreme coastal water levels are (locally) exacerbated by associated high water levels in nearby rivers or high intensity rainfall (Bevacqua et al., 2019) are largely unaccounted for in most damage cost assessments.

2.3.3 Offshore wind energy activities

Offshore wind farms are growing rapidly in the Baltic Sea. Figure 12 shows the expansion of wind farm clusters in southern parts of the Baltic Sea and in the North Sea. According to recent reports, offshore wind power in the Baltic Sea is far from fully exploited and could reach 83 GW (Cecchinato, 2019; Freeman et al., 2019).

Compared to onshore situations, offshore wind energy benefits from richer wind resources. It is also greatly challenged by the harsher offshore environmental conditions, which makes the so-called levelized cost of energy (LCOE) significantly higher. LCOE accounts for, among other things, the transportation of energy from sea to land, the trips to the farms for maintenance, and water depth where the turbines will be installed. Maintenance and construction become more challenging when storms are present, as storms cause rougher conditions for the turbines and farms at sea than over land. There are no land obstacles to effectively consume the atmospheric momentum; instead, waves are generated, swells develop and propagate, and waves break. This can put tremendous loads on construction of fixed as well as floating turbines. At the same time, breaking waves release water drops and sea salt into the air. This, together with severe precipitation at sea during storms, has a significant impact on the erosion process of the turbine blades and affects the turbine performance (e.g. Mishnaevsky, 2019). At sea, the role of icing on blades was considered generally small (e.g. Bredesen et al., 2017), while over the Baltic Sea, ice cannot be ignored (Heinonen et al., 2019). The storm winds at sea reach the cut-off speed of 25 ms^{-1} at hub height more frequently, causing more fluctuation in power production and accordingly significant challenges in the power integration system (e.g. Sørensen et al., 2008; Cutululis et al., 2013). At the same time, strong winds and large waves directly affect activities such as installation and operation and maintenance (O&M), see Diamond et al. (2012), Leiding et al. (2014), Dangendorf et al. (2016) and Kettle (2018, 2019).

Several sections in this report have summarized studies on the climatological changes of a number of relevant parameters including storms, waves, temperature, icing, precipitation, and water levels. Effort is needed in co-ordinating the analysis and implementing these changes of the environmental parameters in offshore wind energy planning. Design parameters need to be calculated to avoid placing turbines in a dangerous wind environment and to identify the suitable turbine design class. Turbulence and the 10-min value of the 50-year wind at hub height are two key design parameters (IEC 61400-1) requiring improved estimation.

With the presence of storms over the sea, special organized atmospheric features develop, contributing to turbulence over a broader frequency/wave number range than under typical stationary surface layer conditions. These features include gravity waves, low-level jets, open cells, and boundary layer rolls. Over the Baltic Sea, gravity waves and boundary layer rolls are present (e.g. Larsén et al., 2012a; Svensson et al., 2017; Smedman, 1991). Over the North Sea, it was found that open cells can add an extra 20–50 % to the turbulence intensity (Larsén et al., 2019b).

For the studies of extreme winds for wind energy applications over Scandinavia, groups in Sweden and Denmark pioneered by using long-term wind measurements (e.g. Abild, 1991; Bergström, 1992; Kristensen et al. 2000). Later, long-term global reanalysis products were used, including in the Baltic Sea area (e.g. Frank, 2001; Larsén and Mann, 2009). At early stages of wind energy development, the reference height of 10 m was most relevant for engineering applications. Today, the turbines are much bigger and the largest (offshore) turbine has a 220 m rotor and 107 m blade. At the same time, wind energy is developing to give greater global coverage over various land/sea conditions. These make the use of mesoscale models an attractive option. A three-dimensional mesoscale numerical model, the MIUU model, was used for the 50-year wind speed to calculate both 10 min mean and 3 s gust values, with a grid space of 1 km (Bergström and Söderberg, 2008). In addition, a variety of mesoscale models have been used for wind resource assessment as well as extreme wind calculations, such as the HIRHAM model, the (e.g. Clausen et al., 2012; Pryor et al., 2012), the KAMM model (e.g. Hofherr and Kunz, 2010; Larsén and Badger, 2012), the REMO, the CCLM models (Kunz et al., 2010), and the WRF model (Bastine et al., 2018). For long-term data, the models are run covering time periods up to decades. In compensation for the computational cost, most of these models have been run at a spatial resolution of tens of kilometres. The effect of spatial and temporal resolution of these mesoscale modelled winds was investigated in Larsén et al. (2012b) using modelled data from WRF, REMO, and HIRHAM. Larsén et al. (2012b) developed a so-called spectral correction method to fill in the missing variability in the modelled time series, thus reducing the underestimation of the extreme wind. To calculate the extreme wind, Larsén et al. (2013;2019a) also developed a selective dynamical downscaling method to efficiently allocate modelling resources to storms at high resolution (i.e. 2 km). The southern part of the Baltic Sea was included in these calculations.

The development of approaches for calculating design parameters over the Baltic Sea has provided different estimations through time. The difference in these estimations (more than 10 %) is bigger than the effect from climate change calculated from different climate scenarios (a few percent points). Climate modelling describes future scenarios and provides a coherent calculation of the whole set of environmental parameters, including wind, temperature, icing, and precipitation. One such output is from the research project Climate and Energy Systems (CES) supported by the Nordic Research Council (Thorsteinsson, 2011). This study features both opportunities and risks within the energy sector associated with climate change up to the mid-21st century. Fifteen combinations of regional and global climate models were used. The results, however, did not portray a consensus on the change in storms and extreme winds in the future over the Scandinavian seas (see also Sect. 2.2.1 and Belusic et al., 2019).

2.3.4 Shipping

There are several aspects where changes in extreme events and natural disasters have the potential to influence shipping; one relates to ice conditions. As stated above (Sect. 2.2.6 and 2.2.11), winters on the Baltic Sea can be different with highly variable ice conditions. This has been observed when the ice loads encountered by ships have been measured in full scale by instrumenting ship hulls for ice load measurements, see example in Fig. 13 (Kujala, 2017). Typically, the highest loads occur when ships are moving through heavily ridged areas or are stuck in moving, compressive ice. The highest measured loads occurred in severe ice winters, such as in 1985 and 1987. Extreme events can also cause significant damage to the ship shell structures, as shown in Fig. 13(Kujala, 1991). Typically, ice-induced damage is in the form of local dents on the shell structures, to the depth about 50–100 mm and width as well height about 0.5 m by 0.5 m. The figure shows an example of the extensive damage outside Luleå (upper figure), when the ship left the harbour independently without ice-breaker (IB) assistance and got stuck in compressive ice. The whole shell structure was then permanently damaged to a depth of about 0.5 m and length and height of several metres. The ice-strengthened ships are not designed for this type of situation as the design principle is that ice-breakers will prevent ships from getting stuck in ice.

Increasing maritime traffic in areas where ice-breaker assistance is needed will increase the demand for such assistance. The workload of an ice-breaker in its operational area, at a specific time, is strongly dependent on the area specific ice conditions and ship traffic. This leads to large area- and time-specific variations in the demand for ice-breaking assistance. Even under constant ice conditions, it is hard to estimate local demand for assistance solely from the estimated increase or decrease in local maritime traffic. There are a number of studies related to the development of the transit simulation models for ships navigating in ice (e.g. Patey and Riska, 1999; Kamesaki et al., 1999; Montewka et al., 2015; Kuuliala et al., 2017 and Bergström et al., 2017). Typically, all these models simulate the speed variation of a single ship when it is sailing in varying ice conditions such as level ice, ridged ice, and ice channel. In addition, the real-time data from the vessels' automatic identification systems (AIS) have been used to study the convoy speed when IBs assist merchant ships (see Goerlandt et al., 2017). Monte Carlo random simulation can also be used to study the uncertainties and variations on the ice conditions and on the calculation methods to evaluate ship speed in various ice conditions (Bergström et al., 2017).

The newest development includes simulation tools built around a deterministic IB-movement model (Lindeberg et al., 2015, 2018). The new approach is that the simulation model also includes the decision principles of IBs to determine which ships will be assisted and when. The model also includes the possible assistance and towing principles of merchant ships behind an IB. The tool can be used for predicting local demand for ice-breaking assistance under changing ice and traffic conditions. It can also be used to predict how the traffic flow will react to changes in the IB operational areas of the modelled system by adding/removing IBs from the system and/or by modifying the boundaries of IB operational areas.

Typically, during a normal winter starting in December and ending in April, there are about 10,000 ship visits to our icebound harbours in the Baltic Sea and the traffic is assisted by five to nine IBs. The developed model can be used to study the effect of winter hardness on the IB activities and waiting time for merchant vessels (Lindeberg et al., 2018). The new environmental requirements will cause a decrease in the engine power used by ships, which might mean that the need for IB assistance will increase. As studied by Lindeberg et al. (2018), the new so-called energy efficiency design index (EEDI) ships will increase the merchant vessel waiting time by 100 % when 50 % of the new ships will fulfil the EEDI requirements, so this means that in the future we might need more IBs to guarantee smooth marine traffic. EEDI is a new energy-efficient requirement that will decrease the engine power on typical merchant ships. The EEDI requires a minimum energy efficiency level per capacity mile (e.g. tonne mile) for different ship types and size segments are established by the International Maritime Organisation (IMO). Since 1 January 2013, following an initial two-year phase zero, new ship designs need to meet the reference level for their ship type.

The model can also be used to study the effect of winter hardness on the amount of needed IB assistance. For example, during the hard winter of 2010–2011, the total number of IBs assisting was nine with the total amount of assisting miles equal to 77056 nm, and during the mild winter of 2016–2017, it was eight IBs and 29502 nm assisted.

In addition to ice conditions, the maritime shipping in the Baltic Sea is affected by wind and wave conditions and icing due to sea spray. Although the mean wind and wave conditions are relatively low in the Baltic Sea, some of the high wind events and especially the severest storms affect the maritime traffic (cf. Sect. 2.2.10 for extreme wave events). In the severest storms, smaller vessels need to find shelter or alternative routes, and large vessels need to reduce speed or increase engine power. Increasing the vessels' engine power during these events will also increase the ship emissions (Jalkanen et al., 2009). Also, getting safely in and out of harbours is an issue during high wind and wave events.

In the changing climate, the ice winters are estimated to get shorter and the ice extent smaller (Sect. 2.2.6). The time of the year that in the present climate has ice cover partly coincides with the windiest time of the year. This means that the wave climate in the Bay of Bothnia and eastern part of the Gulf of Finland, where there is still ice every winter in the present climate, is estimated to get more severe, and this can cause increasing dynamics of the ice, making navigation in ice more demanding.

However, the occurrence of extreme wave events is not only dependent on the changes in the ice conditions but also on the changes in the wind conditions. Moreover, the Baltic Sea sub-basins are relatively small and the high wind events are often fetch-limited, thus the wind direction plays a large role in the generation of the high wave events. As the frequency of strong westerly winds is projected to increase (see Sect. 2.2.1), this will most likely lead to an increase in the high wave conditions from this sector.

Icing due to sea spray causes problems for maritime traffic in the Baltic Sea. In a future climate, this can happen more often as the ice winters get milder and the sea is open during the time of the year when sea surface temperatures are close to the freezing point, so the probability of getting freezing water on the ship deck will potentially increase.

3 Knowledge gaps

As extreme events by definition are rare, long time series of data and/or large ensembles with model simulations with high spatial coverage are a necessity for a full understanding of return periods and for mapping expected changes in intensities of extreme events. When also adding the impact of climate change and to some extent an unknown response of the climate system to partly unknown changes in forcing, the uncertainty increases further, especially locally. This is particularly true for compound events (i.e. interaction of multiple hazard drivers) and freak events (i.e. events that have very low probabilities but which can potentially have disastrous impacts). These kinds of events are largely unexplored in the scientific literature.

As previously discussed, many extreme events in the Baltic Sea region are related to the large-scale atmospheric dynamics, including storms originating from the North Atlantic region. Knowledge gaps concerning the response of large-scale atmospheric circulation in a warming climate include the dynamic response of reduced Arctic sea ice and changing oceanic conditions as well as the possibility of changes in the jet stream patterns and/or changing blocking frequencies over Europe.

Besides storms that are related to extratropical cyclones, strong winds can also be induced by extreme convective weather, including downbursts, tornadoes, detached thunderclouds, derechos, and other mesoscale convective systems (Rauhala et al., 2012; Punkka, 2015). Furthermore, wind gusts driven by convective downdrafts or turbulent mixing can also occur during larger-scale windstorms (Laurila et al., 2019). Other severe small-scale extreme events include for example Meteo-tsunamis, long waves created by air-sea interaction occurring in shallow seas during warm summers, they are amplified when arriving at the coasts and can reach several meters (Pellikka et al., 2020). All these phenomena may be harmful to infrastructure, the severity of the impacts depending on the intensity and location of occurrence of the events. New convection-permitting climate models with grid spacing of a few kilometres (Sect. 2.2.7), as well as an increasing observation density owing to the use of weather radars, satellites, and lightning-location sensors, open new possibilities to assess their probabilities of occurrence in the recent past and in the projected future climate.

A local characteristic is the uncertainty in local responses to large-scale variability and global change. One particular feature is soil water response to heat waves, but also features such as changes in frequency of major Baltic inflows (Lehman et al., 2021; Meier et al., 2021). In the Baltic Sea region, the state of the cryosphere has already changed remarkably. Past mean changes in frost, snow, icing, lake, and sea ice conditions have been rather well estimated by regional models, but their future variability and change ranging from synoptic to centennial time scales are uncertain. Moreover, the impact of extreme cryosphere changes on forestry, reindeer herding, spring floods, extreme wave heights, and shipping is largely unknown. Concerning flood assessments, the majority of the studies are devoted to high flood extremes. The low flow periods are less well described due to the absence of remarkable changes in flow regime especially in Northern Europe because of the large model uncertainty in precipitation during the summer (or warm period) when low flow usually occurs.

The prolongation of the growing season of phytoplankton is identified, but it may not be caused solely by a simple direct influence of increased radiation and temperature. The temperature may also act via stronger stratification, shifts in grazing pressure, infections, or other factors which still have to be identified in detail. Earlier phytoplankton spring blooms, a longer summer minimum, and a later autumn bloom may have decisive impacts on the food web and need to be investigated. The first major marine heat wave recorded occurred in the Baltic Sea in 2018. Further research is needed to estimate probabilities of marine heat waves in the future, but also to deepen our understanding about how biogeochemical processes are altered in those conditions.

Simulation of storm tracks and their associated precipitation generally improve with increasing resolution beyond that used in most current climate models (Michaelis et al., 2017; Barcikowska et al., 2018). Higher resolution results in more sensitivity to warming (Willison et al., 2015). Understanding of high-intensity extremes requires improved reanalysis products and carefully homogenized long time series data as well as higher-resolution climate models. Here the better use of new tools might lead to an increased understanding. The new tools include remote sensing data and new types of in situ or remote sensor systems in combination with traditional observational networks. Combining new data with higher-resolution models as well as new methodologies (machine learning, neural networks) has great potential.

The following aspects are the most important to address in future research:

- Coupled high-resolution process and Earth System Models for detailed understanding of extremes and feedback mechanisms between different processes (see also Gröger et al., 2021).
- Addressing natural variability by assessing long-term observational time series and large samples of simulated states of the climate system.
- Further development of statistical methods (including machine learning) for improved understanding of risks and return periods of rare events, including compound and freak events.
- Dynamics of the larger scale, in particular addressing regional and local responses. While the local effects of large-scale circulation changes are reasonably understood, it is not clear which factors control or change the dynamics of the larger scale itself. This is particularly true for changes in velocity and meandering of the jet stream and effects on blocking frequencies.
- Increase process-level understanding of the impact of the physical extremes on biogeochemical cycles and fluxes such as an enhanced flux of matter from land to sea during extreme mild and wet winters or enhanced greenhouse emissions from sea bottom to atmosphere during marine heat wave events.
- Interaction of multiple hazard drivers, since compound events are potentially very damaging for society.
- Further quantification of economic costs of extreme events as well as impacts on health, ecosystem, and environment.

4. Conclusions and key messages

In this review, we have focused on extreme events and natural hazards in the Baltic Sea region. Temporal and spatial scales of the events that are causing these hazards range over many orders of magnitude. Typical short-term phenomena are dynamical events such as storms or heavy precipitation that are causing severe economic and human losses regionally and locally. In contrast, heat waves and cold spells are gradually developing events that prevail for weeks to months. Their impact on society and nature can cover the entire Baltic Sea catchment region.

In Fig. 14, we summarize how the hazards are related to the atmospheric, oceanic, and hydrological conditions. The weather in the Baltic Sea region is largely determined by the state of the large-scale atmospheric circulation. In winter, the variability is largely governed by the NAO with dominating strong westerlies and cyclones in its positive phase while more stable continental weather dominates in its negative phase. Also, in summer there are large differences between more cyclone-dominated weather with relatively mild air from the Atlantic and blocking-dominated weather with high pressure systems and warm continental air. Large-scale atmospheric circulation is the main source of inter-annual variability of seasons, and the extreme states are manifested in, for example, the extent of the seasonal ice cover.

Regional atmospheric events, cyclones, and blocking are directly causing storm damage or triggering heat waves and forest fires, respectively. Cyclones are also generating storm surges and hazardous coastal flooding and ocean waves. Summertime blocking situations are frequently causing heat waves, while in winter they are connected to cold spells. For long-lasting situations, impacts of blocking are not restricted to land as marine heat waves are also generated and consequently massive algal blooms are formed, as in 2018.

An important aspect is that the most hazardous events are often combinations of several factors (i.e. compound events). For example, every cyclone can generate a storm surge, but the level of coastal flooding depends on the total water volume in the Baltic Sea. Positive water volume, which is caused by persistent westerlies, can provide an additional 50 cm (Leppäranta and Myrberg, 2009) to the maximum sea level. Moreover, a single storm always causes a seiche oscillation, and a sequence of storms can produce combined sea level changes due to the storm surge and seiche oscillation. In cities located at the river mouth, a sea flood can be further amplified by the river flood.

Trends in circulation patterns are difficult to detect; the long-term temporal behaviour of NAO is essentially irregular. There is, however, weak evidence that stationary wave amplitude has increased over the North Atlantic region, possibly as a result of weakening and/or a north-eastward shift of the North Atlantic storm track. There is an upward trend in the number of shallow and moderate cyclones, whereas there is no clear change, although there is possibly a small decrease in the number of deep cyclones during the past decades. Sea level extremes are expected to increase in a changing climate and are directly related to changes in mean sea level, wind climate, storm tracks, and circulation patterns.

European summers have become warmer over the last three decades, partly explained by changes in blocking patterns (see Sect. 2.1). There is a clear link between warmer summers and an increased risk of drying (particularly in spring) and heat waves in most of the area. Floods decrease in a large part of the Baltic Sea in spring, but streamflow has increased in winter and autumn during the last decades while the mean flow shows insignificant changes. Stronger precipitation extremes associated with warmer climate can have strong impacts on society, particularly in urban regions, and are strongly associated with flooding and more intense cloud bursts. Results from new, high-resolution convection-permitting climate models indicate that increases in heavy rainfall associated with cloud bursts may increase even more than has previously been found in coarser-scale regional climate models.

Sea-effect snowfall events can be a serious threat to the coastal infrastructure and should be considered also in the future, although likely with an overall lower risk on an annual basis. More research is still needed for deepening understanding of sea-effect snowfall and for developing a reliable way to assess the occurrence of such events in the changing conditions. Another wintertime phenomenon of potentially hazardous consequences is ice ridging, being one of the sea ice extremes with the greatest impact potential on coastal infrastructures and shipping.

Phytoplankton blooms are extreme but natural biological events. However, eutrophication/de-eutrophication, pollution, and changes in irradiation, temperature, salinity, carbon dioxide, etc. may change their magnitude, timing, and composition. Examples of extreme and mostly potentially toxic blooms are given, but reasons can hardly be identified. Their sudden and sporadic appearance complicates trend analyses and modelling. One trend that seems to be prominent is the prolongation of the phytoplankton growing season. Climate change is the most probable reason for this.

Table 1 summarizes the changes of some extreme events for the past decades and, using scenarios, for the upcoming decades. Here, a positive trend means increasing probability of occurrence and a negative trend means a decreasing probability of occurrence.

Table 1: Selected event and the estimated frequency of occurrence. Scale for changes (major decrease, minor decrease, no change, minor increase, major increase). Confidence scale (*low*, medium, **high**).

Event	**Past decades**	**Future scenario**
Number of moderate and shallow extratropical cyclones	minor increase	no significant change
Number of deep extratropical cyclones North Atlantic	*minor increase*	*minor increase*
Extreme ocean waves North of 59°N South of 59°N	 no significant change (in strength and frequency) no significant change (in strength and frequency)	 *minor increase in frequency in wintertime* *no significant change*

Extreme sea levels (relative mean sea level plus storm surge) North of 59°N South of 59°N	 **minor decrease** **minor increase**	 *minor increase* *major increase*
Ice ridging	*unknown*	*major decrease*
Intense precipitation	minor increase	**increase**
Sea-effect snowfall	*unknown*	*unknown*
Heat waves	minor increase	major increase
Cold spells	major decrease	major decrease
Marine heat waves	*minor increase*	increase
Phytoplankton blooms	*minor increase*	*minor increase*
Extreme mild ice winters	**major increase**	**major increase**
Severe ice winters	**major decrease**	major decrease (uncertainties due to change in large-scale circulation)
Drying North of 59°N South of 59°N	 *decrease* *increase*	 *mainly decrease, increase in the north in the spring* *increase in some regions in spring and summer*
River flooding	increasing in winter/autumn, decreasing in spring	*decrease in spring* **increase in winter**

For the selected societal elements discussed here, a combination of extremes and their changes are controlling the development and potential future damage, in addition to numerous other factors. For forest fires, drought, and heat waves, the risk might double during the present century in some areas; however, in other areas the risk might decrease due to increased precipitation. The frequency of coastal flooding responds mainly to sea level, but also to wind, wave, and precipitation features. The number of people exposed to coastal flooding in terms of annual damage is expected to increase by orders of magnitude. Baltic coastal cities are expected to be the main source of future coastal flood losses. The offshore wind energy sector responds mainly to extreme wind and wave conditions. Here, loads and damage are important, but also conditions for operation and management activities imposing limitations in the potential use. Shipping in the Baltic Sea is affected by wind and wave conditions, icing due to sea spray, and ice conditions;

although mean wind and wave conditions are relatively low, the most severe storms affect maritime traffic. As ice winters are projected to get shorter, the wave climate is expected to get more severe (particularly in the eastern part of the Bay of Bothnia and Gulf of Finland).

Competing interests

The authors declare that they have no conflict.

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Author contribution

The review was organised by a team (EK, JH, MS) lead by AR. All authors were responsible for one or several sections and contributed to the overall text and conclusions.

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Figures.

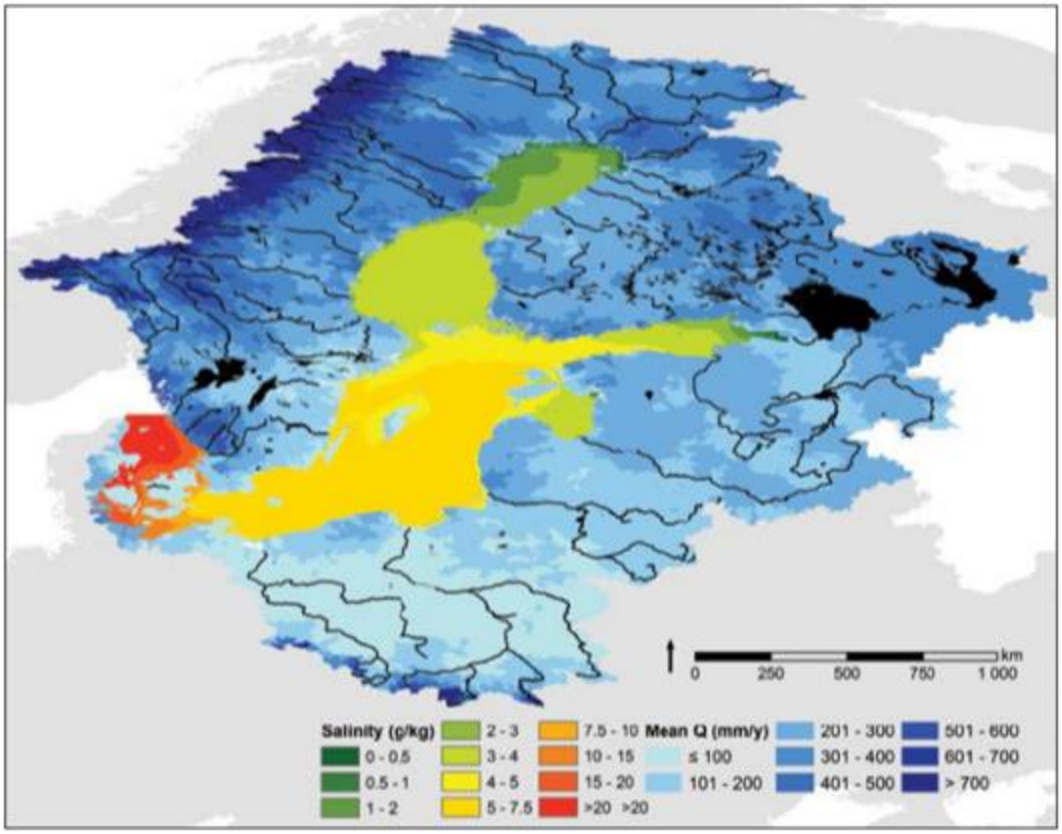


Figure 1. The Baltic Sea drainage basin together with the spatial variability in annual mean water discharge (Q) calculated with the HYdrological Predictions for the Environment (HYPE) model and with annual mean sea surface salinity in the Baltic Sea. This salinity diagram shows the gradient from high (red) to low (green) salinities, calculated with the Rossby Centre Ocean model. Courtesy of René Capell, Swedish Meteorological and Hydrological Institute. Figure from Meier et al. (2014).

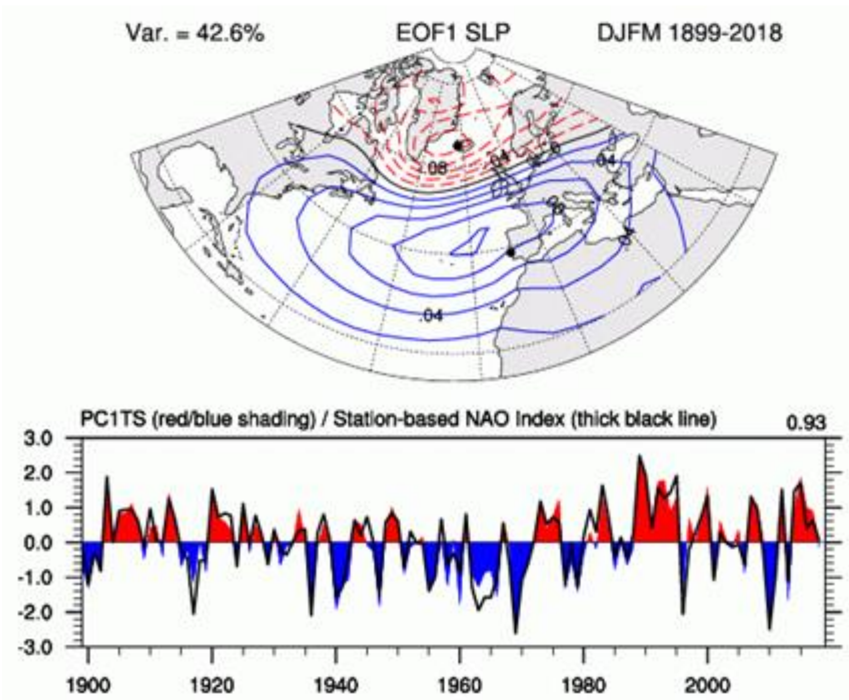


Figure 2: Principal component (PC) time series of the leading EOF of seasonal (DJFM) SLP anomalies over the Atlantic sector (20°N–80°N, 90°W–40°E), 1899–2018 (colours) and station-based index (Lisbon and Stykkisholmur) (black line, see points on map). The correlation is 0.93 over 1899–2018. From Hurrell (2018).

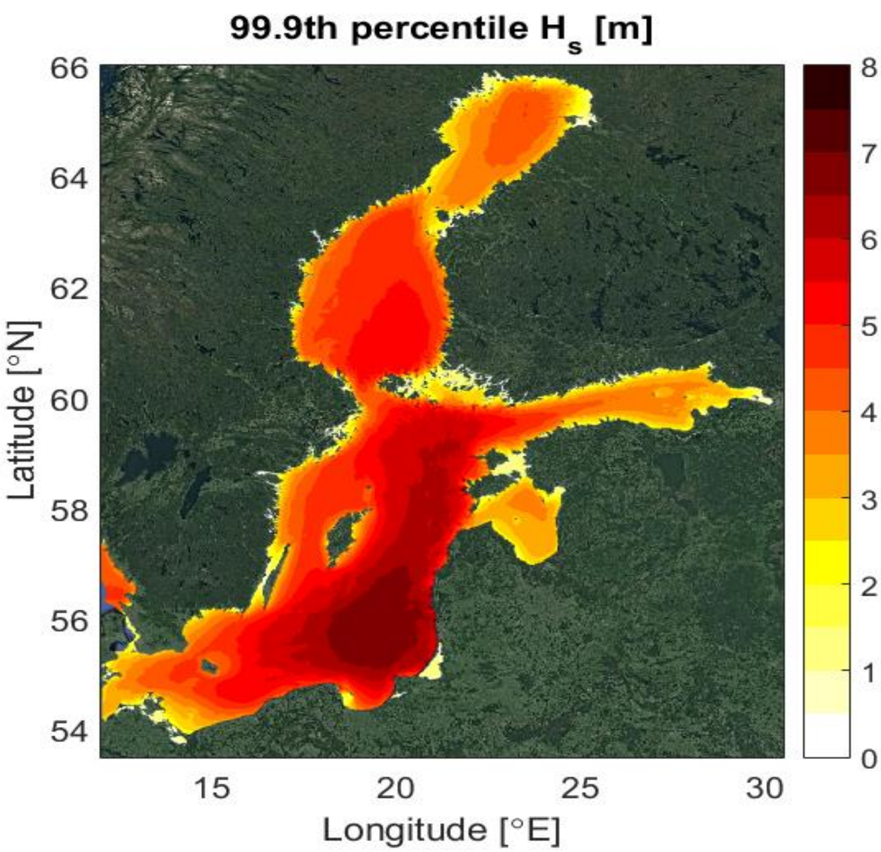


Figure 3: Ice-free statistics (Type F in Tuomi et al. (2011)) for the 99.9th percentile significant wave height (H_s) using a high-resolution wave hindcast for the years 1998–2013 (Nilsson et al., 2019).

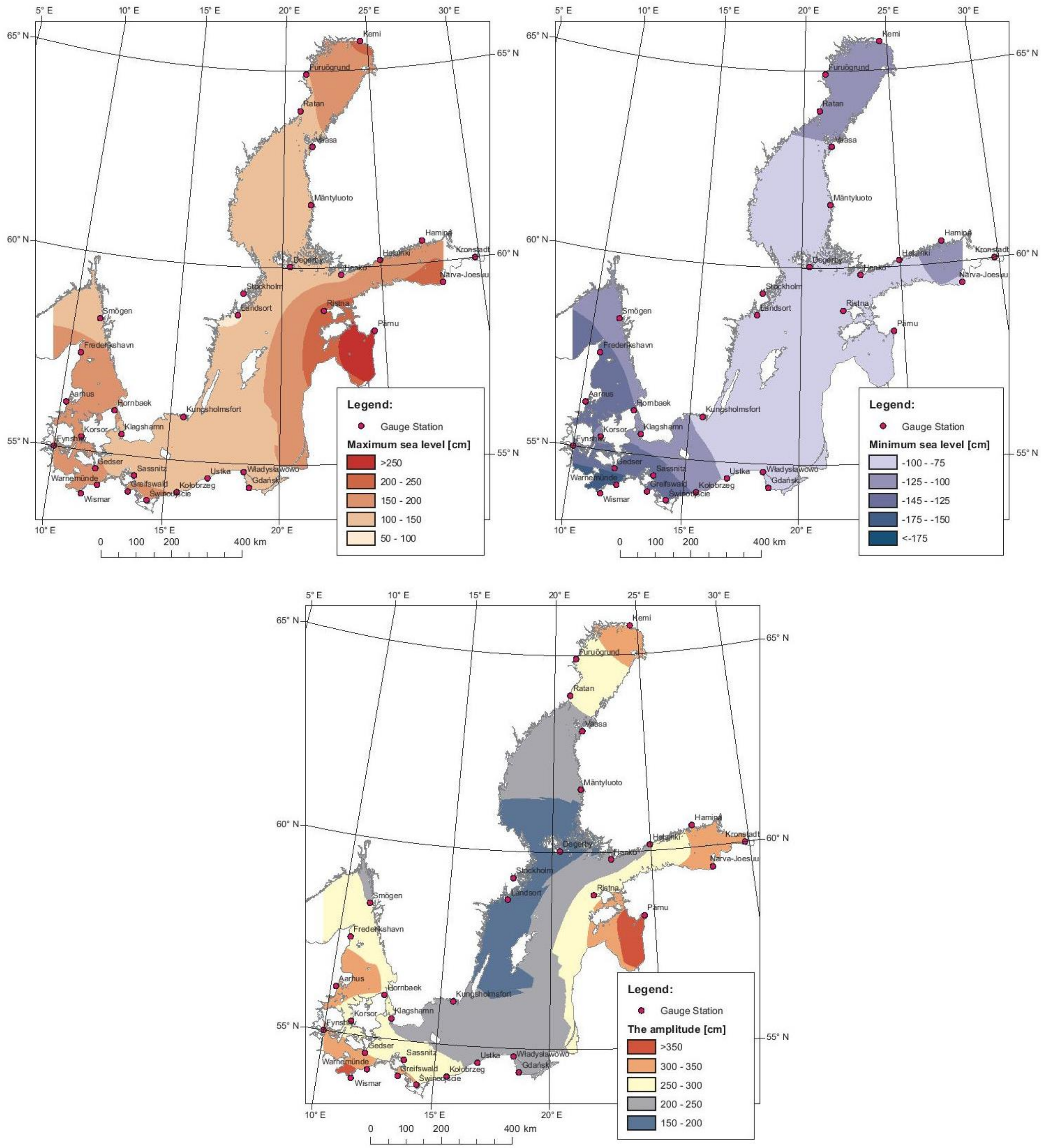


Figure 4. Surface water topography of the Baltic Sea for maximum levels (a), minimum levels (b), and the amplitude of variations (c) from the period 1960–2010 (Wolski et al., 2014).

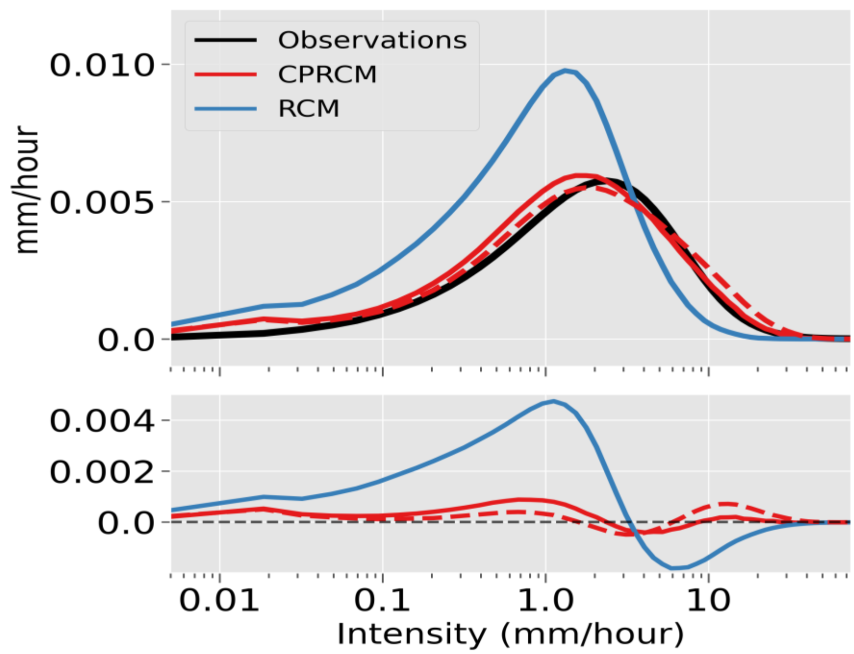


Figure 5. The top panel shows contributions per intensity bin to the total June-August mean precipitation over Sweden, units in mm per hour. The observations are from a combined radar–rain gauge data set. The lower panel shows differences with respect to the observations. The coarse scale RCM is operated at 12 km horizontal resolution while the convectivonpermitting CPRCM runs at 3 km. The CPRCM data are shown both at the native resolution (dashed) and remapped to the RCM grid (solid). The figure has been modified from Lind et al. (2020).

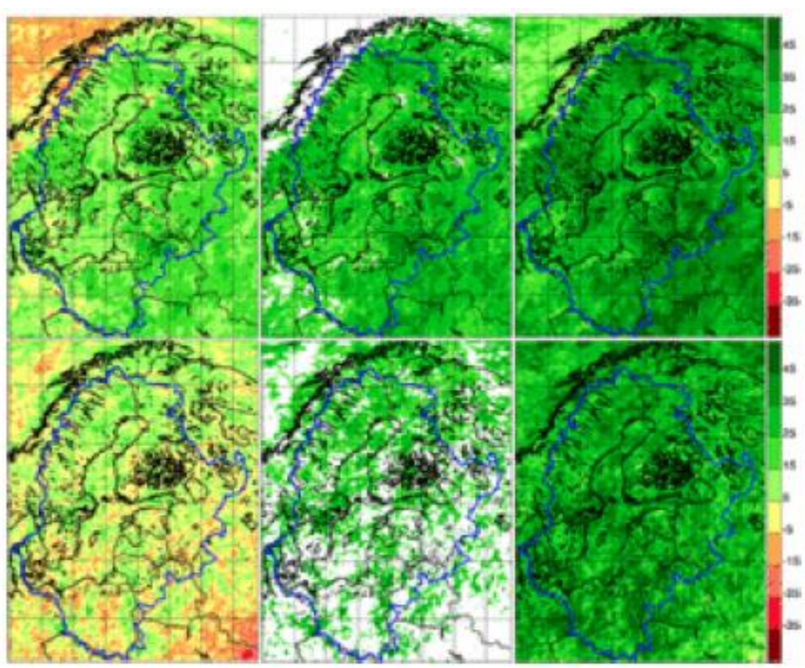


Figure 6. Change in 10-year return value of daily precipitation change (%) between 1971–2000 and 2071–2100 for 15 simulations from Euro-CORDEX according to the RCP8.5 scenario. Top row: inter; bottom row: summer. Left column: lowest quartile; middle column: median value; right column: higher quartile. For the medians, only points where 75 % of models agree on the sign are shown. Reproduced from Christensen and Kjellström (2018).

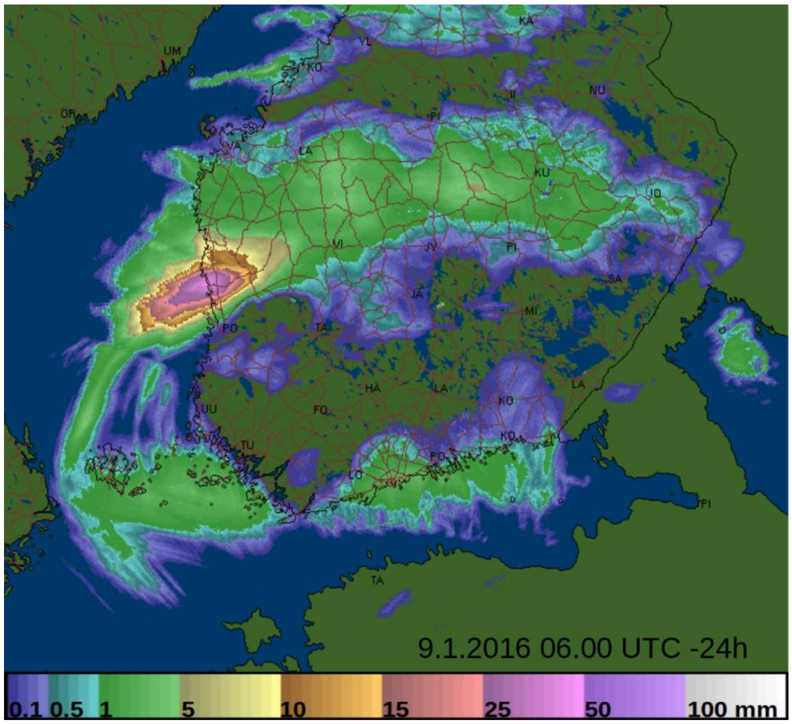


Figure 7. Radar image of precipitation accumulation (mm/day) during recent national snowfall record in Finland. The sea-effect snowfall accumulated 73 cm of new snow in less than a day to Merikarvia, Finland, in 8 January 2016. Figure from radar service of FMI intranet.

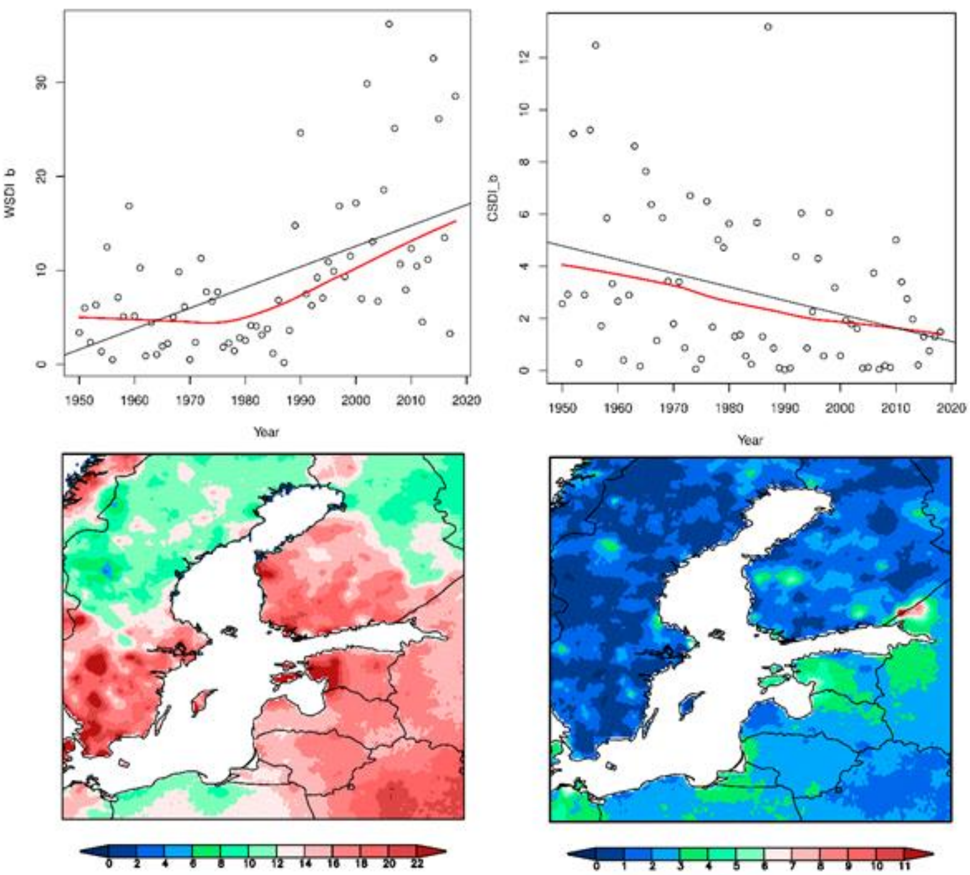
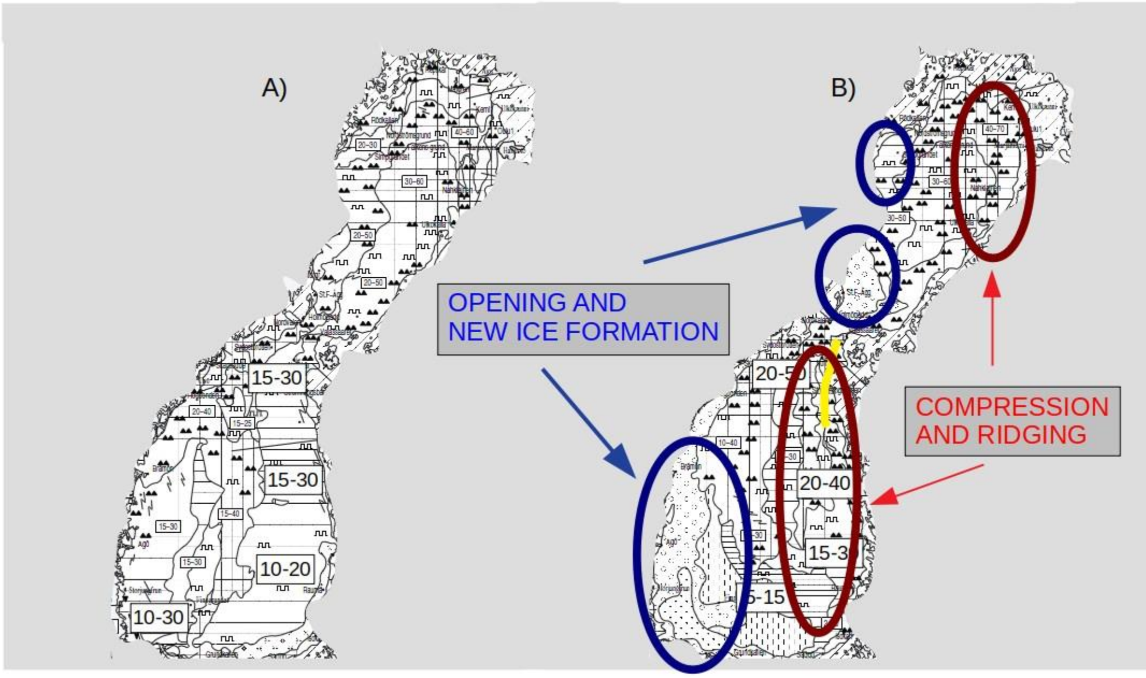


Figure 8. Annual warm spell duration index (WSDI; left) and annual cold spell duration index (CSDI; left). Top: Time series of the spatial averages over the area of 53-67N and 12-31E in 1950–2018. A fitted curve and a linear fit are also shown. Bottom: Spatial distributions of the 30-year means during the period 1989–2018. The baseline period in the calculations is 1961–1990. Data: wsdiETCCDI and csdiETCCDI created by climind 1.0.0 on 19 November 2019; Cornes et al. (2018).



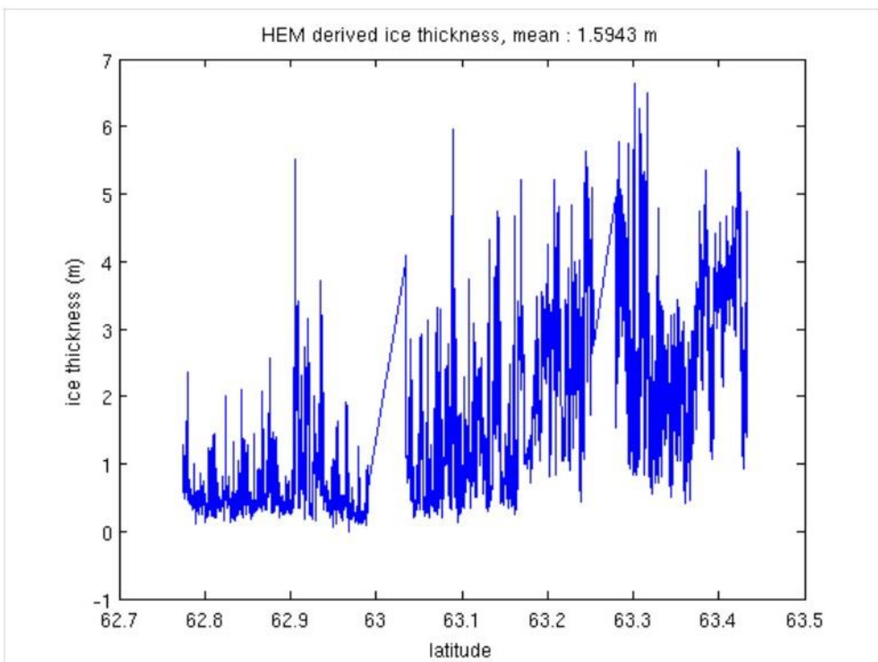


Figure 9. Ice charts before and after the major compression event in February 2011. Regions experienced opening and compression/ridging are indicated as blue and red circles, respectively. Lower panel depicts ice thickness along the yellow transect shown in the ice chart above.

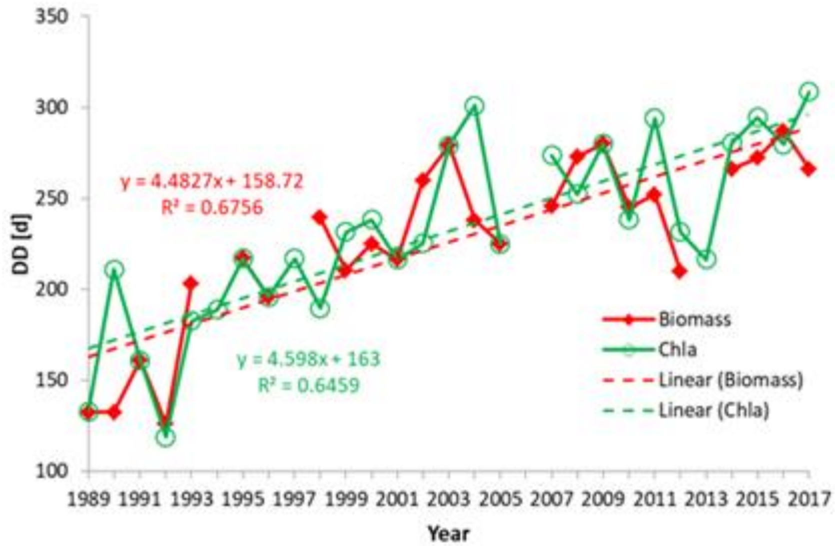


Fig. 10: Trends in the duration of the vegetation period (DD), based on phytoplankton biomass and chl *a* data, with regression lines and corresponding formulas (Wasmund et al., 2019).

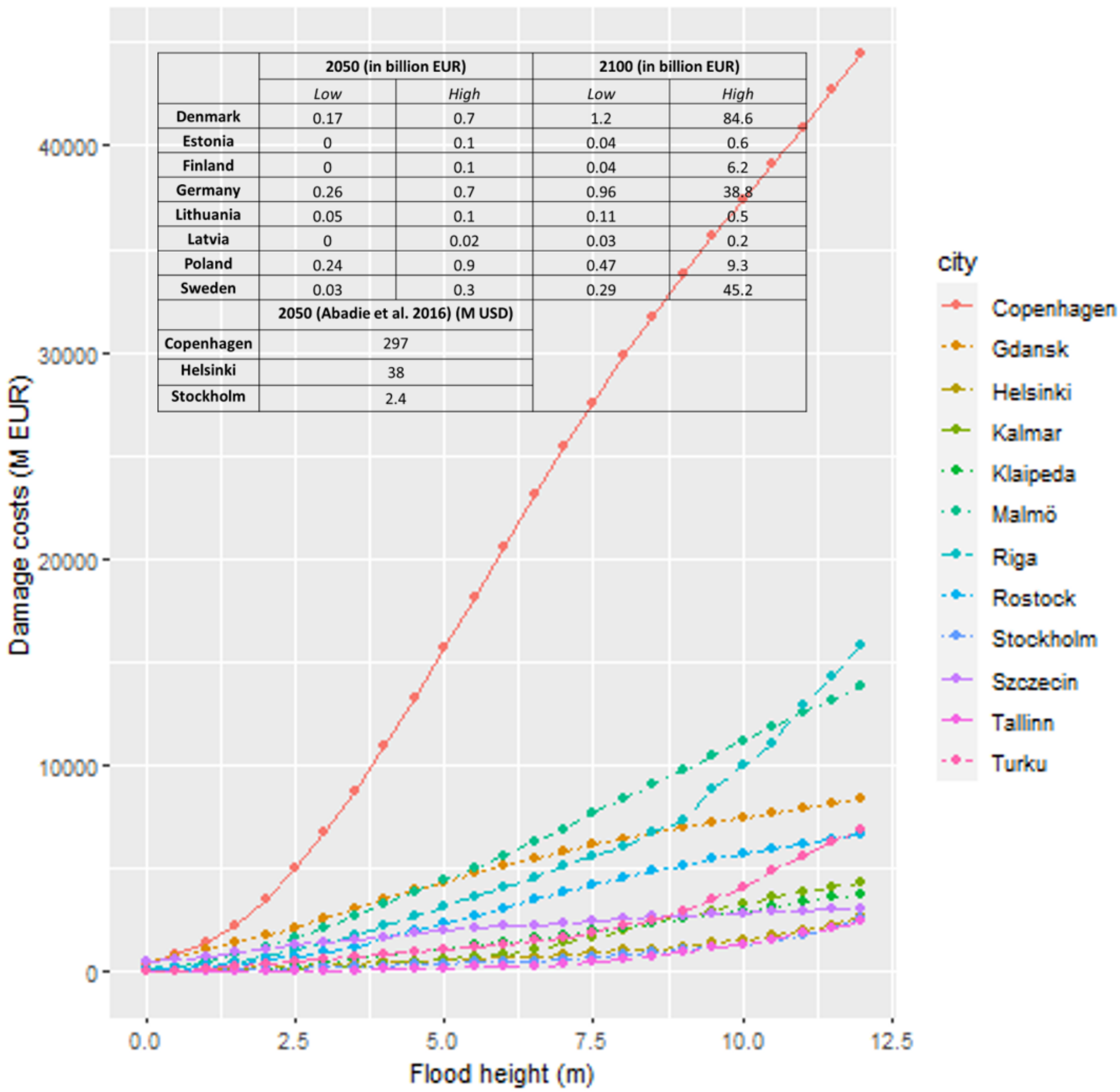


Figure 11. Estimated damage cost curves of a coastal flood event for select cities along the Baltic Sea based on Prahl et al. (2017). The table insert shows high/low estimates of the expected annual damages (EAD) to Baltic countries from extreme water levels by Vousdoukas et al. (2018, 2019, 2020) as well as specific estimates for major Baltic cities in 2050 by Abadie et al. (2016). Note that the former is in billions of EUR, whereas the latter was estimated in millions of USD.

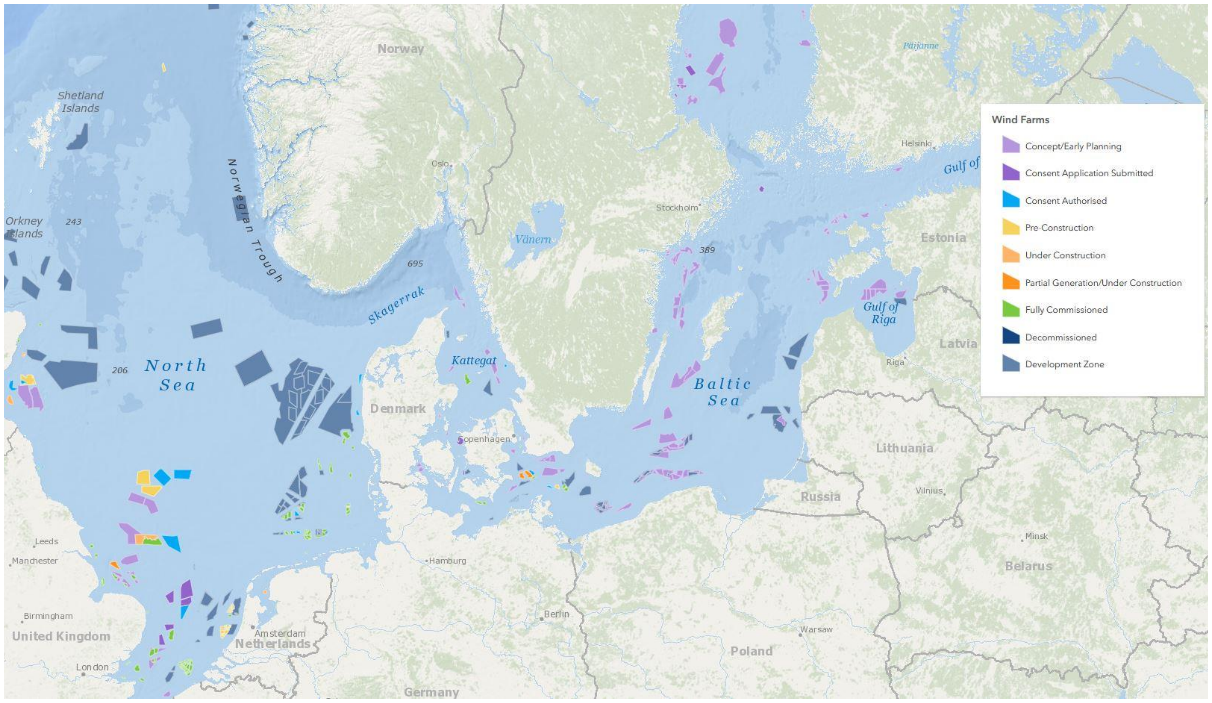


Figure 12. Overview of wind farms over part of the Baltic and the North Sea in different development states (www.4coffshore.com, 2021-03-09, courtesy of 4COffshore.com).

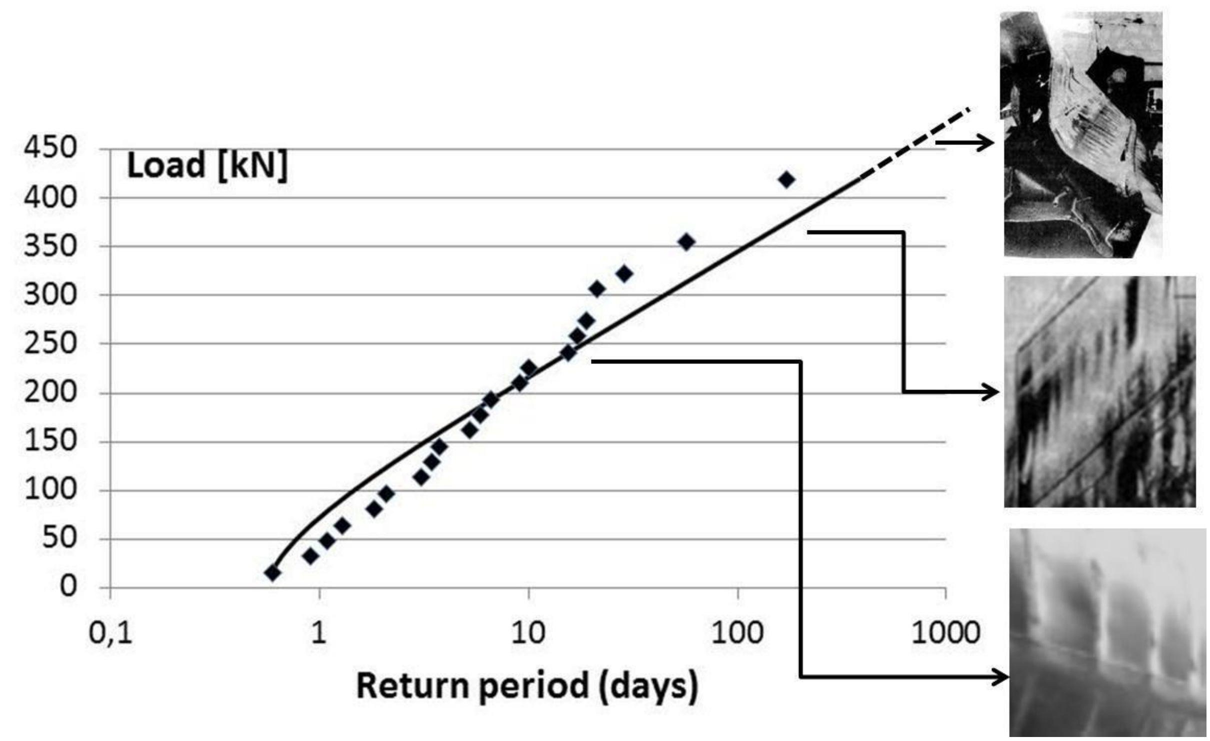


Figure 13. Measured load on one frame at the bow of MS *Kemira* measured during 1985–1991 (Kujala, 2017), showing also the possible effect of the increasing load on the damage of the ship shell structures.

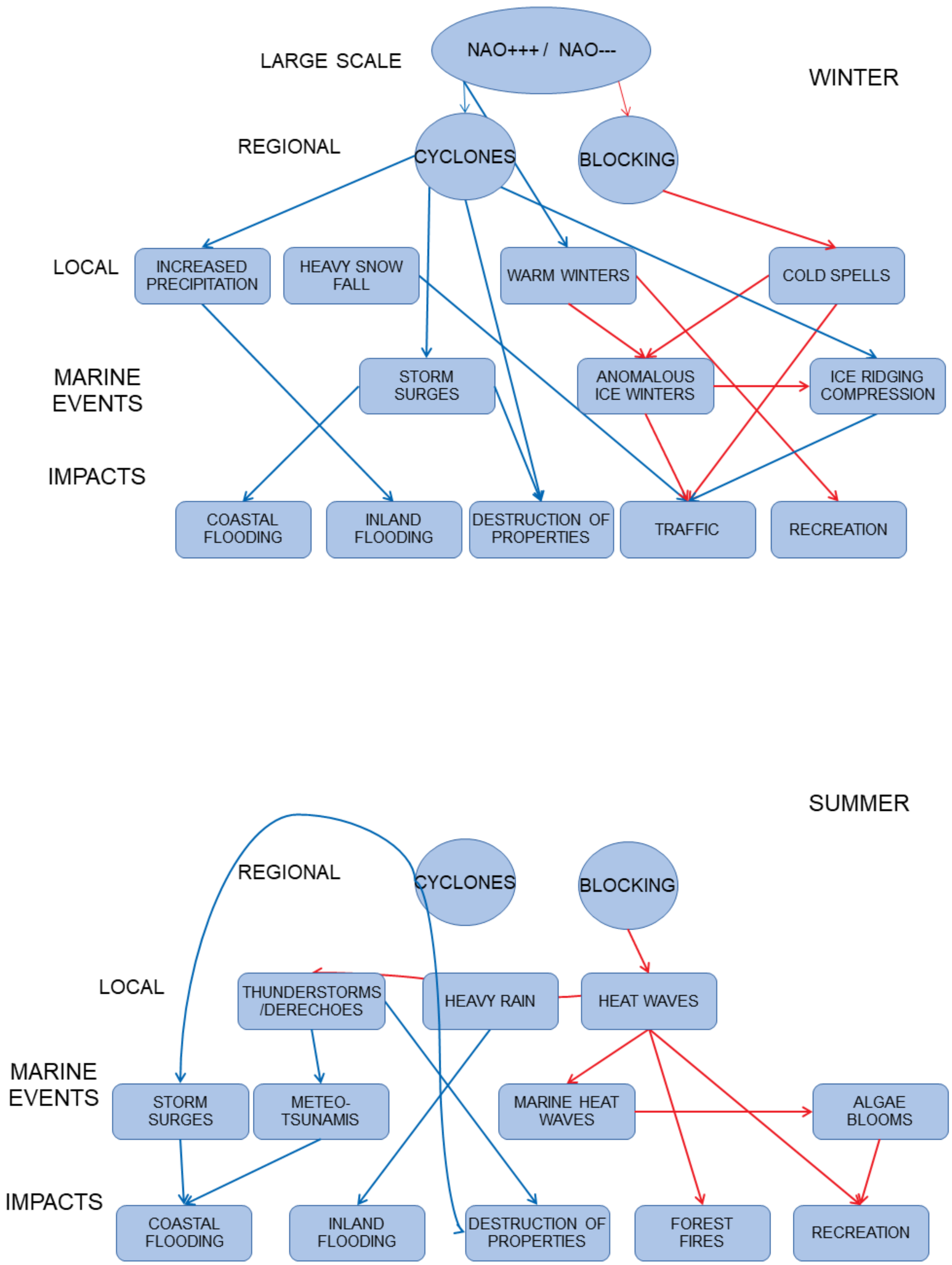


Figure 14. Simplified diagram to illustrate the relationship between atmospheric, hydrological, and marine processes and their impact on society in winter and summer.