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Earth System Dynamics
Discussions

Natural Hazards and Extreme Events in the Baltic Sea region

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Abstract.
A natural hazard is a naturally occurring extreme event with 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 and 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 summarise existing knowledge of extreme events in the Baltic Sea region with the focus on 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, but also concerning specific events, for example, occurrences of marine heat waves and small-scale variability of precipitation. Suggestions for future research includes 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 impact 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 studies.

1 Introduction

Natural hazards and extreme events may have severe implications on society including threat to human life, economic losses and damaged ecosystems. A better understanding of their major causes and implications enables society to be better prepared, to save human lives and mitigate economic losses. Many natural hazards are of hydro-meteorological origins (storms, storm surges, flooding, droughts)

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

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$ losses (Munich Re, 2018), while a heatwave and drought caused roughly 3.9bn$ losses. According to the EEA (European Environment Agency), increase in frequency and/or magnitude of extreme events such as floods, droughts, windstorms or heat-waves will be among the most important consequences of climate change (EEA 2010). Despite climate change having received considerable scientific attention the knowledge on changing extremes and their impacts is still to some extent fragmented, in particular when it comes to compound events (Zscheischler et al., 2018). The confidence level of the knowledge of relation between global warming and hot extremes is high while confidence is only medium for heavy precipitation/drought (IPCC, 2018). Furthermore, the confidence level reduces 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 by "extreme" depends on the parameter and the application in relation thresholds for generating 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 time frames (days, month, season, annual) with respect to the 1961-1990 reference time period (Seneviratne et al., 2012). Using predefined extreme indices allow 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, analyzing 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., 2009c; 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 or threshold-based extremes and their relations to impacts. In the reviewed literature a range of definitions are used.

The Baltic Sea watershed drains nearly 20% of European land areas (see Figure 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 larger for extreme events due to larger statistical uncertainties for rare event. 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).

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

Earth System Dynamics Discussions

Changes in extreme events can be caused by a combination of changes in local/regional conditions with changes of the 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 summarise existing knowledge of extreme events in the Baltic Sea region. We focus on past and present state, as well as future climate scenarios and expected changes when possible. The events considered here 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). The text focuses on the current base of knowledge, but also identifies knowledge gaps and research needs.

Since almost three decades, the knowledge on the Baltic Sea ecosystem has also 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 Baltic Earth (baltic.earth/grandchallenges) with a general summary (Meier et el., 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 (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 (i.e. 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 km 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 spans extended periods cannot be expected to be homogeneous in time. This is particularly important for the increasing number of re-analyses 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

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

Earth System Dynamics Discussions Open Access EGU

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 minimise 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 like cyclone statistics (for example changes in their intensity, number and position). Reanalysis products includes NCEP/NCAR (from 1948 onwards; Kalnay et al. 1996; Kistler et al. 2001), ERA-Interim, starting in 1979 (Dee et al. 2011) or, more recently, ERA5 (Hersbach et al. 2020). Other reanalyses use a limited data assimilation scheme to go further back in time, like the 20th Century Reanalysis 20CR (from 1871 onwards; Compo et al. 2011) or CERRA (Schimanke et al., 2019). On the regional scale, detailed regional reanalysis 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, also dynamical downscaling with regional models or empirical-statistical downscaling using statistical models are used. A large multi-model coordinated 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. Coordinated 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 a., 2011). An RCP represents a climate forcing scenario (e.g. including changes in greenhouse gas emissions, aerosols, land use etc.) trajectory 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 continuously growing population and 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, representing an integrated and more ecologically friendly world; B2 of a divided but more ecologically friendly world.

2 Current state of knowledge

2.1 Changes in circulation patterns

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

Earth System Dynamics
Discussions

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 is one of 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 centers 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 also other wind directions are 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 behavior 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 section 2.2.7). Other studies (e.g., Deser et al., 2017; Marshall et al., 2020) do not find a significant trend. It has been speculated that these 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 are 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 for 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). It was already stated by IPCC (2013) 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 for 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) find 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,

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

Earth System Dynamics
Discussions

the very modest warming in October in southern Finland, and about a half of the very large 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, in particular 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, e.g. under extended blocking situations, would lead to nonlinear 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, now and potential future change)

2.2.1 Winds 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) or '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 section 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,b). 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 NH extratropics during 1979-2010 reveal a large spread across the reanalysis product, strong seasonal differences, as well as 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 datasets 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. (2016a) 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 et al. (2016b) 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 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 et al., 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 behavior 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 decreases 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, e.g. south of Greenland. For this region the N-S gradient is rather increasing as the weakest warming in the entire NH 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 N. 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 in how far 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 windstorms, like Mauri in 1982 (Laurila et al., 2019). There is limited information concerning past or future trends concerning occurrence of wind gusts.

2.2.2 Extreme waves

Vertical motions on the ocean surface consists 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

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

(Hansom et al. 2015) because locally higher wave heights in not particularly stormy conditions can lead to damages and fatalities and may become labeled in the media as extreme, giant, freak, monster or rogue waves. Rogue waves are typically defined as a maximum wave height of more than two times the significant wave height. The horizontal resolution of wave modeling hindcast studies for the Baltic Sea have 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).

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 above 14 m, equaling or exceeding the previous record from December 22nd 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 99.9^{th} percentile for significant wave height in the Baltic Sea of 6.9 m. They found 45 unique extreme wave events with modeled significant wave height above 7 m during the 41 year-simulation. Twelve of which had a maximum above 8 m, six events 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 also discussed further in Weisse et al. (2021).

Many studies have been conducted to characterize the variations in the wave fields using measurements (e.g. Kahma et al. 2003, Pettersson and Jönsson 2005, Broman et al. 2006) and using modeling (e.g. Jönsson et al. 2003, Räämet and Soomere, 2010, Björkqvist et al. 2018) describing also 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 the months November until 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 99.9^{th} percentile significant wave height in Figure 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, as well as 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).

Some studies have also been conducted on near-shore extreme waves; e.g. Gayer et al. 1995, Paprota et al. 2003, 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 in understanding and prediction of ocean extremes and freak waves (e.g. Cavaleri et al. 2017, Janssen et al. 2019) have been achieved, a practical definition using usually more well-predicted parameters, such as significnat wave height, is presently used in warnings (Björkqvist et al. 2018).

From long-term in-situ observations and modeling results trends in wave climate 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 (section 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 predictable. A spatial pattern with an increase in the central and western parts of the sea and a decrease in the east was observed.

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 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 more high-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 temporal 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 from 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 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 both changes in wind climate (section 2.1 and 2.2.1) and ice conditions (section 2.2.10 and 2.2.11).

2.2.3 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 large damage to the coastal infrastructure and endanger 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 centimeters. Only exceptions are the southwestern 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 maximum 1 m variation in monthly mean sea

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

levels (Leppäranta and Myrberg 2009). Due to the shape of the Baltic Sea, the highest and lowest sea levels are found in the end 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 1960-2010, are shown in Fig. 4 (from Wolski et al. 2014).

The observed maxima and minima on the Baltic Sea coast along with 100-year return levels based on interpolated coastal tide gauge observations 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 detrended daily tide gauge records of seven stations in Denmark and Sweden on the Baltic Sea coast, using GEV (Generalized Extreme Value) and quantile regression methods. 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. 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 8 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 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 per cent in RCP4.5 and by 15 per cent 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 meters in 2100. The large variation between the models causes a large uncertainty in the evaluation of the change in extreme sea levels during the present century. These sea level estimates should be considered preliminary. 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 are 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). An extended discussion on sea-levels is seen in Weisse et al. (2021).

2.2.4 Precipitation

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

Earth System Dynamics
Discussions

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 snow fall events can generate large amounts of snow in coastal areas downstream of the Baltic Sea (section 2.2.5). 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 favorable 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 includes: PTHBV covering Sweden at 4 km grid (Johansson and Chen, 2005); the Finnish data set at 1 km and10 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., 2018). 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, one 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 with 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 of reproducing 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 also the simulation of the diurnal cycle is 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 km, are found to improve the simulation of both spatial and temporal features of precipitation (e.g. Belušić et al, 2020). Importantly, this involves also 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 Figure 5 showing 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 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 one in three years event, has become 45% more frequent

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

comparing the last thirty years with the preceding 30 years. For even more extreme precipitation events like one in ten, twenty or even fifty years the large variability makes it difficult to draw any firm conclusions about changes especially for small areas with only few observational 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 gauges were pooled across the whole country. For less intense events like 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 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 experience increases (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 strongest at sub-daily time scales than for 1-day or 5-day events. Newly developed convective 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. (2014) showed stronger increase in summertime intense precipitation in a 1.5 km model compared to a 12 km on for the southern UK. Similarly, Lenderink et al. (2019) showed 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 to 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 strong impacts on society. Large amounts of precipitation are strongly associated with flooding which is common in the Baltic Sea region. More intense cloud bursts are strongly associated with urban flooding but also with adverse effects on agriculture and infrastructure in rural areas. Stronger climate change signals in recently developed convective permitting models compared to previous state-of-the-art models can have strong impacts for the provision of climate services and as advice in the context of climate change adaptation.

2.2.5 Sea-effect snowfall

Sea-effect (lake- or bay-effect) snowstorms may disrupt several sectors of society and can cause millions of euros of damage (Juga et al. 2014). Intense and prolonged sea-effect snow events can produce tens of centimeters 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 leading to highly increased 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 damages and failures in power transmission due to heavy snow loading. Road maintenance and snow transportation to disposal sites is costly if there is not enough space for snow storage along the streets (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, the public transport; busses, 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 snowdrift 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, Finland, in February 2012 (Juga et al. 2014) caused severe pile-ups on the main roads, with hundreds of car accidents and tens of injured persons. On the other hand, no damages 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, 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 effects of excess snowfall to society (Juga et al. 2014, Vajda et al. 2014).

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 occurs over the sea close to the coast (Andersson and Nilsson 1990). With suitable wind direction, these snow bands 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 favorable wind directions vary from north to northeast (Jeworrek et al. 2017) due to the cold air outbreaks from the northeastern 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. Favorable conditions for the development of convective snow-bands include an optimum strong wind, large air-sea temperature difference, low vertical wind shear, high atmospheric boundary layer height and favorable wind directions (Jeworrek et al., 2017; Olsson et al. 2020).

Using simulations conducted with the regional climate model RCA4 for the period 2000-2010, annually 4 to 7 days was seen to be favorable 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 also the annual maximum ice extent is projected to decrease (BACC II, 2015; Luomaranta et al., 2014,

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

Höglund et al., 2017; see also Sec. 2.2.10), extending the time period when convective snowbands can form. Besides, wintertime precipitation amounts are increasing (Sec. 2.2.4). On the other hand, on an annual mean basis, conditions might become less favorable 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 (Sec. 2.2.4).

The sea-effect snowfall events typically have temporal and spatial scales smaller than what is covered by the observational network and resolved by climate models. The high resolution ERA5 data was used in a case study for January 2016. The preliminary results were promising towards the use of re-analysis data over sea but the data cannot produce intensive enough convective snowfall over land (Olsson et al. 2018). Newly developed convective permitting regional climate models (see Sec. 2.2.4), in turn, open up new possibilities to assess the future evolution of the probability of the occurrence.

2.2.6 River floods

A detailed assessment of climate change of river floods for northern Europe was provided in BACC I (2008) and BACC II (2015). The regional features in the Baltic Sea Basin during last decades according to Stahl et al. (2010) consist in positive trends with increasing streamflow in winter months in most catchments of the Basin, while in spring and summer months, strong negative trends were found (decreasing streamflow, shift towards drier conditions).

After the last BACC publication in 2015 there are only few studies devoted to the past hydrological regime changes. Arheimer (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 flows events over the past 100 years. There was a slight decrease in flood frequency, although in a shorter perspective it seems that autumn floods increased over the last 30 years. The flood decreasing is connected with seasonality change in the study region. Changes in flood time occurrence in Europe were also established by Bloschl et al (2017). In the Baltic Sea region they detected the floods shifting from late March to February due the earlier snow-melting, driven by temperature increases in the region and a decreasing frequency of arctic air mass advection (see section 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 northwest 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 were 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, and (Beldring et al., 2008; Veijalainen et al., 2010b; Apsīte et al., 2011; Kriaučiūnienė et al., 2008; Szwed et al., 2010). 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 Olsson et. al. (2015) moderate changes in annual mean flow by 2051–2090 are expected in Finland. Winter, summer discharges and early spring discharge peaks will decrease more notably, the autumn mean flow will increase in northern Finland and decrease in catchments with high lake percentage in southern Finland. A significant decrease in magnitude of spring floods and a significant increase in autumn floods are shown for Sweden (Arheimer at al. 2015). For spring floods, the trend obtained using two climate projections (Hadley and Echam) 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. There are slight increases in some parts of Sweden and Norway, north-eastern Europe, according to Donelly 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. Roudier et al. (2016) established the relatively strong decrease in flood magnitude in parts of Finland, NW Russia and North of Sweden with the exception of southern Sweden and some coastal areas in Norway where increases in floods are projected. Northern streams in Finland predicted to lose much of the seasonality of their flow regimes by 2070 to 2100 that is explained by projected air temperature increase and maximal flow decrease. (Mustonen et.al., 2018). 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 Southwestern Finland. Almost everywhere the increase in 100-year floods (QRP100) is stronger than the 10-year floods (QPR10). The continuation of current changes in hydrological regime observing within the territory of Belarus in recent decades (increase of winter and decrease of spring streamflow) has been projected for 4 main river basins in the country (Western Dvina, Neman, Dnepr and Pripyat` rivers) by Volchek et al. (2017).

According to Thober et al (2018) in northern Europe floods 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 et al., 2015, Alfieri *et al.,* 2015, Roudier *et al.,* 2016). The streamflow in the east of the Baltic Sea Basin (the Western Dvina River within Russia and Belarus) will be characterized by mostly decrease of mean streamflow in the upper stream and increase in the lower part of the river basin. The projected maximal streamflow is expected to decrease with largest changes in the lower part of the river basin up to 25 %.

2.2.7 Warm and cold spells in the atmosphere

A significant surface air temperature increase in the Baltic Sea region during the last century has been detected, with the largest warming trends in spring (and winter south of 60°N) and the smallest in summer (BACC I, 2008; BACC II 2015; Rutgersson et al., 2014; Meier et al., 2021 and references therein). More recent studies conducted e.g., for Poland (Owczarek and Filipiak, 2016), the three Baltic States (Jaagus et al., 2014, 2017), Finland (Irannezhad et al., 2015; Aalto et al. 2016), Sweden (SMHI, 2019) and the whole Baltic Sea drainage basin (Räisänen, 2017), indicate that mean temperatures continue to rise in the region and that the increases are larger than the global average warming.

Extreme events related to air temperature include individual high (or low) temperatures, but what is often more influential is extended periods with high (or low) temperatures. The Baltic Sea area is generally less exposed to severe heat waves compared to, for example southern parts of Europe. During the recent 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 of adaptation of people living in the Baltic Sea region to relatively cool climate, high summer-time

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

temperatures pose a significant risk to health also in the current-day climate (e.g., Kollanus and Lanki 2014; Åström et al., 2016; Ruuhela et al., 2018).

In general, the magnitude, temporal and spatial extent, and frequency of heat waves depend on large-scale fluctuations in atmospheric circulation (see section 2.1), particularly on the occurrence of blockings and other circulation patterns (Horton et al., 2015; Brunner et al., 2017) but 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 Sec 2.2.9) and solar radiation are of importance. For example, Tomczyk and Bednorz (2014) showed a clear link between heat waves along the southern coast of the Baltic Sea and the circulation patterns. Furthermore, the heat wave in 2018 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, the record high temperature in Finland in 2010 (37.2 °C) was likely contributed by several factors in addition to the very warm air mass (Saku et al., 2011), and in a recent simulation study it was found that replacing a dense urban layout by a suburban type 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 (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 Figure 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 for a recent time span (1989-2018) (Figure 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 but changes of both positive and negative signs in northern and eastern parts of the country and statistically insignificant 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 become increasingly frequent, but also increasingly 'normal', from a statistical point of view (Rey et al. 2020). Accordingly, quantitative estimates of the rates of the future changes strongly depend on the selected definition of the heat wave (Jacob et al., 2014). The mean length (number) of heat waves where the 20 °C daily mean temperature is exceeded has been projected to increase by about 50 % (60 %) 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).

Accompanied with more frequent and longer warm spells are decreases in the frequency, duration and severity of cold spells, both based on observations (Easterling et al., 2016) and model projections (Sillmann et al., 2013; Jacob et al., 2013). 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),

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

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 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 a half of the very large warming in December in Finland during the period in 1979–2018 (Räisänen, 2019).

Analogously to WSDI, the cold spell duration (CSDI) is defined as the annual or seasonal count of days with at least 6 consecutive days when 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 (Figure 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 (Matthews 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 per year by 2071-2100 with respect to 1971-2000 (Jacob et al. 2014).

2.2.8. 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 summer 2018 when the surface mixed layer became extraordinarily warm in many locations. Accompanied with the atmospheric heat wave in summer 2018 large parts of the Baltic Sea were anomalously warm from mid-June to August. According to the satellite data, SST at peak of the warming 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, 23-25°C in the western parts (Naumann et al., 2018). For the entire Baltic Sea May to August was a positive SST anomaly by 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 Finland, temperature at bottom (31 meters) was higher than 20°C. That was the all-time record since 1926. Humborg et al. 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 on occurrence and impact of the 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 number of warm SST days and the record-breaking anomalies of summer mean SST will change in future. According to their study, both of these indicators will become more common in

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

future but more important findings are that SST extremes exhibit large variability in time scales of decades and the changes are manifested more pronounced in open sea areas than coastal regions.

2.2.9 Drought (Irina Danilovich)

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 the different parts of the region and cause meteorological, soil moisture and hydrological droughts. This section is devoted to the conditions and some consequences caused by long-term precipitation deficit. Drying conditions are frequently connected with extreme temperatures are referred to in section 2.2.7. Change in precipitation during the twentieth century in the Baltic Sea basin has been variable and characterized by extremeness increasing as also reflected in the river flow regime accordingly (see section 2.2.4 and 2.2.6).

There are some tendencies characterizing changes in dry conditions. 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 et al., 2011; Przybylak et al., 2007; Stonevičius et al.,2018; Danilovich et. al., 2019). However, Bordi et al. (2009) in an earlier study found 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 increases in summer (Lehtonen et al., 2014a). The time-mean 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 reduce 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 range between strong drying and wetting conditions in Central Europe (Orlowsky and Seneviratne, 2013).

In hydrological regime an increase of minimum flows in northern parts of Europe, Scandinavia and the Baltic countries will experience a general increase in 20 yr minimum flows of up to 20% – in some inland tributaries up to 40% – by the end of the 21st century (Forzieri et. al., 2014). The decrease of drought magnitude and duration is expected for central and northern Europe (except southern Sweden) according to Roudlier et al. (2014). 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). 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 in most of the basin, due to the 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

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

project on average a small decrease in the lowest water levels during droughts in Finland (Veijalainen, 2019).

2.2.10 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. On an average winter, maximum 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). During extreme cold conditions, the entire Baltic Sea can be 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) defined classification on 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 drivers of ice winter extremes and their observed and expected changes.

Annual maximum ice extent is a cumulative indicator of the severity of winter. It is largely driven by the large-scale atmospheric circulation and it's inter-annual variability is well correlated with the NAO index (Omstedt and Chen, 2001; Vihma and Haapala, 2009). They concluded that during the winters with the 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 the 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 in 2020. According to Uotila et al. (2015), winter 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. In addition, the enhanced transport of warm Atlantic air masses to the Baltic Sea region, anomalous low ice extent in winter 2015 was partly due to higher than average downward long-wave radiation because of increased cloudiness which decreased heat loss 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 an average in terms of MIB. The others are classified as mild or extremely mild ice winters. The winter 2020 was 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 economical losses for marine traffic (see section 2.1.1.4).

Ongoing changes towards a milder climate demands a revision of the Seinä and Palosuo (1996) definition of extremely mild and severe ice winters. Their classification was based on a choice that 11% of the lowest MIB's were classified as extremely mild winters. Correspondingly, 11 % of the largest MIB's 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 Baltic sea ice will experience considerable shrinking and thinning on average in future (BACC I, 2008; BACC II, 2015). This is particularly clear for the Bothnian Sea, Bothnian Bay and Gulf of Finland. However, changes in natural variability and extreme sea ice winters is an open question since the model studies have been focused on changes in mean conditions.

2.2.11 Ice ridging

Sea ice extremes depend on temporal and spatial scale in consideration but more importantly on geographical location and climate conditions – five-meter-thick pressure ridges are common off the Hailuoto island in the Bay of Bothnia every winter, but rarely present in the Southern Baltic Sea. Capacity of the society of managing sea ice related hazards depends also on the likelihood of occurrence of sea ice. In some regions, even a thin ice cover can cause large economical losses to society if the sea ice freezing is occurring 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, i.e. pressure ridges, can be 30 meters 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 meter 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 sea time 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, 2013a). Implicitly, ice compression events have been observed by ships navigating in ice.

The most severe ice winters during the last ten years occurred in 2010 and 2011 due to the negative NAO (Cattiaux et al, 2010). In winter 2011, 14 ship accidents occurred due to harsh ice conditions (Hänninen, 2018). For a comparison, during the average winters there are only 1-5 accidents. Several compression events were also reported during the same winter 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 in 2011 were characterized by cold and calm weather in the Northern Baltic Sea. Consequently, the Gulf of Bothnia became totally ice covered already early in February. Because of the weak winds, the Bothnian Sea was mainly covered by 15 – 30 cm thick undeformed ice (Figure 9). This situation created favorable preconditions for an intensive ice compression and ridging event. After a cold and calm period a change in weather pattern occurred on 24th February when a cyclone arrived in the Bothnian Sea region. The wind speed increased up to 18 m/s and strong southwesterly winds prevailed for the following five days. Consequently, pack ice drifted towards the north-eastern sector of Bothnian Sea. Ice field experienced compression, strong deformations and the undeformed level ice field was redistributed to a heavily deformed ice. In the south-west area of the Bothnian Sea a coastal lead was generated due to divergent ice motion (Figure 9). Based on helicopter electromagnetic

Earth System Dynamics
Discussions

measurements (Ronkainen et al., 2018) mean sea ice thickness along ~100 km transects in the heavily deformed areas increased up to 0.9 m and 1.6 m meters. Thickness of individual ridges were 4 - 8 meters (Figure 9). Sea ice compression, or internal stress of ice, has not been regularly measured in the Baltic Sea but the crews of the ice breakers and merchant vessels are reporting observations of ice pressure from the bridge. Indications of the ice pressure include: closing of ship channels, reduction of ships speed, besetting in ice and compression of ice against the hull of the ships. During the period from 24 February to 7 March 142 ice compression cases were reported in the Gulf of Bothnia. From these 25 reported severe compressions, or 3-4 on a scale of four (FMI ice service; Lensu et al, 2013b). Compression and thick ice caused a total closedown of marine traffic for several days. Even the largest merchant vessels need to be assisted by the ice breakers. In many cases, the ice breakers needed to assist the merchant vessels one at the time i.e. traditional assistance in convoys was not possible.

Sea ice extent and thickness are projected to decrease remarkably in the Baltic (Meier et al., 2021). It's 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 future.

2.2.12 Phytoplankton blooms

One component of the marine ecosystem here considered an extreme event is phytoplankton blooms (for the marine ecosystem in general see Viitasalo et al., 2021). 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 favorable conditions, i.e. 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. Blooms are visible mass-occurrences of phytoplankton after excessive growth. They become visible by increased water turbidity, sometimes even discoloration (red tides) or surface scums. The mass-occurrence of toxic species (harmful algal blooms) may have detrimental impact on the environmental components, lead to toxic incidents, and may also cause economic harm, e.g. by constraints of the touristic use of the coastal waters (Wasmund, 2002). Phytoplankton forms the basis of the pelagic food web and feeds after sedimentation also the benthos. Its blooms are natural phenomena and a vital component of the ecosystem. Only the excessive blooms caused by cultural eutrophication may be considered a nuisance and should be reduced to a natural level (HELCOM, 2007). This natural level is still not 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 (BMI) are rare events, which lead to re-oxygenation in the deep water and fixation of phosphorus in the sediment. The latest BMI occurred in December 2014 (Mohrholz et al., 2015). Its effect on oxygen concentrations in the deep water was only of short duration and DIP concentrations were increasing again since 2015 both in the deep and surface water 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 suddenly 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 impressive 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 since the 1960s (Finni et al. 2001). Cyanobacteria seem to increase on a world-wide scale due to global warming (Karlberg and Wulff 2013). Cyanobacterial species mostly 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 occur patchy, representative sampling is difficult and data may be insufficient for a reliable trend analysis. The development of cyanobacteria blooms is annually reported 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 be even contradictory (Olofsson et al. 2020). A few recent extreme blooms are selected to be 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 2018 (see also marine heat waves, section 2.2.8) caused the strongest cyanobacterial bloom of the 2010's (https://www.syke.fi/en-US/Current/Algal_reviews/Summary_reviews/Summary_of_algal_bloom_monitoring_2018_S(47752)). Remarkably, the typical cyanobacteria genus of the summer blooms was also abundant in winter under the ice on the western and eastern Finnish coast, as identified for example on 7 January 2019 (http://www.syke.fi/fi-FI/Ajankohtaista/Tiedotteet/Viileassakin_vedessa_viihtyvaa_sinilevaa(48957)).

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). 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 SW coast of Finland raised the attention of regional authorities (https://www.syke.fi/en-US/Current/Press_releases/Last_summers_fish_kill_was_caused_by_a_t(38306)). Global warming is generally becoming a threat that may influence the phytoplankton stronger (Cloern et al., 2016; Reusch et al., 2018). Future changes in eutrophication and as well as a changing climate will influence the occurrence of harmful algal bloom. 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), but 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 the central Baltic Sea (Kahru et al., 2016). Based on weekly

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

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 (Figure 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 extends 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 e.g. global warming or changes in the atmospheric circulation could have large and potentially disastrous consequences to 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 a., 2021).

2.3.1 Forest fires

Fires play a key role in the natural succession and maintains 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).

Large forest fires are often associated with long-lasting drought and heat waves. During the exceptionally warm and dry summer of 2018, numerous large fires burned a total of almost 25,000 hectares of forest in Sweden (Statens offentliga utredningar, 2019; Sjöström and Granström, 2020). 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). 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 kilometers 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 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).

Compared to other boreal regions, forest fires in Northern Europe are small. This is mainly due to effective fire suppression. In addition, heterogeneity of Fennoscandian forests with lakes and swamps creates natural obstacles for fires. Large fires are more common in Russia, Canada and Alaska (e.g., Stocks et al., 2002; Vivchar, 2011; Smirnov et al., 2015). However, also in Fennoscandia large fires were not uncommon 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 (Wallenius, 2011).

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

Earth System Dynamics
Discussions

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., 2005a). In northern Europe, the distribution of lightning-ignited fires follows approximately the thunderstorm climatology with less ignitions in the north (Granström, 1993; Larjavaara et al., 2005b). 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. In northern European boreal forests, climate and particularly precipitation variability has been an important decadal-scale driver of fires even during the recent centuries with strong human influence on fire occurrence (Aakala et al., 2018). In boreal forests in general, interannual variability in burned area can be by a large part 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 at decadal to centennial time scales (Stocks et al., 2002). Although during the last century these large fire years have tended to occur in northern Scandinavia in association with warm and dry summers, historically years with large forest fires have occurred more frequently during cooler than warmer periods (Drobyshev et al., 2016). Drobyshev et al. (2016) related this to coupled ocean–atmosphere dynamics favouring high pressure systems over Scandinavia in association with low sea surface temperatures in the North Atlantic. Moreover, 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). Drobyshev et al. (2014) hence concluded that fire regimes across Scandinavia might show even an asynchronous response to future climate changes.

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 the recent decades, long-lasting drought events have become more intense throughout Europe (see section 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, occurred in northern Europe recently once in a decade, may occur more often than twice in a decade in the late 21st century (Ruosteenoja et al., 2018).

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). 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 in size may double or even triple during the present century. Nevertheless, there is considerable uncertainty in 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.

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

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

The projected regional sea level rise (e.g. Grindsted et al. 2015) coupled with the expected intensification of sea level extremes (e.g. Vousdoukas et al. 2018) discussed in Section 2.2.3 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 flood in 1497, 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 large damages at the German and Danish coast 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 approx. 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 decreasing relative to the observed and projected influence of sea level rise on storm surge heights. Hence, Vousdoukas et al. (2018) finds 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 damages in the future and accounts for 88–98% of the total damages. Interestingly, the highest relative contribution from changes in cyclones is here 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 whether the wind storms are expected to become more frequent (Sec 2.2.1). In particular, for Finland and Sweden - due to land uplift - the physical footprint of sea level rise in future damage estimates is weakened. Conversely, socioeconomic 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 damages (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, which could exceed 4-5 metres in some locations (see Section 2.2.3).

Apart from recent work by Paprotny and Terefenko (2017) for Poland, environmental and economic impact assessments at the regional to national level generally belong to the grey literature. Similarly,

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

impact assessments at the local (city) level have so far mainly been carried out by, e.g., 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. Here Copenhagen stands out, Prahl et al. (2017) has calculated a set of macroscale damage cost curves (Figure 11, main part), i.e., damage cost as a function of flood height, for the largest 600 cities in Europe, including all of the major cities along the Baltic Sea. Land-use information is being used and not population coupled with GDP per capita as the basis for approximating the location of assets; i.e., 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 defenses, 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 (Figure 11, main part).

For comparison, Abadie et al. (2016) have carried out a variant 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 Figure 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 a RCP8.5 scenario is shown in Figure 11. For Copenhagen and Stockholm the damage cost estimates of Prahl et al. are largely consistent with those of Abadie et al. (2016).

Vousdoukas et al. (2018, 2019, 2020) has 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 production, population dynamics and exposed assets based on select shared socioeconomic pathways. Flood defenses are considered as recorded in the FLOPROS database (Scussolini et al. 2015). As seen in the Table in Figure 11 (upper rows), at the end of the century Denmark is expected to suffer the largest damages from increased coastal flooding due to climate change due to its long coast line, 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 different approaches, data and scales used for the impact modelling, including key assumptions, in particular relating to the economics. To improve confidence in impact assessments, a comparable assessment of methods, models, and assumptions are 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

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

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 others, the transportation of energy from sea to land, the trips to the farms for maintenance, and water depth where the turbines will be installed. The 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 load 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 cutoff 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 the activities such as installation, operation and maintenance (O&M). See e.g. Diamond et al. (2012), Leiding et al. (2014), Dangendorf et al. (2016) and Kettle (2018,2019).

Several sections in this report 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 coordinating 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.

In the presence of storms over the sea, special organized atmospheric features develop, contributing to turbulence over broader frequency/wave number range than the 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 rolls are present (e.g. Larsén et al. 2012; Svensson et al. 2017, Smedman 1991). Over the North Sea, it was found that open cells can add an extra of 20 - 50% to the turbulence intensity (Larsén et al. 2019b).

For the studies of the extreme winds over Scandinavia for wind energy applications, 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 are used, including the Baltic Sea area (e.g. Frank 2001; Larsén and Mann 2009). At early stages of the 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 larger global coverage over various land/sea conditions. These make the use of the mesoscale models an attractive option. The three-dimensional mesoscale numerical model, the MIUU-model for the 50-year wind speed was used to calculate both 10-min mean and 3-s gust values,

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

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 for decades. In compensation with the computational cost, most of these models have been run at a spatial resolution of tens of kilometers. The effect of spatial and temporal resolution of these mesoscale modeled winds was investigated in Larsén et al. (2012) using modeled data from WRF, REMO and HIRHAM. Larsén et al. (2012) developed a so-called spectral correction method to fill in the missing variability in the modeled time series, thus reducing the underestimation of the extreme wind. To calculate the extreme wind, Larsén et al. (2012, 2019) also developed a selective dynamical downscaling method to efficiently allocate modeling 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). Climate modeling describes future scenarios and provides a coherent calculation of the whole set of environmental parameters, including wind, temperature, icing and precipitation. One of such outputs 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 portrait a consensus on the change in storms and extreme winds in the future over the Scandinavian seas (see also section 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 of influencing shipping, one relates to ice conditions. As stated above (Section 2.2.10 and 2.2.11) winters on the Baltic Sea can be different with highly varying 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 Figure 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 1985 and 1987. Extreme events can also cause remarkable damages on the ship shell structures as shown in Fig 14 (Kujala, 1991). Typically, the ice-induced damages are local dents on the shell structures, with the depth about 50-100 mm and width as well height about 0.5m*0.5 m. The figure shows an example of the extensive damage outside Luleå (upper figure), when the ship left the harbour independently without icebreaker assistance and got stuck in compressive ice, and then the whole shell structures got permanent damage with the depth of about 0.5 m and the length and height several meters. The ice-strengthened ships are not designed for this type of situation as the design principle is that icebreakers will prevent ships from getting stuck in ice.

Increasing maritime traffic in areas where icebreaker (IB) assistance is needed will increase the demand for icebreaking assistance. The workload of an IB 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 icebreaking 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

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

Earth System Dynamics
Discussions

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, 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 Automatic Identification System of vessels (AIS) data has been used to study e.g. 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, 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 and when they will be assisted. 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 icebreaking 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, i.e. 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 10000 ship visits to our icebound harbors in the Baltic Sea and the traffic is assisted by 5-9 IBs. The developed model can be used to study e.g. 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 used engine power of ships, which might mean that the need for IB assistance will increase. As studied by Lindeberg et al. (2018), the new so called EEDI ships will increase the merchant vessel waiting time 100 % when 50 % of the new ships will fulfill the EEDI requirements, so this means that in future we might need more IBs to guarantee smooth marine traffic. EEDI is a new energy efficient requirement, which will decrease the engine power on typical merchant ships.

The model can also be used to study the effect of winter hardness on the amount of needed IB assistance, e.g. during the hard winter of 2010-2011, the total number of IBs assisting was nine with the total amount of assisting miles: 77056 nm and during a 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 area relatively low in the Baltic Sea, some of the high wind events and especially the severest storms affect the maritime traffic (cf. Section 2.2.2 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 (Section 2.2.10). 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 still is 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 the 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

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

Earth System Dynamics
Discussions

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 section 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 every now and then. 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 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 in particular true for compound events (i.e interaction of multiple hazard drivers) and freak events (i.e. events that have very low probabilities but which potentially can 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). 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 km (Sec. 2.2.4), as well as increasing observation density owing to the use of weather radars, satellites and lightning-location sensors, open new possibilities to assess their probabilities of occurrence of in the recent past and 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 the 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 or 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.

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

The prolongation of the growing season of phytoplankton is identified, but it may be not only caused by a simple direct influence of increased radiation and temperature. The temperature may also act via stronger stratification, shifts in grazing pressure or 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 impact on the food web and need to be investigated. The first major marine heat wave recorded occurred in the Baltic in 2018. Further research is needed to estimate probabilities of marine heat waves in the future but also to deepen our understanding 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), and higher resolution results in more sensitivity to warming (Willison et al., 2015). Understanding of high-intensity extremes requires improved re-analysis 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 increased understanding. This includes remote sensing data, new types of sensor systems in combination with traditional in-situ observational networks. Combining new data with higher resolution models as well as new methodologies (machine learning, neural networks) has great potential.

Following aspects are the most important to address in relation to future research:

- Coupled high resolution process and Earth System models for detailed understanding of extremes and feedback mechanisms between different processes (see also Görger 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 and 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 circulation itself. This is in particular true for changes in velocity and meandering of the jet stream, effects on blocking frequencies.
- Increase process level understanding of impact of 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 emission 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 to quantify economical costs of extreme events as well as impacts on health, ecosystem and environment.

4. Conclusions and key messages

In this review, we have been focused on extreme events and natural hazards in the Baltic Sea region. Temporal and spatial scales of the events which are causing these hazards ranges over many orders of magnitudes. Typical short-term phenomena are dynamical events like storms or heavy precipitation which are causing severe economical and human losses regionally or locally. Contrastingly, heat waves and cold spells are gradually developing events which prevail from weeks to months. Their impact on society and nature can cover the entire Baltic Sea catchment region.

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

In Figure 14, we summarize how the hazards are related to the atmospheric, ocean 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 causing directly storm damages 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 but also marine heat waves are 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 is always causing 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 behavior 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 northeastward 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, 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 section 2.1). There is a clear link between warmer summers and an increased risk of drying (in particular 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, in particular in urban regions, and are strongly associated with flooding and more intense cloud bursts. Results from new, high-resolution convective-permitting climate models indicate that increases in heavy rainfall associated with cloud bursts may increase even more than what 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 the understanding of the sea-effect snowfall and for developing a reliable way to assess the occurrence of such events also in the changing conditions. Another wintertime phenomena 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 4 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 decreasing probability of occurrence.

Table 4: Selected event and the estimated frequency of occurrence. Scale for changes (major decrease, minor decrease, no change, minor increase, major increase). Color, 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	no significant change (in strength and frequency)	minor increase in frequency in wintertime
South of 59°N	no significant change (in strength and frequency)	no significant change
Extreme sea levels (relative mean sea level plus storm surge)		
North of 59°N	minor decrease	minor increase
South of 59°N	minor increase	major increase
Ice ridging	unknown	major decrease

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

Intense precipitation	minor increase	minor 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 (some uncertainties related to changes in the large scale circulation)
Drying North of 59°N	decrease	mainly decrease, increase in the north in the spring
South of 59°N	increase	increase in some regions in spring and summer
River Flooding	increasing in winter/autumn, decreasing in spring	decrease in spring increase in winter (low\high confidence)

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 might lead to a doubling 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 wind, wave and precipitation features. The number of people exposed to coastal flooding in terms of annual damage is expected to increase with orders of magnitude. Baltic coastal cities are expected to be the main source of future coastal flood losses. Offshore wind application respond mainly to extreme wind and wave conditions, here loads and damages 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

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

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 Bay of Bothnia and Gulf of Finland).

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Figures.

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Preprint. Discussion started: 6 April 2021

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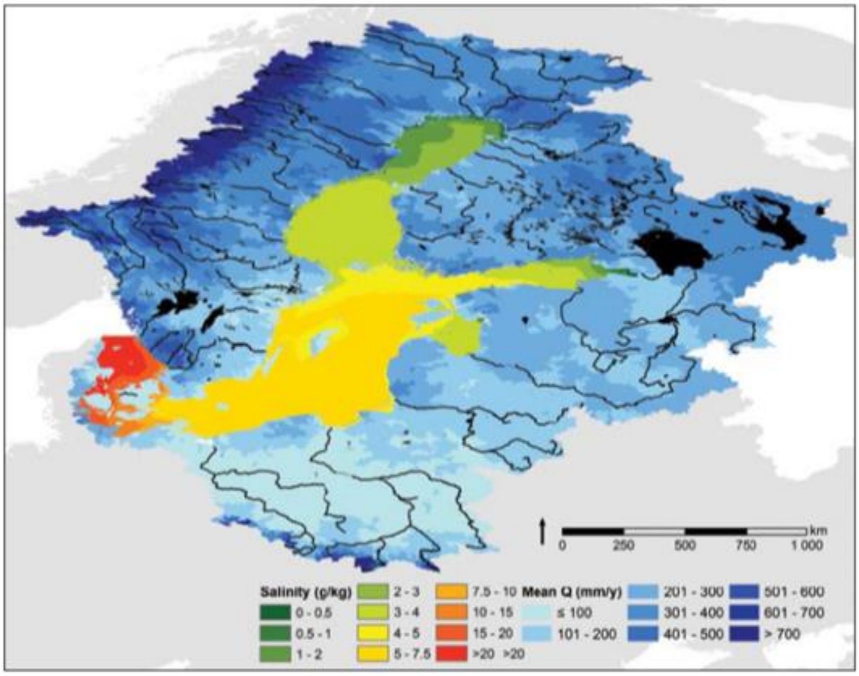

Figure 1. The Baltic Sea drainage basin together with the spatial variability in annual mean water discharge (Q) calculated with the Hydrological Predictions for the Environment (HYPE) model and with annual mean sea surface salinity in the Baltic Sea. This salinity diagram shows the gradient from high (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).

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Preprint. Discussion started: 6 April 2021

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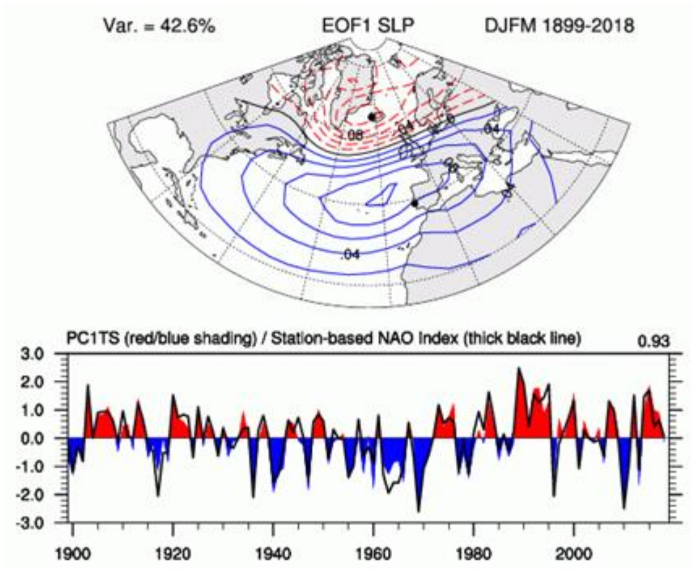

Fig. 2: Principal component (PC) time series of the leading EOF of seasonal (DJFM) SLP anomalies over the Atlantic sector (20°N-80°N, 90°W-40°E), 1899-2018 (colours) and station-based index (Lisbon and Stykkisholmur) (black line, see points on map). The correlation is 0.93 over 1899-2018. From Hurrell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

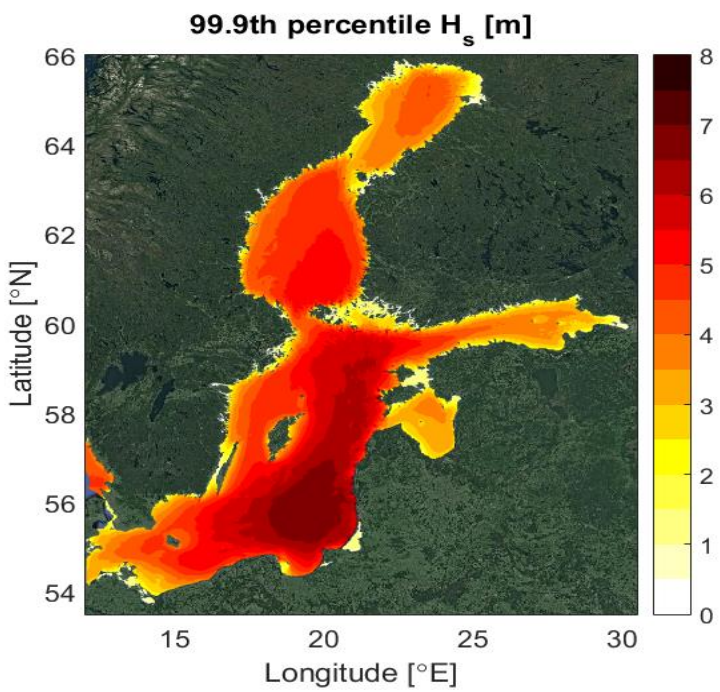

Fig. 3: Ice-free statistics (Type F in Tuomi et al. (2011)) for the 99.9th percentile significant wave height (H_s) using a high-resolution wave hindcast for the years 1998-2013 (Nilsson et al. 2019).

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

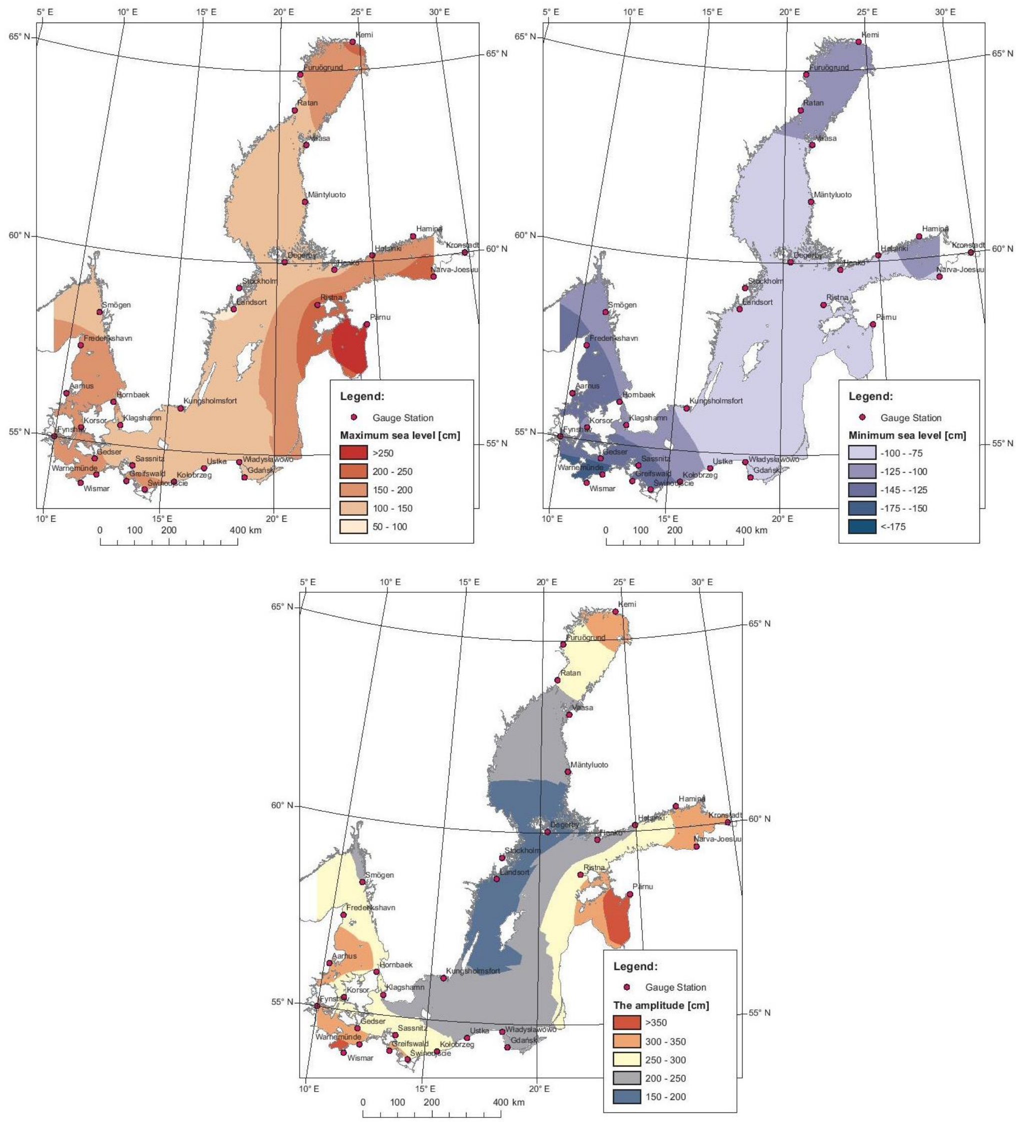

Fig. 4: Surface water topography of the Baltic Sea for maximum levels (a), minimum levels (b) and the amplitude of variations (c) from the period 1960–2010 (Wolski et al. 2014).

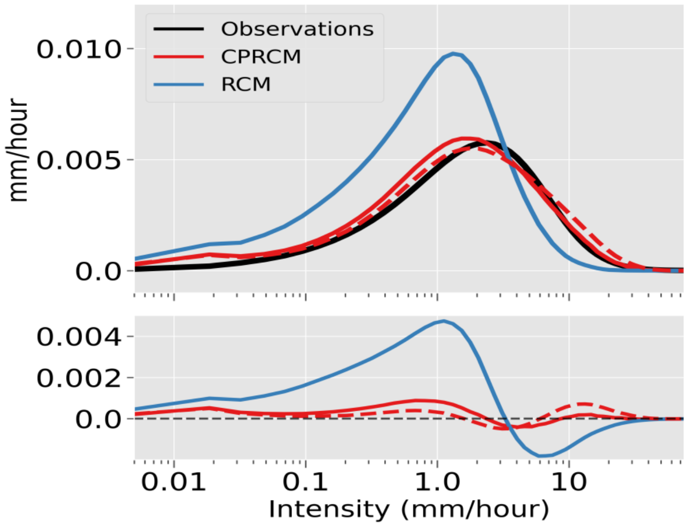

Figure 5 The top panel shows contributions per intensity bin to the total June-August mean precipitation over Sweden, units in mm per hour. The observations are from a combined radar-rain gauge data set. The lower panel shows differences w.r.t. the observations. The coarse scale RCM is operated at 12 km horizontal resolution while the convective-permitting 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).

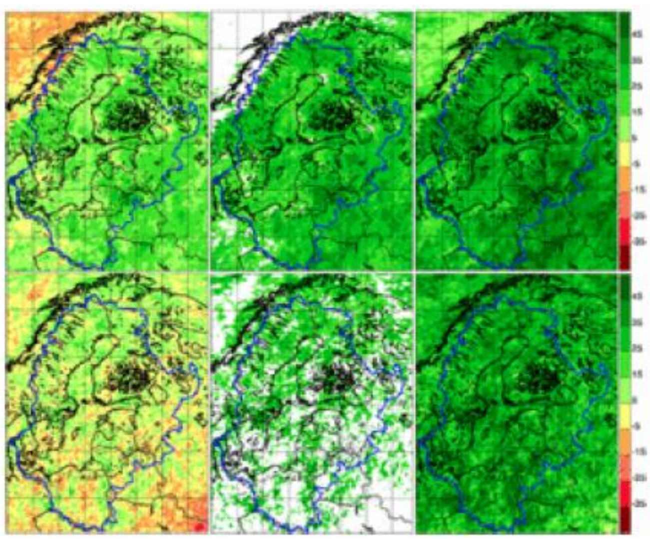

Fig 6. Change in 10-year return value of daily precipitation change (%) between 1971-2000 and 2071-2100 for 15 simulations from Euro-CORDEX according to the RCP8.5 scenario. Top row: Winter, bottom row: Summer. Left column: lowest quartile; middle column: median value; right column: higher quartile.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

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Preprint. Discussion started: 6 April 2021

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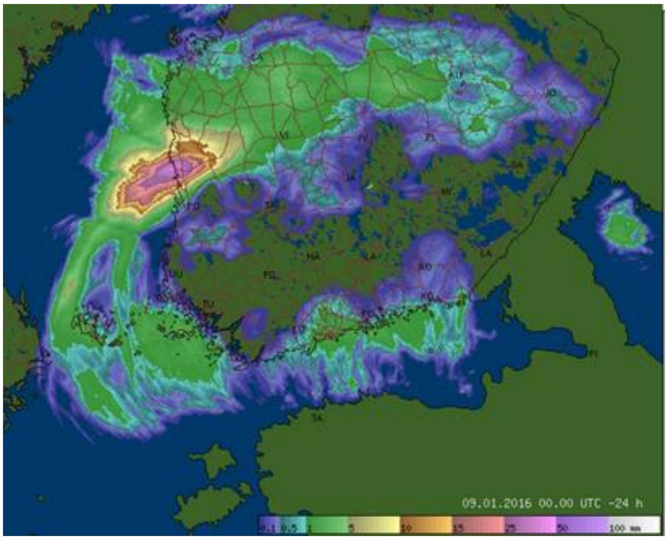

Figure 7. Radar image of precipitation accumulation (mm/day) during recent national snowfall record in Finland. The sea-effect snowfall accumulated 73 cm of new snow in less than a day to Merikarvia, Finland in 8.1.2016. Figure from radar service of FMI intranet.

https://doi.org/10.5194/esd-2021-13
Preprint. Discussion started: 6 April 2021

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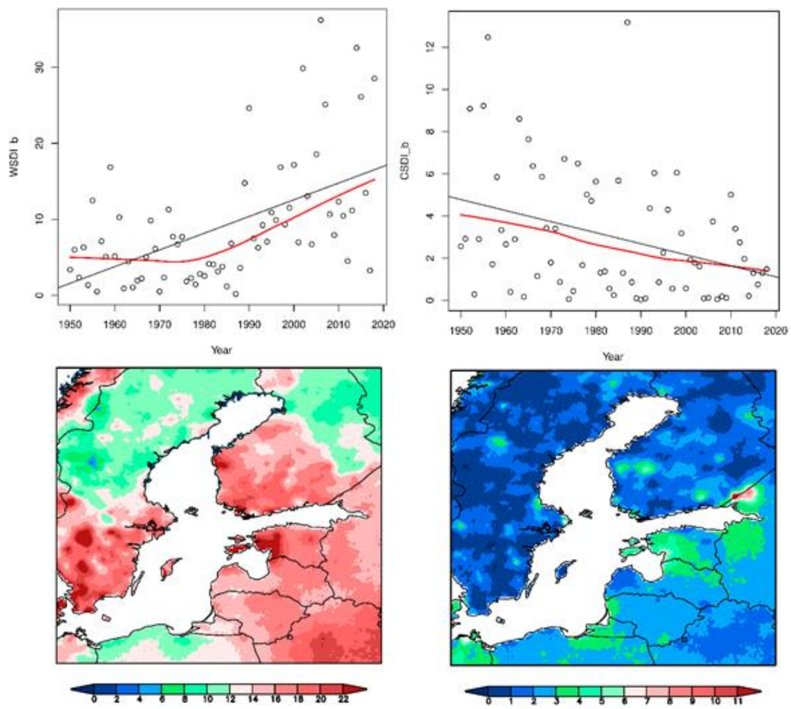

Figure 8 Annual warm spell duration index (WSDI; left) and annual cold spell duration index (CSDI; left). Top: Time series of the spatial averages over the area of 53-67N and 12-31E in 1950-2018. A fitted curve and a linear fit are also shown. Bottom: Spatial distributions of the 30-year means during 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 Nov 2019; Cornes et al. (2018).

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Preprint. Discussion started: 6 April 2021

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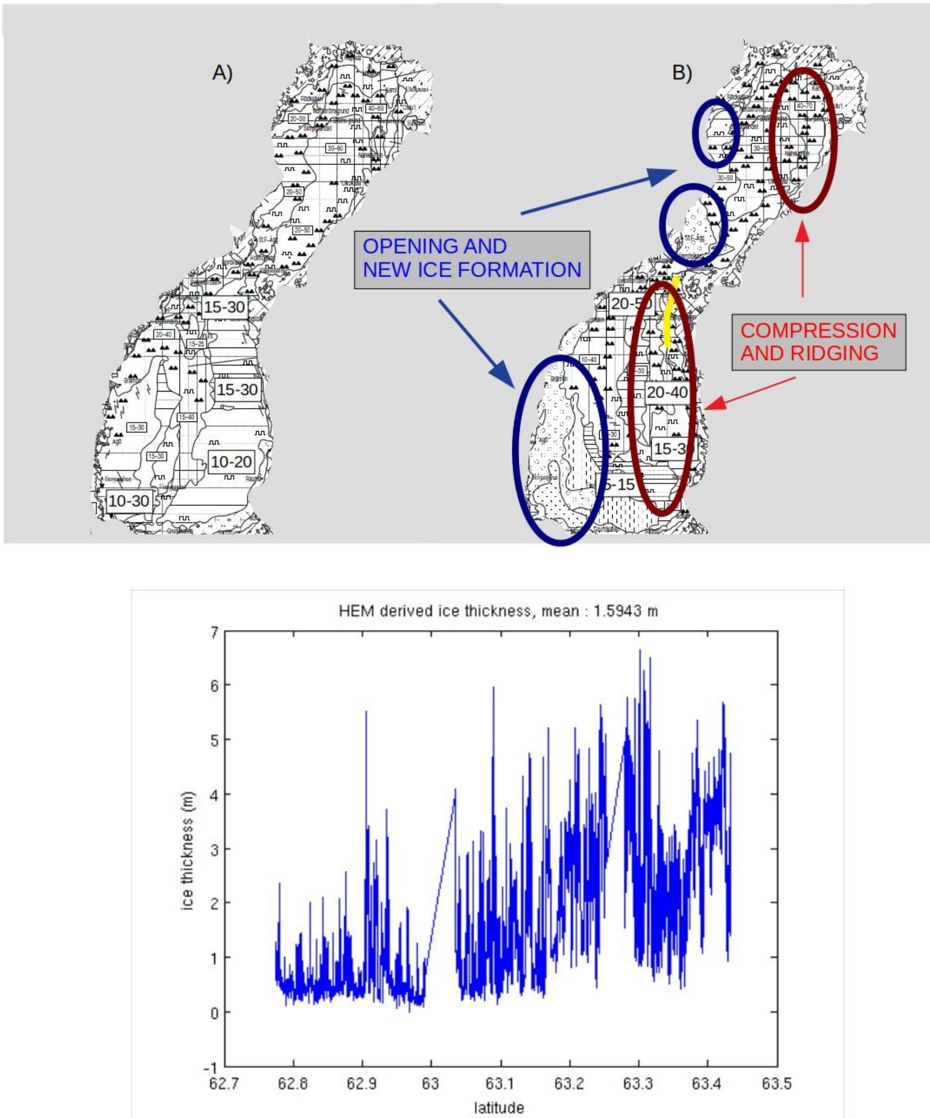

Figure 9. Ice charts before and after the major compression event in February 2011. Regions experienced opening and compression/ridging are indicated as blue and red circles, respectively. Lower panel depicts ice thickness along the yellow transect shown in the ice chart above.

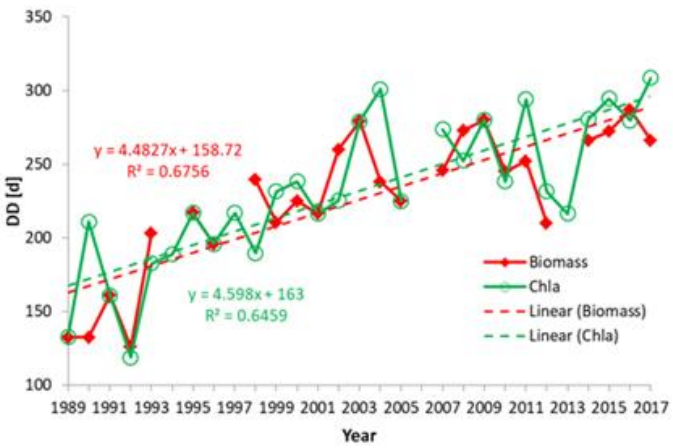

Fig. 10: Trends in the duration of the vegetation period (DD), based on phytoplankton biomass and chl *a* data, with regression lines and corresponding formulas (Wasmund et al. 2019).

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Preprint. Discussion started: 6 April 2021

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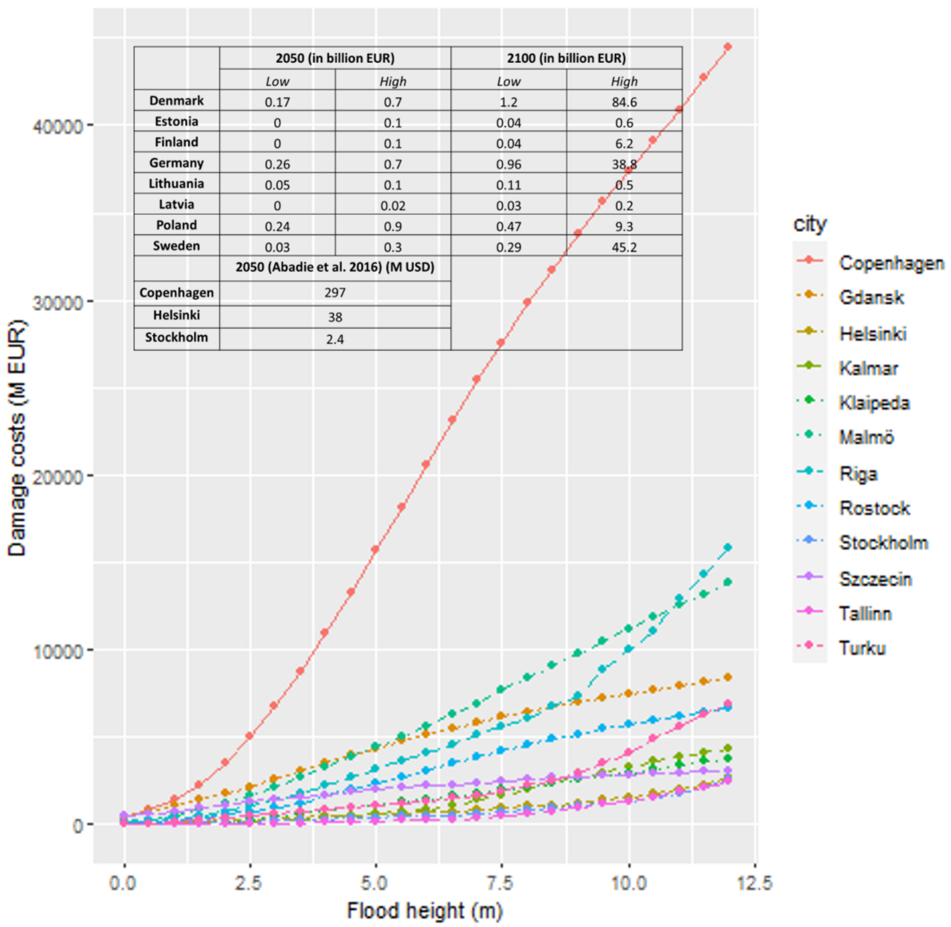

	2050 (in billion EUR)		2100 (in billion EUR)	
	Low	*High*	*Low*	*High*
Denmark	0.17	0.7	1.2	84.6
Estonia	0	0.1	0.04	0.6
Finland	0	0.1	0.04	6.2
Germany	0.26	0.7	0.96	38.8
Lithuania	0.05	0.1	0.11	0.5
Latvia	0	0.02	0.03	0.2
Poland	0.24	0.9	0.47	9.3
Sweden	0.03	0.3	0.29	45.2
	2050 (Abadie et al. 2016) (M USD)			
Copenhagen	297			
Helsinki	38			
Stockholm	2.4			

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.

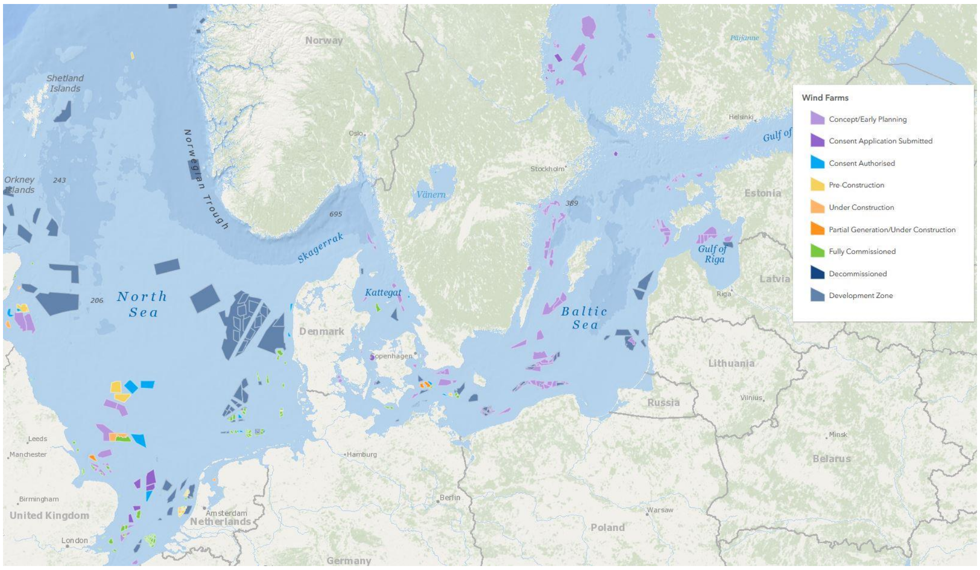

Figure 12 Overview of wind farms over part of the Baltic and the North Sea in different development states (www.4coffshore.com, 2021-03-09).

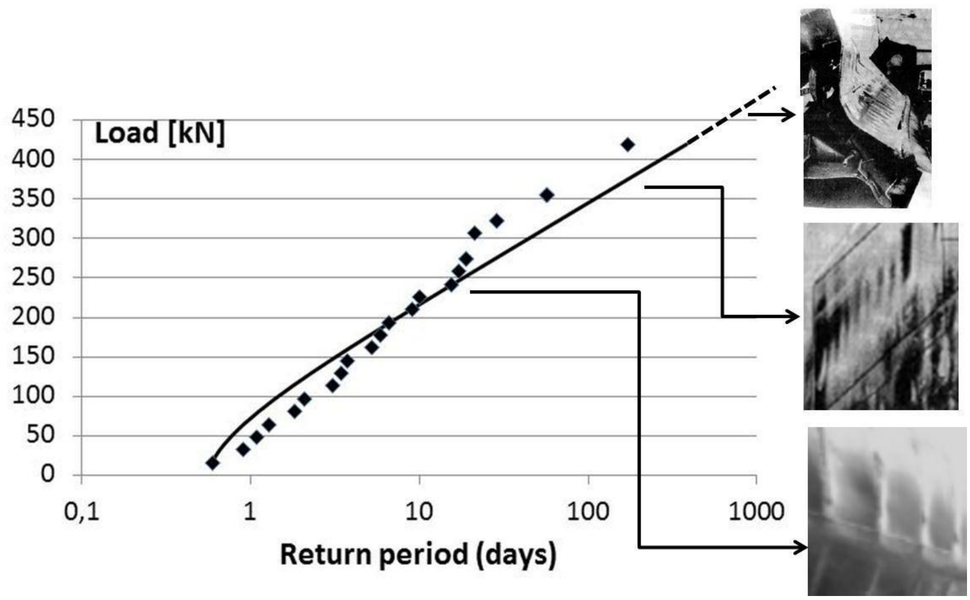

Figure 13. Measured load on one frame at the bow of MS Kemira measured during 1985-1991 (Kujala, 2017), showing also the possible effect of the increasing load on the damage of the ship shell structures.

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Preprint. Discussion started: 6 April 2021

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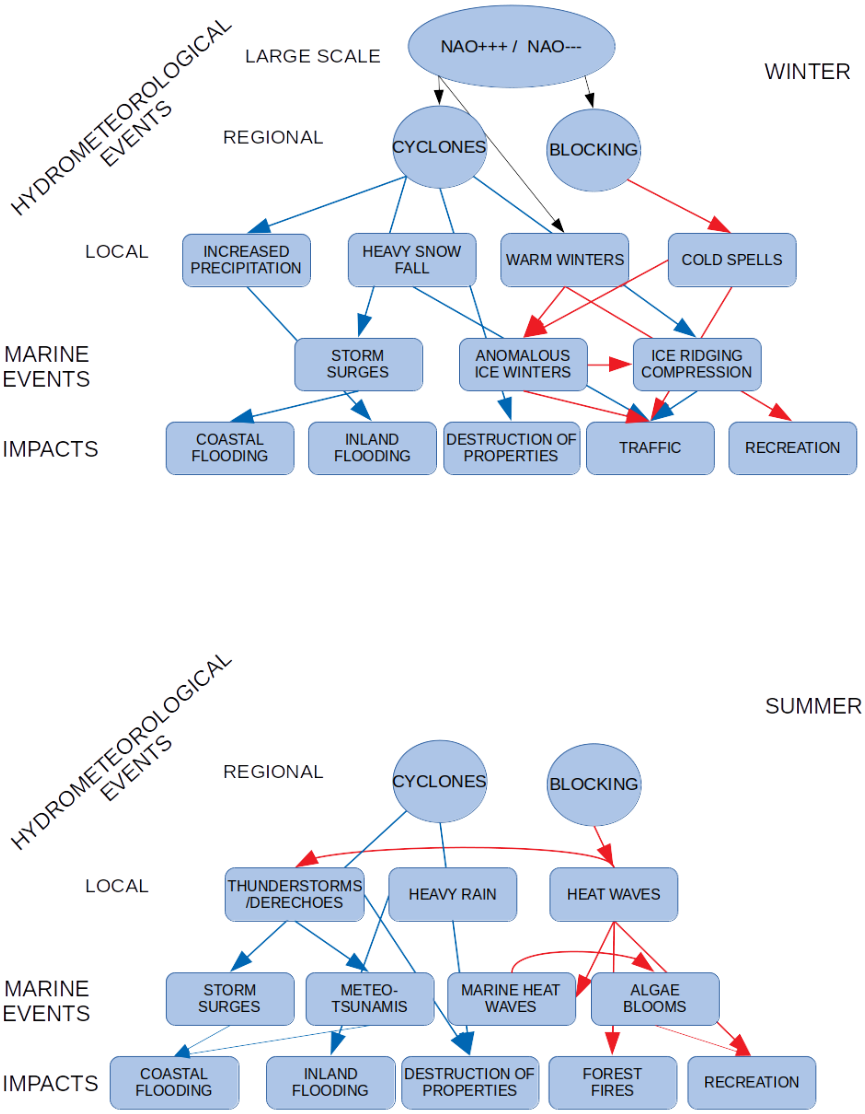

Figure 14. Simplified diagram to illustrate the relationship between atmospheric, hydrological and marine processes and their impact on society in winter and summer.