Natural hazards and extreme events

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1. Introduction (input from all)

A natural hazard is a naturally occurring extreme event with a negative effect on people or the environment. Natural hazards and extreme events may have severe implications for human life as they potentially generate economic losses and damage ecosystems. A better understanding of their major causes and implications enables society to be better prepared and to save human lives and mitigate economic losses. Many natural hazards are of hydro-meteorological origins (storms, waves, flooding, droughts) and are often caused by a mixture of several factors (e.g. a storm surge in combination with precipitation and river runoff, which might generate extreme flooding).

In 2013 natural hazards worldwide were responsible for the death of more than 20,000 people and costs of more than $134 billion (Munich Re, 2014). According to the EEA (European Environment Agency), increase in frequency and/or magnitude of extreme events such as floods, droughts, windstorms or heatwaves will be among the most important consequences of climate change (EEA 2010). While climate change has received considerable attention in the scientific community, the knowledge on changing extremes and their impacts is still fragmented, the confidence level of the knowledge of relation between climate change and extremes ranges from low to medium (IPCC, 2012; 2013), the confidence level reduces when approaching the local scale (IPCC, 2014). Changes in the recent climate of mean parameters in the Baltic Sea region are relatively well described ((BACC Author Team 2008, 2014; Rutgersson et al., 2014), but the uncertainty is much larger for extreme conditions. Compared to some highly exposed areas, extreme events in the Baltic Sea region poses less risk to human lives. However, extreme events pose a substantial threat to infrastructures or ecosystems albeit their relative rareness. Changes in extreme events are caused by a combination of changes in local/regional conditions with changes in the global forcing, atmospheric circulation patterns are thus of crucial importance. We here separate extreme events based on their time-scale, focusing on synoptic-scale events and monthly scale events.

Kommentiert [AR1]: Numbers from web

Recent intense sea-effect snowfall events on the Baltic Sea have accumulated 73 cm of new snow in a day to Merikarvia, Finland (8.1.2016, Olsson et al. 2017) and up to 40 cm near Copenhagen, Denmark (22.11.2015). One of the worst snowfall events accumulated 130 cm of new snow between 4th and 7th December 1998 in Gävle, Sweden. It prevented public transportation and even schools and offices were kept closed. For shipping extreme waves poses a significant threat and one example xx On 12 January 2017, an intensive low-pressure system generated a monster wave in the northern Baltic Sea above 14 m, equaling or exceeding the previous record from December 22nd 2004 (EUMETSAT 2017, The Local 2017, Björkqvist et al. 2017a).

Monthly scale events include heat-waves and drying, algea blooms and ice seasons…

We here summarise existing knowledge of extreme events in the Baltic Sea region (including the Baltic Sea and its drainage basin as well as related regions of relevance for the Baltic Sea). We focus on past and present state, but also include future scenarios and expected changes. We also address changes in the forcing and implications for society. The text focuses on the current base of knowledge, but also identifies knowledge gaps and research needs.

1.1 Methods, past and present state

For the past and present state, we focus on time periods covering up to the last 200 yrs, 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 covering an extended time period, although many national (sub-) daily observations still await digitization and homogenization. A 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). Satellites were introduced in 1978, which significantly improved data coverage, providing higher resolution in space and time. Data that spans extended periods cannot be expected to be homogeneous in time. It is therefore important that conclusions concerning long-term trends are drawn from homogenized data. The time period and data density vary depending on the type of extreme being studied…

It is during the latter part of the investigated period that the potential recent anthropogenic influence could be seen. As little long-term observations are available for many variables, it remains difficult to interpret recent changes in the context of the last 200 yr.

1.2 Methods, future scenarios

Kommentiert [AR2]: expand

For future scenarios climate models are traditionally being used, these include model-components of atmosphere, ocean and vegetation. In some cases, also dynamical downscaling with regional models are used. Climate models are based on emission scenarios depending on assumptions of anthropogenic emissions. There are based on suggested global development assumptions A1, A2, B1, B2, where the respective scenarios represent xx (ref). Later assumptions are simpler and based on changes in radiadive forcing where xx, RCPs pathways corresponding to assumed changes in radiative forcing.

CMIP5…

Precipitation processes acts on scales ranging from micrometers to thousands of kilometers which results in strong spatial and temporal variability of precipitation. Representing this variability constitutes a true challenge for climate models and careful evaluation against observations is key before they 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 50km 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 convective permitting models with grid spacing of a few km, are found to improve the simulation of both spatial and temporal features of precipitation. 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).

- *General introduction to the topic*
- *General, global and regional relevance for societies, why should we care beyond scientific curiosity…*
- *Historical background, early findings, methodological developments…*
- *BALTEX contributions, if applicable*

1. *Current state of knowledge*
    - *Past and present state [observations, hindcasts, re-analyses…]*
        - *i. Current methods, advantages and shortcomings*
    - *Projected future states [projections]*
        - *ii. Current methods, advantages and shortcomings*

2.1 Extreme conditions (current knowledge, now and potential future change)

2.1.1 Synoptic scale events

2.1.1.1 Winds storms (**Martin Stendel**)

2.1.1.2 Extreme waves (**Erik Nilsson**)

Kommentiert [AR3]: Could it be shortened a bit?

Vertical motions on the ocean surface consists of an extensive spectrum of frequencies and periods ranging from the very short capillary waves of less than 1 second to the long swell waves on the order of tens of seconds and infra-gravity waves, seiches, tsunamis, surges, tides and trans-tidal waves of even longer periods (Munk 1950, Holhuijsen2007). Here we focus on the wind generated waves and mainly on the significant wave height, $H_{s.}$ Choosing an average measure of the sea state such as H_s to serve as an indicator value when discussing extreme waves is not trivial (Björkqvist et al. 2017a) because the highest individual wave H_{max} in a wave record is approximately 1.6-2.0 times higher than the significant wave height (Pettersson et al. 2018).

On 12 January 2017, an intensive low-pressure system generated a monster wave in the northern Baltic Sea above 14 m, equaling or exceeding the previous record from December 22nd 2004 (EUMETSAT 2017, The Local 2017, Björkqvist et al. 2017a). Significant wave heights measured around 8 m according to the Finnish Meteorological Institute (FMI) for this case, which gives an example of the approximate extreme wave heights that occurs in the Baltic Sea. 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. 2017a), when the closest measurement location to where the maximum was estimated to have occurred showed a significant wave height of 7.2 m. A numerical model study for the time period 1965 to 2005 (Björkqvist et al. 2018) showed a 99.9th percentile for 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.

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 (Björkqvist et al. 2017a) is often needed to be able to issue warnings and provide accurate estimates of the conditions seafarers will face along their routes. Successful implementation of current third-generation wave models in the Baltic Sea exists (e.g. Tuomi, 2008; Räämet and Soomere, 2010; Tuomi et al., 2011) and numerical wave models are used operationally for the Baltic Sea by FMI, Danish Meteorological Institute (DMI) and the German Weather Forecast Service (Soomere et al. 2008). Björkqvist et al. (2017a) analyzed five wave events on the northern Baltic Proper that had exceeded a significant wave height of 7 m and discussed important parameters for issuing warnings, which included significant wave height, wave steepness and possibly other parameters related to the duration of events.

The difficulty for numerical wave models to provide detailed spatial information about parameters important for such warnings has become clear for near-shore conditions that generally pose a big challenge for wave models (Tuomi et al. 2014, Björkqvist et al. 2017b). The resolution of wave modeling hindcast studies have also varied from about 1.1-1.85 km in Nilsson et al. 2019 and Björkqvist et al. 2018 to coarse 22 km (Jönsson et al. 2003). Björkqvist et al. (2018) also question if common resolutions of about 6-11 km in previous studies can replicate features and spatial information of the wave field with sufficient accuracy. As well as if the quality and resolution of wind forcing is a limiting factor, which has varied tremendously from high-resolution of about 5-6 km (Weisse et al. 2009) to coarse 111 km (Räämet and Soomere 2010) in different hindcast studies. The hindcast lengths for the whole Baltic Sea has also varied from 1 year (Jönsson et al. 2003) to 41 and 43 years (Björkqvist et al. 2018, Cielkiewicz and Papliska-Swerpel, 2008) and recently Siewert et al. (2015) performed a 52-year simulation for the western Baltic Sea. An extremely high-resolution 100 m horizontal resolution study of wave climate have also been conducted for a limited area covering Lithuanian territorial water (Jakimavicius et al. 2018). When it comes to assessing the probability of extreme wave conditions modeling many of the historical events is needed, but also a reasonable resolution is needed to be able to more realistically capture some of the small-scale spatial and time variations often missed by the models (Guo-Larsén et al. 2015). A compromise is often needed due to limits on available computational resources (Nilsson et al. 2019) and Soomere et al. (2008) discussed that potentially “poor man´s ensemble modelling” (or concensus forecast) using results predicted by different operational forecasts could be useful for predictions of future storms, but would require increased cooperation of national operational services.

Many studies have been conducted to characterize the variations in the Baltic Sea 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 the seasonal dependence (e.g. Soomere 2008, Räämet and Soomere, 2010). Variations and influence from sea-ice have also been studied (e.g. Tuomi et al., 2011, Björkqvist et al. 2018, Nilsson et al. 2019) which is a particular feature of great importance for basins located on northerly latitudes corresponding to the Baltic Sea (54 to 66 N). These studies, although often not focused on the most extreme wave conditions have provided a deep understanding for what time of year and which parts of the Baltic Sea the most significant extreme waves are likely to occur. Björkqvist et al. (2018) showed using one of the longest and most high-resolution wave climatologies conducted 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, as shown in Fig. 2.1.1.2_1 using the wave hindcast from Nilsson et al. (2019), which gives a consistent result compared to the 99th percentile presented in Fig.5 in Björkqvist et al. (2018) for a longer 41-year time period.

This is consistent with the typical synoptic weather pattern of middle latitudes (Soomere 2003, Nilsson et al. 2019) but modulated by bathymetry and fetch conditions, as well as meso-scale weather effects. The pattern of 100-year return value estimates of significant wave height from

Aarnes et al. (2012), based on 10 km resolution simulations for 1958-2009, is generally agreeing with the areas identified by Björkqvist et al (2018) and the more extreme conditions represented here by the 99.9th percentile in Fig. 2.1.1.2_2. The northern basins typically experience reduced wave heights, both due 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. Nilsson et al. 2019).

Some studies have been conducted to near-shore extreme waves, as an example Paprota et al. (2003) discussed the formation of extreme waves and wave events in the Baltic Sea along the Polish coasts based on three locations with wave measurements and found the highest recorded wave to be 7.6 m. The maximum significant wave height for this site was about 4 m. Gayer et al. (1995) studied extreme significant wave heights at the Warnemunde harbor based on wave modeling and measurements and estimated 100-year return periods ranging from 3.49-4.18 m depending on method. Sulisz et al. (2016) analyzed wind-wave records from the southern Baltic Sea about 5 km from the Polish coast and reported a large number of freak-type waves. They also discussed an individual wave over 12 m high in 20.5 m water depth measured during a field campaign, but did not provide a detailed account for this event. Sulisz et al. (2016) also argued that hazardous waves may even exceed 20 m during severe storms in the Baltic Sea, but this appears to be an extrapolation based on measurement and modeling results rather than observation, which makes it uncertain if such a wave, has ever occurred in the Baltic Sea.

Few studies have been conducted to analyze variations to the wave field in a future climate under climate projection scenarios on a regional scale for the Baltic Sea (e.g. Dreier et al. 2015 for the German Baltic Sea Coast). They examined both increases and decreases in extremes of about 14% on sites with significant wave heights of up to about 4.5 m. Most global studies of wave climate under different climate scenarios would not report results for the Baltic Sea because of the uncertainty from coarse resolution on near-shore results. One exception is the study of Mentaschi et al. (2016) who reported increase of extreme wave energy flux (on average 20%, with maxima up to 30%) for the Baltic Sea. This study was conducted using a global wave model driven by an ensemble of global coupled models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) under the high emission Representative Concentration Pathways scenario 8.5. Zaitseva-Pärnaste and Soomere (2013) showed significant correlation between energy flux and ice season and given the coarse representation of the Baltic Sea in Mentaschi et al. (2016) the results should be interpreted carefully. They did not show if changes occurred in the simulations mainly due to significant wave height or wave period, but tried to relate their results to changes in North Atlantic Oscillation index. Groll et al. (2017) analysed wave conditions in the Baltic Sea under two IPCC AR4 emission scenarios (A1B and B1) and found higher significant wave height for most regions and simulations. Median wave results showed temporal and spatially consistent changes (sometimes larger than 5%), whereas extreme waves (99th percentile) showed much more variability in space and among the simulations and these changes were smaller (less than 5%), and more uncertain (Groll et al. 2017). The changes reported were attributed to, not only higher wind speeds, but also from a shift to more westerly winds and relatively consistent with results from a single scenario simulation by Suursaar et al. (2016). Multi-decadal and the inter-simulation variability illustrated the uncertainty in the estimation of a climate change signal (Groll et al. 2017).

Kommentiert [AR4]: Higher than what?

Trends in wave height for the region of interest seem small but statistically significant (0.005 m/year for 1993-2015) from satellite altimetry (Kudryatseva and Soomere, 2017), and from in-situ observations and modeling (e.g. Soomere and Räämet 2011b) results seem inconclusive and possibly site-specific. A station of low mean wave height of about 0.55 m (Zaitseva-Pärnaste et al. 2009), have

Kommentiert [AR5]: Unclear to me

shown decreasing mean but increasing 99%-ile trends for 1966-2006, which may be interpreted as an increase in the wave heights of extreme storms on the background of a decreasing trend of the overall wave activity (Soomere and Healy, 2008). If only small anthropogenic effects for the Baltic Sea wave fields are to be expected for the next century is hence uncertain.

To what extent sea-ice variations in the modeling of a warmer climate are being simulated realistically enough, may be one of the most important issues for the prediction of Baltic Sea wave fields. If significant reduction of ice in the northern Baltic Sea basin occur some changes to the wave field are likely to be seen. In such a case comparisons of ice-free and ice-time included statistics (Tuomi et al. 2011, Björkvist et al. 2018) may be considered to give indications of increased significant wave heights on the order of about 0.3 m both for mean values and 99th percentile values (Björkvist et al. 2018). This would still likely not make the northern basins experience extreme wave heights higher than the southern Baltic Proper because of the limited fetch conditions. To our knowledge, more directly focused studies on the effects of reduced sea-ice and its consequences for extreme wave heights under climate projection scenarios for the Baltic Sea have not been conducted, although Groll et al. (2017) provided an example study.

Soomere and Räämet (2014) studied decadal changes in the Baltic Sea wave heights for the time period 1970 to 2007 using adjusted geostrophic wind forcing and no ice cover for their wave modeling. They found variations of up to 15% of the long-term average value of significant wave height, with typical time intervals between high and low annual average values of 10-12 years. Studying the 99%-ile wave heights they instead reported time intervals between high and low values of about 5 years. When it comes to long-term trends Soomere and Räämet (2011a) reported local changes of about -10 to 12 cm for the annual mean significant wave height for the time period 1970-2007, implying small overall trend for the Baltic Sea with increases in some areas and decreases in wave heights in other areas. Visual wave observations and numerical simulations showed no clear trend in severe wave heights (95%-ile and 99%-ile) in the northeastern Baltic Proper and in the western part of the Gulf of Finland (Räämet et al. 2010). Suursaar and Kullas (2009) on the other hand found an increasing trend in 90% and 99%-ile wave height for the West Estonian coast based on simplified modeling using fetch limited equations. Soomere et al. (2012) found no long-term trend but modest interannual (about 12% of the long-term mean of 0.76 m) for the Arkona Basin in the southern Baltic Sea. Coastal areas in the southern Baltic Sea are subject to flooding and erosion problems and attempts have been made to estimate implications of extreme wave and water levels (e.g. Hanson and Larson 2008). Using simplified wave modeling based on wind observation and coarse resolution climate model results they discuss that a run-up level, with a 100 year return period from today, in the year 2100 may occur up to thirteen times more frequently if wind speed increases significantly in the future. Interpretations of implications of a changing wave climate should, however, be done carefully for extreme conditions because the changes in means are not necessarily linked to changes in extremes.

Kommentiert [AR6]: Is it possible to shorten this and end the section with a very brief summary?

2.1.1.2 Sea level (**Jani Särkkä**)

The rising global mean sea level causes a major hazard for the population living in the vicinity of the coast. The effects of the climate change on the sea level extremes may lead to increase in the extreme sea levels on top of the mean sea level rise, and might lead to more increased occurrence of extremes. Even if the sea level extremes last a limited time, they are capable of producing large damage to the coastal infrastructure and endanger human lives.

Extreme sea levels are a major threat to coastal areas along the Baltic Sea coast due to flooding and erosion. The sand dunes may experience large deformations during a single storm. Recently a major flood occurred in the Gulf of Finland in January 2005. In the Baltic Sea, extreme sea levels are caused by atmospheric factors as wind and 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 the Baltic Sea causes about maximum 1 m variation in mean sea levels. Often the most extreme local sea levels occur when mean sea level is already high. Due to the shape of the Baltic Sea, the highest sea levels are found in the end of bays, as in the eastern end of the Gulf of Finland, northern end of the Gulf of Bothnia, and in the Gulf of Riga. Also southwestern end (Kiel and Lübeck) may experience high sea levels, such as on 4 January 2017, when records for sea level maxima were measured at the tide gauges of Oskarshamn, Simrishamn, Skanör and Klagshamn on the southern coast of Sweden. The observed maxima and minima on the Baltic Sea coast along with 100-year return levels based on observations 1960-2010 were studied by Wolski et al. (2014). They interpolated coastal tide gauge observations for the entire Baltic Sea area. The largest and smallest extremes were in the end of bays, whereas the amplitude of variation was smallest in the central Baltic Sea. 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. They used GEV (Generalized Extreme Value) and quantile regression methods and 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. The return levels for Kungsholmsfort and Stockholm differ between
Ribeiro et al. (2014) and Wolski et al. (2014), even if the used extreme value methods are similar. In an earlier study, quantile regression was used to study changes in monthly mean sea levels in the Baltic Sea (Barbosa (2008)).

There are studies focusing impact of a changing climate and projected future states. Gräwe and Burchard (2012) studied changes in storm surges in the Western Baltic Sea up to 2100 with IPCC scenarios A1B and B1 and using boundary conditions from a regional atmospheric model and a medium-scale ocean model. They found that the wind speed increases by 3-5 per cent, which leads to 20 cm higher surge levels. The rise in mean sea level (50 cm for A1B and 25 cm for B1) also increases surge levels. In the western parts (near Kiel) the rise in surge levels exceeds the mean sea level rise, in the eastern parts surge levels rise less than mean sea level. This is caused by the nonlinear interaction between mean sea level and surges. The 30-year return levels rise 0.6 m (0.4 m) in A1B (B1) scenario to 2.4 m (2.2 m). The changes in surge levels can be explained by the increase in mean sea level and wind speed. Meier (2006) studied projections of 100-year return levels of sea levels in 2071-2100, comparing results to hindcast simulations 1903-1998 (Meier et al. (2004)). Coupled atmosphere-ocean model RCAO was used with two different global model and two greenhouse gas scenarios. In the high-case scenario, the 100-year return levels increased considerably in the Gulf of Finland (in St. Petersburg from 221 cm to 362 cm, in Helsinki from 154 cm to 248 cm). In the Gulf of Riga there was also an increase of 130 cm, and in the Gdansk Bay increase of 111 cm. In the Gulf of Bothnia the increase was smaller: 41 cm at Kemi, 16 cm at Ratan. The strengthening of the westerly winds explains the increase of return levels in the Gulf of Finland and Gulf of Riga. There are only minor signs of increase in the Gulf of Bothnia. The storm surges in the western Baltic seem to be underestimated, as is also stated in Meier et al. (2004). The projected storm surge levels for the Baltic Sea coast in 2040 and 2100 were calculated as a part of Europe-wide study of Vousdoukas et al. (2016). The storm surge levels include only the effect of the atmosphere on the sea level, omitting relative mean sea level rise and land uplift. An ensemble of outputs from eight global climate models and RCP4.5 and RCP8.5 greenhouse gas scenarios was used to force a shallow-water sea level model. Time slices 2010-2040 and 2070-2100 were computed. Extreme storm surge levels for return periods up to 500 years were calculated using peak-over-threshold approach for extreme value analysis. Results were averaged over the Baltic Sea coast. The present-day 100-year sea level extreme was projected to take place every 44 years in 2040 under RCP8.5 and every 72 (51) years in 2100 under RCP4.5 (RCP8.5). The ensemble means of extreme storm surge levels (return periods from 5 to 100 years) increase in the northern Baltic Sea coast for both RCPs and end years. The increase is largest in the Bothnian Bay and in the Gulf of Finland, reaching about 0.5 m. In the southern Baltic Sea coast, there is smaller or no increase in most scenarios. When the storm surge levels are averaged over the Baltic Sea coast, the increase in the storm surge levels of return periods from 5 to 500 years is only 10-20 cm for different scenarios due to the different behavior of extremes along the Baltic Sea coast. The seasonal variation of storm surge levels was inferred from mean seasonal maxima and standard deviation of the mean. The differences in the seasonal maxima along the Baltic Sea coast were small. The increases in the maxima were also rather similar between different seasons, being under 5 per cent for different scenarios. The inter-annual variation in the seasonal maxima, indicated by the standard deviation, increased by 6 (15) per cent in RCP4.5 (RCP 8.5) by 2100. This indicated that the variations in the maxima might increase more than the 30-year mean, indicating that the maxima could have higher increasing trend than the mean sea level has. The combined effect of mean sea level, tides, waves and storm surges was studied in Vousdoukas et al. (2017), where six global climate models were used. The waves raise the sea level at the coast by wave setup, caused by wave shoaling and breaking near the shore. Vousdoukas et al. (2017) used 0.2 times significant wave height as an estimate of the effect of the wave setup on coastal sea level. The 100-year sea level due to combined effect of waves and storm surges was projected to rise maximally 35 cm in the Baltic Sea by 2100 in RCP8.5, the rise being largest in the eastern coast of the Baltic Sea. The 100-year sea level in the Baltic Sea from 2000 to 2100 was studied. 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 incertainty in the evaluation of the change in extreme sea levels during the present century. Hieronymus et al. (2018) studied the effect of mean sea level rise and increasing wind speeds on the return levels of sea level extremes in the Baltic Sea.

The mean sea level rise increases the return levels by the same amount with negligible local variation. The increase in wind speeds has larger effect in the return levels in areas where the extreme sea levels are highest (Gulf of Finland and Bothnian Bay).

The sea level extremes can be evaluated from distributions. Rarely occurring extremes have to be calculated using extreme value analysis or other extrapolation methods for the distribution, as the observational data with good quality is often limited to less than 100 years in the Baltic Sea. The study on the future probabilities of coastal floods in Finland by Pellikka et al. (2018) was based on extrapolating tide gauge data, evaluating the distribution of mean sea level rise, and adding the effect of land uplift and changes in wind climate. They found that return levels will increase by 2100 in the Gulf of Finland and in the Bothnian Sea, whereas no major changes are expected in the Bothnian Bay due to stronger land uplift. The extrapolations can be done using tide gauge observations or sea level simulations. The tige gauge observations often include local effects, as wave setup, that are not present in the offshore sea level. Eelsalu et al. (2014) found that sea level distributions on the Estonian coast were quite different between observations and hindcast simulation. They produced an ensemble of projections using different extrapolation methods to assess the uncertainties in return levels. The variability of the present climate can be studied using climate simula-tions. By combining data from six downscaled climate scenario simulations and extrapolating the data, Särkkä et al. (2017) evaluated the sea level variability at Helsinki. They found that 100-year return level is 180 cm and 10000-year return level is 220-230 cm, depending on the chosen extrapolation method. In studying the extremes of the Baltic Sea level, the sea level can be divided into two components: first component describes the weekly-scale water level which is mainly regulated by the water exchange between the North Sea and the Baltic Sea, and the second component describes the local storm surges that have sub-weekly scale (Soomere et al. (2015)). The trends in hindcast sea levels on the Estonian and Latvian coasts were studied by Soomere and Pindsoo (2016) based on RCO model simulation 1961-2004. The weekly-scale water level has an uniform trend (4 cm in decade) in the studied area, but the trends in storm surges vary from almost zero to 5-7 cm/decade in the eastern Gulf of Finland and Gulf of Riga.

The effects of the climate change on the wind climate are not yet clearly understood. How will the frequencies and strengths of cyclones change? It is uncertain whether changes in past cyclone activity are inside the natural variability. The frequency of tropical cyclones is expected to decrease or remain unchanged. The wind speed of cyclones is likely to increase, and in some areas the frequency of intense storms might increase substantially (Knutson et al. (2010)). The projected changes in storm tracks are difficult to determine (Shaw et al. (2016)). The resolution of the global climate scenario simulations that were used without regional downscaling in Vousdoukas et al. (2016) for the sea level simulation might not be sufficient for the Baltic Sea. Further conclusions should be made when more refined forcing is used in the simulations. Also hindcast sea level simulations will benefit from the ERA5 atmospheric reanalysis from 1950 to present by ECMWF. The dependence between extreme storm surges and wind waves has to be assessed when the joint effect of storm surge and wave setup on the coast is studied. Marcos et al. (2019) evaluated this dependence for the global coastline from hindcast simulations. For the Baltic Sea, this dependence should be included when return levels of compound events of storm surges and waves are calculated.

Kommentiert [AR7]: Should be linked to wind and circulation sections.

To summarise, even if we already have a lot of climate scenario data, updated scenarios are needed to assess the future projections for sea level extremes. The large variation in the climate scenario simulations up to 2100 leaves us a large uncertainty in the assessment of the future behavior of sea level extremes. New downscaled climate simulations are needed to produce high-quality sea level simulations.

2.1.1.4 Ice ridging (**Jari Haapala**)

Kommentiert [AR8]: Could this be expanded

Sea ice extremes depends on temporal and spatial scale in consideration but more importantly on location – five meter thick pressure ridges are common off the Hailuoto island in the Bay of Bothnia every winter but five centimeter thick ice cover is a rare situation in the Southern Baltic Sea. Societal capacity of managing sea ice related hazards depends also on likelihood occurrence of sea ice. In some regions, even a thin ice cover can cause more economical losses to society than massive thick ice ridges if the sea ice freezing is occurring in a region where marine traffic is operated by non-ice class vessels.

In a local scale, predominant feature of drift ice is it’s large variation in thickness. Due to the differential ice motion, pack ice experiences opening, closing, rafting and ridging. In the Baltic Sea, thickest ice, i.e. pressure ridges, can be 30 meter thick (Leppäranta & Myrberg, 2009, Ronkainen et al., 2018). After initial formation of ridges, they remain in the pack ice as obstacles for a shipping.

Ridges are formed when pack ice experiences convergent motion. In the Baltic, this is common when pack ice is drifting against the fast ice. In those coastal boundary zones (Oikkonen et al, 2017), mean ice thickness can be half 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 it’s internal stress increases. Internal stress, or called also as ice pressure or ice compression, depends on strength of wind and ocean stresses 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 ice 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 even stationary under strong winds.

For a shipping, ridges are well observed obstacles which mainly impact on duration of navigation but sea ice compression is more difficult to observe and can cause total stoppage of navigation or even damages to structures of ships. Sea ice compression can directly observed by in-situ sea ice stress measurements but those measurements are rare in the Baltic. Implicitly, ice compression events have been observed by ships navigating in ice.

The most severe ice winter during the last ten years occurred in 2011. In that winter 14 ship accident happened due to harsh ice conditions (Hänninen, 2018). For a comparison, during the other winters only1-5 accidents occurred. Several compression events were also reported during winter 2011. The most hazardous occurred at the end of February when marine traffic was totally halted for few days.

A case study : Ice compression in the Bothnia Sea on February 2011.

- Preconditioning : February was cold and calm → Bothnia Sea was totally ice covered, mainly undeformed 15-30 cm thick ice (Figure 1)
- Storm approached the GoB on 24th February, SW winds 15-17 m/s.
- Ice begins to move and compress against the eastern coast and the Quark
- Coastal flaw lead was generated in the SW region of the GoB (Figure 1)
- Due to compression pack ice experienced heavy deformation and undeformed level ice field redistributed to heavily deformed ice field (Figure 1)
- Mean sea ice thickness along ~100 km transects were 0.9 m and 1.6 m meters (Figure 2).
- During the period from 24 February to 7 March 142 cases were reported from the campaign area or north of latitude 63N. From these 25 reported severe compression, or 3-4 on a scale of four (FMI ice service)
- Considerably reduction in speed of ships navigating in ice (Figure 3)

Open question

Warmer but stormy winters in future?

Kommentiert [AR9]: Are there existing studies to add here?

2.1.1.5 Precipitation (**Erik Kjellström**)

Kommentiert [AR10]: Maybe a figure?

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 cloud bursts. The scales of the precipitation extremes vary with precipitation type from minutes to hour at the km-scale associated with single cloudbursts, to large-scale frontal systems covering hundreds of kilometers yielding precipitation during hours to days. Convection frequently occurs embedded in frontal systems, thereby locally increasing the precipitation intensity associated with these systems. Land-sea contrasts and orographic details modulate the precipitation and can therefore have a strong impact on the intensity of an event. One additional particular phenomenon in the Baltic Sea region is the lake effect snow fall events that can generate large amounts of snow in coastal areas downstream of the Baltic Sea (covered in 2.1.1.6). 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.

Despite the fact that the Baltic Sea region is an area with relatively good observational coverage over a long time, lack of observations is a major obstacle not only for assessing long-term trends and past extreme events but also for model evaluation. The density of the observational network is still low compared to the fine-scale resolution required for evaluation of today's most fine-scale climate models (e.g. c. 10 km for state-of-the-art EURO-CORDEX and 1-3 km for next generation convection permitting models). In particular there is a lack of data over the Baltic Sea, but also for remote land areas where observational stations are sparse. 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. This includes: PTHBV covering Sweden at 4 km grid (Johansson and Chen, 2005); the Finnish data set at 10 km grid by Tietäväinen et al. (2010); 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 Baltic Sea region.

Associated with global warming is an intensification of the global hydrological cycle (Bengtsson, 2010). This leads to more precipitation in northern Europe, a feature projected by climate models that generally show increasing precipitation in an annual mean sense for northern Europe including the Baltic Sea region (IPCC, 2013; BACCI and BACCII). 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). 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). 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 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.

2.1.1.6 Snow Canons (Taru Olsson, Anna Luomaranta, Kirsti Jylhä)

Kommentiert [AR11]: Figures tob e added?

Sea-effect (and lake- or bay-effect) snowstorms can cause millions of euros of damage to the society (Juga et al. 2014). 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). Prolonged sea-effect snow events can last for days in the Baltic Sea region and easily produce ten to twenty cm or even more of snow accumulation, which can cause also power outages, and roof and tree damages. The most extreme observed values of lake-effect snow have been as large as 30 cm/h and 75 cm/day (Markowski and Richardson 2010).

Our current knowledge of lake- and sea-effect snowfall 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, **ADD**). Sea effect snowfall can occur also on the Baltic Sea, and there is an increasing number of studies in this area concerning the formation (Olsson et al. 2017, Mazon et al. 2015, Savijärvi 2015, Savijärvi 2012, Andersson and Nilsson 1990, Gustafsson et al. 1998) and statistical analysis (Jeworrek et al. 2017) of sea-effect snowfalls, as well as effects of excess snowfall to society (Juga et al. 2014, Vajda et al. 2014).

The lake-effect snowfall is typically generated in the early winter when cold air flows over the relatively warm open sea. The warm water heats the cold air above the water and acts as a constant source of moisture, which will lead to convection. The rising air generates bands of clouds which quickly grow into snow clouds. Snowfalls can be enhanced when the moving air mass is uplifted by the orographic effect on the shores or by concave shape of the coast as it packs air and forces the air to rising motion inflating convection. The highest precipitation occurs over the sea close to the coast (Andersson and Nilsson 1990). With suitable wind direction, these snowbands can hit the shores and bring heavy snowfalls to the coastal land area. The sea/lake-effect is very sensitive to the wind direction because a long fetch over the water body is needed so that the cloud band has enough time to form (Laird et al. 2003). On the Baltic Sea the most favourable wind directions vary from north to northeast (Jeworrek et al. 2017) because the cold air out breaks usually comes from the northeast. Nevertheless, as the Baltic Sea is like a large lake with two major bays (the Gulf of Bothnia and the Gulf of Finland), the sea-effect snowfall can occur on any coast with reasonably cold air masses over Scandinavia. In contrast to the snowfall events experienced around the Great Lakes the narrowness of these two gulfs and flat topography around the Gulf of Finland may cause differences (Savijärvi 2012).

The minimum criteria given by Jeworrek et al. (2017) for the development of convective snowbands in the western parts of the Baltic Sea region were i) maximum 10 m wind speed higher than 10 m/s; ii) mean 2 m temperature lower than 8 °C; iii) maximum temperature difference (between surface and 850 hPa levels) more than 13 °C; iv) mean wind shear (between 700 hPa and 975 hPa) less than 60° of 50% of the Baltic Sea area; v) mean wind direction (at 900 hPa) between 0° (from the north)

and 90° (from the east); and vi) maximum atmospheric boundary layer height more than 1000 m. Using simulations conducted with the regional climate model RCA4 for the period 2000-2010, they found that annually 4 to 7 days would be favorable for snowband formation in the western Baltic Sea area.
1-2 figures (+ text) to be added from Jeworrek et al. (2017) and/or Olsson et al. (2017, 2018)

It is essential to know the frequency and intensity of the sea-effect snowbands in the present-day climate in order to be able to assess possible changes in the characteristics of snowbands due to climate change in future. For example, the duration of the ice cover in the Baltic Sea has already decreased in different parts of the sea (Haapala et al., 2015).

Kommentiert [AR12]: Link to other sections

The sea-effect snowfall events can typically have temporal and spatial scales smaller than what can be covered by the traditional weather station network and resolved by climate models. Therefore additional information about these cases and their impacts need to be gathered. Advanced methods are required in order to be able to produce a comprehensive view about their probability of occurrence in the past and to assess influences of climate change in the future. Such methods include for example simulations with high-resolution numerical models combined with information from re-analysis datasets. High-resolution meteorological data is vital as input for Sea-effect snowfall simulations. *ADD SOMETHING: Recent development in reanalyses*; ERA5 (Olsson et al. 2018)

Kommentiert [AR13]: Would be nice!

2.1.1.6 River floods (**Irina Danilovich**)

River flooding affects more people worldwide than any other natural hazard. The flood risks are affected by global warming and large-scale changes in water cycle. Every year, hydrological extremes affect people in different regions. There is growing concern that flooding will become more frequent and extreme due to climate change. That is the reason for the growing of the hydrological studies in the different regions and particular in the Baltic Sea states. Changes in river flood regimes are traditionally analyzed using statistical approaches and observed data or process-based numerical modeling and a scenario approach. The present section present review of results from both approaches for the last years.

Hydroclimatic changes in the Baltic Sea Basin have been previously documented by several groups of authors. The detailed assessment of climatic change for northern Europe was provided by the BACC Author Team (2008, 2015). The regional peculiarities of streamflow formation 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). Regional pattern was detected by Hisdal et al. (2010), while Wilson et al. (2010) showed trends towards increased annual, winter and spring streamflow. The tendency for a decrease in annual discharge in the southern catchments was recognized by Hansson et al. (2011) and Gailiuš et al. (2011). A significant increase in winter river discharge and a tendency for decreasing spring floods have been reported for the east Baltic states (excluding Russia and Belarus) by Reihan et al. (2007). An increasing trend in annual mean discharge for the period of 1961–2000 was found for Latvian rivers, the trend was statistically significant for many rivers including Daugava (Kaviņš et al., 2008 and Kļaviņš and Rodinov, 2008). Trends in the annual maximum and minimum discharges for the major rivers Daugava, Lielupe, Venta, Gauja and Salaca indicate a statistically significant decrease in maximum discharge. After last BACC publication in 2015 there are only few studies devoted to the past hydrological regime changes. For example, Arheimer (2015) studied change in hydrological regime in Sweden over the last 100 years and concluded that the observed anomalies in annual maximum daily flow were normally within 30% deviation from the mean of the reference period. There were no obvious trends in the magnitude of high flows in the observed time series. There was a slight decrease in flood frequency during this period, although in a shorter perspective it seems that autumn floods increased substantially over the last 30 years. The earlier spring snowmelt floods throughout north and eastern Europe due to warmer temperature was established by Günter B. at al (2017). Also they found delayed winter storms associated with polar warming have led to later winter floods around the North Sea and some sectors of the Mediterranean coast; and earlier soil moisture maxima have led to earlier winter floods in western Europe. Our results highlight the existence of a clear climate signal in flood observations at the continental scale. The studies of river regime fluctuations due to climate change within the northwest Russia (Nasonova et al., 2018), (Frolova et al., 2017), and Belarus (Polishchuk and Chekan, 2009), (Volchek et al., 2010, 2012, 2013), (Loginov et al., 2014), (Partasenok, 2014) show no significant long-term trends in an annual streamflow. 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. This increase was connected with the growth of thaws repeatability, which led to frequent floods occurring during winter low-water period while spring runoff and snow-melt floods 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 frequency of extreme flow events and their growing duration.

For the future state in a changing climate. According to the BACC (2008 and 2015) the majority of hydrological studies in the Baltic Sea Basin have been done at the national levels. The Table 1 presented main results of the hydrological projections for last 10 years. The decrease of annual and seasonal streamflow by 2-40% according to the Special Report on Emissions Scenarios (*SRES*) scenario A1B, A2 and B2 was projected for the rivers in Norway (Beldring et al., 2008), Finland (Veijalainen et al., 2010b), Latvia (Apsīte et al., 2011), Lithuania (Kriaučiūnienė et al., 2008) and Poland (Szwed et al., 2010). The 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). The estimations of the projected runoff changes over Russian northwest show the considerable change of seasonal runoff dynamics for the Volga (Georgievsky et al., 2018) and the Northern Dvina basins (Krylenko et al., 2015). The latest achievements in the hydrological projections (after last BACC publication) are presented below. The positive changes in mean flow in the northern and eastern Europe were established by Alfieri et al. (2015). Significant negative changes in maximal flow are instead mainly located in southern Spain and in north-eastern Europe, including the Baltic countries, Scandinavia and north-western Russia. The simulations of river flow were done by Arheimer at al. (2015). The changes in the river flow will varied in 30% for different parts of Sweden. A significant decrease in magnitude of spring floods and a significant increase in autumn floods are expected for the region. For spring floods the trend obtained using climate projections indicates a 10–20% reduction by the end of the century compared to the 1970s. For autumn floods, the trend was in the opposite direction, with 10–20% higher magnitudes by the end of the century. There are slight increases in the some parts of Sweden and Norway, north-eastern Europe, Austria, the northwest Balkans and Hungary according to Donelly et all. (2017). However, the extent of these regions increases between the 1.5 and 2 °C scenarios and between the 2 and 3 °C scenarios, particularly in northern Europe. High runoff levels are set to increase over large parts of continental Europe, increasing in intensity, robustness and spatial extent with increasing warming level. Roudier et al. (2015) 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. 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 at al (2018) in the northern Europe floods decrease by up to −5% under 3 K global warming and high flows increase up to 12%. A decrease of floods in this region has been observed in several studies (Arheimer et al., 2015, Alfieri *et al.,* 2015, Roudier *et al.,* 2016). The streamflow in the Western Dvina River will be changed according to the projections of Danilovich et al. (2019 – in print). The decadal mean flow changes will be varied according to the norm. The spatial pattern of the projections will be characterized by mostly negative changes of runoff in the upper stream and positive changes in the lower part of the Western Dvina river basin. The projected maximal streamflow showed general decrease with largest changes in the lower part on the river basin up to 25 %. However, despite general decrease of spring runoff in the nearest decade (2021-2030) the slight increase of maximal discharges was projected up to 10 %. To sum up:

1) Calculations in the last years cover wider domain and often presented for Europe, Northern Europe, and Baltic Sea region instead of previous hydrological studies in the Baltic Sea Basin which have been done at national levels mostly.
2) The majority of the studies are devoted to flood extremes and much less to low water regime.
3) During the last years a majority of the studies focus on hydrological projections and fewer on historical regimes and events in rivers.
4) The EURO-CORDEX climate data and the same RCP scenarios were used for last studies that make comparable results of hydrological projections.
5) The projections showed the absence or slight changes in the mean streamflow and significant decrease in the high flow.
6) The methods used to make impact studies have progressed during last 10 years for the Baltic Sea region.

Kommentiert [AR14]: I am not entirely clear about this sentence?

2.1.2 Monthly scale events

2.1.2.1 Heat waves – atmosphere and marine (NN)

2.1.2.2 Algea blooms (**Norbert Wasmund**)

Phytoplankton (algae and cyanobacteria) undergoes typical annual successions, induced by the regular changes of abiotic (solar radiation, temperature, nutrient concentrations) and biotic (feeding, infections, competition, allelopathy) factors. Under favourable conditions, 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”) and 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 have to be reduced to a natural level (HELCOM, 2007). This natural level is still not achieved in most areas of the Baltic Sea (HELCOM, 2018).

When HELCOM was established in 1974, eutrophication was identified as a major problem in the Baltic Sea. Meanwhile, the concentrations of growth-limiting macronutrients, dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP), are decreasing (Andersen et al., 2017).

Global warming is becoming a threat that may influence the phytoplankton stronger (Cloern et al., 2016), (Reusch et al., 2018). Trends in eutrophication and climate are under observation, but sudden extreme events may disturb trend analyses or even break the trends.

Major Baltic Inflows (BMI) are “extreme 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 (Fig. 2.1.2.2_1), and it did not introduce new phytoplankton species into the Baltic Sea. In contrast, after a warm water inflow of Kattegat water in autumn 2005, *Cerataulina pelagica* and *Dactyliosolen fragilissimus* appeared in high biomasses as newcomers in the south-eastern Baltic Sea and established there as autumn species (Łotocka, 2006), (Olenina and Kownacka, 2010).

Two extreme spring blooms become apparent from Fig. Fig. 2.1.2.2_1. The bloom in spring 2008 was based on the usually non-blooming haptophyte *Prymnesium polylepis* and has been observed in the whole Baltic Sea, except the Bothnian Bay, Gulf of Riga and the Kattegat (Hajdu et al., 2015). The exceptional bloom of *Peridiniella catenata* from May 2018 in the Eastern Gotland Basin developed after a long winter period and a sudden strong warming leading to a shallow stratification accompanied by high primary production (Rehder, in preparation).

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. Their development since 1990 is annually reported in HELCOM Environment Fact Sheets (Öberg, 2017), (Wasmund et al., 2018). As they may be toxic, they are also registered in the IOC-ICES-PICES Harmful Algae Event Database (HAE-DAT; http://haedat.iode.org/), supported also by the ICES-IOC Working Group on Harmful Algal Bloom Dynamics (WGHABD). Only a few extreme blooms may be 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 (Justyna Kobos, pers. comm.).

Also in the Gulf of Finland, the exceptionally warm summer 2018 caused the strongest cyanobacterial bloom of the 2010's, dominated by *Aphanizomenon* spp. (https://www.syke.fi/en-US/Current/Algal_reviews/Summary_reviews/Summary_of_algal_bloom_monitoring_2018_S(47752) ; Sirpa Lehtinen, pers. comm). Remarkably, the typical cyanobacteria genus of the summer blooms (*Aphanizomenon*) 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); Sirpa Lehtinen, pers. comm.).

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 Aland archipelago and the Gulf of Gdansk (Hakanen et al 2012, Justyna Kobos pers communication). Highest cell concentrations so far recorded for this species were measured in Åland in August 2015 (Savela et al. 2016) and were associated with a novel neurotoxin, Gymnodimine D. 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 (Anke Kremp, pers. comm. https://www.syke.fi/en-US/Current/Press_releases/Last_summers_fish_kill_was_caused_by_a_t(38306)).

A phenomenon worth mentioning is the extension of the vegetation period 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 measurements of phytoplankton biomass and chl a concentrations at a coastal station in the Bay of Mecklenburg from 1988 to 2017, Wasmund et al. (subm.) 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 vegetation period (Fig. 2.1.2.2_2). The earlier start of the vegetation period was correlated with a slight increase in sunshine duration during spring whereas the later end of the vegetation period was correlated with a strong increase in water temperature in autumn.

Kommentiert [AR15]: Is it possible to extrapolate this to the future?

2.1.2.3 Ice seasons (**Jari Haapala**)

2.1.2.4 Drying (**Sergei Zhuravlev, Irina Danilovich**)

2.2 Changes in forcing (**Martin Stendel**)

Arctic ice, persistence, blocking impacts…

2.2 Possible implications for society

2.3.1 Forest fires (Ilari Lehtonen)

2.3.2 Coastal flooding (**Martin Drews**)

2.3.3 Dams and infrastructures (NN)

2.3.4 Off-shore activities (NN)

2.3.5 Shipping (**Pentti Kujala**), Pentti Kujala, Morten Lindeberg

There are many areas where changes in extreme events and natural disasters has the potential of influenceing shipping, one relates to ice conditions. There are also other human and xx activities potentially influencing the industry. Increasing maritime traffic in areas where icebreaker (IB) assistance is needed will naturally also increase the demand for icebreaking assistance. The work load 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 traffic. There are a number of previous studies related to the development of the transit simulation models for ships navigating in ice, see e.g. Patey and Riska (1997), 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 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 a MATLAB-based simulation tool built around a deterministic icebreaker-movement model (Lindeberg et al.,2015, 2018). The new approach is that the simulation model includes also the decision principles of icebreakers to determine which ships and when will be assisted. The model also includes the possible assistance and towing principles of merchant ships behind an icebreaker. 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.

1 BASIC PRINCIPLES OF THE MODEL

Kommentiert [AR16]: Is it possible to shorten this part a bit and link it more closely to changes in ice conditions?

1.1 *Constructing the fairway-network for simulation*

The goal is to construct a fairway network that resembles the winter traffic system of interest. This is accomplished by using two different network building-blocks (BB): (1) a BB resembling a fairway section between two points, and (2) a junction-BB, with three legs going out from the junction point. Leg lengths can be set to zero.

A port (port-node) can be assigned at the end of any BB-leg/section. Usually, majority of the merchant ships enter the simulated network from the same point, which is referred to as the input-node. The input-node differs from a port-node only in the way that a ship cannot spend time (port-time) in the input node, i.e. it functions only as a source and/or a sink. A port-node can also function as a source/sink for a ship.

1.2 *IB operational areas*

As default, one IB is assigned to each BB. Also, as default, the movements of an IB are constrained by the borders (points of connection) of adjacent BBs. This area (or “paths”), formed by the constraining borders, is referred to as the IB operational area. However, an IB operational area can be expanded by assigning the area of adjacent BBs to a single IB. Now the IB is constrained by the borders formed by the adjacent operational areas, and not the individual BB-borders. An IB operational area, no matter how many BBs it spans, always has one single IB operating within it. The total number of icebreakers in the system is indirectly controlled by defining the IB-operational areas in the fairway-network. In addition, there is a possibility of assigning two IBs into one single BB, in which the IBs are programmed to work (assist) optimally in regard to each other (cooperate). However, the operational area of this kind of BB cannot be expanded. Figure 1 below shows an example fairway network.

1.3 *Model input and output*

For each ship, the time when it enters the network, and from where in the network it enters, and its destination(s) within the network, and the estimated duration(s) of its port visit(s), are all inputted into the program. In addition to this, the program needs HV-curves for the inputted ships and IBs (see 3.1), and an ice-data grid.

The model output consists of all details of all the events that take place in the simulation: individual ship stop-positions and times, individual assistance paths and durations. Possible towing events are also registered: towing start and stop positions and durations, for each towing event. The motor power (60/80/100%) that IBs use during transitions (not assisting) and durations of each transition, are also registered. In addition, the waiting times (waiting for assistance) of individual ships, which are calculated from the above-mentioned information, are also included in the output.

2 ICE CONDITIONS AND SHIP SPEED

Ice thickness and ice-type are the main ice parameters that the model uses. After providing the program with the start and end-coordinate points (long-lat.) of each fairway section, the program automatically reads the ice data from an ice-data grid into the fairways sections.
There is no limit on how often the ice-data can be updated, but a 24hour period has been used. The resolution of the ice-data is equal to the distance-resolution of the model (adjustable parameter), i.e. the smallest distance that can be used when designing the fairway sections. 1 nautical mile has been used as the resolution.

2.1 *Equivalent ice thickness*

The ice-data provided by the Finnish Meteorological Institute (FMI) has five different ice-types: Level ice, Rafted ice, Slightly Ridged ice, Ridge ice, Heavily Ridged ice, and Brash ice.
By using a model for calculating equivalent ice thickness, the ice thickness of rafted and ridged ice types can be transformed into a corresponding thickness in level ice, see Sormunen et al., 2018) fir further detail.

The equivalent ice thickness model was applied to a sample thickness of 0.5 m level ice. For each ice type, the increase in level ice thickness was converted into a percental thickness increase, which then is used for calculating the thickness increase for the corresponding ice type, for any thickness. Rafted ice gave a 7.5 % increase, slightly ridged ice gave +22.5%, Ridged ice gave +60% and Heavily ridged ice gave a 105% thickness increase.

2.2 *HV-curves*

An HV-curve models the ship speed as a function of ice thickness. The ones used by the simulation model are cubic equations. It is possible to have a specific HV-curve for each specific ice type, see Sormunen et al., (2018) for further detail. The equivalent ice thickness model (3.1) was utilized. Hence, the ship speed, in all the different ice types, could be modelled by solely using the HV-curve for level ice. As an exception was the Brash ice type, where the speed was modelled by an HV-curve resembling channel-like conditions.
Every ship-type has its own individual HV-curves, including IBs. The merchant ship HV-curves are assumed to be modelled at 85% engine power, whereas the IBs have three sets of HV-curves, one set for 60 % engine power, another for 80 % and a third one for 100 % engine power. In addition, each merchant ship-type has an HV-curve for the speed under IB assistance, which also uses the equivalent ice thickness.

2.3 *Icebreaker movements*

All IB movements in the system strive to minimize the waiting-time that is gained by ships that have stalled in ice (i.e. ships in need of assistance).
Finding the IB movements that would result in the absolute minimum waiting-time of the whole system for the whole simulation period, would be a too difficult problem. Therefore, in this model,

an IB’s awareness of its surroundings is limited to its operational area, i.e. when striving to minimize the waiting-time, it only considers ships that are, or will be in near future, within its operational area. The timespan of ‘near future’ is case dependent, but it is at the very least the duration from assistance start (in the last BB prior to entering the operational area) to the time when the ship enters the operational area. In other words; the length of the described time-period is equal to the length of the time-period that is spanned by the moment at which the IB becomes aware of a ship that is soon about to enter the operational area, and by the moment when the ship enters the operational area. Therefore, if the described time-period would be zero, the IB would become aware of a ship at the time the ship enters the operational area.

In situations where a ship doesn’t need assistance in the last BB prior to entering the operational area, or when a ship enters the network the first time, the time (before the ship enters the operational area) when the IB becomes aware of such a ship is determined by an adjustable parameter (~8 hours was used).

A ship will stop and wait for assistance when its speed drops below a limit value (adjustable parameter in the model [3 kn is used]). The assistance speed is determined from the ship specific assistance-HV curve. With assistance is a convoy, then the assistance speed is determined from the assistance-HV curve that gives the slowest speed. In addition, the assistance speed is always limited by the IB’s maximum speed in the current situation.

A ship is towed if the assistance speed drops below a limit value (adjustable parameter). The target towing speed is also an adjustable parameter, but the actual towing speed is determined from the IB’s HV curves. The IB uses the smallest effect option (60/80/100%) which allows the target towing speed to be reached. In addition, the maximum towing speed is limited by the open water top speed of the ship being towed.

In a convoy situation, ships can follow the towed ship if their speed (form the ship specific assistance-HV curve) doesn’t fall below a limit value (adjustable parameter). If the speed drops below the limit, the ship(s) stops.

The idea with having two limit-speed parameters for towing start (one for the initial ship (towed) and the other for the ships following it) is that the following ship(s) can be set to have a smaller limit-speed parameter value than the limit-speed parameter governing the initial towing start.

For the towing to be terminated, the towed ship’s assistance-HV curve must give a minimum speed (adjustable parameter) over a specified distance, i.e. the speed must not drop below the minimum speed at any point during the distance. The distance is an adjustable parameter.

3 APPLICATION OF THE MODEL

Typically, during a normal winter starting in December and ending in April, there are about 10000 ship visit to our icebound harbors and the traffic is assisted by 5-9 icebreakers. 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 on the used engine power of ships, which might mean that the need of 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 icebreakers to guarantee the smooth marine traffic.

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 9 with the total amount of assisting miles: 77056 nm and during a mild winter of 2016-2017, it was 8 IBs and 29502 nm assisted.

4 CONCLUSIONS

The present model cannot be compared to any other existing models as there aren't any easily comparable models available. This is the first this type of model including all the main elements of the Finnish winter navigation system: icebreakers, merchant vessels with varying ice classes, effect of real ice conditions and the process of icebreaking and assisting ships in convoys and even with towing.

This will be important tool when Finland has to decide how many icebreakers we need in future including the possible effects of varying winters and changes on the ice-going capability of merchant vessels.

3. Knowledge gaps (input from all)

- *Knowledge gaps [this is what we do not know]*
- *Research needs [this is what we need to know]*
- *Methodological needs*
    - *Methodological shortcomings*
    - *Methodological challenges*
- …

The changing climate will affect the circumstances also in the Baltic Sea. In the future, the sea might be unfrozen longer in winter (IPCC, 2015) and also the annual maximum ice extent is projected to decrease (Luomaranta et al., 2014), extending the time period when convective snowbands can form. Conditions might become more favourable for easterly flow to occur/dominate (**REFERENCE**) more often in sea-effect snowfall season ??

Adaptation plans due to changing climate require information on the possible changes in the intensity and frequency of the snowfalls in the future. → higher resolution climate models

4. Conclusions and key messages (input from all)

Sea/lake-effect snow fall events can be a serious threat to the coastal infrastructure and this threat cannot be expected to decrease in the future even in the warming climate. 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 of future climate.

Tables:

Table 2.1.1.6_1. Projected changes in hydrology over the Baltic Sea basin in the recent studies

Region	Year	Climate model	Hydro model	Scenario	Results
Denmark	2008	1)HIRHAM 2) ECHAM4-HIRHAM	NAM	SRES A2	1)Annual discharge increase up to 11-14% 2)Annual discharge increase up to 9-34%
Lithuania	2008	ECHAM5 and HadCM3	HBV	SRES A1B	Annual discharges decrease up to 41%
Norway	2008	2GCM/RCM	HBV	SRES A2 B2	Winter and autumn discharge decrease
Finland	2010	3 GCM/ 4RCM	1) WSFS 2) TUFLOW	SRES A2, A1B B1	1) North – no changes, west and centre – floods increase 2) Floods decrease 3) Floods decrease up to 8-22%
Poland	2010	ECHAM5-MPI-M-REMO			Water decrease in the median value from −32 to −50 mm
Latvia	2011	HadAM3H-RCAO	HBV	SRES A2 B2	Annual discharges decrease up to 2-24%
Sweden	2010, 2011	ECHAM5/RCA3	HBV	SRES A1B	Uncertainness in the projections
Baltic Sea Basin	2014	5 GCM	HYPE	A1B A2	Discharge – increase on 10-30%; Magnitude - variable and highly uncertain
Baltic States	2015	7 EURO-CORDEX GSM/RCM	Lisflood	RCP8.5	Qmean – increase to 2080 up to 10-30% Qmax –decrease to 2080 up to 20-30% Percantage change of Mean annual exceedance frequency of the 100-year return period peak flow 18-242
Sweden	2015	2 GSM: RCM: RCA3	S-HYPE	A1B	Annual daily high flows - decrease by on average −1 % per decade; Peaks from snowmelt in the spring −2 % per decade;

					Autumn flows - increase by+3 % per decade
Baltic Sea Basin	2015	EURO-CORDEX 5 GCM/RCM	E-HYPE, Lisflood, VIC	RCP2.5 4.5, 8.5	RP10 north decrease -10-51%, south increase 10-20% RP100 north decrease -10-61%, south increase 10-40%
Baltic Sea Basin	2017	EURO-CORDEX 4 GSM/4 RCM	: E-HYPE, Lisflood, WBM and LPJmL	RCP2.5 4.5, 8.5	Ensemble mean changes in 30-year period mean runoff for: 1.5 0.03-0.06 mm/d 2 0.03-0.12 mm/d 3 0.06-0.15 mm/d
Belarus	2017	1GCM/RCM	WatBal	A1B, B1	Mean flow - variations around norm at 10-20% to 2035 High flow – increase from slight changes in south-west to 70% in north-east
Northern Europe	2018	5 GCM	Noah-MP, and PCR-GLOBW	RCPs 2.6, 6.0, 8.5	Floods: the annual maximum streamflow (Qmax) – relative change to 1971-2000 period, % Northern part of BS region 1.5 – 6.7; 2 -6.2; 3 -5.0. South-east part of BS region 1.5 – 2.5; 2 -2.2; 3 -8.7.
Western Dvina (upper and middle stream)	2019 (in print)	EURO-CORDEX 1GCM/RCM	Hydrograph	RCP 4.5, 8.5	Mean flow – variations within norm; High flow – decrease up to 25%.

Figures.

Figures

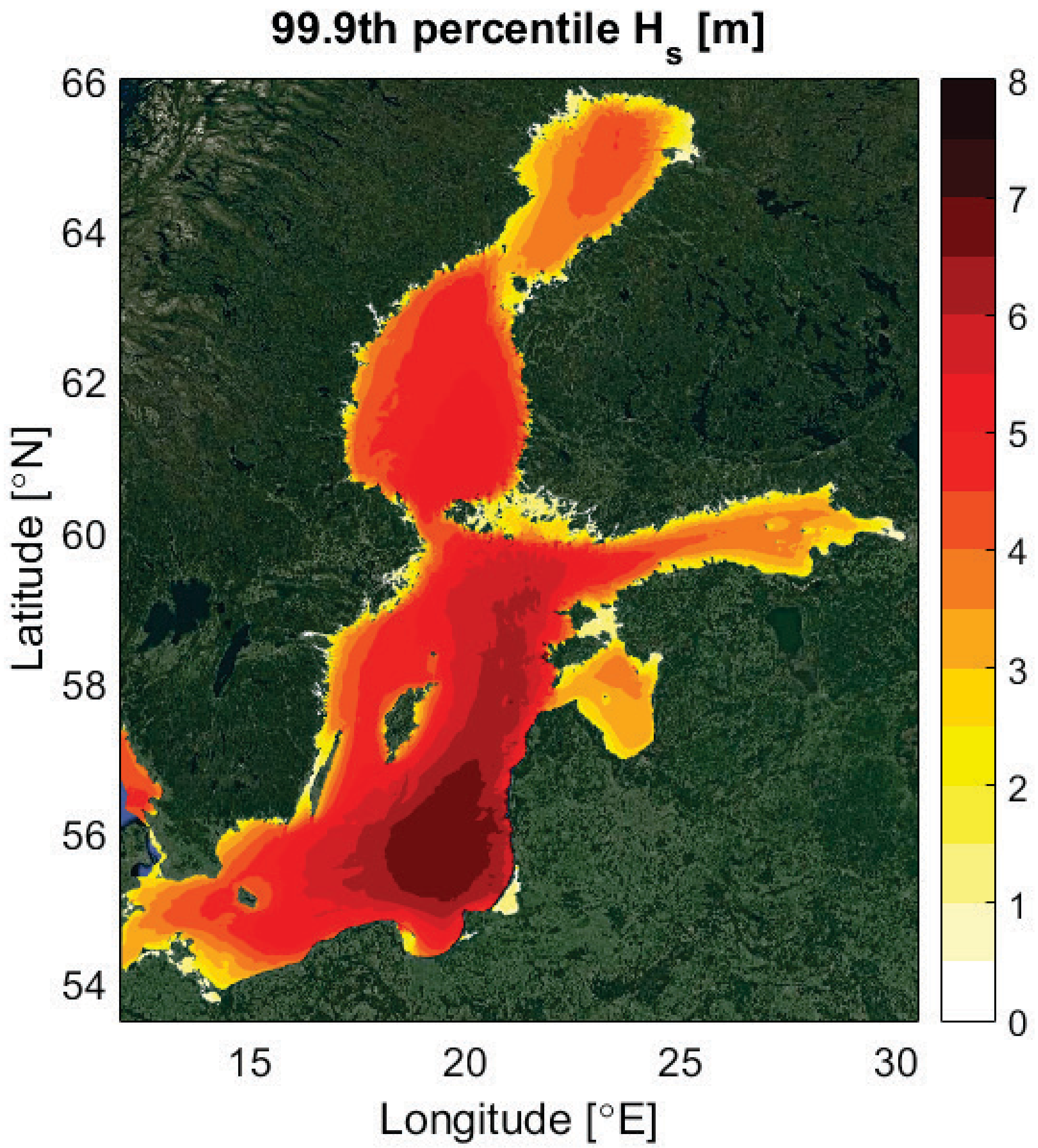

Fig. 2.1.1.2 _2: Ice-free statistics (Type F in Tuomi et al. (2011)) for the 99.9th percentile significant wave height using a high-resolution wave hindcast for the years 1998-2013 (Nilsson et al. 2019).

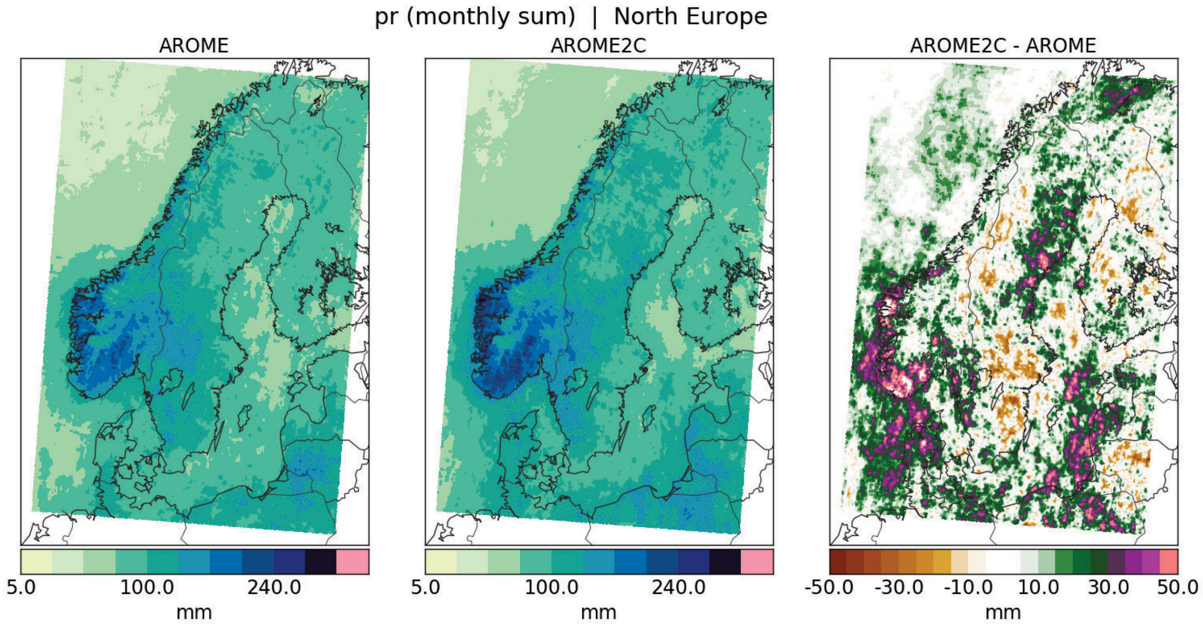

Figure 2.1.1.5 Precipitation extremes

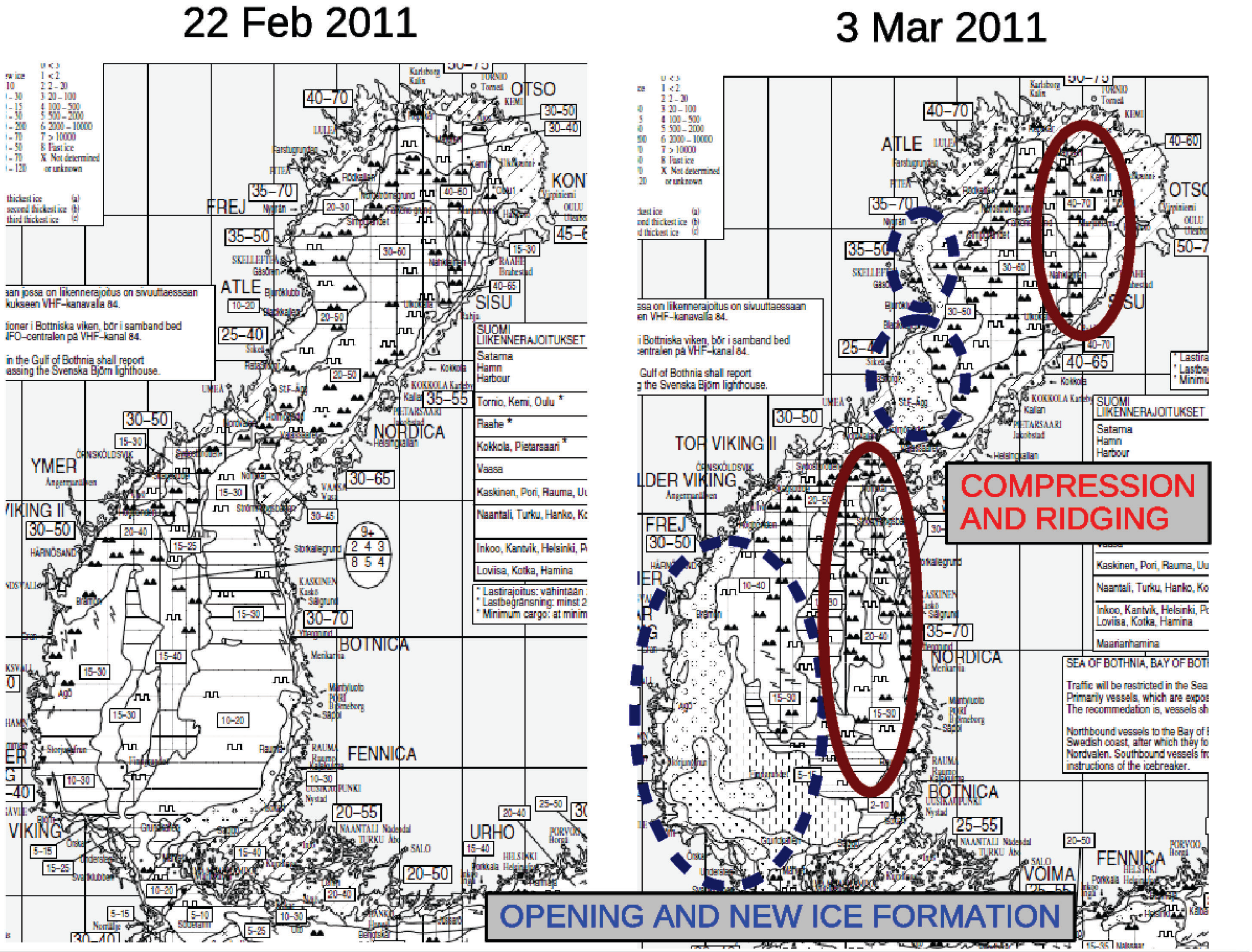

Figure 2.1.1.2_1. Ice charts before and after the major compression event in February 2011.

Figure 2.1.1.2_2. Sea ice thickness after the compression event.

Figure 2.1.1.2_3. Daily avarage speed of the ships navigating in the ice before and during the compression even

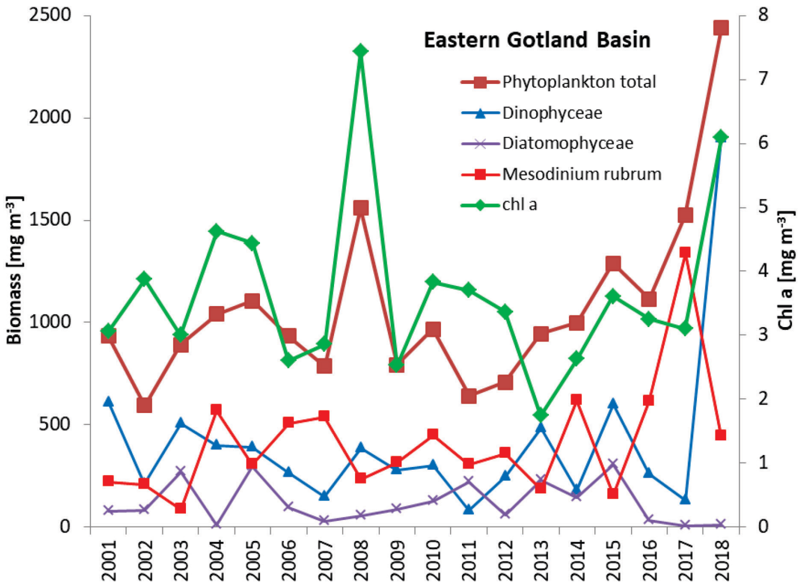

Fig. 2.1.2.2 _1: Trends from 2001 to 2018 in the biomass of total phytoplankton and its three main representatives and in the chorophyll a (chl *a*) concentration in spring data (March to May) of surface water (0-10 m depth) in the Eastern Gotland Basin (Wasmund, unpubl.).

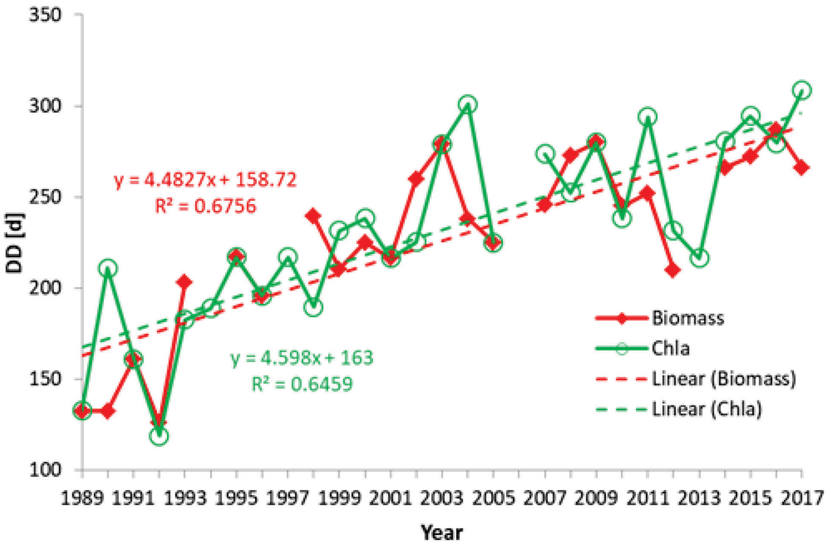

Fig. 2.1.2.2_2: Trends in the duration of the vegetation period (DD), based on phytoplankton biomass and chl *a* data, with regression lines and corresponding formulas (Wasmund subm.).

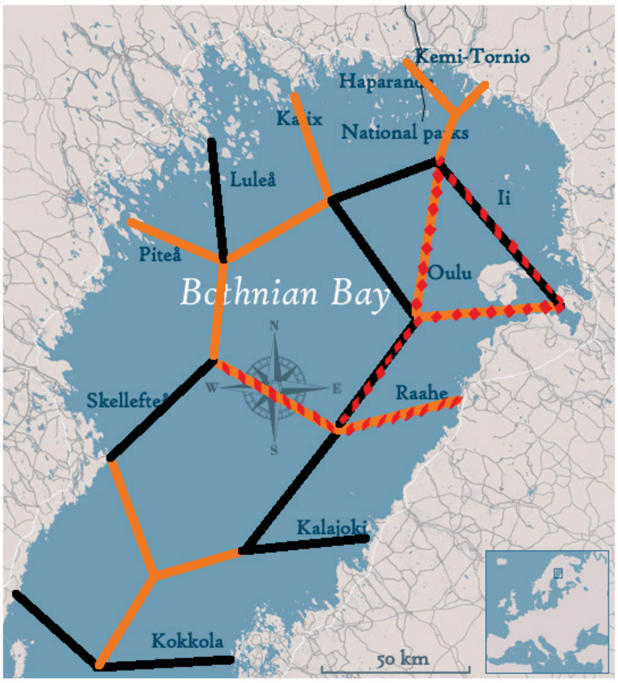

Figure 2.3.5_1. An example fairway-network constructed with the BBs. This network is composed by 16 BBs (10 section BBs and 6 junction BBs). A junction BB is orange in color and a section BB is black. One operational area is explicitly shown: the BBs that comprise the operational area are marked with red stripes.

The example network of Figure 1 could have been constructed in many ways, i.e. by using different leg lengths and/or different BB choices. There is not one right way to construct a network, but in general the junction-BB should be used where ever possible (less BBs). In addition, when constructing a network, the suitable BB choices are largely dependent on the IB operational areas.

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