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)

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).

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

134 example observations from satellites) are introduced, this structure changes. Making use of all available
135 observations, a frozen scheme for the data assimilation of observations into state-of-the-art climate
136 models is used to minimise inhomogeneities caused by changes in the observational record over time.
137 However, studies indicate that these inhomogeneities cannot be fully eliminated (e.g., Stendel et al.,
138 2016). In addition, systematic differences between the underlying forecast models, such as due to their
139 different spatial resolutions (Trigo 2006; Raible et al. 2008) and differences in detection and tracking
140 algorithms (Xia et al. 2012) may affect parameters like cyclone statistics (for example changes in their
141 intensity, number and position). Reanalysis products includes NCEP/NCAR (from 1948 onwards;
142 Kalnay et al. 1996; Kistler et al. 2001), ERA-Interim, starting in 1979 (Dee et al. 2011) or, more recently,
143 ERA5 (Hersbach et al. 2020). Other reanalyses use a limited data assimilation scheme to go further back
144 in time, like the 20th Century Reanalysis 20CR (from 1871 onwards; Compo et al. 2011) or CERRA
145 (Schimanke et al., 2019). On the regional scale, detailed regional reanalysis with higher resolution
146 models and more observations have been developed (e.g. Dahlgren et al., 2016; Kaspar et al., 2020).

147 ## 1.2   Methods, future scenarios

148 The development of general circulation models (GCMs) has created a useful tool for projecting how
149 climate may change in the future. Such models describe the climate at a set of grid points, regularly
150 distributed in space and time. In some cases, also dynamical downscaling with regional models or
151 empirical-statistical downscaling using statistical models are used. A large multi-model coordinated
152 climate model experiment, CMIP Project Phase was initiated, currently version 5 (CMIP5, Taylor et al.,
153 2012) is the main source of information while the next phase CMIP6 (Eyring et al., 2016) is increasingly
154 being used. Coordinated downscaling activities including regional climate models (RCMs) include
155 those of the European research projects PRUDENCE (Déqué et al. 2007) and ENSEMBLES (Kjellström
156 et al. 2013) as well as the WCRP supported international CORDEX project with its European branch
157 EURO-CORDEX (Jacob et al., 2014).

158 Projections of climate change depend inherently on scenario assumptions of future human activities.
159 Widely used are the Representative Concentration Pathways (RCPs) (van Vuuren et a., 2011). An RCP
160 represents a climate forcing scenario (e.g. including changes in greenhouse gas emissions, aerosols,
161 land use etc.) trajectory adopted by the IPCC for its Fifth Assessment Report (AR5) in 2014. RCPs
162 describe different climate futures, all of which are considered possible depending on how strong the
163 forcing of the climate system is. The four RCPs used for AR5, namely RCP2.6, RCP4.5, RCP6, and
164 RCP8.5, are labelled after their associated radiative forcing values in the year 2100 (2.6, 4.5, 6.0, and
165 8.5 W/m^2, respectively, (Moss et al, 2008; Weyant et al., 2009) relative to that in pre-industrial times,
166 e.g. 1750. RCP4.5 is used in many studies assuming increasing carbon dioxide emissions until 2040 and
167 after that decreasing. RCP8.5 assumes a continuously growing population and rapidly increasing carbon
168 dioxide and methane emissions and is increasingly seen as an unlikely worst-case scenario (Hausfather
169 and Peters, 2020). Prior to the RCPs, scenarios from the Special Report on Emission Scenarios
170 (Nakicenovic et al., 2000) were widely used. The main scenario families included were: A1,
171 representing an integrated world with rapid economic growth; A2, a more divided world with regional
172 and local focus; B1, representing an integrated and more ecologically friendly world; B2 of a divided
173 but more ecologically friendly world.

174 # 2   Current state of knowledge

175 ## 2.1   Changes in circulation patterns

The atmospheric circulation in the European/ Atlantic sector plays an important role for the regional climate of the Baltic Sea basin and the surrounding areas (e.g., Hurrell 1995; Slonosky et al. 2000, 2001). Large-scale flow characteristics 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,

261 the very modest warming in October in southern Finland, and about a half of the very large warming in
262 December.

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

270 ## 2.2   Extreme conditions (current knowledge now and potential future change)

271 ### 2.2.1 Winds storms

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

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

291 Recent trend estimates of the total number of cyclones over the NH extratropics during 1979-2010 reveal
292 a large spread across the reanalysis product, strong seasonal differences, as well as decadal-scale
293 variability (Tilinina et al., 2013; Wang et al., 2016; Chang et al., 2016; Matthews et al., 2016; Gregow
294 et al., 2020). Common to all reanalysis datasets is a weak upward trend in the number of moderately
295 deep and shallow cyclones (7 to 11% per decade for both winter and summer), but a decrease in the
296 number of deep cyclones in particular for the period 1989-2010. Chang et al. (2016a) have reported a
297 minor reduction in cyclone activity in Northern Hemisphere summer due to a decrease in baroclinic
298 instability as a consequence of Arctic temperatures rising faster than at low latitudes. Chang et al.
299 (2016b) also notice that state-of-the art models (CMIP5) generally underestimate this trend. In Northern
300 Hemisphere winter, recent studies claim an increase in storm track activity related to Arctic warming.
301 Recent research (Feser et al. 2021) reveals no clear trend, but an increasing similarity over time in
302 reanalyses, observations and dynamically downscaled model data.

303 Despite large decadal variations, there is still a positive trend in the number of deep cyclones over the
304 last six decades, which is consistent with results based on NCEP reanalyses between 1958 and 2009
305 over the northern North Atlantic Ocean (Lehmann et al. 2011). Using an analogue-based field
306 reconstruction of daily pressure fields over central to northern Europe (Schenk and Zorita 2012), the
307 increase in deep lows over the region might be unprecedented since 1850 (Schenk 2015). For limited
308 areas the conclusions are rather uncertain. Past trends in homogenized wind speed time series (1959-
309 2015), in both mean and maximum, have been generally negative in Finland (Laapas et al., 2017).

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

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

333 So, in summary, there is no clear consensus in climate change projections in how far changes in
334 frequency and/or intensity of extratropical cyclones have an effect on the Baltic Sea region.

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

2.2.2 Extreme waves

340 Vertical motions on the ocean surface consists of an extensive spectrum of frequencies and periods
341 (Munk 1950, Holthuijsen 2007). Here we focus on the wind generated waves and mainly on the
342 significant wave height representing the average height of the highest third of the waves. Significant
343 wave height serves as an indicator when discussing extreme waves, however, the highest individual
344 wave in a wave record is 1.6-2.0 times higher than significant wave height (Björkqvist et al. 2018,
345 Pettersson et al. 2018). Some ambiguity exists when it comes to which sea states can be called extreme

346 (Hansom et al. 2015) because locally higher wave heights in not particularly stormy conditions can lead
347 to damages and fatalities and may become labeled in the media as extreme, giant, freak, monster or
348 rogue waves. Rogue waves are typically defined as a maximum wave height of more than two times the
349 significant wave height. The horizontal resolution of wave modeling hindcast studies for the Baltic Sea
350 have varied from about 1.1-1.85 km to about 22 km (Nilsson et al., 2019; Björkqvist et al., 2018; Jönsson
351 et al. 2003). The small-scale spatial and time variations are often missed by the models and coarse
352 resolution (6-11 km) may not provide sufficient accuracy to study extremes (Larsén et al. 2015;
353 Björkqvist et al. 2018).

354 On 12 January 2017, an intensive low-pressure system generated a wave in the northern Baltic Sea
355 referred to in the media as a monster wave above 14 m, equaling or exceeding the previous record from
356 December 22nd 2004 (EUMETSAT 2017, Björkqvist et al. 2018). Significant wave heights measured
357 around 8 m according to the Finnish Meteorological Institute (FMI). Even higher waves with significant
358 wave heights up to 9.5 m have been estimated to occur in the northern Baltic Proper during the wind
359 storm Gudrun in January 2005 (Soomere et al. 2008, Björkqvist et al. 2018). A high-resolution
360 numerical model study for the time period 1965 to 2005 (Björkqvist et al. 2018) showed a 99.9th
361 percentile for significant wave height in the Baltic Sea of 6.9 m. They found 45 unique extreme wave
362 events with modeled significant wave height above 7 m during the 41 year-simulation. Twelve of which
363 had a maximum above 8 m, six events exceeded 9 m, and one event showed significant wave height
364 over 10 m. Extreme waves in the Baltic Sea can have a significant impact on sea level dynamics and
365 coastal erosion also discussed further in Weisse et al. (2021).

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

380 Some studies have also been conducted on near-shore extreme waves; e.g. Gayer et al. 1995, Paprota et
381 al. 2003, Sulisz et al. 2016 discussed the formation of extreme waves and wave events along Polish and
382 German coasts and reported a large number of freak-type waves. Although significant progress in
383 understanding and prediction of ocean extremes and freak waves (e.g. Cavaleri et al. 2017, Janssen et
384 al. 2019) have been achieved, a practical definition using usually more well-predicted parameters, such
385 as significnat wave height, is presently used in warnings (Björkqvist et al. 2018).

386 From long-term in-situ observations and modeling results trends in wave climate are inconclusive and
387 possibly site-specific (e.g. Soomere and Räämet 2011b). From reviewing multiple studies discussing
388 changes and trends in significant wave heights at Baltic Sea sites across time periods of more than 30
389 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

433   levels (Leppäranta and Myrberg 2009). Due to the shape of the Baltic Sea, the highest and lowest sea
434   levels are found in the end of the bays, as in the eastern end of the Gulf of Finland, northern end of the
435   Gulf of Bothnia, and in the Gulf of Riga, whereas the amplitude of variation is smallest in the central
436   Baltic Sea. The Baltic Sea areas with the largest sea level variations, based on tide gauge data 1960-
437   2010, are shown in Fig. 4 (from Wolski et al. 2014).

438   The observed maxima and minima on the Baltic Sea coast along with 100-year return levels based on
439   interpolated coastal tide gauge observations 1960-2010 were studied by Wolski et al. (2014). They
440   observed an increase in the yearly number of storm surges (defined as sea levels 70 cm above zero level
441   of the European Vertical Reference Frame or local mean sea level in Finland and Sweden). The increase
442   was largest in the Gulf of Finland (Hamina and Narva) and in the Gulf of Riga (Pärnu). Ribeiro et al.
443   (2014) investigated the changes in extreme sea levels in 1916-2005 from detrended daily tide gauge
444   records of seven stations in Denmark and Sweden on the Baltic Sea coast, using GEV (Generalized
445   Extreme Value) and quantile regression methods. They observed a statistically significant trend in
446   annual sea level maxima in the Gulf of Bothnia (1.9 mm/year for Ratan and 2.6 mm/year for
447   Furuögrund). For other locations, the maxima could be considered stationary. Marcos and Woodworth
448   (2017) studied the tide gauge data concluding that the changes in the 100-year return levels after 1960
449   in the Baltic Sea were explained by the mean sea level rise. Projected extreme sea levels for the Baltic
450   Sea coast in 2100 were calculated by Vousdoukas et al. (2016) considering only the effect of the
451   atmosphere on the sea level (storm surges) while omitting global mean sea level rise and land uplift.
452   The Delft3D sea level model was forced with 8 global climate models from CMIP5 database, and the
453   projected changes were calculated from ensemble means of model simulations. In 2100, the present-day
454   100-year storm surge was projected to take place every 72 years under RCP4.5 and every 44 years under
455   RCP8.5. The ensemble means of storm surges (return periods from 5 to 100 years) increase along the
456   northern Baltic Sea coast with time for both RCPs. The increase is largest in the Bothnian Bay and in
457   the Gulf of Finland, reaching about 0.5 m. Along the southern Baltic Sea coast, there is smaller or no
458   increase in most scenarios. When the storm surges are averaged over the Baltic Sea coast, the increase
459   in the storm surges of return periods from 5 to 500 years is only 10-20 cm for different scenarios. By
460   2100, the inter-annual variation in the seasonal maxima, indicated by the standard deviation, increased
461   by 6 per cent in RCP4.5 and by 15 per cent in RCP 8.5. This indicated that the variations in the maxima
462   might increase more than the 30-year mean, suggesting that the maxima could have a higher increasing
463   trend than the mean sea level has. The extreme sea levels along Europe's coasts, caused by the combined
464   effect of mean sea level, tides, waves and storm surges were studied by Vousdoukas et al. (2017). In the
465   Baltic Sea, the 100-year sea level due to waves and storm surges was projected to rise 35 cm (average
466   over the Baltic coast) by 2100 in RCP8.5. The rise is largest in the eastern coast of the Baltic Sea, and
467   the intra-model variation of the 100-year level increases up to 0.6 meters in 2100. The large variation
468   between the models causes a large uncertainty in the evaluation of the change in extreme sea levels
469   during the present century. These sea level estimates should be considered preliminary. To increase the
470   confidence in the future projections of storm surges in the Baltic Sea, we must rely on future research
471   where a larger set of regional and global climate models are used with refined sea level models. The
472   dependence between extreme sea levels and wind waves has to be assessed when the joint effect of
473   storm surge and wave setup on the coast is studied. For the Baltic Sea, this dependence should be
474   included when joint probabilities of compound events of high sea levels and waves are calculated, as is
475   done in Kudryavtseva et al. (2020). An extended discussion on sea-levels is seen in Weisse et al. (2021).

476   **2.2.4 Precipitation**

477   Precipitation extremes in the Baltic Sea region are mainly related to i) synoptic-scale mid-latitude low
478   pressure systems and ii) convective precipitation events associated with meso-scale convective systems
479   or resulting from single intense cloudbursts. Additionally, sea-effect snow fall events can generate large
480   amounts of snow in coastal areas downstream of the Baltic Sea (section 2.2.5). Climatologically,
481   summer is the season with the strongest convective activity and this is also the season with the strongest
482   cloudbursts. Precipitation extremes associated with low pressure systems are most frequent in fall and
483   winter when the large-scale atmospheric circulation is favorable for bringing low-pressure systems
484   towards northern Europe.

485   High-resolution gridded data sets that may be used for evaluation of climate model performance for
486   precipitation includes: PTHBV covering Sweden at 4 km grid (Johansson and Chen, 2005); the Finnish
487   data set at 1 km and10 km grid by Aalto et al. (2016) ; the REGNIE data set at 1 km grid covering
488   Germany (Rauthe et al., 2013); CPLFD-GDPT5 for Poland at 5 km (Berezowski et al., 2016) and
489   seNorge2 for Norway at 1 km grid (Lussana et al., 2018). Another recent data set is the joint product
490   consisting of PTHBV data in combination with precipitation estimates from radar data over Sweden
491   resulting in the 4x4 km, one hourly resolution HIPRAD (HIgh-resolution Precipitation from gauge-
492   adjusted weather RADar) data set covering 2009-2014 (Berg et al., 2016). Finally, it is noted that these
493   national data sets are derived with slightly different methods implying that they cannot directly be
494   compiled and used as one high-resolution data set for the entire Baltic Sea region.

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

511   According to BACC I (2008) and BACC II (2015) precipitation trends in the Baltic Sea basin over the
512   past 100 years have varied in time and space. Examples exist of both increasing and decreasing trends
513   in different areas for different periods and seasons. Positive trends were detected for the cold part of the
514   year for Fennoscandia by Benestad et al. (2007) and Estonia, Latvia and Lithuania by Jaagus et al.
515   (2018). Along with warming it is also noted that the fraction of snowfall to total precipitation is
516   decreasing with time (Hynčica and Huth, 2019; Luomaranta et al. 2019).

517   Increasing intensity of precipitation events resulting from the larger water-holding capacity of a warmer
518   atmosphere is an expected impact of climate change (Bengtsson, 2010). Based on European E-OBS
519   data, Fischer and Knutti (2016) demonstrate that heavy daily precipitation, defined as the 99.9th
520   percentile that roughly corresponds to a one in three years event, has become 45% more frequent

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 the sign of change in seasonal mean precipitation, heavy rainfall is projected to increase in intensity for most of Europe including the Baltic Sea region (Nikulin et al., 2011; Rajczak et. al., 2013; Christensen and Kjellström, 2018) as illustrated in Fig. 6. Snowfall is projected to decrease on an annual mean basis but in winter daily snowfall amounts and extreme events may 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 convection permitting regional climate models have been shown to sometimes yield different climate change signals for extreme precipitation events compared to coarser scale models (> 10 km grid spacing). For instance, Kendon et al. (2014) showed stronger increase in summertime intense precipitation in a 1.5 km model compared to a 12 km one for the southern UK. Similarly, Lenderink et al. (2019) showed 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,

608 Höglund et al., 2017; see also Sec. 2.2.10), extending the time period when convective snowbands can
609 form. Besides, wintertime precipitation amounts are increasing (Sec. 2.2.4). On the other hand, on an
610 annual mean basis, conditions might become less favorable for sea-effect snowfall due to a shorter
611 thermal winter (Ruosteenoja et al., 2020) and a smaller share of snowfall compared to rain in the
612 warming climate (Sec. 2.2.4).

613 The sea-effect snowfall events typically have temporal and spatial scales smaller than what is covered
614 by the observational network and resolved by climate models. The high resolution ERA5 data was used
615 in a case study for January 2016. The preliminary results were promising towards the use of re-analysis
616 data over sea but the data cannot produce intensive enough convective snowfall over land (Olsson et al.
617 2018). Newly developed convective permitting regional climate models (see Sec. 2.2.4), in turn, open
618 up new possibilities to assess the future evolution of the probability of the occurrence.

convection

619 **2.2.6 River floods**

620 A detailed assessment of climate change of river floods for northern Europe was provided in BACC I
621 (2008) and BACC II (2015). The regional features in the Baltic Sea Basin during last decades according
622 to Stahl et al. (2010) consist in positive trends with increasing streamflow in winter months in most
623 catchments of the Basin, while in spring and summer months, strong negative trends were found
624 (decreasing streamflow, shift towards drier conditions).

625 After the last BACC publication in 2015 there are only few studies devoted to the past hydrological
626 regime changes. Arheimer (2015) concluded that the observed anomalies in annual maximum daily flow
627 for Sweden were normally within 30% deviation from the mean of the reference period. There were no
628 obvious trends in the magnitude of high flows events over the past 100 years. There was a slight decrease
629 in flood frequency, although in a shorter perspective it seems that autumn floods increased over the last
630 30 years. The flood decreasing is connected with seasonality change in the study region. Changes in
631 flood time occurrence in Europe were also established by Bloschl et al (2017). In the Baltic Sea region
632 they detected the floods shifting from late March to February due *to* the earlier snow-melting, driven by
633 temperature increases in the region and a decreasing frequency of arctic air mass advection (see section
634 2.1).

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

644 For future climate a decrease of annual mean (Latvia, Lithuania and Poland) and seasonal streamflow
645 according to the SRES scenario A1B, A2 and B2 was projected for the rivers in Norway and Finland,
646 and (Beldring et al., 2008; Veijalainen et al., 2010b; Apsīte et al., 2011; Kriaučiūnienė et al., 2008;
647 Szwed et al., 2010). An annual streamflow increase by 9-34% has been projected for Denmark (Thodsen
648 et al., 2008, Jeppesen et al., 2009). Large uncertainties in the future hydrological regime were reported
649 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

695 temperatures pose a significant risk to health also in the current-day climate (e.g., Kollanus and Lanki
696 2014; Åström et al., 2016; Ruuhela et al., 2018).

697 In general, the magnitude, temporal and spatial extent, and frequency of heat waves depend on large-
698 scale fluctuations in atmospheric circulation (see section 2.1), particularly on the occurrence of
699 blockings and other circulation patterns (Horton et al., 2015; Brunner et al., 2017) but other factors,
700 such as local soil moisture feedbacks (Brulebois et al., 2015; Miralles et al., 2014; Whan et al., 2015;
701 Cahynová and Huth, 2014; see also Sec 2.2.9) and solar radiation are of importance. For example,
702 Tomczyk and Bednorz (2014) showed a clear link between heat waves along the southern coast of the
703 Baltic Sea and the circulation patterns. Furthermore, the heat wave in 2018 in Finland was strongly
704 affected by abundant incoming short-wave radiation due to unusually clear skies (Sinclair et al., 2019;
705 Liu et al., 2020). Regarding the local/regional amplitude of a heat wave, land cover use may also play a
706 role. For example, the record high temperature in Finland in 2010 (37.2 °C) was likely contributed by
707 several factors in addition to the very warm air mass (Saku et al., 2011), and in a recent simulation study
708 it was found that replacing a dense urban layout by a suburban type land use resulted in small but
709 systematic decreases in air temperatures in July (Saranko et al., 2020).

710 A widely used heat wave indicator is the warm spell duration (WSDI), defined as the annual (or
711 seasonal) count of days with at least 6 consecutive days when the daily maximum temperature exceeds
712 the corresponding 90th percentile. If using the period 1961-1990 as a baseline when calculating the 90th
713 percentiles, as done in Figure 8 (top left), a statistically highly significant increasing trend across the
714 period 1950-2018 can be found in annual WSDI, when averaged over land areas of the Baltic Sea region
715 (with a Theil-Sen's slope of 1.7 per decade). In southern Sweden, the Baltic States and southern and
716 western Finland, 30-year averages of annual WSDI were about 14 days per year or more during for a
717 recent time span (1989-2018) (Figure 8, bottom left), while during the baseline period the annual count
718 there had been about 6-8 on average. Similar results have been obtained by Irannezhad et al. (2019) and
719 Matthes et al. (2015). The former detected statistically significant increases in annual WSDI near the
720 western coast of Finland for the period 1961–2011, but changes of both positive and negative signs in
721 northern and eastern parts of the country and statistically insignificant increases elsewhere. The latter
722 considered WSDI in 1979-2013 separately in winter and summer and reported statistically significant
723 increases in summer at several Swedish and Norwegian weather stations and in winter also at Finnish
724 stations.

725 In the future, heat waves are projected to occur more often and to become longer and more intense.
726 Today's warm spells tend to become increasingly frequent, but also increasingly 'normal', from a
727 statistical point of view (Rey et al. 2020). Accordingly, quantitative estimates of the rates of the future
728 changes strongly depend on the selected definition of the heat wave (Jacob et al., 2014). The mean
729 length (number) of heat waves where the 20 °C daily mean temperature is exceeded has been projected
730 to increase by about 50 % (60 %) in southern Finland under RCP4.5 between the periods 1900-2005
731 and 2006-2100 (Kim et al. 2018). A bias-adjusted median estimate for changes in WSDI in Scandinavia
732 for the period 2071-2100, with respect to 1981-2010, is about 15 days under RCP8.5, with an uncertainty
733 range of about 5-20 days (Dosio, 2016).

734 Accompanied with more frequent and longer warm spells are decreases in the frequency, duration and
735 severity of cold spells, both based on observations (Easterling et al., 2016) and model projections
736 (Sillmann et al., 2013; Jacob et al., 2013). Cold winter weather in the Baltic Sea region is closely
737 associated with a negative phase of NAO and warm conditions in the Greenland region, and this
738 statistical relationship has strengthened during the recent period of rapid Arctic warming (1998–2015),

suggesting that Arctic influences might intensify in the future, perhaps leading to more unusual and persistent weather events (Vihma et al., 2020). On the other hand, northerly winds from the Arctic are milder than before (Screen, 2014). A cold winter, with unusually low temperatures like those in southern parts of the Baltic Sea area in 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

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

824 project on average a small decrease in the lowest water levels during droughts in Finland (Veijalainen,
825 2019).

2.2.10 Ice seasons

827 Maximum Ice extent of the Baltic Sea (MIB) is one of the essential variables describing climate change
828 and variability in the Baltic Sea. On an average winter, maximum ice extent is 165,000 km^2 indicating
829 that the Bay of Bothnia, coastal areas of the Bothnian Sea, the Archipelago Sea, the Eastern Gulf of
830 Finland and the Bay of Riga are ice covered (BACC II, 2015). During extreme cold conditions, the
831 entire Baltic Sea can be ice covered and during the mildest winter only the Bay of Bothnia is ice covered.
832 Based on the MIB time-series which dates back to 1720, Seinä and Palosuo (1996) defined classification
833 on ice winters according to ice extent. Years with MIB less than 81,000 km^2 were classified as extremely
834 mild ice winters and MIB larger than 383,000 km^2 as extremely severe ice winters. Here we discuss
835 drivers of ice winter extremes and their observed and expected changes.

836 Annual maximum ice extent is a cumulative indicator of the severity of winter. It is largely driven by
837 the large-scale atmospheric circulation and it's inter-annual variability is well correlated with the NAO
838 index (Omstedt and Chen, 2001; Vihma and Haapala, 2009). They concluded that during the winters
839 with the NAO index > + 0.5, the average MIB is 121,000 km^2, with a range from 45,000 to 337,000
840 km^2, while during winters with the NAO index < - 0.5, the average MIB is 259,000 km^2, with a range
841 from 150,000 to 405,000 km^2. Extremely mild ice winters (MIB < 60,000 km^2) have occurred in 1930,
842 1961, 1989, 2008, 2015 and in 2020. According to Uotila et al. (2015), winter 2015 was the first winter
843 when the Bay of Bothnia was definitely only partly ice covered. That winter was dominated by strong
844 south-westerlies associated with a record high NAO index. In addition, the enhanced transport of warm
845 Atlantic air masses to the Baltic Sea region, anomalous low ice extent in winter 2015 was partly due to
846 higher than average downward long-wave radiation because of increased cloudiness which decreased
847 heat loss of the ocean surface layer. Also, episodes of warm foehn winds due to cyclones passing over
848 the Scandinavian mountains were observed in that winter. Uotila et al. (2015) concluded that extremely
849 mild winters were more common during the 1985 – 2015 period than in any other 30-year period since
850 1720. After 2015, only one winter has been an average in terms of MIB. The others are classified as
851 mild or extremely mild ice winters. The winter 2020 was all time record low ice winter. In that winter,
852 central parts of the Bay of Bothnia were again ice free and the MIB was only 37,000 km^2. Extremely
853 severe winters (MIB > 383,000 km^2) have not been observed since 1987. During the last 30 years, the
854 most severe winter occurred in 2011 which caused major problems and economical losses for marine
855 traffic (see section 2.1.1.4).

856 Ongoing changes towards a milder climate demands a revision of the Seinä and Palosuo (1996)
857 definition of extremely mild and severe ice winters. Their classification was based on a choice that 11%
858 of the lowest MIB's were classified as extremely mild winters. Correspondingly, 11 % of the largest
859 MIB's were counted as an extremely severe winter. If we are utilizing the same thresholds for the last
860 30 years data, limits for the extremely mild and severe winters would be ~ 50,000 km^2 and ~ 240,000
861 km^2, respectively.

862 According to climate projections, Baltic sea ice will experience considerable shrinking and thinning on
863 average in future (BACC I, 2008; BACC II, 2015). This is particularly clear for the Bothnian Sea,
864 Bothnian Bay and Gulf of Finland. However, changes in natural variability and extreme sea ice winters
865 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

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

996 measurements of phytoplankton biomass and chl *a* concentrations at a coastal station in the Bay of
997 Mecklenburg from 1988 to 2017, Wasmund et al. (2019) found an earlier start of the spring bloom with
998 a rate of 1.4 days/year and a later end of the autumn bloom with 3.1 days/year and a corresponding
999 extension of the growing season (Figure 10). The earlier start of the growing season was correlated with
1000 a slight increase in sunshine duration during spring whereas the later end of the growing season was
1001 correlated with a strong increase in water temperature in autumn. As the growing season extends
1002 recently from February to December at the investigated site, a further extension is practically not
1003 possible. However, this process may be still ongoing in other regions of the Baltic Sea.

2.3   Possible implications for society

1005 Extreme events and projected changes caused by e.g. global warming or changes in the atmospheric
1006 circulation could have large and potentially disastrous consequences to Baltic societies. This section
1007 examines the potential implications of extremes and changes of extremes on forest fires, coastal
1008 flooding, offshore wind activities and shipping in the Baltic Sea area, all of which are linked to key
1009 economic sectors. These are also linked to the Multiple drivers of the Baltic Sea systems (Reckerman
1010 et a., 2021).

2.3.1   Forest fires

1012 Fires play a key role in the natural succession and maintains biological diversity in boreal forests, they
1013 also pose a threat to property, infrastructure and people's lives (e.g., Rowe and Scotter, 1973;
1014 Zackrisson, 1977; Esseen et al., 1997; Virkkala and Toivonen, 1999; Ruokolainen and Salo, 2006).

1015 Large forest fires are often associated with long-lasting drought and heat waves. During the
1016 exceptionally warm and dry summer of 2018, numerous large fires burned a total of almost 25,000
1017 hectares of forest in Sweden (Statens offentliga utredningar, 2019; Sjöström and Granström, 2020).
1018 Also, during the heat wave of 2014, a single conflagration in Västmanland burned nearly 15,000
1019 hectares. In Russia, the persistent heat wave of 2010 resulted in devastating forest fires (Bondur, 2011;
1020 Witte et al., 2011; Vinogradova et al., 2016). Fires have a deteriorating impact on air quality (Konovalov
1021 et al., 2011; R'Honi et al., 2013; Popovicheva et al., 2014), in extreme cases even in regions hundreds
1022 of kilometers away from the actual fire (Mei et al., 2011; Mielonen et al., 2012; Vinogradova et al.,
1023 2016). The emissions of gases and aerosols through fires as well as changes in surface albedo also have
1024 impacts on climate. Due to increasing fire activity, boreal forests may even shift from carbon sink to a
1025 net source of carbon to the atmosphere, resulting in a positive climate feedback (Oris et al., 2014; Walker
1026 et al., 2019). The impact of aerosols is more complex, yet generally short-lived. However, heat-trapping
1027 soot from large conflagrations can enter into the stratosphere and persist there for months (Ditas et al.,
1028 2018; Yu et al., 2019). Changes in surface albedo due to fires tend to decrease radiative forcing in the
1029 long term (e.g., Randerson et al., 2006; Lyons et al., 2008).

1030 Compared to other boreal regions, forest fires in Northern Europe are small. This is mainly due to
1031 effective fire suppression. In addition, heterogeneity of Fennoscandian forests with lakes and swamps
1032 creates natural obstacles for fires. Large fires are more common in Russia, Canada and Alaska (e.g.,
1033 Stocks et al., 2002; Vivchar, 2011; Smirnov et al., 2015). However, also in Fennoscandia large fires
1034 were not uncommon before the cultural transition to modern agriculture and forestry led to a steep
1035 decline in annual burned area by the end of the 19th century (Wallenius, 2011).

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 four 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 that 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

1079   The projected regional sea level rise (e.g. Grindsted et al. 2015) coupled with the expected
1080   intensification of sea level extremes (e.g. Vousdoukas et al. 2018) discussed in Section 2.2.3 will widely
1081   affect both natural and human systems along the Baltic Sea.

1082   In the past, several major floods have occurred on the Baltic Sea coast. While there are few surviving
1083   sea level measurements or other historical records dated before the 19th century traces of extreme floods
1084   are found from sand layers. Studies of coastal sediments, compared with historical records, imply that
1085   the flood in 1497, which damaged cities on the southern Baltic coast, was the largest storm surge on the
1086   Polish coast in 2000 years (Piotrowski et al., 2017). St. Petersburg has also proved vulnerable to coastal
1087   and fluvial flooding, and the highest documented surge occurred in 1824, when the water level rose to
1088   367 cm at Kronstadt, and possibly even to 410 cm at St. Petersburg (Bogdanov and Malova, 2009) over
1089   local mean sea level. In the era of tide gauges, the most severe flood along the southern Baltic coast
1090   happened in 1872. This storm caused large damages at the German and Danish coast and 271 lives were
1091   reported lost (Rosenhagen and Bork, 2008). At Travemünde, Germany, the sea level rose to 340 cm
1092   (Jensen and Müller-Navarra, 2008); at Skanör, along the southern Swedish coast, the sea level reached
1093   approx. 240 cm (Fredriksson et al., 2016). For the Gulf of Finland and the Gulf of Riga, the most severe
1094   flooding on record was caused by the Gudrun wind storm in 2005, when the observed sea level reached
1095   197 cm in Hamina (Finland), 230 cm in St. Petersburg (Russia), 207 cm in Ristna (Estonia), and 275
1096   cm in Pärnu (Estonia) (Suursaar et al., 2006).

1097   In a European perspective, the uncertain influence of climate change on the frequency and intensity of
1098   waves and wind as a predictor of future damage costs due to coastal flooding is decreasing relative to
1099   the observed and projected influence of sea level rise on storm surge heights. Hence, Vousdoukas et al.
1100   (2018) finds that the indirect effect of mean sea level rise, uplifting high sea levels under extreme
1101   weather conditions, serves as the main driver of the increased coastal flood damages in the future and
1102   accounts for 88–98% of the total damages. Interestingly, the highest relative contribution from changes
1103   in cyclones is here projected along the Baltic Sea coast. This stems from a combination of low relative
1104   sea level rise along the Baltic Sea catchment that is due to the land uplift and intensifying waves and
1105   storm surges due to climate change based on the projections used by Vousdoukas et al. (2017). In
1106   general, there is no consensus whether the wind storms are expected to become more frequent (Sec
1107   2.2.1). In particular, for Finland and Sweden - due to land uplift - the physical footprint of sea level rise
1108   in future damage estimates is weakened. Conversely, socioeconomic development along the coast is
1109   likely to be a main driver and modulate the intensification of coastal hazards amongst Baltic Sea
1110   countries.

1111   In the absence of improved coastal management practices and coastal adaptation, the expected
1112   population exposed to coastal flooding along the Baltic Sea coastline annually as well as the expected
1113   annual damages (EAD) due to coastal flooding are both likely to increase by orders of magnitude (e.g.
1114   Forzieri et al. 2016, Vousdoukas et al. 2018, Mokrech et al. 2014, Brown et al. 2018). While the impacts
1115   on managed as well as natural coastal and near-coastal terrestrial ecosystems may be significant, Baltic
1116   coastal cities are likely to be mainly responsible for future coastal flood losses due to their high
1117   concentration of people, infrastructure and valuable assets. To keep future coastal flood losses low,
1118   climate change adaptation measures urgently need to be installed or reinforced (Vousdoukas et al. 2020,
1119   Abadie et al. 2019) to withstand extreme sea levels, which could exceed 4-5 metres in some locations
1120   (see Section 2.2.3).

1121   Apart from recent work by Paprotny and Terefenko (2017) for Poland, environmental and economic
1122   impact assessments at the regional to national level generally belong to the grey literature. Similarly,

1123 impact assessments at the local (city) level have, so far, mainly been carried out by, e.g., engineering
1124 consultancies, to facilitate the development of local adaptation strategies (Thorarinsdottir et al. 2017).
1125 Due to local constraints and a lack of best practices, the methodologies behind such detailed assessments
1126 often vary greatly and are not comparable.

1127 Figure 11 shows different damage estimates related to coastal flooding, including for some of the most
1128 exposed cities along the Baltic Sea. Here, Copenhagen stands out. Prahl et al. (2017) has calculated a set
1129 of macroscale damage cost curves (Figure 11, main part), i.e., damage cost as a function of flood height,
1130 for the largest 600 cities in Europe, including all of the major cities along the Baltic Sea. Land-use
1131 information is being used, and not population coupled with GDP per capita, as the basis for approximating
1132 the location of assets; i.e., this ensures that flooded assets are inherently co-located with the city. For
1133 the hydrological modelling, a high-resolution digital elevation model for Europe is used together with
1134 a simple static-inundation model that only accounts for hydraulic connectivity. While this approach
1135 readily allows for estimation of the damage costs associated with flooding for any European coastal
1136 city, the "coarseness" of the methodology (including the underlying empirical and categorical
1137 information on land-use and flood defenses, which goes into the calculations), can lead to
1138 overestimation of the damage cost curves, especially for low-lying urban and high-value areas. This is
1139 particularly found to be the case for (but not restricted to) Copenhagen (Figure 11, main part).

1140 For comparison, Abadie et al. (2016) have carried out a variant set of economic impact assessments for
1141 Copenhagen, Helsinki and Stockholm in 2050 based on an improved version of the same large-scale
1142 modelling framework, cf. the insert of Figure 11 (lower rows). Using the same input as Prahl et al.
1143 (2017), Abadie et al. (2016) have developed a European scale assessment framework, where a
1144 continuous stochastic diffusion model is used to describe local sea level rise, and Monte Carlo
1145 simulations yield estimates of the (risk) damage caused by the modelled sea level rise. This is paired
1146 with an economic damage function developed for each city and point in time. The results found by
1147 Abadie et al. for the RCP8.5 scenario are shown in Figure 11. For Copenhagen and Stockholm the damage
1148 cost estimates of Prahl et al. are largely consistent with those of Abadie et al. (2016).

1149 Vousdoukas et al. (2018, 2019, 2020) has estimated the EAD from coastal flooding for all countries in
1150 Europe (excluding adaptation) by combining future climate model projections with a set of gridded
1151 projections of gross domestic production, population dynamics and exposed assets based on selected
1152 shared socioeconomic pathways. Flood defenses are considered as recorded in the FLOPROS database
1153 (Scussolini et al. 2015). As seen in the table in Figure 11 (upper rows), at the end of the century
1154 Denmark is expected to suffer the largest damages from increased coastal flooding due to climate change
1155 due to its long coast line, followed by Germany, Poland and Sweden.

1156 The large observed variation in cost estimates related to future coastal flooding in the Baltic Sea may
1157 easily be ascribed to different approaches, data and scales used for the impact modelling, including key
1158 assumptions, in particular relating to (the) economics. To improve confidence in impact assessments, a
1159 comparable assessment of methods, models, and assumptions are needed in order to establish more solid
1160 evidence within the area. Likewise, impacts due to compound events where, for example, extreme coastal
1161 water levels are (locally) exacerbated by associated high water levels in nearby rivers or high intensity
1162 rainfall (Bevacqua et al. 2019) are largely unaccounted for in most damage cost assessments.

1163 **2.3.3 Offshore wind energy activities**

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

Compared to onshore situations, offshore wind energy benefits from richer wind resources. It is also greatly challenged by the harsher offshore environmental conditions, which makes the so-called Levelized Cost Of Energy (LCOE) significantly higher. LCOE accounts for, among 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.

With the presence of storms over the sea, special organized atmospheric features develop, contributing to turbulence over a broader frequency/wave number range than under typical stationary surface layer conditions. These features include gravity waves, low level jets, open cells and boundary layer rolls. Over the Baltic Sea, gravity waves and boundary layer rolls are present (e.g. Larsén et al. 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 were 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,

28 Rephrase

Are they running for decades? Rephrase

1208 with a grid space of 1 km (Bergström and Söderberg 2008). In addition, a variety of mesoscale models
1209 have been used for wind resource assessment, as well as extreme wind calculations, such as the
1210 HIRHAM model, the (e.g. Clausen et al. 2012; Pryor et al. 2012), the KAMM model (e.g. Hofherr and
1211 Kunz 2010; Larsén and Badger 2012), the REMO, the CCLM models (Kunz et al. 2010) and the WRF
1212 model (Bastine et al. 2018). For long-term data the models are run for decades. In compensation with *for*
1213 the computational cost, most of these models have been run at a spatial resolution of tens of kilometers.
1214 The effect of spatial and temporal resolution of these mesoscale modeled winds was investigated in
1215 Larsén et al. (2012) using modeled data from WRF, REMO and HIRHAM. Larsén et al. (2012)
1216 developed a so-called spectral correction method to fill in the missing variability in the modeled time
1217 series, thus reducing the underestimation of the extreme wind. To calculate the extreme wind, Larsén et
1218 al. (2012, 2019) also developed a selective dynamical downscaling method to efficiently allocate
1219 modeling resources to storms at high resolution, i.e. 2 km. The southern part of the Baltic Sea was
1220 included in these calculations.

1221 The development of approaches for calculating design parameters over the Baltic Sea has provided
1222 different estimations through time. The difference in these estimations (more than 10%) is bigger than *percentage points*
1223 the effect from climate change calculated from different climate scenarios (a few percent). Climate
1224 modeling describes future scenarios and provides a coherent calculation of the whole set of
1225 environmental parameters, including wind, temperature, icing and precipitation. One of such outputs is
1226 from the research project Climate and Energy Systems (CES) supported by the Nordic Research Council
1227 (Thorsteinsson 2011). This study features both opportunities and risks within the energy sector
1228 associated with climate change up to the mid-21st century. Fifteen combinations of Regional and Global
1229 Climate Models were used. The results, however, did not portrait a consensus on the change in storms
1230 and extreme winds in the future over the Scandinavian seas (see also section 2.2.1 and Belusic et al.,
1231 2019).

1232 **2.3.4 Shipping**

variable

1233 There are several aspects where changes in extreme events and natural disasters have the potential of
1234 influencing shipping; one relates to ice conditions. As stated above (Section 2.2.10 and 2.2.11), winters
1235 on the Baltic Sea can be different with highly ~~varying~~ ice conditions. This has been observed, when the
1236 ice loads encountered by ships have been measured in full scale by instrumenting ship hulls for ice load
1237 measurements, see example in Figure 13 (Kujala, 2017). Typically, the highest loads occur when ships
1238 are moving through heavily ridged areas or are stuck in moving, compressive ice. The highest measured
1239 loads occurred in severe ice winters, such as 1985 and 1987. Extreme events can also cause remarkable
1240 damages on the ship shell structures as shown in Fig 14 (Kujala, 1991). Typically, the ice-induced
1241 damages are local dents on the shell structures, with the depth about 50-100 mm and width as well
1242 height about 0.5m*0.5 m. The figure shows an example of the extensive damage outside Luleå (upper
1243 figure), when the ship left the harbour independently without icebreaker assistance and got stuck in
1244 compressive ice, and then the whole shell structures got permanent damage with the depth of about 0.5
1245 m and the length and height several meters. The ice-strengthened ships are not designed for this type of
1246 situation as the design principle is that icebreakers will prevent ships from getting stuck in ice.

1247 Increasing maritime traffic in areas where icebreaker (IB) assistance is needed will increase the demand
1248 for icebreaking assistance. The workload of an IB in its operational area, at a specific time, is strongly
1249 dependent on the area specific ice conditions and ship traffic. This leads to large area- and time-specific
1250 variations in the demand for icebreaking assistance. Even under constant ice conditions, it is hard to
1251 estimate local demand for assistance solely from the estimated increase or decrease in local maritime

traffic. There are a number of studies related to the development of the transit simulation models for ships navigating in ice, (e.g. Patey and Riska, 1999; Kamesaki et al., 1999; Montewka et al., 2015; Kuuliala et al., 2017 and Bergström, 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 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

1295 relatively small and the high wind events are often fetch-limited, thus the wind direction plays a large
1296 role in the generation of the high wave events. As the frequency of strong westerly winds is projected
1297 to increase (see section 2.2.1), this will most likely lead to an increase in the high wave conditions from
1298 this sector.

1299 Icing due to sea spray causes problems for maritime traffic in the Baltic Sea every now and then. In a
1300 future climate, this can happen more often as the ice winters get milder and the sea is open during the
1301 time of the year when sea surface temperatures are close to freezing point, so the probability of getting
1302 freezing water on the ship deck will potentially increase.

3   Knowledge gaps

1304 As extreme events, by definition, are rare, long time series of data and/or large ensembles with model
1305 simulations with high spatial coverage are a necessity for a full understanding of return periods and for
1306 mapping expected changes in intensities of extreme events. When also adding the impact of climate
1307 change and to some extent an unknown response of the climate system to partly unknown changes in
1308 forcing, the uncertainty increases further, especially locally. This is in particular true for compound
1309 events (i.e interaction of multiple hazard drivers) and freak events (i.e. events that have very low
1310 probabilities but which potentially can have disastrous impacts). These kinds of events are largely
1311 unexplored in the scientific literature.

1312 As previously discussed, many extreme events in the Baltic Sea region are related to the large-scale
1313 atmospheric dynamics, including storms originating from the North Atlantic region. Knowledge gaps
1314 concerning the response of large-scale atmospheric circulation in a warming climate include the
1315 dynamic response of reduced Arctic sea ice and changing oceanic conditions as well as the possibility
1316 of changes in the jet stream patterns and/or changing blocking frequencies over Europe.

1317 Besides storms that are related to extratropical cyclones, strong winds can also be induced by extreme
1318 convective weather, including downbursts, tornadoes, detached thunderclouds, derechos and other
1319 mesoscale convective systems (Rauhala et al., 2012; Punkka, 2015). Furthermore, wind gusts driven by
1320 convective downdrafts or turbulent mixing can also occur during larger-scale windstorms (Laurila et
1321 al., 2019). All these phenomena may be harmful to infrastructure, the severity of the impacts depending
1322 on the intensity and location of occurrence of the events. New convection permitting climate models
1323 with grid spacing of a few km (Sec. 2.2.4), as well as increasing observation density owing to the use
1324 of weather radars, satellites and lightning-location sensors, open new possibilities to assess their
1325 probabilities of occurrence of in the recent past and projected future climate.

1326 A local characteristic is the uncertainty in local responses to large-scale variability and global change.
1327 One particular feature is soil water response to heat waves, but also features such as changes in
1328 frequency of major Baltic inflows (Lehman et al., 2021; Meier et al., 2021). In the Baltic Sea region,
1329 the state of the cryosphere has already changed remarkably. Past mean changes in frost, snow, icing,
1330 lake and sea ice conditions have been rather well estimated by the regional models, but their future
1331 variability and change, ranging from synoptic to centennial time scales, are uncertain. Moreover, the
1332 impact of extreme cryosphere changes on forestry, reindeer herding, spring floods, extreme wave
1333 heights or shipping is largely unknown. Concerning flood assessments, the majority of the studies are
1334 devoted to high flood extremes. The low flow periods are less well described due to the absence of
1335 remarkable changes in flow regime especially in northern Europe, because of the large model uncertainty
1336 in precipitation during the summer (or warm period) when low flow usually occurs.

The prolongation of the growing season of phytoplankton is identified, but it may 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.

1379 In Figure 14, we summarize how the hazards are related to the atmospheric, ocean and hydrological
1380 conditions. The weather in the Baltic Sea region is largely determined by the state of the large-scale
1381 atmospheric circulation. In winter, the variability is largely governed by the NAO with dominating
1382 strong westerlies and cyclones in its positive phase while more stable continental weather dominates in
1383 its negative phase. Also, in summer there are large differences between more cyclone-dominated
1384 weather with relatively mild air from the Atlantic and blocking-dominated weather with high pressure
1385 systems and warm continental air. Large scale atmospheric circulation is the main source of inter-annual
1386 variability of seasons and the extreme states are manifested in, for example, the extent of the seasonal
1387 ice cover.

1388 Regional atmospheric events, cyclones and blocking, are causing directly storm damages or triggering
1389 heat waves and forest fires, respectively. Cyclones are also generating storm surges and hazardous
1390 coastal flooding and ocean waves. Summertime blocking situations are frequently causing heat waves
1391 while in winter they are connected to cold spells. For long lasting situations, impacts of blocking are
1392 not restricted to land but also marine heat waves are generated and consequently massive algal blooms
1393 are formed, as in 2018.

1394 An important aspect is that the most hazardous events are often combinations of several factors (i.e.
1395 compound events). For example, every cyclone can generate a storm surge, but the level of coastal
1396 flooding depends on the total water volume in the Baltic Sea. Positive water volume, which is caused
1397 by persistent westerlies, can provide an additional 50 cm (Leppäranta and Myrberg, 2009) to the
1398 maximum sea level. Moreover, a single storm is always causing a seiche oscillation and a sequence of
1399 storms can produce combined sea level changes due to the storm surge and seiche oscillation. In cities
1400 located at the river mouth, a sea flood can be further amplified by the river flood.

1401 Trends in circulation patterns are difficult to detect, the long-term temporal behavior of NAO is
1402 essentially irregular. There is, however, weak evidence that stationary wave amplitude has increased
1403 over the North Atlantic region, possibly as a result of weakening and/or northeastward shift of the North
1404 Atlantic storm track. There is an upward trend in the number of shallow and moderate cyclones, whereas
1405 there is no clear change, possibly a small decrease, in the number of deep cyclones during the past
1406 decades. Sea level extremes are expected to increase in a changing climate and are directly related to
1407 changes in mean sea level, wind climate, storm tracks and circulation patterns.

1408 European summers have become warmer over the last three decades, partly explained by changes in
1409 blocking patterns (see section 2.1). There is a clear link between warmer summers and an increased risk
1410 of drying (in particular in spring) and heat waves in most of the area. Floods decrease in a large part of
1411 the Baltic Sea in spring but streamflow has increased in winter and autumn during the last decades while
1412 the mean flow shows insignificant changes. Stronger precipitation extremes associated with warmer
1413 climate can have strong impacts on society, in particular in urban regions, and are strongly associated
1414 with flooding and more intense cloud bursts. Results from new, high-resolution convective-permitting
1415 climate models indicate that increases in heavy rainfall associated with cloud bursts may increase even
1416 more than what has previously been found in coarser-scale regional climate models.

1417 Sea-effect snowfall events can be a serious threat to the coastal infrastructure and should be considered
1418 also in the future, although likely with an overall lower risk on an annual basis. More research is still
1419 needed for deepening the understanding of the sea-effect snowfall and for developing a reliable way to
1420 assess the occurrence of such events also in the changing conditions. Another wintertime phenomena of

1421 potentially hazardous consequences is ice ridging, being one of the sea ice extremes with the greatest
1422 impact potential on coastal infrastructures and shipping.

1423 Phytoplankton blooms are extreme, but natural biological events. However, eutrophication/de-
1424 eutrophication, pollution and changes in irradiation, temperature, salinity, carbon dioxide etc. may
1425 change their magnitude, timing and composition. Examples of extreme and mostly potentially toxic
1426 blooms are given, but reasons can hardly be identified. Their sudden and sporadic appearance
1427 complicates trend analyses and modelling. One trend that seems to be prominent is the prolongation of
1428 the phytoplankton growing season. Climate change is the most probable reason for this.

1429 Table 4 summarizes the changes of some extreme events for the past decades and using scenarios for
1430 the upcoming decades, here a positive trend means increasing probability of occurrence and a negative
1431 trend decreasing probability of occurrence.

1432 Table 4: Selected event and the estimated frequency of occurrence. Scale for changes (major decrease,
1433 minor decrease, no change, minor increase, major increase). Color, confidence scale (Low, medium,
1434 high).

Event	Past decades	Future scenario
Number of moderate and shallow extratropical cyclones	Minor increase	no significant change
Number of deep extratropical cyclones North Atlantic	Minor increase	Minor increase
Extreme ocean waves North of 59°N South of 59°N	 no significant change (in strength and frequency) no significant change (in strength and frequency)	 minor increase in frequency in wintertime no significant change
Extreme sea levels (relative mean sea level plus storm surge) North of 59°N South of 59°N	 minor decrease minor increase	 minor increase major increase
Ice ridging	unknown	major decrease

Intense precipitation	minor increase	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 South of 59°N	decrease increase	mainly decrease, increase in the north in the spring increase in some regions in spring and summer
River Flooding	increasing in winter/autumn, decreasing in spring	decrease in spring increase in winter (low\high confidence)

1435 For the selected societal elements discussed here, a combination of extremes and their changes are
1436 controlling the development and potential future damage, in addition to numerous other factors. For
1437 forest fires, drought and heat waves might lead to a doubling during the present century in some areas,
1438 however, in other areas the risk might decrease due to increased precipitation. The frequency of coastal
1439 flooding responds mainly to sea level, but also wind, wave and precipitation features. The number of
1440 people exposed to coastal flooding in terms of annual damage is expected to increase with orders of
1441 magnitude. Baltic coastal cities are expected to be the main source of future coastal flood losses.
1442 Offshore wind application respond mainly to extreme wind and wave conditions. Here loads and
1443 damages are important, but also conditions for operation and management activities imposing
1444 limitations in the potential use. Shipping in the Baltic Sea is affected by wind and wave conditions, icing
1445 due to sea spray and ice conditions, although mean wind and wave conditions are relatively low, the

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

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5. References.

Aakala, T., Pasanen, L., Helama, S., Vakkari, V., Drobyshev, I., Seppä, H., Kuuluvainen, T., Stivrins, N., Wallenius, T., Vasander, H., and Holmström, L. (2018) Multiscale variation in drought controlled historical forest fire activity in the boreal forests of eastern Fennoscandia. Ecological Monographs 88: 74–91.

Aalto, J., P. Pirinen, and K. Jylhä, 2016: New gridded daily climatology of Finland: Permutation-based uncertainty estimates and temporal trends in climate, J. Geophys. Res. Atmos., 121, 3807-3823. doi:10.1002/2015JD024651

Aarnes, O. J., Ø. Breivik, and M. Reistad, 2012: Wave extremes in the northeast Atlantic. J. Climate, 25, 1529–1543, https://doi.org/10.1175/jcli-d-11-00132.1

Abild J, Nielsen B. Extreme values of wind speeds in Denmark. *Technical Report M-2842*, Risø National Laboratory, Roskilde, Denmark, 1991.

Abadie, LM., Galarraga I., Markandya, A. and Sainz de Murieta, E. (2019). Risk measures and the distribution of damage curves for 600 European coastal cities. Environ. Res. Lett. 14 064021.

Abadie, LM., Sainz de Murieta, E., Galarraga, I (2016). Climate Risk Assessment under Uncertainty: An Application to Main European Coastal Cities. Frontiers in Marine Science 3 (16 December 2016), https://doi.org/10.3389/fmars.2016.00265.

Alfieri, L., Burek, P., Feyen, L., and Forzieri, G. (2015) Global warming increases the frequency of river floods in Europe, Hydrol. Earth Syst. Sci., 19, 2247-2260.

Andersen, J.H., Carstensen, J., Conley, D.J., Dromph, K., Fleming-Lehtinen, V., Gustafsson, B.G., et al. (2017). Long-term temporal and spatial trends in eutrophication status of the Baltic Sea. *Biological Reviews* 92**,** 135-149. doi: 10.1111/brv.12221.

Andersson, T., and Nilsson, S., 1990: Topographically induced convective snowbands over the Baltic Sea and their precipitation distribution, Weather Forecast, 5, 299-312.

Apsīte E, Bakute A, Elferts D, Kurpniece L, Pallo I (2011) Climate change impacts on river runoff in Latvia. Clim Res 48:57-71.

Arheimer B. and Lindström G. (2015) Climate impact on floods: changes in high flows in Sweden in the past and the future (1911–2100). Hydrol. Earth Syst. Sci., 19, 771–784.

Åström D O, Tornevi A, Ebi KL, Rocklöv J, Forsberg B. 2016. Evolution of minimum mortality temperature in Stockholm, Sweden, 1901–2009. Environ Health Perspect 124:740–744; http://dx.doi.org/10.1289/ehp.1509692

BACC Author Team (2008). Assessment of Climate Change for the Baltic Sea Basin. Springer-Verlag Berlin Heidelberg, p. 474

BACC Author Team (2015). Second Assessment of Climate Change for the Baltic Sea Basin. Springer International Publishing, p. 501

Baker-Austin, C., Trinanes, J. A., Salmenlinna, S., Löfdahl, M., Siitonen, A., Taylor, N. G., & Martinez-Urtaza, J. (2016). Heat Wave-Associated Vibriosis, Sweden and Finland, 2014. Emerging infectious diseases, 22(7), 1216–1220. https://doi.org/10.3201/eid2207.151996

Barcikowska, MJ, Weaver SJ, Feser F, Russo S, Schenk F, Stone DA. et al. (2018) Euro-Atlantic winter storminess and precipitation extremes under 1.5°C vs. 2°C warming scenarios. Earth Syst Dyn 9:679–699, doi:10.5194/esd-9-679-2018

Barnes EA (2013) Revisiting the evidence linking Arctic amplification to extreme weather in midlatitudes. Geophys Res Lett 40:1–6. doi: 10.1002/grl.50880

Bastine D., Larsén X. G., Witha B., Dörenkämper M, Gottschall J. (2018): Extreme winds in the new European Wind atlas. In Journal of Physics: Conference Seris, Vol. 1102, No 1, 012006

Beldring S, Engen-Skaugen T, Forland EJ, Roald LA (2008) Climate change impacts on hydrological processes in Norway based on two methods for transferring regional climate model results to meteorological station sites. Tellus A 60:439-450.

Belusic D., Berg P., Bozhinova D., Bärring L., Döscher R., Eronn A., Kjellström E., Klehmet K., Martins H., Nilsson C. and Olsson J., Photiadou C., Segersson D. and Strandberg G. (2019), Climate Extremes For Sweden, DOI: https://doi.org/10.17200/Climate_Extremes_Sweden. SMHI, Editor: Döscher R.

Belušić, D., de Vries, H., Dobler, A., Landgren, O., Lind, P., Lindstedt, D., Pedersen, R.A., Sánchez-Perrino, J.C., Toivonen, E., van Ulft, B., Wang, F., Andrae, U., Batrak, Y., Kjellström, E., Lenderink, G., Nikulin, G., Pietikäinen, J.-P., Rodríguez-Camino, E., Samuelsson, P., van Meijgaard, E. and Wu, M., 2020. HCLIM38: A flexible regional climate model applicable for different climate zones from coarse to convection-permitting scales. Geosci. Model Dev., 13, 1311–1333, DOI: 10.5194/gmd-13-1311-2020

Benestad, R.E., 2003: How often can we expect a record event? Climate Research, 25(1), 3-13.

Benestad, R.E., 2006: Can we expect more extreme precipitation on the monthly time scale? Journal of Climate, 19(4), 630-637.

1520 Benestad RE, Hanssen-Bauer I, Førland EJ (2007) An evaluation of statistical models for downscaling
1521 precipitation and their ability to capture long-term trends. Int J Climatol 27:649-665

1522 Bengtsson, L., 2010. The global atmospheric water cycle, Environ. Res. Lett., 5, 025002,
1523 doi:10.1088/1748-9326/5/2/025002.

1524 Berezowski, T., Szczesniak, M., Kardel, I., Michałowski, R., Okruszko, T., Mezghani, A. and
1525 Piniewski, M., 2016. CPLFD-GDPT5: High-resolution gridded daily precipitation and temperature
1526 data set for two largest Polish river basins. Earth Syst. Sci. Data, 8, 127–139, DOI 10.5194/essd-8-
1527 127-2016.

1528 Berg, P., Norin, L. and Olsson, J., 2016. Creation of a high resolution precipitation data set by
1529 merging gridded gauge data and radar observations for Sweden. J. Hydrol., 541(A), 6-13, DOI
1530 10.1016/j.jhydrol.2015.11.031.

1531 Bergström H. and Söderberg S. (2008): Wind Mapping of Sweden, Elforsk report 09:04.

1532 Bergström, M., Erikstad. S. and Ehlers, S. 2017. The influence of model fidelity and uncertainties in
1533 the conceptual design of arctic maritime transport systems. Ship Technology Research Schiffstechnik
1534 pp. 40-64, Volume 64.

1535 Bevacqua, E., Maraun, D., Vousdoukas, M.I., Voukouvalas, E., Vrac, M., Mentaschi, L., and Widmann,
1536 M. (2019). Higher potential compound flood risk in Northern Europe under anthropogenic climate
1537 change. *Science Advances* 18, Sep 2019: Vol. 5, no. 9, eaaw5531DOI: 10.1126/sciadv.aaw5531

1538 Björkqvist, J.-V., Tuomi, L., Tollman, N., Kangas, K., Pettersson, H., Marjamaa, R., Jokinen, H. and
1539 Fortelius. C., 2017, Brief communication: Characteristic properties of extreme wave events observed in
1540 the northern Baltic Proper, Baltic Sea Nat. Hazards Earth Syst. Sci., 17, 1653–1658,
1541 https://doi.org/10.5194/nhess-17-1653-2017

1542 Björkqvist J.-V, Ingvar Lukas, Victor Alari, Gerbrant Ph. van Vledder, Sander Hulst, Heidi Pettersson,
1543 Arno Behrens, Aarne Männik, 2018, Comparing a 41-year model hindcast with decades of wave
1544 measurements from the Baltic Sea,Ocean Engineering,Volume 152, Pages 57-71, ISSN 0029-8018,
1545 https://doi.org/10.1016/j.oceaneng.2018.01.048.

1546 Blackport, R., and Screen, J.A. (2020). Insignificant effect of Arctic amplification on the amplitude of
1547 midlatitude atmospheric waves. *Science Advances*, *6*(8), eaay2880.

1548 Blessing S, Fraedrich K, Junge M, Kunz T, Linkheit F (2005) Daily North Atlantic Oscillation (NAO)
1549 index: statistics and its stratospheric polar vortex dependence. Meteorol Z 14:763–769

1550 Bogdanov V.I. and Malova T.I. 2009. On Assessments of the Height of the Largest Catastrophic
1551 Flood that Occurred in St. Petersburg in the Neva River Mouth on November 7 (19), 1824. Doklady
1552 Earth Sciences, 424(1), 123-126.

1553 Boland EJD, Bracegirdle J and Shuckburgh EF (2017) Assessment of sea ice-atmosphere links in
1554 CMIP5 models. Clim. Dyn. 49, 683–702. doi:10.1007/s00382-016-3367-1.

1555 Bondur, V. G. (2011) Satellite monitoring of wildfires during the anomalous heat wave of 2010 in
1556 Russia. Izv. Atmos. Ocean. Phys. 47, 1039–1048, https://doi.org/10.1134/S0001433811090040

1557 Bredesen, R. E., R. Cattin, N. Clausen, N. Davis, P. Jordaens, Z. Khadiri-Yazami, R. Klintström, A.
1558 Krenn, V. Lehtomäki, G. Ronsten, M. Wadham-Gagnon, H. Wickman (2017): Wind Energy Projects
1559 in Cold Climates, IEA Wind TCP Recommended Practice 13 2nd Edition: Wind Energy in Cold
1560 Climate.

1561 Broman, B., Hammarklint, T., Rannat, K., Soomere, T., Valdmann, A., 2006. Trends and extremes of
1562 wave fields in the north-eastern part of the Baltic Proper. Oceanologia 48 (S), 165–184.

1563 Brown, S., Nicholls, R. J., Goodwin, P., Haigh, I. D., Lincke, D., Vafeidis, A. T., & Hinkel, J. (2018).
1564 Quantifying Land and People Exposed to Sea-Level Rise with no Mitigation and 1.5∘C and 2.0∘C
1565 Rise in Global Temperatures to Year 2300. Earth's Future, 6, 583-600

1566 Brulebois, E., Castel, T., Richard, Y., Chateau-Smith, C., and Amiotte-Suchet, P. (2015).
1567 Hydrological response to an abrupt shift in surface air temperature over France in 1987/88. J Hydrol
1568 531:892–901, doi: 10.1016/j.jhydrol.2015.10.026

1569 Brunner L, Hegerl GC, Steiner AK (2017) Connecting Atmospheric Blocking to European
1570 Temperature Extremes in Spring. J Clim 30:585–594, doi: 10.1175/JCLI-D-16-0518.

1571 Budikova D (2009) Role of Arctic sea ice in global atmospheric circulation: A review. Global Plan
1572 Change 68:149–163

1573 Cattiaux, J., Vautard, R., Cassou, C., Yiou, P., Masson-Delmotte, V., and Codron, F. (2010), Winter
1574 2010 in Europe: A cold extreme in a warming climate, *Geophys. Res. Lett.*, 37, L20704,
1575 doi:10.1029/2010GL044613.

1576 Cahynová M, Huth R (2014) Atmospheric circulation influence on climatic trends in Europe: an
1577 analysis of circulation type classifications from the COST733 catalogue. Int J Climatol 36:2743–2760,
1578 doi: 10.1002/joc.4003.

1579 Cammalleri, C., Naumann, G., Mentaschi, L., Bisselink, B., Gelati, E., De Roo, A., and Feyen, L. (2020)
1580 Diverging hydrological drought traits over Europe with global warming, Hydrol. Earth Syst. Sci.
1581 Discuss., https://doi.org/10.5194/hess-2020-93.

1582 Cassou C (2008) Intraseasonal interaction between the Madden-Julian Oscillation and the North
1583 Atlantic Oscillation. Nature 455:523–527

1584 Cattiaux J and Cassou C (2013). Opposite CMIP3/CMIP5 trends in the wintertime Northern Annular
1585 Mode explained by combined local sea ice and remote tropical influences. Geophys Res Lett 40:3682–
1586 3687. doi:10.1002/grl.50643.

1587 Cavaleri, Luigi & Benetazzo, Alvise & Barbariol, Francesco & Bidlot, Jean & Janssen, Peter. (2017).
1588 The Draupner event: the large wave and the emerging view. Bulletin of the American Meteorological
1589 Society. 98. 729–735. 10.1175/BAMS-D-15-00300.1.

1590 Cecchinato M. (2019): Boosting offshore wind energy in the Baltic Sea. Editors Iván Puneda and
1591 Daniel Fraile, WindEurope Taskforce Baltic.

Chang EKM, Ma CG, Zheng C, Yau, AMW (2016a) Observed and projected decrease in Northern Hemisphere extratropical cyclone activity in summer and its impacts on maximum temperature. Geophys Res Lett 43:2200–2208, doi:10.1002/2016GL068172.

Chang EKM and Yau AMW (2016b) Northern Hemisphere winter storm track trends since 1959 derived from multiple reanalysis datasets. Clim Dyn 47:1435–1454. doi:10.1007/s00382-015-2911-8.

Christensen, O.B. and Kjellström, E., 2018. Projections for Temperature, Precipitation, Wind, and Snow in the Baltic Sea Region until 2100. In: von Storch, H., (ed.). Climate of the Baltic Sea region. Oxford Research Encyclopedia of Climate Science. DOI: 10.1093/acrefore/9780190228620.013.695.

Christiansen, B., Alvarez-Castro, C., Christidis, N., Ciavarella, A., Colfescu, I., Cowan, T., et al. (2018). Was the Cold European Winter of 2009/10 Modified by Anthropogenic Climate Change? An Attribution Study. J. Clim. 31, 3387–3410. doi:10.1175/JCLI-D-17-0589.1.

Ciasto LM, Li C, Wettstein JJ, Kvamstø, NG (2016) North Atlantic Storm-Track Sensitivity to Projected Sea Surface Temperature: Local versus Remote Influences. J Clim 29:6973–6991. doi:10.1175/JCLI-D-15-0860.1

Clausen, N-E., Larsén, X. G., Pryor S.C. and Drews M. (2012). Wind power. Chapter 7 in book: Climate Change and Energy System – Impacts, Risks and Adaption in the Nordic and Baltic countries, ISBN: 978-92-893-2190-7, Nordic Council of Ministers, Copenhagen 2012.

Cloern, J.E., Abreu, P.C., Carstensen, J., Chauvaud, L., Elmgren, R., Grall, J., et al. (2016). Human activities and climate variability drive fast-paced change across the world's estuarine-coastal ecosystems. *Global Change Biology* 22(2)**,** 513-529. doi: 10.1111/gcb.13059.

Coles, S., 2001: An Introduction to Statistical Modeling of Extreme Values. SpringerVerlag, Heidelberg, Germany, 208 pp.

Compo GP, Whitaker JS, Sardeshmukh PD, Matsui N, Allan RJ, Yin, X, Gleason BE, Vose RS, Rutledge G, Bessemoulin P, Brönnimann S, Brunet M, Crouthamel RI, Grant AN, Groisman PY, Jones PD, Kruk M, Kruger AC, Marshall GJ, Maugeri M, Mok HY, Nordli Ø, Ross TF, Trigo RM, Wang XL, Woodruff SD, Worley SJ (2011) The twentieth century reanalysis project. Q J Roy Met Soc 137:1–28

Cordeira, J.M. and N.F. Laird, 2008: The Influence of Ice Cover on Two Lake-Effect Snow Events over Lake Erie. *Mon. Wea. Rev.,* **136**, 2747–2763, https://doi.org/10.1175/2007MWR2310.1

Cornes, R. C., van der Schrier, G., van den Besselaar, E. J. M., & Jones, P. D. (2018). An ensemble version of the E-OBS temperature and precipitation data sets. Journal of Geophysical Research: Atmospheres, 123, 9391– 9409. https://doi.org/10.1029/2017JD028200

Coumou D, Lehmann J, Beckmann J (2015) The weakening summer circulation in the Northern Hemisphere mid-latitudes. Science 348:324–327, doi:10.1126/science.1261768

Cutululis, N. A., Litong-Palima, M., Sørensen, P. E., & Detlefsen, N. (2013). Offshore Variability in Critical Weather Conditions in Large-Scale Wind Based Danish Power System. In 2013 IEEE Power and Energy Society General Meeting: Shaping the Future Energy Industry IEEE.

1629 Dahlgren P, Landelius T, Kållberg P, Gollvik S (2016) A high-resolution regional reanalysis for
1630 Europe. Part 1: Three-dimensional reanalysis with the regional HIgh-Resolution Limited-Area Model
1631 (HIRLAM). Quarterly Journal of the Royal Meteorological Society, 142(698), 2119-2131

1632 Dangendorf S., Arns A., Pinto, J.G., Ludwig, P., and Jensen, J.: The exceptional influence of storm
1633 'Xaver' on design water levels in the German Bight, Environmental Research Letters, 11,
1634 doi:10.1088/1748-9326/11/5/054001, 2016.

1635 Davini P, Cagnazzo C (2014) On the misinterpretation of the North Atlantic Oscillation in CMIP5
1636 models. Clim Dyn 43:1497–1511. doi: 10.1007/s00382-013-1970-y.

1637 Davini P, d'Andrea F (2016) Northern Hemisphere Atmospheric Blocking Representation in Global
1638 ClimateModels: Twenty Years of Improvements? J Clim 29:8823–8840, doi:10.1175/JCLI-D-16-
1639 0242.1

1640 Danilovich I, Zhuravlev S, Kurochkina L and Groisman P (2019) The Past and Future Estimates of
1641 Climate and Streamflow Changes in the Western Dvina River Basin. Front. Earth Sci. 7:204. doi:
1642 10.3389/feart.2019.00204

1643 Déqué, M., Rowell, D. P., Lüthi, D., Giorgi, F., Christensen, J. H. and coauthors. 2007. An
1644 intercomparison of regional climate simulations for Europe: assessing uncertainties in model
1645 projections. Clim. Change 81(Suppl. 1), 53–70, doi:10007/s10584-006-9228-x.

1646 Danco, J. F., A. M. DeAngelis, B. K. Raney, and A. J. Broccoli, 2016: Effects of a Warming Climate
1647 on Daily Snowfall Events in the Northern Hemisphere. J. Climate, 29, 6295–6318,
1648 https://doi.org/10.1175/JCLI-D-15-0687.1.

1699 Dee DP, Uppala SM, Simmons AJ, Berrisford P, Poli P, Kobayashi S, Andrae U, Balmaseda MA,
1700 Balsamo G, Bauer P, Bechtold P, Beljaars ACM, van de Berg L, Bidlot J, Bormann N, Delsol C,
1701 Dragani R, Fuentes M, Geer AJ, Haimberger L, Healy SB, Hersbach H, Holm EV, Isaksen L,
1702 Kallberg P, Kohler M, Matricardi M, McNally AP, Monge-Sanz BM, Morcrette J-J, Park B-K, Peubey
1703 C, de Rosnay P, Tavolato C, Thepaut J-N, Vitart F. 2011. The ERA-Interim reanalysis: configuration
1704 and performance of the data assimilation system. Q. J. R. Meteorol. Soc. 137: 553–597.
1705 DOI:10.1002/qj.828

1782 Deser C, Hurrell JW and Phillips, AS (2017). The role of the North Atlantic Oscillation in European
1783 climate projections. Clim. Dyn. 49, 3141–3157. doi:10.1007/s00382-016-3502-z.

1784 Dethloff K, Rinke A, Benkel A, Køltzow M, Sokolova E, Kumar Saha S, Handorf D, Dorn W,
1785 Rockel B, von Storch H, Haugen JE, Røed LP, Roeckner E, Christensen JH and Stendel M (2006) A
1786 dynamical link between the Arctic and the global climate system. Geophys Res Lett 33, L03703 doi:
1787 10.1029/2005GL025245

1788 Diamond, K. E.: Extreme weather impacts on offshore wind turbines: Lessons learned, American Bar
1789 Association Section of Environment, Natural Resources and Environment, 27, 39–41, Fall 2012.

1790 Ditas, J., Ma, N., Zhang, Y., Assmann, D., Neumaier, M., Riede, H., Karu, E., Williams, J., Scharffe,
1791 D., Wang, Q., Saturno, J., Schwarz, J. P., Katich, J. M., McMeeking, G. R., Zahn, A., Hermann, M.,
1792 Brenninkmeijer, C. A. M., Andreae, M. O., Pöschl, U., Su, H., and Cheng, Y. (2018) Strong impacts

1793 of wildfires on the abundance and aging of black carbon in the lowermost stratosphere. Proceedings of
1794 the National Academy of Sciences of the United States of America, 115, E11595-E11603.

1795 Donat MG, Alexander LV, Herold N and Dittus AJ (2016) Temperature and precipitation extremes in
1796 century-long gridded observations, reanalyses, and atmospheric model simulations, J. Geophys. Res.
1797 Atmos., 121, 11,174– 11,189, doi:10.1002/2016JD025480.

1798 Dong B, Sutton RT, Shaffrey L (2017) Understanding the rapid summer warming and changes in
1799 temperature extremes since the mid-1990s over Western Europe. Clim Dyn 48:1537–1554, doi:
1800 10.1007/s00382-016-3158-8

1801 Donnelly C, Greuell W, Andersson J, Gerten D, Pisacane G, Roudier P and Ludwig F (2017) Impacts
1802 of climate change on European hydrology at 1.5, 2 and 3 degrees mean global warming above
1803 preindustrial level Clim. Change 143 13–26.

1804 Dosio, A. (2016), Projections of climate change indices of temperature and precipitation from an
1805 ensemble of bias-adjusted high-resolution EURO-CORDEX regional climate models, J. Geophys.
1806 Res. Atmos., 121, 5488–5511, doi:10.1002/2015JD024411.

1807 Douville H, Colin J, Krug E, Cattiaux J, Thao S (2016) Midlatitude daily summer temperatures
1808 reshaped by soil moisture under climate change. Geophys Res Lett 43:812–818, doi:
1809 10.1002/2015GL066222

1810 Douville H, Plazzotta M (2017) Midlatitude Summer Drying: An Underestimated Threat in CMIP5
1811 Models? Geophys Res Lett 44:9967–9975, doi: 10.1002/2017GL075353

1812 Dreier, N., Christian Schlamkow, Peter Fröhle, Dörte Salecker and Zhenshan Xu, 2015, Assessment
1813 of changes of extreme wave conditions at the German Baltic Sea coast in the basis of future climate
1814 change scenarios. J. Marine Science and Technology, Vol. 23, No. 6, pp. 839-845 (2015) 839, DOI:
1815 10.6119/JMST-015-0609-3

1816 Drobyshev, I., Granström, A., Linderholm, H. W., Hellberg, E., Bergeron, Y., and Niklasson, M.
1817 (2014) Multi-century reconstruction of fire activity in Northern European boreal forest suggests
1818 differences in regional fire regimes and their sensitivity to climate. Journal of Ecology 102: 738–748.

1819 Drobyshev, I., Bergeron, Y., de Vernal, A., Moberg, A., Ali, A. A., and Niklasson, M. (2016) Atlantic
1820 SSTs control regime shifts in forest fire activity of Northern Scandinavia. Scientific Reports 6: 22532,
1821 doi:10.1038/srep22532

1822 Dury, M., Hambuckers, A., Warnant, P., Henrot, A., Favre, E., Ouberdous, M., and François, L.
1823 (2011) Responses of European forest ecosystems to 21st century climate: Assessing changes in
1824 interannual variability and fire intensity. iForest 4: 82–99.

1825 EEA, 2010

1826 Esseen, P. A., Ehnström, B., Ericson, L., and Sjöberg, K. (1997) Boreal forests. Ecol. Bull. 46: 16–47.

1827 Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.:
1828 Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and
1829 organization, Geosci. Model Dev., 9, 1937-1958, doi:10.5194/gmd-9-1937-2016, 2016.

1830   EUMETSAT, 2017, Record waves in the Baltic Sea. Online. [2019-03-27],
1831   https://www.eumetsat.int/website/home/Images/ImageLibrary/DAT_3559396.html

1832   Feldstein SB (2002) The recent trend and variance increase of the annular mode. J Climate 15:88–94

1833   Feser F, Barcikowska M, Krueger O, Schenk F, Weisse R, Xia L (2015a) Storminess over the North
1834   Atlantic and Northwestern Europe – A Review. Q J Roy Met Soc. 141:350–382

1835   Feser F, Barcikowska M, Haeseler S, Lefebvre C, Schubert-Frisius M, Stendel M, von Storch H, Zahn
1836   M (2015b) Hurricane Gonzalo and its extratropical transition to a strong European storm. In:
1837   Explaining Extreme Events of 2014 from a Climate Perspective. Bull Amer Met Soc 96:S51–S55

1838   Feser, F., Krueger, O., Woth, K., & van Garderen, L. (2021): North Atlantic winter storm activity in
1839   modern reanalyses and pressure-based observations. J. Clim. doi: https://doi.org/10.1175/JCLI-D-20-
1840   0529.1

1841   Finni T, Kononen K, Olsonen R, Wallström K. The history of cyanobacterial blooms in the Baltic Sea.
1842   AMBIO. 2001;30:172–178.

1843   Fischer EM, Luterbacher J, Zorita E, Tett SFB, Casty C, Wanner H (2007) European climate response
1844   to tropical volcanic eruptions over the last half millennium. Geophys Res Lett 34:L05707 doi:
1845   10.1029/2006GL027992

1846   Fischer EM and Knutti R (2016) Observed heavy precipitation increase confirms theory and early
1847   models. Nature Clim Change 6, 986–991. https://doi.org/10.1038/nclimate3110

1848   Flannigan, M., Stocks, B., Turetsky, M., and Wotton, M. (2009) Impacts of climate change on fire
1849   activity and fire management in the circumboreal forest. Global Change Biology 15: 549–560.

1850   Forzieri, G., Feyen, L., Russo, S. et al. Multi-hazard assessment in Europe under climate change.
1851   (2016). Climatic Change 137, 105–119.

1852   Forzieri G., Feyen L., Rojas R., Flörke M., Wimmer F., and Bianchi F. (2014) Ensemble projections of
1853   future streamflow droughts in Europe. Hydrol. Earth Syst. Sci., 18, 85–108.

1854   Francis JA and Vavrus SJ (2012) Evidence linking Arctic Amplification to Extreme Weather.
1855   Geophys Res Lett 39:1–6. doi:10.1029/2012GL051000.

1856   Francis JA, Vavrus SJ (2015) Evidence for a wavier jet stream in response to rapid Arctic warming.
1857   Env. Res Lett 10:14005, doi: 10.1088/1748-9326/10/1/014005

1858   Frank H.P. (2001): Extreme winds over Denmark from the NCEP/NCAR reanalysis. *Technical Report
1859   Risoe-R-1238 (EN)*, Risø National Laboratory, Roskilde, Denmark.
1860   http://www.risoe.dk/rispubl/VEA/ris-r-1238.htm.

1861   Fredriksson C., Tajvidi N., Hanson H., Larson M. 2016. Statistical analysis of extreme sea water
1862   levels at the Falsterbo Peninsula, South Sweden. Vatten, 72, 129-142.

Freeman K., Frost C., Hundleby G., Roberts A., Valpy B., Holttinen H., Ramírez L. and Pineda I. (2019): Our energy, our future – how offshore wind will help Europe go carbon-neutral, Editor: Walsh C.

Frölicher TL, Fischer EM, Gruber N. Marine heatwaves under global warming. *Nature*. 2018;560(7718):360-364. doi:10.1038/s41586-018-0383-9

Frolova, N.L., Belyakova, P.A., Grigoriev, V.Y. *et al.* Runoff fluctuations in the Selenga River Basin. *Reg Environ Change* **17,** 1965–1976 (2017). https://doi.org/10.1007/s10113-017-1199-0

Gastineau G and Frankignoul C (2015) Influence of the North Atlantic SST variability on the atmospheric circulation during the twentieth century, J Climate 28:1396–1416 doi: 10.1175/JCLI-D-14-00424.1

Gayer, G., Gunther, H., and Winkel, N.: Wave climatology and extreme value analysis for the Baltic Sea area off the Warnemunde harbour entrance, Deutsche Hydrographische Zeitschrift, 47, 109–130, 1995.

Gillett NP, Arora VK, Matthews D and Allen MR (2013). Constraining the Ratio of Global Warming to Cumulative CO2 Emissions Using CMIP5 Simulations. J. Clim. 26, 6844–6858. doi:10.1175/JCLI-D-12-00476.1.

Gobler, C.J., Doherty, O.M., Hattenrath-Lehmann, T.K., Griffith, A.W., Kang, Y., and Litaker, R.W. (2017). Ocean warming since 1982 has expanded the niche of toxic algal blooms in the North Atlantic and North Pacific oceans. *Proceedings of the National Academy of Sciences of the United States of America* 114(19)**,** 4975-4980. doi: 10.1073/pnas.1619575114.

Gong H, Wang L, Chen W, Chen X and Nath D (2017) Biases of the wintertime Arctic Oscillation in CMIP5 models. Environ Res Lett 12:14001. doi: 10.1088/1748-9326/12/1/014001.

Görger et al., 2021. Coupled modelling. ESD.

Granström, A. (1993) Spatial and temporal variation in lightning ignitions in Sweden. Journal of Vegetation Science 4: 737–744.

Grinsted et al. (2015). Sea level rise projections for northern Europe under RCP8.5. Clim Res 64, 15-23.

Grise, KM, Polvani LM (2014) The response of midlatitude jets to increased CO2: Distinguishing the roles of sea surface temperature and direct radiative forcing. Geophys. Res. Lett. 41, 6863–6871, doi:10.1002/2014GL061638

Gregow, H., Rantanen, M., Laurila, T.K., Mäkelä, A. (2020) Review on winds, extratropical cyclones and their impacts in Northern Europe and Finland. Reports 2020:3, Finnish Meteorological Institute, http://hdl.handle.net/10138/320298

Groll, N., Iris Grabemann, Birgit Hünicke and Michael Meese, 2017, Baltic Sea wave conditions under climate change scenarios, BOREAL ENVIRONMENT RESEARCH 22: 1–12

1898   Groetsch, P.M.M., Simis, S.G.H., Eleveld, M.A., and Peters, S.W.M. (2016). Spring Blooms in the
1899   Baltic Sea have weakened but lengthened from 2000 to 2014. *Biogeosciences Discussions* 01/2016.
1900   doi: 10.5194/bg-2015-636.

1901   Groenemeijer P., Vajda A., Lehtonen I., Kämäräinen M., Venäläinen R., Gregow H., Púcik T. (2016).
1902   Present and future probability of meteorological and hydrological hazards in Europe. D2.5 Report,
1903   RAIN Project. Retrieved from http://rain-project.eu/wp-content/uploads/2016/09/D2.5_
1904   REPORT_final.pdf

1905   Gudmundsson L., Seneviratne S.I., Zhang X,   (2017) Anthropogenic Climate Change Detected in
1906   European Renewable Freshwater Resources, Nature Climate Change 7, no. 11: 813–16,
1907   https://doi.org/10.1038/nclimate3416;

1908   Gustafsson, N., Nyberg, L. and Omstedt, A. 1998. Coupling of a high-resolution atmospheric model
1909   and an ocean model for the Baltic Sea. Mon. Weather Rev. 126, 28222846.

1910   Haarsma RJ, Selten FM, Drijfhout SS (2015) Decelerating Atlantic meridional overturning circulation
1911   main cause of future west European summer atmospheric circulation changes. Environ Res Lett
1912   10:094007, doi: 10.1088/1748-9326/10/9/094007

1913   Hakanen, P., Suikkanen, S., Franzén, J., Franzén, H., Kankaanpää, H., Kremp, A**.** (2012). Bloom and
1914   toxin dynamics of *Alexandrium ostenfeldii* in a shallow embayment at the SW coast of Finland,
1915   northern Baltic Sea. Harmful Algae 15: 91-99.

1916   Hänninen, S. 2018. Talvimerenkulun onnettomuudet 2011–2018. (Trafin tutkimuksia; No. 12).
1917   Helsinki. https://arkisto.trafi.fi/filebank/a/1545233991/7a154fa85f1f4078a1b0ca2fb06906aa/33305-
1918   Trafi_12_2018_Talvimerenkulun_onnettomuudet_2011-2018.pdf

1919   Hansom J.D., Switzer A.D., Pile, J. (2015) Chapter 11 - Extreme Waves: Causes, Characteristics, and
1920   Impact on Coastal Environments and Society, Editor(s): John F. Shroder, Jean T. Ellis, Douglas J.
1921   Sherman,   Coastal   and   Marine   Hazards,   Risks,   and   Disasters,   Elsevier,   307-334,
1922   https://doi.org/10.1016/B978-0-12-396483-0.00011-X

1923   Hausfather, Z. and G. P. Peters. Emissions – the 'business as usual' story is misleading , *Nature* 577,
1924   618-620 (2020), *doi: 10.1038/d41586-020-00177-3*

1925   Heinonen J., Rissanen S., Kurkela J., Tikanmäki M. and Jussila V. (2019) Ice load portal for
1926   preliminary design of offshore wind turbines in the Gulf of Bothnia – case studies. WindEurope
1927   Offshore 2019, 26-28, Nov., Copenhagen.

1928   HELCOM (2007). HELCOM Baltic Sea Action Plan. doi:
1929   http://www.helcom.fi/Documents/Baltic%20sea%20action%20plan/BSAP_Final.pdf.

1930   HELCOM (2018). State of the Baltic Sea - Second HELCOM holistic assessment 2011-2016. *Baltic
1931   Sea Environment Proceedings* 155.

1932   Hersbach H, Bell B, Berrisford P, et al. (2020). The ERA5 global reanalysis. Quartely Journal of the
1933   Royal Meteorological Society,146, 1999–2049. https://doi.org/10.1002/qj.3803

1934 Hjelmfelt, M. R., 1990: Numerical Study of the Influence of Environmental Conditions on Lake-
1935 Effect Snowstorms over Lake Michigan. *Mon. Wea. Rev.*, **118**, 138–150.

1936 Hoerling MP, Hurrell JW, Xu T (2001) Tropical origins for recent North Atlantic climate change.
1937 Science 292:90–92

1938 Hofherr, T. and Kunz, M.: Extreme wind climatology of winter storms in Germany, Clim. Res. 41,
1939 105–123, 2010.

1940 Höglund A., P. Pemberton, R. Hordoir, and S. Schimanke, Ice conditions for maritime traffic in the
1941 Baltic Sea in future climate. Boreal Environment Research vol 22, pp 245-265, 2017

1942 Holthuijsen, L.H., 2007. Waves in Oceanic and Coastal Waters. Cambridge University Press, New
1943 York, United States of America.

1944 Horton DE, Johnson NC, Singh D, Swain DL, Rajaratnam B, Diffenbaugh NS (2015) Contribution of
1945 changes in atmospheric circulation patterns to extreme temperature trends. Nature 522:465–469, doi:
1946 10.1038/nature14550

1947 Humborg C, Geibel MC, Sun X, McCrackin M, Mörth C-M, Stranne C, Jakobsson M, Gustafsson B,
1948 Sokolov A, Norkko A and Norkko J (2019). High Emissions of Carbon Dioxide and Methane From
1949 the Coastal Baltic Sea at the End of a Summer Heat Wave. *Front. Mar. Sci.* 6:493. doi:
1950 10.3389/fmars.2019.00493

1951 Hurrell JW (1995) Decadal trends in the North Atlantic Oscillation, regional temperatures and
1952 precipitation. Science 269:676–679

1953 Hurrell JW, Kushnir Y, Ottersen G, Visbeck M (2003) An overview of the North Atlantic Oscillation.
1954 In: The North Atlantic Oscillation: Climatic significance and environmental impact. Geoph Monog
1955 Series 134:1–36

1956 Hurrell J (2018) Hurrell North Atlantic Oscillation (NAO) Index (station-based),
1957 https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-
1958 based.

1959 Hynčica M and Huth R (2019) Long-term changes in precipitation phase in Europe in cold half year.
1960 Atmospheric Research, 227, 79-88.

1961 IPCC *"Representative Concentration Pathways (RCPs)"*. IPCC. *Retrieved 13 February 2019*.

1962 IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to
1963 the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin,
1964 G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)].
1965 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp

1966 IPCC, 2018: Global warming of 1.5°C. An IPCC Special Report on the impacts of global
1967 warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission
1968 pathways, in the context of strengthening the global response to the threat of climate change,
1969 sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O.
1970 Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S.

1971   Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T.
1972   Waterfield (eds.)].

1973   IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to
1974   the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team,
1975   R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

1976   Ineson S, Scaife AA, Knight JR, Manners JC, Dunstone NJ, Gray LJ, Haigh JD (2011) Solar forcing
1977   of winter climate variability in the northern hemisphere. Nature Geosci 4:753–757

1978   Irannezhad, M., Chen, D. and Kløve, B. (2015), Interannual variations and trends in surface air
1979   temperature in Finland in relation to atmospheric circulation patterns, 1961–2011. Int. J. Climatol., 35:
1980   3078-3092. doi:10.1002/joc.4193

1981   Jaagus, J., Briede, A., Rimkus, E. et al. Variability and trends in daily minimum and maximum
1982   temperatures and in the diurnal temperature range in Lithuania, Latvia and Estonia in 1951–2010.
1983   Theor Appl Climatol 118, 57–68 (2014). https://doi.org/10.1007/s00704-013-1041-7

1984   Jaagus, J., Briede, A., Rimkus, E. *et al.* Changes in precipitation regime in the Baltic countries in
1985   1966–2015. *Theor Appl Climatol* 131, 433–443 (2018). https://doi.org/10.1007/s00704-016-1990-8

1986   Jaagus J, Sepp M, Tamm T, Järvet A, Mõisja K. Trends and regime shifts in climatic conditions and
1987   river runoff in Estonia during 1951–2015. Earth Syst Dyn. 2017; 8: 963–976.
1988   https://doi.org/10.5194/esd-8-963-2017

1989   Jacob, D., Petersen, J., Eggert, B. et al. EURO-CORDEX: new high-resolution climate change
1990   projections for European impact research. Reg Environ Change 14, 563–578 (2014).
1991   https://doi.org/10.1007/s10113-013-0499-2

1992   Jalkanen J-P, Brink A, Kalli J, Pettersson H, Kukkonen J, Stipa T. A modelling system for the exhaust
1993   emissions of marine traffic and its application in the Baltic Sea area. Atmospheric Chemistry and
1994   Physics. 2009;9:9209–9223. doi: 10.5194/acp-9-9209-2009.

1995   Janssen, P. & J. E. M. Janssen, A. (2019). Asymptotics for the long-time evolution of kurtosis of
1996   narrow-band ocean waves. Journal of Fluid Mechanics. 859. 790-818. 10.1017/jfm.2018.844.

1997   Jensen J. and Müller-Navarra S. 2008. Storm Surges on the German Coast. Die Küste, 74, 92-124.

1998   Jeppesen E, Kronvang B, Meerhoff M, Søndergaard M, Hansen KM, Andersen HE, Lauridsen TL,
1999   Beklioglu M, Özen A, Olesen JE, 2009. Climate change effects on runoff, catch ment phosphorus
2000   loading and lake ecological state, and potential adaptations. J. Envir. Qual. 38:1930-1941.

2001   Jeworrek, J., Wu, L., Dieterich, C., and Rutgersson, A., 2017: Characteristics of convective snow
2002   bands along the Swedish east coast, Earth Syst. Dynam., 8, 163-175, doi:https://doi.org/10.5194/esd-
2003   8-163-2017 .

2004   Johansson B. and Chen, D., 2005. Estimation of areal precipitation for runoff modelling using wind
2005   data: a case study in Sweden, Clim. Res., 29, 53-61.

2006 Jönsson, A., Broman, B., and Rahm, L., 2003, Variations in the Baltic Sea wave fields, Ocean Eng.,
2007 30, 107–126, https://doi.org/10.1016/S0029-8018(01)00103-2.

2008 Joshi MM, Charlton AJ, Scaife AA (2006) On the influence of stratospheric water vapor changes on
2009 the tropospheric circulation. Geophys Res Lett 33:L09806. doi: 10.1029/2006GL025983

2010 Juga, I., M. Hippi, P. Nurmi, and V. Karsisto, 2014. Weather factors triggering the massive car
2011 crashes on 3 February 2012 in the Helsinki metropolitan area. In proceedings of SIRWEC 17th
2012 International Road Weather Conference, Andorra, 30 January – 1 February 2014. Available from:
2013 http://sirwec.org/wp-content/uploads/Papers/2014-Andorra/D-21.pdf

2014 Kahma, K.K., Pettersson, H., Tuomi, L., 2003. Scatter diagram wave statistics from the northern
2015 Baltic Sea. MERI – Rep. Ser. Fin. Inst. Mar. Res. 49, 15–32.

2016 Kahru, M., Elmgren, R., and Savchuk, O.P. (2016). Changing seasonality of the Baltic Sea.
2017 *Biogeosciences* 13, 1009-1018. doi: 10.5194/bg-13-1009-2016.

2018 Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G,
2019 Woollen J, Zhu Y, Leetmaa A, Reynolds R, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo
2020 KC, Ropelewski C, Wang J, Jenne R, Joseph D (1996) The NCEP/NCAR 40-Year Reanalysis Project.
2021 Bull Am Met Soc 77:437–471

2022 Kamesaki, K., Kishi, S., Yamauchi, Y., 1999. Simulation of NSR shipping based on year-round and
2023 seasonal operation scenarios. INSROP Working Paper 164-1999. INSROP.

2024 Karlberg M. & Wulff A. 2013. Impact of temperature and species interaction on filamentous
2025 cyanobacteria may be more important than salinity and increased pCO_2 levels. Mar. Biol. 160: 2063-
2026 2072.

2027 Kaspar et al., Regional atmospheric reanalysis activities at Deutscher Wetterdienst: review of
2028 evaluation results and application examples with a focus on renewable energy. Adv. Sci. Res., 17,
2029 115–128, 2020

2030 Kasvi E., Lotsar, E., Kumpumäki., Dubrovin T., Veijalainen, N. (2019). Effects of Climate Change and
2031 Flow Regulation on the Flow Characteristics of a Low-Relief River within Southern Boreal Climate
2032 Area. Water. 11. 1827. 10.3390/w11091827.

2033 Kellomäki, S., Peltola, H., Nuutinen, T., Korhonen, K. T., and Strandman, H. (2008) Sensitivity of
2034 managed boreal forests in Finland to climate change, with implications for adaptive management.
2035 Philos. T. Roy. Soc. B 363: 2341–2351.

2036 Kendon, E. J., Roberts, N. M., Senior, C. A. and Roberts, M. J. ,2012. Realism of rainfall in a very
2037 high resolution regional climate model, J. Clim., 25, 5791-5806.

2038 Keskinen, A. 2012: Lumilogistiikan tehostaminen kaupungeissa (Enhanced snow removal logistics in
2039 suburban areas). Master thesis of Science in Technology, Aalto University, Espoo, Finland (In Finnish,
2040 abstract in English), http://urn.fi/URN:NBN:fi:aalto-2012112434012.

2041 Kettle, A.J.: The North Sea surge of 31 October–1 November 2006 during Storm Britta, Advances in
2042 Geosciences, 45, 273–279, https://doi.org/10.5194/adgeo-45-273-2018, 2018.

2043 Kettle, A.J.: Storm Tilo over Europe in November 2007: storm surge and impacts on societal and energy
2044 infrastructure, Advances in Geosciences, 499, 187–196, https://doi.org/10.5194/adgeo-49-187-2019,
2045 2019.

2046 Kilpeläinen, A., Kellomäki, S., Strandman, H., and Venäläinen, A. (2010) Climate change impacts on
2047 forest fire potential in boreal conditions in Finland. Climatic Change 103: 383–398.

2048 Kim BM, Son SW, Min SK, Jeong JH, Kim SJ, Zhang X, Taehyoun S and Yoon J-H (2014)
2049 Weakening of the stratospheric polar vortex by Arctic sea-ice loss. Nat. Commun. 5, 1–8.
2050 doi:10.1038/ncomms5646.

2051 Kim, S., Sinclair, V.A., Räisänen, J. and Ruuhela, R. (2018), Heat waves in Finland: present and
2052 projected summertime extreme temperatures and their associated circulation patterns. Int. J. Climatol,
2053 38: 1393-1408. doi:10.1002/joc.5253

2054 Kistler R, Collins W, Saha S, White G, Woollen J, Kalnay E, Chelliah M, Ebisuzaki W, Kanamitsu M,
2055 Kousky V, van den Dool H, Jenne R, Fiorino M (2001) The NCEP-NCAR 50-Year Reanalysis:
2056 Monthly Means CD-ROM and Documentation. Bull Am Met Soc 82:247–267

2057 Kjellström, E., Thejll, P., Rummukainen, M., Christensen, J.H., Boberg, F., Christensen, O.B., Fox
2058 Maule, C., 2013. Emerging regional climate change signals for Europe under varying large-scale
2059 circulation conditions, Clim. Res. 56, 103–119, DOI: 10.3354/cr01146.

2060 Klais, R., Tamminen, T., Kremp, A., Spilling, K., and Olli, K. (2011). Decadal-scale changes of
2061 dinoflagellates and diatoms in the anomalous Baltic Sea spring bloom. *PLoS ONE* 6(6)**,** e21567. doi:
2062 10.1371/journal.pone.0021567.

2063 Kollanus V, Lanki T. 2000-luvun pitkittyneiden helleaaltojen kuolleisuusvaikutukset Suomessa
2064 [Mortality effects of prolonged heat waves in the 2000s in Finland]. Duodecim. 2014;130(10):983-90.
2065 Finnish. PMID: 24961059.

2066 Konovalov, I. B., Beekmann, M., Kuznetsova, I. N., Yurova, A., and Zvyagintsev, A. M. (2011)
2067 Atmospheric impacts of the 2010 Russian wildfires: integratingmodelling and measurements of an
2068 extreme air pollution episode inthe Moscow region. Atmos. Chem. Phys., 11, 10031–10056,
2069 doi:10.5194/acp-11-10031-2011

2070 Kownacka, J., Busch, S., Göbel, J., Gromisz, S., Hällfors, H., Höglander, H., Huseby, S.,
2071 Jaanus, A., Jakobsen, H.H., Johansen, M., Johansson, M., Jurgensone, I., Liebeke, N.,
2072 Kraśniewski, W., Kremp, A., Lehtinen, S., Olenina, I., v.Weber, M., Wasmund, N., 2020:
2073 Cyanobacteria biomass, 1990-2019. HELCOM Baltic Sea Environment Fact Sheet [Online],
2074 https://helcom.fi/wp-content/uploads/2020/09/BSEFS-Cyanobacteria-biomass-1990-2019-
2075 1.pdf

2076 Kriaučiūnienė J, Meilutyte-Barauskiene D, Rimkus E, Kazys J, Vincevicius A (2008) Climate change
2077 impact on hydrological processes in Lithuanian Nemunas river basin. BALTICA 21:51-61.

2078 Kucharski F, Molteni F, Bracco A (2006) Decadal interactions between the western tropical Pacific
2079 and the North Atlantic Oscillation. Clim Dyn 26:79–91

2080 Kudryavtseva N. and Tarmo Soomere, 2017, Satellite altimetry reveals spatial patterns of variations in
2081 the Baltic Sea wave climate, Earth Syst. Dynam., 8, 697–706, 2017, https://doi.org/10.5194/esd-8-
2082 697-2017

2083 Kudryavtseva, N.; Räämet, A., and Soomere, T., 2020. Coastal flooding: Joint probability of extreme
2084 water levels and waves along the Baltic Sea coast. *In:* Malvárez, G. and Navas, F. (eds.), *Global
2085 Coastal Issues of 2020. Journal of Coastal Research*, Special Issue No. 95, pp. 1146–1151.

2086 Kujala, P. 1991. Damage statistics of ice-strengthened ships in the Baltic Sea 1984-1987. Winter
2087 Navigation Research Board. Report. No. 50. 61 p. + app. 5 p.

2088 Kujala, 2017.Ice load on ship hull. In Encyclopedia of Maritime and Offshore Engineering, online ©
2089 2017 John Wiley & Sons, Ltd. This article is © 2017 John Wiley & Sons, Ltd. DOI:
2090 10.1002/9781118476406.emoe021. Also published in the Encyclopedia of Maritime and Offshore
2091 Engineering (print edition) ISBN: 978-1-118-47635-2

2092 Kunz, M., Mohr, S., Rauthe, M., Lux, R., and Kottmeier, Ch.: Assessment of extreme wind speeds
2093 from Regional Climate Models – Part 1: Estimation of return values and their evaluation, Nat. Hazards
2094 Earth Syst. Sci., 10, 907–922, https://doi.org/10.5194/nhess-10-907-2010, 2010.

2095 Kuuliala, L., Kujala, P., Suominen, M. and Montewka, J. 2017. Estimating operability of ships in
2096 ridged ice fields. Cold Regions Science and Technology.Volume 135, March 2017, Pages 51–61

2097 Laird, N., R. Sobash, and N. Hodas, 2009: The Frequency and Characteristics of Lake-Effect
2098 Precipitation Events Associated with the New York State Finger Lakes. *J. Appl. Meteor.
2099 Climatol.,* **48**, 873–886, https://doi.org/10.1175/2008JAMC2054.1

2100 Laapas, M. and Venäläinen, A. (2017), Homogenization and trend analysis of monthly mean and
2101 maximum wind speed time series in Finland, 1959–2015. Int. J. Climatol, 37: 4803-4813.
2102 doi:10.1002/joc.5124

2103 Larjavaara, M., Pennanen, J., and Tuomi, T. (2005a) Lightning that ignites forest fires in Finland.
2104 Agricultural and Forest Meteorology 132: 171–180.

2105 Larjavaara, M., Kuuluvainen, T., and Rita, H. (2005b) Spatial distribution of lightning-ignited forest
2106 fires in Finland. Forest Ecology and Management 208: 177–188.

2107 Larsén X. and Mann J. (2009): Extreme winds from the NCEP/NCAR reanalysis data. Wind Energy.
2108 DOI:10.1002/we.318.

2109 Larsén X. and Badger J. (2012): Calculation of extreme wind atlases using mesoscale modeling, Final
2110 project report DTU Wind Energy. DTU Wind Energy E, No. 0125, ISBN 978-87-93278-87-5

2111 Larsén X., Larsen S. and Hahmann N. A. 2012: Origin of the waves in "A case study of mesoscale
2112 spectra of wind and temperature, observed and simulated": Lee waves of the Norwegian mountains,
2113 *Q. J. R. Meteorol. Soc.* **137** DOI:10.1002/qj.916, 138: 274-279.

2114 Larsén X., Du. J., Bolanos R., Imberger M., Kelly M., Badger M. and Larsen S. (2019a): Estimation
2115 of offshore extreme wind from wind-wave coupled modeling. Wind Energy. Vol. 22, Issue 8,
2116 DOI:10.1002/we.2339.

2117 Larsén X., Larsen S., Petersen E. and Mikkelsen T. (2019b): Turbulence Characteristics of Wind-
2118 Speed Fluctuations in the Presence of Open Cells: A Case Study. Boundary-Layer Meteorology
2119 Volume 171, Issue 2, pp 191–212, https://doi.org/10.1007/s10546-019-00425-8.

2120 Larsén, X., Christina Kalogeri, George Galanis, George Kallos, 2015, A statistical methodology for
2121 the estimation of extreme wave conditions for offshore renewable applications, Renewable Energy,
2122 80, 205-218, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2015.01.069.

2123 Larsén X., Ott S., Badger J., Hahmann A. and Mann J. (2012): Recipes for Correcting the Impact of
2124 Effective Mesoscale Resolution on the Estimation of Extreme Winds, JOURNAL OF APPLIED
2125 METEOROLOGY AND CLIMATOLOGY, vol 51, 521 – 533.

2126 Laurila, T.K., V.A. Sinclair, and H. Gregow, 2019: The Extratropical Transition of Hurricane Debby
2127 (1982) and the Subsequent Development of an Intense Windstorm over Finland. Mon. Wea. Rev.,
2128 https://doi.org/10.1175/MWR-D-19-0035.1

2129 Laurila, T.K., V.A. Sinclair, and H. Gregow, 2021: Climatology, variability and trends in near-surface
2130 wind speeds over the North Atlantic and Europe during 1979–2018 based on ERA5. International
2131 Journal of Climatology, https://doi.org/10.1002/joc.6957

2132 Leckebusch, G., C., U. Ulbrich, On the relationship between cyclones and extreme windstorm events
2133 over Europe under climate change, Global and Planetary Change, Volume 44, Issues 1–4, 2004, 181-
2134 193, https://doi.org/10.1016/j.gloplacha.2004.06.011.

2135 Lehmann A, Getzlaff K, Harlaß J (2011) Detailed assessment of climate variability in the Baltic Sea
2136 area for the period 1958 to 2009. Clim Res 46:185–196

2137 Lehman et al., 2021. Salinity Dynamics, ESD.

2138 Lehtonen, I., Ruosteenoja, K., and Jylhä, K. (2014a) Projected changes in European extreme
2139 precipitation indices on the basis of global and regional climate model ensembles. International
2140 Journal of Climatology 34: 1208–1222.

2141 Lehtonen, I., Ruosteenoja, K., Venäläinen, A., and Gregow, H. (2014b) The projected 21st century
2142 forest-fire risk in Finland under different greenhouse gas scenarios. Boreal Environment Research 19:
2143 127–139.

2144 Lehtonen, I., Venäläinen, A., Kämäräinen, M., Peltola, H., and Gregow, H. (2016) Risk of large-scale
2145 fires in boreal forests on Finland under changing climate. Nat. Hazards Earth Syst. Sci. 16: 239–253.

2146 Leiding, T., Tinz, B., Rosenhagen, G., Lefevre, C., Haeseler, S., Hagemann, S., Bastigkeit, I., Stein,
2147 D., Schwenk, P., Mueller, S., Outzen, O., Herklotz, K., Kinder, F., and Neumann, T.: Meteorological
2148 and Oceanographic Conditions at the FINO platforms during the severe storms Christian and Xaver,
2149 DEWI Magazin, No. 44, 16–25, 2014.

2150 Lenggenhager S, Croci-Maspoli M, Brönnimann S, Martius O (2018) On the dynamical coupling
2151 between atmospheric blocks and heavy precipitation events: A discussion of the southern Alpine flood
2152 in October 2000. QJR Meteorol Soc, doi:10.1002/qj.3449

2153 Lenderink, G., Belušić, D., Fowler, H., Kjellström, E., Lind, P., van Meijgaard, E., van Ulft, B. and de
2154 Vries, H., 2019. Systematic increases in the thermodynamic response of hourly precipitation extremes
2155 in an idealized warming experiment with a convection-permitting climate model. Environ. Res. Lett.
2156 14, 074012, DOI: 10.1088/1748-9326/ab214a.

2157 Lensu, M., Suominen, M., Haapala, J., Külaots, R. and B. Elder, 2013a. Measurements of pack ice
2158 stresses in the Baltic, Proc. of The International Conferences of Port and Ocean Engineering under
2159 Arctic Conditions, (POAC'13), 2013. http://www.poac.com/Papers/2013/pdf/POAC13_209.pdf

2160 Lensu, M., Haapala, J., Lehtiranta, J., Eriksson, P., Kujala, P., Suominen, M., Mård, A., Vedenpää, L.,
2161 Kõuts, T. and Lilover, M.-J. 2013b. Forecasting of compressive ice conditions. Proceedings of the
2162 International Conference on Port and Ocean Engineering under Arctic Conditions, (POAC'13), 2013.
2163 http://www.poac.com/Papers/2013/pdf/POAC13_208.pdf

2164 Leppäranta, M. and Myrberg, K. 2009. Physical Oceanography of the Baltic Sea. Springer-Verlag,
2165 Berlin-Heidelberg-New York, 378 s.

2166 *Leppäranta*, M. 2011. The *drift* of *sea ice*. (2nd ed.) (Springer Praxis Books). Heidelberg: Springer-
2167 Verlag. https://doi.org/10.1007/978-3-642-04683-4.

2168 Lind, P., Belušić, D., Christensen, O.B., Dobler, A., Kjellström, E., Landgren, O., Lindstedt, D., Matte,
2169 D., Pedersen, R.A., Toivonen, E., Wang, F., 2020. Benefits and added value of convection-permitting
2170 climate modeling over Fenno-Scandinavia. Clim. Dyn. DOI: 10.1007/s00382-020-05359-3.

2171 Lindeberg, M. Kujala, P. Toivola, J. Niemelä, H.,2015. Real-time winter traffic simulation tool –
2172 based on a deterministic model. Scientific Journals of the Maritime University of Szczecin. 2015, 42
2173 (114), 118–124. ISSN 2392-0378 (Online)

2174 Lindenberg J, Mengelkamp HT, Rosenhagen G (2012) Representativity of near surface wind
2175 measurements from coastal stations at the German Bight. Meteorol Z 21:99–106

2176 Lindberg, M., Kujala, P., Karjalainen M., Toivola, J., 2018. Simulation model of the Finnish winter
2177 navigation system. IMDC2018, June 10-14, Espoo.

2178 Liu, X., He, B., Guo, L., Huang, L., & Chen, D., 2020: Similarities and differences in the mechanisms
2179 causing the European summer heatwaves in 2003, 2010, and 2018. Earth's Future, 8, e2019EF001386.
2180 https://doi.org/10.1029/2019EF001386

2181 Łotocka, M. (2006). The first observed bloom of the diatom Dactyliosolen fragilissimus (Bergon)
2182 Hasle 1996 in the Gulf of Gdansk. *Oceanologia* 48**,** 447-452.

2183 Luomaranta, A., Aalto, J. and Jylhä, K., 2019: Snow cover trends in Finland over 1961-2014 based on
2184 gridded snow depth observations. Int J Climatol., 7, 3147-3159. https://doi.org/10.1002/joc.6007

2185 Luomaranta, A., Ruosteenoja, K., Jylhä, K., Gregow, H., Haapala, J. and Laaksonen, A., 2014:
2186 Multimodel estimates of the changes in the Baltic Sea ice cover during the present century, Tellus A:
2187 Dynamic Meteorology and Oceanography, 66:1, DOI: 10.3402/tellusa.v66.22617

2188 Lyons, E. A., Jin, Y., and Randerson, J. T. (2008) Changes in surface albedo after fire in boreal forest
2189 ecosystems of interior Alaska assessed using MODIS satellite observations. Journal of Geophysical
2190 Research 113: G02012.

2191 Mäkelä, H. M., Venäläinen, A., Jylhä, K., Lehtonen, I., and Gregow, H. (2014) Probabilistic
2192 projections of climatological forest fire danger in Finland. Climate Research 60: 73–85.

2193 Manning, C., Widmann, M., Bevacqua, E., Van Loon, A. F., Maraun, D., and Vrac, M. (2019)
2194 Increased probability of compound long-duration dry and hot events in Europe during summer (1950–
2195 2013). Environmental Research Letters 14: 094006.

2196 Marcos, M., and Woodworth, P. L. (2017). Spatiotemporal changes in extreme sea levels along the
2197 coasts of the North Atlantic and the Gulf of Mexico, J. Geophys. Res. Oceans, 122, 7031–7048,
2198 doi:10.1002/2017JC013065.

2199 Marshall AG, Scaife AA (2009) Impact of the QBO on surface winter climate. J Geophys Res
2200 114:D18110. doi: 10.1029/2009JD011737

2201 Marshall J, Johnson H, Goodman J (2001) A study of the interaction of the North Atlantic Oscillation
2202 with the ocean circulation. J Climate 14:1399–1421

2203 Marshall, G.J., Jylhä, K., Kivinen, S. et al. The role of atmospheric circulation patterns in driving
2204 recent changes in indices of extreme seasonal precipitation across Arctic Fennoscandia. Climatic
2205 Change (2020). https://doi.org/10.1007/s10584-020-02747-w

2206 Martel J, Mailhot A, and Brissette F (2020) Global and Regional Projected Changes in 100-yr
2207 Subdaily, Daily, and Multiday Precipitation Extremes Estimated from Three Large Ensembles of
2208 Climate Simulations. J Climate 33: 1089–1103 https://doi.org/10.1175/JCLI-D-18-0764.1.

2209 Matthews T, Murphy C, Wilby RL and Harrigan S (2016). A cyclone climatology of the British-Irish
2210 Isles 1871-2012. Int J Climatol 36:1299–1312.

2211 Mazon, J., S. Niemelä, D. Pino, H. Savijärvi, T. Vihma, 2015: Snow bands over the Gulf of Finland in
2212 wintertime. Tellus A, 67. doi:http://dx.doi.org/10.3402/tellusa.v67.25102

2213 Medvedev, I. P., Rabinovich, A. B., and Kulikov, E. A.: Tides in Three Enclosed Basins: The Baltic,
2214 Black, and Caspian Seas, Frontiers in Marine Science, 3, 46,
2215 https://doi.org/10.3389/fmars.2016.00046, 2016.

2216 Mei L., Xue Y., de Leeuw G., Guang J., Wang Y., Li Y., Xu H., Yang L., Hou T., He X., Wu C.,
2217 Dong J. & Chen Z. 2011. Integration of remote sensing data and surface observations to estimate the
2218 impact of the Russian wildfires over Europe and Asia during August 2010. Biogeosciences 8: 3771–
2219 3791.

2220 Meehl, G.A., C. Tebaldi, G. Walton, D. Easterling, and L. McDaniel, 2009c: The relative increase of
2221 record high maximum temperatures compared to record low minimum temperatures in the U.S.
2222 Geophysical Research Letters, 36, L23701

2223 Meier, M., A. Rutgersson and M. Reckerman (2014). An Earth System Science Program for the Baltic
2224 Sea Region. *Eos*, **95**, 109-110.

2225   Meier et al. (2021): Climate change and impacts in the Baltic Sea region (BACC III) ESD.

2226   Meier, H.E.M., Dieterich, C., Eilola, K. et al. Future projections of record-breaking sea surface
2227   temperature and cyanobacteria bloom events in the Baltic Sea. Ambio 48, 1362–1376 (2019).
2228   https://doi.org/10.1007/s13280-019-01235-5

2229   Mentaschi, L., M. I. Vousdoukas, E. Voukouvalas, A. Dosio, and L. Feyen (2017), Global changes of
2230   extreme coastal wave energy fluxes triggered by intensified teleconnection patterns, Geophys. Res.
2231   Lett., 44, 2416–2426, doi:10.1002/2016GL072488.

2232   Michaelis AC, Willison J, Lackmann GM, Robinson WA (2017) Changes in Winter North Atlantic
2233   Extratropical Cyclones in High-Resolution Regional Pseudo–Global Warming Simulations. J Clim
2234   30:6905–6925, doi:10.1175/JCLI-D-16-0697.1

2235   Mielonen T., Portin H., Komppula M., Leskinen A., Tamminen J., Ialongo I., Hakkarainen J.,
2236   Lehtinen K.E.J. & Arola A. 2012. Biomass burning aerosols observed in Eastern Finland during the
2237   Russian wildfires in summer 2010 — Part 2: Remote sensing. Atmos. Environ. 47: 279–287.

2238   Migliavacca, M., Dosio, A., Camia, A., Hobourg, R., Houston-Durrant, T., Kaiser, J. W., Khabarov,
2239   N., Krasovskii, A. A., Marcolla, B., San-Miguel-Ayanz, J., Ward, D. S., and Cescatti, A. (2013)
2240   Modeling biomass burning and related carbon emissions during the 21st century in Europe. Journal of
2241   Geophysical Research: Biogeosciences 118: 1732–1747.

2242   Milenković, M., Ducić, V., Mihajlović, J., and Babić, V., 2019: Forest fires in Finland – the influence
2243   of atmospheric oscillations. J. Geogr. Inst. Cvijic., 69, 75–82, doi:10.2298/IJGI901075M

2244   Miralles DG, Teuling AJ, van Heerwaarden CC, Vilà-Guerau de Arellano J (2014) Mega-heatwave
2245   temperatures due to combined soil desiccation and atmospheric heat accumulation. Nat Geosci 7345,
2246   doi: 10.1038/ngeo2141.

2247   Mitchell D, Davini P, Harvey B, Massey N, Haustein K, Woollings T et al. (2017). Assessing mid-
2248   latitude dynamics in extreme event attribution systems. Clim Dyn 48:3889–3901,
2249   doi:10.1007/s00382-016-3308-z

2250   Mishnaevsky, L. (2019). Toolbox for optimizing anti-erosion protective coatings of wind turbine
2251   blades: Overview of mechanisms and technical solutions. *Wind Energy*, *22*(11), 1636-1653.
2252   https://doi.org/10.1002/we.2378

2253   Mohrholz, V., Naumann, M., Nausch, G., Krüger, S., and Gräwe, U. (2015). Fresh oxygen for the
2254   Baltic Sea — An exceptional saline inflow after a decade of stagnation. *J. Mar. Sys.* 148**,** 152-166.
2255   doi: 10.1016/j.marsys.2015.03.005.

2256   Mokrech M. et al., 'An Integrated Approach for Assessing Flood Impacts Due to Future Climate and
2257   Socio-Economic Conditions and the Scope of Adaptation in Europe',Climatic Change 128, no. 3–4 (4
2258   December 2014): 245–60, https://doi.org/10.1007/s10584-014-1298-6

2259   Montewka, J., Goerlandt, F., Kujala, P. and Lensu, M. 2015. Towards probabilistic models for the
2260   prediction of a ship performance in dynamic ice. Cold Regions Science and Technology. Volume 112,
2261   April 2015, Pages 14–28.

2262 MossR. ; Mustafa Babiker; Sander Brinkman; Eduardo Calvo; Tim Carter; Jae Edmonds; Ismail
2263 Elgizouli; *Seita Emori*; Lin Erda; Kathy Hibbard; Roger Jones; Mikiko Kainuma; Jessica Kelleher;
2264 Jean Francois Lamarque; Martin Manning; Ben Matthews; Jerry Meehl; Leo Meyer; John Mitchell;
2265 Nebojsa Nakicenovic; Brian O'Neill; Ramon Pichs; Keywan Riahi; Steven Rose; Paul Runci; Ron
2266 Stouffer; Detlef van Vuuren; John Weyant; Tom Wilbanks; Jean Pascal van Ypersele & Monika
2267 Zurek (2008). *Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and*
2268 *Response Strategies (PDF)*. Geneva: Intergovernmental Panel on Climate Change. p. 132.

2269 Munich Re, 2018. https://www.munichre.com/topics-online/en/climate-change-and-natural-
2270 disasters/natural-disasters/the-natural-disasters-of-2018-in-figures.html

2271 Munk, W.H., 1950. Origin and generation of waves, Proc. 1st Conf. Coastal Engineering (Long
2272 Beach), New York, ASCE, pp. 95-108.

2273 Mustonen K-R., Mykrä H., Marttila H., Sarremejane R., Veijalainen N., Sippel K., Muotka T.,
2274 Hawkins C. (2018). Thermal and hydrologic responses to climate change predict marked alterations in
2275 boreal stream invertebrate assemblages. Global Change Biology. 24. 10.1111/gcb.14053.

2276 Nakamura T, Yamazaki K, Iwamoto K, Honda M, Miyoshi Y, Ogawa Y and Ukita J (2015). A
2277 negative phase shift of the winter AO/NAO due to the recent Arctic sea-ice reduction in late autumn.
2278 J. Geophys. Res. Atmos. 120, 3209–3227. doi: 10.1002/2014JD022848

2279 Nakicenovic N, Alcamo J, Grubler A, Riahi K, Roehrl RA, Rogner H-H, & Victor N (2000). *Special*
2280 *Report on Emissions Scenarios (SRES), A Special Report of Working Group III of the*
2281 *Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press. ISBN 0-521-
2282 80493-0

2283 Nasonova, O. N., Ye M. Gusev, E. M. Volodin, and E. E. Kovalev. "Application of the Land Surface
2284 Model SWAP and Global Climate Model INMCM4. 0 for Projecting Runoff of Northern Russian
2285 Rivers. 1. Historical Simulations." Water Resources 45, no. 2 (2018): 73-84

2286 Naumann, M., Umlauf, L., Mohrholz, V., Kuss, J., Siegel, H., Waniek, J.J., et al. (2018).
2287 Hydrographic-hydrochemical assessment of the Baltic Sea 2017. *Meereswiss. Ber., Warnemünde* 107**,**
2288 1-97. doi: 10.12754/msr-2018-0107.

2289 Nikulin, G., Kjellström, E., Hansson, U., Jones, C., Strandberg, G. and Ullerstig, A., 2011. Evaluation
2290 and Future Projections of Temperature, Precipitation and Wind Extremes over Europe in an Ensemble
2291 of Regional Climate Simulations. Tellus, 63A(1), 41-55. DOI: 10.1111/j.1600-0870.2010.00466.x.

2292 Nilsson, E.; Rutgersson, A.; Dingwell, A.; Björkqvist, J.-V.; Pettersson, H.; Axell, L.; Nyberg, J.;
2293 Strömstedt, E. Characterization of Wave Energy Potential for the Baltic Sea with Focus on the
2294 Swedish Exclusive Economic Zone. Energies 2019, 12, 793

2295 Nilsson, E.; Wrang, L.; Rutgersson, A.; Dingwell, A.; Strömstedt, E. Assessment of Extreme and
2296 Metocean Conditions in the Swedish Exclusive Economic Zone for Wave Energy. *Atmosphere* 2020,
2297 *11*, 229.

2298 Ning L and Bradley RS (2016) NAO and PNA influences on winter temperature and precipitation
2299 over the eastern United States in CMIP5 GCMs. Clim Dyn 46:1257–1276. doi:10.1007/s00382-015-
2300 2643-9.

2301 Niziol, T. A., Snyder, W. R., and Waldstreicher, J. S., 1995: Winter weather Forecasting throughout
2302 the Eastern United States. Part IV: Lake Effect Snow, Weather Forecast., 10, 61–77.

2303 Öberg, J. 2017. Cyanobacteria blooms in the Baltic Sea in 2017. *HELCOM Baltic Sea Environment*
2304 *Fact Sheets* [Online], http://helcom.fi/baltic-sea-trends/environment-fact-
2305 sheets/eutrophication/cyanobacterial-blooms-in-the-baltic-sea/. [Accessed 28.11.2017].

2306 Oikkonen A., Haapala J., Lensu M. and J. Karvonen. 2016. Sea ice drift and deformation in the coastal
2307 boundary zone. Geophysical Research Letters Vol.43 p. 10303-10310. doi: 10.1002/2016GL069632

2308 Olenina, I., and Kownacka, J. (2010). An unusual phytoplankton event five years later: the fate of the
2309 atypical range expansion of marine species into the south-eastern Baltic. *HELCOM Indicator Fact*
2310 *Sheets 2010. Online.* doi: http://www.helcom.fi/baltic-sea-trends/environment-fact-
2311 sheets/eutrophication/an-unusual-phytoplankton-event/.

2312 Oliver ECJ, Burrows MT, Donat MG, Sen Gupta A, Alexander LV, Perkins-Kirkpatrick SE,
2313 Benthuysen JA, Hobday AJ, Holbrook NJ, Moore PJ, Thomsen MS, Wernberg T and Smale DA
2314 (2019) Projected Marine Heatwaves in the 21st Century and the Potential for Ecological Impact.
2315 *Front. Mar. Sci.* 6:734. doi: 10.3389/fmars.2019.00734

2316 Olofsson, M., Suikkanen, S., Kobos, J., Wasmund, N., Karlson, B. (2020) : Basin-specific changes in
2317 filamentous cyanobacteria community composition across four decades in the Baltic Sea. Harmful
2318 Algae 91 : 101685. Doi 10.1016/j.hal.2019.101685.

2319 Olsson J, Yang W, Graham LP, Rosberg J, Andreasson J (2011) Using an ensemble of climate
2320 projections for simulating recent and near-future hydrological change to lake Vanern in Sweden.
2321 Tellus A 63:126-137.

2322 Olsson J, Berg P, Eronn A, Simonsson L, Södling J, Wern L, and Yang W (2017a) Extremregn i
2323 nuvarande och framtida klimat: analyser av observationer och framtidsscenarier, Klimatologi 47,
2324 SMHI, 70pp (in Swedish).

2325 Olsson, T., Jakkila, J., Veijalainen, N., Backman, L., Kaurola, J., and Vehviläinen, B. (2015), Impacts
2326 of climate change on temperature, precipitation and hydrology in Finland – studies using bias
2327 corrected Regional Climate Model data, Hydrol. Earth Syst. Sci., 19, 3217–3238,
2328 https://doi.org/10.5194/hess-19-3217-2015.

2329 Olsson, T., Perttula, T., Jylhä, K., and Luomaranta, A. (2017b), Intense sea-effect snowfall case on the
2330 western coast of Finland, Adv. Sci. Res., 14, 231-239, https://doi.org/10.5194/asr-14-231-2017.

2331 Olsson, T., Post, P., Rannat, K., Keernik, H., Perttula, T., Luomaranta, A., Jylhä, K., Kivi, R., and
2332 Voormansik, T. (2018), Sea-effect snowfall case in the Baltic Sea region analysed by reanalysis,
2333 remote sensing data and convection-permitting mesoscale modelling, Geophysica Vol. 53, No. 1.

2334 Olsson, T., Luomaranta, A., Jylhä, K., Jeworrek, J., Perttula, T., Dieterich, C., Wu, L., Rutgersson, A.,
2335 and Mäkelä, A. (2020), Statistics of sea-effect snowfall along the Finnish coastline based on regional
2336 climate model data, Adv. Sci. Res., 17, 87–104, https://doi.org/10.5194/asr-17-87-2020.

2337 Omstedt, A., and Chen, D. (2001), Influence of atmospheric circulation on the maximum ice extent in
2338 the Baltic Sea, *J. Geophys. Res.*, 106(C3), 4493– 4500, doi:10.1029/1999JC000173.

Oris, F., Asselin, H., Ali, A. A., Finsinger, W., and Bergeron, Y. (2014) Effect of increased fire activity on global warming in the boreal forest. Environmental Reviews 22: 206–219.

O'Neil J.M., Davis T.W., Burford M.A. & Gobler C.J. 2012. The rise of harmful cyanobacteria blooms: The potential roles of eutrophication and climate change. Harmful Algae 14: 313-334.

Orlowsky, B. and Seneviratne, S. I.: Elusive drought: uncertainty in observed trends and short- and long-term CMIP5 projections, Hydrol. Earth Syst. Sci., 17, 1765–1781, doi:10.5194/hess-17-1765-2013, 2013.

Overland J, Francis JA, Hall R, Hanna E, Kim SJ, Vihma T (2015) The melting Arctic and midlatitude weather patterns: Are they connected? J Clim 28:7917–7932, doi: 10.1175/jcli-d-14-00822.1

Owczarek, M., & Filipiak, J. (2016). Contemporary changes of thermal conditions in Poland, 1951-2015, Bulletin of Geography. Physical Geography Series, 10(1), 31-50. doi: https://doi.org/10.1515/bgeo-2016-0003

Paprota M., J. Przewłócki, W. Sulisz, B. E. Swerpel, 2003, EXTREME WAVES AND WAVE EVENTS IN THE BALTIC SEA, Proceedings of MAXWAVE Final Meeeting, October 8-10, 2003, Geneva, Switzerland.

Paprotny, D., Terefenko, P. (2017). New estimates of potential impacts of sea level rise and coastal floods in Poland. Nat Hazards (2017) 85:1249–1277.

Partasenok (Danilovich), I. (2014) Winter cyclone frequency and following freshet streamflow formation on the rivers in Belarus. Environ. Res. Lett. 9 (ref. 095005).

Patey, M., Riska, K., 1999. Simulation of ship transit through ice. INSROP, INSROP Working Paper 155-1999.

Peings Y and Magnusdottir G (2016). Wintertime atmospheric response to Atlantic multidecadal variability: effect of stratospheric representation and ocean–atmosphere coupling. Clim. Dyn. 47, 1029–1047. doi:10.1007/s00382-015-2887-4

Peterson, T.C. and M.J. Manton, 2008: Monitoring changes in climate extremes – A tale of international collaboration. Bulletin of the American Meteorological Society, 89(9), 1266-1271.

Pettersson, H., Kalén, O. and Brüning, T., 2018. Wave Climate in the Baltic Sea in 2017. HELCOM Baltic Sea Environment Fact Sheets. Online. [2019-03-26], http://www.helcom.fi/baltic-sea-trends/environment-fact-sheets/.

Pettersson, H., Jönsson, A., 2005. Wave Climate in the Northern Baltic Sea in 2004, HELCOM Baltic Sea Environment Fact Sheets. Online. 10.9.2015. http://www.helcom.fi/baltic-sea-trends/environment-fact-sheets/.

Piotrowski A., Szczucinski W., Sydor P., Kotrys B., Rzodkiewicz M., Krzyminska J. 2017. Sedimentary evidence of extreme storm surge or tsunami events in the southern Baltic Sea (Rogowo area, NW Poland). Geological Quarterly, 61(4), 973-986.

2374 Poljanšek K. et al., 'Science for Disaster Risk Management 2017: Knowing Better and Losing Less',
2375 EUR 28034 EN (Luxembourg: Publications Office of the European Union, 2017);

2376 Pontoppidan, M., Reuder, J., Mayer, S., & Kolstad, E. W., 2017. Downscaling an intense precipitation
2377 event in complex terrain: the importance of high grid resolution, Tellus A: Dynamic Meteorology and
2378 Oceanography, 69(1), 1271561.

2379 Popovicheva, O., Kistler, M., Kireeva, E., Persiantseva, N., Timofeev, M., Kopeikin, V., and Kaspar-
2380 Giebl, A. (2014) Physicochemical characterization of smoke aerosol during large-scale wildfires:
2381 Extreme event of August 2010 in Moscow. Atmospheric Environment, 96: 405–414,
2382 doi.org/10.1016/j.atmosenv.2014.03.026

2383 Prahl, Boris F; Boettle, Markus; Costa, Luis; Rybski, Diego; Kropp, Jürgen P (2017): Damage cost
2384 curves for European coastal city clusters at flood heights between 0.0 m and 12.0 m based on the
2385 EVRS2000 vertical datum. PANGAEA, https://doi.org/10.1594/PANGAEA.875259, In supplement
2386 to:

2387 Prahl, Boris F; Boettle, Markus; Costa, Luis; Kropp, Jürgen P; Rybski, Diego (2017): Damage and
2388 protection cost curves for coastal floods within the largest 600 European cities. Scientific Data

2389 Prein, A. F., Gobiet, A., Truehetz, H., Keuler, K., Goergen, K., Teichmann, C., Fox Maule, C., van
2390 Meijgaard, E., Déqué, M., Nikulin, G., Vautard, R., Colette, A., Kjellström, E. and Jacob, D., 2016.
2391 Precipitation in the EURO-CORDEX 0.11˚ and 0.44˚ simulations: high resolution, high benefits?
2392 Clim. Dyn., 46, 383-412, doi: 10.1007/s00382-015-2589-y.

2393 Prudhomme C et al. (2014) Hydrological droughts in the 21st century, hotspots and uncertainties from
2394 a global multimodel ensemble experiment. Proc Natl Acad Sci 111:3262–3267.
2395 doi:10.1073/pnas.1222473110.

2396 Pryor, S. C., R. J. Barthelmie, N. E. Clausen, M. Drews, N. MacKeller, and E. Kjellström, 2012:
2397 Analysis of possible changes in intense and extreme wind speeds over northern Europe under climate
2398 change scenarios. Climate Dyn., 38, 189–208.

2399 Przybylak R, Vízi Z, Araźny A, Kejna M, Maszewski R, Uscka-Kowalkowska J (2007) Poland's
2400 climate extremes index, 1951-2005. Geogr Polonica 80:47-58

2401 Punkka A-J, 2015. Mesoscale convective systems in Finland. Finnish Meteorological Institute
2402 Contributions 116, Helsinki, Finland. http://urn.fi/URN:ISBN:978-951-697-866-9

2403 Räämet, A. and Soomere, T., 2010, The wave climate and its seasonal variability in the northeastern
2404 Baltic Sea, Estonian J. Earth Sci., 59, 100–113, https://doi.org/10.3176/earth.2010.1.08

2405 Raible C, Della-Marta PM, Schwierz C, Blender R (2008) Northern Hemisphere extratropical
2406 cyclones: a comparison of detection and tracking methods and different reanalyses. Mon Wea Rev
2407 136:880–897

2408 Räisänen, J. (2017, October 26). Future Climate Change in the Baltic Sea Region and Environmental
2409 Impacts. Oxford Research Encyclopedia of Climate Science. Retrieved 14 Aug. 2019, doi:
2410 10.1093/acrefore/9780190228620.013.63

Rajczak J, Pall P, Schär C (2013) Projections of extreme precipitation events in regional climate simulations for Europe and the Alpine Region. J Geophys Res Atmos 118:3610–3626. doi:10.1002/jgrd.50297

Randerson, J. T., Liu, H., Flanner, M. G., Chambers, S. D., Jin, Y., Hess, P. G., Pfister, G., Mack, M. C., Treseder, K. K., Welp, L. R., Chapin, F. S., Harden, J. W., Goulden, M. L., Lyons, E., Neff, J. C., Schuur, E. A. G., and Zender, C. S. (2006) The impact of boreal forest fire on climate warming. Science 314: 1130–1132.

Rauthe, M., Steiner, H., Riediger, U., Mazurkiewicz, A., and Gratzki, A., 2013. A Central European precipitation climatology – Part I: Generation and validation of a high-resolution gridded daily data set (HYRAS). Meteorol. Zeitschrift 22, 235–256. doi:10.1127/0941-2948/2013/0436.

Rauhala J, Brooks H.E, Schultz D.M (2012) Tornado Climatology of Finland. Monthly Weather Review, 140, 1446-1456. doi: 10.1175/MWR-D-11-00196.1

Ravestein P, van der Schrier G, Haarsma R, Scheele R, van den Broek M (2018) Vulnerability of European intermittent renewable energy supply to climate change and climate variability. Renew Sustain Energy Rev 97:497–508, doi: 10.1016/j.rser.2018.08.057

Reckerman et a., 2021. Multiple drivers. ESD.

Rennert KJ, Wallace JM (2009) Cross-frequency coupling, skewness, and blocking in the Northern Hemisphere winter circulation. J Climate 22:5650–5666

Reusch, T.B.H., Dierking, J., Andersson, H.C., Bonsdorff, E., Carstensen, J., Casini, M., et al. (2018). The Baltic Sea as a time machine for the future coastal ocean. *Sci. Adv.* 4(eaar8195).

Rey J, Rohat G, Perroud M, Goyette S, and Kasparian J (2020) Shifting velocity of temperature extremes under climate change. Environ. Res. Lett. 15 034027, https://doi.org/10.1088/1748-9326/ab6c6f

R'Honi, Y., Clarisse, L., Clerbaux, C., Hurtmans, D., Duflot, V., Turquety, S., Ngadi, Y., and Coheur, P.-F. (2013) Exceptional emissions of NH_3 and HCOOH in the 2010 Russian wildfires. Atmos. Chem. Phys., 13, 4171–4181, doi:10.5194/acp-13-4171-2013

Ribeiro, A., Barbosa, S. M., Scotto, M. G., and Donner, R. V.: Changes in extreme sea-levels in the Baltic Sea, Tellus A: Dynamic Meteorology and Oceanography, 66, 20 921, https://doi.org/10.3402/tellusa.v66.20921, 2014.

Rodwell MJ, Rowell DP, Folland CK (1999) Oceanic forcing of the wintertime North Atlantic Oscillation and European climate. Nature 398:320–323

Ronkainen, I., Lehtiranta, J., Lensu, M., Rinne, E., Haapala, J., and Haas, C. 2018. Interannual sea ice thickness variability in the Bay of Bothnia, The Cryosphere, 12, 3459-3476, https://doi.org/10.5194/tc-12-3459-2018

Rosenhagen G. and Bork I. Rekonstruktion der Sturmflutwetterlage vom 13. November 1872. MUSTOK-Workshop 2008. Siegen.

2447 Roudier, Philippe & Andersson, Jafet & Donnelly, Chantal & Feyen, Luc & Greuell, Wouter &
2448 Ludwig, Fulco (2016). Projections of future floods and hydrological droughts in Europe under a +2°C
2449 global warming. Climatic Change. 135. 10.1007/s10584-015-1570-4.

2450 Rowe, J. S., and Scotter, G. W. (1973) Fire in the boreal forest. Quaternary Research 3: 444–464.

2451 Ruuhela, R., Otto Hyvärinen and Kirsti Jylhä. Int. J. Environ. Res. Public Health 2018, 15, 406;
2452 doi:10.3390/ijerph15030406

2453 Ruokolainen, L., and Salo, K. (2006) The succession of boreal forest vegetation during ten years after
2454 slash-burning in Koli National Park, eastern Finland. Annales Botanici Fennici 43: 363–378.

2455 Ruosteenoja, K., Markkanen, T., Venäläinen, A., Räisänen, P., and Peltola, H. (2018) Seasonal soil
2456 moisture and drought occurrence in Europe in CMIP5 projections for the 21st century. Climate
2457 Dynamics 50: 1177–1192.

2458 Ruosteenoja, K.; Vihma, T.; Venäläinen A. (2019) Projected changes in European and North Atlantic
2459 seasonal wind climate derived from CMIP5 simulations. J. Climate, 32, 6467-6490. DOI:
2460 10.1175/JCLI-D-19-0023.1. https://doi.org/10.1175/JCLI-D-19-0023.1

2461 Ruosteenoja K, Markkanen T, Räisänen J. (2020) Thermal seasons in northern Europe in projected
2462 future climate. Int J Climatol., 40, 4444–4462. https://doi.org/10.1002/joc.6466

2463 Rutgersson A, Jaagus J, Schenk F, Stendel M (2014) Observed changes and variability of atmospheric
2464 parameters in the Baltic Sea region during the last 200 years. Clim Res 61:177-190.
2465 https://doi.org/10.3354/cr01244

2466 Räisänen, J. A., 2017: Future Climate Change in the Baltic Sea Region and Environmental Impacts.
2467 Oxford Research Encyclopedias: Climate Science. Storch, H. V. (ed.). Oxford: Oxford University
2468 Press. DOI: 10.1093/acrefore/9780190228620.013.634

2469 Räisänen, J. Effect of atmospheric circulation on recent temperature changes in Finland. Clim Dyn 53,
2470 5675–5687 (2019). https://doi.org/10.1007/s00382-019-04890-2

2471 Saku, S., R. Solantie, K. Jylhä, A. Venäläinen, H. Valta, 2011: Äärilämpötilojen alueellinen vaihtelu
2472 Suomessa. (Spatial variations of extreme temperatures in Finland). Finnish Meteorological Institute,
2473 Reports, 2011:1, 92 p. (In Finnish with abstract in English)

2474 Saranko, O., Fortelius, C. Jylhä, K., Ruosteenoja, K., Brattich, E., Di Sabatino, S., Nurmi, V., 2020:
2475 Impacts of town characteristics on the changing urban climate in Vantaa. Science of The Total
2476 Environment, 727, https://doi.org/10.1016/j.scitotenv.2020.138471

2477 Savela, H., Harju, K., Spoof, L., Lindehoff, E., Meriluoto, J., Vehniäinen, M., Kremp, A. (2016).
2478 Quantity of the dinoflagellate sxtA4 gene and cell density correlates with paralytic shellfish toxin
2479 production in *Alexandrium ostenfeldii* blooms. Harmful Algae 52: 1-10.

2480 Savijärvi, H., 2012: Cold air outbreaks over high-latitude sea gulfs. Tellus A 2012, 64, 12244,
2481 DOI:10.3402/tellusa.v64i0.12244

2482   Scaife AA, Knight JR, Vallis G, Folland CK (2005) A stratospheric influence on the winter NAO and
2483   north Atlantic surface climate. Geophys Res Lett 32:L18715 doi: 10.1029/2005GL023226

2484   Schenk F (2015) The analog-method as statistical upscaling tool for meteorological field
2485   reconstructions over Northern Europe since 1850. Dissertation Univ Hamburg

2486   Schenk F, Zorita E (2012) Reconstruction of high resolution atmospheric fields for Northern Europe
2487   using analog-upscaling. Clim Past 8:1681–1703

2488   Schimanke, S., Undén, P., Isaksson, L., Edvinsson, L., Ridal, M., Olsson, E., Hopsch, S., and
2489   Andersson, S.: Copernicus regional reanalysis for Europe, European Meteorological Society Annual
2490   Meeting Abstracts, 16, EMS2019-134, https://meetingorganizer. copernicus.org/EMS2019/EMS2019-
2491   134.pdf, 2019

2492   Schubert SD, Wang H, Koster RD, Suarez MJ, Groisman PY (2014) Northern Eurasian heat waves
2493   and droughts. J Clim 27:3169–3207, doi: 10.1175/JCLI-D-13-00360.1

2494   Screen JA, Simmonds I, Deser C and Tomas R (2013) The Atmospheric Response to Three Decades
2495   of Observed Arctic Sea Ice Loss. J Clim 26:1230–1248. doi:10.1175/JCLI-D-12-00063.1.

2496   Seinä A, Palosuo E (1996) The classification of the maximum annual extent of ice cover in the Baltic
2497   Sea 1720–1995. MERI-Report Series of the Finnish Inst of Marine Res 27:79–91

2498   Seneviratne SI, Wilhelm M, Stanelle T, van den Hurk B, Hagemann S, Berg A et al. (2013) Impact of
2499   soil moisture-climate feedbacks on CMIP5 projections: First results from the GLACE-CMIP5
2500   experiment. Geophys Res Lett 40:5212–5217, doi: 10.1002/grl.50956

2501   Seneviratne, S.I., N. Nicholls, D. Easterling, C.M. Goodess, S. Kanae, J. Kossin, Y. Luo, J. Marengo,
2502   K. McInnes, M. Rahimi, M. Reichstein, A. Sorteberg, C. Vera, and X. Zhang, 2012: Changes in
2503   climate extremes and their impacts on the natural physical environment. In: Managing the Risks of
2504   Extreme Events and Disasters to Advance Climate Change Adaptation [Field, C.B., V. Barros, T.F.
2505   Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M.
2506   Tignor, and P.M. Midgley (eds.)]. A Special Report of Working Groups I and II of the
2507   Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK,
2508   and New York, NY, USA, pp. 109-230.

2509   Shaw, T. A., Baldwin, M., Barnes, E. A., Caballero, R., Garfinkel, C. I., Hwang, Y.-T., Li, C.,
2510   O'Gorman, P. A., Rivière, G., Simpson, I. R., and Voigt, A.: Storm track processes and the opposing
2511   influences of climate change, Nature Geoscience, 9, 656–664, https://doi.org/10.1038/ngeo2783,
2512   2016.

2513   Sherstyukov, B. G., and Sherstyukov, A. B. (2014) Assessment of increase in forest fire risk in Russia
2514   till the late 21st century based on scenario experiments with fifth-generation climate models. Russian
2515   Meteorology and Hydrology 39: 292–301.

2516   Shvidenko, A. Z., and Schepaschenko, D. G. (2013) Climate change and wildfires in Russia.
2517   Contemporary Problems of Ecology 6: 683–692.

2518   Shepherd TG, Boyd E, Calel RA, Chapman SC, Dessai S, Dima-West IM et al. (2018) Storylines: an
2519   alternative approach to representing uncertainty in physical aspects of climate change. Clim Change
2520   151:555–571, doi: 10.1007/s10584-018-2317-9

2521   Shindell DT, Schmidt GA, Mann ME, Rind D, Waple A (2001) Solar forcing of regional climate
2522   change during the Maunder minimum. Science 294:2149–2152

2523   Sillmann, J., Kharin, V. V., Zwiers, F. W., Zhang, X., and Bronaugh, D. (2013), Climate extremes
2524   indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections, J. Geophys. Res.
2525   Atmos., 118, 2473– 2493, doi:10.1002/jgrd.50188.

2526   Sinclair, V. A., Johannes Mikkola, Mika Rantanen and Jouni Räisänen, 2919: The summer 2018
2527   heatwave in Finland, Weather, 74, 403-409.

2528   Sinclair, V.A. Rantanen, M., Haapanala, P., Räisänen, J. and Heikki Järvinen, H. (2020) The
2529   characteristics and structure of extra-tropical cyclones in a warmer climate. Weather Clim. Dynam., 1,
2530   1–25, doi: 10.5194/wcd-1-1-2020

2531   Sjöström, J., and Granström, A. (2020) Skogsbränder och gräsbränder i Sverige – Trender och
2532   mönster under senare decennier. Myndigheten för samhällsskydd och beredskap, Karlstad, 104
2533   p.Weather Clim. Dynam., 1, 1–25, 2020

2534   Sjöström, J., Plather, F. V., and Granström, A. (2019) Wildfire ignition from forestry machines in
2535   boreal Sweden. Int. J. Wildland Fire, 28, doi:10.1071/WF18229

2536   Slonosky VC, Jones PD, Davies TD (2000) Variability of the surface atmospheric circulation over
2537   Europe, 1774–1995. Int J Climatol 20:1875–1897

2538   Slonosky VC, Jones PD, Davies TD (2001) Atmospheric circulation and surface temperature in
2539   Europe from the 18th century to 1995. Int J Climatol 21:63–75

2540   Smedman A.-S. (1991) Occurrence of roll circulation in a shallow boundary layer. Boundary-layer
2541   Meteorol. 51:343-358.

2542   SMHI (Swedish Meteorological and Hydrological Institute), 2019. SMHI Homepage: Climate
2543   indicators – temperature. Available: https://www.smhi.se/en/climate/climate-indicators/climate-
2544   indicators-temperature-1.91472 [accessed 7 April 2020].

2545   Smirnov, N. S., Korotkov, V. N., and Romanovskaya, A. A., 2015. Black carbon emissions from
2546   wildfires on forest lands of the Russian Federation in 2007–2012. Russian Meteorology and
2547   Hydrology 40: 435–442.

2548   Soomere, T., 2008 Extremes and decadal variations of the northern Baltic Sea wave conditions. In:
2549   Pelinovsky E, Kharif C (eds) Extreme ocean waves. Springer Berlin, pp 139-157.

2550   Soomere, T., Behrens, A., Tuomi, L., and Nielsen, J. W., 2008, Wave conditions in the Baltic Proper
2551   and in the Gulf of Finland during windstorm Gudrun, Nat. Hazards Earth Syst. Sci., 8, 37-46,
2552   https://doi.org/10.5194/nhess-8-37-2008

2553 Soomere, T., Räämet, A., 2011a. Long-term spatial variations in the Baltic Sea wave fields. Ocean
2554 Sci. 7 (1), 141–150.

2555 Soomere, T., Räämet, A. 2011b, Spatial patterns of the wave climate in the Baltic Proper and the Gulf
2556 of Finland, OCEANOLOGIA, 53 (1-TI), pp. 335–371.

2557 Soomere, T , R. Weisse, and A. Behrens, 2012, Wave climate in the Arkona Basin, the Baltic Sea,
2558 Ocean Sci., 8, 287–300, www.ocean-sci.net/8/287/2012/ doi:10.5194/os-8-287-2012

2559 Soomere, T, K. Rannat, J. Elken, K. Myrberg, 2003, Natural and anthropogenic wave forcing in the
2560 Tallinn Bay, Baltic Sea, Transactions on the Built Environment, vol. 70, WIT Press, ISSN 1743-3509.

2561 Soomere T, 2003, Anisotropy of wind and wave regimes in the Baltic proper, Journal of Sea Research,
2562 49, 305– 316

2563 Sørensen P., Cutululis N., Vigueras-Rodriguez A., Madsen H., Pinson P., Jensen L., Hjerrild J. and
2564 Donovan M: Modeling of power fluctuations from large offshore wind farms. Wind Energy, vol 11,
2565 No. 1, p 29 – 43, 2008.

2566 Sousa PM, Trigo RM, Barriopedro D, Soares PM, Ramos AM, Liberato ML (2017) Responses of
2567 European precipitation distributions and regimes to different blocking locations. Clim Dyn 48:1141–
2568 1160

2569 Spangehl T, Cubasch U, Raible CC, Schimanke S, Korper J, Hofer D (2010) Transient climate
2570 simulations from the Maunder minimum to present day: role of the stratosphere. J Geophys Res
2571 115:D00110 doi: 10.1029/2009JD012358

2572 Spinoni J., Vogt J., Naumann G., Barbosa P., Dosio A. (2018). Will drought events become more
2573 frequent and severe in Europe?. International Journal of Climatology. 38. 1718-1736. 10.1002/joc.5291.

2574 Stahl K, Hisdal H, Hannaford J, Tallaksen LM, van Lanen HAJ, Sauquet E, Demuth S, Fendekova M,
2575 Jódar J (2010) Streamflow trends in Europe: evidence from a dataset of near-natural catchments. Hydrol
2576 Earth Syst Sci 14:2367-2382

2577 Stahl K. et al., 'Filling the White Space on Maps of European Runoff Trends: Estimates from a Multi-
2578 Model Ensemble', Hydrology and Earth System Sciences 16, no. 7 (11 July 2012): 2035–47,
2579 https://doi.org/10.5194/hess-16-2035-2012

2580 Statens offentliga utredningar, 2019. Skogsbränderna sommaren 2018. Betänkande av 2018 års
2581 skogsbrandsutredning. Statens offentliga utredningar 2019:7, Stockholm, 336 p.

2582 Stendel M., van den Besselaar, E., Hannachi, A., Kent, E.C., Lefebvre, C., Schenk, F., van der
2583 Schrier, G. and Woollings, T. (2016) Recent Change—Atmosphere. In: Quante M., Colijn F. (eds)
2584 North Sea Region Climate Change Assessment. Regional Climate Studies. Springer DOI:
2585 10.1007/978-3-319-39745-0_2.

2586 Stendel, M., J. Francis, R. White, P.D. Williams and T. Woollings (2020): The Jet Stream and Climate
2587 Change. Chapter 15 in Letcher, T. (ed.): Climate Change: Observed Impacts on Planet Earth, 3rd
2588 edition, Elsevier (in press)

2589 Stephenson DB, Pavan V, Bojariu R (2000) Is the North Atlantic Oscillation a random walk? Int J
2590 Climatol 20:1–18

2591 Stephenson, T.S., C.M. Goodess, M.R. Haylock, A.A. Chen, and M.A. Taylor, 2008: Detecting
2592 inhomogeneities in Caribbean and adjacent Caribbean temperature data using sea-surface
2593 temperatures. Journal of Geophysical Research – Atmospheres, 113, D21116

2594 Stocks, B. J., Mason, J. A., Todd, J. B., Bosch, E. M., Wotton, B. M., Amiro, B. D., Flannigan, M. D.,
2595 Hirsch, K. G., Logan, K. A., Martell, D. L., and Skinner, W. R. (2002) Large forest fires in Canada,
2596 1959–1997. Journal of Geophysical Research 108: D8149, doi:10.1029/2001JD000484.

2597 Stonevičius, E., Rimkus, E., Bukantis, A., Kriaučiūienė, J., Akstinas, V., Jakimavičius, D., ... &
2598 Pliūraitė, V. (2018). Recent aridity trends and future projections in the Nemunas River basin. *Climate
2599 Research*, *75*(2), 143-154.

2600 Strong C, Magnusdottir G (2011) Dependence of NAO variability on coupling with sea ice. Clim Dyn
2601 36:1681–1689

2602 Sun L, Perlwitz J and Hoerling M (2016). What caused the recent "Warm Arctic, Cold Continents"
2603 trend pattern in winter temperatures? Geophys Res Lett 43, 5345–5352. doi:10.1002/2016GL069024.

2604 Suursaar Ü., Kullas T., Otsmann M., Saaremäe I., Kuik J., Merilain M. 2006. Cyclone Gudrun in
2605 January 2005 and modelling its hydrodynamic consequences in the Estonian coastal waters. Boreal
2606 Environment Research, 11, 143-159.

2607 Sulisz, M. Paprota and A. Reda, 2016, Extreme waves in the southern Baltic Sea, Ciencias Marinas
2608 (2016), 42(2): 123–137, http://dx.doi.org/10.7773/cm.v42i2.2599

2609 Svensson, N., Sahlée, E., Bergström, H., Nilsson, E., Badger, M., & Rutgersson, A. (2017). A Case
2610 Study of Offshore Advection of Boundary Layer Rolls over a Stably Stratified Sea Surface. *Advances
2611 in Meteorology*. https://doi.org/10.1155/2017/9015891

2612 Szwed, M., G. Karg, I. Pinskwar, M. Radziejewski, D. Graczyk, A. Kedziora, and Z. W.
2613 Kundzewicz1, Nat. Hazards Earth Syst. Sci., 10, 1725–1737, 2010

2614 Tamarin T, Kaspi Y (2017) The poleward shift of storm tracks under global warming: A Lagrangian
2615 perspective. Geophys Res Lett 44:10666-10674, doi:10.1002/2017GL073633.

2616
2617 Taylor, K.E., R.J. Stouffer, G.A. Meehl, An overview of CMIP5 and the experiment design, Bull.
2618 Amer. Meteor. Soc., 93, 485-498, DOI:10.1175/BAMS-D-11-00094.1, 2012.

2619 Teuling AJ (2018) A hot future for European droughts. Nat Clim Change 8:364–365, doi:
2620 10.1038/s41558-018-0154-5

2621 Thorsteinsson (2011) Climate Change and Energy Systems – Impacts, risks, adaption in the Nordic
2622 and Baltic countries. Edited by Thorsteinn Thorsteinsson and Halldór Björnsson. ISBN 978-92-893-
2623 2190-7, https://norden.diva-portal.org/smash/get/diva2:701000/FULLTEXT01.pdf

2624 Thorarinsdottir, T. L., Guttorp, P., Drews, M., Kaspersen, P. S. & de Bruin, K (2017). Sea level
2625 adaptation decisions under uncertainty. Water Resour. Res. 53, 8147–8163, 2017.

2626 Thober S., Kumar R., Wanders N., Marx A., Pan M., Rakovec O., Samaniego1 l., Sheffield J., Wood
2627 E F. and Zink1 M. (2018) Multi-model ensemble projections of European river floods and high flows
2628 at 1.5, 2, and 3 degrees global warming. Environmental Research Letters, Volume 13, Number 1.

2629 Thodsen H, Hasholt B, Kjarsgaard JH (2008) The influence of climate change on suspended sediment
2630 transport in Danish rivers. Hydrol Process 22:764-774.

2631 Tilinina N, Gulev SK, Rudeva I and Koltermann P (2013) Comparing Cyclone Life Cycle
2632 Characteristics and Their Interannual Variability in Different Reanalyses. J Clim 26:6419–6438. doi:
2633 10.1175/JCLI-D-12-00777.1.

2634 Tomczyk A. M. & Bednorz, E., 2014: Heat and cold waves on the southern coast of the Baltic Sea.
2635 Baltica 27, 45-54. DOI: 10.5200/baltica.2014.27.05

2636 Trewin, B. and H. Vermont, 2010: Changes in the frequency of record temperatures in Australia,
2637 1957-2009. Australian Meteorological and Oceanographic Journal, 60(2), 113-119.

2638 Trigo IF (2006) Climatology and interannual variability of storm-tracks in the Euro-Atlantic sector: a
2639 comparison between ERA-40 and NCEP/NCAR reanalyses. Clim Dyn 26:127–143

2640 Tuomi, L., Kahma, K. K., and Pettersson, H., 2011, Wave hindcast statistics in the seasonally ice-
2641 covered Baltic Sea, Boreal Environ. Res., 16, 451–472, available at:
2642 http://www.borenv.net/BER/pdfs/ber16/ber16-451.pdf, (last access: 31 May 2019)

2643 Tuomi L, Kanarik H, Björkqvist J-V, Marjamaa R, Vainio J, Hordoir R, Höglund A and Kahma KK
2644 (2019) Impact of Ice Data Quality and Treatment on Wave Hindcast Statistics in Seasonally Ice-
2645 Covered Seas. *Front. Earth Sci.* 7:166. doi: 10.3389/feart.2019.00166

2646 Twardosz, R., Kossowska-Cezak, U. & Pełech, S. Extremely Cold Winter Months in Europe (1951–
2647 2010). Acta Geophys. 64, 2609–2629 (2016). https://doi.org/10.1515/acgeo-2016-0083

2648 Uotila, P., Vihma, T. and J. Haapala. 2015. Atmospheric and oceanic conditions and the extremely
2649 mild Baltic Sea ice winter 2014/15, Geophys. Res. Lett., doi:10.1002/2015GL064901, 2015.

2650 van den Hurk B, Kim H, Krinner G, Seneviratne SI, Derksen C, Oki T et al. (2016) LS3MIP (v1.0)
2651 contribution to CMIP6: the Land Surface, Snow and Soil moisture Model Intercomparison Project –
2652 aims, setup and expected outcome. Geosci Model Dev 9:2809–2832, doi:10.5194/gmd-9-2809-2016

2653 van der Linden EC, Haarsma RJ, van der Schrier G (2019) Impact of climate model resolution on soil
2654 moisture projections in central-western Europe. Hydrol Earth Syst Sci 23:191–206, doi: 10.5194/hess-
2655 23-191-2019

2656 van Haren R, Haarsma RJ, de Vries H, van Oldenborgh GJ, Hazeleger W (2015) Resolution
2657 dependence of circulation forced future central European summer drying. Environ Res Lett 10:55002.
2658 Available at: http://stacks.iop.org/1748-9326/10/i=5/a=055002

van Vuuren, D.P., Edmonds, J., Kainuma, M. *et al.* The representative concentration pathways: an overview. *Climatic Change* 109, 5 (2011). https://doi.org/10.1007/s10584-011-0148-z

Vajda, A., Tuomenvirta, H., Juga, I., Nurmi, P., Jokinen, P., and Rauhala, J., 2014: Severe weather affecting European transport systems: the identification, classification and frequencies of events. Nat Hazards, 72, 169-188. https://doi.org/10.1007/s11069-013-0895-4

Valiuškevičius G., Stonevicius E., Stankunavicius G., Brastovickytė-Stankevič J. (2018) Severe floods in Nemunas River Delta. Baltica. 31. 89-99. doi: 10.5200/baltica.2018.31.09

P (2010) Northern Hemisphere atmospheric stilling partly attributed to an increase in surface roughness. Nat Geosci 3:756–761

Valiukas D (2011) Sausringi laikotarpiai Vilniuje 1891–2010 m (Dry periods in 1891-2010 in Vilnius) Geography 47:9-18 (in Lithuanian with English summary)

Vautard et al (2014). The European climate under a 2 C global warming. Environ. Res. Lett. 9 034006

Veijalainen N., Ahopelto L.,Marttunen M., Jääskeläinen J.,Britschgi R., Orvomaa M., Belinskij A.,Keskinen M. (2019). Severe Drought in Finland: Modeling Effects on Water Resources and Assessing Climate Change Impacts. Sustainability. 11. 2450. 10.3390/su11082450.

Veijalainen N, Lotsari E, Alho P, Vehvilainen B, Kayhko J (2010b) National scale assessment of climate change impacts on flooding in Finland. J Hydrology 391:333-350.

Veraverbeke, S., Rogers, B. M., Goulden, M. L., Jandt, R. R., Miller, C. E., Wiggins, E. B., and Randerson, J. T. (2017) Lightning as a major driver of recent large fire years in North American boreal forests. Nature Climate Change 7: 529–534.

Vihma, T, Graversen, R, Chen, L, et al. Effects of the tropospheric large-scale circulation on European winter temperatures during the period of amplified Arctic warming. Int J Climatol. 2020; 40: 509–529. https://doi.org/10.1002/joc.6225

Vihma, T. and Haapala, J.: Geophysics of sea ice in the Baltic Sea: A review, Prog. Oceanogr. 80, 129–148, 2009.

Vihma, T. (2017). Weather extremes linked to interaction of the Arctic and Midlatitudes. Clim. Extremes 226, 39–50.

Vinogradova, A. A., Smirnov, N. S., and Korotkov, V. N. (2016) Anomalous wildfires in 2010 and 2012 on the territory of Russia and supply of black carbon to the Arctic. Atmospheric and Oceanic Optics 29: 545–550.

Viitasalo et al., 2021. Biogeochemical processes. ESD.

Virkkala, R., and Toivonen, H. (1999) Maintaining biological diversity in Finnish forests. Finnish Environment Institute, Helsinki, 56 p.

Vivchar, A., 2011. Wildfires in Russia in 2000–2008: estimates of burnt areas using the satellite MODIS MCD45 data. Remote Sens. Lett. 2: 81–90.

2696 Volchek A., Korneyev V., Parfomuk S., Bulak I. (2017) Water resources and their forecast according
2697 to the climate change in the territory of Belarus. Brest, Alternativa. 228 p.

2698 Vousdoukas, M. I., Voukouvalas, E., Annunziato, A., Giardino, A., and Feyen, L.: Projections of
2699 extreme storm surge levels along Europe, Climate Dynamics, 47, 3171–3190,
2700 https://doi.org/10.1007/s00382-016-3019-5, 2016.

2701 Vousdoukas, M.I., Mentaschi, L., Hinkel, J. *et al.* Economic motivation for raising coastal flood
2702 defenses in Europe. *Nat Commun* **11,** 2119 (2020). https://doi.org/10.1038/s41467-020-15665-3

2703 Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Verlaan, M., and Feyen, L.: Extreme sea levels
2704 on the rise along Europe's coasts, Earth's Future, 5, 304–323, https://doi.org/10.1002/2016EF000505,
2705 2017.

2706 Vousdoukas, M.I., Mentaschi, L., Voukouvalas, E. et al. (2018) Climatic and socioeconomic controls
2707 of future coastal flood risk in Europe. Nature Clim Change 8, 776–780

2708 Vousdoukas, M.I., Mentaschi, L., Voukouvalas, E. and Feyen, L. (2019). PESETA III – Task 8:
2709 Coastal Impacts, EUR 28243 EN, Publications Office of the European Union, Luxembourg, 2019,
2710 ISBN 978-92-79-63951-7, doi:10.2788/204754, JRC103909

2711 Wallenius, T. (2011) Major decline in fires in coniferous forests – reconstructing the phenomenon and
2712 seeking for the cause. Silva Fennica 45: 139–155.

2713 Walker, X. J., Baltzer, J. L., Cumming, S. G., Day, N. J., Ebert, C., Goetz, S., Johnstone, J. F., Potter,
2714 S., Rogers, B. M., Schuur, E. A. G., Turetsky, M. R., and Mack, M. C. (2019) Increasing wildfires
2715 threaten historic carbon sink of boreal forest soils. Nature 572: 520–523.

2716 Walther A., Jeong J.-H., Nikulin G., Jones C. and Chen D., 2013. Evaluation of the warm season
2717 diurnal cycle of precipitation over Sweden simulated by the Rossby Centre regional climate model
2718 RCA3, Atmos. Res., doi:10.1016/j.atmosres.2011.10.012

2720 Wang XL, Feng Y, Chan R and Isaac V (2016) Inter-comparison of extra-tropical cyclone activity in
2721 nine reanalysis datasets. Atmos Res 181:133-153 doi:10.1016/j.atmosres.2016.06.010.

2723 Wang J, Kim HM, Chang, EKM (2017) Changes in Northern Hemisphere Winter Storm Tracks under
2724 the Background of Arctic Amplification. J Clim 30:3705–3724, doi:10.1175/JCLI-D-16-0650.1.

2726 Wanner H, Brönnimann S, Casty C, Gyalistras D, Luterbacher J, Schmutz C, Stephenson DB, Xoplaki
2727 E (2001) North Atlantic Oscillation - concepts and studies. Surv Geophys 22:321–381

2728 Wasmund N. 1997. Occurrence of cyanobacterial blooms in the Baltic Sea in relation to
2729 environmental conditions. Int Rev Gesamten Hydrobiol 82(2): 169-184.

2730 Wasmund, N. (2002). "Harmful algal blooms in coastal waters of the south-eastern Baltic Sea.," in
2731 *Baltic coastal ecosystems.,* eds. G. Schernewski & U. Schiewer. (Berlin, Heidelberg, New York.:
2732 Springer), 93-116.

2733 Wasmund, N., Kownacka, J., Göbel, J., Jaanus, A., Johansen, M., Jurgensone, I., et al. (2017). The
2734 diatom/dinoflagellate index as an indicator of ecosystem changes in the Baltic Sea. 1. Principle and

handling instruction. Frontiers in Marine Science *Frontiers in Marine Science* 4(22)**,** 1-13. doi: 10.3389/fmars.2017.00022.

Wasmund, N., Nausch, G., and Feistel, R. (2013). Silicate consumption: an indicator for long term trends in spring diatom development in the Baltic Sea. *J. Plankton Res.* 35**,** 393-406. doi: 10.1093/plankt/fbs101.

Wasmund N., Nausch G., Gerth M., Busch S., Burmeister C., Hansen R. & Sadkowiak B. 2019. Extension of the growing season of phytoplankton in the western Baltic Sea in response to climate change. *Mar Ecol. Prog. Ser.* 622: 1-16.

Wasmund N., Nausch G. & Voss M. 2012. Upwelling events may cause cyanobacteria blooms in the Baltic Sea. Journal of Marine Systems 90: 67-76.

Weisse et al. (2021). Sea level variations and change. ESD.

Weyant, John; Azar, Christian; Kainuma, Mikiko; Kejun, Jiang; Nakicenovic, Nebojsa; Shukla, P.R.; La Rovere, Emilio; Yohe, Gary (April 2009). Report of 2.6 Versus 2.9 Watts/m^{2}RCPP Evaluation Panel (PDF). Geneva, Switzerland: IPCC Secretariat.

Whan K, Zscheischler J, Orth R, Shongwe M, Rahimi M, Asare EO et al. (2015) Impact of soil moisture on extreme maximum temperatures in Europe. Weather Clim Extrem 9:57–67, doi: 10.1016/j.wace.2015.05.001

Wilcke, R. A. I., Kjellström, E., Lin, C., Matei, D., Moberg, A., and Tyrlis, E.: The extremely warm summer of 2018 in Sweden – set in a historical context, Earth Syst. Dynam., 11, 1107–1121, https://doi.org/10.5194/esd-11-1107-2020, 2020.

Willison J, Robinson WA, Lackmann GM (2015) North Atlantic Storm-Track Sensitivity to Warming Increases with Model Resolution. J Clim 28:4513–4524, doi:10.1175/JCLI-D-14-00715.1

Witte, J. C., Douglass, A. R., da Silva, A., Torres, O., Levy, R., and Duncan, B. N. (2011) NASA A-Train and Terra observations of the 2010 Russian wildfires. Atmos. Chem. Phys., 11, 9287–9301, https://doi.org/10.5194/acp-11-9287-2011

Wolski, T., Wiśniewski, B., Giza, A., Kowalewska-Kalkowska, H., Boman, H., Grabbi-Kaiv, S., Hammarklint, T., Holfort, J., and Lydeikaitė, Z.: Extreme sea levels at selected stations on the Baltic Sea coast, Oceanologia, 56, 259 –290, https://doi.org/10.5697/oc.56-2.259, 2014.

Woodruff SD, Worley SJ, Lubker SJ, Ji Z, Freeman JE, Berry DI, Brohan P, Kent EC, Reynolds RW, Smith SR, Wilkinson C (2011) ICOADS Release 2.5 and Data Characteristics. Int J Climatol 31:951–967

Woollings T, Barriopedro D, Methven J, Son SW, Martius O, Harvey B et al. (2018). Blocking and its Response to Climate Change. Curr Clim Change Reports 4:287–300, doi: 10.1007/s40641-018-0108-z

Wotton, B. M., Nock, C. A., and Flannigan, M. D. (2010) Forest fire occurrence and climate change in Canada. International Journal of Wildland Fire 19: 253–271.

2774 Wright, D.M., D.J. Posselt, and A.L. Steiner, 2013: Sensitivity of Lake-Effect Snowfall to Lake Ice
2775 Cover and Temperature in the Great Lakes Region. *Mon. Wea. Rev.,* 141, 670–689,
2776 https://doi.org/10.1175/MWR-D-12-00038.1

2778 Xia L, Zahn M, Hodges KI, Feser F (2012) A comparison of two identification and tracking methods
2779 for polar lows. Tellus A 64:17196

2781 Yang W, Andreasson J, Graham LP, Olsson J, Rosberg J, Wetterhall F (2010) Distribution-based
2782 scaling to improve usability of regional climate model projections for hydrological climate change
2783 impacts studies. Hydrol Res 41:211-229.

2784 Yang, W., Gardelin, M., Olsson, J., and Bosshard, T. (2015) Multi-variable bias correction:
2785 Application of forest fire risk in present and future climate in Sweden. Natural Hazards and Earth
2786 System Sciences 15: 2037–2057.

2787 Yu, P., Toon, O. B., Bardeen, C. G., Zhu, Y., Rosenlof, K. H., Portmann, R. W., Thornberry, T. D.,
2788 Gao, R.-S., Davis, S. M., Wolf, E. T., de Gouw, J., Peterson, D. A., Fromm, M. D., and Robock, A.
2789 (2019) Black carbon lofts wildfire smoke high into the stratosphere to form a persistent plume.
2790 Science, 365: 587–590.

2791 Zackrisson, O. (1977) Influence of forest fires on the north Swedish boreal forest. Oikos 29: 22–32.

2792 Zaitseva-Pärnaste, I., Tarmo Soomere, 2013, Interannual variations of ice cover and wave energy flux
2793 in the northeastern Baltic Sea, Annals of Glaciology, 54(62), doi:10.3189/2013AoG62A228

2794 Zappa G, Shaffrey LC, Hodges KI (2013) The ability of CMIP5 models to simulate North Atlantic
2795 extratropical cyclones. J Clim 26:5379–5396, doi:10.1175/JCLI-D-12-00501.1

2797 Zappa G, Masato G, Shaffrey L, Woollings T, Hodges K (2014) Linking Northern Hemisphere
2798 blocking and storm track biases in the CMIP5 climate models. Geophys Res Lett 41:135–139,
2799 doi:10.1002/2013GL058480

2801 Zappa G, Shepherd TG (2017) Storylines of Atmospheric Circulation Change for European Regional
2802 Climate Impact Assessment. J Clim 30:6561–6577. doi:10.1175/JCLI-D-16-0807.1.

2804 Zappa G, Pithan F, Shepherd T G (2018) Multimodel Evidence for an Atmospheric Circulation
2805 Response to Arctic Sea Ice Loss in the CMIP5 Future Projections. Geophys Res Lett 45:1011–1019,
2806 doi:10.1002/2017GL076096.

2807 Zorita, E., T.F. Stocker, and H. von Storch, 2008: How unusual is the recent series of warm years?
2808 Geophysical Research Letters, 35, L24706.

2809 Zscheischler, J., Westra, S., Van Den Hurk, B. J. J. M., Seneviratne, S. I., Ward, P. J., Pitman, A., ...
2810 Zhang, X. (2018). Future climate risk from compound events. *Nature Climate Change*, *8*(6), 469-477.
2811 https://doi.org/10.1038/s41558-018-0156-3

2814 Figures.

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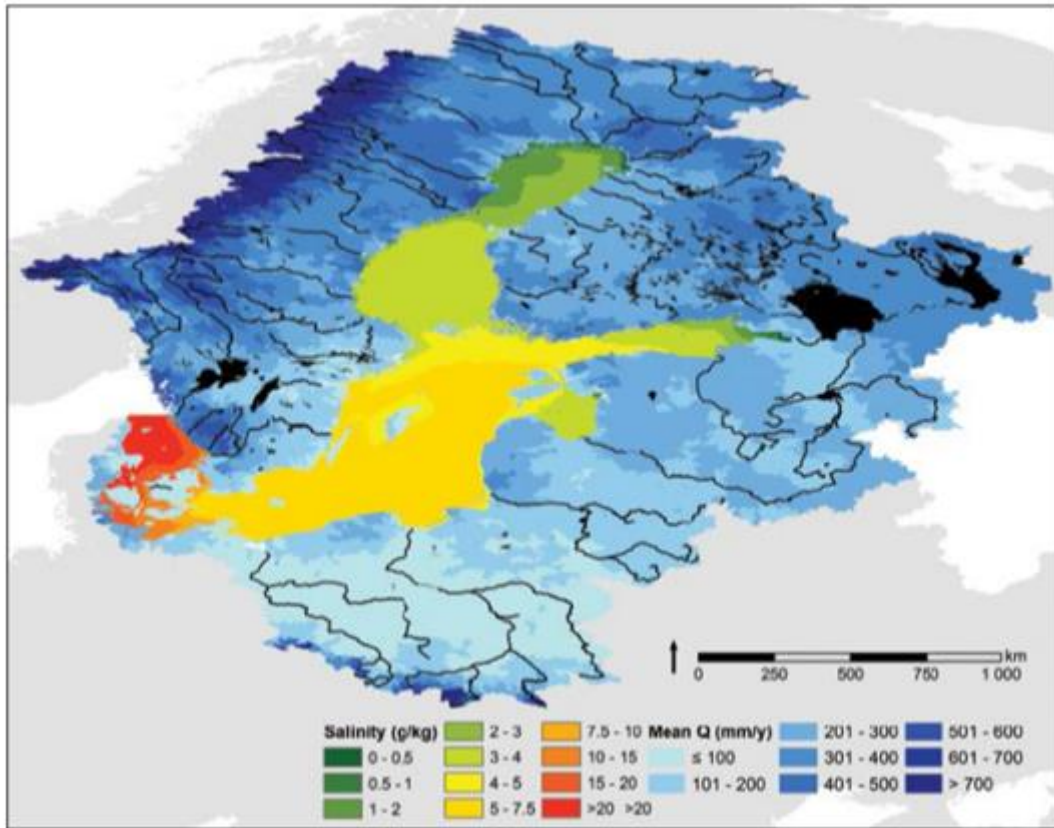
Figure 1. The Baltic Sea drainage basin together with the spatial variability in annual mean water discharge (Q)
calculated with the Hydrological Predictions for the Environment (HYPE) model and with annual mean sea
surface salinity in the Baltic Sea. This salinity diagram shows the gradient from high (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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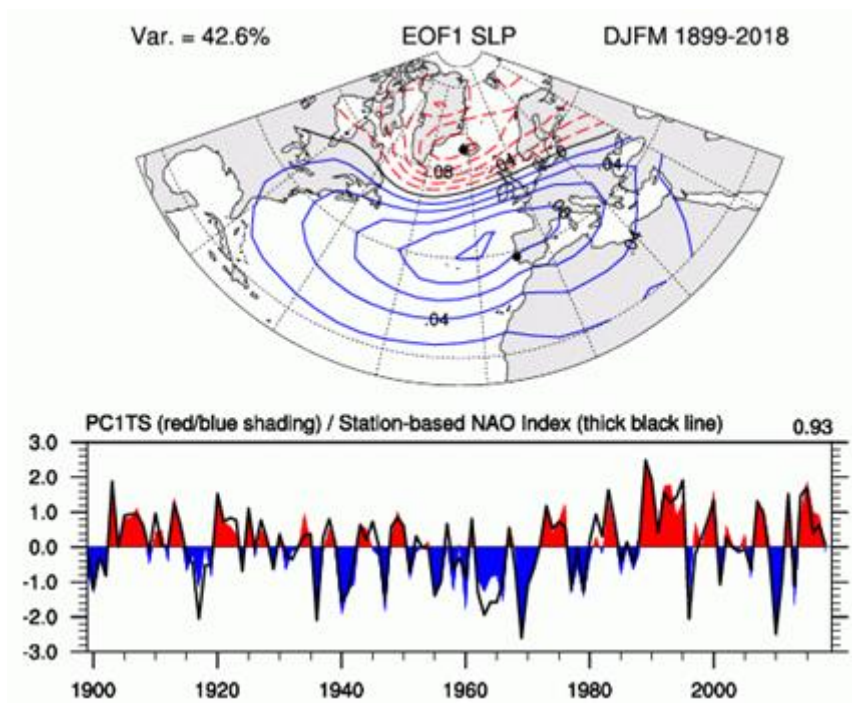
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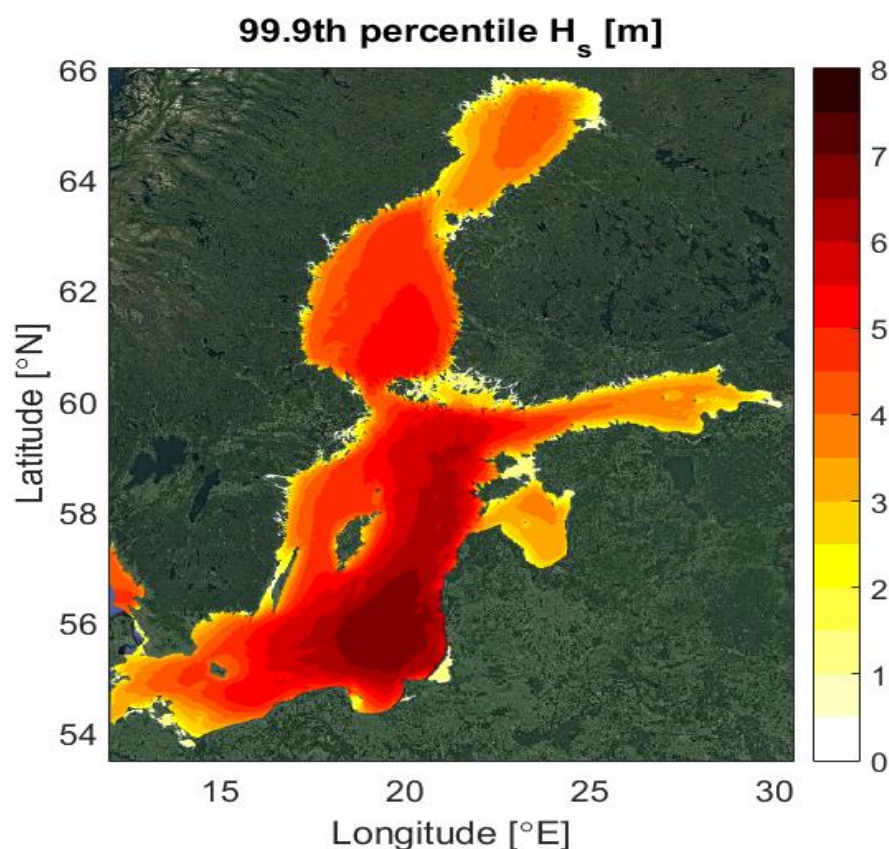
2823 Fig. 2: Principal component (PC) time series of the leading EOF of seasonal (DJFM) SLP anomalies over the
2824 Atlantic sector (20°N-80°N, 90°W-40°E), 1899-2018 (colours) and station-based index (Lisbon and
2825 Stykkisholmur) (black line, see points on map). The correlation is 0.93 over 1899-2018. From Hurrell (2018).

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2827 Fig. 3: Ice-free statistics (Type F in Tuomi et al. (2011)) for the 99.9[th] percentile significant wave height (H_s)
2828 using a high-resolution wave hindcast for the years 1998-2013 (Nilsson et al. 2019).

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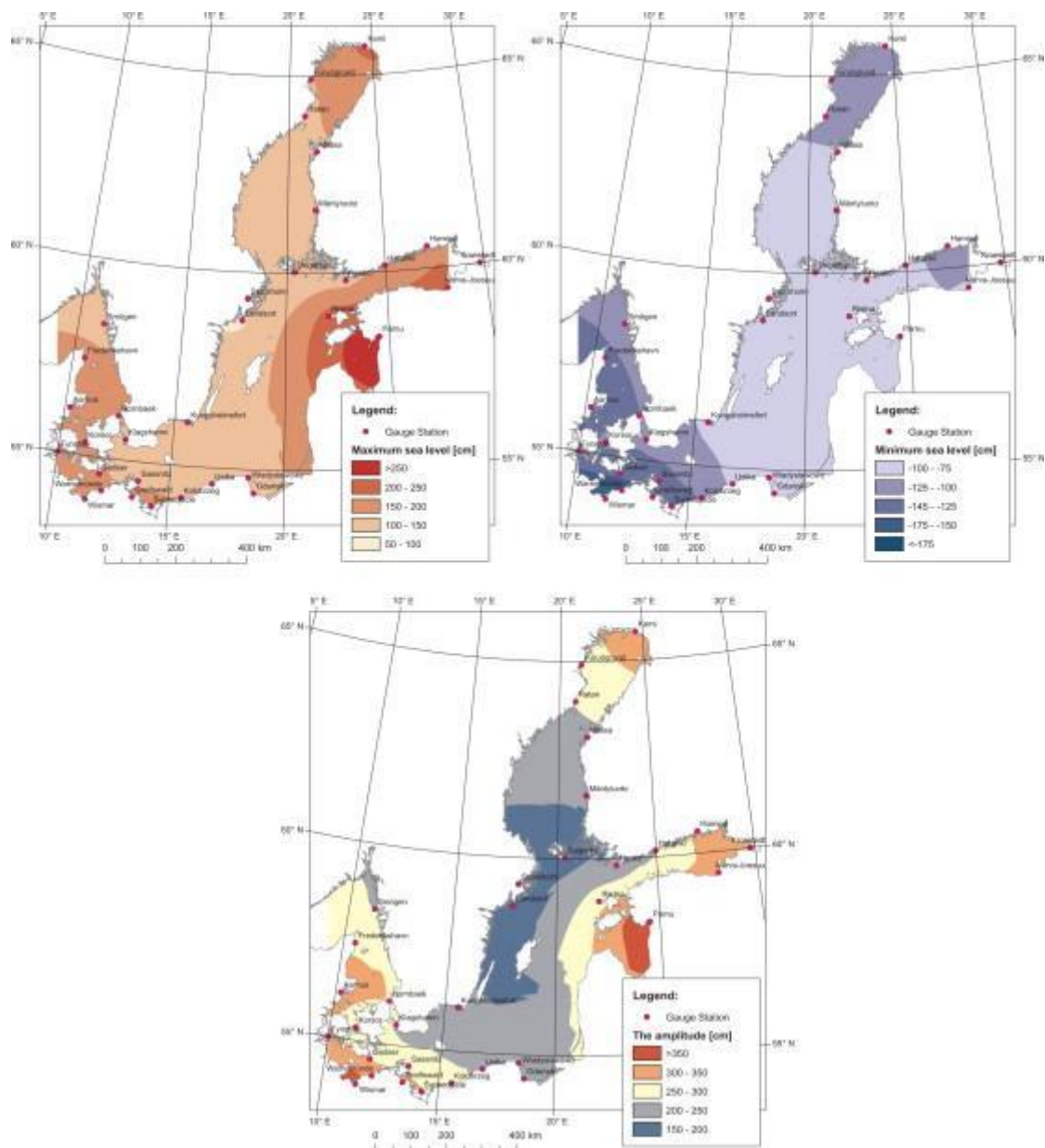
2830 Fig. 4: Surface water topography of the Baltic Sea for maximum levels (a), minimum levels (b) and the
2831 amplitude of variations (c) from the period 1960–2010 (Wolski et al. 2014).

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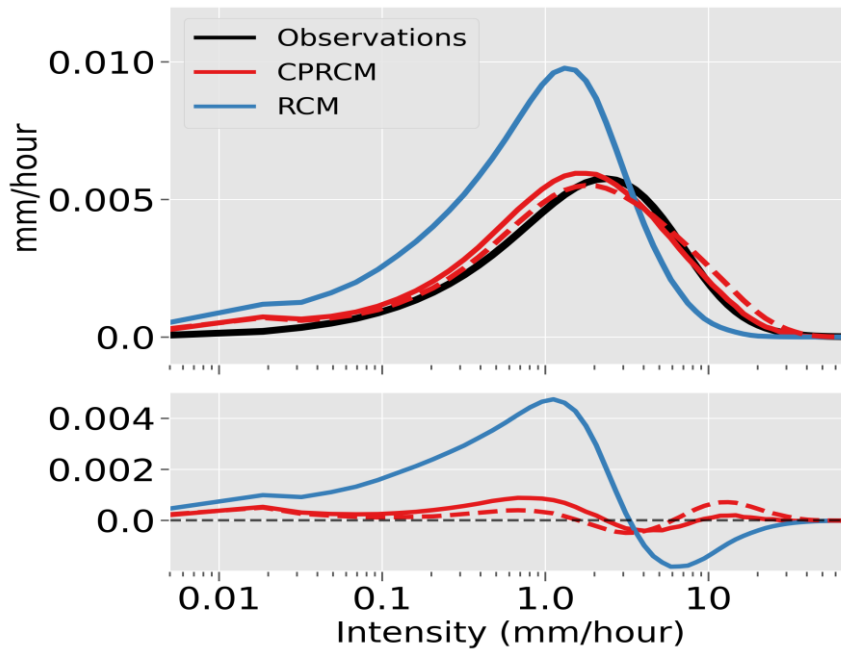
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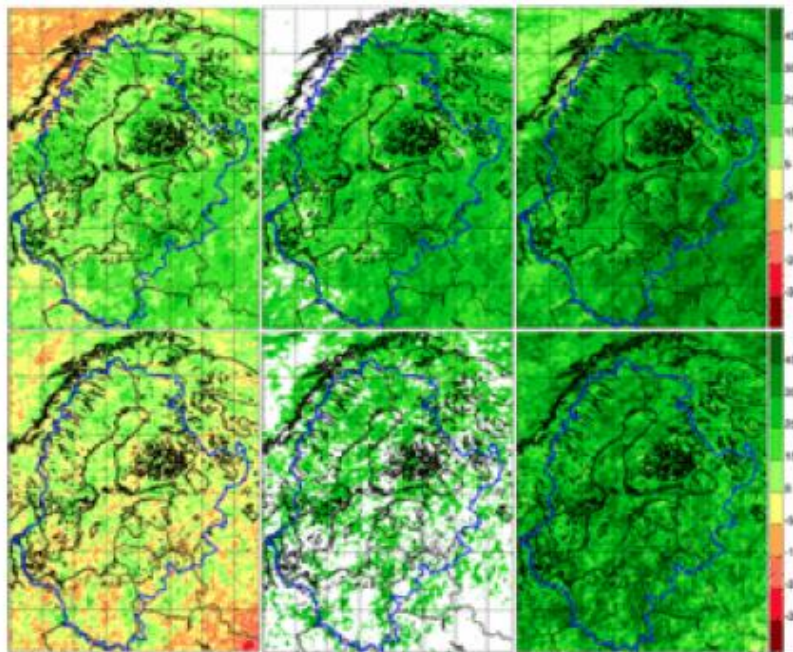
Figure 5 The top panel shows contributions per intensity bin to the total June-August mean precipitation over
Sweden, units in mm per hour. The observations are from a combined radar-rain gauge data set. The lower panel
shows differences w.r.t. the observations. The coarse scale RCM is operated at 12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

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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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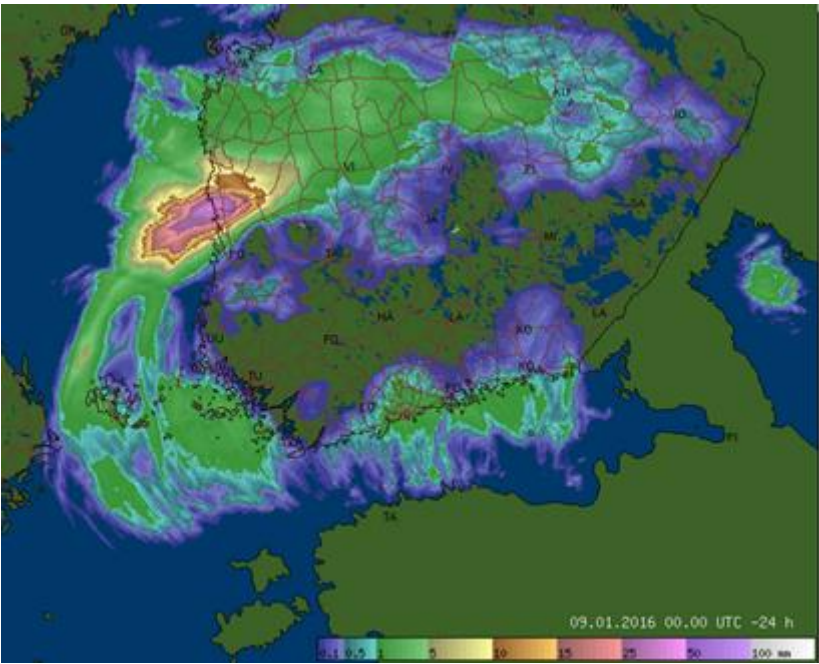
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2847 Figure 7. Radar image of precipitation accumulation (mm/day) during recent national snowfall record in
2848 Finland. The sea-effect snowfall accumulated 73 cm of new snow in less than a day to Merikarvia, Finland in
2849 8.1.2016. Figure from radar service of FMI intranet.

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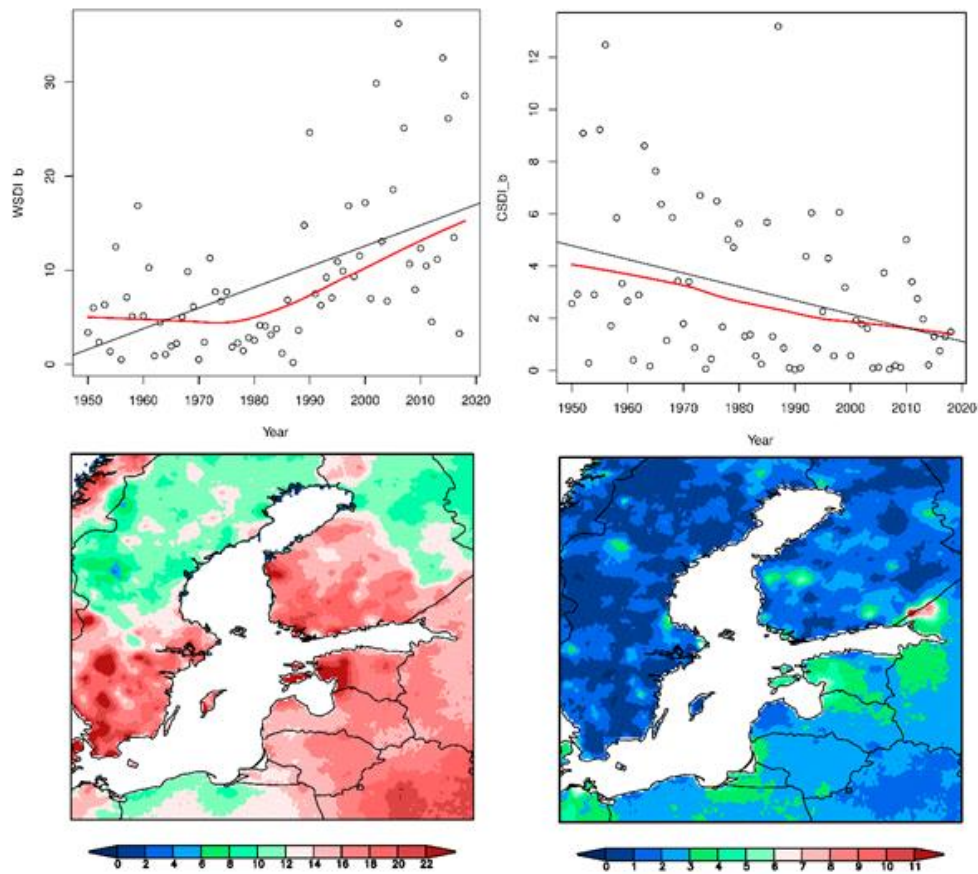
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2853 Figure 8 Annual warm spell duration index (WSDI; left) and annual cold spell duration index (CSDI; left). Top:
2854 Time series of the spatial averages over the area of 53-67N and 12-31E in 1950-2018. A fitted curve and a linear
2855 fit are also shown. Bottom: Spatial distributions of the 30-year means during the period 1989-2018. The baseline
2856 period in the calculations is 1961-1990. Data: wsdiETCCDI and csdiETCCDI created by climind 1.0.0 on 19
2857 Nov 2019; Cornes et al. (2018).

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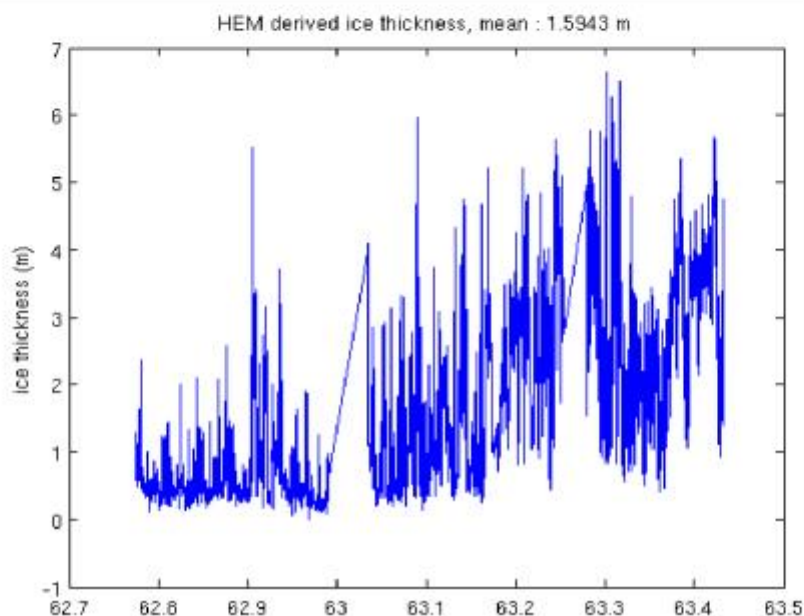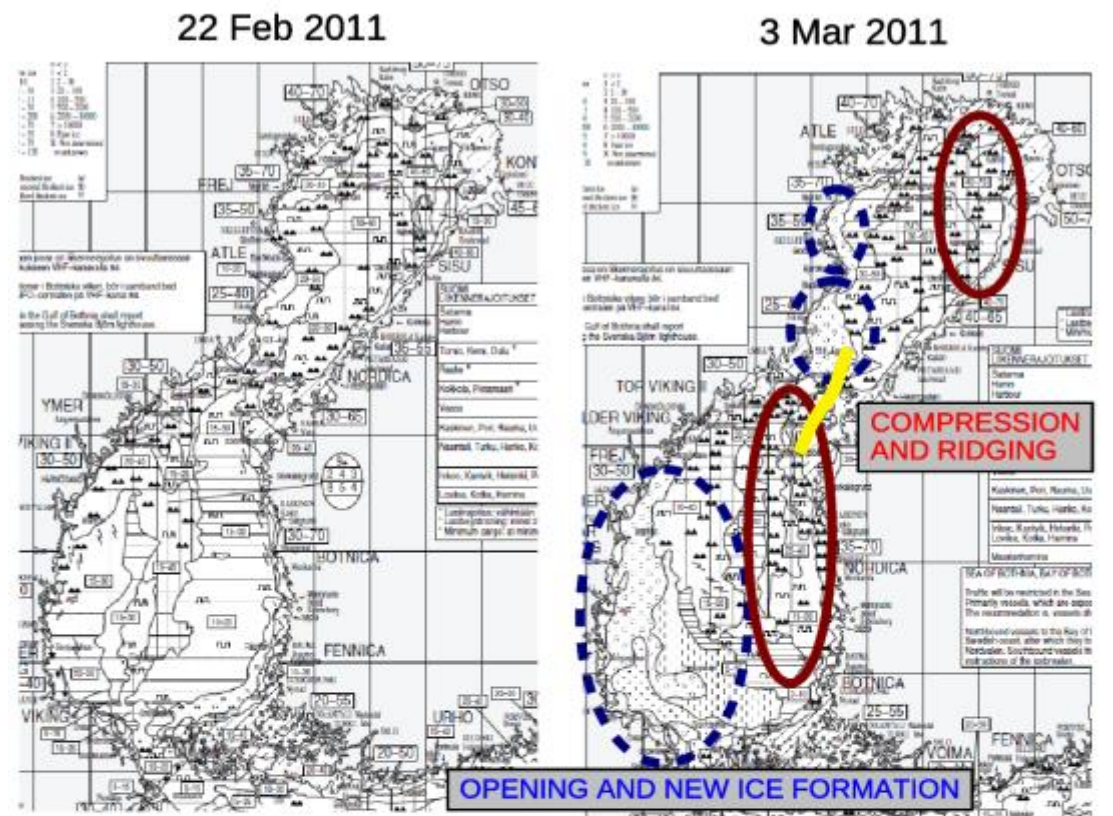
Figure 9. Ice charts before and after the major compression event in February 2011. Regions experienced
opening and compression/ridging are indicated as blue and red circles, respectively. Lower panel depicts ice
thickness along the yellow transect shown in the ice chart above.

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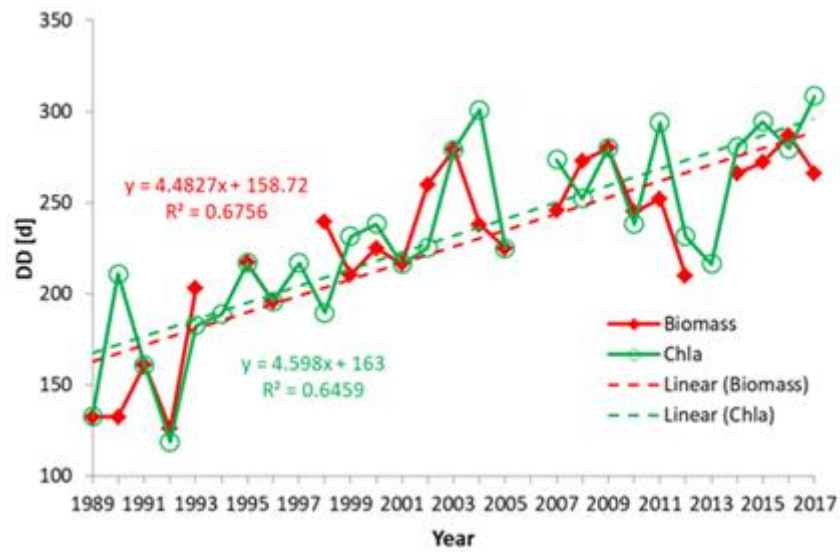
2867 Fig. 10: Trends in the duration of the vegetation period (DD), based on phytoplankton biomass and chl *a* data,
2868 with regression lines and corresponding formulas (Wasmund et al. 2019).

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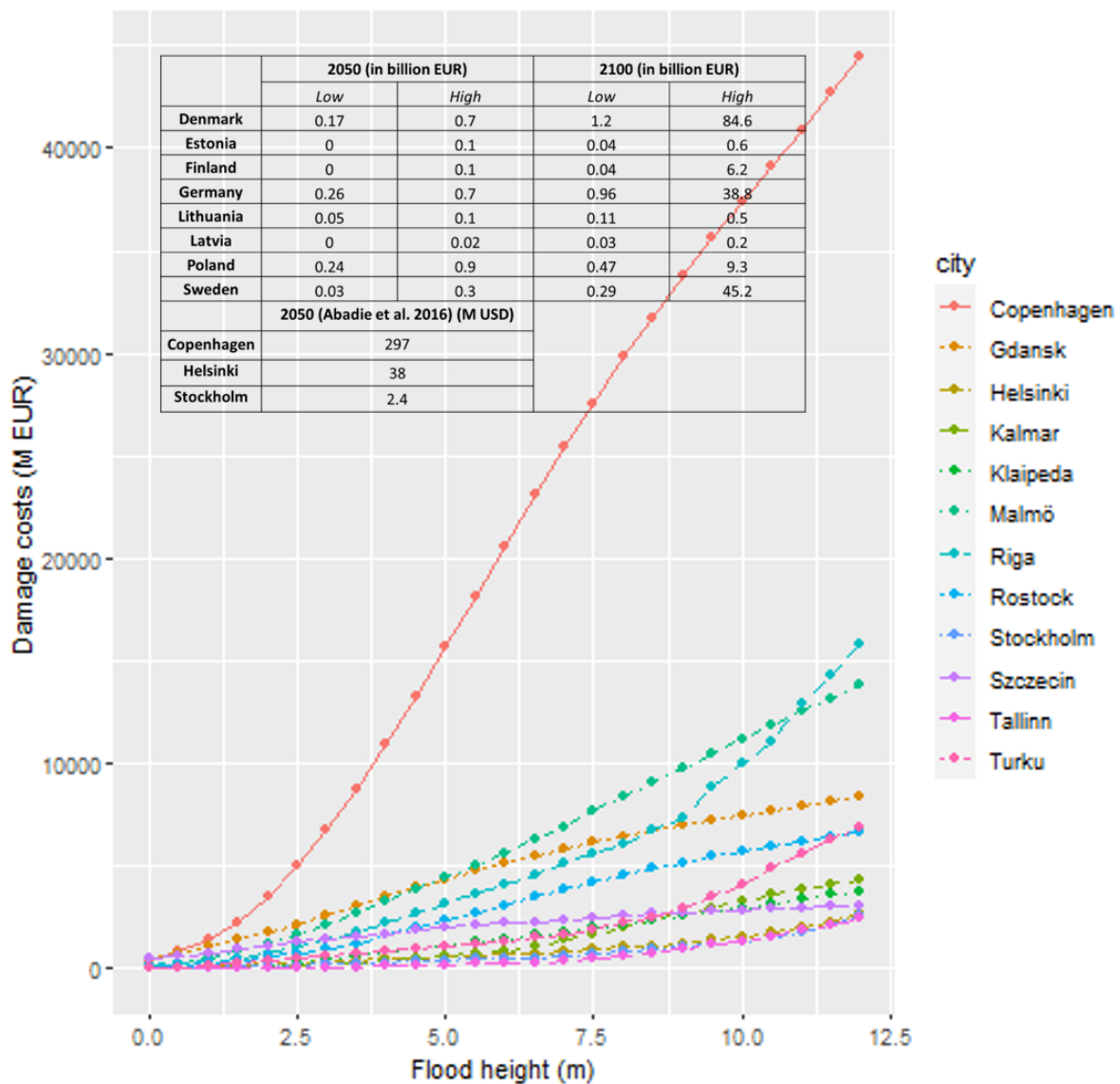
Figure 11. Estimated damage cost curves of a coastal flood event for select cities along the Baltic Sea based on Prahl et al. (2017). The table insert shows high/low estimates of the expected annual damages (EAD) to Baltic countries from extreme water levels by Vousdoukas et al. (2018, 2019, 2020); as 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.

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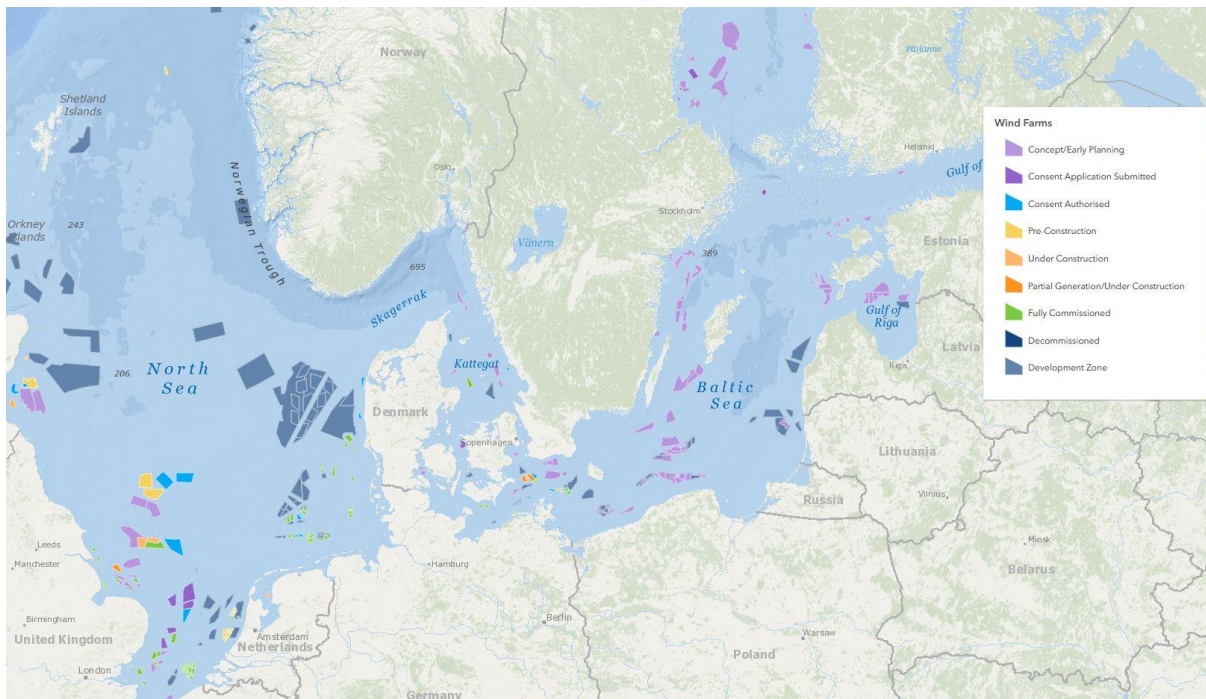
2881 Figure 12 Overview of wind farms over part of the Baltic and the North Sea in different development states
2882 (www.4coffshore.com, 2021-03-09).

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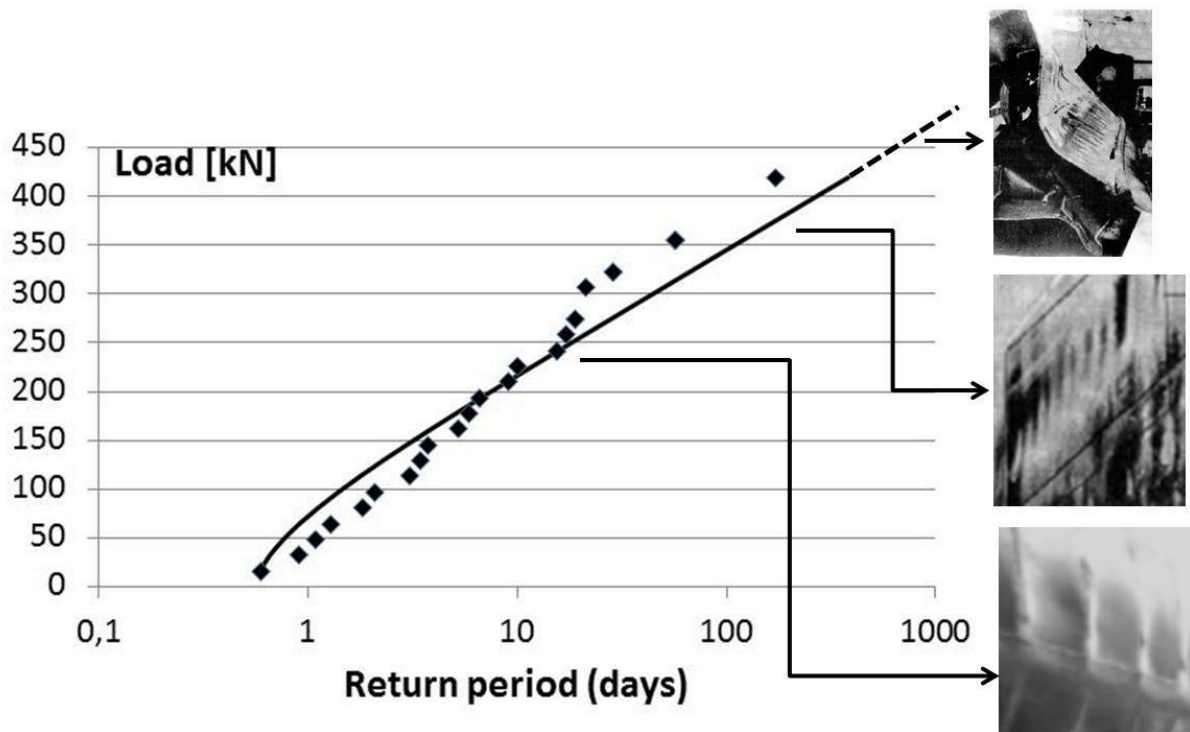
2884 Figure 13. Measured load on one frame at the bow of MS Kemira measured during 1985-1991 (Kujala, 2017),
2885 showing also the possible effect of the increasing load on the damage of the ship shell structures.

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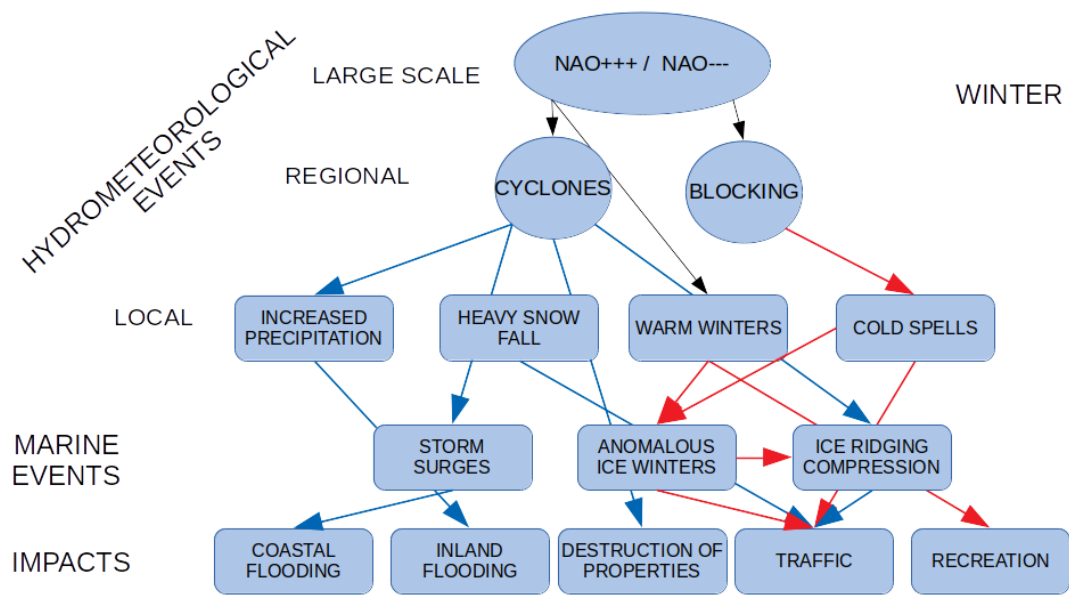
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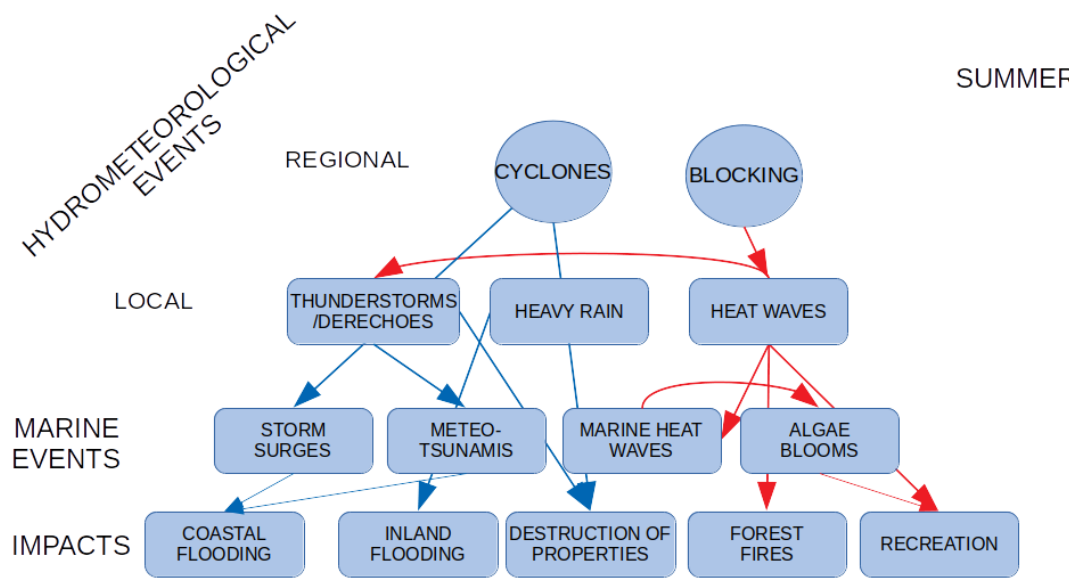
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2891 Figure 14. Simplified diagram to illustrate the relationship between atmospheric, hydrological and marine
2892 processes and their impact on society in winter and summer.

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