# Methods for Coastal Flooding Risk Assessments

## An Overview of Methods used in Scandinavia and the UK and a discussion of their suitability for Iceland

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**Lykilsíða**

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**Útdráttur:**

Loftslagsbreytingar hafa áhrif á fólk á marga vegu og áhrifin munu aukast með tímanum. Einn af mörgum þáttum sem breytast er sjávarstaða. Síðan í upphafi 20. aldar hefur hún risið með auknum hraða og mun að öllum líkindum halda því áfram næstu aldir. Hækkandi sjávarstöðu fylgir aukin flóðahætta sem krefst aðlögunar. Þar gegna hættumat og áhættumat mikilvægu hlutverki, þannig að hægt sé að grípa til við-eigandi aðgerða á réttum stöðum svo að draga megi úr neikvæðum áhrifum sjávarflóða. Sjávarflóð hafa valdið tjóni á Íslandi í gegnum tíðina og munu að líkindum gera það aftur. Ekki er til heildstætt sjávar-flóðaáhættumat fyrir landið en slík vinna er nú í undirbúningi á Veðurstofu Íslands. Til þess að auðvelda undirbúning verkefnisins og val á aðferðum er verklagi nokkurra nágrannaþjóða í þeim efnum lýst í þessari skýrslu, þ.e. Danmerkur, Noregs, Svíþjóðar og Bretlands. Eins er hér að finna umræðu um hversu hentugar aðferðirnar eru fyrir Ísland og í sérstökum bakgrunnskafla er þáttum sem hafa áhrif á sjávar-stöðu, sjávarstöðumælingum og sjávarstöðubreytingum m.a. lýst. Þetta eru í meginatriðum svipaðar aðferðir og notaðar eru við áhættumat í öllum löndunum, en þó með ólíkum útfærslum. Tölfræðilegur endurkomutími flóða og upplýsingar um söguleg flóð eru notaðar til þess að meta hættuna og tjónnæmi er metið í fjórum tjónnæmisflokkum. Loks eru hættumatið og tjónnæmismatið sett saman til þess að meta áhættuna og finna áhættusvæði. Ekki er hægt að fylgja að fullu aðferðum nágrannalandanna við vinnslu áhættumats fyrir Ísland þar sem gögn um söguleg flóð og sjávarstöðubreytingar eru ekki fullnægjandi. Þó er talið að hægt sé að nýta sér hugmyndir erlendu hættumatsaðferðanna við hönnun hættumats fyrir Ísland, jafnvel þótt útfærslan verði ólík. Við mat á tjónnæmi og áhættu þyrfti ekki eins mikla aðlögun að íslenskum aðstæðum.

| **Lykilorð:**<br>Sjávarflóð, sjávarstaða, sjávarstöðuhækkun, áhættumat, náttúruvá | **Undirskrift framkvæmdastjóra sviðs:** |
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# Abstract

Flood risk increases with rising sea levels and coastal settlements need to adapt to this increasing risk. For that, hazard and risk assessments are an important step. Coastal floods have caused problems in Iceland in the past and are thought to do so in the future as well. Therefore, a coastal flooding risk assessment needs to be made for Iceland. A risk assessment is currently in the early steps of preparation and a fitting method needs to be developed. To facilitate the process, an overview of the methods used in neighbouring countries is provided here and the suitability of the methods for Iceland is discussed.

**Keywords:** Coastal flooding, sea level, sea level rise, risk assessment, natural hazard

# Contents

# 1  Introduction

The dynamic world we live in is continuously changing and developing. Changes in one field often lead to shifts in others. Since the industrial revolution, human lifestyle has significantly influenced the Earth's atmospheric composition, which is directly and indirectly an important factor in a delicate balance of numerous natural phenomena. Anthropogenic actions have thus caused, or sped up alterations in various phenomena, many of which directly impact humans (IPCC, 2013). One such aspect is sea level. Sea levels have been rising with increasing rates since the early 20$^{th}$ century and are virtually certain to continue to do so for centuries to come (Church, Clark, et al., 2013). About 70% of 1970 - 2005 sea level rise has been attributed to human activities (Aimée B. A. Slangen et al., 2016) and rising sea levels cause increased flood risk to which we need to adapt (Church, Clark, et al., 2013). For that, hazard evaluation and risk analysis are important so that suitable preventive measures can be taken in appropriate areas to reduce the negative impact of coastal flooding events (European Union, 2007). These can e.g. be in the form of physical defences and awareness in coast-near planning (Quante and Colijn, 2016). Work on risk analysis and adaptation is in different stages in the countries of the world.

Coastal floods have caused problems in Iceland in the past (Jóhannsdóttir, 2017) and are likely to do so in the future as well. Large coastal floods can be expected in Iceland every 10 - 20 years and the probability of such events can rise with climate change (Almannavarnir, 2011). The rising mean sea levels are significant drivers of increased flood risk but other factors play a big role as well (Church, Clark, et al., 2013). Vertical isostatic movement is fast in Iceland and therefore, its pattern will be an important factor in determining spread and severity of future floods in the country (Björnsson et al., 2018). Other factors that are more difficult to predict, such as storm tracks and -intensity, are also likely to play an important role in future extreme sea level events (Church, Clark, et al., 2013). As part of a coastal protection process, municipalities can request assessment for specific locations which may then be added to a coastal protection plan (Siglingastofnun, 2011), and according to the civil protection authorities, several regions have highlighted the need for risk analysis and measures in this regard (Almannavarnir, 2011). However, an overall coastal flooding risk analysis has been lacking, and the Meteorological Office of Iceland (IMO) has instigated work on a coastal flooding risk analysis for the country, as part of a more general risk assessment of flooding hazards.

A vital step in the risk assessment preparation is to look at how these are made in other countries to learn from them. It is thus in IMO's interest to receive an overview of methods used in neighbouring countries. Hence, an overview of coastal flooding risk assessment methods in Denmark, Norway, Sweden and the UK is provided in this report. As hazard evaluation is an essential early step of risk analysis that has yet to be carried out in Iceland, emphasis is put on hazard estimation description where possible. To set the stage, emphasise the importance and motivation behind coastal flooding risk analysis and introduce the challenges of such assessments, a separate chapter that introduces different aspects of the hazard of coastal flooding, both in general and specifically in the countries of interest is presented first. There, sea levels, sea level measurements and sea level rise are explained as well as extreme sea level events. Following the overview of coastal flooding risk assessment methods, their suitability for application in Iceland is discussed and conclusions are drawn.

This report seeks to answer three main research questions: *a) What methods are used to monitor sea level rise in the Scandinavian countries and the UK?, b) What methods are used to assess the risk caused by the hazard of sea level rise in Scandinavia and the UK?* and *c) Are any of these methods suitable for Iceland?* The first subject is covered in section 2.2.1, question b) is answered in chapter 3 for each country and then summarised in the discussion and question c) is discussed in the discussion as well. An encapsulated answer to all the questions is then provided in the conclusion. This work was conducted as a part of a masters thesis (Jóhannsdóttir, 2019). There, it was also shown that a hazard assessment can be made through a scenario production and used as a part of risk analysis if further developed.

# 2 Background

In the past few decades, climate change science has developed significantly with an impressive number of various climate change related research papers published each year (IPCC, n.d.). One aspect of climate change is the ongoing global mean sea level rise that is virtually certain to continue for centuries to come. Global mean sea level has likely been rising with increasing rate since the early 20$^{th}$ century and it is thought very likely to outpace the rate of 1971-2010 in the 21$^{st}$ century for all the RCP scenarios of IPCC (see appendix A) (Church, Clark, et al., 2013) . Linked to rising mean sea level, there has likely been an increase in extreme coastal high water in the late 20$^{th}$ century. An increase in future sea level extremes is also expected to follow increased mean sea level in the future (Seneviratne et al., 2012). The return period of events where a given threshold is surpassed can decrease drastically with higher mean sea level (Church, Clark, et al., 2013). Several recent studies (see e.g. Buchanan, Oppenheimer, and Kopp, 2017; Fletcher et al., 2017) have shown that a considerable increase in the amount of extreme water levels can result from moderate mean sea level rise.

Rising mean sea levels can have great impact on coastal settlements and many will face distinct problems because of that in the 21$^{st}$ century. They can increase flood risk, influence erosion and coastal ecosystems, impact groundwater quality by salt water intrusion, change river sediment deposition, cause passive high-tide inundation of low-lying coastal areas and cause higher order impacts on nature and societies derived from the previously mentioned effects (Madsen, 2009; Mimura, 2013; Vitousek et al., 2017; Wahl, Brown, et al., 2018; Wong et al., 2014). One of these challenges is the increased frequency of oceanic floods. The more frequent high sea level events further generate increased flooding and/or erosion risk and will affect marine ecosystems. Hence, coastal communities can be significantly impacted and need to react to the changes (Wahl, Brown, et al., 2018). A further complication follows the uncertainty of the changes in magnitude and frequency of the floods and the impact they will have.

The rising sea levels have already started to cause problems in certain areas, extreme sea level return frequency has already increased significantly at multiple places (Church, Clark, et al., 2013). There are concerns that low lying countries and small islands will loose land area both due to inundation and erosion in the future, even in worst cases so that a considerable proportion of their populations or even the whole population will have to migrate to other countries (Mimura, 2013; Nicholls and Cazenave, 2010). Many large coastal cities, for instance London, Hamburg, Rotterdam, Tokyo, Shanghai and Bangkok already rely heavily on coastal defences. Shanghai and Tokyo have already defended them selves against a few metre sea level rise and the UK and Netherlands have decided to defend their cities against 21$^{st}$ century sea level rise. However, not all consequences of flood protection are welcome, as experience shows that defences have a tendency to attract people to move to the floodplain, which then increases the risk of disastrous consequences in the case of the defences breaching (Nicholls and Cazenave, 2010; Wong et al., 2014). Protection against several metre sea level rise is not possible everywhere, e.g. on small islands (Wong et al., 2014) and necessary adaption responses can outrun the capacity of some small islands in terms of financial and human

resource requirements, possibly leading to impoverishment and further challenges (Esteban et al., 2019).

In this chapter, an overview of the factors affecting global and local sea level, available sea level data, observed sea level changes, future sea level projections, the causes of extreme sea levels and future extreme sea level projections will be provided with a special discussion of these factors for the countries of interest; Denmark, Norway, Sweden, Great Britain and Iceland. These sections give an overview of the theoretical background of coastal flooding research and the various affecting factors that need to be thought of in terms of coastal flooding, both globally and locally. They give an insight into the increasing risk and the challenges of coastal flooding studies as well as the available data to work with when assessing the hazard for both present and future conditions. Hence, it should provide an overview of factors that it will be good to keep in mind when a method for risk assessment for Iceland is designed, both in general and to compare Icelandic conditions to those of the countries of interest when looking into their methods.

## 2.1   Factors affecting sea level

Changes in mean sea level occur over every temporal and spatial scale. They result from aspects of climate change, mainly thermal oceanic expansion and melting of ice on land, and climate variability such as wind forcing changes caused by NAO (North Atlantic Oscillation) or El Niño variability (Quante and Colijn, 2016; Rhein et al., 2013). Of the observed 20th century global mean sea level rise, 75% can be traced back to the combined effects of thermal expansion of the ocean and the melting of glaciers. The proportional contribution of ice-sheets to the sea level rise has risen over the last decades and is expected to increase significantly towards 2100 and onward. The Antarctic ice sheet has the most potential of contributing to sea level rise but up until now, the Greenland Ice Sheet has been a larger contributor (Church, Clark, et al., 2013). In 2006 - 2015, the combined sea level rise from melting glaciers and ice sheets exceeded the effect of thermal expansion of the ocean and was the dominant force of sea level rise. It is likely that ice mass loss from Antarctica in 2007 - 2016 was triple that of 1997 - 2006 while mass loss from Greenland doubled over the same period (IPCC, 2019).

Regional sea level changes may, however, differ considerably from mean sea level changes. Satellite altimetry data and tide gauge records (see chapter 2.2) have clearly shown that sea level changes are not uniform around the globe (Church, Clark, et al., 2013; Church and White, 2011; Hay et al., 2015; A. B. A. Slangen et al., 2014). An example is that over the period of 1993-2012, areas in the Western Pacific experienced three times faster sea surface height raise than the global average while in the Eastern Pacific, sea surface height decline was evident (Church, Clark, et al., 2013). Thus, regional sea level research is important to be able to produce more reliable region specific sea level projections (Quante and Colijn, 2016).

Regional sea levels are rather associated with natural or anthropogenic climate modes in e.g. ocean dynamical processes, sea floor movements and gravity changes as a result of water mass redistribution, than factors that contribute to changes in the global average (Church, Clark, et al., 2013). Ocean water density alters due to changes in temperature or salinity. These variations affect the

ocean volume and result in steric height changes. Since the total salt load is relatively constant on a global scale, the steric changes are dominated by the temperature effect on a global scale. On a regional scale, the salinity effect can be of a similar magnitude and often these counteract each other (Ivchenko et al., 2007; Madsen, 2009). Changes in influx, evaporation, wind and air pressure, ocean current variability and gravity changes due to mass redistribution are also important for local sea level. Additionally, the relative sea level, that is the sea level relative to land, is dependent on the regional isostatic rebound or isostatic depression of the area, i.e. land uplift after mass removal (e.g. melting of ice sheets) or land depression due to increased loading (e.g. ice sheet growth) respectively. Other physical processes such as tectonics, erosion, sediment deposition, sediment compaction or groundwater storage changes can cause coastal changes and have significant local effects on relative sea level (Mimura, 2013; Simpson, Nilsen, et al., 2015).

The processes affecting regional sea levels have effects on different time scales and thus the relative contributions to sea level variation depend on the timescales of consideration. Although sea level rise is evident at most coastlines, coastal areas close to former and current ice sheets and glaciers usually experience relative sea level decline. This is caused by the ice mass itself. The ice has gravitational pull so that the ocean is attracted towards it. As the ice melts, this gravitational attraction declines which results in regional sea level fall. The ice melt also results in decreased loading on the crust which leads to land uplift in the area, further lowering the relative sea level. Farther away from the melting ice sheets, sea level rise is enhanced compared to the global mean due to the additional ocean water. Maps of this effect are often referred to as maps of the *fingerprint* of the melt (Björnsson et al., 2018; Church, Clark, et al., 2013).

### 2.1.1 Main factors affecting sea level in Scandinavia, the UK and Iceland

In the cold Nordic Seas and Arctic Ocean, salinity changes can influence steric height changes as much as temperature changes. Neither can the halosteric contributions to steric height changes be neglegted in the North Atlantic. In other areas, temperature is often the dominant factor (Ivchenko et al., 2007; Simpson, Nilsen, et al., 2015). In the North- and Baltic Seas, the winter NAO (North Atlantic Oscillation) index influences the regional sea level variability pattern on a decadal scale, mainly through wind and pressure forcing but also through steric effects (Dangendorf, Calafat, et al., 2014; Dangendorf, Wahl, et al., 2012; Madsen, 2009; K. Richter, Nilsen, and Drange, 2012; Yan, Tsimplis, and Woolf, 2004). Decadal sea level variability over open North Atlantic ocean, especially the Subpolar North Atlantic, in the satellite altimetry era has been found to be driven by steric changes. Wind also influences low frequency dynamic sea level variability along the European shelf (Chafik et al., 2019). It has also been suggested that NAO wind forcing plays an important role in regional North Atlantic coastal sea level variability on annual to centennial timescales (Saher et al., 2015).

In Denmark, the dominating factor controlling mean sea level variability on a few year timescale is wind, while steric changes have the largest influence over decades (Dangendorf, Calafat, et al., 2014). On short timescales, atmospheric pressure variations have the largest influence on mean sea level variability at the Norwegian coasts while factors controlling steric height have increasing effect with extended timescales. On timescales up to a few years, steric height variations due to

temperature and salinity have slightly lesser influence on coastal sea level fluctuations in than the air pressure effect, which is the most important contributor. At decadal timescales, temperature and salinity have roughly equal influence to that of atmospheric pressure. In general, the effect of wind driven circulation, which generates steric changes, increases with longer timescales (Calafat, Chambers, and Tsimplis, 2013; Dangendorf, Calafat, et al., 2014; K. Richter, Nilsen, and Drange, 2012; Simpson, Nilsen, et al., 2015). For Sweden, it has been found that over the period of tide gauge observations, wind was the most influential factor on sea level variability in the Baltic Sea while in the North Sea it is primarily tidal. Along the Swedish coast, wind forcing is the primary driver of sea level extremes but less so for the Kattegat/Skagerak region than for the Baltic (M. Hieronymus, J. Hieronymus, and Arneborg, 2017). Like in Norway, atmospheric pressure is the most influential contributor to mean sea level changes on timescales up to a few years in the UK but steric changes dominate on decadal timescales (Dangendorf, Calafat, et al., 2014). A strong correlation between a reconstruction of the NAO index and detrended relative salt marsh sea level records as well as a positive correlation between Reykjavík tide gauge data and air pressure and wind speed suggest that wind pattern variations connected to shifts in NAO control Icelandic sea level variability. Long periods of a positive NAO index, that is with strong Icelandic lows, cause a sea level rise along the West coast of Iceland. Maximum rates of sea level rise in West Iceland in the past few centuries have been linked with large shifts in the NAO index from negative to positive. No strong evidence of other factors affecting the rapid sea level trend were found (Saher et al., 2015).

The fingerprint of the melting Greenland ice sheet causes an absolute sea level fall in its vicinity and hence greatly affects the sea level in Iceland and the UK (Björnsson et al., 2018; Palmer et al., 2018). This effect has no to a small sea level fall effect on the absolute sea level around Scandinavia. Along Norway's western coast and Sweden's northeastern coast, the melting of Greenland will cause a small sea level decrease while it will have very little impact around Denmark, southern Sweden and Norway's Southeast coast (Simpson, Nilsen, et al., 2015).

The most significant contributor to long term relative sea level trends in Scandinavia is undoubtably the isostatic rebound after the melting of the Fennoscandian ice sheet at the end of last ice age. The rate of uplift can be assumed to be constant for timescales of hundreds of years but it differs regionally depending on the thickness of the former Fennoscandian ice sheet. It varies so that it is fastest by the Swedish coast around Kvarken in the Gulf of Bothnia and decreases in all directions from there (figure 1) (Lantmäteriet, n.d.(b); Nerheim et al., 2017). The traditional view of isostatic rebound in Denmark used to be that the northern part was slowly rising while the southern and western parts were sinking. This was estimated from an assumed absolute sea level rise along with relative sea level trends. However, an underestimation of land uplift is probable in these assessments (Madsen, 2009). A land uplift model for Denmark produced by DTU Space with GNSS data from Geodatastyrelsen, precision levelling and the Danish Meteorological Institute's water level data, shows land uplift of just under 2 mm/yr in northern Denmark and down to almost 0 mm/yr in the South (Miljø- og Fødevareministeriet / Miljøstyrelsen, DTU Space, and Geodatstyrelsen, 2016). In (figure 1), the land uplift relative to the geoid from the official NKG2016LU land uplift model (Olav Vestøl et al., 2019) that was developed in 2016 and is used in the Nordic and Baltic countries, is shown for the Scandinavian countries of interest. The results of the model are in agreement with DTU Space's model; in most of Denmark, the land uplift relative to the geoid is 0-1 mm/year while

the northernmost part of Jutland reaches 2 mm/year. For Norway, the uplift along the coast varies between 1-5 mm/yr according to Simpson, Nilsen, et al. (2015). NKG2016LU shows coastal uplift of 1 - 4.5 mm/yr for the Norwegian coast and the corresponding numbers for Sweden vary between 1 and 10 mm/yr. In Sweden, the land uplift is slowest in the South at around 1 mm/year in Skåne (Lantmäteriet, n.d.(b)).

A smaller ice sheet that covered Ireland and most of Britain at its maximum extent, the Celtic ice sheet, was situated on the forebulge of the Fennoscandian ice sheet during last ice age. The melting of this ice sheet also caused an isostatic rebound in the UK (Shennan, Bradley, and Edwards, 2018). The northern parts of the British isles are rising, centered at the mountainous region of Scotland, while the southern coasts are subsiding (figure 1) (Bradley et al., 2009; Shennan, Milne, and Bradley, 2012; Wahl, Haigh, et al., 2013). This pattern is correlated with the thickness and extent of this most recent ice sheet in the area. The maximum vertical uplift velocity is $1.07 \pm 0.35$ mm/yr around Edinburgh and the fastest subsidence rate is $-1.2 \pm 0.40$ mm/yr around England's easternmost region (Bradley et al., 2009).

The melting of Iceland's glaciers causes a fingerprint effect so that absolute sea levels fall in their vicinity. The low viscosity of the mantle under Iceland causes the isostatic response of the Icelandic crust to happen unusually fast. Hence, even though Iceland too was covered with an ice sheet during the last ice age, the resulting isostatic rebound was finished thousands of years ago. However, there
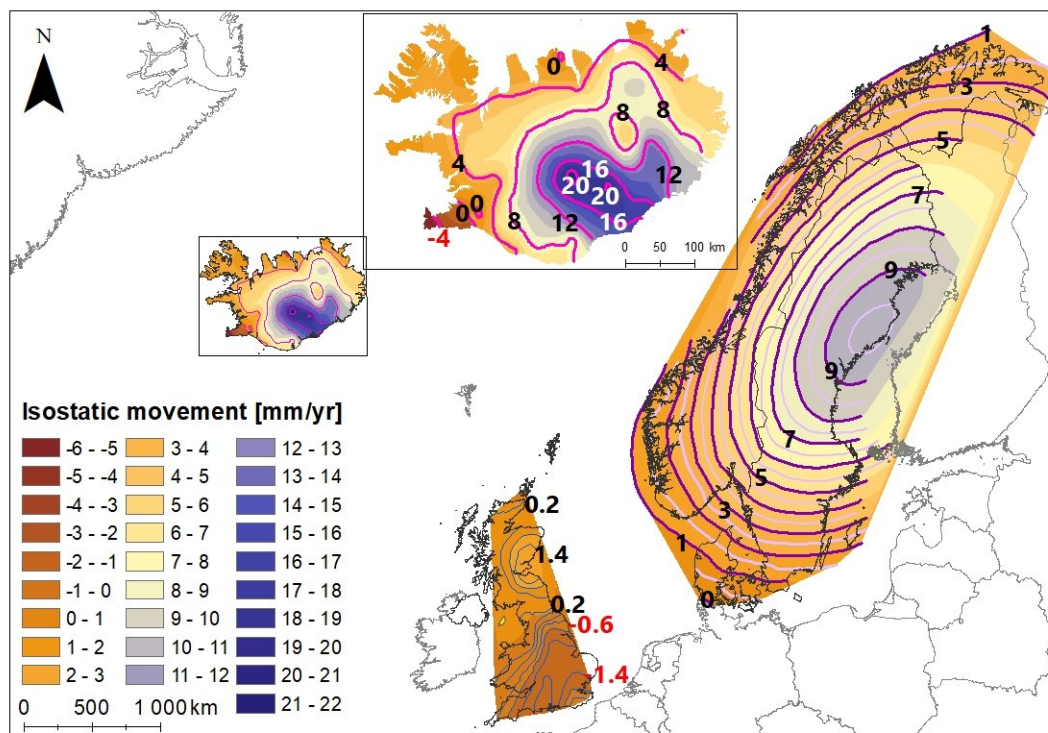


*Figure 1* Absolute vertical isostatic changes in the countries of interest [mm/yr]. Scandinavia: Land uplift relative to the geoid, modified from the Nordic Geodetic Comission's levelled land uplift model NKG2016LU_lev (Lantmäteriet, n.d.(b)). UK: Based on CGPS data, modified from figure 1b p. 16 in Bradley et al. (2009). Iceland: Based on 1993 - 2004 GPS data, modified from figure 5.18, p. 101 in Björnsson et al. (2018).

are ongoing isostatic changes in Iceland. The vertical motion of the Icelandic crust is very region specific with the fastest uplift in the Southeast close to the largest glacier, and a general land rise along the southern coast and in the countries interior (figure 1). This rise results from recent melt of the Icelandic glaciers, which have been melting since the late 19th century. An acceleration in land uplift is even evident in the Southeast. STL analysis of vertical GPS measurements in 1997-2015 from Höfn in Hornafjörður show over 8 mm/yr uplift in the first eight years of measurements and a rate of almost 14 mm/yr in the latter eight years. Along the coast, subsidence is evident in some areas. The Reykjanes peninsula subsides the fastest, peaking at the South-Western most point. The divergent plate boundary and local geothermal energy production cause subsidance in the area. Much of the western coast and the middle of the northern coast is also subsiding. The causes of the land subsidence in the latter are not yet known and need to be investigated further. They are perhaps caused by tectonic movements (Árnadóttir et al., 2009; Björnsson et al., 2018).

## 2.2    Sea level data

The oldest near continuous sea level data series in the world is from Stockholm where manual relative sea level measurements began in 1774 (SMHI, 2018b). Even older intermittent sea level information from Amsterdam exist from 1700 (Rhein et al., 2013). Today, two main methods are being used in the world to monitor sea level changes; tide gauges and satellite altimetry. Tide gauges measure relative sea level, that is the sea level relative to a fixed point on land (Dangendorf and Marcos, 2018; Hamlington and Thompson, 2016). A few near continuous tide gauge records exist that reach back to early 19th century but most series are much shorter (Hamlington and Thompson, 2016). In contrast, satellite altimetry has only been available since the early 1990's. Satellite altimetry measures the sea surface height, namely the sea level compared to a fixed reference frame (the center of the earth, the geoid or a reference ellipsoid) for latitudes up to 66° N and S (ESA and CNES, n.d.; National Center for Atmospheric Research Staff, 2016; Quante and Colijn, 2016). Now, additional altimeters at different orbits perform slightly less accurate measurements up to 82° N and S (Rhein et al., 2013). These records are used to estimate sea surface changes and calculate global mean sea level, a temporal average sea level averaged over the oceans (Church, Clark, et al., 2013).

Since the tide gauges measure the ocean elevation relative to a point on land, vertical land motion needs to be taken into account when estimating sea surface changes (Hamlington and Thompson, 2016; Quante and Colijn, 2016). The land motion can be caused by natural processes, such as glacial isostatic adjustments or tectonics, and/or anthropogenic processes, for instance land subsidence due to groundwater abstraction (Dangendorf and Marcos, 2018; Quante and Colijn, 2016). The distribution of gauges is not optimal. They are unevenly spread along the coastlines of the world, clustered around heavily populated areas with a great majority in the Northern Hemisphere. This uneven distribution and local factors influencing sea level make mean global sea level calculations problematic since sea level changes are not uniform. Hence, many different factors need to be taken into account in mean global sea level calculations from tide gauge networks (Hamlington and Thompson, 2016; Meyssignac et al., 2018). Complicating things further, there exists no global reference system for tide gauge sea level measurements so that the different national data varies considerably (Dangendorf and Marcos, 2018). The satellite altimetry data series do not provide data as far back in time

and are of poorer temporal resolution. The temporal resolution of tide gauges can be of the order of minutes while satellite temporal resolution depends on the return period of the orbit. Satellite altimetry does, however, provide better spatial resolution and is not dependent on the isostatic movement of points fixed on land. Therefore, the global mean sea level can be calculated more easily and with less uncertainties from satellite altimetry. Attempts have been made to combine the strengths of both data sets, combining them by projecting spatial variations in satellite altimetry data on tide gauge data variability. Mean sea level changes of the 20th century are reassessed by these methods, probably improving global mean sea level estimates (Church and White, 2011; Dangendorf and Marcos, 2018; Hamlington and Thompson, 2016; Ray and Douglas, 2011).

While instrumental data gives valuable information on local and global sea levels for the time span of the instrumental record, it only provides information of a relatively short interval. Proxy records from salt marsh sediments and fossils therein and archeological evidence can be used to indirectly infer mean sea levels thousands of years back. Geological evidence of former sea levels can be used to reconstruct the sea level history of the past on geological time scales, thousands to millions of years, through different climate conditions. In the geological record, a clear link can be seen between climate and sea level. By understanding the climate sensitivity, useful information and context for current and future sea level changes can be obtained (Church, Clark, et al., 2013; Quante and Colijn, 2016). When considering short term variability in relative sea level and especially extreme values, knowledge of historical events can be helpful. Written sources of the most dramatic events in the past can be used as indicators of what may happen in the future after adapting the event to modern or future conditions. Statistical models based on the instrumental record do not necessarily include the most drastic events possible since confidence intervals usually describe how well the models fit the data used without considering how well the data represents what may happen. Therefore, information about historical events should be used as compliment with statistically calculated extreme levels based on shorter time series (Fredriksson et al., 2017). Proxy records, paleo-data and preserved sources with descriptions of events from the past can thus give valuable information about what has happened in the past and can be expected in the future and are often used alongside instrumental data.

### 2.2.1 Sea level data for Scandinavia, the UK and Iceland

In all the countries of interest except Iceland, national tide gauge networks are operated. Yet, they are all partners in international cooperation organisations that provide tide gauge data, such as the Permanent Service for Mean Sea Level (PSMSL) that is responsible for collection, analysis, interpretation and publication of data from The Global Sea Level Observing System (GLOSS). All the countries except Iceland also take part in European satellite programmes, that e.g. provide altimetry data, through the European Space Agency (ESA) (Danish Ministry of Energy Utilities and Climate, 2017; Department for Business Energy & Industrial Strategy, 2017; ESA, n.d.; Government Offices of Sweden, 2017; Norwegian Ministry of Climate and Environment, 2018; PSMSL, n.d.) and are Global Navigation Satellite System (GNSS) data providers (SONEL, n.d.).

The North Sea is home to one of the most dense tide gauge networks in the world, with over 15 tide gauge series that span at least 100 years along its coastline (Quante and Colijn, 2016). In Denmark,

the national tide gauge network consists of 90 automatic stations run in cooperation of the Danish Meteorological Institute, the Danish Coastal Authority and local authorities. Tide gauges are also operated in Greenland and the Faroe Islands. Data from tide gauges that are part of the PSMSL network is published online and for other stations, data is available from the responsible bodies but is not published online (Danish Ministry of Energy Utilities and Climate, 2017; PSMSL, n.d.).

The Norwegian sea level observing system is run by the Norwegian Mapping Authority. It consists of the national tide gauge network along with GNSS stations. The Norwegian Mapping Authority operates 23 permanent tide gauges on the Norwegian mainland, one in Jan Mayen and one in Svalbard with a few records reaching all the way back to the late 19th century. Data is received and broadcasted a few times per hour from all but one of these tide gauges (Norwegian Ministry of Climate and Environment, 2018; Simpson, Nilsen, et al., 2015). Hundreds of temporary tide gauge data series also supplement the permanent stations and improve the spatial observation coverage. Along with keeping track of sea levels, the system also provides information of extreme sea levels, tides and reference sea levels for planning. This real-time and historical data is available to the public on the Norwegian Mapping Authorities website[1] (Norwegian Ministry of Climate and Environment, 2018).

In Stockholm, manual measurements of sea levels started in 1774. In the mid 1880s, the Swedish king Oskar II decided that mareographs should be installed along the Swedish coast line. One of them was installed in Stockholm in 1889 and at the same site, measurements are still performed with newer instruments today, making it the worlds longest sea level data series (SMHI, 2018b). Today, The Swedish Meteorological and Hydrological Institude (SMHI) runs a network of 24 tide gauges that measure sea level averaged over 10 minute periods in a relative elevation system. The data is gathered every hour and presented online[2] within 30 minutes, relative to a theoretical mean sea level calculated from annual means where uplift and sea level rise have been taken into account (SMHI, 2016). Not only real-time and historical sea level data can be downloaded from the SMHI website, but also ocean temperature-, wave-, current-, vertical profile chemistry-, marine biology- and marine weather data can be found there.

The UK National Tide Gauge Network was established in 1953 after storms in the North Sea that lead to major flooding (NTSLF, 2019). It is run by the National Tidal and Sea Level Facility (NTSLF) which implements sea level measurements, models tides and storm surges and performs statistical extreme sea levels estimations. 44 tide gauges around the UK are operated and additionally the NTSLF monitors sea level around the British Overseas Territories and at sites in the South Atlantic (Department for Business Energy & Industrial Strategy, 2017). The tide gauge network provides high quality data so that warnings may be provided at times of possible coastal flooding around the British Isles (NTSLF, 2019). 15 minute quality checked historical sea level data that dates back to January 1993 and hourly values for older data along with near real-time data can be accessed at the NTSLF website[3].

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[1]`kartverket.no/sehavniva`
[2]`https://www.smhi.se/en/weather/sweden-weather/sea-observations/havsvst_en.htm`
[3]`https://www.ntslf.org/data`

Sea level measurements around Iceland are unfortunately limited. At present, no official institution is responsible for sea level measurements in Iceland and only one long-time tide gauge series exists. That one is from the old harbour in Reykjavík that reaches back to 1956 (Sigurðarson, 2018). This data series is a part of the PSMSL network and on the PSMLS website, 1957 - 1965 data from Grindavík is also available (PSMSL, n.d.). A few measurement instruments have been put up in harbours around the country along with small weather stations that now are the responsibility of the harbour authority in question. The main purpose with those was to provide near real time information on the local sea level to users but also to monitor slow sea level changes. Additionally, measurements since the late 1980s exist from more locations that were used to determine an elevation system for harbours and sailing. Currently, 21 data series of electronic measurements, spanning at least a few years are known to exist. Thereof, 11 since the 1990s and apart from the above mentioned series, others are younger, with some of them only spanning a few years. The length of usable data from these series ranges from 4 to 23 years. For a while, no continuous measurements were being made in the east between Húsavík and Höfn in Hornafjörður but recently an instrument was put up in Mjóeyri harbour in Fjarðarbyggð (Sigurðarson, 2018).

Since the practical sea level information for harbour users do not include accurate measurements of relative elevation changes between land and sea due to isostatic rebound or absolute sea level rise, the maintenance of the tide gauges has in most cases been lacking. Lack of calibrations, technical problems and malfunctions are among reasons for the low quality of much of the data and the state of the instruments that are still running is in many cases not known. The Reykjavík series from the old harbour is the only one known to be of good quality (not only for some periods) (ibid.), even though more frequent calibrations would have been needed there too and it is unclear how it is best to calibrate the instrument since 1994 (Tryggvason, 2017). Proposals of a new sea level measurement system have been made where an official institution will be responsible for sea level measurements in 15 - 18 places around the country (Sigurðarson, 2018). The author is currently unaware of any one site where all this data is available but data from some harbours is available online[4].

## 2.3 Observed sea level changes

Global sea level has been similar to present levels in the past 2000-3000 years with variations of $\pm$ 25 cm at most over timescales of several centuries. The few pre-1900 tide gauge records, evidence from paleo coastal sediments and reconstructed mean sea levels modelled using combined tide gauge data and satellite altimetry suggest an acceleration in global mean sea level rise in the late 19th and early 20th century (figure 4) (Church, Clark, et al., 2013; Quante and Colijn, 2016). The global mean sea level rise of last century and early 21st century was fast (see table 1) and strong evidence suggest that the 20th century sea level rise rate is faster than in the previous two thousand years (Church, Clark, et al., 2013). It is estimated to have been 1.7 $\pm$ 0.2 mm/yr from 1901-2010, resulting in 19 (17-21) cm global mean sea level rise in the period. Different approaches using tide gauge data agree on this rate within the uncertainty (Rhein et al., 2013). Church and White (2011) found the same rate of average sea level rise for 1900-2009 and reported global mean sea level rise of 21 cm in 1880-2009.

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[4]e.g. for Faxaflói since 2009 at `http://vedur.mogt.is/harbor/`

They found a statistically significant acceleration in mean sea level rise since 1880 and reported a rate of 1.9 ± 0.4 mm/yr for 1961-2009. For 1993-2009, they found the rate to be 2.8 ± 0.8 mm/yr and 3.2 ± 0.4 mm/yr for using tide gauge and satellite altimetry data respectively. Beckley et al. (2010) found the mean sea level rise rate to be 3.3 ± 0.4 mm/yr for 1993-2009 and noted that the rate of 2004-2008 was only 2.0 ± 0.4 mm/yr. Multiple studies using different methods agree on the rate to have been about 3.2 ± 0.4 mm/yr between 1993 and 2010, which is statistically higher than the rate of the 20th century. It has been concluded that the global mean sea level rise rate since 1993 has very likely been faster than the mean rate of the 20th century (Church, Clark, et al., 2013; Rhein et al., 2013).

The rate of sea level rise varied considerably during the 20th century with more than 2 mm/yr in 1940s and 1970s and almost 3 mm/yr in the 1990s (Church and White, 2011). Other studies confirm this fluctuating rate and it is considered likely that the global mean sea level rose at a similar rate in 1920-1950 as in 1993 to 2010. It has been concluded as virtually certain that global mean sea levels rose during the 20th century and as likely that the global mean sea level rise has accelerated since 1900. Several different studies using different methods analysing the longer data series from the European coastlines have even allowed for concluding it to be very likely that the mean sea level rise in Northern Europe has been accelerating since the early 1800s (Rhein et al., 2013).

Some newer studies have, however, found significantly slower rates of sea level rise for the 20th century than were reported in the Fifth Assessment Report of the IPCC (Church, Clark, et al., 2013). Using different approaches, it has been shown that widely used methodological adjustments can have much impact on the estimated rates so that they need to be investigated further (Dangendorf and Marcos, 2018). With other approaches than the previously mentioned studies, by combining tide gauge records and physics based and model derived geometries of distinct contributing signals, Hay et al. (2015) found the 90 % confidence interval of global sea level rise rate in 1901-1990 to

*Table 1* *Estimates of global mean sea level rise (GMSLR).*

| Period | GMSLR rate [mm/yr] | Method | Reference |
|---|---|---|---|
| 1901 - 2010 | 1.7 ± 0.2 | Tide gauge reconstruction | Rhein et al., 2013 |
| 1993 - 2010 | 3.2 ± 0.4 | Satellite altimetry | |
| 1900 - 2009 | 1.7 ± 0.2 | Tide gauge reconstruction | Church and White, 2011 |
| 1961 - 2009 | 1.9 ± 0.4 | Tide gauge reconstruction | |
| 1993 - 2009 | 2.8 ± 0.8 | Tide gauge reconstruction | |
| 1993 - 2009 | 3.2 ± 0.4 | Satellite altimetry | |
| 1993 - 2009 | 3.3 ± 0.4 | Satellite altimetry | Beckley et al., 2010 |
| 1901 - 1990 | 1.2 ± 0.2 | Tide gauge data and geometries | Hay et al., 2015 |
| 1993 - 2010 | 3.0 ± 0.7 | Tide gauge data and geometries | |
| 1901 - 1990 | 1.1 - 1.2 | Bayesian techniques | Hay et al., 2017 |
| 1902 - 2012 | 1.3 ± 0.2 | Hybrid approach | Dangendorf and Marcos, 2018 |
| 1993 - 2012 | 3.1 ± 1.4 | Hybrid approach | |
| 1901 - 1990 | 1.4 ± 0.6 | Tide gauge reconstruction | IPCC, 2019 |
| 1902 - 2010 | 1.5 ± 0.4 | Tide gauge reconstruction | |
| 1993 - 2015 | 3.16 ± 0.37 | Satellite altimetry | |
| 2006 - 2015 | 3.6 ± 0.5 | Satellite altimetry | |

have been $1.2 \pm 0.2$ mm/yr. They were also able to close the 20th century sea level budget and found the rate to have been $3.0 \pm 0.7$ mm/yr in 1993-2010 which is consistent with earlier estimates. Their conclusion was thus that the acceleration between the periods was faster than previously thought which could affect future sea level rise projections. Later, Hay et al. (2017) again found the global mean sea level rise to have been 1.1 - 1.2 mm/yr in 1901-1990 using Bayesian fingerprinting estimates. Dangendorf and Marcos (2018) found a similar linear long term trend since 1902; $1.3 \pm 0.2$ mm/yr, using a hybrid approach combining various methods. They also estimated the 1993-2012 rate to have been $3.1 \pm 1.4$ mm/yr which is consistent with previous satellite estimations. Their estimations show especially large differences from previously reported rates before the 1970s. Before 1920s it is estimated to have been 0.5 mm/yr. Then it rose to 1.8 mm/yr in the 1940s and decreased again to 0.6 mm/yr in the 1960s. The rate accelerated to about 3 mm/yr about 2000 and has been similar since.

Recently, IPCC published a special report on the ocean and the cryosphere. There, these newer findings are discussed and consequently, a very likely 1902 - 2010 sea level rise trend of $1.5 \pm 0.4$ mm/yr is given. That is consistent with the fifth assessment report but has a larger uncertainty range. The rate for 1901–1990 is reported 1.4 mm/yr (0.8 – 2.0 mm/yr, very likely range). Satellite altimetry estimates of global mean sea level rise in 1993 - 2015 is 3.16 mm/yr (2.79 - 3.53 mm/yr), a bit lower than the estimate of the fifth assessment report for 1993 - 2010. The reason lies in a newly discovered drift in an altimeter, which is taken into account in the newer estimate. The rate of GMSL rise for 2006–2015 is reported 3.6 mm per year, with a very likely range of 3.1 – 4.1 mm/yr (IPCC, 2019).

### 2.3.1 Observed sea level changes in Scandinavia, the UK and Iceland

Not many regional-wide studies of mean sea level changes have been made for the North Sea, most studies of the area have been made on a country bases (Quante and Colijn, 2016; Wahl, Haigh, et al., 2013). Woodworth (1990) performed a study of the North Sea 29 years ago and found a significant acceleration of 0.4 mm/yr over timescales of 100 - 300 years. However, neither he nor Shennan and Woodworth (1992) two years later found a statistically significant acceleration in sea level rise in the region in the 20th century. Wahl, Haigh, et al. (2013) made an extensive study on the North Sea using tide gauges, satellite altimetry and more accurate estimates of vertical land movement. They identified periods of sea level rise acceleration in the 1970's and late 19th century and deceleration in the 1950's-1960's in the tide gauge series. They also found considerably higher rates of recent sea level rise, especially at the end of the 20th century. These regional long term trends are similar to global sea level trends trends but higher in the last few decades than the global mean.

In 1900-2011, the long term absolute mean sea level trend was $1.53 \pm 0.16$ mm/yr with slightly higher values in the Inner North Sea and lower, but not statistically lower, in the English Channel; $1.59 \pm 0.16$ and $1.18 \pm 0.16$ mm/yr respectively. The year-to-year variability was greater in the southern parts of the North Sea than at the Norwegian shores, the east coast of the UK and the English Channel. The relative mean sea level trends within the region varied considerably due to the vertical land movement pattern, with Scotland, Denmark, Norway (and Sweden) rising and other

areas subsiding (Wahl, Haigh, et al., 2013). Based on satellite altimetry, the trend in absolute sea level in the North Sea was about 1-3 mm/yr in 1992-2014, depending on location (EEA, 2017).

In the Baltic, the mean sea level rose 1.5 mm/yr in the 20th century (Nerheim et al., 2017). The absolute sea level rise for the Scandinavian coast of the Baltic in period 1891-1990 was found to be 1.8 mm/yr (O. Vestøl, 2006). In 1992-2014, the absolute sea level trend in the Baltic was about 2-4 mm/yr, depending on location. The fastest rates were in the Gulf of Bothnia, where the fastest isostatic rebound also occurs and the rate was slower in the southern parts of the Baltic (EEA, 2017). The isostatic uplift pattern in the area causes a clear north-south gradient in relative sea level changes. In general, there is a relative sea level rise of up to 1 mm/yr at the southern Baltic Sea coast, while a negative sea level trend of up to 8.2 mm/yr is evident in the Gulf of Bothnia (A. Richter, Groh, and Dietrich, 2012). Reconstructed relative sea level changes from different places in the North Atlantic show little sea level variability in the North Atlantic over the past millenium until an acceleration in the late 19th to early 20th century. Reconstructions around Iceland, however, show earlier variability suggesting a significant influence of regional or local factors on sea level variability (Gehrels et al., 2006; Saher et al., 2015).

A summary of absolute and relative sea level changes is shown in figures 2 and 3 respectively. Sea level has been rising in Denmark in the 20th and 21st centuries. At present, the relative sea level is rising along the entire Danish coastline with an exception in North Jutland where the fastest land uplift is apparent. There, the land is rising at approximately the same rate as the sea level, resulting in little apparent relative sea level rise. Today, the fastest relative sea level rise is about 1.5 mm/yr in the south where land uplift is close to zero (Danish Ministry of Energy Utilities and Climate, 2017; Olesen et al., 2014). The variation in relative sea level rise is caused by the effect of isostatic uplift. When the tide gauge series of nine stations around Denmark with long series that reach back to 1900 are detrended for the land uplift, they all show the same trends, with absolute average sea level rise of 1.7 - 2.2 $\pm$ 0.3 mm/yr. This is close to the global mean sea level trend for the 20th century (Olesen et al., 2014). When the effect of land uplift is removed from the trend of the same nine tide gauge stations, the absolute sea level trend of 1.9 $\pm$ 0.3 mm/yr relative to the reference period 1986-2005 is clearly distinguishable from interannual variability (EEA, 2017). Madsen (2009) also found the isostatic land rise to cause the most variability. She reported that relative sea level trends from tide gauge measurements around Denmark in the 20th century varied between -0.23 and +1.15 mm/yr with a 90% confidence interval of 0.08 - 0.26 mm/yr. She also found a 90 % confidence interval average trend of 1.5 $\pm$ 0.5 mm/yr, for stations with over 100 years of data. The global mean is well within the large error bounds caused by the uncertainties in land uplift at that time but she concluded a slower sea level rise in Denmark than the global average. She also found decadal variability on the order of a few cm from 19 year running mean in-situ observations, reported a relative deceleration around 1950 - 1970 and larger than average sea level trend in the 1980s and early 1990s.

Breili, Simpson, and Nilsen (2017) investigated sea level changes along the Norwegian coast for three periods; 1960-2010, 1984-2014 and 1993-2016. As expected, much spatial variation was evident along the coast due to the isostatic uplift pattern. They also noted that their estimations were highly sensitive to the study period, with changes in rate estimations of up to 1 mm/yr by shifting the start of the period by one year. They estimated the absolute sea level rise after making corrections
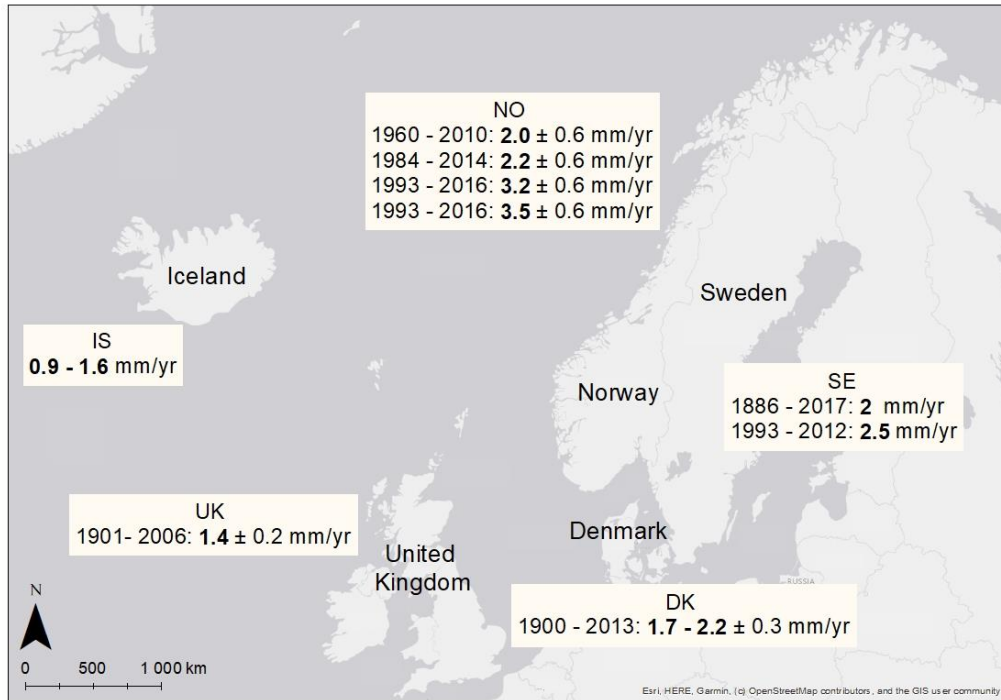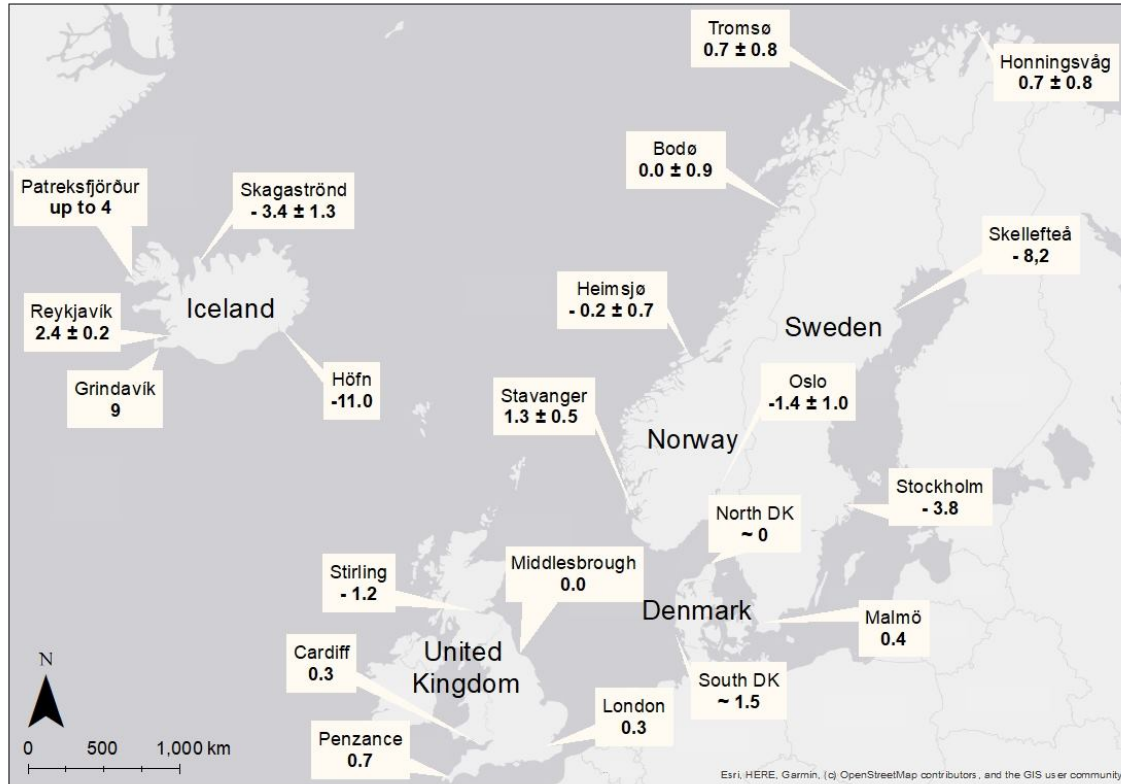
***Figure 2*** *Observed absolute sea level changes in the countries of interest. DK: Range of values depending on location (Olesen et al., 2014). NO, SE and UK: Average values along the coast (Breili, Simpson, and Nilsen, 2017; SMHI, 2019; Woodworth, Teferle, et al., 2009). IS: Estimation for Reykjavík using relative sea level rise and land subsidence (Sigurðarson, 2018).*

for vertical land movement to be $2.0 \pm 0.6$ mm/yr in 1960-2010, $2.2 \pm 0.6$ mm/yr in 1984-2014 and $3.2 \pm 0.6$ mm/yr in 1993-2016. After applying inverse barometer corrections, the rate of 1993-2016 was found to be $3.5 \pm 0.6$ mm/yr. Simpson, Nilsen, et al. (2015) have reported similar values with uncertainty of 0.6-0.8 mm/yr; 1.9 mm/yr for 1960-2010, 2.4 mm/yr for 1984-2014 and 3.6 mm/yr for 1993-2014 from tide gauge observations. Additionally, two different datasets of satellite observations gave on one hand 3.1 mm/yr and 3.4 mm/yr on the other for 1993-2014. The reported rates of the former two periods are close to global mean sea level rise rates and the estimations for the latest periods are not far from the global average rates that Church and White (2011) and Beckley et al. (2010) found for 1993-2009.

Since 1886, the absolute mean sea level around Sweden has risen just over 25 cm, which corresponds to 2 mm/yr. SMHIs sea level measurements show an acceleration in absolute sea level rise in recent decades, with the rate in 1993-2012 being 2.5 mm/yr. The inter annual variability in the data is large and the sea level rise rate is not the same at the east- and west coasts (SMHI, 2019). In 2014, the sea level had risen 20 cm since the late 1800s around Sweden (Kjellström et al., 2014). This is close to the global mean of 19 cm in 1901-2010. Regional variations in sea level at the Swedish coastline are similar to global variations (Nerheim et al., 2017). Sea level is subsiding relative to land along most of Sweden's coastline. The relative sea level changes at the East coast range from subsidence of -8.2 mm/yr at the Gulf of Bothnia down to relative rise of 0.1 mm/yr at Karlskrona in the South-East. It reaches a relative rise of 0.4 mm/yr in the South but is subsiding relative to land along most of the West coast as well (A. Richter, Groh, and Dietrich, 2012).

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***Figure 3*** *Observed relative sea level changes in countries of interest in mm/yr. DK: Approximate values (Danish Ministry of Energy Utilities and Climate, 2017). NO: Rates found with 1984 - 2014 tide gauge data (Simpson, Nilsen, et al., 2015). SE: 100 year secular relative sea level changes from tide gauge data (BACC II Author Team, 2015). UK: Rates of the past 1000 years (Shennan, Milne, and Bradley, 2012). IS: Rates found with the existing tide gauge data. They are often calculated from short time series and are perhaps not representative of longer periods (Björnsson et al., 2018; Tryggvason, 2016, 2017).*

Absolute sea level rose by 1.4 ± 0.2 mm/yr around the UK in 1901-2006 (Woodworth, Teferle, et al., 2009). The same rate has been reported for 1901 - 2016 (Department for Business Energy & Industrial Strategy, 2017). That is a bit lower value than the global average mean sea level rise of 1.7 ± 0.2 mm/yr from 1901-2010 but still within the error margins. Shennan, Milne, and Bradley (2012) reported 1.2 mm/yr relative land uplift, that is relative sea level fall, in the mountainous region of Scotland and decreasing uplift in all directions from there. The zero vertical movement isovelocity cuts through the middle of Ireland, through England between Birmingham and Liverpool close to Stoke-on-Trent and up through Middlesbrough. The southern parts of Ireland and England are subsiding with the fastest relative rate of 0.7 mm/yr at the South-Westernmost tip of England. The Eastern English coast is subsiding nearly as fast.

Sea level reconstructions spanning about 500 years from a salt marsh in west Iceland, corroborated by tide-gauge data from Reykjavík for the 20th century, show a 0.6 m relative sea level rise in west Iceland since 1570 (Saher et al., 2015). In 1820 ± 20, a rapid acceleration in relative sea level rise in west Iceland started. Since then, relative sea level has risen circa 0.4 m (Gehrels et al., 2006). In three distinct periods, the relative sea level rise rate exceeded the 20th century global mean absolute sea level rise of 1.7 mm/yr; about 2 mm/yr in 1620 - 1650 and about 3 mm/yr in 1780 - 1850 and

1950 - 2000 (Saher et al., 2015). These fastest rates are almost five times the rate of the previous millennia (Björnsson et al., 2018).

Out of the 21 electronic sea level measurement series around Iceland, only eight have been analysed; Höfn in Hornafjörður, Landeyjahöfn, Grindavík, Reykjavík old harbour, Ólafsvík, Patreksfjörður and Skagaströnd (Sigurðarson, 2018). For Landeyjahöfn, the period of useable measurements is too short to look into relative sea level changes (Tryggvason, 2016). For the subsiding Höfn in Hornafjörður a 11.0 (6.3 - 15.8) mm/yr relative sea level decline was reported in 1999-2008 while a relative sea level rise of 9 mm/yr was reported for Grindavík in 1997-2015 (Björnsson et al., 2018; Tryggvason, 2016). A best line through sea level data from Reykjavík, Icelands longest tide-gauge series, gives a 2.0 $\pm$ 0.6 mm/yr relative sea level rise since 1956 which corresponds to 20 $\pm$ 6 cm per century (Björnsson et al., 2018). Average relative sea level changes for corrected Reykjavík data give 2.4 $\pm$ 0.2 mm/yr rise for 1956 - 2017 (Tryggvason, 2016). That is the same mean rate as was found for 1956 - 1989 in Guðmundsson and Einarsson (1991). Jónsson, Gauksson, and Björnsson (2017) found 1996 - 2013 Reykjavík relative sea level rise to be 2.8 $\pm$ 0.3 mm/yr. In the most recent years, little absolute sea level changes are observed (Sigurðarson, 2018). Recent absolute sea level rise for Reykjavík has been found to be 0.9 - 1.6 mm/yr (ibid.). For Ólafsvík, only 10 years of measurements are considered reliable data even though data since 1997 exists. The 2008 - 2017 relative sea level rise in Ólafsvík was 5 $\pm$ 2 mm/yr. Data exists from Patreksfjörður for 1994 - 2011 but is nonconsecutive for 2003 - 2011. This data points to up to 4 mm/yr relative sea level rise for the period. Data from Skagaströnd is intermittent in 2003 - 2011 but considered reliable. There, relative sea level fall of 3.4 $\pm$ 1.3 mm/yr was evident in 2003 - 2017 (Tryggvason, 2017).

## 2.4   Sea level projections

From the current scientific understanding it can be claimed that it is virtually certain that sea level rise will continue during the 21st century and beyond. This is true, even if atmospheric green house gas concentrations are stabilised. It is very likely that global mean sea level rise rate will exceed the average rate of the 20th century during the 21st century for all RCP scenarios (see appendix A). In The Fifth Assessment Report of the IPCC, an assessment of a likely (66-100 % probability) range of sea level rise for the 21st century is given. Figure 4 shows the compilation of data from paleo sea level data, tide gauges and satellite altimeters since 1700 along with the likely ranges of global mean sea level rise projections and the central estimates for RCP2.6 and RCP8.5 in the 21st century. It can be seen that the median global mean sea level rise projections until 2100 for RPC2.6 and RCP8.5 relative to the sea level in the 1700s are roughly 0.7 m and 1 m respectively, with the combined likely ranges reaching from about 0.55 m to over 1.2 m. The corresponding likely sea level rise ranges by 2100 compared to the 1986-2005 sea level are 0.44 [0.28-0.61] m for RCP2.6 and 0.74 [0.52-0.98] m for RCP8.5. The median projection sea level rise rate of RCP2.6 shows it getting roughly constant before the middle of the century at 4.5 mm/yr and slightly slowing down thereafter. For RCP 8.5, however, the acceleration is projected to continue throughout the century, reaching 11 [8-16] mm/yr in 2081-2100 (Church, Clark, et al., 2013).
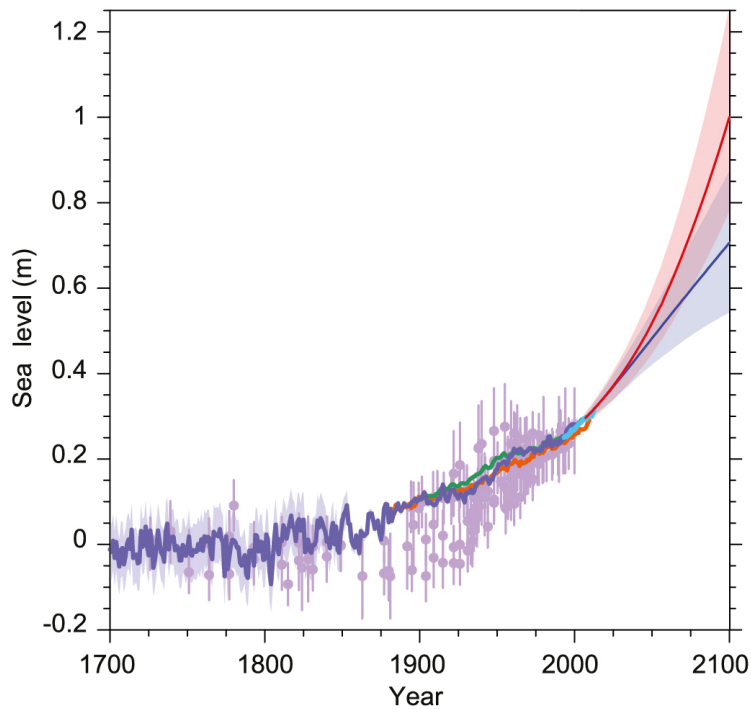
***Figure 4*** *Observed global mean sea level changes and future projections. A compilation of paleo sea level data (purple), tide gauge data (orange and green), altimeter data (bright blue) and central estimates and likely ranges for projections of global mean sea level rise for RCP2.6 (blue) and RCP8.5 (red) scenarios, all relative to pre-industrial values. Figure 13.27 from IPCC's Fifth Assessment Report; Climate Change: The Physical Science Basis, p. 1204 (Church, Clark, et al., 2013).*

Newer global mean sea level rise projections have been made (table 2). Palmer et al. (2018) based their projection on the materials and methods described in IPCC's report but used another reference period, 1981-2000 and used an updated estimate of the Antarctic ice dynamics contribution. By changing the baseline period, the global mean sea level projections increased by 0.01 m and the Antarctic dynamics systematically increased projected values more substantially, and especially raised the upper bound of the likely range. They project the global mean sea level rise by 2100 to be 0.29 - 0.66 m for RCP2.6 and 0.56 - 1.12 m for RCP8.5. IPCC's values for the same reference period would be 0.27 - 0.61 m and 0.53 - 0.98 m.

The US Global Change program made a new projection for global mean sea level rise in 2017 (Sweet et al., 2017). They defined six scenarios ranging from low to extreme and calculated 19 year average global mean sea level centered for the years 2020, 2030, 2050 and 2100 relative to 2000. The low scenario represents a continuation of about 3 mm/yr rise and is similar to the lowest end of the very likely range of RCP2.6. It gives a 0.3 m global mean sea level rise relative to 2000 in 2100. Their intermediate scenario, that is the third out of six, is similar to the high end of the likely range of RCP8.5 and gives a global mean sea level rise rate of 15 mm/yr and a rise of of 1.0 m in 2100 relative to 2000. Their extreme scenario is based on a combination of the RCP8.5 scenario and the maximum possible sea level rise due to ice melt defined by DeConto and Pollard (2016), who found that the melting of the Antarctic ice sheet could contribute a 114 cm sea level rise by 2100 under RCP8.5. This scenario is said to be consistent with the estimates of physically possible worst case.

This extreme scenario leads to a projection of 2.5 m global mean sea level rise by 2100 relative to the 2000 sea level with an average 44 mm/yr sea level rise.

In a recent updated estimation of the IPCC, the uncertainty of the Antarctic contribution is taken into account. As there is limited evidence for changes in other components, they are kept identical to the ones used in the Fifth Assessment Report. The results are consistent with the previous estimate but the uncertainty in the global mean sea level projections for RCP8.5 increased as a result of the uncertainty in the Antarctic contribution (table 2) (IPCC, 2019).

A large uncertainty regarding collapse of the ice sheets with assessments of the timing ranging from a hundred years to millenia makes long term sea level projections extremely difficult. More measurements of the oceans, glaciers and the atmosphere around Antarctica, better representation of physical processes and a higher resolution of the models is needed for better projections (Nerheim et al., 2017). Therefore, not many process based models that go beyond 2100 exist. At the time of the Fifth Assessment report of IPCC, they all indicate a positive sea level contribution beyond 2100 from thermal expansion, glaciers and changes in the Greenland ice sheet but more uncertainty follows the Antarctic ice sheet. It was also noted that the underlying models likely underestimate the future contribution of the melting of Antarctica to sea level rise systematically. Yet, the models indicated global sea level rise of less than 1 m by 2300 relative to pre-industrial levels for RCP2.6 but 1 m to over 3 m global mean sea level rise for RCP8.5. For all scenarios, sea levels continue to rise until 2500 and sea level is virtually certain to continue to rise beyond 2500 for increasing global mean surface air temperature. Long term mass loss of ice sheets was estimated to be able to lead to several metre sea level rise and if the warming is sustained for several millenia, a rise of 1 - 3 m/°C was projected (Church, Clark, et al., 2013). Exploratory extended global mean sea level projections were also made in Palmer et al. (2018). For RCP2.6, a rise of 0.6 - 2.2 m until 2300 is projected and 1.7 - 4.5 m for RCP8.5. In the report of Sweet et al. (2017), projections until 2200 were considered. They found the range of rise since 2000 from the low to the extreme scenarios of 0.3 - 2.5 m for 2100 to become 0.39 - 9.7 m in 2200. There, it is also noted that most projections imply that global mean sea level rise will not stop in 2200.

*Table 2* *Different projections of global mean sea level rise (GMSLR) until 2100. Likely ranges are shown for the RCP scenarios while the last three are projected 19 year averages centered at 2100 relative to 1991 - 2009 average (centered at 2000).*

| Period | Scenario | GMSLR [m] | Reference |
|---|---|---|---|
| 1986 - 2005 to 2100 | RCP2.6 | 0.28 - 0.61 | Church, Clark, et al., 2013 |
| | RCP8.5 | 0.52 - 0.98 | |
| 1981 - 2000 to 2100 | RCP2.6 | 0.29 - 0.66 | Palmer et al., 2018 |
| | RCP8.5 | 0.56 - 1.12 | |
| 2000 to 2100 | Low | 0.3 | Sweet et al., 2017 |
| | Intermediate | 1.0 | |
| | Extreme | 2.5 | |
| 1986 - 2005 to 2100 | RCP2.6 | 0.29 - 0.59 | IPCC, 2019 |
| | RCP8.5 | 0.61 - 1.10 | |

Even though the IPCC's projection of a likely range of sea level rise for the 21$^{st}$ century improved the understanding of future sea level rise, neither a projection of a very likely range of sea level rise or an upper bound of future sea level rise could be made based on the scientific understanding extant at the time. There still existed too many uncertainties for that to be possible (Church, Clark, et al., 2013). For coastal planners, information beyond the likely range of future sea level is preferable and the upper bound of sea level rise at a given time would be an ideal piece of information. A physical upper bound of sea level rise is, however, difficult to define unambiguously, except in the limit when all ice has melted and the ocean stopped warming. Finding this number for 2100 would not help a coastal planner since nothing in our understanding of the world points to this happening by that time. A true upper bound is thus as of now impossible to provide. Instead, high-end sea level rise scenarios have been produced for different uncertainty tolerances by fitting probability distributions to available model collection data. An obstacle of that application is that there is less confidence that the physical processes contributing to sea level rise outside of the likely range are understood and there is no physical reasoning that the probability distributions should hold their shape at the tails. This lack of evidence is the reason behind the decision of the IPCC report writers for not providing estimations beyond the likely range. In some cases, lower confidence estimations of contributions, such as of the Antarctic ice sheet, have been added but these also give varying results (Hinkel et al., 2019).

The recent fast acceleration of sea level rise implies that the low end of IPCC's RCP2.6 projections is unlikely (Björnsson et al., 2018). Several studies that use different approaches, both physical and statistical, that report very likely ranges of global mean sea level rise by 2100 have found similar ranges; 25-80 cm for RCP2.6 and 50-130 cm, even up to 160-180cm, for RCP8.5. Even the likelihood of exceeding the projections of the US Global Change program (Sweet et al., 2017) were reported based on Kopp et al. (2014). Yet, this was done with discussion about the many uncertainties. Findings newer than the roughly agreeing models imply that these projections may underestimate the rate of ice sheet melt, especially for high-end warming scenarios. Various physical feedbacks that were not included in ice sheet models until recently can add significantly to sea level rise. These include ice sheet and -cliff instability and ice shelf hydrofracturing. Other, less investigated processes, such as dynamics at the base of ice sheets, might also be equally important to the widely researched surface processes. These large uncertainties cause much variety in model results, depending on the processes included. As an example, DeConto and Pollard (2016), whos estimations the US Global Change program report (Sweet et al., 2017) used as a basis for their extreme scenario, projected much more Antarctic ice melt by 2100 than reported in other recent publications (see e.g. Golledge, Kowalewski, et al., 2015; Ritz et al., 2015) since they included early surface melting that caused hydrofracturing, a complete collapse of ice shelves and marine ice cliff instability. However, this is the result of a single model and this physically possible chain of processes has until now not been observed. Even newer estimations (e.g. Golledge, Keller, et al., 2019) are much lower than their estimation.

In a recent IPCC report, the uncertainty of the processes going on in Antarctica are highlighted. It is mentioned that accelerated ice flow and retreat has been observed in West Antarctica, which might mark the onset of an irreversible ice sheet instability. The large uncertainties accompanied with ice sheet instability are a result of limited measurements, deficient modelling of ice sheet processes

and insufficient understanding of interactions between the atmosphere, oceans and ice sheets (IPCC, 2019). In summary, by going beyond the likely range, lower confidence information is provided, resulting in different studies that consider different processes giving very different sea level rise assessments for the same percentiles. This problem is expected to continue in the future (Hinkel et al., 2019).

### 2.4.1 Sea level projections for Scandinavia, the UK and Iceland

The relative sea level rise in Europe is projected to be similar to global average values along most European coasts. The main exceptions are the northern parts of the North-Atlantic and Baltic coasts because of the post-glacial rebound of the area (EEA, 2017). The overall picture of sea level rise in Scandinavia is colored by the regional isostatic uplift, leading to slower relative sea level rise than the global mean (Nerheim et al., 2017). The southern parts of Denmark and Sweden, where uplift is close to zero (figure 1), will experience a sea level rise of almost the same rate as the regional sea surface change (Madsen, 2009; Nerheim et al., 2017). In the UK and Iceland, some areas are rising and others subsiding due to glacial isostatic adjustment with following effects on relative sea level changes (Árnadóttir et al., 2009; Palmer et al., 2018). The affect of melting ice sheets not only adds water to the oceans but also causes the Earths gravitational field to alter so that the sea level lowers in their vicinity but rises in other areas. For this reason, long term future sea level rise in Scandinavia, the UK and Iceland will rather be caused by the changes of the Antarctic ice sheet than the Greenlandic one (Nerheim et al., 2017; Palmer et al., 2018; Simpson, Nilsen, et al., 2015). For the same reason, the vicinity of the Greenland ice sheet causes future absolute sea level rise around the UK and Iceland to be lower than the global average and has zero or slightly negative effect on absolute sea level rise around Scandinavia (table 3) (Björnsson et al., 2018; Palmer et al., 2018; Simpson, Nilsen, et al., 2015).

*Table 3 Projected proportion of global absolute mean sea level rise around the countries of interest [%]. Numbers retrieved from Björnsson et al., 2018; Olesen et al., 2014; Palmer et al., 2018; Simpson, Nilsen, et al., 2015*

|  | **Denmark** | **Norway** | **Sweden** | **UK** | **Iceland** |
|---|---|---|---|---|---|
| **%** | 85 - 98 | 80 - 90 | ~80 | 89 | 33 |
| **Number represents** | 1986 – 2005 to 2081 – 2100 projections for all RCP scenarios are within the range. | 1986 – 2005 to 2081 – 2100 projections for all RCP scenarios are within the range. | Number for the Baltic calculated using scenarios from IPCC's AR4. | UK average for RCP4.5 at 2100. | Iceland average of 1986 – 2005 to 2081 – 2100 global mean sea level rise, mean over all RCP scenarios. |
| **Reference** | Olesen et al., 2014 | Simpson, Nilsen, et al., 2015 | BACC II Author Team, 2015 | Palmer et al., 2018 | Björnsson et al., 2018 |

The Baltic has been estimated to experience about 80% of the absolute global mean sea level rise until 2100. This gives a regional relative sea level variation between a 0.60 m rise close to Hamburg and southern Denmark and a drop of 0.35 m in the Bothnian Bay for a mid-range scenario (SRES A1B). For a high-end scenario, a range of 0.1 - 1.1 m relative sea level rise is projected (BACC II Author Team, 2015). Based on an ensemble of the CMIP5 climate model and RCP4.5, the sea level change of the Baltic from 1986-2005 to 2081-2100 varies from more than 0,4 m sea level drop in the Gulf of Bothnia and a 0.4 m rise between Denmark and Sweden. In the North Sea, the projected sea level rise is 0.2 m to over 0.4 m in the south and projected sea level rise is also over 0.4 m in most of the European North Atlantic with lower values close to land (EEA, 2017). The regional mean absolute sea level rise in the North Sea has been estimated to be 0.33 m for RCP2.6 and 0.57 m for RCP 8.5 (SMHI, 2018a). A summary of projected relative sea level change by the countries of interest is shown in figure 5.

In the period of 2081-2100, the absolute mean sea level around Denmark will rise 0.34 (0.1-0.6) m for RCP2.6, 0.43 (0.2-0.7) m for RCP4.5 and 0.61 (0.3-0.9) m for RCP8.5 relative to the 1986-2005 level according to IPCC's Fifth Assessment Report (Olesen et al., 2014). Based on an ensemble of the CMIP5 climate model and RCP4.5, the sea level rise around Denmark from 1986-2005 to 2081-2100 will range from 0.2 to over 0.4 m (EEA, 2017). In the Second Assessment of Climate Change for the Baltic Sea Basin (BACC II Author Team, 2015), the relative mean sea level rise
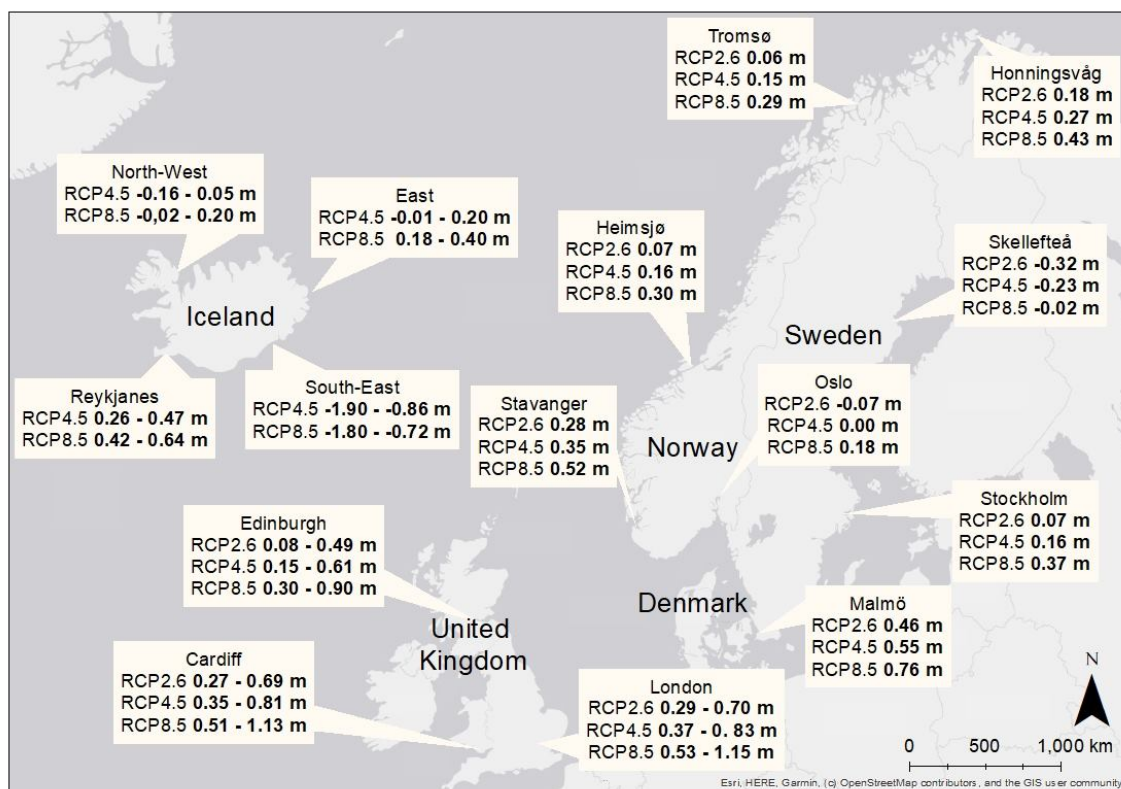


*Figure 5* *Projected relative mean sea level changes by the countries of interest. NO: Relative sea level change from 1986–2005 to 2081–2100 (Simpson, Nilsen, et al., 2015). SE: Relative sea level change from 1995 to 2100 (SMHI, 2017). UK: Relative sea level change until 2100 relative to 1981 - 2000 (Palmer et al., 2018) IS: Relative change for the rest of the century (Björnsson et al., 2018).*

around Denmark in 2090-2099 relative to 1990-1999, is estimated to be between 0,3 m in the north to 0.6 m in the south for a medium scenario (SRES A1B) while the absolute sea level height rise is roughly 0.55-0.6 m in the period. A high end estimate of the projected sea level rise gave a rise of around 1.05 m and a relative sea level rise range of about 0.8-1.1 m for the same period. The Danish Meteorological Institude (DMI) has estimated an upper limit of the absolute mean sea level rise around Denmark corresponding to the RCP8.5 scenario. It is meant for uncertainty assessment uses and estimated to be 1.2 m for the period 2081-2100 relative to 1986-2005. For the year 2100 it is 1.4 m relative to the same period (Ministry of the Environment and Food of Denmark / Enviromental Protection Agency, 2015; Olesen et al., 2014). An online map database for Denmark where water level can be set and water levels of different severity for different points in time calculated is available online[5].

The sea level rise around Norway will be 0.1 - 0.4 m from 1986-2005 to 2081-2100 based on an ensemble of the CMIP5 climate model and RCP4.5(EEA, 2017). In a more precise study, and localised for Norway, sea level changes until 2100 have been projected. The assessments were based on IPCC's Fifth Assessment Report and the CMIP5 model output. They included a new vertical land motion field and consequent gravity changes and estimations of sea level changes due to gravitational effects of mass redistribution. Spatial variations in ocean density, -mass redistribution and -dynamics, ocean mass changes and vertical land motion, and resulting gravitational effects were taken into account. The projected sea surface height changes around the Norwegian coast in 2081-2100 relative to 1986-2005 are estimated to be between 80-90 % of global mean sea level change. The likely range of projected sea surface height change around Norway from 1986-2005 to 2081-2100 is 0.35 (0.15 - 0.55) m, 0.4 (0.20 - 0.65) and 0.6 (0.30 - 0.85) for RCP2.6, RCP4.5 and RCP8.5 respectively. The likely relative sea level change has been estimated to be between -10 and 30 cm for RCP2.6, 0 - 35 cm for RCP4.5 and 15 - 55 cm for RCP8.5, depending on location. Regardless of scenario, most of Norway will thus experience relative sea level rise before the end of the century and climate driven sea level rise will dominate over the vertical land motion in the 21st century. Only coastal municipalities in areas of fastest uplift might experience slight sea level fall under RCP2.6. In the report, a sea level rise over ~0.5 m above the likely projection ranges are judged plausible but of low probability. Calculated present and 2090 mean high water as well as 20, 200 and 1000 year storm surges (see section 2.5) for Norway can be visualised in an online GIS database[6]. Longer projections were not made (Simpson, Nilsen, et al., 2015; Simpson, Ravndal, et al., 2017).

In the Second Assessment of Climate Change for the Baltic Sea Basin (BACC II Author Team, 2015), the absolute sea level rise around Sweden from 1990-1999 to 2090-2099 is estimated to be between over 0.45 m and just under 0.6 m for a mid-range scenario (SRES A1B) with increasing values towards Southeast. The resulting relative sea level change along the Swedish coast was estimated to range from a 0.3 m sea level drop in the Bothnian Bay and nearly 0.5 m sea level rise furthest South, with values around zero close to Stockholm and about 0.1 close to the Norwegian

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[5]Water level can be set and 20, 50 and 100 year low, middle, high, very high and reference water levels calculated from data from 55 Danish tide gauge stations can be visualised for 2010, 2050 and 2100. Available at `https://www.klimatilpasning.dk/vaerktoejer/havvandpaaland/`.

[6]`https://www.kartverket.no/en/sehavniva/visualize-sea-level/`

boarder. For a high-end scenario, the range of relative sea level rise is about 0.1 - 1.0 m and about 0.6 m by the Norwegian boarder. Based on an ensemble of the CMIP5 climate model and RCP4.5, the sea level changes around Sweden from 1986-2005 to 2081-2100 have been projected to range from <-0.4 to 0.4 m (EEA, 2017). The sea level changes around Sweden have also been estimated for RCP2.6, RCP4.5 and RCP8.5. SMHI (2017) simply used the difference between the global mean sea level rise reported in IPCC's Fifth Assessment Report (Church, Clark, et al., 2013) and the vertical land uplift from the NKG2016LU land uplift model (Lantmäteriet, n.d.(b)) to estimate the future mean sea levels around Sweden to 2100 relative to 1986-2005. The 1986-2005 sea level was estimated from 29 tide gauge stations around the coast with interpolated values in between. The results are available in an online GIS database[7], where the mean sea level in 2050 and 2100 is calculated for RCP2.6, RCP4.5 and RCP8.5. As expected, the sea level rise will be highest in the South where the isostatic uplift is close to zero. There, relative sea level can rise up to about one meter by 2100 as reported for the global mean in the Fifth Assessment Report of the IPCC. The isostatic uplift in the north will compensate for much of the sea level rise and a relative sea level subsidance is expected to continue until 2050 by the coasts in the north.

The relative sea level around the UK will have risen between 0.2 and over 0.4 m depending on location in 2081-2100 relative to 1986-2005 according to an estimate based on an ensemble of the CMIP5 climate model and RCP4.5 (EEA, 2017). In a new report, exploratory extended projections of sea level rise have confirmed that average sea level will continue to rise around the UK in the coming centuries for all RCP scenarios. As for Norway and Sweden, the sea level changes have been projected for RCP2.6, RCP4.5 and RCP8.5. The projections build on methods and materials described in IPCC's Fifth Assessment Report and take glacial isostatic adjustments, effects of local oceanographic processes and spatial sea level change patterns due to land based ice and land water storage into account. Relative sea level rise in the UK will be lowest in south-western Scotland and the Scottisch coast will experiece less sea level rise than English and Welsh coastlines. In the northern UK, relative sea level rise is projected to be significantly lower than in the South, where relative sea level rise will be close to the projected global average. The absolute mean sea level rise will be lower in the UK than the global mean. However, some regions face larger mean sea level rise projections than the global average. The reason behind this difference is primarily a combination of the isostatic rebound of the area after the melting of the Celtic ice sheet and spatial sea level patterns (mass fingerprints) associated with mass balance and ice dynamic changes of the Greenland ice sheet (Palmer et al., 2018).

In projections until 2300, the local estimated sea level rise range for the UK is broad, spanning a difference of 1.7 m for RCP2.6 and 2.9 m for RCP8.5. The reason lies in the large degree of uncertainty coupled with information about sea levels for such long time horizons. When looking at the capital cities, the projected mean relative sea level rise is larger in London and Cardiff (0.5 - 2.2 m for RCP2.6 and 1.4 - 4.3 m for RCP8.5) than in Edinburgh and Belfast (0.0 - 1.7 m for RCP2.6 and 0.7 - 3.6 m for RCP8.5). There is less uncertainty of the mean relative sea level rise until 2100, leading to a narrower range of projections but the same geographical pattern is evident. London and Cardiff have projected central estimated values close to the global average, 0.29-0.70

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[7]https://gis.swedgeo.se/smhi_havsniva/

m and 0.27-0.69 m respectively for RCP2.6 and 0.53-1.15 m and 0.51-1.13 for RCP8.5 compared to 1981-2000. Edinburgh and Belfast have lower projections; there the average sea level is projected to have risen 0.08-0.49 m and 0.11-0.52 for RCP2.6 and 0.30-0.90 m and 0.33-0.94 m for RCP8.5 by 2100 (ibid.).

Future absolute sea level rise in the 21$^{st}$ century around Iceland is projected to be 33 % of global mean sea level rise on average. It will be smallest in the Southeast, about 15-20% of global mean sea level rise, almost 30 % in the North and over 30 % in the West fjords. In the East, it is assessed to reach 40% of global mean sea level rise. Based on IPCC data, the absolute mean sea level rise around Iceland from 1986-2005 to 2081-2100 will be 21-22 cm on average for RCP4.5. For RCP2.6 the sea level will rise 6 - 15 cm around Iceland and 10-20 cm for RCP8.5. Based on IPCC's Fifth Assessment Report data, the fingerprint of the mass loss of the Greenland ice sheet has been estimated to cause a 7 ± 3 cm sea level fall around Iceland from 1986 - 2005 to 2081 - 2100, with largest impact in the West fjords and smallest in the Southeast. Updated fingerprint calculations for the melting of Icelandic glaciers using IPCC's mass loss scenarios for the same time span estimate that aside from the Southern coast, Icelandic glacier melt will cause about 4 cm sea level decrease on average. A larger sea level decrease caused by mass loss of Icelandic glaciers will be evident at the southern and southeastern coast, up to 14 cm. For all RCP scenarios until 2100, the absolute sea level rise will be most in the East where the fingerprint of the Greenland ice sheet has the lowest impact but the least absolute sea level rise will be found in the Southeast, where the largest effects of the melting of Icelandic glaciers are found (Björnsson et al., 2018).

Relative sea level changes around Iceland will vary considerably depending on region. In the 21$^{st}$ century, the largest relative sea level fall will be in the Southeast assuming that the isostatic changes remain unchanged. For a global mean sea level rise of 50 cm until 2100 (likely for RCP 4.5 and RCP6.0), the relative sea levels are expected to fall 86 - 190 cm in the area and for a 100 cm global mean sea level rise (IPCC's high end of likely range for RCP8.5), they are thought to fall 72 - 180 cm. In the South, a 4 - 25 cm relative sea level fall is expected for a 50 cm global mean sea level rise but for a 100 cm global mean sea level rise, the predicted range reaches from a 10 cm relative sea level fall to a 12 cm rise. In the Northwest, the projected sea level change range also reaches both sides of zero for both scenarios and the same applies to Skjálfandaflói, Öxarfjörður and the East for a 50 cm global mean sea level rise. The largest values are expected in the areas that are subsiding, that is in the Southwest and West, Eastern Tröllaskagi and the Reykjanes peninsula. In the Southern and Southwestern Reykjanes peninsula, the largest sea level rise is predicted; 26 - 47 cm for a 50 cm global mean sea level rise and 42 - 64 cm for a global mean sea level rise of 100 cm. Hence, sea level rise is not expected to cause major problems in the South and Southeast in the century. In other areas where there is no significant land uplift, the sea level rise will reach the maximum of the sea level changes of the past thousands of years (ibid.). To put this into perspective, it has been found that if the sea levels around Reykjavík are raised by 30 cm, floods that now are 100 - 200 year floods are likely to become 2 year return levels (Sigurðarson, 2018). Again, it is important to keep in mind that there is a large uncertainty of the melting of the Greenland and Antarctic ice sheets which will greatly affect the future sea levels around Iceland and it is important to remember that the sea level rise will continue after 2100 (Björnsson et al., 2018).

## 2.5  Extreme sea level

Extreme sea level events can lead to run-up at beaches and overtopping of natural and man made coastal defence structures such as sea walls, dunes and dikes. They are caused by the combined effect of mean sea level, astronomical tides, storm surges and a dynamic wave component (Wahl, Brown, et al., 2018). Extreme sea level events often result from a combination of contributions simultaneously, from e.g. high mean sea level anomalies, high tides, large waves and storm surges driven by low air pressure and surface wind stress (Vitousek et al., 2017). Local conditions often play a key role in extreme sea level events. The near shore bathymetry or the shape of the coastline may e.g. have decisive affect on the magnitude of a storm surge for a given wind direction and -speed (Quante and Colijn, 2016). The local topographical impact on surge events makes it challenging to produce a clear picture of past and future changes of a large area (EEA, 2017). Although many different components affect sea level extreme events, the predominant driver in long term changes seems to be time-mean sea level rise (EEA, 2017; Quante and Colijn, 2016). Yet, several recent studies indicate that changes in wave and storm surge climate might play an important part in 21$^{st}$ century extreme sea level changes in some places (EEA, 2017).

It is possible that future changes in storm intensity and storm tracks will lead to changes in storm surges that further contribute to changes in sea level extremes. Severe storms that can create storm surges include tropical- and extratropical cyclones (Wong et al., 2014). The specific characteristics of climate change influence on tropical cyclones are not yet well understood but it is likely to vary between regions (Christensen et al., 2013). There is low confidence in global 20$^{th}$ century tropical and extratropical cyclone activity. Still, it is virtually certain that since the 1970s, the strongest tropical cyclones in the North Atlantic have increased in intensity and frequency. Several studies have also shown that there has been a poleward shift in the Atlantic cyclone activity since the 1950s and that wintertime cyclones in the high-latitude Atlantic were more frequent and intense while they were fewer in the mid-latitude Atlantic. Some studies have also shown an increase in amount and intensity of extreme Atlantic cyclones and others opposite trends for the eastern Pacific (Hartmann et al., 2013).

Globally, it is likely that the frequency of tropical cyclones will remain unchanged or decrease under the 21$^{st}$ century while their mean precipitation and highest wind speeds are likely to increase. There is, however low confidence in region specific projections of intensity and frequency of tropical cyclones. Yet it has been noted that high resolution modelling suggest it more likely than not that the frequency of the most intense storms will increase in some regions during the 21$^{st}$ century. Anthropogenic change is unlikely to cause a decrease in the amount of extratropical cyclones by more than a few percent. There is only medium confidence of storm track shift projections for the northern hemisphere while a small shift is likely in the southern hemisphere. It is unlikely that storm tracks in the North Atlantic will simply shift poleward, the response in the North Atlantic storm tracks is more complicated than so, while it is more likely than not for the North Pacific. The magnitude of regional storm track changes and consequent impact on regional climate projections are low in confidence (Christensen et al., 2013). Uncertainties in regional scale storm projections and a small number of regional storm surge studies lead to low confidence in storm surge change projections (Wong et al., 2014).

There have not been performed many global studies on extreme sea levels, most focus has been on regional data (Rhein et al., 2013). The first study of changes in extreme sea levels was performed in 2010 by Menéndez and Woodworth (2010). They confirmed a rise in worldwide extreme high water levels since the 1970s and found that the bulk of the changes could be traced back to underlying changes in mean sea level. They also found the European Atlantic coast to be one of the regions with the most sea level variations and that the changes in extreme sea level events there are caused by changes in the mean sea level and natural climate fluctuations in storminess. Several studies have confirmed the mean sea level to be the most important driver in local and regional long term extreme sea level changes (e.g. Seneviratne et al., 2012; Weisse et al., 2014; Woodworth, Menéndez, and Gehrels, 2011). However, it is important to note that such a simple relationship does not apply to all locations and mean sea level changes do not tell the whole story, other processes are important in some locations (Marcos and Woodworth, 2018). Several studies using global analysis of tide gauges have also found an increase in the magnitude of extreme sea level events in all regions studied since the 1970s and onward. As an example, the 50-year flood height has risen anywhere by 2 - 10 cm per decade since the 1970s. As a result, it has been concluded likely that there has been an increase the magnitude of high sea level extremes since the 1970s. The general conclusion from studies using regional data is that regional sea level extremes have been increasing since the 1950s (Rhein et al., 2013).

At many locations, sea level rise has already caused a significant increase in the return frequency of sea level extremes and it has been concluded very likely that mean sea level change will contribute to future sea level extreme increase (Church, Clark, et al., 2013; Seneviratne et al., 2012). Changes in storminess will also affect future sea level extremes but region specific projections of storminess and storm surges are of low confidence (Church, Clark, et al., 2013). Coastal flooding will have increased frequency, severity and duration with rising sea levels (Vitousek et al., 2017). The baseline upon which extreme sea levels act is modified by sea level rise so that the frequency distribution is shifted towards higher values. The sea level rise thus increases the risk associated with extreme sea levels (Quante and Colijn, 2016). Even a moderate mean sea level rise is thought to be able to cause considerable increase in the number of extreme water level events (see e.g. Buchanan, Oppenheimer, and Kopp, 2017; Fletcher et al., 2017). In some places, a large increase in flood frequency means that events considered extreme water level events today will become the norm by the end of the century (EEA, 2017). It is likely that there will be an increase in the occurrence of sea level extremes in some regions in the 21$^{st}$ century and very likely that it will happen by 2100 (Church, Clark, et al., 2013).

Coastal communities will be negatively impacted by increased frequency of extreme sea levels in a variety of ways, such as increased flooding and erosion risk and ecological and economical impacts on marine ecosystems (Wahl, Brown, et al., 2018). The precise local effect of sea level rise on episodic coastal flooding events is, however, difficult to predict. Coastal storms are of unpredictable nature, coastal geomorphological factors such as bathymetry, bed friction, sediments and topography can alter and hence affect flooding events and some physical processes, for instance tidal currents and waves, have complicated nonlinear interactions. Hence, local coastal hazard vulnerability assessments commonly rely on detailed and computationally onerous numerical modelling

to attempt to simulate wave related near shore water levels and topography interactions to find resulting flooding (Vitousek et al., 2017).

A growing population lives in coastal lowlands and 270 million people lived in areas exposed to a hundred year flood already in 2010. This population is expected to grow to 670 million by 2100 if coastal protection is not improved and 450 million with improved coastal protection measures. 80 % of these people live in Asia and the Pacific and this proportion is not expected to change much through the 21$^{st}$ century (Mimura, 2013). In a newer study, Yokoki et al. (2018) estimated the affected population and economic damages from future sea level rise due to ocean dynamic sea level changes (not including ocean mass changes). The study was done for the different RCP scenarios of IPCC's Fifth Assessment Report (see appendix A) and for different shared socioeconomic pathways (SSP) scenarios, that is different societal development scenarios defined by O'Neill et al. (2017). They found that in 2100, the potentially inundated coastal areas with high tides varied from 370,000 km$^2$ for RCP2.6 to 420,000 km$^2$ for RCP8.5. The economic damage and population affected were more dependent on SSP than RCP, with the affected population ranging between 55.3 million for RCP2.6 and SSP1 to 106 million for RCP8.5 and SSP3. In a recent estimate of IPCC, 11% of the global population is reported to live in low elevation coastal zones (lower than 10 m above sea level). That is about 680 million people and the number is projected to increase to more than a billion under all SSPs by 2050 (IPCC, 2019).

Some coastal regions of Asia and Africa as well as numerous small islands are especially vulnerable to sea level rise and climate change. These continents are hubs for projected population growth but also much economic development. The low development levels and rapid population growth projections in coastal areas of Africa leave it highly threatened. Most Asian countries adjacent to the sea are highly threatened because of commonly densely populated deltas and many growing cities (Mimura, 2013; Nicholls and Cazenave, 2010). Ten years ago, a study of 33 deltas chosen to represent the world's deltas showed that delta surface vulnerable to flooding could increase by 50% by 2100 under the sea level rise projected by IPCC's fourth assessment report (Syvitski et al., 2009). However, small islands will suffer the most proportional impact increase and the island regions of the Pacific, Indian Ocean and the Caribbean are vulnerable to coastal flooding derived from relative or climate induced sea level rise. Low lying islands such as Tuvalu and the Maldives might be abandoned completely in the 21$^{st}$ century (Nicholls and Cazenave, 2010).

### 2.5.1 Extreme sea levels in Scandinavia, the UK and Iceland

Along the European coastline, changes in extreme water levels have been detected and traced back to local mean sea level changes. Future changes are mainly thought to result from mean sea level changes (EEA, 2017). Wave and storm surge changes have been shown to contribute to interannual-to-decadal variability but they show no considerable effect on long term trends. Effects of changes in storminess are not detectable or very little when mean sea level changes and tide variations are removed from trends (Weisse et al., 2014). Hence, the contribution of storminess to changes in extreme sea levels is small in most of Europe and no long term trends in storminess are thought to be separatable from long term natural variability. However, the main uncertainties for future extreme sea level projections in Europe is caused by the uncertainty in future storminess changes since wave

and storm surge climate changes might have substantial impact on future extreme sea level event changes (EEA, 2017). In some studies, increases in storm surges have been projected to become a significant contributor to extreme sea level event changes in northern Europe (Howard et al., 2014; Vousdoukas et al., 2016).

Several studies have shown that due to rising sea levels, the Danish coastline will be substantially more exposed to storm surges than before in the future, especially by the Wadden Sea. Even a small increase in mean sea level around Denmark will lead to great increases in storm surge frequency. In Copenhagen for example, a relative sea level rise of 0.5 m would cause today's 100 year storm surge of 1.5 m to occur every other year (EEA, 2017; Olesen et al., 2014). Another large contributor to raised storm surge levels in Denmark will be the changes in wind patterns. They are thought to raise storm surge heights at the western coasts of Jutland by 0.3 m by 2100 (Olesen et al., 2014). In Church, Clark, et al. (2013) a multiplication factor for frequency changes from 2010 to 2100 of flooding events under projected regional relative sea level rise for RCP4.5 at tide gauge stations around the world is presented. For Denmark, it will be 1-5. The most increase in storm surge height will be at coasts that are already vulnerable to storm surges, with the most effect being caused by sea surface height increase and/or storminess increase (EEA, 2017). The effects of different possible future changes in water levels around Denmark can be visualised in an online GIS database[8]. Monitoring programmes on coastal development and potential impact by future storms and a storm surge warning system are in place for the Jutland coast and run by the Danish Coastal Authority (Harjanne et al., 2016).

In southern Norway, daily to monthly sea surface variability is dominated by weather effects and less by the astronomical tides. Therefore, storm surges can have consequences in the area regardless of the tides. In western and northern Norway, however, storm surges that occur during low tides have little or no impact since the astronomical tides amplitude can be larger than the storm surge height. This makes it relevant to compare the return heights to the highest astronomical tide and not only consider the mean sea level along the coasts of Norway. For example, when a 200 year return level is compared to mean sea level, the difference is largest in the North, up to 3 m and decreases down to about 1 m southwards. When the same return level is compared to the highest astronomical tide, the difference is under 1 m along the northern and most of the western coast, about 1 m at most of the southern coast and between Rørvik and Lofoten but reaches up to about 1.5 in the South-East, the Oslo area. Hence, future changes in the tidal regime likely need to be considered when making coastal risk assessments like growing evidence suggest. Storm surge change projections along the Norwegian coast are in general of low confidence but those that do exist imply a weak increase in future storm surge heights (Simpson, Nilsen, et al., 2015). The multiplication factor of frequency change of flooding events by 2100 relative to 2010 under RCP4.5 in Church, Clark, et al. (2013) for Norway is location dependent. It ranges from 1-5 to 25-50, with the highest value in the South but it is only 1-5 for Oslo (EEA, 2017). Simpson, Nilsen, et al. (2015) found future sea level rise able to greatly increase the likelihood of exceeding present day return heights. An example is that the frequency of exceedance for 200 year return levels is expected to rise much in Stavanger and Bergen between 2001 and 2100, so that the level is expected to be exceeded about 40 times in the period

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[8]https://www.klimatilpasning.dk/vaerktoejer/havvandpaaland/

under RCP8.5. Only small changes in frequency are expected for Oslo. Mean high water and 20, 200 and 1000 year storm surges now and in 2090 can be visualised in an online GIS database[9].

A highest calculated sea level under observed conditions (the past 130 years) has been calculated for tide gauge stations in Sweden as the maximum sea level of the coastal area before storm added to the maximum net sea level increase of the station. The results ranged from 115 to 278 cm above the mean sea level and was 20-40 cm higher than the highest observed water level. The difference between a 100 year return sea level and the highest calculated sea level was 20-50 cm. Yet, historical data shows evidence of higher sea level events than the highest calculated sea level under observed conditions. Unfortunately, a statistical estimation of return levels for the highest sea levels could not be made (Nerheim et al., 2017; Schöld et al., 2017). For Sweden as other places, rare high water events will become more common in the future. In some places, present return levels of 100 years are projected to become 2 year return heights (Nerheim et al., 2017). The Church, Clark, et al. (2013) flooding event frequency change multiplication factor by 2100 is 0 - 1 along the Bothnian Bay. This means that due to the fast isostatic uplift of the area, the flooding frequency is projected to reduce by 2100 under RCP4.5. It rises to 1-5 further South, including Stockholm and is 5-10 for southern Sweden.

Under all RCP climate scenarios, coastal flood risk is expected to increase in the UK until 2100 and beyond. An increase in both magnitude and frequency of extreme water level events is expected (Palmer et al., 2018). The flood frequency change multiplication factor between 2010 and 2100 under RCP4.5 is in general higher for the UK than the Scandinavian countries. There, flooding events are thus expected increase more in frequency, with the multiplication factors ranging from 5-10 to over 100. The highest value is evident at the South-Western most point of England (Church, Clark, et al., 2013; EEA, 2017). The projected changes in extreme coastal water levels around the UK are mainly caused by time-mean sea level rise. Additionally, changes in storminess during the 21st century potentially contribute. By 2050 and 2100, projected return height levels for all four key locations around the UK presented in the UKCP18 Marine report will increase (Palmer et al., 2018). Projected future return level curves for a range of locations and years are available at the UKCP18 user interface[10].

In the 20th century, 50 coastal floods caused damages in Icelandic villages. Based on experience, large flooding events can be expected every 10 - 20 years. Sea level at the Icelandic coast rises the most when strong low pressure systems, high tides and strong wind go together (Almannavarnir, 2011). Iceland is frequently hit by severe storms, particularly during winter and the South and West coasts are most exposed to storm surges and extreme wave conditions (Tómasson, Gíslason, and Karlsson, 1997). When patterns in data of known historical floods were explored, this pattern was evident. That is, floods were most frequent in the South-West and West and during winter time (Jóhannsdóttir, 2017). In a 2011 overall risk assessment for Iceland, the highest risk of oceanic floods was found to be in Árnessýsla, Rangárvallasýsla and West-Skaftafellssýsla counties, in other words, along the South and South-West coast. Historically, many floods are known to have caused damage in Stokkseyri and Eyrarbakki (figure 6) and a few places along the South coast are under

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[9] https://www.kartverket.no/en/sehavniva/visualize-sea-level/
[10] https://ukclimateprojections-ui.metoffice.gov.uk

special surveillance. One such case is Vík in Mýrdalur that experienced unusual coastal changes in the last century. Following the 1918 eruption in Katla and coastal expansion due to sedimentation on the beach at Vík, there was considerable construction near the beach in a location that is now in danger due to beach erosion. Other high risk areas identified are the Reykjanes peninsula, the capital area, Akranes and the Westfjords (Almannavarnir, 2011).

In areas of relative sea level rise, large floods will become more frequent in the future. An example is that the present 100 year flood levels in Reykjavík can become 10 year events for a 50 cm sea level rise (ibid.). Sigurðarson (2018) even estimated a 30 cm sea level rise in Reykjavík able to cause flood levels of 100-200 year events to become biannual events. Land uplift patterns along the South coast are such that it decreases towards West with little vertical movement around Stokkseyri and Eyrarbakki (figure 1). Hence, these already endangered towns will face an increased risk of oceanic floods with rising sea levels while land uplift will somewhat compensate for the absolute sea level rise in Vík. A relative sea level fall is even expected in Vík for a 50 cm global sea level rise (see table 5.8 in Björnsson et al., 2018). Other high risk areas have little to negative uplift and will thus face increased flood risk in the future.
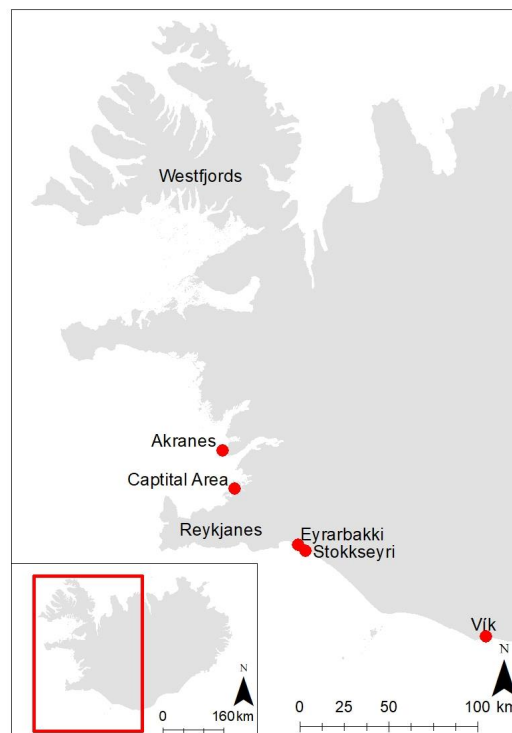


**Figure 6** *High risk areas of coastal flooding in Iceland according to a 2011 national risk assessment (Almannavarnir, 2011).*

# 3 Coastal flooding risk analysis

Every year, natural hazards cause thousands of deaths and much damage around the world. However, no risk is solely associated with the hazard it self. Risk only arises when the hazard generates a possibility for a disaster in interaction with built and natural environments and social vulnerability (Gardoni, Murphy, and Rowell, 2016). A hazard thus only becomes a risk source if it can cause damage (Aven, Ben-Haim, et al., 2018). Elements that are potentially exposed and vulnerable to the hazard are sometimes called receptors (Aldridge et al., 2017). To evaluate the risk, that is the potential of negative consequences of an event with respect to what humans value (Aven, Ben-Haim, et al., 2018), a risk analysis is often performed. Risk analysis can cover many aspects, such as risk assessment, risk perception, risk characterisation, risk management, risk communication and risk governance. It includes both negative and positive consequences but usually the analysis concentrates on the undesirable effects (Aven, H. B. Andersen, et al., 2018). Risk analysis may be divided into three categories of research; risk assessment, risk evaluation and risk management. Here, the focus will be on risk assessments, that is the act of evaluating the level of risk associated with a hazard (Gardoni, Murphy, and Rowell, 2016). Risk assessment is a systematic procedure to recognize and understand hazards, their potential consequences, threats and risk sources (Aven, H. B. Andersen, et al., 2018). As the overall target with this project is to find a risk assessment method that could be suitable for Iceland, preliminary flood risk assessment methods from Denmark, Norway, Sweden and the UK will be introduced in this chapter. A fitting risk assessment method can then hopefully be designed for Iceland with inspiration from the methods of the neighbouring countries.

In October 2007, the European Parliament and Council legislated a directive on assessment and management of flood risks for EU countries (European Union, 2007). The aim with the directive is to reduce the negative impacts of floods on human health, the environment, cultural heritage and economic activities. It requires member states to plan for all sorts of floods; river-, lake-, flash-, urban- and coastal floods, including storm surges and tsunamis. The work is to be done in three stages. First a preliminary flood risk assessment is to be made to find areas of potentially significant flood risk (step 1). Then, flood hazard maps (step 2a) and flood risk maps (step 2b) are to be made of the identified areas and finally, flood risk management plans need to be made for them (step 3). The steps are to be taken within six year planning periods. The first took place in 2010 - 2015, where preliminary flood risk assessments were to be finished in 2011, flood hazard and risk maps were to be ready by the end of 2013 and flood risk management plans prepared by 2015. In the following six year periods, this work is to be updated and reviewed. At present, the second plan period is ongoing; 2016 - 2021 and in December 2018, new reports came out where the preliminary flood risk assessments are reassessed and updated. Steps 2 and 3 are to be finished by the end of 2019 and 2021 respectively.

EU's floods directive applies to the EU member states of interest, that is Denmark, Sweden and the UK. However, different ways are used in the countries to fulfill its requirements. In Denmark and the countries of the UK, an organisation has been made responsible to make sure that the steps of the directive are followed so reports are made on a nation wide basis (K. J. Andersen, Piontkowitz,

Jebens, Thomsen, and Henriksen, 2018; Environment Agency, 2018; Natural Resources Wales, n.d.; RPS Consulting Engineers, 2018; SEPA, n.d.(b)). In Sweden, on the other hand, the work is divided to different bodies at different administrative levels (Hedelin, 2017). There, coastal floods were not included in the assessments of the first six year period since the resolution of elevation data was too low to study flooding at low lying areas by the coast (MSB, 2011). In the new December 2018 preliminary flood risk assessment, new, higher resolution elevation data was used. The new preliminary flood risk assessment thus includes coastal floods (MSB, 2018).

Both Norway and Iceland are members of the European Economic Area (EEA) but not the EU. EU's floods directive has not been incorporated in the EEA agreement and the directive has neither been implemented in Norway nor Iceland (EFTA, n.d.). The 2007 EU law was, however, marked as "Text with EEA relevance" (European Union, 2007), so at the time, the idea was to implement the law in the EEA as well. Therefore, a preliminary flood risk assessment for Norway since 2011 exists. There, it is even stated that "[a]ccording to the European Flood Directive, [...] all member states and members of the EEA Agreement are committed to undertake a preliminary flood risk assessment for all river basin districts" (Peereboom, Waagø, and Myhre, 2011, p. 5).

The same general rule applies in Norway as in Sweden, that the body responsible for activities in normal situations keeps its responsibility under exceptional conditions. The municipalities are responsible for flood risk assessments in Norway but an official body acts as supporting expert on the matter (Harjanne et al., 2016). This arrangement leads to different risk assessments made around the country and due to this arrangement, Norwegian risk assessments other than the 2011 preliminary flood risk assessment following the EU floods directive will not be looked at here. However, a report on past and present observations as well as predictions to 2100 was made for Norway in 2015 and suits as the professional basis for sea levels in Norway (Klimatilpasning, 2016). The methods of this report will be looked into as the results of this research are used as a benchmark in municipal planning and risk assessments (DSB, 2016).

In this chapter, an overview of the methodologies of preliminary coastal flood risk assessments in the EU countries of interest is provided. This is the methodology used on a nation wide basis to identify areas of potential flood risk. The procedure of Norwegian hazard estimation is also looked at and the approach of the Norwegian 2011 preliminary flood risk assessment is discussed. For methods of more detailed hazard and risk mapping on a larger scale for each identified area, see reports on step two of the floods directive from 2013 or December 2019 when they arrive. In the end, the applicability of these methods in Iceland is discussed.

## 3.1 Coastal flooding risk analysis in Denmark

The minister of environment and food is responsible for the implementation of EU's floods directive in Denmark through the coastal authority, Kystdirektoratet. In December 2018, a report came out where risk areas for oceanic and riverine floods are reassessed and updated as the first step in the second cycle of the floods directive. There, the oceanic flood risk is estimated on a five step scale from very low to very high on a 100 m x 100 m grid along the whole coastline. The Coastal Risk

Assessment Framework (CRAF) tool developed by Deltares in the EU funded RISC-KIT project[11] was used for the risk assessment with the method adjusted to Danish conditions (K. J. Andersen, Piontkowitz, Jebens, Thomsen, and Henriksen, 2018). In this section, an overview of the methodology used for oceanic flood risk assessment in Denmark is provided. The report and the resulting maps with all theme layers are available online[12], as well as the *Havvand på land* database used in the project that shows which areas get flooded for a given sea level rise[13].

Risk is the combined effect from the hazard and the vulnerability at a site and thus the two were estimated to find the risk. A flood is defined as temporary cover of water at areas that are normally not under water. Potential flood extent and depth were used to estimate the hazard. The actual flood hazard also consists of other factors such as the speed and duration of the flood, whether any defences are in place and whether they will hold. Since these factors are time consuming to model, they were not included in this study. Three data sets were used to perform the hazard analysis; an elevation model of terrain topography, statistical sea level data and *Havvand på land*, a database that shows which areas go under water for a certain sea level so that for each grid cell, the water level that causes it to be flooded was identified (K. J. Andersen, Piontkowitz, Jebens, Thomsen, and Henriksen, 2018; K. J. Andersen, Piontkowitz, Jebens, Thomsen, Henriksen, et al., 2018).

To estimate the hazard, historical floods and statistical data on high water levels were looked into. In the first plan period, 127 historical storm surges since 1532 were studied. The data availability and -quality as well as the severity of the phenomenon it self were estimated on a scale of 0 - 3 for five categories: water level, meteorological circumstances, extent, damages and human consequences. Based on the results, 41 areas were chosen for closer analysis. The revised method uses the same historical flood basis, adding eight recent events that are analysed and described in the new report. High water statistics for Denmark are kept up to date by Kystdirektoratet through updating them every five years. Eventually, the hazard was estimated from the extent and depth of the larger of the highest registered historical water level or a statistical 1000 year flood (K. J. Andersen, Piontkowitz, Jebens, Thomsen, and Henriksen, 2018; K. J. Andersen, Piontkowitz, Jebens, Thomsen, Henriksen, et al., 2018).

To model floods, Denmark was divided into 36 zones based on factors such as placement of tide gauges, the flood statistics, geographic-, oceanographic- and hydrodynamic conditions. In each zone, the identified extreme water level, the elevation model and *Havvand på land* were used to calculate the depth of an extreme flood in each grid cell. Both the elevation model and *Havvand på land* have a resolution of 0.4 m x 0.4 m and thus the result too. Since the final product was to have a 100 m x 100 m resolution, the mean water depth of the smaller grid cells within the larger cells gave the used value for the latter. The 100 x 100 m grids for all of the 36 zones were then gathered in one file and the water depths were indexed on a scale of 1 - 5 with the statistical Natural Breaks method. A low index represents shallow water and higher indices deeper water. In the end, a map of the hazard index is produced. It is important to keep in mind that this analysis does not include the time aspect so that the method can overestimate the flooded area. The consequences of the flood

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[11]`www.risckit.eu`

[12]at `https://oversvommelse.kyst.dk` and `https://oversvommelse.kyst.dk/webgis` respectively.

[13]The *Havvand på land* database is accessible at `https://www.klimatilpasning.dk/vaerktoejer/havvandpaaland/havvand-paa-land/`.

also largely depend on what is in the area. Hence, the hazard map does not give information of the flood risk. For that, information on what there is to damage in the area, that is the vulnerability, is needed too (K. J. Andersen, Piontkowitz, Jebens, Thomsen, Henriksen, et al., 2018).

Flood vulnerability includes all possible consequences of a flood in an area with flood hazard. It can be divided into direct/indirect and tangible/intangible damages. In the first plan period, only two kinds of direct vulnerability categories were used to identify risk areas. The affected number of households and the potential economic losses were calculated and the upper quartile of the examined areas was then used as a criteria for potential considerable risk. Therefore, only areas with total property value of 2 billion DKK and at least 500 affected addresses could be considered as risk areas. Only using these criteria is not enough, however, since large areas and towns that have low property value but have regularly been flooded did not come out as at risk and many important factors such as other infrastructure and the environment were not considered in the first vulnerability assessment. Since then, it has been implemented in the flooding directive that the harm floods can cause on people's health, the environment, cultural heritage and economic activities must be assessed and included in the risk assessment. The revised method thus defines eight vulnerability categories to better reflect vulnerability in Denmark; Population density, land use, cultural heritage, infrastructure, potentially polluting firms, preparedness, critical infrastructure and economic activity (ibid.).

The objects of each vulnerability category were indexed on a five step scale from very low to very high vulnerability. A low vulnerability index represented local or small damage while higher indices indicated more damage. By doing that, it was assured that not all types of vulnerability within the categories were considered as important for the functionality of the society. The use of indices also allowed for combining different kinds of vulnerabilities that otherwise would be difficult to do. Finally the combined vulnerability for each 100 m x 100 m grid cell was calculated by aggregating the highest index of each category within the cells. That way, vulnerability increased with higher combined score. The aggregated score was then further divided into five groups with an algorithmic Natural Breaks method so that the lowest scores got the index 1 and were defined as grids with low vulnerability and the highest scoring grid cells had high vulnerability and got the index 5 (K. J. Andersen, Piontkowitz, Jebens, Thomsen, and Henriksen, 2018; K. J. Andersen, Piontkowitz, Jebens, Thomsen, Henriksen, et al., 2018).

After estimating both the hazard and vulnerability of each grid cell on the scale of 1 - 5, the resulting hazard- and vulnerability indices were combined to find the risk. The risk was calculated by multiplying the hazard and vulnerability indices for each grid cell (1).

$$Risk = Vulnerability \times Hazard \qquad (1)$$

Hence, only grid cells with flood hazard got a risk index. Depending on the outcome, each grid cell was then categorised as of very low risk to very high risk with the Natural Breaks method as shown in table 4. Lastly, a risk map was made where each category was represented with a specific colour. This map should give a good idea about where and how much risk there is from oceanic floods. It gives a good overview for municipalities on whether further analysis is needed and whether and

where actions are needed. Since this was a national assessment, there can, however, be errors in local results that could be improved with local knowledge and closer modelling (K. J. Andersen, Piontkowitz, Jebens, Thomsen, and Henriksen, 2018; K. J. Andersen, Piontkowitz, Jebens, Thomsen, Henriksen, et al., 2018).

***Table 4*** *The classification of risk depending on the risk index calculated with (1).*

| Index | Risk |
|-------|------|
| 1-4 | Very low |
| 5-6 | Low |
| 7-12 | Medium |
| 13-16 | High |
| 17-25 | Very high |

From the first to second plan period, identified risk areas in Denmark increased from 10 to 14 of which all but one are threatened by oceanic floods. Four new risk areas were identified and two already existing ones were expanded. The revised method also incorporated the dynamic aspect of the flood risk, that is the possibility of increased or decreased hazard and/or vulnerability with time. After an area is identified as a risk area, a more detailed risk analysis and mapping is made by Kystdirektoratet in cooperation with the municipality in question. This work is to be finished in December 2019. The municipalities are then responsible for making risk management plans based on Kystdirektoratets work (K. J. Andersen, Piontkowitz, Jebens, Thomsen, and Henriksen, 2018).

Currently, step 2 is ongoing where closer hazard and risk maps of the identified risk areas are made (ibid.). In the first plan period, future sea level rise was taken into account in this step. Then maximum water depth and current velocity in flooded areas of the risk areas were estimated for different scenarios. Floods of large, medium and low likelihood were modelled for today's circumstances, that is 20 and 100 year floods and extreme floods. 20 and 100 year floods were modelled for estimated 2050 climate and a 100 year flood in 2100 climate according to the A1B scenario of IPCC's fourth assessment of climate change. For these calculations, 0.5 - 2.0 mm/yr land uplift was used along with 30 cm sea level rise for 2050 and 80 cm sea level rise for 2100 (Kystdirektoratet, 2013).

## 3.2   Coastal flooding risk analysis in Norway

In Norway, risk and vulnerability assessments are on the hands of the municipalities. This is a part of the Norwegian planning and building act (Harjanne et al., 2016). A guidance on how to integrate sea level rise and storm surges in local planning has been made by the Norwegian Directorate for Civil Protection (DSB). This was done following IPCC's fifth assessment report. IPCC's results were then soon downscaled for Norway and DSBs guidelines updated accordingly (DSB, 2016). The results of the comprehensive work on past, present and future sea levels in Norway (Simpson, Nilsen, et al., 2015) forms the official basis for sea levels in Norway. For coastal planning purposes, finding an upper limit of sea level projections is important. Hence, sea levels above the likely ranges as reported by IPCC are explored in this work as well (Klimatilpasning, 2016). To define separate safety categories for planning, the guidelines recommend using the mean values of the reported present 20, 200 and 1000 year floods, adding the 95th percentile of RCP8.5 sea level rise projections

for 2081-2100 in the area (DSB, 2016). In the following paragraphs, the methodology of the hazard projections and evaluations from this work is introduced.

Simpson, Nilsen, et al. (2015) downscaled the findings of the fifth assessment report of the IPCC for Norway. They further developed the method by adopting a new, more accurate vertical land movement field, including following gravitational changes. Additionally, they included an assessment of sea level changes caused by changes in the gravitational field due to ocean mass redistribution. They also used a statistical method to find return levels at tide gauges along the coast and found a way to extrapolate data along most of the coastline so return levels were found for most of the coast. Combining the future sea level projections and the return levels, allowances, that is "the height by which an asset needs to be raised so that the probability of flooding remains preserved for an uncertain future sea level change" (ibid., p. 107), could be calculated. They state that using allowances can be an appealing option in planning.

Return periods of water levels are usually calculated with statistical methods. Different statistical methods can be used for this purpose, such as the popular *Gumbel*, a generalised extreme value (GEV) method and *Peaks over threshold (POT)* methods. For Norway, comparisons of different methodologies have shown that the *Average conditional exceedance rate* (ACER) method is suitable and has advantages over others (Skjong, Naess, and Næss, 2013). This is the method used to calculate the official return periods for Norway and is used in the work of Simpson, Nilsen, et al. (2015) as well. The Norwegian use of the ACER method to find return periods is described in the appendix.

After finding return periods with the ACER method, the next step was to extrapolate the extreme water levels along the Norwegian coastline. The values from the tide gauges could not simply be used for other points at the coast since the tide varies in both time and amplitude along the coast. To extrapolate, data series from temporary tide gauges were analysed to find the relationship between the tidal behaviour of the area around the temporary tide gauge and the closest permanent one. Using that along with oceanographic and local knowledge, the coastline was divided into coastal areas of similar tidal behaviour. The extrapolation was then performed by determining the astronomical tide from the tidal zones and then adding the meteorological effect seen at the closest permanent tide gauge. In this way, adjusted time series were produced for each coastal zone. Only the amplitudinal factor of the tide has been found to affect extreme sea levels and hence, the face shift was left out. To find return heights for the coastline, the produced time series were analysed with the ACER method. This way, return levels for almost all the coastline, namely all parts with sufficient data, were found (ibid.).

Lastly, these present return levels calculated for municipalities and the sea level projections described earlier, were combined to make practical use of the information. This was done by adopting the method of Hunter (2012). He proposed a new method to calculate so called *allowance*. An allowance tells you how much you need to raise an asset so that the chance of flooding remains the same under sea level change. He found that this allowance so that the frequency of water levels exceeding a certain level would remain constant could be found by combining sea level rise projections and the extreme-value theory. For that he used IPCC's fourth assessment report and the Gumbel method for extreme sea levels (Simpson, Nilsen, et al., 2015). Simpson, Nilsen, et al.

(ibid.) used their sea level projections found by downscaling and updating the IPCC method and the return levels along the coastline that were calculated with the ACER method in their allowance calculations. Their method of allowance calculations is described in the appendix.

A preliminary flood risk assessment following EU's floods directive since 2011 exists for Norway. It has not been updated since. For comparison, the methods of the 2011 report will be discussed briefly in the next few paragraphs.

The Norwegian Water Resources and Energy Directorate (NVE) performed the preliminary flood risk analysis. Storm surges were included in the assessment but sea level rise as a result of climate change was excluded. Other flood types considered were fluvial (river)-, flash- and storm water (urban) floods. A statistical 1000 year flood was used for mapping of the coastal flood hazard. It was calculated with a frequency analysis from long term data from 22 tide gauge stations along the coastline. Using tide distribution information, storm surge levels could be calculated for the whole coastline (Peereboom, Waagø, and Myhre, 2011).

For the risk assessment, the four obligatory receptor categories of the floods directive were discussed. For the purpose of this preliminary assessment on a national scale, it was assumed that the level of threat to the environment and cultural heritage sites was unimportant. Areas of significant value that fall within these categories were to be identified in the next step of the floods directive with closer hazard and flood risk mapping. The receptor used for the human health category was population. Both inhabitants in residential buildings and probable number of people in critical infrastructure buildings were estimated on a 25 m x 25 m grid. The metre for economic activity was composed of the average flood loss per metre of flood water and the costs of repairing or replacing damaged infrastructure. The economic consequences were estimated by using a 1999 estimation of average flood loss per meter of flood water and scaling it to the that times property values. The different building types were then given different weights. Restoring costs were achieved from the same report and upscaled similarly (ibid.).

Both the population and economic activity receptors were mapped and overlaid by the hazard map. A threshold value defining risk of significance was decided for the amount of people affected by the flood hazard. By choosing 1000, over a quarter of the population presumably at risk was included. This was the criteria used for identification of risk areas. The economic activity at possible risk was highly correlated in space with the distribution of human health map because of the similar ways of estimating them. Therefore, economic activity was not taken into account. A threshold value was not found for other receptor categories than human health since they were not thought to add new information (ibid.).

## 3.3 Coastal flooding risk analysis in Sweden

In Sweden, natural hazard management is decentralised. There, bodies that are responsible for activities in normal situations keep their responsibility in the case of natural hazards. Hence, local administrators are responsible for hazard management in their area. However, a centralised organisation, the Swedish Civil Contingencies Agency (MSB), is responsible for a holistic view of risk

management for all hazards in the country (Harjanne et al., 2016). This governmental structure makes the approach of implementation of EU's floods directive slightly different than in Denmark and the UK (Hedelin, 2017).

The work of implementation of EU's floods directive has been divided between several bodies at different administrative levels. The ministry of defence has the overall governmental responsibility of the implementation. The responsibility of work coordination is, however, on the hands of the MSB. They are also supposed to follow steps 1 and 2a of the implementation through. In other words, MSB is to prepare preliminary flood risk assessments and flood hazard maps of the risk areas. County administrative boards are then responsible for flood risk map preparation and flood risk management plans (Hedelin, 2017; MSB, 2019a). That is done on a water district basis. The country has been divided into five super regional water districts and one of the county administrative boards within each district has been chosen the water district authority. The water district authority has the responsibility of flood risk map and flood risk management plan production within the water districts (Hedelin, 2017).

In the first six year period of the floods directive, coastal flooding was not included in the Swedish assessments. This was because of poor resolution of elevation data available, which was not good enough to study floods in low lying coastal areas (MSB, 2011). The horizontal resolution of the 2011 assessment elevation data was 50 m x 50 m. Later, higher resolution elevation data of 2 m x 2 m grid were made available and used. The flood modelling of the preliminary flood risk assessment published in December 2018 was thus much more detailed than before and included coastal flooding (MSB, 2018).

The preliminary flood risk assessment (ibid.) was made in three steps. First, maps of potential flooding were made and areas at risk of flooding identified. Then, an analysis of population, number of employed persons, human health, environment, cultural heritage and economic activities within the areas was performed. The last step was a choosing process where towns that suffer the largest consequences of large floods were pinpointed. In the rest of this chapter, the method of the preliminary coastal flooding risk analysis will be described further.

The first step was to create flood extension maps for different sea levels. Areas that end up under water for sea levels of 1.0 - 5.0 m over zero in the official elevation system RH 2000 were mapped for each half-metre in an elevation analysis (ibid.). RH 2000 uses the standard elevation point of the European Union, Normaal Amsterdams Peil (NAP) as reference point (Lantmäteriet, n.d.(c); Stichting Normaal Amsterdams Peil, n.d.). NNH+ elevation data (Lantmäteriet, n.d.(a)) from Lantmäteriet was collected for areas close to the coast. The analysis was performed on a county basis or for even smaller zones where complicated archipelagos lie close to the coast (SWECO, 2017). The method simply identified areas under a certain elevation and deemed them flooded even though this will perhaps not be the case everywhere in reality. Areas smaller than 5000 m$^2$, e.g. small islands, were eliminated from the analysis and are illustrated as flooded. No dynamic modelling was made in this step and since this analysis is solely based on elevation, it can be used for any climate scenario and with no regard to isostatic changes (MSB, 2018). The result is similar to the Danish *Havvand på land* and can be accessed online.[14]

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[14]https://gisapp.msb.se/Apps/oversvamningsportal/avancerade-kartor/kustoversvamning.html

For the risk analysis, sea level projections for the end of the century were used. Projections of 100 year flood elevation as well as extreme sea level projections around the country for the end of the century were gained from the Swedish Meteorological and Hydrological Institute (SMHI). These were then rounded up to the next mapped half-metre, giving a certain safety margin. Based on end-of-century 100 year statistical flood and extreme sea levels, SMHI also advised MSB on how to divide the coastline for the analysis. Almost three thousand 100 year flood levels were calculated based on nine climate models using the RCP4.5 scenario (MSB, 2018). In the next few paragraphs, the method of calculating the future extreme sea level is described.

In 2015 - 2017, a special project on increasing the knowledge on present and future mean and extreme sea levels around Sweden was ongoing at SMHI. The results were ment to provide a basis on which decisions on present and future sea level and extreme sea level impacts could be made. One part of the project was to investigate methods for calculating very high sea level around Sweden. One of the methods Södling and Nerheim (2017) used compared 10, 100 and 200 year floods calculated with five different statistical extreme value analysis methods. They used Swedish sea level data from eight long data series for the comparison. The results showed that the different methods give results that deviate more and more as the floods become rarer. They did not find it possible to choose one method as superior of the others and deemed it difficult to get reliable results for very rare floods with statistical extreme value analysis. Therefore, it was concluded that other methods needed to be used to calculate extreme sea levels.

Since neither highest observed levels nor ordinary statistical methods can give a complete picture of highest possible sea levels, Nerheim et al. (2017) created a new method to calculate extreme sea levels. The method is called the 'highest calculated sea level' (SE: högsta beräknade havsvattenstånd) and is based on an analysis of registered storms at SMHI's measuring stations. The idea is to find the sea level produced if the highest measured sea level before a storm comes in is raised by the largest measured sea level rise caused by a storm.

A storm surge was defined as a combination of the sea level before the event and the sea level rise during the event and is described by (2):

$$Storm\ surge = Sea\ level\ before\ storm + Net\ sea\ level\ increase \qquad (2)$$

*Sea level before storm* is the mean sea level over the last seven days, two days before the storm. That is, nine to two days before the storm. The *net sea level increase* is the sea level rise during the storm. It is found by subtracting the *sea level before storm* from the highest measured sea level during the event. The largest values for each component were found for each tide gauge (ibid.).

The Swedish coast was divided in eight coastal areas. Since much covariance in sea level exists within coastal areas, the largest *sea level before storm* within the coastal area was used for all the stations in the area. Then the *highest calculated sea level* for each station was calculated by plugging the largest values into (2). This value is often about 20 - 40 cm higher than the highest observed sea level at a tide gauge. The likelihood of the occurrence of this highest calculated sea level could not be calculated but is judged to be low. The method does not give the highest possible sea levels but

rather an upper limit of sea levels under the circumstances of the period of measurements used for the calculations. This has indeed been confirmed by the fact that the method has not been able to catch the largest described historical events, even though many of the tide gauge data series are long (ibid.).

The method of this *highest calculated sea level* was then further developed to estimate future high sea levels. That was done by assuming that future extreme events are similar to present extreme events. The many effects that climate change might have on factors that influence coastal floods such as storm intensity are not included. SMHI have found results that suggest that a simple aggregation of high sea level events and mean sea levels can be used for this purpose. Hence, future extreme events were calculated with (3)

$$\textit{Low likelihood future high sea level event} = \hspace{4cm} (3)$$
$$\textit{Low likelihood future mean sea level + Present high sea level event}$$

where *present high sea level event* is the maximum *net sea level rise* during an event. *Low likelihood future mean sea level* was found by subtracting the isostatic uplift from the 95th percentile for RCP8.5 global mean sea level rise. Studies have shown that these are the two factors that have the largest effect on future sea level changes around Sweden and that regional anomalies from the global rise are not significant (ibid.). This *low likelihood future high sea level event* was used for the preliminary risk assessment for Sweden. The method did not include local effects of waves (MSB, 2018) but the effect of waves is discussed in Nerheim et al. (2017). Closer estimations for identified risk areas pinpointed in the preliminary risk assessment have been made by SMHI where local factors are taken into account where appropriate as part of step 2 of the floods directive (MSB, 2019b). The highest observed as well as the highest calculated sea levels for todays and future climate can be visualised in an online GIS database at SMHI's website.[15]

Since most consequences of floods occur in urban areas, only urban areas were looked at in the preliminary risk assessment. All towns with at least 200 residents that lie within the end-of-century 100 year floods and extreme sea levels were identified. Out of these and similarly identified towns in potential flood risk from other sources, the top 25% in terms of population and employees were chosen for further analysis. Special focus areas were then chosen from these. Within the identified towns, 33 subcategories of the four categories required to be looked at in the floods directive (human health, environment, cultural heritage and economic activities) were then looked at. At least one of these subcategories had to be affected within the flooded areas so that the urban area would be identified as at considerable flooding risk (MSB, 2018).

For the flood risk to be substantial enough to fall within the regulation of flood risk, the focus areas needed to have an impacted subcategory within each of the four main categories. After filtering those out, it was checked whether historical events with considerable consequences were known to have occurred in the areas (ibid.). A special report with an overview of historical high sea levels and coastal floods and their consequences in 1980-2017 was made for this purpose (Simonsson et al., 2017). At least one historical flood with considerable consequences or likelihood of a future event to have considerable consequences was needed in the areas so that they would be identified as risk

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[15]https://www.smhi.se/klimat/havet-och-klimatet/hoga-havsnivaer

areas. Additionally, urban areas that were close to going through all the previously mentioned filters were estimated separately with help of the county administrative boards. In the end, 16 urban areas along the coast were identified as risk areas (MSB, 2018).

Overview maps of the identified areas with the spread of the 100 year flood in 2100 and the 2100 extreme sea levels as well as points marking which of the four main vulnerability categories affected are provided in the report (ibid.). As part step two of the floods directive, SMHI has estimated 100 and 200 year floods as well as extreme sea levels for 2100, taking isostatic changes into account, for all identified risk areas that are by the coast. These are the 16 identified coastal flood risk areas as well as Norrköping and Haparanda which are identified risk areas for floods of other origins (MSB, 2019b). The estimation was made by adding local effects to (3). The methodology is further explained in Nerheim et al. (2017). The reports with the results are available at MSB's website[16] and hazard maps using the calculations are available on MSBs Flood portal.[17] The next task is to produce risk maps for the areas in cooperation with the county administrative boards.

## 3.4 Coastal flooding risk analysis in the UK

Flooding and coastal change risk to communities, businesses and infrastructure is the top climate change risk in the UK. There is high confidence that the risk magnitude is high both now and in the future and more action is needed in the area according to the 2017 UK Climate Change Risk Assessment. Increased flood damage will depend on the magnitude of global warming. It can be somewhat offset by ambitious adaptation approaches for optimistic numbers of global warming, but local impacts will still vary considerably so that some areas will face significantly increased risks. A 4°C warming by the 2050s will inevitably cause increased flood risk in all regions of the UK, even with ambitious adaptation strategies (UK Committee on Climate Change, 2017).

EU's floods directive has been implemented in all the countries of the UK. In this chapter, a summary of the preliminary flood risk assessments made is provided. Additionally, the method of an impact analysis of extreme floods made for England and Wales is described.

### 3.4.1 Coastal flooding risk analysis in England

In 2017, a coastal flooding impact analysis was performed for England and Wales as part of UK's National Risk Assessment (Aldridge et al., 2017). The aim with the report was to provide improved evidence on the coastal flooding hazard in England and Wales and the impact of it. In this assessment, the time frame was set on the next five years at most. Hence, future changes in risk e.g. due to changes in climate and sea levels were not considered. The assessment was made using well established flood risk methodologies, including impact assessment following the Multi-Coloured Manual and the Flood Risk to People method. The analysis was performed in four specific steps. First, statistical modelling based on historical floods provided a range of possible flood scenarios. Five extreme but plausible flood hazard scenarios were chosen as relevant, realistic worst-case scenarios

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[16]https://www.msb.se/sv/Kunskapsbank/Kartor/Oversvamningskartering/

[17]https://gisapp.msb.se/Apps/oversvamningsportal/avancerade-kartor/hot-och-riskkartor.html

that covered the English and Welsh coastline. It is worth mentioning that the scenarios produced are simply scenarios that could arise but not predictions of what will happen. The scenarios were hydraulically modelled so that the flood inundation was simulated. This hazard modelling was coupled with possible scenario flood defence breaches, supported by historical evidence. Based on the hazard modelling, an impact analysis on population, property, infrastructure, transport and agriculture was performed and algorithms were used to convert direct impacts into tangible metrics. These were transformed into economic costs. The last step was to interpret and present the results. They were put forward in a spreadsheet template, enabling users to access the results for a range of spatial scales and levels of detail. In the next few paragraphs, the method will be explained further.

Firstly, an analysis of historical coastal floods was performed. Information on storm tracks, surface pressure fields, surge levels and qualitative information on impacts from 96 historical events was gathered in a database. The information was then used as input in a statistical model to simulate floods with the same spatial characteristics and dependencies as observed in the data, but more extreme. A well established statistical multivariate extreme value flood risk analysis model, developed by Lancaster University, was used for the analysis. Thousands of extreme scenarios were then simulated, giving information about wave height, -period and -direction, wind speed and -direction and surge/sea levels at tide gauge stations as output. By analysing the storm track clustering of the output scenarios, five scenarios that cover different coastal regions were chosen (ibid.).

The next step was to translate the offshore extreme boundary condition information from the statistical model into estimates of flood depths and velocities in the floodplain for the five scenarios. A necessary step was to transform offshore wave conditions to nearshore. This was done with 2D SWAN wave transformation models, taking refraction, wave growth and breaking into account. A 1D SWAN model was used to transform the information through the surfzone and finally the result was used as an input to BAYONET wave overtopping model. The resulting time series of boundary overtopping/overflow over flood defences was used as input in a flood inundation model. Additionally, possible breach locations of flood defences were identified, supported by simplified modelling and available evidence. Breaches were added to the inundation model where appropriate, assuming they would occur at peak inflow. The output was a time series of water depth and velocity in each flooded grid cell of 50 m x 50 m. At the maximum hazard from the depth and velocity, hazard ratings were calculated for each flooded grid cell with a depth related debris coefficient. These hazard ratings were then classified into four categories; low, moderate, significant and extreme degrees of hazard. Hazard scores lower than for the low hazard category were removed (ibid.).

After assessing the hazard, an impact analysis was made. The first step in the analysis was to collect the best available information on the different receptors, that is elements that are potentially exposed and vulnerable to the hazard, that are included in the study. Five receptor categories were used in the assessment; population, property, infrastructure, transport and agriculture. The information was gathered in a standardised receptor database. Then, by merging the flood hazard data and receptor database, receptors potentially at risk were identified and given the hazard attributes (depth, velocity and hazard rating) at the site. This combined database and auxiliary lookup tables were then used to calculate specific impact information for each receptor. A detailed picture of flood impact across receptors was provided by choosing key metrics including physical measurements such as

percentages, counts, lengths and impacted areas and economic costs of damage to properties and agricultural lands. They were both produced as impacts in their own right and used as inputs in metrics that describe wider economic impact (Aldridge et al., 2017).

Regional summaries were made where danger to life, economic damage to properties, disruption of infrastructure and agriculture impacts were aggregated on both local authority and local resilience forum boundaries so that meaningful aggregation of data can be easily analysed by different users. Finally, a template representing the results from over 300 metrics across more than 200 boundaries over different spatial scales and levels of detail was produced to ensure that the information could effectively be presented to users in need of national as well as very local information (ibid.).

In October 2018, A Preliminary Flood Risk Assessment Report came out for England (Environment Agency, 2018). It was made in close collaboration with the organisations that are responsible for risk analysis in Scotland and Wales and is in line with the the European Floods Directive. The Environment Agency did this work for river, sea and reservoir flooding. The assessment was made on a large river catchment scale, that is river basin districts. At first, the most significant recent historical floods were looked at by going through the historical information available, such as newspaper stories and pictures and measurements when available. This gave a picture of the nature of flooding in England and it was found that the most severe coastal floods occur from a combination of high tides and storm surges. The information was used to map the largest recorded extent of historical flooding, understand the extent and route of the flooding, estimate the highest tide levels that can be expected in a time frame and include it in computer models and predictive flood maps. Potential flooding was then mapped by computer modelling and the historical records were used to verify that the results were representative of known past events.

Floodplains have been modelled from three separate data sources; Remotely sensed and/or surveyed ground levels, surveyed channel and structure measurements and hydrologically calculated amounts of water for different flood likelihoods. Using hydraulic calculations from physical model formulas, floodplains were modelled and the results compared to historical data. The model was then updated until realistic results were found and flood maps produced (ibid.). Mapped floodplains are accessible in a national scale online map called *Flood Map for Planning*.[18] There, information based on flooding from rivers or the sea without flood defences is given (Crown copyright, n.d.(b)). It is thought for local planning authorities and developers so that overtopping and/or failure of defences can be taken into account in long term land use planning decisions as well as to help them to plan in a way that vulnerable development can be located in low hazard areas. The map shows three flood zones defined by the chance of flooding in any given year. For oceanic flooding, the low probability flood zone has less than 0.1% chance of flooding, the medium probability is between 0.1 and 0.5% and the high probability category is above 0.5% chance of flooding in any given year. It also shows the location of major flood defences and the areas benefitting from them, main rivers and flood storage areas (Environment Agency, 2018).

As part of the Environmental Agency's National Flood Risk Assessment project, the flood hazard has been mapped where flood defences and their condition are taken into account. A summary of it is provided in an interactive map on the website of government services (Crown copyright,

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[18]https://flood-map-for-planning.service.gov.uk

n.d.(a)).[19] The map is presented as a flood risk map for England that meets the requirements of the EU Floods Directive and includes the results of an assessment of all flood defences so that both flood defences and their condition is considered (Environment Agency, 2018). Since defences can fail or be overtopped, the chance of flooding behind them is not stopped but reduced (Crown copyright, n.d.(b)). On the interactive flood risk map, one can choose between demonstrations of the extent of flooding or depth and flow estimates at monitoring stations. The flood extent panel shows areas of high risk of flooding from rivers or the sea which are defined as having over 3.3% chance of flooding in any given year and the corresponding chances for the medium risk, low risk and very low risk are 1-3.3%, 0.1-1% and under 0.1% respectively (ibid.). Hence, this is rather a hazard map than risk map. Estimations of depth and flow of water at monitoring sites are made using three risk scenarios. The classification identifying water depths and flow for each scenario (high, medium and low chance) at monitoring sites are also available (Crown copyright, n.d.(a)).

In the preliminary flood risk assessment, the hazard maps along with consequences assessments were used to identify risk areas. Four categories of receptors were assessed with rather simple metrics; human health-, economic-, environmental- and cultural heritage consequences. Human health consequences were assessed by multiplying the number of residential buildings at risk of flooding and the amount of people living in them. The number of non-residential buildings and key services at risk of flooding was used for economic consequences. The environmental consequences were found by estimating the area of special areas of conservation at flood hazard and the number of listed buildings in flood hazard areas was used as a metric of cultural heritage consequences. Resulting maps of the number of people, non-residential properties, key services and listed buildings as well as the area of special areas of conservation at high risk of flooding from rivers or the sea in each river basin district were produced (Environment Agency, 2018).

The flood risk was finally estimated combining the hazard and the consequences and a community risk score was calculated. This was done by identifying the properties at flooding hazard. This gave information on how likely each property was to be flooded in any given year. The average probability of flooding in any year ($\overline{p}$) for all properties in the community was found with (4).

$$\overline{p} = \frac{\Sigma p}{n} \tag{4}$$

$\Sigma p$ is the total flood risk within the community, that was found by aggregating the probability of a flood reaching each property ($p$) and $n$ represents the number of properties within the community. A community risk score (RS) was then calculated for all communities by multiplying the total flood risk in % and the average annual probability of flooding for all properties within the community in % (5) (ibid.).

$$RS = 100\Sigma p \times 100\overline{p} = 100\Sigma p \times \frac{100\Sigma p}{n} = \frac{(100\Sigma p)^2}{n} \tag{5}$$

By calculating the risk score in this way, large and small communities were considered on an equal footing. The communities were then ranked based on their risk score and the highest ranked com-

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[19]https://flood-warning-information.service.gov.uk/long-term-flood-risk/map

munities that represented 50% of the total risk of the country were looked at closer. After consulting with local experts to check, adapt and refine the selection of risk areas, taking into account important sites for the environment and cultural heritage, transport infrastructure, possibly polluting industrial sites, vulnerable local sites and planned future development, 116 communities at significant risk of flooding from rivers or the sea were identified. The resulting data is available online[20]. Following this preliminary risk assessment, flood risk and hazard maps for the identified locations are due by the end of 2019 and flood risk management plans in 2021. These will build on the most up-to-date information and data (Environment Agency, 2018).

It is important to note that the authors are well aware of the dynamics of flood risk and that it will change with climate change and development in population and properties on floodplains as well as aging of assets such as flood defences. A climate change guide on how to make allowance for climate change when estimating a levels is available at the government services website and is updated with new projections. This guidance is e.g. used when new coastal defences are designed and for decision making on the safety of new assets. The impact of climate change on flood risk is also pointed at to raise awareness in possibly affected communities.

Other projects have been made and are ongoing in regards of coastal flooding. An example is that The Adaptation Committee of of the Committee of Climate Change commissioned a report project where an the economics of coastal change management from floods and erosion in England were assessed. By combining different databases from the Environment Agency; *Flood Map for Planning*, *National Receptor Database (NRD)* and *MasterMap Building Outlines*, the amount of assets that overlap different flood zones, that is the assets that are at risk from flooding, was calculated. This does thus only involve tangible vulnerability but it provides direct numbers (Krisht et al., 2018). Recently, the Environment Agency also released a report on long term investment scenarios for coastal flood and erosion risk management (Environment Agency, 2019).

### 3.4.2 Coastal flooding risk analysis in Wales

Natural Resources Wales is responsible for the work following EU's Floods Directive in Wales and has been working with the English Environment Agency and the Scottish Environmental Protection Agency. However, lead local flood authorities were made responsible for making preliminary flood risk assessments for Wales (Natural Resources Wales, n.d.). Long term flood risk maps for Wales are accessible online.[21] The map shows the same parameters as the English *Flood Map for Planning* and additionally a historic flood map and flood warning and flood alert areas can also be viewed. Flood hazard and flood risk maps for identified flood risk areas will be provided by the end of 2019 and 2021 respectively (ibid.).

### 3.4.3 Coastal flooding risk analysis in Scotland

The Scottish Environmental Protection Agency (SEPA) is in charge of implementation of the Floods Directive in Scotland. They used SEPA flood hazard maps (SEPA, n.d.(b)) that were made based on

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[20]data.gov.uk

[21]https://naturalresources.wales/evidence-and-data/maps/long-term-flood-risk/

a Coastal Flood Boundary dataset developed by the Environment Agency and Defra and extended it to reach all areas of Scotland. The database gives sea levels for different conditions along the coast. The water levels were then projected inland to find flood extents for different return periods (SEPA, n.d.(a)). Waves were not included in the projections at the majority of locations and thus the hazard is possibly underestimated in some areas. The hazard map provides an overview of areas that have high, medium and low likelihood of flooding. These categories were used for 10, 200 and 1000 year floods respectively (SEPA, n.d.(b)).

Receptors at potential risk of flooding were identified by comparing them to the SEPA flood hazard maps. If any part of a receptor was witin flood boundaries of the hazard map, it was deemed as at risk of flooding. Receptors from seven categories were assessed; Homes and businesses, Community facilities, Roads, rails and airports, Utilities, Cultural heritage, Agriculture and Environment. As in the English National Risk Assessment: Impact analysis report, an impact assessment was made following the The Flood Hazard Research Centre's Multi-coloured Manual and Multi-coloured Handbook (ibid.).

Risk was classified on a 500 m x 500 m grid by overlaying the receptor- and hazard maps. Future Climate Change will change the hazard and therefore, two climate change flood likelihoods were considered in the risk assessment. They do, however, not take receptor development, such as population changes, into account. The risk was then altered by further assessment of influencing factors. The score on the scale very low to very high risk was increased where following factors were present; Social and economic factors that amplify impacts, rural location, deep and/or fast flowing water, coastal erosion, pollution, high groundwater table (ibid.).

Based on the risk assessment, potentially vulnerable areas were finally identified. These are catchment areas where flooding is considered nationally significant. This was done by overlying the risk map with catchment areas. Additionally, low, medium and high likelihood flood events were looked at across receptor groups. That allowed for identification of frequent flood events that have more impact on some receptors than others. Identified receptors that are likely affected in 10 year floods are in the transport, environment and agriculture classes. 200 year floods affect homes and businesses, community facilities and cultural heritage and 1000 year floods utilities (ibid.). The results can be visualised online.[22] Building on the resutlts, a lead local authority within each of Scotland's 14 local plan districts is now responsible to produce flood risk management strategy and local flood risk management plans (ibid.).

### 3.4.4 Coastal flooding risk analysis in Northern Ireland

As in the other UK countries, a Northern Ireland Flood Risk Assessment (RPS Consulting Engineers, 2018) was published in December 2018. It follows the EU floods directive so this is the first step in the second six year cycle. The method used is similar to that of the other UK countries. For coastal floods, 10, 200 and 1000 year floods (high, medium and low probability floods) are used along with both DTM and LiDAR topographical information and flood protection data to map the hazard. Also included in the Northern Ireland risk analysis is a special climate change scenario.

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[22]https://www.sepa.org.uk/data-visualisation/nfra2018/

For coastal flooding this is a 200 year flood + climate change scenario. The output of the hazard mapping was then used as input in annual average damage calculations for four different receptor groups; properties, key infrastructure, environment and cultural heritage.

Receptors were considered at risk if the flood outlines reached them, apart from residential and non-residential properties that were assessed with the Flood RISk Metric tool (FRISM) developed by JBA Consulting. FRISM calculates annual average economic damages at a defined location, considered over a very long time period. It also assesses the number of people at risk by assuming that 2.5 persons live in each residential property. Along with FRISM, the Multi Coloured Manual of the Flood Hazard Resesarch Centre was used as in other UK countries. The number of key infrastructure within each grid cell was used in a key infrastructure grid for the assessment but the natural environment was considered on a site by site basis. Cultural heritage sites (listed buildings, historic parks and gardens, sites and monuments records and sites of archaeological interest) that were intersected with flood outlines were deemed at possible flood risk. The climate change scenario was used to estimate the increase in properties at risk of flooding and identify areas vulnerable to increased flood risk due to climate change effects (RPS Consulting Engineers, 2018).

The receptors were assessed against the scenarios on a 1 km x 1 km grid basis. A grid was created for each receptor and each flood scenario. Average annual damages on residential and non-residential properties in each grid cell were classified into five risk categories between very low and very high. Since this risk analysis includes fluvial (river), coastal and pluvial (surface water) flood sources, the risk from each source was then combined into a single risk layer for properties. A clustering analysis was then performed on this combined risk layer for each river basin district. All cells that were assigned a high or very high risk label (risk classes 4 and 5) were identified and each cell directly connected to them that had a medium or low risk label (risk classes 2 and 3) or other medium or low risk labelled cells was included in the cluster. The output gave the grid cells for initial flood risk areas (ibid.).

The initial flood risk areas were then analysed further with regard to key infrastructure. A key infrastructure grid with the count of key infrastructure in each cell was compared to the initial flood risk areas. Each grid square that was at flood risk for a high probability event and had two or more key infrastructure components was determined. Any grid cell that fulfilled these requirements and was directly connected to the cluster was then added to the initial flood risk area (ibid.).

The extended initial flood risk areas were then finally validated against historical flood data. 82% of the extended initial flood risk area grid cells had evidence of historical floods. The historic records also revealed cells that did not go through the filter of the minimum clustering criteria but still had evidence of previous flooding. The historical flood record heat map was used as evidence to judge whether or not to include cells in the flood risk areas. In that way, they were adjusted to take anomalies into account (ibid.). The results of the risk assessment can be visualised online.[23]

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[23]https://www.nidirect.gov.uk/articles/check-the-risk-of-flooding-in-your-area

# 4 Discussion

In general, similar methods are used for preliminary risk analysis in the countries of interest. First, the hazard is estimated, using statistically calculated return flood levels. Available information on historical floods is used for comparison and even as an alternative estimation of flood outlines. Some nations already include projections of future sea level rise in the preliminary risk analysis while others seem to plan on including that in the next step where closer hazard and risk mapping for identified risk areas is performed. In all the countries, there seems to be awareness that future changes need to be taken into account for planning purposes. In Sweden, a new method was developed to get an estimate of an upper boundary of possible future sea levels. In Norway, Hunter's (2012) method of estimating allowances was further developed. Both of these can provide useful information for planning to the future.

The EU flood directive specifically obligates member states to look into four vulnerability categories for risk analysis and that is done in all the EU countries. The 2011 Norwegian preliminary flood risk assessment stands out in this regard and did not include all the categories in their final assessment. That is, however, an older and not as extensive report as the newer assessments made in cycle two in the other countries. The comparability to the others can thus be questioned. The vulnerability was commonly estimated with some kind of an index. Finally, hazard and vulnerability maps are combined to identify risk areas.

In 2011, the Icelandic civil protection agency performed an extensive national risk assessment that looked into all risk sources that threaten each county, including natural hazards. That was made in a very different way than the preliminary coastal flood risk assessments described in the previous section and did not focus on especially on floods. A questionnaire and checklist method was used to look into each risk factor in the counties. The likelihood and consequences of hazards in each county were thought of with previous events and possible future events in mind. Checklists were used to estimate and categorise the hazards in terms of frequency, severity, likelihood and consequences. The questionnaires and checklists were answered and worked on by civil protection boards in each county in collaboration with the civil protection agency. In terms of coastal flooding risk, 13 areas were categorised in four classes; low-, potential-, high- and very high risk. It was found that many coastal areas are at risk and preventive measures need to be taken (Almannavarnir, 2011). The responsibility of further risk assessment is, however, on the municipalities, which are often not capable of carrying out this responsibility due to their small size (Magnúsdóttir, Þrastardóttir, and Hreggviðsson, 2016). So far, the focus of research in this field has mainly been concentrated on the capital area and a few smaller communities by the South and West coast (Geirsdóttir, Gísladóttir, and Jónsdóttir, 2014). There is serious lack of studies that aim to find the best strategies for managing enhanced coastal flooding risk in Iceland and to ensure that it is taken into consideration in planning decisions.

When considering performing risk analysis in Iceland, the first thing that comes to mind is that data availability is scarce, especially when compared to the countries of interest that all possess long data series of sea level measurements (see section 2.2.1). This lack of data makes it difficult to statistically calculate return levels, which is used to estimate the flood hazard in every country of

interest. The Reykjavík series is the only series long enough so that it could be used for statistical return level calculations. This has already been done with different methods for that series, including the Norwegian use of the ACER method (see appendix B) (Sigurðarson, 2018).

Another way of estimating possible flood extent is to look at historical floods. This has been done in all the EU countries of interest as part of the floods directive. However, data on historical coastal floods and their extent is also limited in Iceland and only a few have been analysed. In 2017, information about known historical floods in Iceland was gathered and analysed. The list of historical coastal floods counts 289 floods in the period of 1191 - 2015 but it is likely that many events are missing, especially older floods. However, even though some information exists on a number of historical floods in Iceland, the information is usually very limited so that the size or extent of the floods is very difficult or even impossible to work out from the information that exists (Jóhannsdóttir, 2017). As a result, none of the hazard assessment methods used in the countries of interest can be used directly. Flood extent estimates for Iceland probably have to be made mainly relying on modelling and/or scenario calculations, with the possibility to use return levels for Reykjavík. The available tide gauge and satellite data should be used as possible. In the case of satellite data, an extrapolation towards the coast similar to what Simpson, Nilsen, et al. (2015) did for Norway might be feasible. The results of the few extent analysis that exist, such as of the extensive Básendaflóð in 1799 (Viggósson, Elíasson, and Sigurðarson, 2016) can be used as a reference for the affected areas.

In contrast to the demand of the EU floods directive of an update every six years, such frequent updates are unlikely to be performed in Iceland. Even though it ensures that the assessment is always up to date and reduces the probability of taking unnecessarily vast measures, that requires both economic and human resources which then would be taken from other important projects. Due to that and the fact that urban planning is done on a long term basis, the inclusion of future sea levels in hazard assessments are recommended. For that, both the Norwegian and Swedish methods are appealing. Perhaps, the need for an estimation of an upper limit of future sea levels is more important in the sinking area of Reykjanes than the rising area of Höfn, where an allowance calculation would probably do.

The isostatic changes in the UK are comparable to Iceland in the way that both countries have subsiding and uplifting areas (see 2.1.1). Hence, reasoning might suggest that the UK would be a good country to learn from in terms of treating diverse areas differently in terms of long term risk analysis. Although this might come to reality in the future, the current UK risk analysis does not seem to treat regions differently in terms of isostatic change. The English (where the most subsidence occurs) and the Scottish (where the most uplift occurs) risk analysis methods do not differ much and in fact, all the UK risk assessment methods are similar. Isostatic changes do not seem to be taken into account. In the overview of the methodology used in the Scottish National Flood Risk Assessment (SEPA, n.d.(b)) it is mentioned that "two climate change flood likelihoods have been considered with the assessment". Unfortunately, no further explanation on what they include is given. For Northern Ireland, a climate change scenario is produced as a 200 year flood plus climate change. This climate change factor is not further explained. It is thus unclear whether isostatic changes are taken into account in these scenarios, it might well be. In the future calculations for both Norway and Sweden, isostatic changes are, however, taken into account. Yet, the risk

assessment methods do not seem to be different due to the uplift of the region and expected low or even negative future relative sea level rise in the northern parts of the countries. The similarities to the isostatic conditions in Iceland do thus not seem to be an important factor that needs to be taken into account when choosing a method for preliminary risk assessment.

The English impact analysis method is outstanding in a way that offshore boundary conditions are transformed to nearshore using wave transformation- and overtopping models. Unfortunately, it is not mentioned how much of an impact this measure had, that is whether it changed the outcome to perform this transformation. The use of such transformation is likely to be relevant in hazard estimations for Iceland since very large waves can be produced in some areas. However, it is advised against such complications if the end result, that is the flood extension and -hazard is little or not affected.

To summarise, it is recommended that the hazard assessment part of the risk assessment is performed using modelling and/or a scenario calculation, using the available data as possible. For the execution, the coastal flooding impact analysis for England and Wales might be an interesting inspiration although it can not be done in the exact same way due to the lack of information on historical flood extents. A simpler possible scenario production could e.g. be made based on the idea of the Swedish highest calculated sea level method. The resulting flood propagation could then be simulated. It is advised that future sea levels are included in the assessment and that the resulting hazard is indexed so that it can easily be combined with vulnerability estimates for risk assessment.

In terms of vulnerability and risk estimates, many of the methods used in the countries of interest are appealing. Long stretches of the Icelandic coast do not host any elements likely to be affected by flooding except for nature and perhaps some roads. The vulnerability categorisation of EU's floods directive is thus likely to be able to successfully estimate vulnerability in Iceland. The exact subcategorisation would need to be adjusted to Icelandic conditions just as other countries have adjusted the vulnerability categories to them. Thus, it is recommended that the vulnerability estimation is made in the same way as in any of the EU countries of interest, preferably through an index production so that it can be easily coupled to the outcome of the hazard assessment. The countries of interest approached the risk assessment itself in slightly different ways and the Danish method seemed appealing for Iceland. The method is well described and relatively straightforward. The readily available tool used for the analysis should make the application uncomplicated. With that said, the approaches of the other countries might well be suitable as well, depending on the way the hazard and vulnerability assessments can be combined.

# 5 Conclusion

All the countries of interest monitor sea level rise through dense tide gauge networks. They also take part in European satellite programmes that amongst others provide satellite altimetry data. Unfortunately, sea level measurements have not been performed as thoroughly in Iceland as in these countries and an official body needs to be made responsible for management of the tide gauges to make sure that measurements from now on will be usable. In general, preliminary risk assessments for the countries of interest were performed in a similar way, even though the physical conditions of sea levels now and for future changes are variable. All of them use statistical return levels to estimate the hazard and look to historical flood outlines as well, at least to some extent. The data needed to make use of such methods for Iceland is sadly scarce which makes directly applying the hazard assessment methods of the preliminary risk assessments for those countries difficult.

Even though a direct use of these methods is problematic, they can still give ideas of how preliminary coastal flood risk assessments can be made for Iceland. It is believed that the coming risk assessment work in Iceland can in some way build on the work performed in the countries of interest to evaluate the hazard through adapting the methods to the available resources for Iceland. In the masters thesis that this work is a part of (Jóhannsdóttir, 2019), it was for instance shown that a hazard assessment can be made through a scenario production which was built on ideas from the above described methods. That particular method would, however, need to be developed further. Many of the vulnerability assessment approaches and methods for the production of a combined risk assessment used in the countries of interest seem feasible and it is believed that those do not need to be altered as much to apply them in Iceland.

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# Appendix: Description of the usage of the ACER method to find return periods and an adopted Hunter method to calculate allowances in Norway

## Finding return periods with the ACER method

The ACER method looks at extreme water levels by fitting a curve to peaks that exceed a specified threshold value rather than solely including maximum yearly values as is often done. The goal is to find return periods of certain water levels but that is complicated by the same storm surge being likely to cause more than one peak. Therefore, a conditional exceedance rate is looked at so that all peaks that exceed the threshold value are included, given that the previous peaks did not. In other words, the ACER function is used to find the rate of water level exceedance over a threshold value $\eta$, given $k$-$1$ previous non-exceedances (Simpson, Nilsen, et al., 2015). $k$ is a parameter that decides how many previous events each event depends on. For a high enough $k$-value, the calculated return levels start to converge (Södling and Nerheim, 2017).

The ACER method tries to approach the behaviour of the data below this convergence with the ACER function $\varepsilon_k(\eta)$ defined by (6):

$$\varepsilon_k(\eta) = q_k(\eta)exp(-a_k(\eta - b_k)^{c_k})), \quad \eta \geq \eta_1 \tag{6}$$

$\eta$ represents the threshold value, $\eta_1$ is the tail marker and $a_k$, $b_k$ and $c_k$ are constants. The function $q_k(\eta)$ varies slowly in comparison to the exponential function in practice and hence it is treated as a constant, $q_k$, as well. To find $k$, a conditional exceedance rate was calculated for distinct water levels ($\eta$) using Norwegian tide gauge data. The average exceedance rate was used to find $k$. Then, the ACER function was run for different $k$-values and the point where the process starts to converge was found. As a result, $k = 3$ was chosen and subsequently the parameters of (6) were found by fitting (6) to estimated ACER functions described above (Simpson, Nilsen, et al., 2015).

Finally, using $k = 3$, the return height $z_m$ for all but one, that is 22, permanent tide gauges in the Norwegian Mapping Authoritie's network were calculated by (7):

$$z_m = b_k + \left( \frac{1}{a_k} \left( ln(q_k N) - ln \left( -ln \left( 1 - \frac{1}{m} \right) \right) \right) \right)^{\frac{1}{c_k}} \tag{7}$$

where $m$ is the return period and $N$ is the average yearly number of peaks in the data. Detrended, 24 to 100 year long time series were analysed, using mean sea levels in 1996-2014 as a reference level (ibid.).

## Calculating allowances with an adopted Hunter method

Allowances were calculated by first defining the number of times ($N_{AC}$) a sea level $z$ was expected to be exceeded over a given time (8):

$$N_{AC} = Nq \, exp(-a(z-b)^c) \tag{8}$$

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The constants *N, q, a, b and c* are the same parameters as in the ACER method for a given *k*. After a certain sea level rise, the number of exceedances of the same sea level should be the same as the sea level *z* minus the sea level rise plus the allowance. This can be represented as (9):

$$N_{\text{ov,AC}} = \int_{-\infty}^{\infty} P(z') \, Nq \, exp(-a(z - \Delta z - z' + A - b)^c)dz' \qquad (9)$$

Δ z + z' is the mean sea level rise where Δ z is the mean value of sea level rise and z' is a random variable with a probability distribution P(z') and mean of 0. In this study, a normal uncertainty distribution with zero mean and standard error $\sigma$ was used (10). Hence, $N_{\text{ov,AC}}$ is the overall number of exceedances of the sea level z - Δ z - z' + A, which should equal *z* when A stands for the allowance.

$$P(z') = \frac{1}{\sigma\sqrt{2\pi}} \, exp\left(-\frac{z'^2}{2\sigma^2}\right) \qquad (10)$$

Equation (9) can be manipulated into (11):

$$N_{\text{ov,AC}} = Nq \, exp(-a(z-b)^c) \int_{-\infty}^{\infty} P(z') \, exp(a(z-b)^c) \, exp(-a(z - \Delta z - z' + A - b)^c)dz' \qquad (11)$$

From (11), it can be seen that $N_{\text{AC}} = N_{\text{ov,AC}}$ is true when (12):

$$\int_{-\infty}^{\infty} P(z') \, exp(a(z-b)^c) \, exp(-a(z - \Delta z - z' + A - b)^c)dz' = 1. \qquad (12)$$

Unfortunately, (12) can not be solved analytically so it was solved for A numerically. The elimination of *z* from (12) is also impossible making the allowance dependent on the return level of interest. Both of these things are possible using the Gumbel method, giving it that advantage over the ACER method when calculating allowances (Simpson, Nilsen, et al., 2015).