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DARK-BLUE HORIZON
SEA LEVEL RISE AND METEOTSUNAMIS ON THE FINNISH COAST

Havu Pellikka

Institute for Atmospheric and Earth System Research
Faculty of Science
University of Helsinki
Helsinki, Finland

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Supervisors	Dr. Milla Johansson Marine Research Unit Finnish Meteorological Institute Helsinki Finland	Prof. Kimmo Kahma Marine Research Unit Finnish Meteorological Institute Helsinki Finland
Pre-examiners	Prof. Tarmo Soomere Laboratory of Wave Engineering Tallinn University of Technology Tallinn Estonia	Prof. Malgorzata Stramska Institute of Oceanology Polish Academy of Sciences Sopot Poland
Opponent	Dr. Ralf Weisse Institute for Coastal Research Helmholtz-Zentrum Geesthacht Geesthacht Germany	
Custos	Prof. Petteri Uotila Institute for Atmospheric and Earth System Research Faculty of Science University of Helsinki Helsinki Finland	

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Author
Havu Pellikka

ORCID iD
<https://orcid.org/0000-0001-8835-5831>

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Dark-blue horizon: Sea level rise and meteotsunamis on the Finnish coast

Abstract

This thesis presents research on two topics related to sea level in the Baltic Sea: regional sea level rise and meteotsunamis, i.e. meteorologically generated tsunami waves. While these phenomena act on very different time scales, they are both relevant for estimates of coastal flooding risks. Main objectives of this work are i) to present projections of mean sea level change in Finland by 2100 as location-specific probability distributions that can be used as a basis for decision-making in coastal management, and ii) to study the occurrence of meteotsunamis on the Finnish coast and the weather conditions that create these waves.

Global mean sea level is rising in the warming climate. This will affect coastal life worldwide, but sea level does not rise uniformly around the globe. Projections of future sea level rise have large uncertainties, especially because the response of the Antarctic ice sheet to climatic changes is poorly known. This makes the upper tail of the probability distribution of sea level rise hard to pin down. In this work, an ensemble of global sea level rise projections is adjusted regionally to form a probability distribution of regional sea level rise. The results suggest that sea level rise in the Baltic Sea will be about 80% of the global mean, without including the effect of land uplift.

To obtain probability distributions of mean sea level change relative to land, the effects of postglacial land uplift and wind-induced changes in mean sea level are combined with the sea level rise distributions. According to the average scenario, the sea level in the Gulf of Finland is expected to rise ca. 30 cm in 2000–2100, while mean sea level decline will continue in the Gulf of Bothnia. However, the high-end scenario projects sea level rise everywhere on the Finnish coast, ranging from 21 cm in Vaasa to 90 cm in Hamina.

Meteotsunamis occur in shallow sea areas worldwide and can reach a height of several metres in extreme cases. In the Baltic Sea, such high, inexplicable sea waves are historically known as *Seebär* on the German-speaking southern coast and *sjösprång* in Swedish-speaking regions. According to old literature and recent eyewitness reports, meteotsunamis can occur all around the Baltic Sea and cause mild damage. The highest reliably documented events have been 1–1.5 metres high.

After decades of no reported occurrences, three meteotsunamis were observed in Finland in the summers of 2010 and 2011. This work gives a detailed description of these events and their meteorological origin. The waves were created by air pressure disturbances propagating over the sea. The speeds of the disturbances were close to the long wave speed in the sea, which amplifies the wave. Such resonance effects, in addition to local coastal bathymetry, are central in the formation of meteotsunamis.

To study the frequency of meteotsunami occurrence on the Finnish coast, meteotsunamis were detected in the original tide gauge charts and high-resolution sea level data from the Gulf of Finland over the past century. In total, 121 potential events were identified in the summer months of 1922–2014, with typical wave heights of 10–30 cm at the tide gauges. A statistically significant increasing trend in the number of meteotsunamis was found in Hamina in the eastern part of the gulf, but not in Hanko in the west. A strong connection between lightning observations (1998–2014) and meteotsunami occurrence was found: lightning numbers were over ten times higher on days when a meteotsunami was recorded compared to other summer days.

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<https://orcid.org/0000-0001-8835-5831>

Nimeke
Sinimusta horisontti: Merenpinnan nousu ja säätsunamit Suomen rannikolla

Tiivistelmä

Tässä työssä käsitellään kahta Itämeren vedenkorkeuteen liittyvää aihetta: alueellista merenpinnan nousua ja säätsunameja eli meteorologisten ilmiöiden synnyttämiä tsunamiaaltoja. Vaikka ilmiöiden aikaskaalat ovat hyvin erilaiset, ovat ne molemmat olennaisia Itämeren meritulvariskien arvioinnin kannalta. Työn tärkeimpinä tavoitteina on i) laskea ennusteet keskimerenpinnan tason muutokselle Suomessa vuoteen 2100 saakka paikkakohtaisina todennäköisyysjakaumina, jotka sopivat käytettäväksi päätöksenteon tukena rannikkosuunnittelussa, sekä ii) tutkia säätsunamien esiintymistä Suomen rannikolla ja niihin liittyviä sääolosuhteita.

Ilmaston lämpenemisen aiheuttama valtamerien pinnannousu vaikuttaa rannikkoseutujen elämään ympäri maailman, mutta merenpinta ei nouse tasaisesti kaikkialla. Merenpinnan nousuennusteissa on myös suuria epävarmuuksia erityisesti siksi, että Etelämantereen mannerjäätikön tulevaisuus muuttuvassa ilmastossa tunnetaan huonosti. Sen vuoksi merenpinnan nousun todennäköisyysjakauman yläpäättä on vaikea arvioida. Tässä työssä käytetään alueellisen merenpinnan nousun jakauman pohjana joukkoa globaaleja ennusteita, joihin sovelletaan alueellisia korjaustekijöitä. Tulosten perusteella merenpinnan nousu Itämerellä on noin 80 % globaalista keskiarvosta, jos ei huomioida maankohoamisen vaikutusta.

Kun merenpinnan nousujakaumiin lisätään maankohoamisen ja tuulen aiheuttamien keskimerenpinnan muutosten vaikutus, saadaan todennäköisyysjakaumat keskimerenpinnan tason muutoksesta maan suhteen. Keskimääräisen skenaarion mukaan merenpinta nousee Suomenlahdella noin 30 cm vuosina 2000–2100, kun taas Pohjanlahdella merenpinta edelleen laskee. Korkeimpien ennusteiden toteutuminen johtaisi kuitenkin merenpinnan nousuun kaikkialla Suomen rannikolla nousun vaihdellessa Vaasan 21 cm:stä Haminan 90 cm:iin.

Säätsunameja esiintyy matalilla merialueilla ympäri maailmaa ja ne voivat saavuttaa ääritapauksissa useiden metrien korkeuden. Itämeren piirissä tällaiset korkeat, selittämättömät aallot tunnetaan vanhastaan saksankielisellä nimellä *Seebär* ja ruotsinkielisellä nimellä *sjösprång*. Vanhojen kirjallisuuslähteiden ja uusien silminnäkijähavaintojen perusteella säätsunameja esiintyy kaikkialla Itämeren rannikolla ja ne voivat aiheuttaa lievää vahinkoa. Suurimmat luotettavasti dokumentoidut tapaukset ovat olleet 1–1,5 metrin korkuisia.

Useiden vuosikymmenten mittaisen hiljaisen jakson jälkeen Suomessa havaittiin kolme säätsunamia kesällä 2010 ja 2011. Tässä työssä kuvataan nuo tapaukset ja niiden meteorologinen tausta yksityiskohtaisesti. Aallot syntyivät meren yllä liikkuvien ilmanpaineen häiriöiden seurauksena. Häiriöiden nopeus oli lähellä pitkien aaltojen nopeutta meressä, mikä kasvattaa aallon korkeutta. Tällaiset resonanssi-ilmiöt ovat rannikon paikallisen pohjatopografian lisäksi keskeisiä säätsunamien muodostumisessa.

Ilmiön yleisyyden tutkimiseksi säätsunameja etsittiin Suomenlahden mareografien alkuperäisiltä piirturirullilta ja korkean resoluution vedenkorkeushavainnoista lähes vuosisadan ajalta. Aineistosta tunnistettiin kaikkiaan 121 potentiaalista säätsunamia kesäkuukausilta 1922–2014; aaltojen tyypillinen korkeus mareografeilla oli 10–30 cm. Säätsunamien lukumäärässä havaittiin tilastollisesti merkitsevä lisääntyvä trendi Haminassa, mutta ei Hangossa. Salamahavaintojen (1998–2014) ja säätsunamien esiintymisen välillä havaittiin selvä yhteys: salamamäärät olivat yli kymmenkertaisia säätsunamien esiintymispäivinä verrattuna muihin kesäpäiviin.

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Preface

The name of this thesis, *Dark-blue horizon*, quotes an eyewitness account of a meteotsunami in the Gulf of Finland on 26 July 1876 (p. 39). Metaphorically, it refers to the projections of increasing coastal flooding risks in the future. It is my wish that this work would be of interest to coastal dwellers and serve societies in adapting to the changing conditions of our future.

It takes many people to complete a doctoral dissertation. First of all, I want to thank my supervisors for all their support: Kimmo Kahma for his admirable enthusiasm, deep expertise and endless ideas, and Milla Johansson for often saving the day with her calm and reassuring reasoning, besides being excellent company in all kinds of excursions into the wild Finnish nature. Professors Matti Leppäranta and Petteri Uotila are acknowledged for their gentle encouragement as well as for smoothly sorting out practical matters. I thank Professors Malgorzata Stramska and Tarmo Soomere for pre-examining this thesis, and Ralf Weisse for taking the time to act as the opponent.

I wish to thank all the co-authors of the papers for their work and dedication. Without their efforts this thesis would not exist. Special thanks to Anu Karjalainen and Hanna Boman who spent weeks carefully going through and digitizing old sea level observations, stored on paper rolls in the basement of the institute.

The flexibility and support of my boss Lauri Laakso was critically important when things got difficult, and he can largely be thanked, or blamed, for the fact that this thesis is now completed. My dear friend and colleague Jan-Victor Björkqvist has often been the first person to turn to at moments of despair and his help over the years is greatly appreciated. I also wish to thank Peter Eriksson and Jani Särkkä for help with translation problems, and Leena Kahma and Marina Kurtén for proofreading.

I am grateful to Jadranka Šepić and Ivica Vilibić for the hospitality they showed in welcoming me to visit the Institute of Oceanography and Fisheries in Split for a couple of months in 2015–2016. Even though it coincided with a dark period in my personal life, I have warm memories from this time in Croatia and my studies on meteotsunamis greatly benefitted from their knowledge. I also wish to thank Ola Kalén for sharing information on Swedish meteotsunamis.

The most important source of funding over my years in sea level science have been the Finnish Research Programmes for Nuclear Power Plant Safety (SAFIR). I thank Kirsti Jylhä for her work in steering the EXWE project over the years, always in a friendly and patient manner despite the often high pressure with tight deadlines.

The work described in this thesis was carried out in the Marine Research Unit of the Finnish Meteorological Institute. Highlights of these years have been the research expeditions on *R/V Aranda*, bringing some salty water, seasickness and glorious sunrises to the research life where one so easily gets buried in numbers and computer code.

Thank you, all colleagues in the Finnish marine research community – special thanks to Simo for hosting innumerable Simo-Kino movie nights, Ulpu and Victor for making music together in *Kolmihuippuinen spektri*, and Elina for trying (and inevitably failing) to get me to work before lunchtime. I am deeply grateful to Meri for offering help when I most needed it.

I thank my family and friends, both former and current, for all their love and support. Ani, my dear four-legged companion, has helped me to stay connected with our common basic needs and took care of getting me outside during the days of writing. My partner Anna has been the greatest support during the past couple of years, and her encouragement to find my own paths and listen to my needs has been invaluable. I hope her life will become easier now that I am turning over a new leaf.

Lastly, I want to honour all the different parts within me, those that had to suffer and those that wanted to see this work finished some day. The last phases of this work have been a learning process of self-compassion, and I hope that this process will continue and bear fruit in the coming days and years.

In Luova Kasvu, Espoo
May 2020

Havu Pellikka

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List of original publications

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- II** Pellikka H., Rauhala J., Kahma K.K., Stipa T., Boman H., and Kangas A., 2014. Recent observations of meteotsunamis on the Finnish coast. *Natural Hazards* 74, 197–215. DOI: 10.1007/s11069-014-1150-3
- III** Pellikka H., Leijala U., Johansson M.M., Leinonen K., and Kahma K.K., 2018. Future probabilities of coastal floods in Finland. *Continental Shelf Research* 157, 32–42. DOI: 10.1016/j.csr.2018.02.006
- IV** Pellikka H., Laurila T.K., Boman H., Karjalainen A., Björkqvist J.-V., and Kahma K.K., 2020. Meteotsunami occurrence in the Gulf of Finland over the past century. *Natural Hazards and Earth System Sciences Discussions*, in review. DOI: 10.5194/nhess-2020-3

Author contributions

In Paper **I**, the author was responsible for calculating the regional sea level rise projections, with support from the co-authors, and wrote sections 4.1–4.4. The paper was also part of Milla Johansson’s PhD thesis (Johansson, 2014). In Paper **II**, the author performed the analyses of sea level and air pressure data and wrote most of the paper. In Paper **III**, the author calculated the mean sea level projections and was mainly responsible for writing the paper in collaboration with all co-authors. In Paper **IV**, the author coordinated the study, had a leading role in the data analyses and wrote most of the paper. The author is fully responsible for the summary. Note that the given name of the author changed in 2016.

...vi ha för oss en orkester av tusen instrument, höga toner av kort våglängd och djupa undertoner som korrespondera mot skvalpningarna i hela Östersjöbäckenet, och jag vågar påstå att partituret aldrig blir i alla detaljer uttytt.

...we have an orchestra of a thousand instruments, high tones of short wavelengths and deep undertones that correspond to oscillations in the whole Baltic Sea basin, and I dare say that the score will never be explained in full detail.

– Henrik Renqvist: *Ett sjösprång*, 1926

1 Introduction

Coastal zones are more densely populated than other areas on Earth, and sea level changes play an important role in life on the coast. In 2000, 640 million people (about 11% of the world population) were living less than 10 m above mean sea level, with the number expected to grow to more than one billion by 2050 (Merkens et al., 2016). Understanding sea level changes on different time scales is crucial for coastal safety, especially in our time when rising sea levels threaten coastal societies and ecosystems worldwide.

The Baltic Sea, the region of interest in this work, is a small and shallow marginal sea of the Atlantic Ocean. Its mean depth of 54 m is tiny in comparison to the mean depth of all oceans, 3.8 km (Sverdrup et al., 1942), and the narrow ocean connection makes it a nearly enclosed basin of brackish water. The Fennoscandian land uplift, a relic of the last ice age, shelters the northern Baltic coasts from the worst consequences of sea level rise. However, changes in the world's oceans affect life around the Baltic Sea as well. The interconnectedness of the Earth system is clearly demonstrated by sea level rise: as a result of an imbalance in the carbon cycle, remote polar ice masses are melting and ocean waters are warming up and expanding, and the implications are felt everywhere on the world's coastlines.

With the global mean sea level steadily rising, sea level researchers are striving to answer the critical question: how fast will sea levels rise in the coming decades and centuries? Future sea level rise is a complicated research question that involves all parts of the climate system and their interactions, as well as societal changes and political decisions. Some perspective can be gained from geological evidence of past changes, but with anthropogenic climate change we are venturing into unknown terrain (Zeebe et al., 2016). Sea level rise projections are subject to deep uncertainty (Bakker et al., 2017), and the uncertainty has not diminished even after 35 years of research (Garner et al., 2018). In fact, the more the research has advanced, the more we understand about the complexity of the problem.

On the other hand, the fast advancement in technology means that changes in the Earth system are being monitored more accurately than ever. The improved accuracy results in many phenomena being revealed that were previously unknown or poorly understood. An example of such a phenomenon is the meteotsunami, a meteorologically generated tsunami wave that can locally reach a height of several metres and cause catastrophic flooding (Monserat et al., 2006). Even though sea level measurements have a long history – in Finland, for example, the first self-recording tide gauge started operation in 1887 in Hanko – we can still make new discoveries in the sea level data.

This thesis wraps up findings from four papers. Two of them (Papers I and III) deal with future changes in mean sea level in the Baltic Sea, more specifically on the coast of Finland. These studies were motivated by the needs of Finnish society to prepare for future changes in mean sea level. The other two papers (Papers II and IV) study meteotsunamis on the Finnish coast. While their occurrence in the Baltic Sea has long been known (Credner, 1889; Doss, 1906; Meissner, 1924; Renqvist, 1926a), knowledge on Baltic meteotsunamis has been scarce and mainly based on eyewitness reports. The two papers included in this thesis are the first modern scientific publications on meteotsunamis in the Baltic Sea.

The sea level changes discussed in this thesis encompass a wide range of temporal and spatial scales. Meteotsunamis are local events with a typical duration of a few hours or less, and even though they can be observed on a wide stretch of the coastline, potentially dangerous fluctuations are generally restricted to individual bays or harbours. The adverse effects of large-scale sea level rise, on the other hand, unfold slowly over the coming decades and centuries and are felt globally, even though regional differences are significant. Yet these phenomena at the opposite ends of the sea level spectrum are both relevant in evaluating coastal flooding risks, and it is at the ends of the spectrum where the most unknown research areas lie.

Harmful effects of sea level rise include more frequent and intense flooding, shore-line erosion, inundation of land and forced migration, saltwater intrusion to arable land and freshwater sources, and degradation of coastal ecosystems (e.g. Oppenheimer et al., 2019). Extreme sea level events, on the other hand, may cause flooding of buildings and other coastal infrastructure as well as challenges to navigation and safety in marine transport. These impacts can have many adverse consequences, from loss of life to financial damage and costs of flood protection, and threaten critical functions of society. In Finland, recent research on mean sea level changes and extreme sea level events has been largely motivated by i) the need to regulate building elevations and minimize flooding risks through coastal planning, and ii) the safety of coastal nuclear power plants. Flooding of the critical compartments of a nuclear power plant would have severe consequences; therefore even extremely rare events need to be considered in the safety assessments (Jylhä et al., 2018).

The main research objectives of this thesis are:

1. To present projections of mean sea level change in Finland by 2100 that are based on current scientific understanding, cover the whole probability range and are easily applicable in coastal management (Papers I and III)
2. To investigate the frequency of meteotsunami occurrence on the Finnish coast through an extensive analysis of sea level data from the past century (Paper IV)
3. To discover what kind of weather phenomena are connected to meteotsunamis occurring on the Finnish coast (Papers II and IV)

This summary presents the main findings of the four papers and sets them in a wider scientific context. It also aims to serve as an introduction to the topics of sea level rise and meteotsunamis to a wide range of readers from different backgrounds. In Chapter 2, I introduce the main factors influencing the variations in the Baltic Sea level, the sources of global sea level rise, its uncertainties and projection methods, as well as the characteristics and the generation mechanism of meteotsunamis. Chapter 3 discusses future changes of mean sea level in Finland, taking into account global sea level rise and its regional deviations, postglacial land uplift, and changes in the wind climate. In Chapter 4, I will first give an overview of historical accounts of meteotsunamis – locally called *Seebär* – in the Baltic Sea and then move on to describe recent events on the Finnish coast, meteotsunami occurrences over the past century and their connection to atmospheric conditions. Finally, Chapter 5 presents discussion and outlooks for future research, and Chapter 6 summarizes the most important findings.

2 Background

2.1 Sea level changes in the Baltic Sea

As a small, semi-enclosed inland sea, the Baltic Sea (Fig. 1) has a characteristic sea level dynamics quite unlike that of most coastal areas in the world. Geographical features that affect the sea level dynamics are the narrow ocean connection in the Danish straits and the complex shape of the coastline. The Danish straits consist of three narrow straits, the Great Belt (smallest width 16 km), the Little Belt (1 km), and Öresund (4 km), with a depth mostly under 20 m. The largest archipelago of the Baltic Sea is the Archipelago Sea between the Gulf of Bothnia and the Gulf of Finland, an enormously complex maze of thousands of islands. The Finnish and Swedish coasts in the north are more complex and broken in general and made up of solid rock, while the southern Baltic coastline is more sandy and predominantly smooth.

The sea level records from the Baltic Sea are among the longest in the world. In Stockholm (Sweden), systematic sea level measurements started in 1774 with weekly readings (Ekman, 1988). Long records from the early 19th century also exist from Kronstadt (Russia), Travemünde (Germany), and Swinemünde (currently Świnoujście, Poland), and more stations emerged during the 19th century (Hünicke et al., 2017). Self-recording instruments were installed around 1890 in many Baltic countries. While continuous measurements may exist on the original paper recordings of the tide gauges, digital sea level data with a sampling interval of less than one hour has become available relatively recently. For example, hourly data from many Swedish stations is available from 1886, 10-min data from around 1995, and 1-min data from the past couple of years (Ola Kalén, pers. comm.).

In Finland, sea level observations with tide poles started in the mid-19th century, and a self-recording tide gauge network consisting of 13 stations was established between 1887 and 1933. The continuously plotting pen-and-ink recorders of the tide gauges were replaced by digital ones around 1990. Digitized measurements are available for every 4 hours before 1970, hourly measurements after that. In addition, raw 15-min data is available since the beginning of the 1980s and 1-min data since 2004. The original tide gauge recordings have been preserved and high-resolution data is thus available nearly over the whole time series since the tide gauge network was established, but most of this data has not been digitized.

2.1.1 Short-term variations and extremes

Short-term sea level variations, caused both by external forcing through the Danish straits and by internal variations within the Baltic Sea basin, are largely controlled by

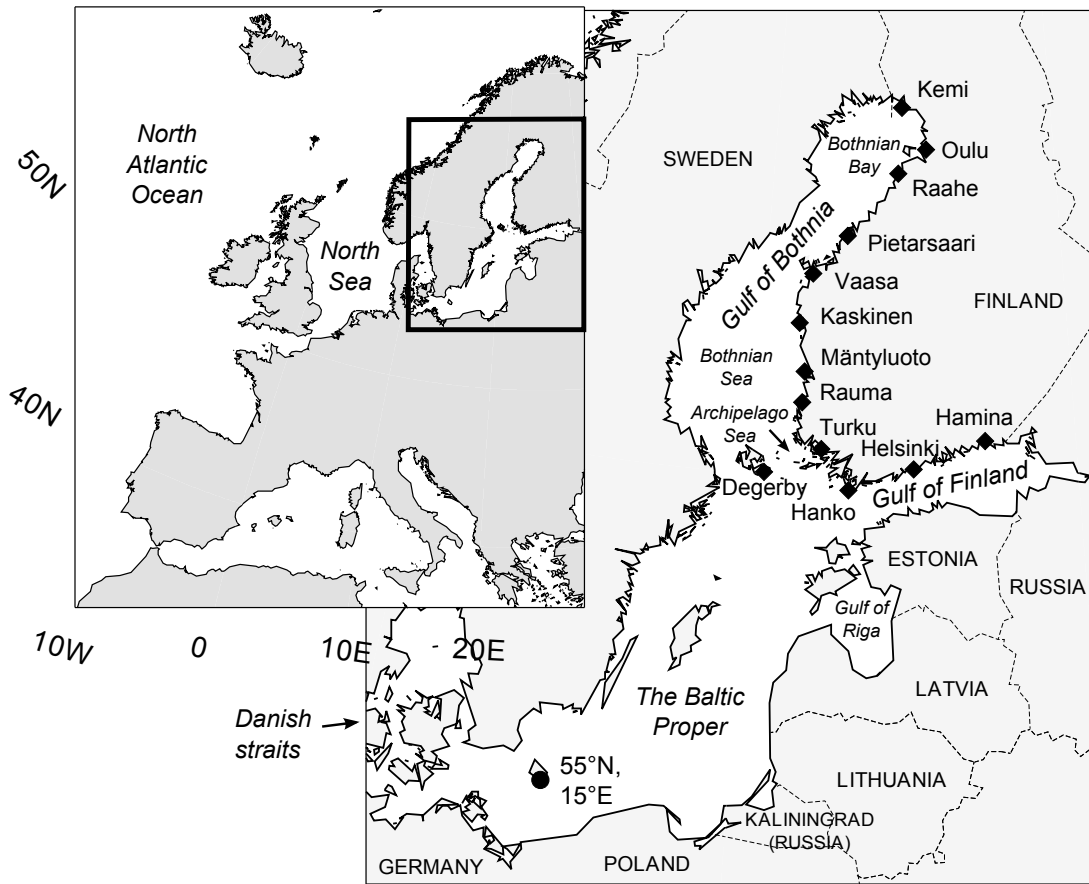


Figure 1: Map of the study area, the Baltic Sea. Finnish tide gauges, from which sea level data was used in this work, are marked with diamonds. The point 55°N, 15°E, marked with a dot, is related to the analysis of wind-induced changes in mean sea level on the Finnish coast.

wind and air pressure conditions over the region. In simplified terms, strong westerly winds push water through the straits into the Baltic Sea, while easterly winds lead to declining sea level in the Baltic. The limited water exchange between the North Sea and the Baltic Sea through the narrow Danish straits plays a very significant role in Baltic sea level variations. The Baltic Sea acts effectively as a closed basin for sea level variations shorter than about one month, while longer-term changes can penetrate through the straits (Samuelsson and Stigebrandt, 1996). Winds affect also the distribution of water within the Baltic Sea basin by piling up water against the coast so that a slope in sea level is formed; westerly winds lead to higher sea levels on the eastern coasts of the sea and lower sea levels on the western side, and vice versa.

Johansson (2014) presented an overview of the magnitude of different factors causing sea level variations in the Baltic Sea. Changes in the water volume in the Baltic Sea basin introduce a natural variability of ca. ± 50 cm around the long-term mean (Vermeer et al., 1988). This variation comes primarily from the water exchange between the North Sea and the Baltic Sea; freshwater fluxes have a smaller effect

(Vermeer et al., 1988; Samuelsson and Stigebrandt, 1996). Phenomena that regularly cause sea level variations of the order of several tens of centimetres include wind-induced internal redistribution of water within the basin, air pressure variations, and seiches (standing waves) in the various sub-basins of the sea, large and small. The tidal range is so small – generally only a few centimetres (Witting, 1911; Medvedev et al., 2013) – that tides are often neglected in analyses of Baltic Sea level. They are not insignificant regarding flooding risks, however; for example, the maximum sea level reached in Helsinki during the record flood of January 2005 would have been 12 cm higher if the storm surge peak had coincided with the tidal maximum instead of the tidal minimum (Särkkä et al., 2017).

An extreme sea level event requires the simultaneous occurrence of several factors causing higher than normal sea levels. In the Baltic Sea, both the highest maxima and the lowest minima tend to occur during the winter months. The largest sea level variations are observed at the end of the elongated gulfs – the Gulf of Finland, the Gulf of Bothnia, and the Gulf of Riga – and near the Danish straits. The highest recorded storm surges have exceeded 3 m above the mean at the end of the Gulf of Finland and in the southwestern Baltic, and 2 m in the Gulf of Riga and at the end of the Gulf of Bothnia (e.g. Averkiev and Klevanny, 2010; Wolski et al., 2014). Close to the open sea areas, the recorded maxima are generally 1–1.5 m above the mean. Among the most vulnerable locations for flooding is St. Petersburg at the end of the Gulf of Finland, where the dynamics of the river Neva also come into play. The most extreme floods – the record being 421 cm in 1824 – have killed hundreds of people and badly damaged the city before the construction of the flood protection dam (Kulikov and Medvedev, 2013, 2017).

In Finland, recorded sea level maxima are 1–2 m above the mean. While coastal floods that cause notable damage are rare, extreme sea level events are a concern in coastal cities. For example, the storm surge of January 2005 that broke sea level records on the southern Finnish coast caused an economical damage of 12 million euros in Finland (Tulvariskityöryhmä, 2009).

The seasonal ice cover is another characteristic of the Baltic Sea that is relevant to short-term sea level variations. The length of the ice season is 5–7 months and the areal extent of the ice cover has large variation from year to year, ranging from 12.5% of the sea in mild conditions to 100% during extremely severe winters (Leppäranta and Myrberg, 2009). The ice cover reduces the wind stress on the sea surface (Lisitzin, 1957; Omstedt and Nyberg, 1991) and suppresses waves (Squire, 2018). Thus, it affects especially high-frequency sea level variations, but can also attenuate sea level variations in the time range of days and weeks.

2.1.2 Long-term changes

Long-term sea level changes in the northern Baltic Sea have historically been dominated by postglacial land uplift that has caused an apparent fall in mean sea level (e.g.

Witting, 1918; Lisitzin, 1964; Ekman, 1988; Vermeer et al., 1988; Johansson et al., 2003). The Earth's crust is still slowly adjusting to the redistribution of mass caused by the last deglaciation. The removal of the huge weight of the ice sheets allows crustal recovery, resulting in land uplift in the deglaciated areas and sinking in the surrounding regions. After the instantaneous elastic rebound, the second phase involves the flow of viscous material in the Earth's mantle back to the deglaciated areas. This slow process takes tens of thousands of years, and even though the rate of land uplift decreases over time, on a time scale of centuries it can be considered linear.

The rate of land uplift is 10 mm/yr in the northern Gulf of Bothnia, 2–4 mm/yr in the Gulf of Finland, and close to zero in the southern Baltic Sea at the German and Polish coasts (Vestøl et al., 2019). The rate of global mean sea level rise has accelerated over the 20th century and currently amounts to 3.6 mm/yr (Oppenheimer et al., 2019). Thus, the postglacial land uplift outweighs or significantly reduces the effect of sea level rise in the northern parts of the region.

In addition to the counteracting trends of global sea level rise and postglacial land uplift, changes in the water volume in the Baltic Sea basin play an important role in variations of the Baltic mean sea level (Johansson et al., 2003). These, in turn, are dominated by water exchange between the North Sea and the Baltic Sea. Variations in the water volume explain most of the year-to-year variability in annual mean sea levels and cause variation also on a time scale of decades (Johansson et al., 2004). As the water transport is regulated by wind and air pressure conditions, regional climatic changes may change the long-term average water volume of the Baltic Sea and hence the long-term mean sea level.

Changes in water density may also affect the volume of water in the Baltic Sea. There is a permanent salinity gradient within the sea, with more saline water (25‰) near the Danish straits and salinity decreasing northwards so that it is close to zero at the opposite end. Because of the smaller water density, the sea level in the northeastern parts is 35–40 cm higher than in the Skagerrak outside the Danish straits (Ekman and Mäkinen, 1996). Changes in the freshwater fluxes and the salinity structure of the Baltic Sea may thus also induce significant long-term changes in Baltic Sea level. Current climate models generally predict increasing river runoff and decreasing salinity in the Baltic Sea, but as the models have severe biases in modelling the water balance, the magnitude and even the direction of future changes are uncertain (Meier, 2015).

2.2 Sea level rise: past and future

2.2.1 Geological context and sources of sea level rise

The Earth has seen large changes in the level of the oceans over geological history. The glacial–interglacial cycles of the Quaternary period (last 2.6 million years) have been accompanied by huge transports of water from the oceans to the continental ice sheets and back to the oceans when the ice sheets have melted, causing sea level variations

of roughly 120–140 m (e.g. Rohling et al., 2009). In the geological perspective, the total volume of glaciers and ice sheets in our present warm interglacial period is small, yet it corresponds to ca. 65 m of sea level rise.

The oceans have risen above their present level during earlier warm climatic periods, such as the Last Interglacial 129–116 000 years ago, when the global mean temperature was 0.5–1.0°C warmer and global mean sea level 6–9 m higher, and the mid-Pliocene ca. 3 million years ago, when temperatures were 2–4°C warmer and sea level up to 25 m higher (Oppenheimer et al., 2019). While direct comparisons may be misleading, these warm periods give hints of the future in a warming climate: the rapid increase in greenhouse gas concentrations will eventually lead to a multi-metre rise in sea level unless steep reductions in global carbon emissions are achieved (Schaeffer et al., 2012; Levermann et al., 2013; Rohling et al., 2013; Winkelmann et al., 2015). The long response times of the ice sheets and deep ocean imply that it takes thousands of years for the global sea level to reach a new equilibrium. Because rapid changes challenge the ability of ecosystems and the human civilisation to adapt, the rate of sea level rise is even more critical for coastal societies than its eventual magnitude.

The sea level rise related to the last glacial–interglacial transition was stabilized some 2000 years ago, and the level of the oceans was rather stable before it started to rise again in the 19th century. The rate of global mean sea level rise is accelerating: tide gauge and altimetry observations show a rise of 1.4 mm/yr over the period 1901–1990, 2.1 mm/yr in 1970–2015, 3.2 mm/yr in 1993–2015, and 3.6 mm/yr in 2005–2015 (Oppenheimer et al., 2019).

The causes of present-day sea level rise can be divided into two categories: *eustatic* rise, in which the amount of water in the ocean increases because water is transported to the oceans from other water reservoirs on Earth (glaciers, ice sheets and other freshwater sources), and *steric* rise, in which the amount of water stays the same but its volume increases, most notably through thermal expansion caused by warming of the sea water.

How water on Earth is distributed between different reservoirs gives an idea of the relative importance of various sources of sea level rise. Only 2.5% of all water on the planet is fresh water, and roughly 69% of the freshwater is found in glacial ice and 30% in groundwater – the remaining tiny fraction is divided between ground ice and permafrost (0.86%), lakes (0.26%), atmosphere (0.04%), swamps (0.03%), rivers (0.006%), and biological water (0.003%; Shiklomanov, 1993). Of all glacial ice, the majority is in the Antarctic ice sheet whose volume corresponds to 58 m of sea level rise, while the sea level equivalent of Greenland ice sheet is 7 m, and that of all mountain glaciers and small ice caps roughly 0.5 m (Oppenheimer et al., 2019). Thus, the ice sheets of Antarctica and Greenland are by far the largest potential source of sea level rise. However, they react to environmental changes over long periods of time, over centuries and millennia. Small glaciers and ice caps are responsible for a large share of the 20th century sea level rise as they react to global warming more quickly (Fig. 2), but their importance will diminish in the long term. Changes in other water reservoirs

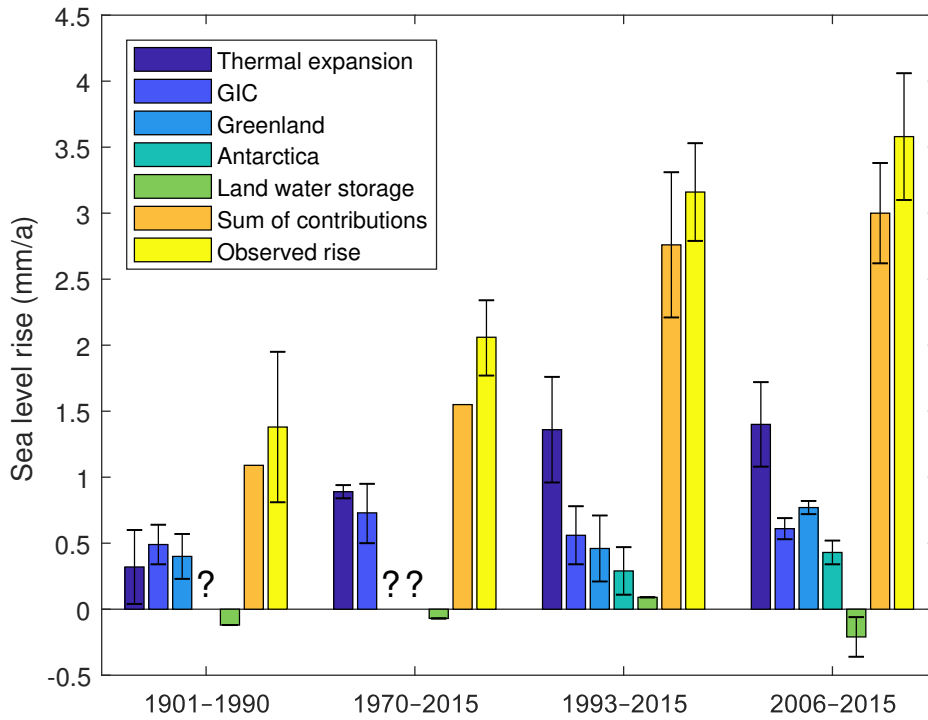


Figure 2: Rate of sea level rise and its sources during the instrumental period (1901–). Error bars show the 5–95% uncertainty ranges. All values are based on observations except thermal expansion in 1901–1990, which is based on models. Frequent observations of ice sheet contributions are not available before the satellite era (1993 onwards); the Greenland contribution for 1901–1990 is based on a geodetic reconstruction. GIC = small glaciers and ice caps. Data from Oppenheimer et al. (2019).

play a minor role and are not well known, but water impoundment behind dams has a small negative effect on sea level rise and groundwater depletion a positive one (Wada et al., 2016).

The sources of sea level rise since the beginning of the 20th century are presented in Figure 2. Thermal expansion is the dominant contributor, but as the ice loss from Greenland and Antarctica has accelerated, the combined effect of glaciers and ice sheets currently outweighs thermal expansion (Oppenheimer et al., 2019). The observed sea level rise is consistent with the sum of the different components since 1993, when frequent observations of ice sheet mass changes became available from satellite altimetry.

2.2.2 Projecting sea level rise

Present-day sea level rise is caused mainly by thermal expansion of sea water and melting of glaciers and ice sheets. Glaciers can lose mass in two ways: through surface melting (if melting is greater than mass accumulation through precipitation) and dynamical changes affecting the flow of ice into the sea. Out of the main contributors of sea level rise, the thermal expansion component and the surface mass balance of

the glaciers and ice sheets are relatively well known, but dynamical changes in the ice sheets are not. Making reliable projections of future sea level rise requires deep understanding of processes regulating the movement of glacial ice in the ice sheets of Greenland and Antarctica, and many of the processes and interactions in the complex ice–ocean–atmosphere system are still poorly understood. Consequently, projections of global sea level rise have large uncertainties, especially in the low-probability, worst-case upper end of the scenario range.

Models used to project future sea level rise can be classified into two categories: process-based and semi-empirical. Process-based models are physical models that attempt to model each sea level rise contribution separately. The main problem in these models is projecting the dynamical component of ice sheet mass changes. Semi-empirical models provide an alternative approach: they build on a statistical relation between global mean sea level and global mean temperature (or some other climate parameter), derived from past observations. This relation is then used together with model projections of future temperatures to obtain projections of future sea level. The method involves an inherent assumption that the observed relationship between global sea level rise and e.g. global temperature will hold in the future, too. Semi-empirical projections cannot take into account processes that were not active during the observation period used to calibrate the model.

The sea level rise projections compiled by the Intergovernmental Panel on Climate Change (IPCC) carry the highest authority and are widely used in decision-making. The range of the IPCC sea level rise projections for the 21st century has evolved as follows: 16–110 cm in the First Assessment report (FAR, 1990), 13–94 cm in the Second (SAR, 1996), 9–88 cm in the Third (TAR, 2001), 18–59 cm in the Fourth (AR4, 2007), and 28–98 cm in the Fifth (AR5, 2013). Most recently, in preparation for the Sixth Assessment Report, the IPCC published a special report on the ocean and cryosphere projecting 29–110 cm of sea level rise (Oppenheimer et al., 2019). All values are for 2100 (AR4 for 2090–2099) relative to a somewhat varying reference period at the end of the 20th century. Beyond 2100, the uncertainties become so large that not many estimates exist in the literature.

The IPCC ranges are not directly comparable, because different approaches have been used especially regarding the most problematic dynamical ice sheet component (Section 2.2.3). However, it can be noted that the uncertainties have not diminished over time even though significant advances have been made in understanding and modelling the different contributors. The same can be seen in sea level projections in general: Garner et al. (2018), who compiled a comprehensive database of sea level projections since the early 1980s, concluded that central estimates of 21st century sea level rise have been rather consistent, but the uncertainty limits have varied widely.

The IPCC has arguably been rather conservative in their sea level projections, and the upper limits given by the IPCC are significantly lower than the highest projections available in the literature (Garner et al., 2018). Because process-based models struggle with projecting future ice loss from Greenland and Antarctica and confidence

in semi-empirical projections is considered low (Church et al., 2013a), the IPCC has not provided worst-case projections (Church et al., 2013b). The latest assessments are given with "medium confidence" which translates to "likely" (66–100%) probability ranges. Because projections covering the whole probability range are needed in practical decision-making, it has become customary to complement the process-based projections with expert elicitations or other educated guesses to estimate the dynamical ice sheet component and obtain an upper limit for future sea level rise (e.g. Horton et al., 2014; Jevrejeva et al., 2014; Kopp et al., 2014). The publication of the IPCC AR4 was followed by a spurt of other published projections using semi-empirical models, probabilistic methodologies, and expert judgment that aim to explore the low-probability, high-end tail of the sea level rise distribution.

2.2.3 Largest source of uncertainty: dynamical changes in ice sheets

The understanding of dynamical changes in ice sheets has evolved rapidly in recent decades as more and more observational data has become available. There are many complex processes involved at the interface between the ice sheet and the ocean, where large floating ice shelves are formed (e.g. Joughin et al., 2012). Warming temperatures have resulted in increased melting both on the surface of the ice sheets and below the ice shelves (Mernild et al., 2011; Pritchard et al., 2012). Surface meltwater, in turn, can cause deepening of crevasses and penetrate through the ice, lubricating the flow of the ice sheet over its bed (Zwally et al., 2002; van der Veen, 2007; Joughin et al., 2008). This meltwater-driven fracturing of ice, together with other processes, has also contributed to the observed breakups of ice shelves (Scambos et al., 2000). While the loss of the floating ice shelves does not raise sea level directly, it can accelerate the flow of grounded ice, because ice shelves resist the flow of ice upstream if there are points of contact between the ice shelf and the ocean bottom or the coastline (Fig. 3d). Rapid speedups of glaciers feeding ice shelves that have broken up have indeed been observed e.g. in the Antarctic Peninsula (Rignot et al., 2004; Scambos et al., 2004).

The largest uncertainty in sea level rise projections, especially in northern latitudes, is the possible instability of the marine sectors of the Antarctic ice sheet (Mercer, 1978; Joughin and Alley, 2011). The collapse of these sectors was judged by the IPCC AR5 as the only mechanism that could cause the sea level to rise substantially above the projected likely range during the 21st century (Church et al., 2013a). According to the marine ice sheet instability hypothesis, parts of an ice sheet that are in contact with the ocean and grounded below sea level, so that the bedrock is sloping down inland from the glacial front (as in Fig 3a, b), are prone to an irreversible, unstoppable collapse once the retreat of the front has begun (Weertman, 1974; Schoof, 2007). This theoretical instability mechanism concerns especially large parts of the West Antarctic ice sheet (WAIS), but also parts of the East Antarctic ice sheet (DeConto and Pollard, 2016). Recent observations indicate that the instability mechanism is real and already contributing to ice loss from WAIS (e.g. Favier et al., 2014; Rignot et al., 2014).

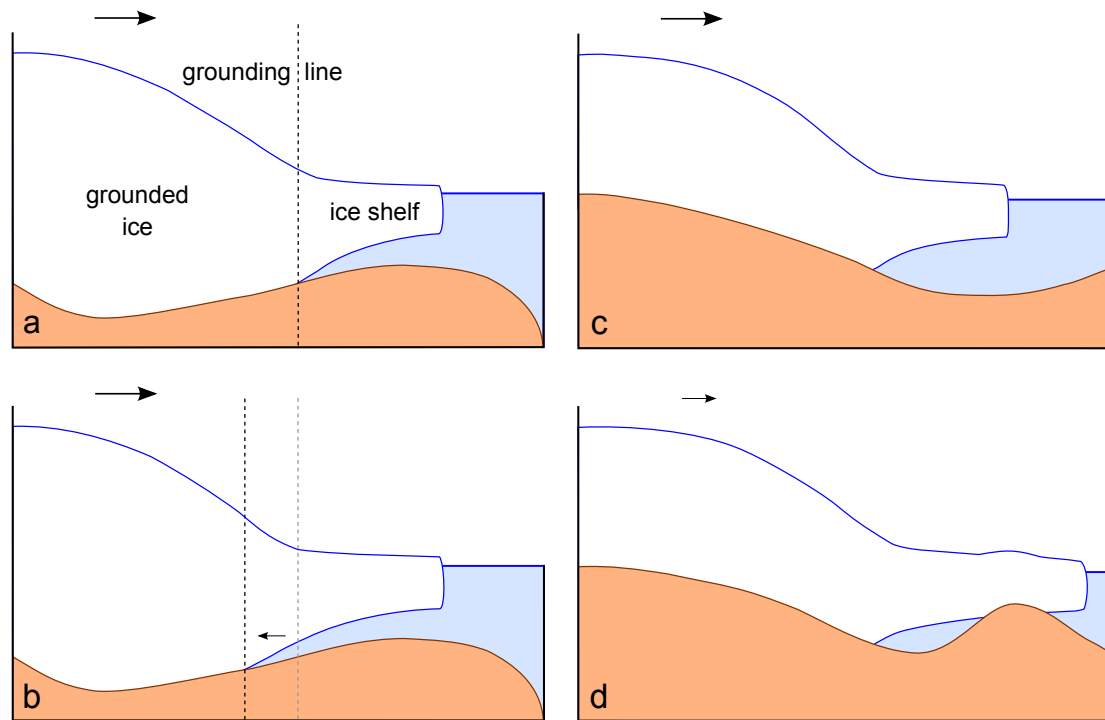


Figure 3: Simplified illustration of the marine ice sheet instability hypothesis. a) Unstable situation with the bedrock sloping down inland from the glacial front. b) The retreat of the grounding line (dashed line) onto a deeper bed leads to a positive feedback loop causing increased ice loss and further grounding line retreat. c) Stable situation with a reversed bed slope. d) Floating ice shelves slow down the flow of grounded ice, if there is contact between the ice shelf and the seabed or the coastline.

The Greenland ice sheet terminates largely on land and is not significantly affected by marine ice sheet instability. Ice from Greenland flows into the sea through outlet glaciers, which are better constrained by coastal topography than the ice streams of Antarctica (e.g. Pfeffer et al., 2008). While ice loss from Greenland is a major contributor to global sea level rise, the "fingerprint effect" reduces the contribution of Greenland close to zero in many northern locations such as the Baltic Sea (see Section 2.2.4). Therefore, the Antarctic ice sheet dominates the uncertainties of sea level rise projections in the Baltic Sea.

The modelling study of DeConto and Pollard (2016) concludes that Antarctica alone could contribute more than 1 m of sea level rise by 2100 and more than 15 m by 2500. This would mean a significant upward revision of recent sea level projections. The model used by DeConto and Pollard (2016) couples ice sheet and climate dynamics and includes processes that have not been properly addressed in previous modelling studies, such as fracturing of the floating ice shelves and the collapse of vertical ice cliffs that are exposed when the ice shelves are lost. The ice cliff instability hypothesis is still under scientific debate, however (Edwards et al., 2019).

The rate of Antarctic ice sheet retreat is slower in other recent modelling studies. Golledge et al. (2015) project an Antarctic contribution of up to 39 cm by 2100, Ritz

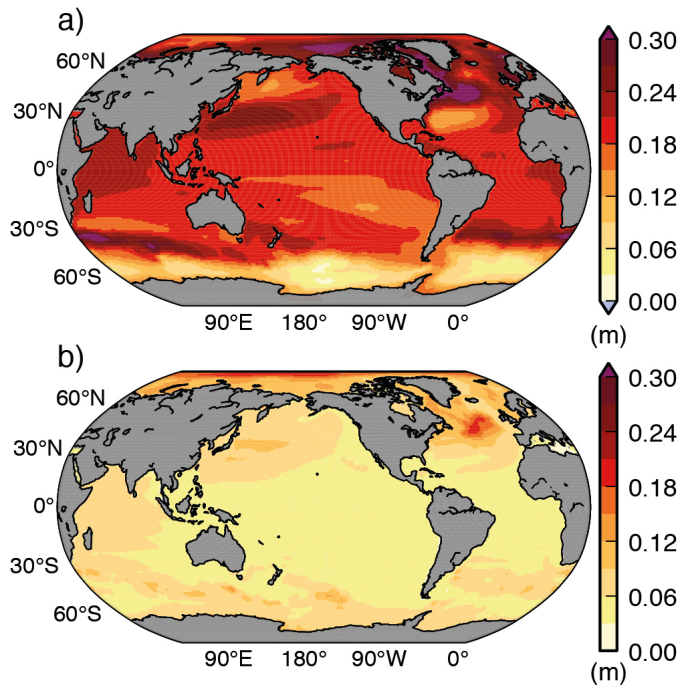


Figure 4: a) Ensemble mean projection of the time-averaged dynamic and steric sea level changes (m) for the period 2081–2100 relative to 1986–2005 based on the RCP4.5 scenario, computed from 21 CMIP5 climate models. The figure includes the globally averaged steric sea level increase of 0.18 ± 0.05 m. b) Root-mean-square deviation of the individual model results around the ensemble mean, characterizing the amount of variation between models. From Church et al. (2013a), their Fig. 13.16.

et al. (2015) one up to 30 cm; the latter do not consider contributions larger than 50 cm realistic during this century. However, they emphasize that unless radical emission reductions are carried out, Antarctica is on the trajectory of significant and sustained retreat and will contribute several metres of sea level rise during the coming centuries. Winkelmann et al. (2015) calculate that the combustion of all available fossil fuel resources would result in Antarctica being nearly ice-free over time (several millennia).

2.2.4 Regional deviations from the global mean

Sea level rise is not uniform but has large geographical variation. Trends in sea surface height obtained from satellite altimetry over the period 1993–2012 (when the global mean sea level rose about 3 mm/yr) show areas of declining sea level as well as areas where the rate of sea level rise is over 10 mm/yr (Church et al., 2013a). Changes in winds, ocean currents, the gravitational field of the Earth, atmospheric pressure, and other factors introduce regional anomalies that result in a complex pattern of *absolute* mean sea level change (sea level relative to the center of the Earth). When considering *relative* sea level change (sea level relative to land), regional differences in vertical land motion come into play, as well.

In the Arctic regions, the sea level rise caused by thermal expansion and dynamical changes in the oceans – changes in sea level induced by changes in winds, ocean currents, and ocean heat and freshwater content – is projected to be above average according to the climate models (Fig. 4). This higher-than-global sea level rise has been attributed to increasing freshwater content because of increased precipitation and river runoff (Landerer et al., 2007; Slangen et al., 2014). The CMIP5 (Coupled

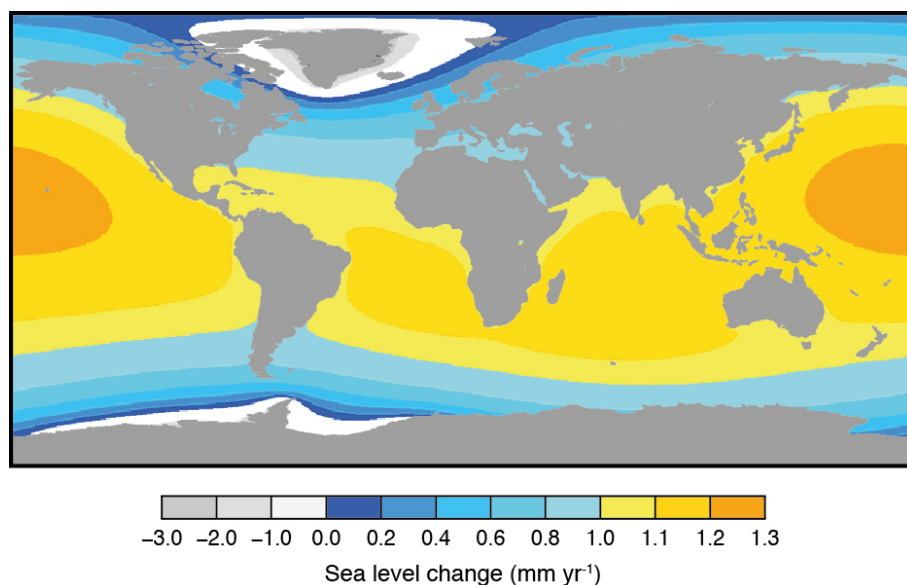


Figure 5: The combined "fingerprint" of the Greenland and West Antarctic ice sheets: modelled relative sea level change resulting from the melting of both ice sheets at a rate of 0.5 mm/yr each (global mean rise 1 mm/yr). From Church et al. (2013a), their Fig. 2 in FAQ 13.1.

Model Intercomparison Project Phase 5) models give higher than average steric and dynamical sea level rise also in the Baltic Sea (Section 3.1.1). These results should be considered approximate, however, as global climate models are too coarse to simulate some important features of the Baltic Sea dynamics, such as the water exchange in the narrow Danish straits.

Melting glaciers and ice sheets also cause globally uneven patterns of sea level rise. This pattern is unique to each melting ice mass and is therefore called the "fingerprint" of the glacier or ice sheet (Fig. 5). Perhaps counterintuitively, the sea level rise is smaller in the vicinity of the melting ice mass and larger far from it (Mitrovica et al., 2001; Bamber and Riva, 2010; Mitrovica et al., 2011). This is because of the gravitational and crustal changes caused by the diminishing weight of the ice. The gravitational pull of the ice mass is weakened, which lowers the sea level near the melting glacier, and the crustal uplift that follows the diminishing weight also lowers the sea level. Close to the melting ice mass, the relative sea level actually declines as a result of these effects even though the meltwater raises the global sea level on average.

In the Baltic Sea, the melting of the Greenland ice sheet is far less important than the melting of the Antarctic ice sheet. In many simulations (Mitrovica et al., 2001; Tamisiea et al., 2003; Bamber and Riva, 2010), the zero line of the Greenland fingerprint runs through the Gulf of Bothnia, meaning that in the northern parts of the gulf the effect of Greenland melting on mean sea level is slightly negative and in the southern parts slightly positive. On the contrary, the sea level rise caused by the Antarctic ice sheet is expected to be slightly (ca. 10%) above the global average everywhere in the Baltic Sea. Smaller mountain glaciers have varying effects because of their diverse

geographical locations, but on average their combined effect is estimated to be below the global average in the Baltic Sea.

2.3 The birth of a meteotsunami

Meteotsunamis – meteorologically generated tsunami waves – are long waves caused by atmospheric disturbances (Defant, 1961; Rabinovich and Monserrat, 1996; Monserrat et al., 2006). They can reach destructive dimensions in extreme cases. One of the highest known events is the 6 m high meteotsunami that flooded the small Croatian town of Vela Luka on 21 June 1978 (Vilibić and Šepić, 2009). Among several fatal events are the nearly 5 m high meteotsunami that drowned three people in the Nagasaki Bay, Japan, on 31 March 1979 (Hibiya and Kajiura, 1982), and the up to 3 m high wave of Lake Michigan that swept fishermen off the piers and killed seven people in Chicago on 26 June 1954 (Bechle and Wu, 2014).

Fortunately, destructive meteotsunamis are rather rare. They only occur in shallow sea areas and big lakes where the wave can be amplified by the shape and bathymetry of the coast. The basic generation mechanism of a meteotsunami is presented in Figure 6. The formation of a strong meteotsunami requires several coinciding factors:

1. An air pressure disturbance moving above a water body. These disturbances may be related to different atmospheric phenomena, such as weather fronts, thunderstorms, cyclones, hurricanes, squall lines, and atmospheric gravity waves.
2. Air–sea interaction: if the disturbance propagates at the same speed as the wave that it generates on the sea surface, there is continuous energy transfer from the atmosphere to the water wave.
3. Further amplification of the wave due to coastal bathymetry. Shoaling occurs when the wave enters shallower water: its speed decreases and height increases. Refraction can converge wave energy at certain places and increase the wave height. Harbour resonance can amplify the height of the waves entering semi-enclosed basins.

Because coastal bathymetry and geometry play a significant role in the amplification of the waves, there are hotspots of meteotsunami occurrence, with narrow and long bays being particularly vulnerable to destructive meteotsunamis. One such hotspot in the Mediterranean is the harbour of Ciutadella, Menorca, where several metres high oscillations – locally called *rissaga* – are regularly observed (Jansa et al., 2007). Indeed, nearly all known destructive meteotsunamis have occurred in bays or harbours and have not affected the nearby open coast (Monserrat et al., 2006).

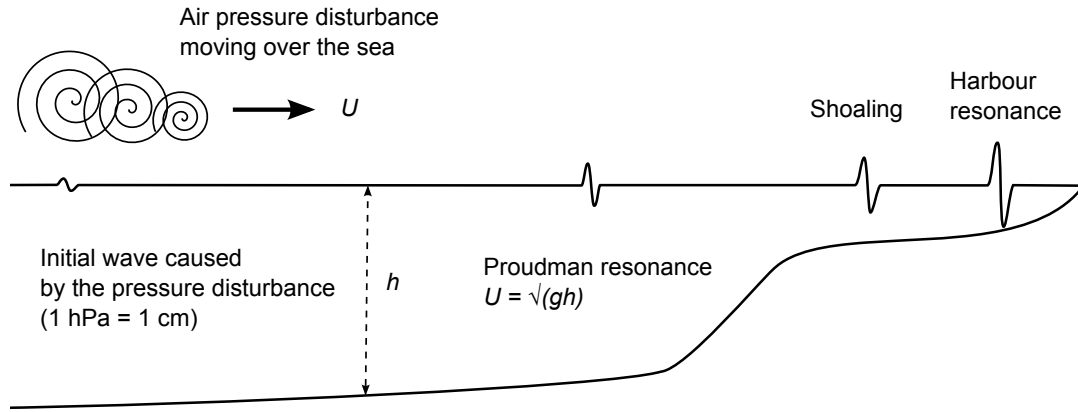


Figure 6: Sketch of the generation of a meteotsunami. The initially small wave is amplified through different resonance mechanisms as the wave approaches the coast.

2.3.1 Resonance effects

The air pressure disturbances creating meteotsunamis are steep but typically small, only a few hectopascals (hPa). These disturbances affect the sea level through the so-called inverted barometer effect: high pressure causes lower sea level and vice versa. Roughly, a 1 hPa change in air pressure corresponds to a 1 cm change in sea level. Thus, an air pressure disturbance of a few hPas alone cannot produce significant waves. Rather, a meteotsunami is formed through resonance effects that amplify the initial wave of small amplitude. More crucial than the strength of the pressure disturbance are its propagation speed and direction as well as the bathymetry and shape of the coastline.

A shallow-water wave (also called a long wave) is one whose wavelength is much larger than the water depth. The phase velocity (c_p) of such a wave depends only on water depth: $c_p = \sqrt{gh}$, where h is water depth and g is standard gravity. When the propagation velocity of an air pressure disturbance is close to that of the long wave, the disturbance continuously feeds the wave it generates. This is called the Proudman resonance (Proudman, 1929, 1953). The amplification is proportional to the fetch and to the spatial steepness of the disturbance (i.e. distance between the front and the disturbance maximum; Hibiya and Kajiura, 1982). Typical velocities of such air pressure disturbances are 20–40 m/s; thus the resonance occurs in ca. 40–160 m deep waters (Monserrat et al., 2006).

There are other resonance mechanisms as well that can transfer energy from an air pressure disturbance to the sea, such as the Greenspan resonance that occurs if the alongshore component of the disturbance velocity corresponds to the phase speed of edge waves (Greenspan, 1956; Monserrat et al., 2006). Edge waves are trapped waves that run along the shoreline. Shelf resonance occurs when the period or wavelength of the meteotsunami corresponds to the resonant period or wavelength of a continental shelf region (Monserrat et al., 2006).

A meteotsunami approaching the coastline can be amplified by air–sea interactions, refraction-induced focusing, and shoaling, but the height of a meteotsunami is usually below 0.5 m on a straight coastline. Harbour resonance occurs when the frequency of the meteotsunami corresponds to the resonant frequency of a semi-enclosed basin (e.g. Rabinovich, 2009). When the arriving wave is repeatedly reflected at the boundaries of the basin, a standing wave can be created through the superposition of the waves travelling in opposite directions. Each bay or harbour has characteristic eigenfrequencies determined by its size and shape. If the meteotsunami has a significant amount of energy at the eigenfrequencies of the basin, the amplification of wave height can be catastrophic.

2.3.2 Characteristics of meteotsunamis

Giving an exact definition of what counts as a meteotsunami is not straightforward, as most sea level variations are of atmospheric origin. A meteotsunami is separated from other meteorologically generated wave phenomena by its dimensions, which are similar to other tsunami waves: periods of meteotsunamis range from a few minutes to two hours and wavelengths from one to hundreds of kilometres (Rabinovich, 2009). However, to stand out from other sea level variations the wave must have a notable height. One suggested height criterion is four times the standard deviation of sea level variations in a certain location (Monserrat et al., 2006).

A meteotsunami can consist of a single wave or several, and the whole event can have a relatively long duration, even a couple of days (Jansa et al., 2007). Favourable atmospheric conditions can generate multiple atmospheric disturbances that cause a sequence of meteotsunamis. For example, the meteotsunami event of 22–27 June 2014 was observed over a wide area from the western Mediterranean to the Black Sea, but strong oscillations were restricted to certain meteotsunami hotspots (Šepić et al., 2016).

Meteotsunamis have physical properties comparable to tsunamis generated by earthquakes, but unlike seismic tsunamis they cannot cause widespread damage. While a meteotsunami event is often observed in multiple locations along a coastline, high oscillations are restricted to individual bays, inlets or other hotspots where the arriving wave is amplified. Another difference compared to seismic tsunamis is that meteotsunamis are not created instantaneously but develop under external forcing.

In the scientific literature, also the term *seiche* has been used (e.g. Hibiya and Kajiura, 1982) before the term meteotsunami was established. Seiches are standing waves created in enclosed or partially enclosed water basins after the water body has been disturbed and starts to oscillate around the equilibrium. Meteotsunamis can acquire destructive dimensions when they create a standing wave in a semi-enclosed bay or harbour. However, seiches include all standing wave oscillations caused by any disturbance. In the Baltic Sea, seiche is a very typical phenomenon in the various sub-basins, large and small, and should not be confused with meteotsunamis.

3 Sea level projections for the Finnish coast

In Papers I and III, regional sea level projections for the Finnish coast were calculated. The aim was to construct projections of mean sea level change over the 21st century as location-specific probability distributions that cover the full probability range, take into account regional anomalies in sea level rise, and include all different scenarios of future greenhouse gas emissions. This objective was largely motivated by the demands of coastal planning: different types of infrastructure tolerate different risk levels, and a single probability distribution is more easily applicable in practical decision-making than a set of different scenarios.

In Paper III, the probability distribution of mean sea level change was further combined with the probability distribution of short-term sea level variations to yield probabilities of future flooding on the Finnish coast. These results were used to set national recommendations for minimum building elevations, targeting the sea level that will be exceeded at most once in the next 200 years, i.e. during the potential lifetime of new buildings (Kahma et al., 2014). In addition to coastal planning, the results have been utilized in flood risk mapping of the Finnish coastline. The basic elements of the methodology – combining the probability distribution characterizing uncertainty in future mean sea level with the observed distribution of short-term variations, as a sum of independent random variables – were used in the Finnish Institute of Marine Research already in 1998 when the previous recommendations for building elevations were given (Kahma et al., 1998), and even before in 1990 in a safety assessment made for a Finnish nuclear power station (Kimmo Kahma, pers. comm.).

Our probability distributions of regional mean sea level change are based on an ensemble of global sea level rise projections. This approach was chosen because of the problems of sea level projections described in Section 2.2.2: uncertainties are large, different methods yield different results, and only a few projections give full probability distributions. As Kopp et al. (2017) and Garner et al. (2018) point out, there is no single method at the moment that could be considered best for estimating future sea level rise at different probability levels, and it is wise to compare different distributions and adopt flexible management frameworks to cope with the uncertainty. The scientific uncertainty also means that the projections inevitably contain some degree of subjective choices, approximations and assumptions. By drawing from an ensemble of projections we hope to include all potential sources of sea level rise, even the low-probability, high-risk ones such as the disintegration of the West Antarctic ice sheet (Section 2.2.3). The method and results obtained from these studies are summarized below.

3.1 Main components of long-term sea level change

The change in mean sea level h_m at a location i on the Finnish coast can be expressed as the sum of the following components:

$$h_m(t, i) = h_l(t, i) - u(i)t + w(t, i) + \epsilon(t, i) \quad (3.1)$$

where t is the time since the reference year, h_l is the large-scale sea level rise, or the regional manifestation of global sea level changes, u is the rate of postglacial land uplift, assumed to proceed linearly on the time scales considered, w represents the local wind-induced component related to the volume and distribution of water within the Baltic Sea, and ϵ incorporates residual variations. The observed annual mean sea levels on the Finnish coast over the 20th century can be fairly accurately reproduced by calculating the sum of the three main components: h_l , u , and w (Fig. 4 in Paper I).

This three-component model was used in both Papers I and III. To obtain probabilistic projections of future mean sea level change, we need to make projections of each of the three components and combine them as probability distributions.

3.1.1 Adapting global projections to the Finnish coast

The ensemble of sea level rise projections used to calculate the regional projections is presented in Table 1. The ensemble in Paper I included 10 members, in Paper III newer projections were included and the IPCC's Fourth Assessment Report (2007) was replaced by the Fifth (2013) to yield a total number of 14 projections.

Global sea level rise is not uniform for many reasons (Section 2.2.4). To take into account regional deviations from the global mean, the global projections published in the literature were adjusted for regional effects. Different projections were calculated for three different sea areas along the Finnish coast: the Gulf of Finland, the Bothnian Sea (southern part of the Gulf of Bothnia), and the Bothnian Bay (northern part; Fig. 1). Glacier and ice sheet contributions were scaled with fingerprint coefficients based on the results of Mitrovica et al. (2001). The contribution of the Greenland ice sheet is expected to be small on the Finnish coast: zero in the Bothnian Bay, 5% of the global average in the Bothnian Sea, and 15% in the Gulf of Finland. The effect of small glaciers and ice caps is also below the global average in Finland, 50–65% depending on location. For the Antarctic ice sheet, a slightly larger rise (105%) compared to the global mean is expected everywhere along the Finnish coastline.

Climate model simulations give an above average thermal expansion and ocean dynamics component in the North Sea–Baltic Sea region (Church et al., 2013a; Slangen et al., 2014). This was taken into account by replacing the global estimates with regional ones. In Paper III, this was done more elaborately than in Paper I by analyzing results from 21 CMIP5 atmosphere–ocean general circulation models. Global climate models are not accurate enough to estimate variations within the Baltic Sea, and regional differences are small compared to uncertainties, so the mean over the whole

Table 1: Ensembles of global mean sea level projections used to calculate the probability distribution of regional sea level rise in Papers I and III. The weights applied to each projection are given in the last two columns.

Projection	SLR (cm)	Probability range	Base year(s)	End year(s)	Method	Paper I	Paper III
IPCC AR4 (Meehl et al., 2007)	18–76 ^a	5–95%	1980–1999	2090–2099	Process-based	2	-
Rahmstorf (2007)	50–140	2.5–97.5% (TAR)	1990	2100	Semi-empirical	0.5	0.5
Horton et al. (2008)	47–100	5–95% (AR4)	2001–2005	2100	Semi-empirical	0.5	0.5
Katsman et al. (2008)	34–87 ^b	10–90%	1990	2100	Process-based	1	1
Pfeffer et al. (2008)	79–201			2100	Expert judgement	1	1
Vermeer and Rahmstorf (2009)	75–190	5–95% (AR4)	1990	2100	Semi-empirical	0.5	0.5
Grinsted et al. (2010)	72–160 ^c	5–95%	1980–1999	2090–2099	Semi-empirical	0.5	0.5
Jevrejeva et al. (2010)	44–178	5–95%	1980–2000	2100	Semi-empirical	0.5	0.5
Katsman et al. (2011)	52–111		1990	2100	Process-based	1	1
Jevrejeva et al. (2012)	36–165	5–95%	1980–2000	2100	Semi-empirical	0.5	0.5
IPCC AR5	26–82	Likely range	1986–2005	2081–2100	Process-based	-	4
(Church et al., 2013a)		(prob. 66–100%)					
Jevrejeva et al. (2014) and Grinsted et al. (2015)	45–183	5–95%	2000	2100	Process-based	-	1
Kopp et al. (2014)	29–121	5–95%	2000	2100	Process-based	-	1
Kopp et al. (2016)	24–131	5–95%	2000	2100	Semi-empirical	-	0.5
Mengel et al. (2016)	28–131	5–95%	1986–2005	2100	Semi-empirical	-	0.5

^aScaled-up ice sheet discharge included, see Table 10.7 of Meehl et al. (2007)

^bValue for global mean sea level rise: local gravity corrections and local steric changes are not included in contrast to the total values presented by Katsman et al. (2008)

^cTheir experiment ‘Moberg’, which gives the best fit to global sea level reconstruction

Finnish coast was calculated. For example in the scenario RCP8.5, the pathway of highest carbon emissions, the regional sea level rise caused by thermal expansion and ocean dynamics was 43 cm (27–60 cm) in 2081–2100 compared to 1986–2005 (5–95% uncertainty range). The corresponding global mean value from Church et al. (2013a) is 27 cm (21–33 cm).

Most semi-empirical projections cannot attribute the projected sea level rise to different sources, as they simply model total sea level rise based on the observed relation between global mean sea level and some other climate variable. These projections were adapted to the Finnish coast using a simple scaling approach, based on the relationship between regional and global sea level rise in the projections where component-wise regionalisation was possible, as described above (Fig. 5 in Paper I and Fig. 2 in Paper III).

After the regionalisation, we fitted Weibull distributions to the individual members of the ensemble (normalized to the time span 2000–2100) and combined them as a mixture distribution to yield the final sea level rise distribution. The projections were given different weights in the mixture (Table 1). Semi-empirical projections were given a lower weight to compensate for their large number in the ensemble and because of lower confidence in these models (Church et al., 2013a). IPCC projections were given a larger weight because they represent the most comprehensive assessments drawing from a wide body of research. The effect of weighting was assessed in both Papers I and III and it was concluded that the method is not very sensitive to the subjective choice of weights. Weighting lowers the results by ca. 5–10 cm compared to the projection where all members of the ensemble are included with similar weights in the mixture.

The resulting 5–95% probability ranges of mean sea level rise in 2000–2100 are shown in Table 2 globally and for the three sea areas on the Finnish coast (for full probability distributions, see Fig. 6 in Paper I and Fig. 5b in Paper III). The results obtained in Papers I and III were very similar despite differences in the projection ensemble and details of the regionalisation. According to the results, the effect of large-scale sea level rise on the Finnish coast will be approximately 80% of the global mean – slightly less in the Gulf of Bothnia and slightly more in the Gulf of Finland. Thus, the larger-than-average thermal expansion contribution is more than compensated by the smaller-than-average glacier and ice sheet contributions.

3.1.2 Changes in wind climate

As was noted in Section 2.1, sea level variations in the Baltic Sea are mostly regulated by atmospheric conditions in the region, both in the short term and in annual and decadal time spans. Interannual variations in mean sea level on the Finnish coast are of the order of 20 cm, and mean sea level is positively correlated with the North Atlantic Oscillation (NAO) index that describes large-scale atmospheric conditions in the region – a correlation that is seen also on other Baltic coasts (e.g. Andersson, 2002; Suursaar and Sooäär, 2007). A positive NAO index is connected to strong westerly

Table 2: Large-scale sea level rise in 2000–2100 (5–95 % probability ranges) globally and in the three sea areas along the Finnish coast, according to the probability distributions calculated in Papers I and III. Note that these results do not include postglacial land uplift and local wind-induced effects.

	Paper I	Paper III
Global	26–155 cm	31–155 cm
Gulf of Finland	24–124 cm	24–126 cm
Bothnian Sea	23–120 cm	24–122 cm
Bothnian Bay	21–114 cm	24–115 cm

winds over the North Atlantic, which push water through the Danish straits and pile it up in the northeastern parts of the Baltic Sea. Variability in the NAO index explains 37–46% of the interannual variation of mean sea level on the Finnish coast, depending on location (Johansson et al., 2003).

In Paper I, even better correlations were found between zonal geostrophic wind and annual mean sea level on the Finnish coast. The best correlation was found with detrended zonal geostrophic wind (U_g) near the entrance of the Baltic Sea, on the island of Bornholm at 55°N, 15°E (Fig. 1). Changes in zonal geostrophic wind explain 84–89% of the interannual variations in mean sea level. The relationship between U_g at Bornholm and the sea level on the Finnish coast, calculated from the 20th century observations, was assumed to remain unchanged in the future. Climate model projections of U_g could then be used to estimate the effect of changes in the wind climate on future mean sea level in Finland (w in Eq. 3.1).

While projections of future U_g are subject to large uncertainties, on average climate models project an increase in the zonal geostrophic wind in the southern Baltic Sea. This was estimated in Paper I to lead to a small additional sea level rise on the Finnish coast: on average, 6–7 cm by 2081–2100 compared to the reference level 1961–2000, with values ranging from a 3–4 cm decrease to a 15–19 cm increase depending on the model and emission scenario. The spread between different model projections was larger than the differences between emission scenarios. These results were also utilized in Paper III to estimate the wind-induced mean sea level component.

3.1.3 Land uplift

Land uplift rates were calculated from the 20th century observations of annual mean sea level from the Finnish tide gauges. Referring to Eq. 3.1, we first removed the observed annual means of the wind-induced component w from the observed annual mean sea levels h_m . The trend in the resulting time series is a combination of the land uplift rate u and the trend in the large-scale sea level rise h_l , which we replaced with the observed 20th century rate of global mean sea level rise – assuming that sea level rise has proceeded linearly. The land uplift rates thus obtained range from 4.05 ± 0.75 mm/yr

in Hamina, in the easternmost part of the Gulf of Finland, to 9.85 ± 0.69 mm/yr in Vaasa (Table 3 in Paper I).

Removing the wind-induced component from the observed annual means before calculating trends improves the accuracy of land uplift estimates compared with older analyses (e.g. Lisitzin, 1964; Vermeer et al., 1988; Johansson et al., 2003), as the wind-induced component has a positive trend over the 20th century and it also introduces large interannual variations in mean sea level. The weakness of this analysis is the lack of exact information on the rate of large-scale sea level rise in the Baltic Sea over the 20th century, which is approximated using the global mean value.

Compared with recently published independent land uplift estimates obtained from geodetic observations and modelling (Vestøl et al., 2019), our land uplift rates are ca. 1 mm/yr higher, with roughly similar error estimates. Some of this difference may be explained by the possible overestimation of the large-scale sea level rise in our analysis (approximated with the global mean rate of 1.7 mm/yr from Church et al., 2013a), which would lead to an overestimation in the land uplift rates, too. Recent studies have revised the estimated rate of 20th century sea level rise downward, for example Hay et al. (2015) suggest 1.2 mm/yr, Dangendorf et al. (2017) 1.1 mm/yr, and Oppenheimer et al. (2019) 1.4 mm/yr.

3.2 Future change in mean sea level in Finland

The probability distributions of the three components, the regional sea level rise h_l , wind-induced changes w and land uplift u , were combined as independent random variables to yield probability distributions of mean sea level change. This calculation was performed for all 13 tide gauges on the Finnish coast. Projected changes in mean sea level on the Finnish coast are presented in Table 3, according to the results of Papers I and III. Despite some methodological updates in Paper III compared to Paper I, such as the updated ensemble of sea level rise projections (Table 1), the differences in projections are small, only a few centimetres. Figure 7 shows the historical mean sea level decline together with projections of future mean sea level change for three coastal cities in Finland based on the results in Paper III.

According to the average scenario, mean sea level decline will continue in the Gulf of Bothnia until the end of the century, while sea level rise of up to 33 cm is expected in the Gulf of Finland. Low scenarios yield declining sea levels everywhere on the Finnish coastline, while high scenarios would cause a rise ranging from 21 cm in Vaasa to 90 cm in Hamina. Thus, the highest sea level rise is projected in the Gulf of Finland, where the rates of land uplift are smallest and also the regional sea level rise is slightly higher.

These results are reflected in the flood probability distributions calculated in Paper III. The mean sea level projections were combined with distributions of short-term sea level variations, assuming that the short-term and long-term variations are independent and their combination is the sum of these two random variables. From

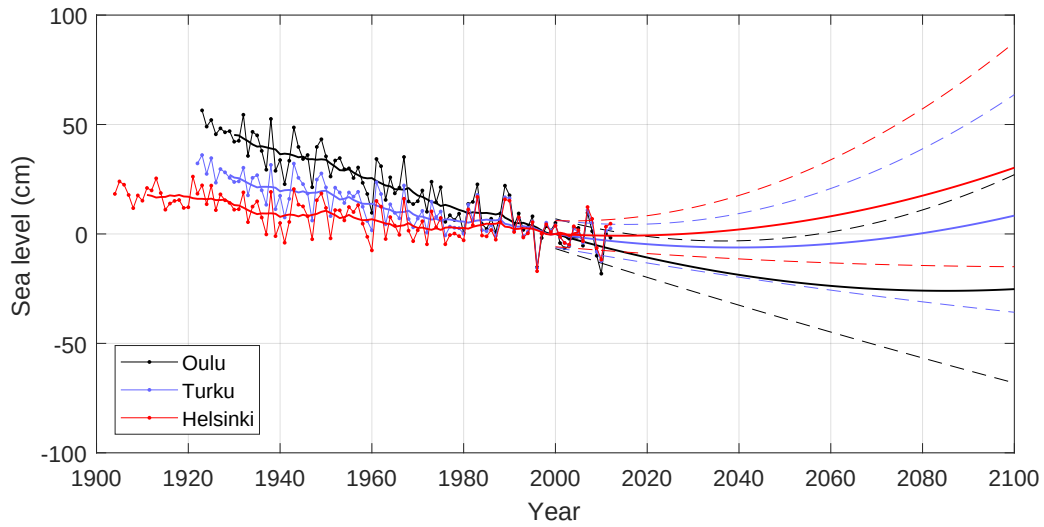


Figure 7: Observed annual mean sea levels (with the 15-year moving average) and scenarios for future mean sea level change relative to the year 2000 in some of the largest coastal cities of Finland: Oulu, Turku, and Helsinki (for locations, see Fig. 1). Solid lines 2000–2100 show the average scenario, dashed lines are the low and high scenarios corresponding to the 5th and 95th percentiles of the probability distribution.

the resulting flood probability distributions (Fig. 7 in Paper III), future sea levels with certain exceedance frequencies can be determined (Table 4 in Paper III). According to the results, flood probabilities will considerably increase in the Gulf of Finland. For example, the highest coastal flood on record created by the storm Gudrun in January 2005 is estimated to occur 3 times per century in the current climate, but every second year on average at the end of the century. Thus, rare floods of today would become commonplace by 2100 in the Gulf of Finland. In the Bothnian Sea and the Bothnian Bay, flooding risks will continue to diminish during the next decades but rise back to the present level or slightly above them in the Bothnian Bay and clearly above the present level in the Bothnian Sea by 2100.

Table 3: Change in mean sea level (cm) in 2000–2100 at the Finnish tide gauges, according to the projections of Papers I and III. The average scenario is the weighted average of the probability distribution, low and high scenarios correspond to the 5th and 95th percentiles, respectively.

Tide gauge	Paper I			Paper III		
	Low	Average	High	Low	Average	High
Kemi	−69	−26	25	−71	−28	24
Oulu	−66	−24	28	−69	−25	27
Raahe	−69	−27	25	−71	−28	24
Pietarsaari	−70	−28	24	−72	−29	23
Vaasa	−72	−30	22	−74	−31	21
Kaskinen	−66	−21	35	−66	−22	33
Mäntyluoto	−57	−13	43	−58	−13	42
Rauma	−49	−4	52	−50	−5	50
Turku	−36	9	65	−36	8	63
Föglö	−38	6	62	−39	6	61
Hanko	−22	24	82	−22	24	80
Helsinki	−15	30	89	−15	30	87
Hamina	−12	33	92	−13	33	90

4 Meteotsunamis in the Baltic Sea

The coasts of the Baltic Sea know many stories of rare, exceptionally high waves. The reports of these events have common characteristics: sudden high waves that come seemingly out of nowhere and disappear as quickly as they appeared; they can occur in clear and calm weather as well as during storms (Doss, 1906). These waves have been called *Seebär* on the German-speaking southern Baltic coast (lit. "sea wave", from old German *Bahre*, "wave") and *sjösprång* (lit. "sea leap") in the Swedish-speaking coastal regions of Sweden and Finland.

Almost a century ago, Finnish geophysicist Henrik Renqvist described the *sjösprång* phenomenon like this:

Sometimes, when the sea is calm, the weather is still, and the isobar maps do not show any peculiarities, the water will suddenly rise with great speed only to soon fall again just as quickly. The phenomenon can be repeated once, twice, or many times. The amplitude between high and low water can be a few decimetres, or a metre, two metres, perhaps more. The interval between two high-water waves can be half a minute, two minutes, a quarter-hour, or an hour. Half an hour after the onset of the phenomenon, the surface can be as calm as before; in other cases, a strange restlessness is seen for several hours. Often, the weather changes shortly after the jump in sea level, in other cases no immediate change is seen.

I want to emphasize that the phenomenon does not occur only when the sea is calm and the weather still, it can just as well be a rough sea with storm, thunder and a pressure nose on the barogram. I have said what I have said in order to make it understandable that the phenomenon is a natural wonder in the eyes of the coastal dweller and a complex problem for science. (Renqvist, 1926b, translated from Swedish)

The descriptions of these events leave little doubt that the mysterious waves are meteotsunamis. The mean depth of the Baltic Sea, 54 m, corresponds to a long wave speed of 23 m/s. Thus, it is a favourable area for meteotsunami generation through Proudman resonance or other resonance effects (Section 2.3.1). Figure 8 shows the bathymetry of the Baltic Sea converted to long wave speed; atmospheric disturbances moving over the sea close to this speed can activate Proudman resonance and generate meteotsunamis. The exact amplification mechanisms of meteotsunamis observed in the Baltic Sea are largely unknown, however.

Despite the work by Renqvist (1926a,b), who documented a meteotsunami in Finland on 15 May 1924, the existence of the phenomenon had been forgotten among Finnish sea level researchers and the eyewitness reports of such events in 2010 came as a surprise. No such reports had been received since at least the beginning of the

1970s (Kimmo Kahma, pers. comm.). Likewise, the *Seebär* phenomenon is mentioned several times in older scientific literature (e.g. Credner, 1889; Doss, 1906; Meissner, 1924; Defant, 1961) but modern analyses of Baltic meteotsunamis are lacking. Below, I attempt to draw a picture of meteotsunami occurrence in the Baltic Sea based on old literature and the results obtained in Papers II and IV.

4.1 Historical events in the Baltic Sea

4.1.1 *Seebär* in the southern Baltic Sea

Doss (1906) lists 25 *Seebär* events from the southern and southeastern Baltic coasts from the mid-18th century to the end of the 19th century, and one possible event in 1696 in Tallinn, Estonia. Most of these events occurred on the coasts of Mecklenburg and Pomerania (present-day German and Polish coasts), but several events are reported also from Liepāja (Latvia) and Pärnu (Estonia), and one from Kranz, currently Zelenogradsk (Kaliningrad).

A notable meteotsunami was observed on the northern coast of the island of Hiiumaa (Estonia) on 15 January 1858. A detailed description of the event was given by August Briancourt, master dyer at the Kertel (Kärdla) cloth factory. The first wave came at 2:10 pm and the water level in the small river flowing into the sea rose 0.9 m, returning to normal 9 minutes later. The second wave at 2:26 pm was even higher (1.05 m) and water fell back to the normal level 15 minutes later. The phenomenon was observed also in the nearby harbours of Tiefenhafen (Suursadam) and Hohenholm (Kõrgessaare). The weather was stormy, with strong winds from SW in the morning, showers of snow, hail, and freezing rain. Doss (1906) furthermore notes that thunder was observed on the same day in Stockholm and Uppsala (Sweden), which is very rare at that time of the year.

Among the scholars of that time, two competing theories were presented to explain the origin of these waves: seismic and meteorological (Doss, 1906). Some believed that the Hiiumaa waves were connected to the earthquake that occurred only 6 hours later in Žilina, Slovakia. Others noted that the waves were observed on the opposite (northern) side of the island and occurred before the earthquake, and no trembling of the earth was noticed in Hiiumaa. The meteorological origin was supported by the fact that the waves seemed to coincide with unusual atmospheric phenomena – pressure jumps, wind shift, storm, thunder. Some referred to the seiche phenomenon, which was known to occur in Lake Geneva and also in the Baltic Sea in connection with sudden strong storms and rapid changes in air pressure. Doss (1906) himself was convinced that the *Seebär* waves are of meteorological origin, and that earthquake-generated waves should not be counted as *Seebär*. A meteorological cause is also pointed out by Meissner (1924) in connection with *Seebär* events observed in Stolpmünde (currently Ustka, Poland) in 1921 and 1922.

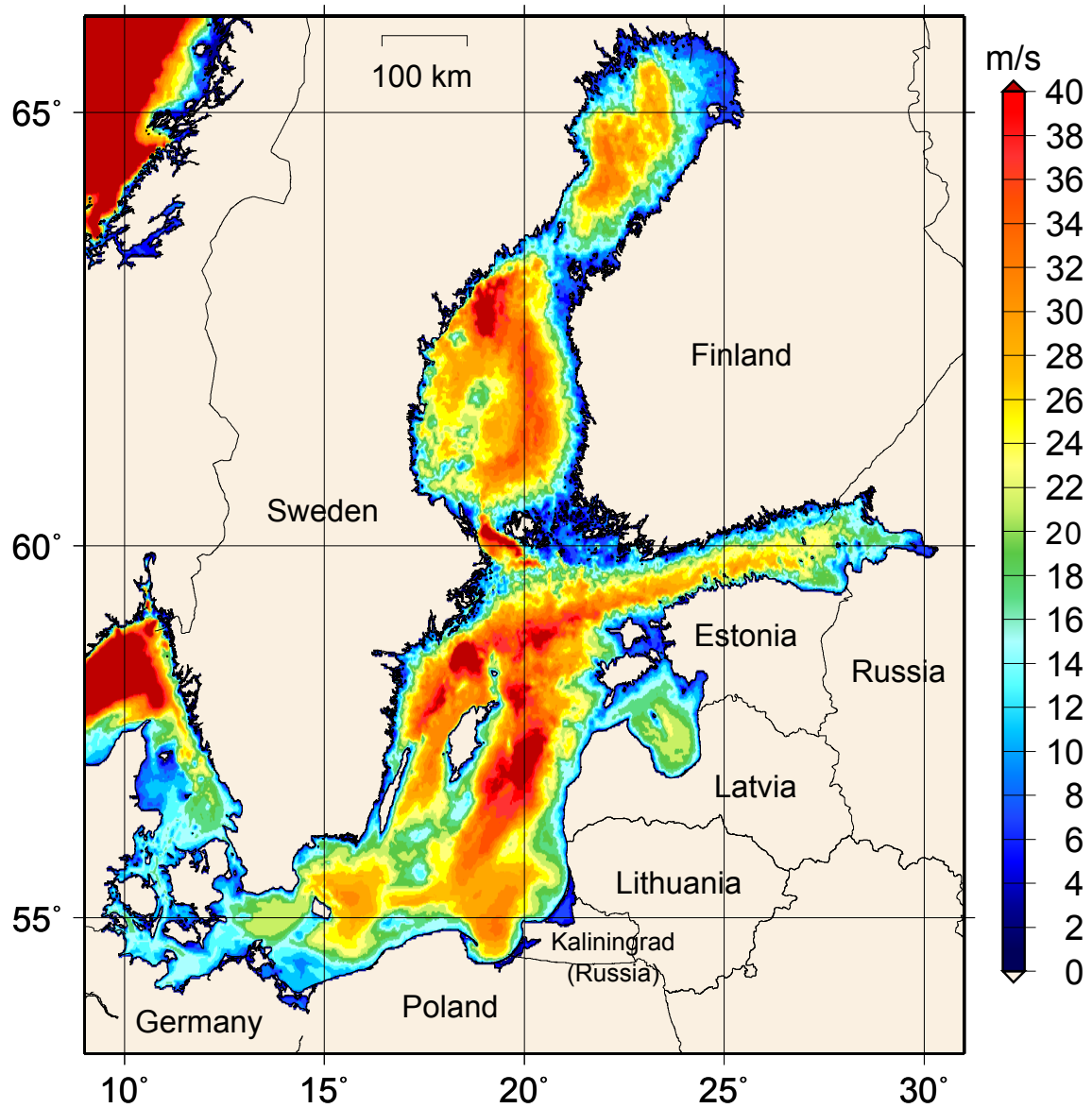


Figure 8: Bathymetric map of the Baltic Sea, with depths converted to long wave speed in the sea according to $\sqrt{gh}$, where g is acceleration due to gravity and h is water depth. Bathymetry data is from the IOWTOPO2 dataset (Seifert et al., 2001) with a spatial resolution of $1' \times 2'$ (ca. 2 km).

Doss (1906) furthermore correctly believed that the shape of the coastline affects the height of the waves, because standing waves can be formed and the waves amplified through interference. Waves entering river mouths can form a bore, which might explain the unusual height (up to 3 m) of the *Seebär* observed in Pärnu. The bridge in the Pärnu river was damaged by these waves in 1841 and 1845, and in 1836, two of the four horses that were on the bridge were lost to the sudden flood, while their owners managed to save themselves (Doss, 1906).

The events in Liepāja (Latvia) in 1825, 1845, 1858, and 1893 were also on some occasions strong enough to cause hazardous situations. In July 1845, the sea level rose so rapidly that people in the beach huts suddenly found themselves in 3–4 feet deep water (Doss, 1906). According to the newspaper accounts, no one was injured, but some bathers lost their clothes and the beach huts were dislocated. The event was over in a quarter of an hour. A waterspout was observed; however, Doss (1906) notes that a waterspout alone could not cause the sea level variations that were observed on a stretch of coast several miles wide.

The oldest known *Seebär* events come from the coasts of Pomerania in the southern Baltic Sea. A strong storm and a destructive flood severely damaged coastal towns along nearly the entire southern Baltic coast from Wismar to Kaliningrad in September 1497 (Piotrowski et al., 2017). In Darłowo (Rügenwalde), according to the chronicle of the local monastery, the storm threw several ships on dry land and carried one of them more than 3 km inland up to the hill where the Church of St. Gertrude is located. Andrzej Piotrowski from the Polish Geological Institute has estimated that the flood height was at least 3 m and, if the story of the ship holds true, it could have been much higher (Piotrowski, 2007). A meteotsunami on top of the storm surge may have contributed to the extreme height of the flood.

In April 1757, near Trzebiatów (Treptow), three successive high waves reportedly snatched an anchored ship from the harbour and moved it far onto the land:

The Baltic Sea often holds its own weather, which has no connection with weather on the land; sometimes, only rarely however, a submarine storm occurs in the Baltic Sea, which one can assume because under a clear and calm sky, a thunder can be heard rolling along the Pomeranian coast, and dead or half-dead marine or coastal fishes are thrown out on the land. That happened for instance on the 3rd of April, 1757: about the noon, at a calm and bright weather, the Baltic coast near Trzebiatów on Rega river became suddenly rolling so much that a big ferry-boat, moored in the harbour, was snatched away by high waves and shifted far on the land. After that (rolling) had been repeated three times, the sea became calm again. Local sailors call this phenomenon "Seebär". (L. W. Brüggemann, 1779, according to Piotrowski, 2007)

Piotrowski et al. (2017) attempted to find geological traces of the *Seebär* events on the coastal plain near the mouth of river Rega. They found a prominent (thickness 0.5–50 cm) and widespread sandy layer, which the authors interpret based on radiocarbon

datings to be a deposit of the 1497 storm surge. A second, thinner and less extensive sandy layer from the 18th century might be related to the *Seebär* event in 1757, but the authors consider it more likely to be left by a storm surge that has caused breaching of the sand dunes and inundation of the coastal plain.

4.1.2 Historical events in Finland

The shallow waters and broken topography of the Finnish coast are favourable for meteotsunami formation when conditions fall in place. One such event in 1876 on the Gulf of Finland was witnessed by linguist Herman Vendell. In a newspaper article, he describes a sailing trip in Kantvik (Kirkkonummi):

It was Seven Sleepers' Day, 27 July 1876. [...] As the sky was cloudless, the weather mild, and the breeze suitably brisk in the morning, I set out to sail on the open sea. Under a south-westerly wind and with full sails it was a pleasure to cut the crests of the smoothly rounded waves. The bow was already pointing homewards, when the wind calmed and, looking behind me, I saw, far out in the Gulf of Finland a dark-blue horizon appearing and heard a rumbling like distant thunder. Having made it back to the boathouse I was caught by a suddenly onrushing remarkably high wave, followed by a whistling storm. In a hurry the boat was secured and the sails furled. But the flood and storm was so fierce that before my companion and I had left the shaking boathouse, the pier was torn away into shreds, and we had to wade in water up to our armpits to the shore. The water rose by some 4 or 5 feet above normal level and carried planks, lumber, and vessels far up onto a meadow [...]. This was followed by the full raging of the forces of nature, which during the evening and the night escalated into an unusually powerful thunder, punctuated by bright bursts of light, and quickly strobing bolts of lightning.

Such natural phenomena are called "sjösprång" in this area. They repeated quite often during the same summer, though to a smaller degree and always during a south-westerly wind. (H. Vendell: Något om sjösprång. Folkvännen 1885, nos. 133 and 134. Translated from Swedish.)

On the evening of 15 May 1924, a strong meteotsunami was observed on the southern Finnish coast. Newspapers reported of unusual rising and falling of the sea level that was repeated several times with short intervals, lifting up old tree trunks from the bottom and revealing long stretches of seafloor in shallow places during the outflow (Renqvist, 1926b). Observations of the phenomenon were reported from more than 20 locations, mostly in the Archipelago Sea and western Gulf of Finland. The waves occurred in the evening between 6 and 9 pm, generally earlier in the west than in the east. However, in Utö and Bågaskär sea level oscillations were observed already between 2 and 6 pm.

The event was studied in detail by Renqvist (1926a,b). The meteotsunami was not observed in Estonia on the opposite side of the Gulf of Finland. The maximum height of the observed waves was 1.2 m in western Gulf of Finland east of Hanko, but in most places the height was around 0.5 m. At the tide gauges of Hanko and Helsinki, only damped oscillations of small amplitude were registered. According to the eyewitness observations, the period of a single wave was 5–15 min and the event was typically over within an hour. It seems that the anomalous observations in Utö and Bågaskär were related to somewhat longer waves.

In the afternoon of 15 May 1924, a mild wind was blowing from the south or southwest and there was a strong east-west temperature gradient over the Baltic Sea: in Stockholm the temperature was 18 degrees, in Hanko only 6. During the evening, mild wind, dark clouds, thunder, wind gusts, and fog were reported from many observation sites, and small jumps in air pressure were registered at meteorological stations in the region. Renqvist (1926a,b) notes that the *Seebär* phenomenon has in earlier literature been connected to thunder and rapid variations in air pressure. However, as electrical forces cannot cause sea level variations and changes in air pressure by themselves cannot explain such high waves, Renqvist was led to seek the explanation from whirlwinds and tornadoes, even though no such phenomena were observed by the eyewitnesses.

4.2 Recent events

4.2.1 Recent meteotsunamis in Finland

In the summers of 2010 and 2011, the Finnish Meteorological Institute received several messages from citizens who had witnessed exceptional sea level events on the Finnish coast. The eyewitnesses reported strange waves with a period ranging from a few minutes to fifteen minutes and height from 30 to 100 cm. Weather conditions were described as not showing anything out of the ordinary. In Paper II, these observations were documented and the events examined using sea level and meteorological data. Tide gauge observations confirmed the eyewitness observations, but the oscillations recorded at the measurement sites had generally a much smaller height. The oscillations coincided with small (1–4 hPa) sudden jumps in surface air pressure at coastal observation stations (Figs. 3, 6, 9, and 12 in Paper II).

The propagation speed of the atmospheric disturbances was estimated from radar imagery. Both events observed in the Gulf of Finland, on 29 July 2010 and 8 August 2010, were caused by an air pressure disturbance propagating northwards across the gulf from Estonia; speeds were 22–24 m/s, corresponding to the long wave speed in 49–58 m deep water. While the speed of the disturbances matched long wave speed in parts of the gulf (Fig. 8), in Paper II it was concluded that the amplification due to Proudman resonance alone was not that significant because of the relatively small width of the gulf (80 km) and the concave bottom topography. In that case, effects

controlled by local bathymetry must have dominated to create the up to 1 m high waves observed by eyewitnesses. The small height, 10–15 cm, of the waves recorded at the tide gauges also points to this conclusion.

Also on 8 August 2010, a squall line propagated northward along the coast of the Gulf of Bothnia, creating a small meteotsunami observed in Raahe. The speed was 18 m/s, corresponding to the long wave speed in 33 m deep water. Because the squall line was propagating along the coastline, it had a long fetch over shallow coastal waters and significant amplification of the wave due to Proudman resonance could occur. Indeed, sea level oscillations at the Raahe tide gauge and the eyewitness observation ca. 6 km to the south were of the same magnitude, about 0.5 m. Another event was observed on 4 June 2011 in the Archipelago Sea, connected with a southeastward moving cold front that created a small pressure jump.

4.2.2 Recent meteotsunamis in Sweden

Several meteotsunami events have been observed in Sweden in recent years. The eyewitness descriptions very much resemble those reported in Finland: sudden sea level variations of up to 1.5 m and strong currents. No systematic study of the Swedish events exists to date, but it seems that meteotsunamis typically occur at least a couple of times each summer and can be quite powerful (Ola Kalén, pers. comm.). Based on the available evidence, it seems that conditions for meteotsunami occurrence in Sweden very much resemble those observed in Finland.

On 8 August 2018, a meteotsunami was observed on the western Swedish coast outside the Danish straits. Erik Wickstrand witnessed the event at Lapposand, Hönö, outside Göteborg, and published a video that shows the seafloor revealed by the outflow of water, stranded boats, and after a couple of minutes the inflow of water back to the small bay¹. According to him, the phenomenon was repeated at least 8–10 times in a similar fashion, before the thunder and rain rolled in. Fisherman Fredrik Andersson, who also observed the event in Hönö, told the newspaper *GT*²: "I have never seen anything like it. My father is 73 years old and has fished all of his life, and he has never experienced anything like it either."

According to a press release by SMHI (Swedish Meteorological and Hydrological Institute)³, the event was caused by a weather front moving eastward over Denmark. The event could be detected in the sea level signal of all Swedish tide gauges around the coast (Ola Kalén, pers. comm.). The tide gauge in Torshamnen, Göteborg, registered 20–25 cm high oscillations, while eyewitnesses reported wave heights of up to 1 m in Göteborg archipelago.

¹Erik Wickstrand: Sjösprång på Lapposand (Hönö). Published 13 Aug 2018, accessed 23 May 2020. https://youtu.be/4i_FNL3f_9s

²GT: Havet försvann – mitt framför Fredriks ögon. Published 11 Aug 2018, accessed 23 May 2020. <https://www.expressen.se/gt/havet-forsvann-mitt-framfor-fredriks-ogon/>

³SMHI: Sjösprång på västkusten. Published 8 Aug 2018, accessed 23 May 2020. <https://www.smhi.se/nyhetsarkiv/sjosprang-pa-vastkusten-1.138339>

The Swedish word *sjösprång* (lit. "sea leap") is a somewhat loose term referring to rapid sea level variations, both storm surges with a period of several hours as well as sudden sea level oscillations of shorter period, 5–20 min (Nyberg, 1979). The description of the latter variant clearly points to a meteotsunami: their generation is known to be connected with an air pressure disturbance moving over the sea at a speed close to the long wave speed in the sea. According to Nyberg (1979), the height of the short-period *sjösprång* on the Swedish coast vary from a few decimetres to 1–2 metres, occasionally even higher. Often there is no local disturbance in weather to be seen; the waves occur in calm weather.

4.3 Meteotsunamis in Finnish sea level data over the past century

Apart from the 15 May 1924 meteotsunami, which aroused widespread attention and was thoroughly examined by Renqvist (1926a,b), and the recent events documented in Paper II, there are no scientifically documented occurrences of meteotsunamis in Finland. A systematic study of such events was needed to find out how common meteotsunamis are on the Finnish coast. This was performed in Paper IV.

The study of meteotsunamis is hindered by the spatial and temporal resolution of the sea level measurement network. Even though sea level measurements have been carried out on the Finnish coast for over a century, digital measurements with a sampling interval of less than one hour are not available before 1980 (Section 2.1). However, the Finnish tide gauges have been equipped with recording devices that plotted the sea level as a continuous curve on paper (Fig. 3 in Paper IV), and these paper records exist in the archives of the Finnish Meteorological Institute. There is a lot of undigitized data available on these paper charts.

The sea level data used in Paper IV consists of the original paper charts of the tide gauges of Hanko and Hamina, in the Gulf of Finland (Fig. 1), from the 1920s to 1989. Because analyzing the charts involves a lot of manual work, the scope of the study was restricted to these two tide gauges and to the summer months of May–October. Even though meteotsunami occurrence in winter is possible, as demonstrated by the sea level event of January 1858 in Hiiumaa (Section 4.1.1), Baltic meteotsunamis are predominantly a summertime phenomenon. The *sjösprång* phenomenon in Sweden is strongly connected to thunderstorms (Nyberg, 1979), which are rare in winter in the region (Mäkelä, 2011). The possible ice cover in the sea further reduces the effect of atmospheric disturbances on sea surface and suppresses sea level oscillations (Section 2.1.1).

The tide gauge charts were browsed through visually, and exceptionally rapid and strong oscillations with a period of max. 2–3 hours were marked for further analysis and digitized. The time series was complemented with events automatically detected from 15-min sea level data since 1980 from three tide gauges in the Gulf of Finland: Hanko, Helsinki, and Hamina. The overlapping ten years in 1980–1989 showed that both the

visual viewing and the automated algorithm were effective methods of detecting rapid variations in the data, and the results could be combined with reasonable confidence.

The atmospheric origin of the waves was studied using barograms from the nearby coastal stations. In most cases, a small but abrupt pressure jump or drop – or several – was found to coincide with the sea level oscillations, indicating that the waves were of meteorological origin. These events were interpreted as small meteotsunamis. A small number of events that were not accompanied by any unusual changes in air pressure were excluded. While notable gaps in the data exist especially because of damping of the sea level records (filtering out of high-frequency signals because of blockages in the pipe connecting the tide gauge well to the sea), the research resulted in a unique dataset of meteotsunami occurrence in the Gulf of Finland spanning nearly a century.

In total, 135 potential events exceeding a location-specific height threshold (10–20 cm) were found in the sea level data of the three tide gauges, and 99 (over 70%) of these were confirmed from the air pressure observations (Table 1 in Paper IV). The rest could not be confirmed because of missing air pressure data. Taking into account that 14 of the events were observed at more than one station, the number of separate events was 121. The longest time series from Hanko (1922–2014) contains 45 events, the time series from Hamina (1928–2014) 65 events (Fig. 5 in Paper IV). While the series from Hanko does not show clear trends in meteotsunami occurrence, in Hamina, meteotsunamis seem to be more common over the latter half of the century than over the first half. Excluding the years with over 80% of missing data, a least squares fit for Hamina gives an increasing trend which is statistically significant at a level of at least $p = 0.01$ (Paper IV).

Three height metrics were used to characterize the heights of the detected meteotsunamis in Paper IV: the maximum height of an individual wave, the total range of variation during the event, and the maximum elevation on top of the background sea level variations. Typical heights of the first two metrics were 10–30 cm, with the highest observed events being close to 60 cm. The maximum elevations were typically roughly half of the total sea level variation. Wave height does not show a statistically significant trend in the time series.

4.4 Connection to atmospheric phenomena

In Paper II it was shown that the three sea level events observed in 2010 and 2011 on the Finnish coast occurred during the passage of air pressure disturbances moving at a speed close to the long wave speed in the sea below, confirming their atmospheric origin and meteotsunami-type character. The disturbances were related to different types of weather phenomena: a gust front, squall lines and a cold front.

The connection between meteotsunami occurrence and atmospheric conditions was further studied in Paper IV. On a monthly scale, the months (May–Oct in 1922–2014) with at least one meteotsunami occurrence were compared with the months with no recorded meteotsunamis. The null hypothesis was that the means in at-

mospheric parameters between these two sets of months would be equal; this was true for mean sea level pressure, 10 m wind speed, and the NAO index. In contrast, surface temperature, dew point temperature, and CAPE (convective available potential energy) showed a statistically significant ($p < 0.01$) difference, with larger average values during the months when meteotsunamis were observed (Table 2 in Paper IV). Means of these atmospheric parameters were calculated from reanalysis data.

Thunderstorm days in Finland have been observed by humans since 1887, and since 1960 with an automatic flash counter network. The yearly means of the number of thunder days (1922–2014) showed a statistically significant ($p = 0.02$) difference between years when meteotsunamis were recorded and when they were not recorded. However, the number of CG (cloud-to-ground) flashes over the whole continent of Finland and meteotsunami occurrence in the Gulf of Finland did not show such a connection, presumably because the geographical areas differ too much.

More specific location information of CG flashes is available since 1998. The daily and monthly CG flash numbers in the Gulf of Finland region were calculated in Paper IV and compared with meteotsunami occurrence. These numbers were clearly and significantly ($p < 0.001$) higher during days and months when meteotsunamis were recorded compared to other times. On meteotsunami days, CG flash numbers in the Gulf of Finland were over 10 times higher compared to an average summer day of no meteotsunami occurrence (Table 2 in Paper IV).

5 Discussion

There are still large uncertainties in sea level projections, but decisions with a time horizon of 100–200 years have to be made now in coastal management. Adaptive measures, e.g. determining the building elevations of new infrastructure, need to aim at a good balance between the opposing risks of flooding damage (if the flood risk estimates are too low) and larger expenses of flood protection (if unnecessary measures are implemented because the estimates are too high). Probabilistic projections are helpful in this balancing as they can be applied to different situations requiring different safety levels.

Our aim was to present the deep uncertainty in sea level projections as a single probability distribution that includes i) all possible future trajectories of greenhouse gas emissions, ii) the high-impact, low-probability risks such as the possible disintegration of the West Antarctic ice sheet, and iii) regional deviations from the global mean. This was achieved by making a weighted combination of different projections that are based on different methods and treat the uncertainties differently. The process inevitably includes some subjective choices and the results are subject to change as the scientific understanding of sea level rise evolves. However, as Hinkel et al. (2015) point out, the ability of societies to adapt to rising sea levels, e.g. by building flood defences, is faster than the rate of sea level rise given sufficient economical resources are available. While it is good to prepare for rising sea levels, at this point it may be enough to leave possibilities for adaptation open in case the high-end scenarios come true.

Current evidence suggests that the upper limit of potential sea level rise by 2100 lies somewhere in the 1.5–2.5 m range. To reach such high levels, the collapse of the West Antarctic ice sheet should begin during this century. There are recent observations indicating that the disintegration caused by the marine ice sheet instability mechanism is already underway on some of the West Antarctic ice streams, and some modelling results indicate that a widespread collapse can begin during this century (Section 2.2.3), but current scientific knowledge cannot give a definite answer to how fast and significant the retreat will be. Solving this question would require novel ideas and breakthroughs in ice sheet modelling (e.g. Joughin et al., 2012; Jevrejeva et al., 2014).

Future efforts to mitigate greenhouse gas emissions play a crucial role in determining the future of the Antarctic ice sheet and global mean sea level rise (e.g. Winkelmann et al., 2015). Even during this century, the difference between a strong mitigation scenario (RCP2.6) and a business-as-usual scenario (RCP8.5) is significant, and the difference is even more striking in a longer time perspective. By 2300, a 1.5°C warming scenario could peak the sea level at 1.5 m above the 2000 level (Schaeffer et al., 2012). Limiting warming to 1.5°C would require deep emission reductions bringing

anthropogenic CO₂ emissions to zero by 2050 (IPCC, 2018). Stronger warming is likely to commit the world to several metres of sea level rise during the next few centuries. While the postglacial land uplift in Finland, 40–100 cm per century, compensates a significant part of the sea level rise, accelerating sea level rise means that the historical trend of declining mean sea levels will reverse in Finland over time – sooner on the southern coast and later in the north.

At the other end of the sea level spectrum, meteotsunamis on the Finnish coast were studied. The phenomenon of sudden, unexpected large waves has long been known among the coastal residents of Baltic Sea. As a shallow sea with a complex coastal topography, the Baltic Sea is a suitable environment for the resonance effects required to produce sizeable meteotsunami waves. The highest reliably documented meteotsunamis in the Baltic Sea have been 1–1.5 m high, but historical sources point to even higher waves. There is evidence of meteotsunamis from all around the Baltic coasts, indicating that these events are widespread in the Baltic Sea.

The results obtained in this work show that Baltic meteotsunamis are more common than has perhaps been thought previously. While stronger events are rare, small meteotsunami-type oscillations with a height of a few decimetres may occur a few times each summer on the Finnish coast. Although relatively modest in size, Baltic meteotsunamis can in some cases clearly be sufficient to cause at least minor damage and endanger coastal safety. Moreover, it seems that under suitable meteorological circumstances several meteotsunamis can occur within a short time period. For example on 8 August 2010, meteotsunamis were observed both in the Gulf of Finland and the Gulf of Bothnia, caused by separate weather phenomena.

The knowledge of meteotsunami occurrence in the Baltic Sea is still sparse and there is plenty of room for further work. Some suggestions include:

- Compiling a catalogue of all known Baltic meteotsunami events, both historical and contemporary. A systematic study of sea level data and newspaper archives would probably reveal more proof of Baltic meteotsunamis (as e.g. Haslett et al., 2009; Haslett and Bryant, 2009 for the United Kingdom).
- Modelling work to examine the generation mechanisms of meteotsunamis in the Baltic Sea in detail. How can the high *Seebär* waves observed in the 15th and 18th centuries on the southern Baltic coasts be explained?
- Modelling work to reveal vulnerable locations for meteotsunami occurrence on the coasts of the Baltic Sea.
- Calculating the probability distribution of meteotsunami occurrence at a given location to improve risk assessments of coastal flooding. How well are meteotsunamis represented in the statistics of sea level extremes used in such assessments?

- What is the reason behind the differing trends of meteotsunami occurrence in Hanko and Hamina, and how will climate change affect meteotsunami occurrence in the future?
- Spreading awareness of Baltic meteotsunamis and strengthening international cooperation among the Baltic Sea countries.

6 Conclusions

The main conclusions of this work, referring to the research objectives presented in Chapter 1, can be summarized as follows:

- Probability distributions of mean sea level change in different locations on the Finnish coast were presented. The regional effect of global sea level rise will be below average, approximately 80% of the global mean, and postglacial land uplift further counteracts sea level rise in the region. However, sea level rise and significant increases in flooding risks are expected over the 21st century in the Gulf of Finland. In the northern parts of the Gulf of Bothnia, land uplift is strong enough to outweigh sea level rise during this century unless the highest projections come true.
- A total number of 121 potential (over 70% of them confirmed) meteotsunami events were identified in the sea level data of three tide gauges in the Gulf of Finland 1922–2014, showing that small meteotsunamis occur regularly on the Finnish coast. Typical wave heights at the tide gauges were 10–30 cm, but higher oscillations are possible in vulnerable locations. A statistically significant increasing trend in the number of meteotsunamis was found in Hamina, in the eastern part of the Gulf of Finland, but not in Hanko in the western part of the gulf.
- Weather phenomena that generate meteotsunamis on the Finnish coast include gust fronts, squall lines and cold fronts propagating over the sea at a resonant speed. Meteotsunami occurrence in the Gulf of Finland shows a strong connection to lightning observations. A statistically highly significant difference between meteotsunami months and other months was also found in convective available potential energy (CAPE) which is an indicator of summertime thunderstorm potential. Meteotsunamis in the region seem to occur practically always in connection with thunder.

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