Response to referee comments: Meteotsunami occurrence in the Gulf of Finland over the past century (Pellikka et al.)

Referee 1 (Agusti Jansa)

We thank Agusti Jansa for the constructive comments that have helped us to clarify and improve some points in our manuscript. To reply to the more specific points we would like to note the following:

#	Comment	Response
1	As general observations, less conclusive (less explained) than the already mentioned results are those referred to differences between the eastern (Hanina) and western part (Hanko) of the Gulf of Finland: the frequency of meteotsunamis and also the time increasing of this frequency is higher in Hanina. These results are mentioned (and can be important), but they are not clearly explained. On the other hand, are both important results (higher frequency and higher increase if the frequency in Hanina) susceptible to be related? Have the authors any idea about this, although not demonstrated?	The differing trends observed at the two locations studied are indeed interesting. As we note below (#5), the tide gauge of Hamina is situated in a location which is potentially more vulnerable for meteotsunami amplification. Also, Hamina's location near the eastern end of the Gulf of Finland probably explains some of the difference in the magnitude and number of the observed meteotsunamis, as the potential distance of air-sea resonance is longer for disturbances moving from west to east. The increasing trend in the time series from Hamina is largely due to the absence of events in the beginning of the series, from the 1930s to the 1950s (Fig. 5 in the manuscript). The reason for this gap in the occurrence of meteotsunamis is unknown. As we speculate in the text (p. 10 l. 28), changes in the propagation direction of atmospheric disturbances may cause differing trends in meteotsunami occurrence at different locations. However, studying the propagation direction of the disturbances is not straightforward as the available high-resolution air pressure data is mostly non-digital. The effect of coastal topography and local resonance effects could be studied with models. These are topics for future work. We have added discussion on the differing locations of the tide gauges in the text, as well as some suggestions for future work.
2	It seems that the authors of the paper consider that the meteorological cause of meteotsunamis has to be a single pressure jump of a considerable magnitude, no other kind of perturbation; but in Mediterranean cases, for instance, smaller magnitude rapid pressure oscillations related to atmospheric gravity waves are claimed as the cause of	We have considered all kinds of rapid pressure disturbances, pressure drops in addition to jumps, and also of smaller magnitude (~1 hPa). We have reworded the text to clarify this. Only events with no unusual accompanying changes in air pressure were excluded from the analysis (a small proportion of all events).

	many meteotsunamis (Monserrat et al, 1991; Jansa et al, 2007). Therefore, could some of the cases not confirmed by the authors as meteotsunamis be related with nonconvective pressure oscillations connected with pure gravity waves? On the hand, the cases illustrated in Fig. 5 would suggest than single pressure jumps can occasionally be accompanied by less amplitude gravity wave signal. Finally, is there an alternative (no meteorological) origin if a rapid large amplitude sea level oscillation is observed in the Gulf of Finland?	It is an interesting question whether nonconvective pressure disturbances connected with atmospheric gravity waves might generate meteotsunamis in the Gulf of Finland. Our results show that the observed meteotsunamis are strongly connected to thunderstorms, and thus convective phenomena seem to be clearly the dominant factor of meteotsunami generation in the study area, but the possibility of other generation mechanisms cannot be ruled out. Sepic et al. (J. Sepic et al. 2015, High-frequency sea level oscillations in the Mediterranean and their connection to synoptic patterns. Progress in Oceanography 137, 284–298) state that meteotsunamis in the Mediterranean have a characteristic synoptic pattern: "(i) an inflow of warm air in the lower troposphere and (ii) a jet at mid-tropospheric levels embedded in (iii) unstable atmospheric layers. These conditions are conducive to generating and trapping atmospheric gravity waves in the lower troposphere - -". It is not impossible that such conditions could occur in Finland (M. Bister, pers. comm.), but more exact analyses are a topic for future work. The northern coastline of the Gulf of Finland is very irregular with bays and narrow inlets of different shapes and sizes, so seiche oscillations in small basins may cause sea level variations in the tsunami frequency range.
3	Have the authors an estimation of periods involved in the large and rapid sea level oscillations identified as meteotsunamis? I suppose not, but can a compatibility of periods do exist with the eigenperiod of the Gulf of Finland itself? (If so, higher amplitude and higher frequency of meteotsunamis over thresholds in Hanina than in Hanko could be more understandable)	We have not included an estimate of the wave periods in the manuscript, as aliasing may distort the periods of short-term variations in the 15-min observations (see #7). We have added a note on this in the manuscript. Typical periods of the observed waves in the recorded signals are 1–2 hours; however, shorter-term variations may have been shifted to this period range because of aliasing. Basin-wide seiches in the Gulf of Finland have generally a considerably longer period than meteotsunamis: around 23–27 hours (e.g. Neumann 1941, Eigenschwingungen der Ostsee, Arch. Dtsch. Seewarte Mar., 61, 1– 59; Lisitzin 1944, Die Gezeiten des Finnischen Meerbusens, Fennia, 68, 1– 19; Jönsson et al. 2008, Standing waves in the Gulf of Finland and their relationship to the basin-wide Baltic seiches, J. Geophys. Res. 113, C03004). Transverse seiche oscillations across the gulf may have periods close to

		meteotsunamis, however; with L = 80 km and H = 40 m, Merian's formula gives the period of a uninodal seiche oscillation of 2.2 hours.
4	To hypothesize about these differences, the authors seem to argue that the variability of the sea level series in Hanina is higher than in Hanko; but why can be this an explanation? On the other hand, I do not understand which are the series they have used to say that; the standard deviation values given (page 7) seem to be very large.	The standard deviations of the filtered 15-min sea level signal were 0.45 cm for Hanko, 0.41 cm for Helsinki, and 0.92 cm for Hamina. We have changed the unit to mm for clarity. We have used the standard deviations only to motivate the choice of height threshold for Helsinki tide gauge, for which no chart data is available.
5	Are the Hanko or Hanina sea level stations within some kind of inlet, channel or harbour susceptible to produce some kind of local resonance?	The tide gauge of Hanko is located on a relatively open coast on the southern side of the tip of the Hanko peninsula (see attached Fig. 1). On the contrary, the tide gauge of Hamina is located in a potentially more vulnerable place for local resonance: inside a rather narrow bay, ca. 5 km long and 1 km wide (see attached Fig. 2). Assuming a mean depth of 6 m (an approximative estimate), the period of a uninodal seiche oscillation in the semi-enclosed basin would be around 35 minutes. These differences in the settings of the two tide gauges probably explain some of the difference in the sea level variability between the two stations, but more detailed modelling studies would be needed to quantitatively resolve this. We have added discussion on this in the manuscript.
6	External resonance (Proudman and other) could produce larger amplification in Hanina than in Hanko if the atmospheric perturbation moves along the Gulf of Finland or with a component in this direction, in which the meteorological cause and the marine response could be coupled more time than if the movement is transverse to the Gulf. With surprise, it seems the transverse is the direction of propagation of the atmospheric cause at least in some cases (Pillikka et al, 2014). Probably it is not easy for a large amount of cases, but have the authors considered the question of the propagation (speed and direction)?	We agree that investigating the propagation speed and direction of the atmospheric disturbances would give us valuable information about the amplification mechanisms and the observed differences in meteotsunami occurrence at the two stations. However, with the air pressure data available (mostly non-digital) investigating the speed and direction is not straighforward, and is a topic for future work.
7	Regarding the objective detection of meteotsunamis with data every 15 minutes, it seems the method runs quite well, but I am a little surprised, because I do not understand well how this detection is possible, unless the period of the sea level	We agree that using 15-min sea level data is not optimal for meteotsunami detection, but higher-resolution data is not available to create a continuous time series. Most of the time series is based on tide gauge charts, however, where sea level is recorded as a continuous curve on paper.

	oscillations is much longer than 15 minutes.	It is possible that some events are missed after 1989 because of the 15-min resolution of the digital sea level data, but this does not seem very likely. Otherwise the number of events would drop in the time series after 1989, which is not the case. Oscillations with a period of less than 30 min are aliased in the 15-min signal, but they are not completely missing; they can be seen in the time series with a distorted period. For example, oscillations with a period of 20 min would be seen in the data as 60-min oscillations. We have added discussion on the effect of data resolution and aliasing in the manuscript.
8	With regard to the cases between 1980-89, I do not understand well why if the visual method catches 3 cases in Hanko, why the objective method misses two of them: if the instrument is not correctly running neither one, nor the other method would have catched the cases.	This issue is due to problems in the digitization of the data, which was performed by a human-assisted computer program over the period 1980–1987, as explained in Section 2.3 of the manuscript. All high-frequency oscillations that were recorded by the instrument (and are shown on the paper charts) are not accurately reproduced in the digitized 15-min data during this period. This problem in the quality of the digitization does not affect the time series after 1987, when the instrumentation of the tide gauges was updated. We have clarified this issue in the text.

Referee 2 (Anonymous)

We thank the referee for the constructive comments that have helped us to clarify and improve some points in our manuscript. To reply to the specific and technical comments we would like to note the following:

#	Comment	Response
1	In the introduction of the manuscript, the authors write that meteotsunami has a period from a few minutes to a few hours. In summary of the eyewitness observations (in Pellikka et al., 2014) authors wrote that meteotsunami in 2020 and 2011 had a period of about 5–10 min. Also, in Pellikka et al., 2014 meteotsunami waves had periods 15–25 min in Helsinki and Hamina by tide gauges. In present research (Pellikka et al., 2020) authors used 15-min tide gauge data. The Nyquist frequency was 2 cycles per hour	Oscillations with a period shorter than 30 min appear as longer-period oscillations in the 15-min signal because of aliasing. We have added discussion on wave periods, the effect of data resolution and aliasing in the manuscript. Please also see our responses #3 and #7 to referee 1. The eyewitnesses of the events in 2010 and 2011 reported wave periods of 5-10 min. Eyewitnesses easily notice the shortest variations, which are easiest to see by eye. These individual cases also do not necessarily represent the whole

	and the minimum period for these data (and for meteotsunamis) was 30 min. The period of meteotsunami in Fig 4a is visually from 40 min to 1 h and in Fig. 4b is about 2 hours. This period is greater than the typical period of meteotsunamis in the Gulf of Finland. The authors should clarify information about the calculated wave periods in the text of the manuscript.	population of events.
2	The authors used atmospheric data from neighboring weather stations for analysis of wave origin. For 70% of cases, meteotsunami were confirmed by small jumps in atmospheric pressure. How much reliably is the one nearest weather station? Perhaps the atmospheric disturbance that caused the meteorological tsunami, did not appear on the current weather station during its propagation but was recorded at other stations in the Gulf of Finland. The authors should check other weather stations for air pressure surges for 30% of cases.	We agree that checking the air pressure data from other nearby stations would be useful. This is not straightforward, however, as the air pressure data used is mostly non-digitized and stored in physical archives. To make the required amount of work feasible, the analysis was restricted to the nearest station.
3	In the Introduction of the manuscript, the authors should review the typical periods and heights of the other sea level variations in the Baltic Sea, in particular storm surges and seiches in the Gulf of Finland. What period have natural oscillations (seiches) in bays of Hamina and Hanko?	We have added discussion on Baltic Sea level variations in the Introduction. The tide gauge of Hanko is located on a relatively open coast, while the tide gauge of Hamina is inside a rather narrow bay, ca. 5 km long and 1 km wide. Assuming a mean depth of 6 m (an approximative estimate), the period of a uninodal seiche oscillation in the semi-enclosed basin would be around 35 minutes. Please also see our response #5 to referee 1 and the attached figures there.
4	In the introduction, the authors should report about meteotsunami in other parts of the Baltic Sea, in particular in the Gulf of Bothnia.	We have included some information on meteotsunamis in the Baltic Sea in the Introduction. To our knowledge, there are no scientific studies on meteotsunami occurrence in the Gulf of Bothnia except the event on 8 Aug 2010 reported in Pellikka et al., 2014: Recent observations of meteotsunamis on the Finnish coast. Natural Hazards 74:197–215.
5	In the introduction, the authors write about the summer resident witnessed in Pellinki, in the Porvoo archipelago. This location should be shown on the map in Fig. 1.	We have added the location in Fig. 1.
6	P. 2, line 18: internal –> eigen or natural	Corrected.
7	P. 3, line 5: Is the study area the northern Baltic Sea? May be the northern part of the Gulf of Finland?	We have reworded the text for clarity.

Fig. 1. Location of the Hanko tide gauge

Fig. 2. Location of the Hamina tide gauge

List of the most relevant changes to the revised manuscript: Meteotsunami occurrence in the Gulf of Finland over the past century (Pellikka et al.)

1. Added information about meteotsunamis in the Baltic Sea. P2, L33 – P3, L3 in the revised manuscript.
2. Added information about sea level variations in the Baltic Sea in general. P3, L8–15 in the revised manuscript.
3. Added a note on the effect of data resolution and aliasing. P4, L16–19 in the revised manuscript.
4. Clarified the explanation on the problem regarding the quality of data digitization. P5, L25–26 in the revised manuscript.
5. Clarified the explanation on air pressure changes detected during the identified meteotsunamis. P7, L27–30 in the revised manuscript.
6. Added discussion on the different locations of the tide gauges and their effect on the results. P10, L31 – P11, L2 in the revised manuscript.
7. Added discussion on the effect of data resolution and aliasing on the results. P11, L3–8 in the revised manuscript.
8. Added suggestions for future research. P12, L11–13 in the revised manuscript.

Meteotsunami occurrence in the Gulf of Finland over the past century

Havu Pellikka[1], Terhi K. Laurila[1], Hanna Boman[1], Anu Karjalainen[1], Jan-Victor Björkqvist[1], and Kimmo K. Kahma[1]

[1]Finnish Meteorological Institute, P.O. Box 503, FI-00101 Helsinki, Finland

Correspondence: Havu Pellikka (havu.pellikka@iki.fi)

Abstract. We analyse changes in meteotsunami occurrence over the past century (1922–2014) in the Gulf of Finland, Baltic Sea. A major challenge for studying these short-lived and local events is the limited temporal and spatial resolution of digital sea level and meteorological data. To overcome this challenge, we examine archived paper recordings from two tide gauges, Hanko for 1922–1989 and Hamina for 1928–1989, from the summer months of May–October. We visually inspect the recordings to detect rapid sea level variations, which are then digitized and compared to air pressure observations from nearby stations. The data set is complemented with events detected from digital sea level data 1990–2014 by an automated algorithm. In total, we identify 121 potential meteotsunami events. Over 70 % of the events could be confirmed to have a ~~small jump~~ rapid change in air pressure occurring shortly before or simultaneously with the sea level oscillations. The occurrence of meteotsunamis is strongly connected with lightning over the region: the number of cloud-to-ground flashes over the Gulf of Finland were on average over ten times higher during the days when a meteotsunami was recorded compared to days with no meteotsunamis in May–October. On a monthly level, statistically significant differences between meteotsunami months and other months were found in the number of CG flashes, convective available potential energy (CAPE), and temperature. Meteotsunami occurrence over the past century shows a statistically significant increasing trend in Hamina, but not in Hanko.

1 Introduction

On 29 July 2010, in Pellinki, in the Porvoo archipelago, Gulf of Finland (Fig. 1), a summer resident witnessed an exceptional event:

> "I have spent all my summers in Pellinki, now for the 50th time, and from 1989 in this place. During that time I have of course seen the water rise, fall and flow in various ways, but what I saw on 29 July was something totally new. When I stepped out of the door on that beautiful and calm morning I heard an exceptional sound, like a foaming torrent. The sound came from the nearby strait, which is rather shallow, perhaps 20 cm at normal water level, and about 80 metres long. The

water was indeed flowing as if in a small rapids and formed clear waterfalls when it ran out at both ends of the strait. From the waterline on the rocks and rocky shores, I saw that the water had gone down about 40 cm in a very short time. I decided to photograph the events because they felt really exceptional. [. . .] My impression is that during that time [40 min] the water rose and fell about 40 cm 3–4 times. In particular, the waves rose very rapidly, in 2–3 minutes." (Eyewitness report, translated from Finnish)

Similar observations were reported from three different locations along the Finnish coastline on the same day, and more reports followed on 8 August 2010 and 4 June 2011. Data from coastal observation stations confirmed the eyewitness observations: tide gauges recorded rapid sea level oscillations, coinciding with sudden jumps in air pressure. Radar imagery revealed that the oscillations were small meteotsunamis caused by squall lines or gust fronts propagating above the sea at a speed close to the long-wave speed in the sea (Pellikka et al., 2014).

Meteotsunamis, or meteorological tsunamis, are long waves created through air–sea interaction (Monserrat et al., 2006). They occur on shallow sea areas all around the world and can be several metres high in extreme cases, with periods ranging from a few minutes to a few hours. The formation of a notable meteotsunami requires several coinciding factors:

~~An~~ First, an air pressure disturbance travels above a water body, creating a small initial wave. The wave is amplified by air–sea interaction, e.g. through the Proudman resonance: the speed of the disturbance matches the long-wave speed in the sea, which depends on water depth ($v = \sqrt{gh}$, where g is acceleration due to gravity and h is water depth). When the wave arrives at the coast, its height is further amplified by the coastal topography through shoaling, refraction, and~~internal oscillations~~/or eigenoscillations in a semi-enclosed bay or harbour.

Meteotsunamis are subject to a recent upsurge in research activity worldwide, especially in the Mediterranean (e.g. Vilibić and Šepić 2009; Vilibić et al. 2014; Bechle et al. 2015; Pattiaratchi and Wijeratne 2015; Vilibić and Šepić 2017). Several studies have examined meteotsunami occurrence in different parts of the world ocean and developed methods to recognize meteotsunamis in past sea level observations (e.g. Pattiaratchi and Wijeratne 2014; Šepić et al. 2015; Masina et al. 2017; Olabarrieta et al. 2017; Dusek et al. 2019). However, sea level time series of a sufficiently high resolution (preferably 1 min; Leonard 2006) are typically rather short, 5–10 years.

The occurrence of meteotsunamis depends on the occurrence as well as on the speed, direction, and intensity of certain atmospheric phenomena, which in turn can be affected by regional climate variability and long-term changes in climate. For example, Olabarrieta et al. (2017) examined 20 years of tide gauge observations from the northeastern Gulf of Mexico and found a correlation between ENSO (El Niño – Southern Oscillation) and meteotsunami activity in the region. Typical atmospheric disturbances that create meteotsunamis under specific conditions include passing fronts, squalls, storms and atmospheric gravity waves (Monserrat et al., 2006). The three meteotsunami events observed in Finland in 2010–2011 were created by a squall line, a gust front, and a cold front passage (Pellikka et al., 2014).

In the Baltic Sea, knowledge on meteotsunamis is mostly restricted to old scientific literature (e.g. Doss, 1906; Meissner, 1924; Renqvist, as well as descriptions from coastal residents and seafarers of encounters with such waves. In the German-speaking regions of the southern Baltic Sea the phenomenon is known as *Seebär*, in the Swedish-speaking coasts as *sjösprång*. Doss (1906) lists

25 *Seebär* events from the southern and southeastern Baltic Sea from the 18th and 19th centuries, some of which caused mild damage. Even fewer studies are available on the *sjösprång* of the northern Baltic coasts, but Renqvist (1926) presents a case study of one such event in the Gulf of Finland on 15 May 1924. In Finland, the phenomenon aroused renewed interest after the meteotsunami observations of 2010–2011. The speed and height of the reported oscillations (up to 1 m in 5–15 minutes) clearly exceed normal sea level variations on the Finnish coast. ~~A similar event in 1924 in the Gulf of Finland was documented by Renqvist (1926), and there are descriptions from coastal residents and seafarers of encounters with such waves. On German-speaking Baltic coasts the phenomenon is known as *Seebär* and in Swedish as *sjösprång*.~~ While the phenomenon is not unprecedented ~~on the Finnish coast~~in Finland, the eyewitness observations in 2010 and 2011 came after several decades of no reported occurrences.

In this paper, we study changes in meteotsunami occurrence over the past century in the Gulf of Finland, ~~northern~~ the easternmost sub-basin of the Baltic Sea (Fig. 1)~~over the past century.~~. Short-term sea level variations in the nearly landlocked Baltic Sea are dominated by meteorological factors, as the tidal range is very small, typically only a few centimetres. Phenomena that cause sea level variations of several tens of centimetres on a regular basis include variations in water volume in the Baltic Sea basin (mainly regulated by water exchange between the North Sea and the Baltic Sea), wind-induced internal redistribution of water within the basin, air pressure variations, and seiches. These sea level variations have a longer period than meteotsunamis, however. For example, seiches in the Gulf of Finland have characteristic periods of 23 and 27 hours (Jönsson et al., 2008). The highest sea level maxima occur when several factors causing above-average sea levels coincide. Maximum recorded storm surge heights are 1.3–2 m above the mean on the Finnish coast of the Gulf of Finland, and even higher at the end of the elongated gulf.

Recent scientific literature lacks a systematic study of meteotsunami occurrence in the Baltic Sea, and to our knowledge, changes in meteotsunami occurrence in a century time scale have not been previously studied anywhere in the world. Traditionally, the sampling interval of tide gauge observations has been 1 hour or longer, which is too coarse for detecting variations in the tsunami frequency range. To overcome this limitation, we must turn to the original tide gauge charts, where sea level variations have been recorded as a continuous curve on paper. As the processing of the charts involves a lot of manual work, the study area is restricted to the Gulf of Finland, where most known meteotsunami cases on the Finnish coast have been observed.

Our research is motivated by coastal safety: while the events observed in Finland in 2010–2011 did not cause notable damage, strong oscillations in sea level may endanger coastal traffic and infrastructure in extreme cases. Understanding the frequency and intensity of meteotsunamis on the Finnish coast is crucial for estimating the probability of such events.

We aim to answer these questions: i) Is it possible to detect past meteotsunami events based on the available sea level and meteorological data sets? ii) How typical and how strong are meteotsunamis in the Gulf of Finland? iii) Are there temporal trends or variations in the frequency of meteotsunamis? iv) Is the occurrence of meteotsunamis correlated with some atmospheric variables?

2 Observations and data quality

2.1 Sea level observations

Sea level data used in this study comes from three tide gauges on the southern coast of Finland (Fig. 1): Hanko (founded in 1887), Helsinki (1904), and Hamina (1928). The quality controlled digital sea level database from these tide gauges contains values for every four hours before 1970, and hourly values after that. Hence, the temporal resolution of this database does not allow the study of meteotsunami waves that typically have much shorter periods. A digital data set, sampled every 15 minutes, is available from 1980 onwards (Fig. 2). From 2004 onwards, there is digital data sampled every minute; however, the longer 15 min data set was used in this study as we are interested in long-term changes in meteotsunami occurrence.

High-resolution sea level data before the 1980s is available only on the original tide gauge charts, which are currently stored in the archives of the Finnish Meteorological Institute (FMI). From the 1920s to the 1990s, most Finnish tide gauges were equipped with a Renqvist–Witting recording device (Fig. 3). The device recorded the movements of the float swimming in the tide gauge well by transferring the motion to a wheel (circumference 1m), on which 10 pens of different colours were fastened. As the wheel turned, the pens plotted the motion on a paper roll in real size (scale 1:1) so that each colour corresponds to a certain decimetre of sea level height (Stenij, 1932). The 4-hourly and hourly values in the digital sea level database have been sampled manually from these paper charts.

The principal data set used in this study consists of the original paper charts from the Hanko and Hamina tide gauges from the periods 1922–1989 and 1928–1989, respectively (Fig. 2). The Helsinki tide gauge was the only Finnish tide gauge not equipped with a Renqvist–Witting device. Instead, a Reitz recorder was used. The glass plate used to read sea level values from Reitz paper charts has not been preserved, and the data is arduous to use. In addition, the small scale of variation in Reitz paper charts hinders the recognition of meteotsunamis. For these reasons, paper charts from the Helsinki tide gauge have been excluded from the study. Digital 15 min sea level data from 1980 onwards is used from all three tide gauges. The 15 min data directly captures oscillations longer than 30 minutes, and 16–30 minute waves are aliased to periods shorter than 4 hours. For example, a 20 minute oscillation shows up as a 60 minute oscillation, which is still inside the meteotsunami frequency range. Possible very fast oscillations, with periods of a few minutes, are lost in the 15 minute data.

Analysing the charts includes a lot of manual work. To restrict the amount of data, only the ice-free summer months from May to October were considered. Even though the possibility of meteotsunamis occurring in winter cannot be ruled out, such cases are expected to be very rare on the Finnish coast (see Sect. 5 for discussion).

A notable meteotsunami with a height of up to ~~1~~ 1.2 m was observed in the western part of the Gulf of Finland and in the Archipelago Sea on 15 May 1924 (Renqvist, 1926). After this event, the Finnish Institute of Marine Research started to collect observations of sudden sea level changes by preparing a specific form for the purpose and distributing it to pilot stations and lighthouses in Finland. Approximately 60 such forms from 1924 to 1938 are stored in the archives of FMI. Among these, 14 forms contain information of possible meteotsunamis in addition to the well-documented case of 15 May 1924. We use these eyewitness observations as an additional source of information on meteotsunami occurrence in the 1920s and 1930s.

2.2 Atmospheric data

We use air pressure observations from coastal stations to confirm the meteorological origin of the possible meteotsunamis discovered in the sea level data. The stations nearest to the tide gauges are Russarö (Hanko), Harmaja (Helsinki), and Rankki (Kotka, about 24km 24 km southwest from Hamina; Fig. 1). Original paper barograms from these stations exist in the archives of FMI and have been used when available. Digital 10 minute data is available from 2001–2006 onwards depending on the station and was used to confirm some of the recent events.

To study the connections between meteotsunami occurrence and climatological factors, meteotsunami observations are compared to monthly climatological data and lightning observations. The North Atlantic Oscillation (NAO) indices are obtained from a data set by Cropper et al. (2014) which includes daily NAO indices since 1850. From this data set, we calculated monthly mean values. The NAO index is calculated from the sea level pressure difference between the Azores and Iceland. It describes large-scale atmospheric conditions in the region, controlling the strength and direction of westerlies and storm tracks.

The atmospheric parameters of mean sea level pressure, 10 metre wind speed, 2 metre temperature and dew point temperature, as well as convective available potential energy (CAPE) are obtained from reanalysis data. Two different data sets were used: ERA-20C (covering the years 1922–2010) and ERA-Interim (1979–2014), both produced by the European Centre for Medium-Range Weather Forecasts. ERA-20C has a horizontal resolution of around 125 km or 1.125° (Poli et al., 2013) whereas in ERA-Interim, it is around 80 km or 0.75° (Dee et al., 2011). We have interpolated the ERA-Interim data to match the resolution of ERA-20C so that the grid points are compatible. The reanalysis data was averaged spatially over the Gulf of Finland region (20.25–30.375° E, 59.0625–61.3125° N). Finally, daily and monthly mean values were calculated.

We also compare the meteotsunami occurrence to lightning observations. From 1887, thunderstorm days in Finland have been observed by humans, and in 1960–1998 with an automatic flash counter network. From 1998 onwards, in addition to the number of flashes, also the location information of the flash is obtained due to a modern lightning locating system (Mäkelä et al., 2014). In this study, we compared the meteotsunami data set to the yearly number of thunder days (1922–2014) and the yearly number of cloud-to-ground (CG) flashes over the whole continent of Finland (1960–2014). In addition, from 1998–2014, we calculated daily and monthly CG flash numbers in the Gulf of Finland region (20–30° E, 58–62° N).

2.3 Data quality

The 15 min digital sea level data (1980–2014) is raw data that has not been subject to thorough processing and quality control. However, the data was browsed through visually, and clearly erroneous spikes and shifts were removed before further analysis. Possible problems in the data are documented and relatively easy to trace. In Hanko and Hamina, the 15 min observations were digitized by a human-assisted computer program over the period 1980–1987. When comparing these observations to the data that was digitized from the tide gauge charts for this study, it was noted that not all some high-frequency oscillations are that were recorded by the instruments on the paper charts are not accurately reproduced in the 15 min data during this period. This problem in the quality of the digitization does not affect the time series after 1987.

On some occasions, sea level variations recorded at the tide gauges have been suppressed due to blockages or damage in the underwater pipe connecting the tide gauge well to the sea. When the pipe is partially blocked, the water level in the well adjusts slowly to sea level changes, and there is a time lag and attenuation in the recorded sea level fluctuations. We refer to this attenuation as damping. In the worst case, damping is so heavy that all sea level variations have been levelled out. Damping particularly hinders the study of high-frequency sea level variations such as meteotsunamis.

To determine the periods when the high-frequency oscillations were damped in the digital 15 min tide gauge records (1980–2014), a spectral analysis was performed. The variance of oscillations with a frequency higher than 0.25 h^{-1} (period shorter than 4 hours) was integrated from the variance density spectra calculated from seven day time series. The high spatial and temporal variability in the recorded shorter oscillations was evident already from a visual inspection of the high-frequency variance. However, to quantify the results, a value exceeded 95 % of the time (i.e. the 5$^{\text{th}}$ percentile) was determined from the Hamina tide gauge records, which were the visually least disturbed. This value was found to be 0.016 m^2. The same value was then used in the analysis of all tide gauges. The results were not very sensitive to the exact choice of this cut-off value, but produced the same main findings regardless.

The time series was then divided into blocks of four consecutive values, thus representing a time period of four weeks. If the variance was below the 5$^{\text{th}}$ percentile over half of the time, the four week period was flagged as a "damped period". While this definition is somewhat arbitrary, a couple of results are evident: i) the records from Hanko are clearly damped during 1985–1989, and ii) none of the three tide gauges suffered from significant damping since the beginning of the 2000s. The maintenance of the tide gauges was considerably improved when automatically registering devices were installed. Before that time reacting to problems was slow, because the tide gauge charts were collected once a month and it took almost one month to read and analyse them.

It was not possible to perform a similar spectral analysis for the data before the 1980s (i.e. the tide gauge charts). However, an experienced person can estimate the degree of damping visually by comparing the behaviour of the sea level curve to normal variations. The degree of damping in the paper charts was roughly estimated as percentages from no damping (0%) to total damping (100%) per each month. For the overlapping period 1980–1989 for which there is both digital and chart data available, the two independent methods of estimating the degree of damping (spectral and visual) produced comparable results.

In the tide gauge charts of Hanko (1922–1989), 3.2 % of the data was missing and 17.3 % damped, while in Hamina (1928–1989), 2.0 % of data was missing and 12.4 % damped. Thus, about 20 % of the Hanko tide gauge charts and 14 % of the Hamina charts were either missing or so heavily damped that they were unusable for meteotsunami detection. In the 15 min data from 1990–2014, the proportion of missing or damped data was small: 6 % in Hanko, 0 % in Helsinki, and 1 % in Hamina.

3 Identifying meteotsunamis

There is no universal definition or criteria for what qualifies as a meteotsunami, as nearly all sea level variations in the tsunami frequency range are of atmospheric origin. In this study, the metrics used for detecting meteotsunamis are the period and height of the sea level oscillations and the occurrence of a rapid change in air pressure simultaneously with the sea level event. For the tide gauge charts, possible cases were selected visually and digitized manually. High-frequency events in the 15 min data were detected with an algorithm that resulted in a manageable amount of possible events to be confirmed or rejected through a visual inspection of air pressure data. A detailed description of the procedures is given in the sections below.

The periods of meteotsunami waves are in the tsunami frequency range spanning from a few minutes to a few hours (Monserrat et al., 2006). The heights of the events were determined from high-pass filtered time series, because slower variations influence the water level also during the meteotsunamis. The filter removed the information below a cut-off frequency of 0.25 h^{-1} in Fourier space and was implemented using the Fast Fourier Transform (FFT).

For each potential meteotsunami event identified in the data, we defined three different height metrics after high-pass filtering the sea level data:

1. h_{max}: The height (top to bottom) of the largest individual wave.
2. h_{tot}: The total range of sea level variation during the event.
3. η_{max}: The rise above zero in the filtered signal.

3.1 Detecting meteotsunamis in tide gauge charts

Rapid sea level variations appear as dense oscillations on the Renqvist–Witting tide gauge charts and are easy to locate by visual inspection (see Fig. 3 for an example). To find all possible meteotsunami events, we carried out a three-phase inspection:

1. The tide gauge charts were browsed visually. Exceptionally rapid sea level changes were selected for further inspection and photographed. Loose criteria were applied at this stage in order not to miss any potential meteotsunamis.
2. From the cases selected in the visual browsing, we digitized those where the sea level behaviour clearly differs from surrounding variations. The digitization was carried out manually with a glass plate designed for reading values from tide gauge charts. The time scale printed on the plate has markings every 1 hour, meaning that times between the full hours needed to be estimated.
3. From the digitized cases, we excluded those that were too slow (period longer than 2–3 hours) or too small (h_{max} <12 cm in Hanko, <20 cm in Hamina).

The criterion for wave height was set as follows: First, we determined h_{max}. Second, we plotted a histogram of all events at the tide gauge in question (not shown) and set the height threshold at the peak of the distribution. It was assumed that the frequency of occurrence should decrease towards higher values and that the peak in the distribution was an artifact resulting from some of the smaller events being included in the visual browsing and some of them being omitted. Therefore, the peak represents the wave height which is clearly visually distinguishable from other sea level variations.

The height criterion applied was different for each tide gauge, because there is large spatial variability in the high-frequency part of the sea level spectrum depending on the location and structure of the tide gauge. In particular, the height of a meteotsunami depends on the bathymetry of the coastal waters and varies strongly from point to point on the coastline. Highest oscillations are observed in bays and inlets whose resonant properties amplify the arriving wave (Monserrat et al., 2006).

Finally, the atmospheric origin of the sea level oscillations was confirmed by examining barograms from nearby coastal stationsfor rapid changes in air pressure. The events were interpreted as meteotsunamis if there was evidence of a pressure jump occurring rapid change in air pressure within a few hours of the sea level oscillations – usually a small, sudden jump or drop that stands out from normal variations based on visual inspection. A small proportion of the events were excluded because there was no indication of air pressure changes. The pressure jumps changes accompanying meteotsunamis are small (typically only 1–3 hPas, Monserrat et al. 2006; Pellikka et al. 2014) and not always easy to distinguish especially if the quality of the air pressure curve is poor. Therefore, and because of missing air pressure data, a notable portion of the potential meteotsunami events was left unconfirmed.

3.2 Detecting meteotsunamis in digital sea level data

Potential meteotsunami events were searched automatically from the 15 min sea level data (1980–2014) of all three tide gauges. It is possible to detect rapid variations in the tsunami frequency range even in 15 min data, but the heights of the events will be somewhat underestimated because of the temporal resolution. First, we calculated the heights of all individual waves (h_{max}) from the high-pass filtered time series, using the differences of adjacent data points to locate wave tops and bottoms (where the derivative of the signal changes sign). From this wave height data set we picked the waves that exceed the height threshold determined in the tide gauge chart analysis: 12 cm for Hanko and 20 cm for Hamina. For Helsinki, no charts were analysed, so we applied a threshold of 10 cm. The spectra of the filtered 15 min data from Helsinki and Hanko are rather similar, while in Hamina, there is clearly more variability in the sea level signal in the tsunami frequency range (standard deviations of the filtered signal are 0.45 cm 4.5 mm for Hanko, 0.41 cm 4.1 mm for Helsinki, and 0.92 cm 9.2 mm for Hamina). To remove multiple occurrences of the same event in the data set, we selected the events that have a time difference of at least 12 h.

As with the chart events, we examined the air pressure data and categorized the events as confirmed, not confirmed, or uncertain depending on whether there was evidence of rapid changes in air pressure. Two examples of the detected meteotsunamis are given in Fig. 4. The first one was digitized from the Hanko tide gauge charts (the original chart is shown in Fig. 3). The second was detected from the 15 min sea level data from Hamina. Both cases have been confirmed from air pressure data.

4 Results

4.1 Meteotsunami occurrence in the Gulf of Finland

For Hanko and Hamina, the methods described above result in two time series of meteotsunamis: one based on original tide gauge charts (1922/1928–1989) and the other on 15 min sea level data (1980–2014). A small number of events (4 from Hanko and 6 from Hamina) were excluded from the data set because there was no evidence of rapid changes in air pressure during the event despite air pressure data being available.

As there is a 10 year overlap (1980–1989) in the time series, we can compare the performance of the different methods of identifying meteotsunamis in the data. For Hamina, the results are nearly identical: both the visual viewing and the automatic detection identify 7 events over the decade, of which 6 are given by both methods. For Hanko, data from the 1980s is largely missing (Fig. 5) and there are only three possible events found in the tide gauge charts, of which one is detected in the 15 min data. The other two are not properly recorded in the 15 min observations because of ~~data quality problems~~ quality problems in the digitized data (see Sect. 2.3). Because of these problems, we use the results from the tide gauge charts in the final data set for the 1980s. Nevertheless, the good agreement between the two data sets in Hamina indicates that both the visual viewing and the automatic detection of rapid variations are effective methods of identifying meteotsunamis in the data and the results can be combined with reasonable confidence.

The detection algorithm successfully identifies the known meteotsunami events from the Gulf of Finland, on 29 July 2010 and on 8 Aug 2010 (Pellikka et al., 2014). The event on 15 May 1924 reported by Renqvist (1926) is also detected from the Hanko tide gauge charts, but the maximum wave height is only 8.3 cm, falling below the height threshold. This highlights the limitations imposed by the sparse observation network: even during strong meteotsunami events, when eyewitnesses have observed exceptional sea level oscillations over a large area (exceeding 1 m in some places), the wave heights observed at the tide gauges can be small (Renqvist, 1926; Pellikka et al., 2014).

Only one of the events detected from the tide gauge charts (24 May 1926 in Hanko) was mentioned in old eyewitness reports collected by the Finnish Institute of Marine Research (Sect 2.1). According to the report from the lighthouse of Seivästö (currently in Pionerskoye, Russia), in the easternmost part of the Gulf of Finland, sea level oscillations of ca. 40 cm occurred within a few minutes in the morning after a nightly thunderstorm. Rapid oscillations were recorded at the Hanko tide gauge during the night, but their height did not exceed the threshold and this event is thus not included in the final data set.

The number of detected events in the different data sets are given in Table 1. In total, 45 potential meteotsunamis were detected from Hanko (1922–2014) and 65 from Hamina (1928–2014). In addition, 25 events were detected in the 15 min observations from Helsinki (1980–2014). When we take into account that 14 of the events were detected at more than one station, we get a total number of 121 separate events. Over 70 % of the events were confirmed from air pressure observations: typically, there is an abrupt change of 1–3 hPa occurring simultaneously with the sea level oscillations or shortly before. The remaining events were left unconfirmed because air pressure data of sufficiently high resolution is not available.

Figure 5 shows all detected and potential meteotsunamis together with the amount of missing data per year. Missing data includes also the data which is so heavily damped that rapid variations in sea level have not been recorded correctly. Detecting trends in the time series is hampered by gaps in the high-frequency data, most notably in the 1940s and 1980s in Hanko and in the 1960s in Hamina.

While the time series from Hanko shows no apparent trend, meteotsunamis in Hamina 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, the slope of a least squares fit for Hamina is 4.4 times larger than for Hanko. The positive slope at Hamina is also statistically significant at a level of (at least) $p = 0.01$, while the weaker positive slope at Hanko is statistically significant only at $p = 0.15$.

Typical heights of the detected meteotsunamis (h_{max}) range between 10–30 cm (Fig. 6). The largest meteotsunami heights were found in Hamina, where the highest event was 51 cm (h_{max}), and the smallest in Helsinki, where the highest event was 17 cm. The maximum variations during the events (h_{tot}) are only slightly higher than the height of the maximum single wave. The maximum water level elevation above zero during the event (η_{max}) is typically roughly half of the height of the maximum variation. This indicates that the high-frequency variations during the meteotsunamis are usually quite symmetrical with respect to the still water level determined by the slower changes (that have here been filtered out). There is no statistically significant linear trend for the magnitude of the meteotsunamis (h_{max}).

4.2 Comparison with atmospheric data

To study the connections between meteotsunami occurrence and the meteorological conditions, we calculated the number of meteotsunamis occurring during each summer month (May–Oct) from 1922 to 2014. Of the 558 months over this time period, 91 months (16 %) have at least one potential meteotsunami occurrence. The number of events in different calendar months is as follows: 26 events in May, 20 in June, 37 in July, 18 in August, 10 in September, and 10 in October.

We then calculated the mean values of certain atmospheric parameters in the two sets of months: those that have at least one meteotsunami occurrence and those that have none (Table 2). The null hypothesis that the means of these two sets are equal was tested with the two-sample *t*-test, using Satterthwaite's approximation in order not to assume equal variances. The main conclusions remain unchanged even if the potential (uncertain) meteotsunamis are excluded from the data set.

Statistically highly significant ($p < 0.001$) differences were found in the number of CG flashes in the Gulf of Finland area as well as CAPE, which is a measure of convective instability in the atmosphere and often used as an indicator of thunderstorm potential. The mean values of both the temperature and dew point temperature also show a statistically significant ($p < 0.01$) difference, the temperatures being higher during months when meteotsunamis have been registered. Mean sea level pressure, wind speed and the NAO index did not show a statistically significant difference.

Similarly, we divided the years 1922–2014 in two categories – with meteotsunamis and no meteotsunamis – and tested the difference in the yearly number of thunder days over Finland. The difference was significant at 5% level but not at 1% level. However, there was no significant difference in the number of CG flashes recorded over the whole continent of Finland in a yearly time scale. Finally, the summer days (May–Oct) over the period May 1998–Oct 2014 were divided in two categories. The daily number of CG flashes was clearly and statistically significantly ($p < 0.001$) larger during the days of meteotsunami occurrence than during normal conditions.

The lightning observations have a strong connection with meteotsunami occurrence. In the summers of 1998–2014, from which there is daily lightning data available from the Gulf of Finland, there have been 42 days on which a potential meteotsunami has occurred in the area. CG flashes have been observed on all of these days except one (30 July 2010), and even on that date, the meteotsunami in Hamina was recorded just after midnight after an active thunder day (5 378 CG flashes observed on 29 July 2010). On average, the number of flashes during a meteotsunami day was roughly 10 times that of an average summer day in the region.

5 Discussion and conclusions

We detected 121 potential meteotsunami events at the tide gauges of Hanko, Helsinki, and Hamina in the Gulf of Finland over the past century (1922–2014). Over 70 % of the events were confirmed to coincide with a ~~rapid~~ sudden change in air pressure. Typical wave height registered at the tide gauges was 10–30 cm. However, higher oscillations have probably occurred in bays, harbours, and straits where the coastal bathymetry has amplified the waves. The events detected in the tide gauge data are comparable with the observed meteotsunami events in 2010 and 2011, during which eyewitnesses reported oscillations of up to over 1 m.

Both the number and height of the detected meteotsunamis were largest in Hamina, the easternmost tide gauge. This is probably related to differences in tide gauge locations: disturbances travelling from west to east propagate a longer distance before they hit Hamina compared to Hanko and Helsinki. Moreover, there are differences in local coastal geometry: the tide gauge of Hanko is located on a relatively open coast, while the tide gauge of Hamina is inside a narrow bay, 5 km long and 1 km wide. In Helsinki, the tide gauge is sheltered by the archipelago but not inside a bay or harbour.

The results are based on 15 min sea level data after 1989, when continuous recordings of sea level variations are no longer available on paper charts. As noted in Sect. 2.1, the 15 min resolution is not ideal for studying meteotsunamis. Oscillations with a period shorter than 30 minutes are distorted by aliasing, and very short-period oscillations cannot be captured. This does not seem to create a significant bias in the results, however. Otherwise, the number of detected meteotsunamis would drop after 1989, which is not the case. Our method also captures the recent meteotsunami events reported by eyewitnesses in 2010 and 2011.

Before the recent eyewitness observations of meteotsunamis in Finland (Pellikka et al., 2014), Finnish sea level researchers did not receive such reports from the general public for at least 30 years. It remains unclear why, as the data shows that meteotsunamis ~~are not a new phenomenon~~ occur almost yearly on the Finnish coast and there is no significant trend in the height of these waves. Lower reporting threshold in the era of Internet and mobile phones is one possible explanation for the upsurge in eyewitness reports. However, data from Hamina gives a statistically significant increasing trend in the number of meteotsunamis over the past century. Further research is needed to explain this increase and the fact that no such trend is observed at Hanko. As we note above, the location of the Hamina tide gauge is potentially more vulnerable to meteotsunami amplification. Also, as the height of a meteotsunami is sensitive to the interplay of the arriving wave and coastal bathymetry, it may well be that changes in the propagation direction of atmospheric disturbances result in differing trends at different locations.

There is an identifiable difference between typical heights at the three locations, with Hamina having the largest meteotsunamis and Helsinki the smallest. However, different degrees of damping due to the blockage of the pipe connecting the tide gauge to the sea were found at all stations. It cannot be conclusively determined to which degree this damping may have affected the amplitude of rapid variations even for data that was not discarded as erroneous. The use of 15 min observations is also expected to introduce a slight negative bias, as the maximum values of 15 min observations are smaller compared to denser data. That said, the finding placing the highest variations in Hamina is expected based on its geographical location furthest in to the Gulf of Finland and inside a small, narrow bay.

Statistically highly significant differences between months when meteotsunamis have been registered compared to normal conditions were found in the number of lightnings over the Gulf of Finland as well as CAPE, which is an indicator of summertime thunderstorm potential. Monthly mean temperatures also show a statistically significant difference. These differences may be partially connected to meteotsunamis being more prevalent during the hottest summer months of June–August and less common in September–October, but the results do demonstrate a strong connection between thunderstorms and meteotsunami occurrence. On a daily level, the cloud-to-ground flash numbers were over ten times larger during days when meteotsunamis have been registered than otherwise. It can be concluded that meteotsunamis in the Gulf of Finland are practically always connected with thunderstorms.

The study was restricted to summer months (May–October) to keep the amount of data archaeology manageable. Meteotsunamis are expected to be rare in winter, as thunderstorms in Finland are predominantly a summertime phenomenon (Punkka and Bister, 2015). Furthermore, ice cover in the sea reduces the effect of atmospheric disturbances on the sea surface and attenuates especially high-frequency sea level variations. The highest sea levels usually occur in the wintertime on the Finnish coast, and thus meteotsunamis do not generally coincide with annual sea level maxima. This lowers the probability of an extremely high sea level occurring as a combination of a storm surge and a meteotsunami, but quantifying this probability is a topic for ~~further~~ future work. Considering coastal safety, an important question is whether meteotsunamis are included in distributions of maximum sea levels. As meteotsunamis are relatively rare, it may be that none have contributed to the monthly maxima, which are often used to estimate coastal flooding risks.

The results show that meteotsunamis as a phenomenon are far more common in the Baltic Sea than previously thought, even though few events are strong enough to be widely noticed or potentially harmful. Many open questions remain regarding Baltic meteotsunamis. An essential topic for future work is to better establish the connections between meteotsunamis and weather patterns. After that, atmospheric parameters could be used to estimate the probability of meteotsunami occurrence and eventually to predict the events. Other suggestions for future research include quantifying potential changes in the propagation direction of atmospheric disturbances and using numerical models to study the resonance phenomena and the effect of local bathymetry on the amplification of the waves.

Data availability. The data that support the findings of this study are available on request from the corresponding author. Data usage is subject to conditions determined by the data policy of the Finnish Meteorological Institute.

Author contributions. KK and HP designed the study. HP analysed the digital sea level data and JVB performed the spectral analyses. AK and HB analysed the tide gauge charts and HP compiled the meteotsunami database. TL calculated the climatological parameters and HP analysed their connection to meteotsunami occurrence. HP wrote the manuscript with contributions from all coauthors.

Competing interests. The authors declare no competing interests.

Acknowledgements. We wish to thank the numerous individuals who, over the decades, have worked to maintain the Finnish tide gauge network and sea level database and with their dedication ensured the high quality and preservation of the data. We are grateful to Pentti Pirinen and Achim Drebs for help with tracking air pressure data from the archives, and Simo Siiriä for technical help. ~~Milla Johansson provided valuable~~ We also wish to thank Jadranka Šepić and Milla Johansson for providing valuable ideas and comments. This work was supported financially by VYR (State Nuclear Waste Management Fund) through SAFIR2014 and SAFIR2018 programs (The Finnish Research Programme on Nuclear Power Plant Safety 2010–2014 and 2015–2018). The study has utilized research infrastructure facilities provided by FINMARI (Finnish Marine Research Infrastructure network).

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	Events	$h_{max} > h_t$	Confirmed
Hanko			
Charts (1922–1989)	39	31	20
15 min (1990–2014)		14	11
		45	**31** (69 %)
Hamina			
Charts (1928–1989)	44	31	18
15 min (1990–2014)		34	26
		65	**44** (68 %)
Helsinki			
15 min (1980–2014)		25	24
		25	**24** (96 %)

Table 1. Number of potential and confirmed meteotsunami events identified in the different data sets. The first column shows the number of events found on the tide gauge charts based on visual inspection. The second column gives the size of the final data set, which are events exceeding a station-specific height threshold h_t. Confirmed events have a rapid change in air pressure occurring simultaneously with the sea level oscillations. The rest could not be confirmed because of missing or inconclusive air pressure data.

	Meteotsunami	No meteotsunami	Significance (p)
Yearly means			
Thunder days (1922–2014)	11.5	9.9	yes (0.02)
CG flashes over Finland (1960–2014)	137 850	140 007	no
Monthly means			
MSLP (1922–2014), hPa	1012.9	1013.6	no
T_{2m} (1922–2014), °C	12.5	11.1	yes (0.006)
D_{2m} (1922–2014), °C	8.4	6.9	yes (0.004)
U_{10m} (1922–2014), m s^{-1}	4.4	4.4	no
CAPE (1922–2010), J kg^{-1}	39.9	20.3	yes (< 0.001)
NAO (1922–2014)	0.12	0.04	no
CG flashes over GoF (1998–2014)	23 534	8 159	yes (< 0.001)
Daily means			
CG flashes over GoF (1998–2014)	4 225	368	yes (< 0.001)

Table 2. Means of certain atmospheric variables on the years, months, or days when there is at least one meteotsunami occurrence and when there are none. The statistical significance of the difference is shown at 5 % level. CG flash = cloud-to-ground flash, MSLP = mean sea level pressure, T_{2m} = temperature (2 m), D_{2m} = dew point temperature (2 m), U_{10m} = wind speed (10 m), CAPE = convective available potential energy, NAO = North Atlantic Oscillation, GoF = Gulf of Finland.

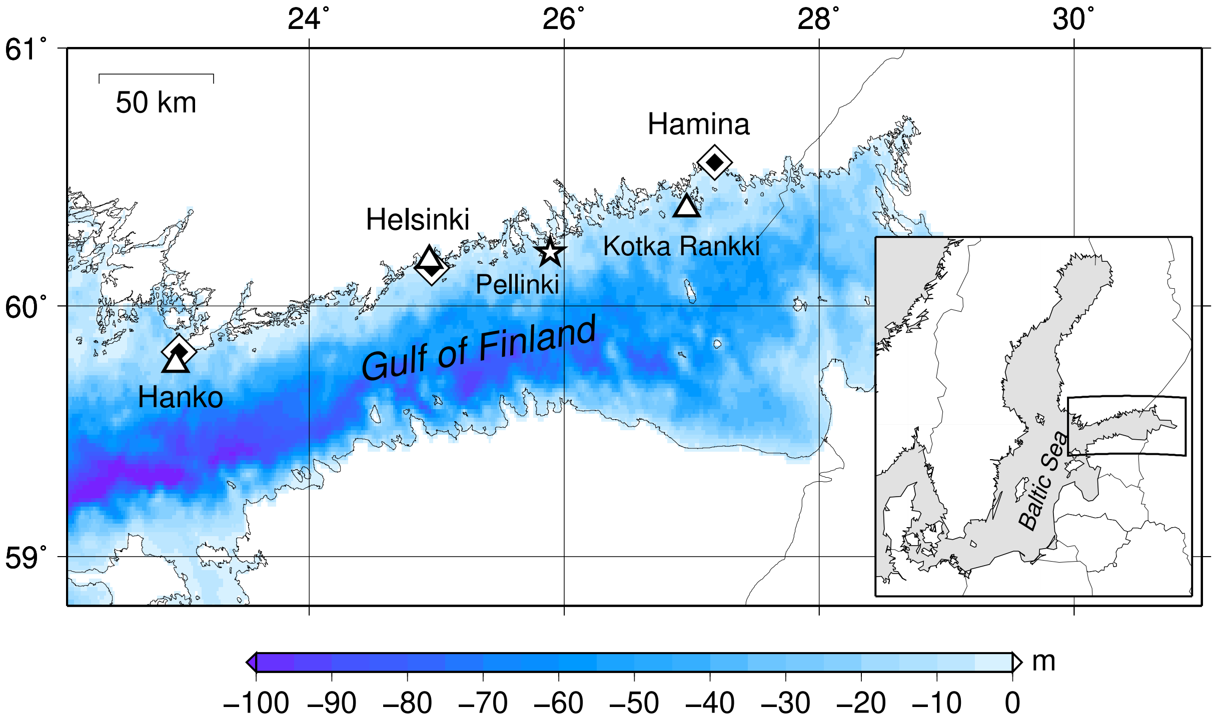

Figure 1. Bathymetric map of the study area, the Gulf of Finland in the Baltic Sea. Locations of the Finnish tide gauges are marked with diamonds. Meteorological stations, which provided the data used in this study, are marked with triangles. The star denotes the site of the eyewitness observation quoted in the Introduction.

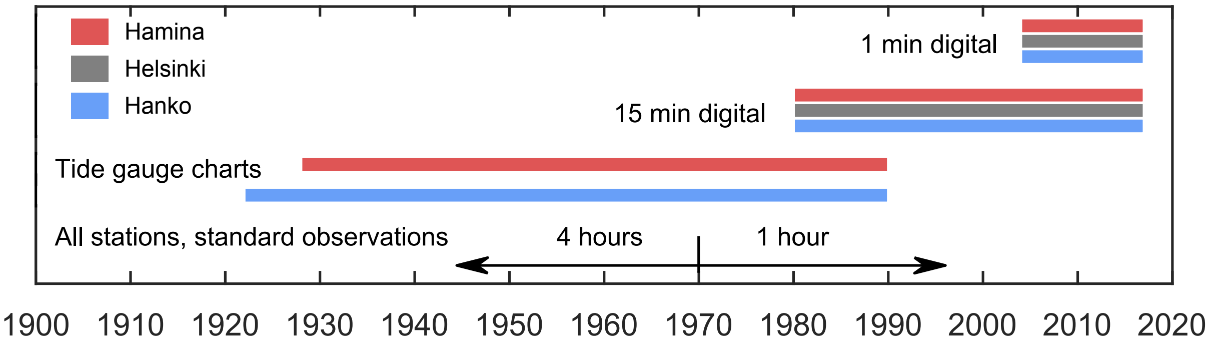

Figure 2. Sea level data available from the tide gauges of Hanko, Helsinki, and Hamina in the Gulf of Finland. Only selected events have been manually digitized from the tide gauge charts.

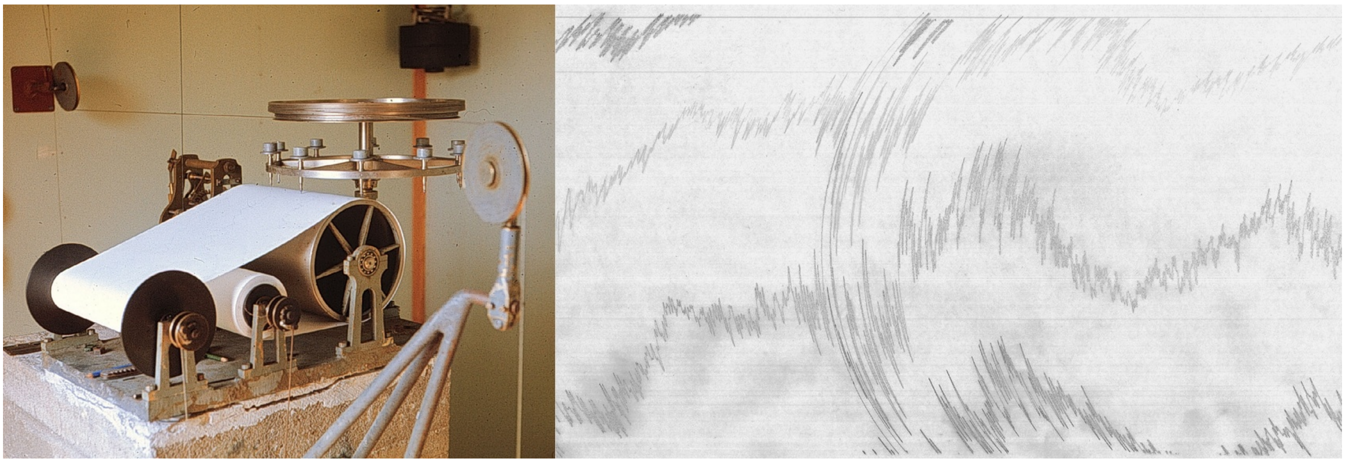

Figure 3. The Renqvist-Witting recording device used at most Finnish tide gauges from the 1920s to the early 1990s and an example of the paper charts recorded by the device at Hanko, showing a meteotsunami event on 9–10 May 1969.

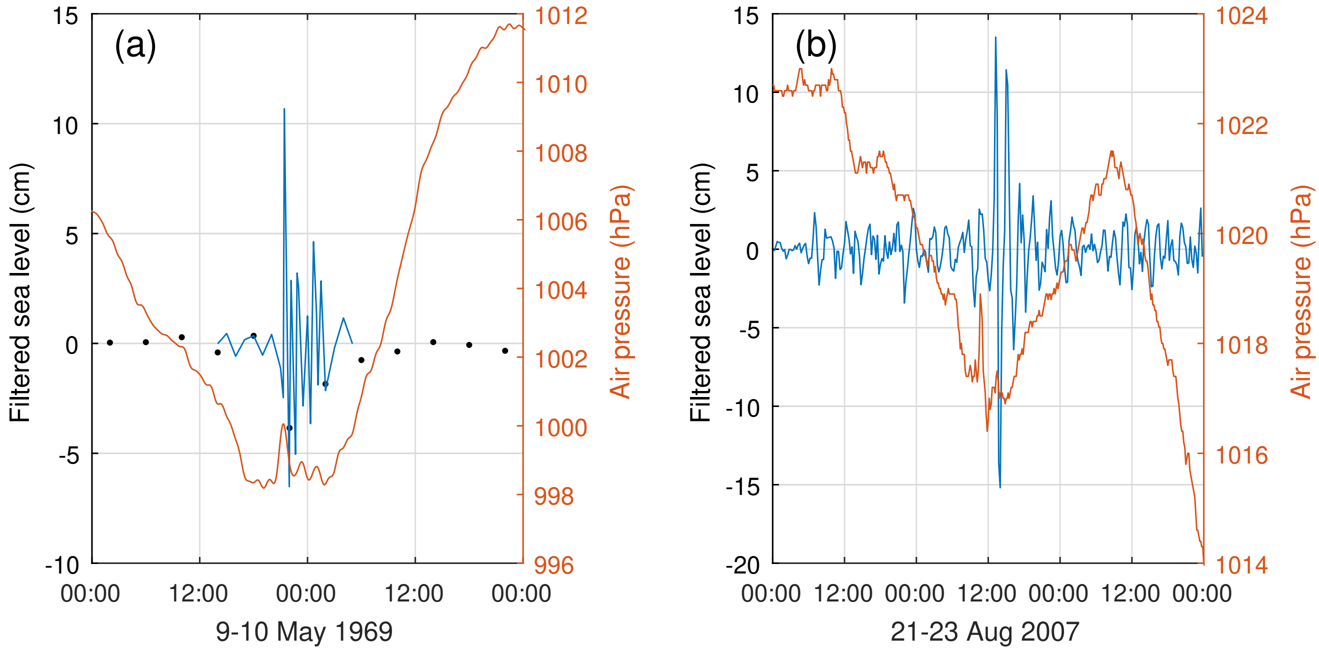

Figure 4. a) A meteotsunami in Hanko on 9–10 May 1969, visually identified and digitized from the tide gauge charts. Black dots show the standard 4 h sea level observations. Air pressure observations from Hanko Russarö, digitized from a paper barogram, are plotted in red. b) A meteotsunami in Hamina on 22 Aug 2007, automatically detected from the high-pass filtered 15 min sea level data. Air pressure observations from Kotka Rankki are plotted in red.

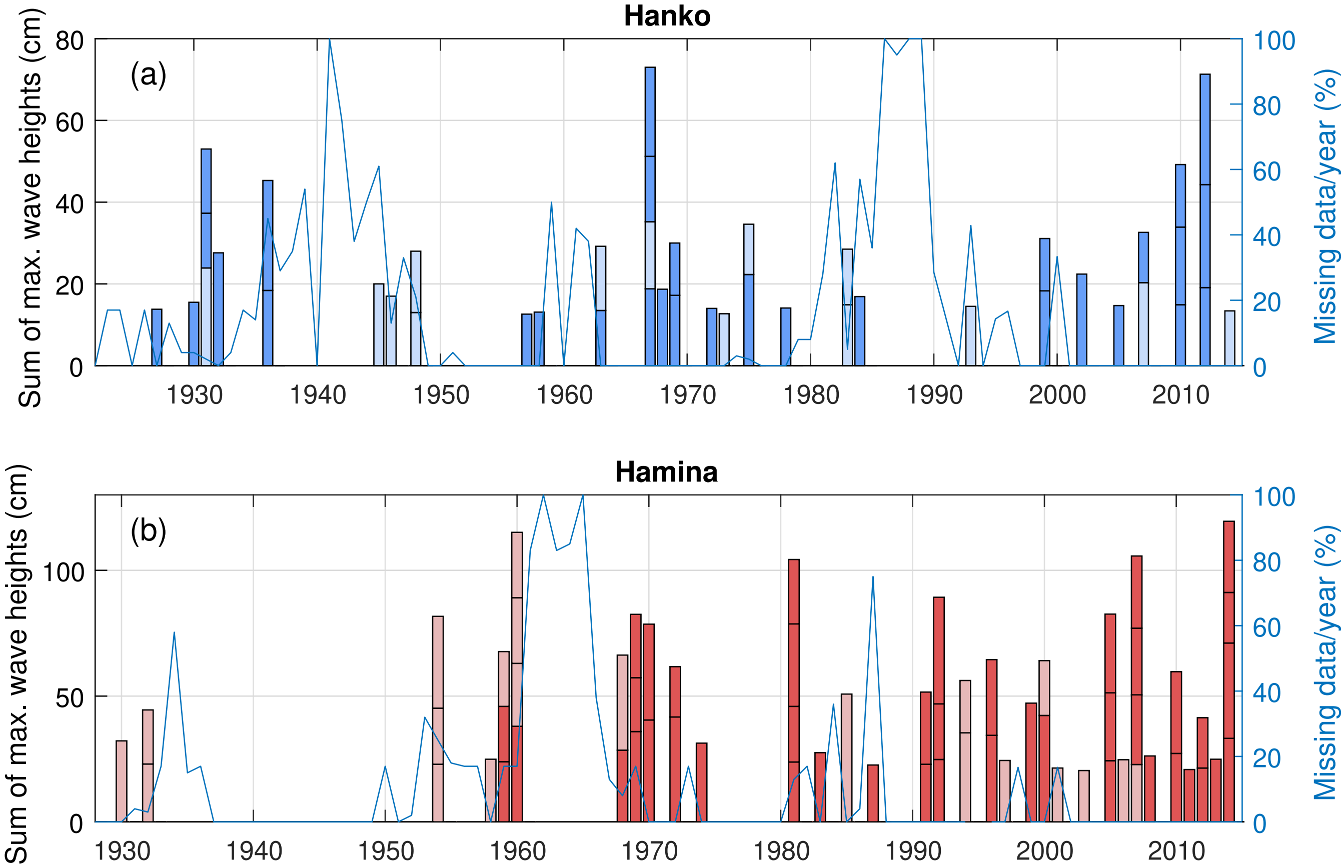

Figure 5. Meteotsunamis identified in the sea level data from the 1920s to 2014 for a) Hanko and b) Hamina. The events of each year are stacked so that the height of the column corresponds to the sum of maximum wave heights of the events during a given year. Dark-coloured events have been confirmed from air pressure data; the light-coloured events are potential meteotsunamis whose atmospheric origin is uncertain. The blue curves show the proportion of missing or damped data per year.

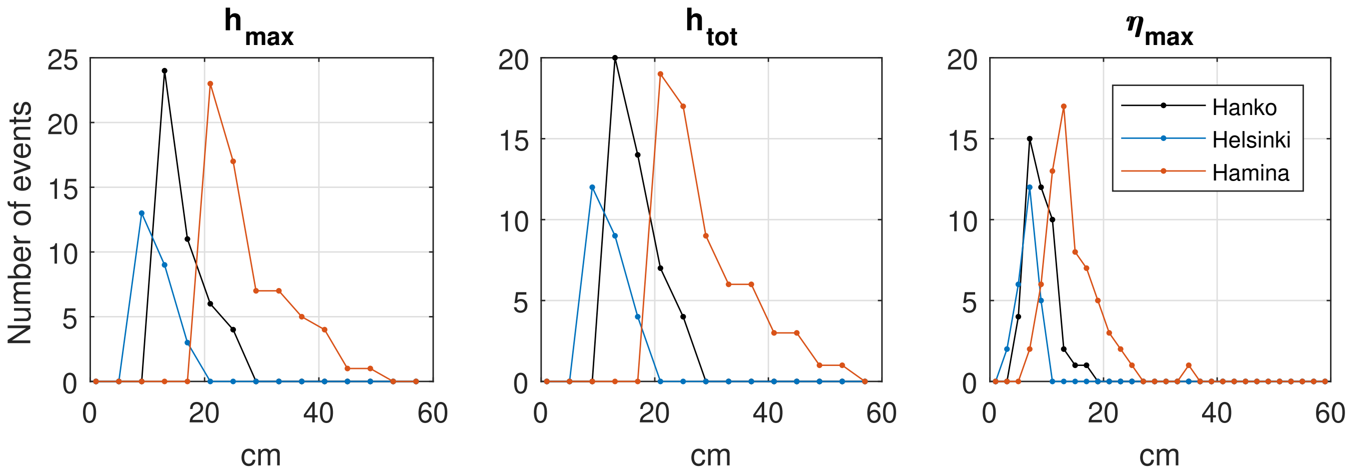

Figure 6. Histograms of meteotsunami heights, including both confirmed and potential events from all three stations: the maximum height of a single wave h_{max}, the total range of variation h_{tot}, and the maximum elevation η_{max}.