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Tsunamis and sea level rise in the North and Baltic Sea and potential consequences for nuclear facilities

Keywords

weather-related hazards, hazard assessment, climate change, North and Baltic Sea, nuclear facilities

Abstract

Weather-related hazards are among the most frequent causes for disturbances of critical infrastructures. Flooding, tsunamis and sea level rise are examples of major threats to all types of nuclear facilities located at the seaside or at rivers. We report about exemplary investigations concerning weather-related hazards for the North Sea and the Baltic Sea. Climate change is expected to increase the already known threats but, in the long term, may also lead to new kinds of hazards. A possible future climate evolution, e.g. from warm (interglacial) to cold (glacial) periods, is not only a topic for seaside industrial facilities but also of concern in the long term safety assessment of deep geological nuclear waste repositories, in particular for high level waste, on the Baltic sea.

1. Introduction

Critical infrastructures are essential for the functioning of modern society, and malfunctioning of one of the critical infrastructure systems may have far-reaching consequences, e.g. in the case of power generation, electric grid, pipelines or transport of goods and people.

In the present paper, weather induced hazards are discussed with the main emphasis on flooding and sea level rise, and their consequences for nuclear facilities such as nuclear power plants and nuclear waste repositories located at the coast line are considered.

The earthquake of December 26, 2004, in the vicinity of the island of Sumatra and the resulting tsunami wave caused one of the major natural disasters of the last centuries. The majority of tsunamis are generated by seaquakes, but tsunamis can also be generated by volcano eruptions or flank failures due to slope instabilities, for which the eruption of the Storegga-sliding about 8200 years ago is a prominent example. Due to the continental drift the probability of sea quakes is lower in the Atlantic Ocean than in the Asian region. Nevertheless, disastrous tsunamis have also occurred in the Atlantic Ocean. One example is the destruction of Lisbon in 1755 by a tsunami wave [20]. Thus, the generation of a tsunami in the Atlantic Ocean and its propagation into the North Sea is possible.

The tsunami in 2004 triggered investigations in Germany about the propagation of a tsunami wave in the shallow North Sea and its impact on the coastlines and estuaries. In the last years, these aspects including aspects of consequences of tsunamis for critical infrastructures including nuclear facilities have been investigated for the North Sea and the Baltic Sea in several studies.

Thus, it is necessary to assess the vulnerability of infrastructures due to weather-related hazards. Even though vulnerability factors are in general very infrastructure specific and hazard dependent, generic factors can be defined and analyzed such as robustness, buffer capacity, protection, quality, age, adaptability and transparency. For that purpose, a semi-quantitative, indicator-based approach can be applied [8].

Extreme weather due to climate change is one such phenomenon that may cause severe threats to the undisturbed functioning of critical infrastructures. The last decades show a growing trend of more frequent and more extreme weather types, e.g., high and low temperatures, periods of drought, strong rainfall resulting in flash floods or storms.

Already today extreme weather and climate changes are evidence of severe challenges to the critical infrastructures. Some recent examples of events from hydrological external hazards and their potential safety significance for nuclear power plants are discussed in [33].

In the foreseeable future, climates change may lead to a further increase in frequency and intensity of weather-related hazards, creating further challenges which could become even more demanding for the infrastructures. Therefore, modelling climate weather change process including extreme weather hazards is an important task and respective activities are ongoing.

In the assessment of the long-term safety functionality of a nuclear waste disposal facility, it is necessary to take into account natural processes that could affect it or modify its geological environment. Predicting climate system evolution on time-scales of several hundred thousand years up to even one million years is very challenging, since it relies on estimating the extremes within which climate and related processes may vary with reasonable confidence.

Extremely high sea levels are an important issue not only for nuclear power plants but also for other national infrastructure and activities, and have to be taken into account in construction and planning in general. Moreover, besides nuclear power plants and other industrial facilities, floods from rivers, estuaries and the sea threaten many millions of people in Europe. Flooding is the most widely distributed of all natural hazards across Europe, causing distress and damage wherever it happens.

2. Tusunami events in the North and Baltic Sea

2.1. Tsunsami events in the North Sea

In the past, tsunamis occurred in the North Sea, but not frequently. There are historical and geological records of several tsunamis: the Storegga tsunami caused sediment deposits in Scotland about 8,200 years ago, and records of at least six earthquake-generated tsunamis exist from 842 to 1761 AC. The highest tsunami height witnessed at the German Bight is comparable to the maximum storm surge recorded and could thus cause similar or higher damage. However, in the past only little research was done on tsunami modeling in the North Sea.

Recently, ten numerical experiments were performed imposing N-waves at the open boundaries of a North Sea model system to study the potential consequences of tsunamis for the German Bight [7]. One of the experiments simulated the second Storegga slide tsunami, seven explored the influence of the incidence direction of the tsunami when entering the North Sea domain in more detail, and the other two explored the influence of tides on tsunami heights.

The main impact was from waves entering the North Sea from the north, even for tsunamis with sources south of the North Sea. Waves entering from the English Channel were attenuated after crossing the Dover strait. The tidal phase had a strong influence on tsunami heights, although in the highest heights were obtained in the absence of tides. The duration of tsunamis is significantly smaller than that of storm surges, even though their flow velocities were found to be comparable or larger, thus increasing their possible damage [7].

The shape and bathymetry of the North Sea and the German Bight are a good protection against tsunami waves. However, the Dutch coast and the British Island are not as well protected as the German coast. An incoming tsunami wave at the Northern boundary of the North Sea is transformed by shoaling, refraction, reflection and energy losses mainly due to wave breaking. The amplitudes of a tsunami wave at the German North Sea coast can be compared to the water level elevations during a storm surge event. The governing processes are, of course, different.

Tidal forcing is at the heart of the North Sea dynamics, and it has been given much consideration in the past. However, there are only insufficient inter-comparison studies on the performance of individual models to adequately simulate tides, and in particular shallow-water tides. These shallow-water tides are very important for the tidal dynamics in coastal areas, where the tidal range is larger than in the open ocean and the propagation of tidal waves is more complex.

One manifestation of this complexity is a marked nonlinearity of the phenomena, which many models do not accurately simulate [37]. Recent developments based on advances in coastal ocean and storm surge forecasting are ongoing.

The Storegga Slide (see *Figure* 1) is one of the largest known submarine slides and is well explored, e.g. in [21]. An earthquake shook Norway's coast between Bergen and Trondheim and the tremors loosened pieces of land of the size of Iceland from shallow water, and sent them crashing into the deep sea. Like a stone thrown into a pond, the landslide produced ripples of waves racing across the North Sea, creating powerful tsunamis. Along the beaches of Scotland the waves were up to six meters high.

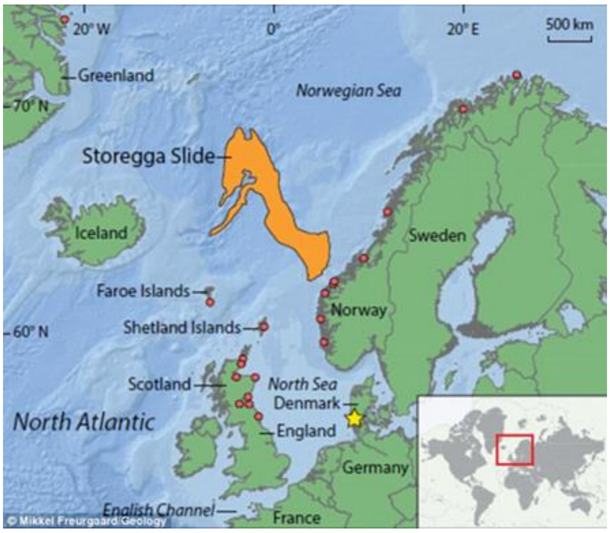

Figure 1. Superposition of tides and extreme wave signal in the German Bight.

Geotechnical records give evidence for three tsunamis in the North Sea between 8000 and 1500 years ago [4]. In the framework of a dedicated study on behalf of the Federal Office for Radiation Protection, the Center of Marine Environmental Sciences (MARUM) simulated the propagation and development of extreme waves in the North Sea towards the German Bight [2].

Based on an implicit finite differences modelling system, a hydrodynamic numerical model of the European continental shelf sea has been set-up in order to provide high resolution data on the hydrodynamics of the North Sea. The rectilinear spherical grid covers the region between W13/N48 and E13/N62 with a resolution of 2.5nm (1/24°) in the latitudinal and 3.75nm (1/16°) in the longitudinal direction (see *Figure* 2).

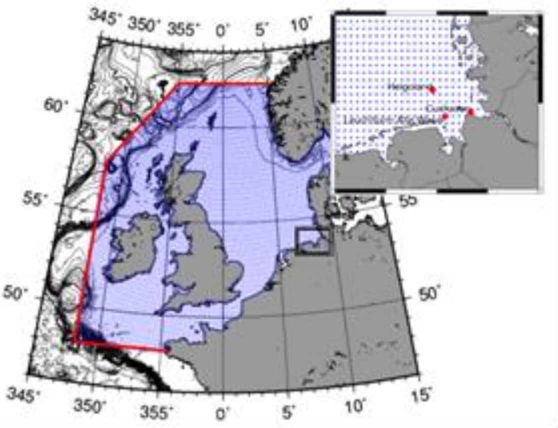

Figure 2. Domain of interest: Model grid nodes are indicated as blue dots. The red line denotes the position of open model boundaries.

The model bathymetry was interpolated from sea floor topography derived by satellite altimetry and digitized sea-charts [36]. For this study the propagation of an extreme wave event (tsunami) initiated by a hypothetical slide at the continental margin off the Norwegian continental margin has been simulated. Soliton waves were prescribed as water level boundary conditions at the northern open sea boundary of the model.

Since a realistic height of a possible wave cannot be defined, a range of different wave heights were tested. Simulations show the propagation of the wave across the model domain, considering uniform mean sea level as initial surface elevation condition:

After entering the North Sea through the northern boundary, the wave is partly deflected towards the West, because of Coriolis force effects, and partly moves in southern direction through the Norwegian deep. The deflected wave then approaches the British East coast and is partly reflected back into the North Sea, where the primary wave and the reflected wave superimpose into complex patterns. For the first wave it takes about 8.5 hours to reach the German Bight (see [2] and [3]).

The heights and characteristics of the waves at the three coastal stations are similar, all featuring the first direct wave, and about four hours later the reflected wave, which then reaches higher maximum water levels (*Figure* 3).

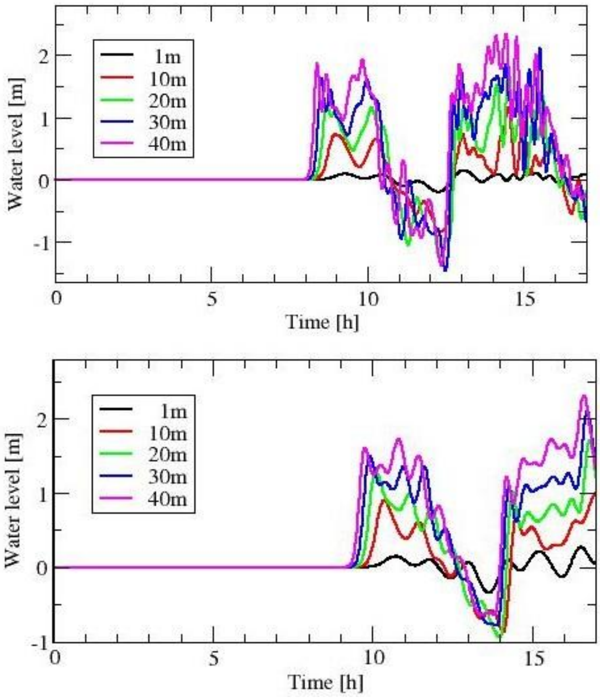

Figure 3. Extreme waves as calculated for the locations of the coastal stations, including the first direct and reflected wave.

Generally, a significant reduction in wave height from the boundary to the German Bight due to bottom friction can be observed.

The characteristics of the wave triggered by the ancient Storegga event were simulated in [21]. At the Northern boundary of the model, a wave height of 3 meters has been calculated which results in maximum deviations of about 0.5 to 0.7m at the tidal gauges in the German Bight.

In contrast to the simulations described above, the natural hydrodynamics of the North Sea is driven by tidal and meteorological forcing. Thus, the superposition of the extreme wave with the astronomical tidal conditions of the North Sea has been simulated *(Figure* 4). Although non-linear effects are present, in principle a linear superposition of tidal elevation and extreme wave dimensions based on uniform mean sea level seem to be possible.

It is noted that in the German Bight the transformed extreme wave is of much smaller height than the astronomical tidal signal: The effect of an extreme wave at the gauges Helgoland and Cuxhaven results in less than 10% of the tidal range and only one fifth of the expected surface elevation of a light storm flood, as defined by German hydrographic agencies. Similarly, at gauge “Alte Weser”, the extreme wave is damped to 0.55 m, which is about 17 percent of the tidal range and less than one third of a light storm flood [2].

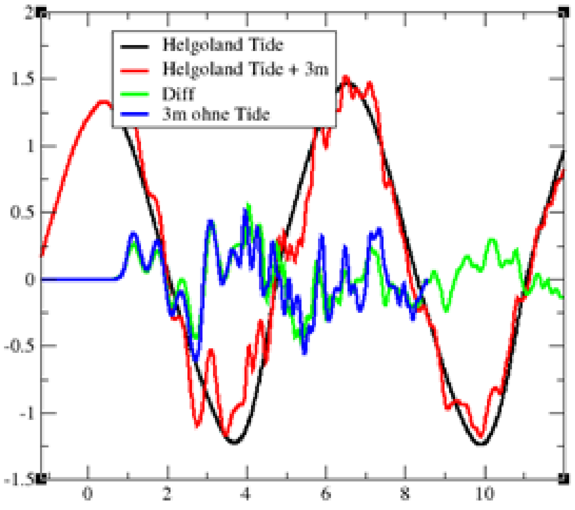

Figure 4. Superposition of tides and extreme wave signal in the German Bight.

Thus it turns out that in comparison to natural hydrodynamic conditions such as tides and storm surges of the German Bight the modelled impact of an extreme event triggered by a mass slide at the northern continental margin seems negligible.

For a known coastline, it is possible to determine the wave characteristics and the impact on the total sea level when they reach the buildings and structures on the site. The wave run up depends, among other things, on the wave height near the shore, the shore bottom slope, the angle of propagation against the shore and shore material properties. However, for a typical site with hundreds of meters between the shoreline and most of the safety critical buildings and where this area is flat, the impact from waves on the average sea water height is expected to be limited.

After the completion of these studies several approaches and computer programmes were developed and applied, e.g. at the Bundesamt für Seeschifffahrt und Hydrographie, which is operating a model system consisting of non-linear, hydrostatic models.

A computer model described in [6] shows the possible consequences of a mega-landslide. They have predicted the progression of such a disaster: Minutes after the landslide 14-meter-high waves would hit Norway's coast. After three hours 20-meter-high breakers would crash onto the Shetland Islands. Two hours later the Faeroe Islands would be covered in waves of up to 14 meters high. After six hours, the tsunamis would still be six meters high, tearing along Scotland's beaches toward the coastal cities of Edinburgh, Aberdeen and Dundee. As they head southwards the waves would become smaller, the oscillating North Sea acting as a break. The model predicts that Germany's North Sea coast would only see light flooding, but even elaborate computer models can be wrong.

Tsunami events whose primary cause is an earthquake pose only a low threat to the German North Sea coast. A more realistic scenario is an earthquake of low magnitude triggering a major slope failure in the North-East Atlantic. Currently, it is not possible to estimate the probability of occurrence of slope failures attributable either to this or to another cause. The most recent slope failure that had an impact on the North Sea was an event off Newfoundland in 1929. However, no evidence for a tsunami has been found in historical records of water levels at Cuxhaven.

The tsunami risk in the North Sea was explored in [7] by means of N-waves imposed at the open boundaries of the refined North Sea model. Each tsunami affected different regions on the North Sea basin and the German Bight. For the German Bight, among all cases analyzed, the most dangerous tsunamis were those generated by earthquakes south of the North Sea, because of their incidence direction.

Thus, the results for the German Bight obtained earlier (see [3], [5] and [20]) are still valid.

2.2. Tsunami events in the Baltic Sea

Estimates for extreme sea water levels (e. g. tsunamis) in the Baltic Sea with a return period (recurrence intervals) of 100.000 and 1.000.000 years are known for Swedish sites. These data are based on extreme value analysis of available series of measurements of yearly maxima.

However, these measurements were taken in a time interval (less than about 120 years) that is very short in the perspective of nuclear safety, which inevitably results in considerable uncertainties in magnitude estimates for very long return periods. Therefore, existing analyses have been reviewed and partly extended with the objective to obtain a better quality regarding the description of extreme sea level events. Levels around or above 3 meter of the normal sea level have been noted around six times at the German Baltic coast during the last 1.000 years (see *Table* 1).

Table 1. Examples of historical extreme sea water level events at the German Baltic Sea coast.

Event (year)	Level above normal sea level [cm] and location	Note
1044, 1304, 320,1449	> 300	
1625	315, Travemünde	Levels as obtained in the Backa flooding 1872
1694	290, Schleswig	
1835	254, Flensburg	
1872 (the Backa flood)	349, Schleswig	Along the German Baltic Sea coast the water level rose by 3,5 meters, and for a duration of 18 hours the water level remained > 2 meters above normal level
Storm surges 1976, 1986/87, 1988, 1989	About 200	

Furthermore, it is important to consider the local conditions when evaluating extreme sea water levels at a specific site. For various reasons, including prevailing wind directions and typical seiche effects, high water levels are judged to be more common in the southern Baltic Sea.

In Sweden the most extreme sea water levels observed are 360 cm in Abbekås, where the sea water level increased by around three meters above the normal level after a long period of strong western winds which forced an abnormal amount of water from the North Sea into the Baltic Sea through the passage at Öresund and the Belts. This was followed by a depression above Denmark and at the same time a hurricane that forced the water in the Baltic Sea southwards. Some of the historical extreme sea water level events in Sweden and Finland are reported in *Table* 2 according to [17].

Table 2. Examples of historical extreme sea water level events in Sweden and Finland.

Event (year)	Level above normal sea level [cm] and location	Note
The storm Per (2007)	144, Forsmark	
The storm Gudrun (2005)	197, Hamina 160, Ringhals 151, Helsinki 150, Gothenburg 132, Hanko	The extreme high sea level had an exceptional duration time, e. g., in Helsinki, where the water level was > 100 cm above normal sea level for 16 hours. The water level at Ringhals corresponds to a 180 year recurrence interval value according to the extreme value analysis performed.
January storm (1984)	177, Kalix	
January storm (1983)	117, Stockholm	
Extreme swell (1959)	The difference between the lowest and highest water level in Ystad, southern Sweden: 132	The resonance period was 10 minutes. The swell was caused by a thunderstorm passing by.
Christmas storm (1902)	206, Lomma	In Ystad the water level rose from –145 to +70 in just over six hours
Backa flooding (1872)	360, Abbekås 280, Pärnu (Estonia) 146, Helsinki	.

As a consequence of the European Union stress tests following the accident in Fukushima, the necessity to perform an updated analysis related to the capability of nuclear power plants to withstand the potential effects from external flooding and other external hazards was identified.

The reassessment was based on an existing methodology by Westinghouse [27] to analyze certain external events including extreme water levels in the Baltic Sea and Skagerrak as one sub-project taking into account the recorded sea water levels in the Baltic Sea described above. It addresses the following fast evolving initiating events:

- Structural impact
- Electric environment
- External flooding
- Impact on sea water (main heat sink).

In [27], for all design basis events the specification of requirements for handling external events are compiled. Subsequently it is reviewed how these specifications are implemented in Nordic nuclear power plants.

One sub-project dealt with extreme water levels in the Baltic Sea and Skagerrak. The scope of this sub-project included the consideration of historically observed events with extreme sea water levels in the Baltic Sea and Skagerrak and the attempt to define the time development of such events. The objective was to assess whether time development allows the initiation of preventive measures such as cold shutdown and core offload, building of temporary barriers to restrain water from entering into buildings, or the installation of temporary drainage pumps. The work also includes a survey of the potential impact from factors affecting extreme water levels such as medium to long term climate change, local conditions on and around sites, and a number of phenomena affecting sea water level.

The objective for this sub-project was to evaluate the relevance of the existing analyses constituting the foundation of the design-basis for external flooding for Swedish and Finnish nuclear power plants. Aspects that should be considered in an external flooding analysis of a nuclear facility were discussed in [17].

The performed reassessment resulted in a number of safety improvements for the two Finnish sites with nuclear power plants[19].

In the Olkiluoto operating boiling water reactor units, the main on-going safety improvements include modifications to high pressure emergency cooling system to remove the dependence on the sea water cooling, installation of a new steam driven emergency cooling pump to be used in the case of total loss of AC power, and installation of new emergency diesel generators with diverse cooling (sea water and air).

In the Loviisa VVER 440 units the main modifications are installation of radiator coolers to provide diverse ultimate heat sink to the atmosphere, improved protection against extreme sea water flooding by local flood protections, and a system for diesel oil distribution from the site storage tank to the emergency diesel generators and to the diesel driven auxiliary emergency feed water pump.

3. Extreme sea water levels and sea level rise

3.1. Current research activities

Extreme sea water levels may result from several interacting factors, and the understanding of a scenario with extreme sea water levels requires good knowledge of these factors, the way they appear at a specific site, and the way they interact. Factors that can have an impact on extreme sea water levels include [17]:

- The average sea water level at a certain time,
- Wind strength and direction,
- Air pressure,
- Waves,
- Special wave phenomena,
- Tide,
- Water density, and
- Special wave phenomena.

Special wave phenomena are waves that are induced by various conditions and can result in extreme water levels, for example; tsunami, resonance effects (that cause one great swell) and seiche (periodic changes in water levels, i.e., a “bath tub effect"). The water levels at specific areas along the coast are also strongly dependent of local topography above and under the water line.

Studies of the site specific data for the Swedish nuclear power plants showed that the duration of an extreme water level is usually shorter at Ringhals and Forsmark, whereas some more persistent extreme water levels have been observed at Oskarshamn [17]. The conditions for Ringhals differ in many ways from the other two sites since Ringhals is the only site situated on the Swedish west coast. An extreme water level event at Ringhals typically builds up relatively fast and has a short duration. The highest extreme values (in available measurement series) are found at Ringhals.

In the Baltic Sea, on the other hand, different conditions create other kinds of effects. Thus, it is common to observe a seiche. In the Baltic, the differences in the water levels are greatest in the southern and northern ends of the Baltic Sea. Less effect from seiche can be noticed especially in data from Forsmark, located more towards the middle of the Baltic.

The characteristics of the water level during the build-up phase of extreme events is critical to the possibility to initiate measures to prevent or mitigate damage to buildings and other structures. It is therefore relevant to study how such processes evolve over time and whether the same build-up scenario can be expected for (yet unobserved) higher and therefore less frequent extreme values as for the (observed) lower but more frequent extremes.

The most rapid rise of sea water level measured is 75 cm per hour, observed at Forsmark. For the Oskarshamn and Ringhals sites the maximum observed build-up rates are around 30 cm per hour. From the available measurement data no relation between the rate of sea level build-up and probability of the occurrence of an extreme sea water level could be identified.

Consideration of extreme sea water levels is also crucial for the safety of the Finnish nuclear power plants, which are all located on coastal areas. Thus, sea level has been studied in the frame of the SAFIR project as a sub-project entitled “Extreme weather and nuclear power plants (EXWE)” since 2008; this project investigates the different processes affecting sea levels on the Finnish coast on different timescales. The overarching objective of sea-level research is to assess sea-level extremes which are physically possible but so rare that they are not adequately included in current statistics.

The earlier studies in SAFIR2010 and SAFIR2014 focused on scenarios for the long-term mean sea level, as well as flooding risks related to short-term sea level variations at a time scale from hours to longer periods, based on conventional hourly sea level data (see e.g. [10] and [15]).

Furthermore, in SAFIR2014 meteotsunamis, or meteorological tsunamis, are investigated. The existence of such hazards was rediscovered after several reports of such phenomena in 2010–2011.

Meteotsunamis are tsunami waves generated by exceptionally rapid air pressure disturbances (e.g. thunderstorms) moving above the sea at a speed that matches the tsunami wave speed in the sea. To investigate the frequency of meteotsunamis in Finland, and eventually to be able to estimate their probability, the research in SAFIR2014 has concentrated on identifying past meteotsunami events in sea level data [14].

The detected meteotsunamis are generally only 10–40 cm high. However, because their strength strongly depends on coastal topography, higher oscillations may have taken place even though they are not observed at the tide gauges. A recent study identified strongest reliably documented events in the Baltic Sea which had a wave height of ca. 1-1.5 m [31].

To study the vulnerability of nuclear power plant sites to meteotsunamis, refraction modeling has been carried out. The refraction model can be used to resolve the large-scale concentrations of wave energy caused by coastal bathymetry. Based on the results, none of the studied sites (Loviisa, Olkiluoto, Hanhikivi) are particularly vulnerable to meteotsunamis [30], and the probability of a strong meteotsunami occurring there is very small.

New advances are expected to be achieved by complementing existing analyses with high-resolution sea level data which gives a more detailed picture about short-term sea level variations. The aim is to produce probability distributions of extreme-sea-level events, which are easily applicable in risk assessments for nuclear power plants.

Several factors with time scales ranging from seconds to centuries affect sea level on the Finnish coast (see Figure 5).

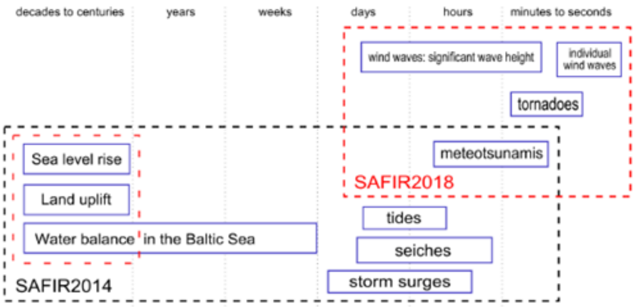

Figure 5. Factors affecting sea level on the Finish coast according to [12].

In the SAFIR2018 programme, the focus of sea level research is shifted from long- to short-term sea level phenomena to complement previous analyses in the EXWE project (SAFIR2014). However, regular updates to long-term mean-sea-level scenarios are needed when new knowledge accumulates (hence, the dashed box on left).

In 2015 and 2016, short-period sea level oscillations, such as meteotsunamis, were studied from sea level data with sub-hourly resolution. The effect of wind waves was also included in the methods for estimating more accurately the location-specific flooding hazards related to storm surges. Data used comprise 10 years of sea level observations with 1-min resolution from 13 tide gauges on the Finnish coast, in the northern Baltic Sea [32].

In addition to these new topics, a literature review on global mean sea level scenarios was performed [12]. The purpose was to ensure whether the previously calculated local mean sea level scenarios (see, e.g., [16]) are still valid or whether an update of those is needed.

The long-term change of the mean sea level on the Finnish coast is affected by three factors: global sea level rise which is also reflected on the Baltic Sea, local postglacial land uplift in Scandinavia, and long term changes in the Baltic Sea water balance.

When calculating scenarios for sea level on the Finnish coast, the most relevant question is what happens with the global sea level rise in the future. Scenarios for mean sea level on the Finnish coast were calculated [11] and updated in [16]. The mean sea level scenarios have been summarized in [13].

Moreover, a literature review on current scenarios for the global mean sea level rise has been conducted [29]. The aim was to find out whether the recent results indicate a need to update the mean sea level scenarios for the Finnish coast.

The sea level is rising globally, mainly due to changes in seawater density (thermal expansion) and melting of land-based glaciers and ice sheets in a warming climate. On the Finnish coast, the postglacial land uplift significantly reduces the effect of the rising sea level. The sea level rise in the Gulf of Finland during this century is projected to be +35 cm (uncertainty ranging from -18 to +99 cm), while in the Gulf of Bothnia the stronger land uplift more effectively balances the sea level rise, average projections for the sea level being from -21 cm to +2 cm with an uncertainty ranging from -68 to +71 cm [11]. The large uncertainty is especially due to insufficient knowledge on the behaviour of the large continental ice sheets (West Antarctica and Greenland) in a warming climate.

In general, there are two methods for calculating global sea level scenarios. In process-based modelling approach, the different factors contributing to sea level rise – melting of ice sheets, glaciers and ice caps, thermal expansion, etc. – are modelled separately. In the semi-empirical approach, a statistical relationship between global mean temperature and sea level is derived from the past observations, and then applied to the modelled temperature scenarios to obtain sea level predictions.

Recent studies have not changed the overall uncertainty range of the global sea level rise projections for this century; they still extend from about 20 to 200 cm. The results do not imply a significant change in the previously published regional sea level scenarios for the Finnish coast. However, recent research has brought more information on the shape of the probability distribution of sea level rise, as well as on regional factors. These could be used to re-evaluate the method used to calculate the scenarios for Finland, but major changes on the scenarios are not expected.

The extreme sea levels clearly differ from one location to another, due to differences in the meteorologically induced sea level behaviour as well as different mean sea level scenarios due to differing land uplift rates. For instance, Loviisa (situated between Helsinki and Hamina) is more vulnerable to future a sea level rise than Olkiluoto (situated near Rauma), and also experiences larger amplitudes of short-term sea level variability.

The vulnerability to sea level extremes also depends on the power plant design. The design criteria for Olkiluoto are based on a +3.5 m sea level height (N60), which is unlikely to be exceeded in present or even future conditions. On the other hand, the Loviisa power plant has lower design criteria, the critical level for flooding being +3.0 m during power operation, and this, together with higher extreme sea levels in the area, makes preparedness for high sea levels an important issue [40].

In the existing Finnish nuclear power plants, preparedness against extreme natural phenomena is continuously being improved. For example, actions have been taken to reduce the risk of heavy rainfall-induced flash floods in the yard area of a nuclear power plants; to avoid a blockage of air intake of emergency diesel generators as a consequence of simultaneous snowfall and wind; to prevent problems due to frazil ice formation; and to implement a supplementary cooling system of nuclear reactors (see, e.g., [42]).

Despite of these already performed activities, further research needs to be conducted. This is because estimates of frequencies of weather-related and sea-level-related hazards are subject to considerable uncertainties. The main source of uncertainty arises from the fact that phenomena beyond the design basis levels of nuclear power plants have a very low probability that corresponds to return periods of thousands or millions of years.

Such extreme weather and sea level events occur so rarely that they are typically unprecedented anywhere in Finland and thereby missing from the relatively short time series of observations. On the other hand, as part of a continuous effort to improve the understanding of extreme weather events, it is useful also to examine moderately rare phenomena, having a return period of tens or hundreds of years.

3.2. Influence of sea level rise on long term nuclear waste disposal

Changes in climate and climate-related processes need also to be addressed in assessments of long-term safety of nuclear repositories. Since climate system evolution is not predictable on time scales up to 1 million years, a broad range of possible future climate scenarios is necessary for the analysis of nuclear waste repository safety. The uncertainty in future climate system evolution is due to incomplete knowledge of past climate evolution and (coupled) processes of the climate system.

Geological archives show that Earth’s climate has evolved from warm (interglacial) to cold (glacial) periods, the latter characterized by ice sheet growth in high northern latitudes and permafrost conditions in ice-free high-latitude regions. For the past 2 million years, the climate in Fennoscandia has been dominated by cold conditions with permafrost and at times extensive ice sheets. Based on this knowledge, periods of cold climate cannot be excluded in the next 100.000 years to 1 million years and thus future climate scenarios including permafrost growth and ice sheet formation are included in the range used for safety assessments for nuclear waste repositories [26].

In safety assessments, climate scenarios are used mainly for three purposes:

- as basis for the description of the repository site development (for instance the landscape-, shoreline-, and lake development),

- in the analysis of the probability for a radionuclide release caused by variations in climate-related processes (for instance by high isostatic pressures from ice sheet load, or through freezing of repository barriers during permafrost periods), and
- in the analysis of the consequences of a radionuclide release, if the safety assessment shows that a release could occur.

The climate domains are first used to describe a reference glacial cycle for the coming 120.000 years. The reference glacial cycle was constructed using a coupled modeling approach, in which data were shared between three models, the ice sheet model, the glacial isostatic adjustment (GIA) and the permafrost model (see *Figure* 6).

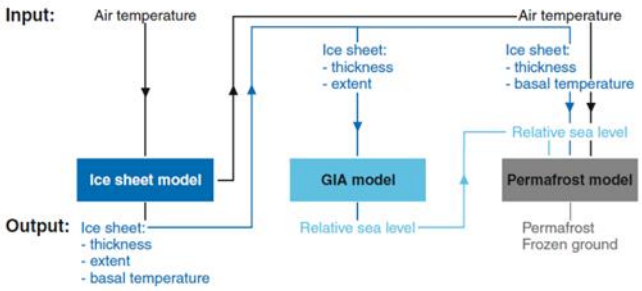

Figure 6. Example of coupled modeling performed for the safety assessment of the spent nuclear fuel repository according to [26].

The model output was used to make a reconstruction of conditions for the last glacial cycle, in turn used for the construction of the reference glacial cycle. Only input and output data shared between the models used to generate the boundary conditions are shown.

For the planned deep geological repository for spent nuclear fuel in Forsmark in Sweden, with the safety assessment covering a period of 1 million years and with many radionuclides being very long-lived, the climate scenarios range from cases with high-end global warming for the coming 100.000 years, through cases with maximally deep permafrost, to cases with maximally large ice sheets during full glacial conditions.

The latter scenarios are needed even if we are heading into a non-historical-analog situation with strong global warming, as the effects of global warming, regardless of its intensity, will have tapered off well before the end of the 1 million years assessment period.

To conclude, all safety assessments for repositories for nuclear waste near coastline, regardless of waste type and repository concept, require a range of possible future climate scenarios to cover the large uncertainty that exists in future climate development on the time scales of 100.000 years and 1 million years which are typically analyzed in such assessments.

4. Concluding remarks

Weather hazards, in particular tsunamis, can impair all types of critical infrastructure. Therefore, several studies are performed in this context and national as well as international activities are ongoing.

In the German project AMSeL Baltic Sea scheduled from August 2015 to July 2017, mean and extreme sea level changes over the past 150 years in the southwestern Baltic Sea are analysed. As a result, detailed knowledge of the spatial and temporal variability in sea level along the German Baltic coast will be available. First results are provided in [34].

Furthermore, a knowledge gap in comparison to the German North Sea coast consisting in a lack of detailed analyses of all available data will be closed.

A further goal is to investigate the interrelationship between the North and Baltic Sea basins, which are connected through narrow and complex straits between Denmark, Norway and Sweden.

Moreover, long-term changes associated with global climate change should be identified. By doing so, the basis for deriving more resilient regional sea level projections for this low-lying and vulnerable area will be developed [35].

INTACT is a project funded European Union which aims to offer decision support regarding critical infrastructure protection against changing extreme weather event risks caused by climate change. The approach adopted by the INTACT project recognizes that a European-wide coordinated and cooperative effort is required because of cross border critical infrastructure activities and impacts as well as an integrated EU-policy [9].

This project started with the development of a database of past extreme weather related events causing damage to critical infrastructure in Europe. It encompasses 27 extreme weather events and more than 200 impacts on critical infrastructure [41]. The database event reports include data on the main effects of the events on electricity (transmission) as well transportation (rail and road). Furthermore, approaches for the assessment of vulnerability of critical infrastructures to weather-related hazards are outlined in [8].

The consensus opinion is that the global sea level will rise in the future due to climate change. Such analyses are still associated with large uncertainties because of the wide range of affecting parameters and the availability of only limited data.

However, nowadays new observations are available, using the remote sensing of wind speed, waves, sea levels and currents; X-band and HF-radar, ADCP, LIDAR, Ku and Ka band pulse-limited and Delay Doppler radar altimetry, which promise high quality space observations also in the coastal zone. Better sea level data near the landfall and storm variables are provided by a closer network of tide gauges and buoys and by observations from space. According to the balance of investment and the demand of disaster relief, some more tide gauge stations should be established in empty or sparse areas [38].

The design basis of coastal nuclear power plants is affected by external risks caused by extreme sea levels and harsh weather conditions. Certain exceptional weather phenomena may also prevent the normal power operation of a functioning plant and consequently lead to a reactor trip.

Therefore, it is necessary to discuss the occurrence and probabilities of extreme climate events and aspects of sea level rise that are relevant from a viewpoint of the safety of nuclear power plants. These include very high or low air temperature events having different durations, excess or scanty precipitation, hail, freezing precipitation, heavy snowfall events in combination with high wind speeds, strong winds caused by tornadoes and downbursts, and high sea levels.

In Finland, the project SAFIR (currently in the third phase from 2015 to 2018) includes an analysis of the expected sea level rise in the Baltic Sea. A conservative assessment for the total increase of the mean sea level in the Baltic during the next 40 years is about 60 cm; the net outcome will also be affected by the isostatic rebound, which differs among the sites.

The mean sea level rise as such will not cause a sudden threat to the power plants because the predicted changes are slow. Even if the level were to rise faster than predicted, nuclear power plant operators would still have enough time to take appropriate countermeasures.

It is the mean sea level rise on time scales of decades which is the main issue taken into account in the design of new nuclear power plants and other facilities not only in Sweden and Finland, but – maybe – also in Poland where the country’s first nuclear power plant project, has formally begun environmental and site selection surveys at two locations – Lubiatowo-Kopalino and Żarnowiec – both close to Poland’s Baltic coast in the northern province of Pomerania.

In that context, a recent analysis of the sensitivity of the Polish coastal zone to sea level rise and coastal floods [28].

The change in mean sea level affects the probabilities of extremely high sea level events in the future, and will thus change the operational environment of the plants. The short-term sea level variations in the Baltic Sea are mainly driven by weather conditions – strong wind and changes in air pressure both affect sea level and also induce internal oscillations – seiches – in the Baltic Sea.

The tidal oscillations in the Baltic Sea level are formed by free tidal waves penetrating from the North Sea and forced tidal waves excited directly in its water area [23]. Maximum tidal heights estimated for a 100-year period are 23cm in the Baltic Sea [24].

The probabilities of extremely high sea levels change in time, due to changes in the mean sea level as well as changes in the meteorologically-induced behaviour of the sea level due to climate change. The latter are less well known (see [39] and [40].

Extremely high sea levels are an important issue not only for nuclear power plants but also for other infrastructures (see, e.g., [1], [18] and [25]) and have to be more generally taken into account in the respective design-basis of the infrastructure.

In **[**26], also the influence of weather hazards on a nuclear waste repository is addressed in case of the repositories in Scandinavia. Comparable activities are performed, e.g., in the United Kingdom [22] and Canada for a deep geologic repository for low and intermediate level waste. For that purpose a recent report provides an assessment of potential flood hazard risks associated with coastal, riverine and direct precipitation flooding.

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