Chapter

Coastal Erosion Due to Decreased Ice Coverage, Associated Increased Wave Action, and Permafrost Melting

Dimitrios Kostopoulos, Efrat Yitzhak and Ove T. Gudmestad

Abstract

It is broadly recognized that the Arctic area has become highly popular for hosting new activities and new infrastructure. This is due to the combination of the need of exploring new areas to satisfy the ever increased energy demand and also the impact of climate change that has created paths for increased trading and maritime activities. Presently, the Arctic environment poses new challenges and unknown hazards, which are considered unpredictable due to the uncertainties of the emerging phenomena. In this chapter, the effects caused by the higher temperatures in the Arctic region on the increased height of waves and storm surges and the extended erosion of the Arctic coastline are examined and presented. This unpredictability is partly due to the dynamic behavior of the Arctic environment and the annual fluctuations of the permanent ice of the Arctic Ocean. Reduced ice coverage, especially during the fall period, creates longer available sea distances for waves to be developed. As extreme case scenario, the associated consequences for the design wave height on a totally ice-free sea are studied. A comparison between the heights of the waves which are generated by the longest possible fetches and those estimated from today's ice limit situation is made based on coastal engineering methods. Further to this, more open sea areas also allow for increased storm surge heights. In the chapter, it is also shown how the decreased ice coverage has an influence on the coastal erosion phenomenon, which is not only enhanced due to the evolving wave dynamics but also thermodynamics and sediment dynamics. The presented results show significant changes of the characteristic wave heights and strong increase of the pace of the coastal erosion. Based on these observations, the authors of this chapter want to stress the challenges that such future conditions in the Arctic area will pose to any Arctic operations, nearby infrastructures and human activities in the area.

Keywords: Arctic Ocean, free ice sea, extreme wave heights, permafrost melting, shore erosion

1. Introduction

The Arctic physical environment is characterized by various dynamic phenomena, sudden ones, like polar lows and unexpectedly strong storms, or time developing and periodical, like gradual coastal erosion of the shoreline. In order to operate safely in this environment, one needs to be undoubtedly supported by daily weather forecasting and monitoring. However, accurate means of doing so and good prognostics are challenged by the lack of historical and scientific data as well as a limited number of stations for data collection, which make the Arctic Ocean a hazardous environment with challenging marine and weather conditions.

Recent events testify the aforementioned hazardousness. For example, on July 24, 2010, in the Varandey area in northern Russia, the oil treatment and storage terminal located kilometers inland was flooded and the airport runway closed, due to the fact that the coast was severely damaged by excessive flooding. This flooding event was the outcome of combined storm waves, surges, and tides. Other northern production sites, such as the Northstar artificial oil and gas production island in the Beaufort Sea, have also been damaged by significantly high waves. In that case during the design phase, the facilities, which are located 19 km northwest of Prudhoe Bay, Alaska and 10 km north of the Alaskan coast at a water depth of 10 m, were designed using historical data and assumptions of fetch length and wave height occurrence which did not correspond to events that happened some years after production startup.

In this chapter, we are analyzing some of these challenges and phenomena, taking into consideration the significant changes that have occurred in the Arctic area during the last decades. For instance, throughout the years, the average monthly Arctic sea ice extent has dropped dramatically from 12.5 million km^2 in 1980s to about 10.8 million km^2 in 2016, showing a declining trend of 4.1% per decade (see **Figure 1**) [1]. This means that at coastlines and areas that before used to be covered by snow permanently, people now observe waves up to 4 m in height. Due to the retraction of the ice cover, new paths for trading and transportation are seasonally opened, like the North Sea Route (the Northeastern Passage), which is now used as a transport path with ships for liquefied natural gas (LNG) from the Sabetta LNG facilities on Yamal to the Chinese market. During the summer period and early autumn, when the passage is almost ice free, operators can travel from Europe to Asia using this path to the north of Russia with the service of icebreakers.

The wave forces that are generated due to the ice-free surface enhance the ice shrinkage and reduce the ice thickness, helping ice edges to detach more easily from the main ice core. Another observation is the increase of the temperature and seasonal record peaks that might be also a consequence of the annual shrinkage of the permanent ice extent which works as natural mirror and shield against the heat. The increase of the temperature does consequently lead to increased ice melting creating a loop of domino effects.

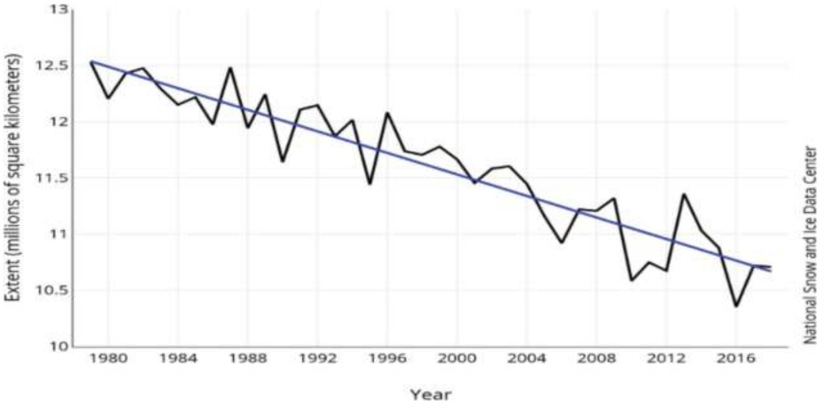

Figure 1.
Monthly June Arctic sea ice extent for 1979–2018 shows a decline of 4.1% per decade [1].

All the aforementioned changes testify to a likely future situation where ice surface will shrink further and possibly occasionally disappear. Shipping and operations in the area will face a different environment of what they are designed for today. Some new challenges might occur. As long as waves are considered, it is probable that assets will face a more hazardous environment with higher waves generated in an open ocean. Some business people might claim that conditions will be more favorable for operations in the Arctic if temperature increases, since this will alleviate winterization issues. However, no one can predict with certainty what the environmental conditions will be and how the aforementioned changes will influence the phenomena by reducing or increasing some risks.

In relation to the definition of the risk of an activity, A, is the multi-dimensional combination of its probability P, its consequences, C, and the related uncertainties, U, of what the outcome will be (A, P, C, and U). The uncertainty of the activity is well linked to the knowledge that one has about the activity. Therefore, since in the Arctic area there is lack of knowledge due to scarce historical data or measurements of previous hazardous events for a sufficient long period, risks can be considered inherently high in the Arctic area where safety for the assets or humans may not be guaranteed.

Thus, there is a need to understand better the challenges that might occur in the future by assessing some potential future scenarios. One such scenario is an open Arctic Ocean where there is no ice. In this chapter, this scenario is related to the potential increase of the wave height in specific areas. One specific method for predicting maximum wave heights is used, here, covering the subject briefly and giving food for further research and analysis.

Winds blowing over the sea generate ocean surface waves (wind-sea and swell) which are related to the distance (length of fetch) and the duration of wind. As both wind-sea and swells depend on the open water sea fetch, further reductions in seasonal ice cover will result in larger waves [2].

Such larger waves can have multiple consequences to the coasts around but also to the marine operations in the area. Wave activity when reaching the shallow areas along the coast leads to currents and water circulation that can cause excessive erosion and enhanced sediment transportation. Also, present navigation experience

Figure 2.
Feedback loop of the wave ice interaction.

can be challenged due to higher waves generated by rapid storms and changing seafloor conditions. In the future Arctic Ocean, wave conditions like those will be changing the known environment for nature and humans.

Moreover, the existence of ice on the sea surface makes the phenomenon of wave and ice interaction complex. Ice masses suppress waves, diminishing them, but also waves alter and influence the thickness and the growth of the ice. Waves start penetrates more and more into the weakened sea-ice reaching the marginal ice zone, the part of the ice cover that interacts with the open ice-free ocean. This loop produces a positive feedback that could accelerate the loss of ice especially during summer and early fall [3] (**Figure 2**).

2. Methodology

As mentioned before, the aim of this chapter is not to execute an excessive assessment of the ice melting impact on the design wave heights, but rather stress and highlight the challenge that might occur in a worst-case scenario when there is no ice in the Arctic. In this way, one can have a better understanding of the magnitude of change that could be expected. These effects are also present, possibly in a less extend and locally, when there is a partial reduction of the ice surface and not total disappearance.

The methodology chosen is based on the assumption that the Arctic Ocean in a free-ice period can be considered as a gigantic ocean, surrounded by the northern coasts of the neighboring countries. When one aims to estimate the characteristic wave height, two factors are the main contributors that need to be taken into consideration. One is the fetch length, the length of water over which a given wind can blow, and this is also the main factor that creates storm surge which also leads to coastal erosion and flooding. The other factor is the wind characteristics, such as duration and velocity. Thus, focus initially was given on areas that have the longest potential fetch distance, assuming that the wind conditions (duration and speed) are similar from all directions.

Taking all the aforementioned factors into consideration and also the available data and their quality, the northern part of Svalbard Island is chosen to be examined. As per now, this part of the Arctic region is covered by ice during most of the year, but in a free ice future scenario, long fetches are revealed that can potentially generate high waves. Moreover, statistical studies have showed that the percentage of north easterly winds occurring annually at the examined area is significant which testifies the relevance of the choice of location and direction for the study. Five different meteorological stations at the north and northeast area of Svalbard are selected to acquire the desired wind data. These data are analyzed to extract information regarding the most extreme wind incidents and storms from 2000 to 2014. The collected data refer to the early fall period of the year (September and October), as this is the period when the Arctic is expected to have the lowest ice percentage.

The stations are as follows [4]:

- KARL XII (99935): Latitude: 80.653, Longitude: 25.008
- KONGSØYA (99740): Latitude: 78.9277, Longitude: 28.892
- VERLEGENHUKEN (99927): Latitude: 80.059, Longitude: 16.25
- KVITØYA (99938): Latitude: 80.07, Longitude: 31.5
- HOPEN (99720): Latitude: 76.5097, Longitude: 25.0133

Since the main focus of this study is to examine the difference in wave height estimates due to the shrinkage of ice coverage, the directions that are examined are those that showed the most dramatic change in length. Thus, for the examined area, the directions that are chosen are all between 320 and 55°. As shown in **Figure 3**, in the case of ice coverage disappearance, the increase of the fetch length in some directions is up to three times longer than the one today (from presently 500 to 2000 km to the northern coast of Russia and from 200–250 to 1500–3000 km to the coasts of Canada and Alaska).

The calculation of the maximum characteristic wave height is made by using the Jonswap method. This method is chosen as it is judged appropriate for open sea waves and considers the influence of the fetch length. According to this method, a wind generated wave can be either fetch limited (limited by the available distance over which it has been generated) or duration limited (limited by the period of time that the wind is blowing).

In order to find the largest wave height that can occur due to the wind phenomena in the region, all the characteristic significant waves, H_s, for the directions of interest were assessed. In Svalbard, the examined directions were NNW, N, and NNE (North-Northwest 340°, North 0°, and North-Northeast 32.5°). Those directions were chosen because we wanted to cover as much as we could of the examined area for three different directions. For that reason, straight lines were drawn for each 2.5° with the use of maps from Google Earth (see **Figure 3**) until the opposite coasts were reached.

For each and every one of the three wind directions that were examined (NNW, N, and NNE), wind was assumed from an angle of 45°, that is, from −22.5 to +22.5° for each direction (usually the spreading used is 90°, but here, because of the limited examined area, we had to choose a smaller and more narrow area, the half). The fetch length, F, was drawn for every α_i = 2.5° angle around each direction, and they are calculated by the following quation [5]:

$$F = \frac{\sum_{i=-N}^{N} F_i \cos^2 a_i}{\sum_{i=-N}^{N} F_i \cos^2 a_i} \tag{1}$$

where N is the number of each fetch line drawn between −22.5 and + 22.5° for each of the three directions (NNW, N, and NNE).

The examined directions were chosen based on the morphology of the area; the islands and coasts of Greenland at the northwest part, for example, do not allow the development of long enough fetches to be considered.

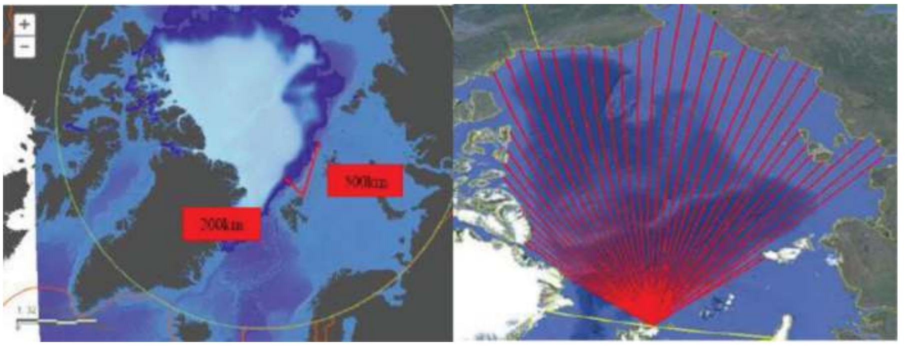

Figure 3.
Present maximum and minimum available fetch lengths north of Svalbard during early autumn periods (left). Future fetch lengths available in a free ice Arctic Ocean, between 320 and 55° in steps of 2.5°.

As long as the wind duration is considered, it is important to mention, here, that it would have been reasonable to have data with annual percentage of occurrence for each wind velocity in each direction. However, such data were not available; therefore, all the calculations are performed for specific events collected by the five stations over the past 15 years. So, for every fetch direction, one average wind speed is calculated. This means that every storm observed in the data is related to the three main directions (NNW, N, and NNE), and a mean wind velocity is calculated which is used to describe the wind at 10 m altitude.

Steps of the Jonswap method [5]:

Step 1. Calculation of the frictional wind velocity

$$u_* = W\sqrt{0.001(1.1 + 0.035W)} \tag{2}$$

where W = mean velocity at 10 m height.

Step 2. Calculation of the equivalent fetch, F_{eq}, depending on the duration of the wind:

$$\frac{gF_{eq}}{u_*} = 0.00523\left(\frac{gt_d}{u_*^2}\right)^{1.5} \tag{3}$$

where g = gravity acceleration, 9.81 m/s^2; t_d = the duration of the wind blowing; F_{eq} = the equivalent fetch length.

Step 3. Checking whether the wave is duration or fetch limited:

- If $F_{eq} > F$, then the wave is fetch limited, and the fetch, F, of the specific direction (Eq. (1)), needs to be used for the calculation of the characteristic height, H_s.

- If $F_{eq} < F$, then the wave is duration limited, and the F_{eq} should be used for the height calculation.

Step 4. Calculation of the characteristic wave height

$$\frac{gH_s}{u_*^2} = 0.0413\left(\frac{gF}{u_*^2}\right)^{0.5} \tag{4}$$

$$\frac{gH_s}{u_*^2} = 0.0413\left(\frac{gF_{eq}}{u_*^2}\right)^{0.5} \tag{5}$$

H_s = characteristic wave height.

Step 5. Calculation of the characteristic period of the wave

$$\frac{gT_s}{u_*} = 0.71345\left(\frac{gF}{u_*^2}\right)^{0.33} \tag{6}$$

T_s = characteristic wave period.

3. Results

Based on the previous methodology, the results of the calculation are as shown below. **Table 1** is showing the maximum possible fetch distances, as calculated using

Final fetches for each direction	
Direction	**Fetch F (km)**
North-Northeast	2661
North	3130
North-Northwest	2494

Table 1.
Final fetch lengths for each examined direction in a future ice-free Arctic.

Significant wave height and characteristic period							
Wind direction	**W (m/s)**	**t_d (hours)**	**u***	**F_{eq} (km)**	**Comment**	**H_s (m)**	**T_s (s)**
NNW	16.60	90	0.68	630.51	Duration limited	7.13	11.12
N	11.38	102	0.44	2418.72	Duration limited	9.03	14.94
NNE	14.55	36	0.58	2307.72	Duration limited	11.70	16.20

Table 2.
Final wave significant heights and characteristic periods in a future ice free Arctic.

Significant wave height and characteristic period							
Wind direction	**W (m/s)**	**t_d (hours)**	**Fetch (km)**	**F_{eq} (km)**	**Comment**	**H_s (m)**	**T_s (s)**
NNW	16.60	90	160	630.51	Fetch limited	3.59	11.12
N	11.38	102	150	2418.72	Fetch limited	2.25	14.94
NNE	14.55	36	350	2307.72	Fetch limited	4.52	16.20

Table 3.
Final wave significant heights and characteristic periods in today's conditions.

Eq. (1). This fetch is as expected in the case of an ice-free Arctic Ocean. Based on the aforementioned available fetch, the significant height of the waves together with the characteristic wave period was calculated and shown in **Table 2**.

Since the aim of the chapter is to compare the waves of the future ice-free scenario with those of today, wave characteristic heights based on current conditions are calculated and shown in **Table 3**.

All in all, the results show a significant increase of the height in the case of an ice-free Arctic Ocean. Actually, since the waves were duration limited, it is possible that such waves can be generated even with some permanent ice coverage. In detail, in the NNW direction, the wave height was almost doubled, from 3.59 to 7.13 m. In the North direction, the most significant change is observed with more than three times magnification of the characteristic height, from 2.25 to 9.03 m. Last, in the NNE direction, the prediction shows an increase from 4.52 to 11.70 m.

4. Discussion

The examined scenario of ice retraction should not be considered as topical only in the Svalbard area. Many measurements and experimental campaigns have been made in the eastern part of the Arctic Ocean, close to Beaufort Sea, where the sea ice cover has retreated significantly. Due to this dramatic retreat, especially in September 2012, 5 m height waves were observed in the middle of the basin. These were extremely large waves compared to what has been observed previously, testifying the assumption and the prediction of wave height enhancement due to ice surface shrinkage [2].

Apart from experimental campaigns and measurements, other studies using prognostic models have shown significant changes in estimated wave heights. These changes are undoubtedly linked to the increase of the fetch length created by the free-ice sea area. What is worth mentioning here is that the results showed also a rise in surface winds in the Arctic area, mainly in Kara, Laptev, and East Siberian Seas. On the contrary, at the western part of the Arctic region, in the Barents Sea, a drop of the winds and consequently the wave heights were observed [6].

Moreover, research supports the assumption that in areas where the ice coverage is shrinking, the wave phenomena will change. Results have shown a growth in wind speeds and an increase of the frequency of occurrence of waves of 2 m height. On the other hand, the same studies have shown that the change in extreme wave heights is marginal. The areas where the change is more significant are those of the northern parts of Barents Sea, Kara, and Chukchi Seas, whereas, in areas where the sea is already ice free during September and October, like the North Atlantic and the main part of the Barents Sea, extreme waves would be less frequently witnessed and great changes in extreme wave heights could not be expected [7]. In conclusion, the eastern Arctic regions and areas close to the north Canadian coasts will be influenced most by the absence of the ice [6].

It should be noted that the discussion above relates to wave heights only. To estimate the sea level during a storm surge in the case of wind in direction toward shore has been outside our scope. A storm surge that encounters a shallow shore could climb up the coast easily, causing floods and increased erosion, while a storm surge that approaches a steep shore is more likely to break early, thus, cliff or steep shore might be sufficient obstacle to prevent a storm surge from piling-up and reaching far inland. The combined storm surge and waves will cause flooding and damages far inland. An unprecedented amount of erosion could occur due to the effect of flooding and wave action, in particular, as higher temperatures cause the increased melting of permafrost along the shores, these effects will be discussed below.

5. The melting of the permafrost

Warmer climate and rising temperatures affect the Arctic in many aspects. Thawing permafrost is of the phenomenon that is detected in the Arctic. Measurements over long periods of time show that the permafrost temperature has rose by up to 2°C, and shallow permafrost layers in some areas have thawed completely. Consequently, the permafrost extent has shrunk by 30–80 km in Russia and up to 130 km in Canada [8]. In addition, a decrease in the snow cover creates a feedback mechanism of increasing temperatures. These phenomena lead to unstable grounds and emissions of greenhouse gases and toxicants that had been encapsulated in the frozen ground, and the permafrost is thawing in areas which were permanently frozen until recently [9]. The Arctic shores easily erode when hit by storm surges and strong waves. As a result of melted materials being washed away, the shore becomes even more susceptible to erosion [10].

The permafrost's thermal properties, conductivity, heat capacity, thermal diffusivity, latent heat, and thermal expansion, are among the key variables in determining permafrost melting and erosion rate. The thawing rate of a given soil depends on the soil composition (soil particles, ice, water, and air content of the soil) and the conditions of the physical environment. By knowing the content of frozen water in the ground and combining it with the assumptions that:

- Ice melts at temperatures above 0°C.
- The soil's thawing temperature is 0°C.
- All melted ground will wash away and erode by the impact of storm surge and waves.

It is possible to roughly estimate the amount of ground that will erode. When trying to assess coastal erosion, many uncertainties and parameters must be taken into consideration [10]. It was also necessary to make some simplifications and assumptions in order to get a model which can predict soil temperature.

An important parameter is the Degree days, the product of temperature and number of days. The degree days for an average temperature of 3°C over a period of 7 days is, for example, 3·7 = 21°C·d. The thawing index (I_{st}) is the number of degree days where the temperature is above the melting temperature (for water, 0°C). To calculate I_{st}, the degree days of each month were calculated: a monthly average temperature was calculated and multiplied by the number of days in each month. Under the assumption that the soil melting temperature is 0°C, I_{st} of the soil is the summation of degree days above 0°C for a one-year period.

The thermal models for coastal erosion that we used are described in [11]. For thawing depth estimation, first an evaluation of the permafrost soil consistency (soil profile and water content) was made, and then we were using the Stefan's equation (see [9–11]) to estimate the thawing depth in a partly frozen soil.

6. Permafrost erosion models

Several assumptions were made for estimating the amount of eroded soil during the one year period:

- Erosion occurs between May and September (the erosion process is negligible between October and April, due to sea ice and frozen soil).
- A big storm surge hits the shores at the end of each season (Spring, Summer, and Autumn) and erodes all melted soil.
- A season would count as a 50-day period.

As the average erosion rate in Varandey area was 2.7 m/year between 2005 and 2007 [11], based on these assumptions, the amount of eroded soil could be estimated.

The assumption that all melted material is being removed by a storm surge at the end of each "season" means that a new frozen soil layer is now exposed to heat and melting processes. A melted soil layer that stays intact could create an insulation layer that prevents heat penetration and decreases the melting processes, so the overall melted and eroded soil amount would be much smaller. For example, a single storm surge that hits the shore at the end of fall would hardly influence the erosion rate.

An erosion rate sensitivity analysis was made to assess and better understand the effect of the number of storms in a year on the total erosion rate. Three different

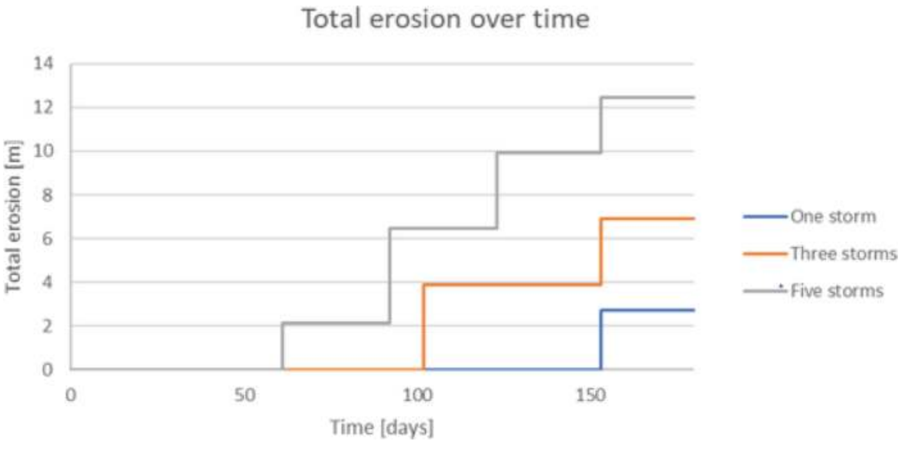

Figure 4.
The effect of number of storms on the total erosion as a function of time [10].

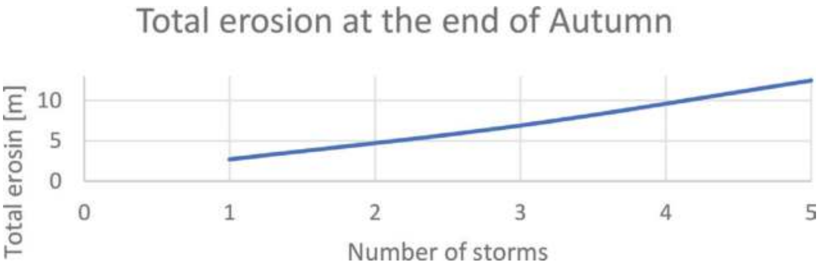

Figure 5.
Total erosion as a function of number of storm surges [10].

cases of storm surge were examined: the period between May and September was divided into sub-periods. It was then assumed that a storm surge hits the shore at the end of each sub-period and erodes all melted material.

As can be seen in **Figure 4**, the results correspond to the expectations—the erosion rate is increased as the number of storms rises. This result is further detailed in **Figure 5**, which shows the total erosion as number of storms/storm surges.

7. Conclusions

Undoubtedly, people and operations are facing extreme challenges in the Arctic Ocean. From polar lows and sudden storms to icing and iceberg drifts. However, more and more often, people are coming across extreme waves and permafrost erosion to an extent that has never been witnessed before. One of the reasons of this change is believed to be the melting of the ice and the alteration of the physical environment in the Arctic area. Wind blows over larger areas of the sea surface which consequently leads to more extreme wave phenomena and coastal erosion. Additionally, the increase of the annual average temperature and the prolongment of the warm periods influence the aforementioned phenomena which consequently lead to an increasing coastal erosion.

In this chapter, it is shown how such an ice shrinkage can influence the development of the waves by increasing the fetch length that will generate the examined waves. Additional research supports the aforementioned assumption, since measurements have testified that increase of the wave heights in areas where the waves were relatively mild. Of course, the outcomes from such research activities vary and further studies are needed to get a better view of the situation. What one can be certain of, though, is that permanent ice surface shrinkage will create a different wave and wind environment in the Arctic area. It is hard to say which of these factors will be the dominant and influence more significantly the situation.

The consequences of higher storm surge levels and higher waves and increased wave forces can be unpredictable. For instance, for already existing oil and gas platforms, which were designed according to historical data, unknown wave phenomena can, irreversibly, threaten human lives and assets. Therefore, in the case of higher waves, operators need to execute a reassessment of the air gap of the platform to avoid deck slamming; likewise, the strength of structures and safety factors should be reconsidered by including the uncertainties generated by the physical environment.

Due to increased wave action and melting of permafrost, Arctic coastlines and coastal infrastructure would see an increased stress from enhanced erosion and sediment circulation when sediment transportation along the coast alters.

In practice, newly opened Arctic seas will boost and encourage trading and navigation in the region since they will provide new paths with significant economic benefits. Shipping and offshore activities in areas which today we struggle to develop would be possible, but uncertainties related to storms and associated waves will remain, unless further studies are not made. Hazards that occur in open oceans might occur in the Arctic as well. For example, such hazards could be tsunamis, generated by earthquakes and motions of the seabed.

These are some examples of threats that so far were sleeping in the sea under the permanent ice coverage. Now, with its excessive melting, all these threats start coming on to the surface, putting in danger coastlines, people, and operations in the region.

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