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Technical and economic challenges for Arctic Coastal settlements due to melting of ice and permafrost in the Arctic

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Technical and economic challenges for Arctic Coastal settlements due to melting of ice and permafrost in the Arctic

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Abstract. The safety of Arctic coastal villages/ settlements is of concern due to melting of the ice cover and the permafrost in the Arctic. The immediate concerns for Arctic coastal settlements are due to a number of causes. These causes can be listed as follows: increased distances of open seas during the storm season, larger storm surges due to longer distances of open water without ice cover, larger waves due to longer fetch lengths, increased permafrost melting caused by warmer summer seasons, larger erosion of melted shoreline, increased number of storms causing accumulation of storm erosion effects, large flooding events destroying houses and facilities as well as infrastructure and fresh water reservoirs. There will be possible offshore slides due to melting of offshore permafrost with potential for tsunami generation, and riverbanks will erode due to the melting of permafrost. Slides caused by increased wetness (for example quick clay slides) will occur and housing and water reservoirs will be damaged. Furthermore, the winter seasons are shorter where winter roads can be utilized and the seasons for hunting from the ice cover is shorter. There will be economic losses for the villages/ settlements due to changing climate and in the case of needed relocation of the villages, the economic costs are huge. The paper discusses the effects of these concerns and will suggest certain mitigating measures, which only to a limited extent can relieve the situation. The ultimate solution will be relocation of the inhabitants and in some cases the settlement may be relocated to safe location further inland.

1. Introduction

There is a growing concern that the shrinking ice cover of the Arctic Seas (Figure 1, from [1]) will influence in a very negative way on Arctic Coastal Settlements/ Villages through effects of flooding and erosion. Furthermore, the melting of permafrost accelerates the difficulties to continue the traditional activities in these settlements.

This paper will summarize the meteorological and oceanographic effects causing these physical phenomena. Some Arctic communities, like Tuktoyaktuk (a coastal settlement [2], on the north-western coast of Canada), Varandey (a settlement, [3] – [6], in the Pechora Sea), Kivalina ([7], [8], Alaska, north of Bering Strait) and Newtok, Alaska (located, see Figure 2, on the Ningaluk River and now being relocated), have large problems with shrinking coastlines and work is in progress to protect and if necessary, to relocate the settlements to protected areas.

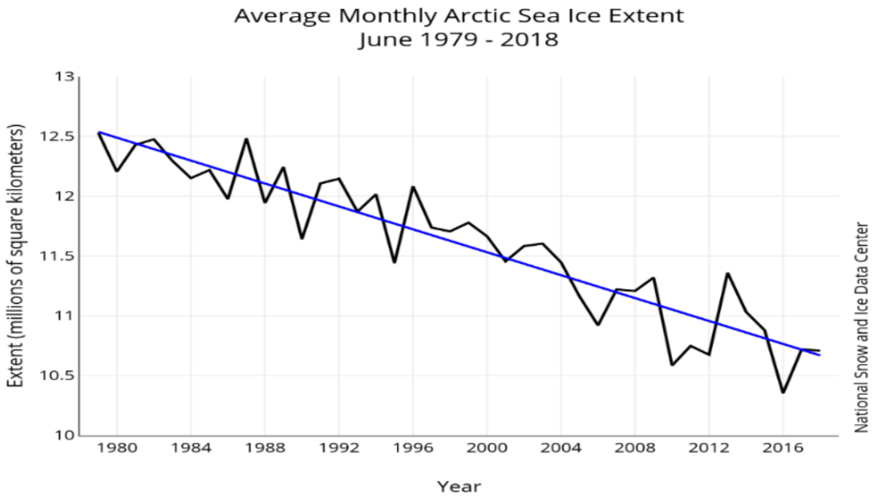

Figure 1. The variation of the ice extent in June in Arctic seas between 1979 to 2018: a decline of 4.1 percent is seen per decade during this period [1].

2. Effects causing shoreline erosion

One should be aware of the effects which contribute to the erosion. These will be discussed below.

2.1. Shrinking ice cover and longer fetch lengths for waves

One effect of the shrinking ice cover in the Arctic during the late summer and early fall season (when storms set in) is a longer fetch length for waves. In accordance with US Army Coastal Engineering Manual [9], the determination of the wave height and period as function of the fetch length, is given in the following. One can use these equations to calculate the increased wave height during storm periods of the year, when there is little ice-cover in the Arctic:

a) First, the frictional wind velocity is to be calculated:

$$u_* = W\sqrt{0.001(1,1 + 0.035W)} \tag{1}$$

Here:

W = mean velocity at 10 m height, m/s.

b**)** Then, the equivalent fetch length, F_{eq}, which depends on the duration of the wind, is to be calculated:

$$\frac{gF_{eq}}{u_*^{\,2}} = 0.00523\left(\frac{gt_d}{u_*}\right)^{1,5} \tag{2}$$

Where:

g = gravity acceleration, 9.81 m/s^2

t_d = the duration of the wind blowing

F_{eq} = the equivalent fetch length, m

c)Thereafter, one has to check whether the wave is limited by the duration of the wind of the fetch length:

If $F_{eq} > F$, the wave is limited by the fetch-length and the actual open water distance. The fetch, F, of the actual wind direction, shall be used to calculate the characteristic significant wave height, Hs.

If $F_{eq} < F$, the wave is limited by the duration of the wind, and the value F_{eq} is to be used for calculation of the significant wave height.

d)The calculation of the characteristic wave height proceed as follows:

$$\frac{gH_s}{u_*^{\,2}} = 0.0413\left(\frac{gF}{u_*^{\,2}}\right)^{0,5} \tag{3}$$

$$\frac{g\mathbf{H_s}}{u_*^2} = 0.0413\left(\frac{gF_{eq}}{u_*^2}\right)^{\mathbf{0,5}} \quad (4)$$

Note that H_s is the characteristic significant wave height.

e) Calculation of the characteristic period of the wave:

$$\frac{g\mathbf{T_s}}{u_*} = 0.71345\left(\frac{gF}{u_*^2}\right)^{\mathbf{0,33}} \quad (5)$$

T_s = characteristic wave period

Through the analysis, one finds the effect of the distance of the open water on the significant wave height. It is obvious that larger waves will increase the exposure of the coast to erosion [10], [11].

2.2. Storm surge effects

During a storm, the water is blown in the direction of the storm, causing a pile up of water near the shore. This effect is very pronounced in areas with gently sloping sea bottoms like the coast of Netherlands and the Gulf coast of the US. The flooding of the New Orleans area during the Katerina hurricane was mainly due to storm surge effects and waves caused the overtopping of the dykes [12]. Similar conditions exist in parts of the Arctic seas where the relatively shallow seas have gentle slope towards the shore.

The height of the storm surge depends on the inverse barometer effect (reduced atmospheric pressure in a low-pressure wind field), the wind velocity, the fetch length and the invers of the water depth. It is important to understand the effects of fetch on the height of the storm surge η as reduced ice cover would lead to increased surge effects. According to [13] the effects can be summarized as:

i. Inverse barometer effect, 1hPa pressure decrease ≒ 1cm surge:

$$\eta_p = \frac{\Delta P}{\rho g} \quad (6)$$

ii. Wind surge setup

$$\eta_w = \frac{3}{2}\frac{\tau_s L}{\rho g h} \quad (7)$$

Where:

τ_s (= $\rho_{air}\, C_D V^2$) (wind stress: function of square of wind speed), L (horizontal scale of fetch), 1/h (inverse of water depth).

For further references on storm surge effects, see [14], [15].

The combined effects of the tidal amplitude, the storm surge and the wave height define the level of the water impacting the shore line. It should be noted that any general sea level rise should be added when studying long term effects. The effects of sea level rise have been studied for many years, see for example [16] where a summary of the concerns is given. Furthermore, any reduction in shore level due to melting and collapsing permafrost would also cause water to access further inland.

The hazardous situation discussed above is confirmed by recent events. An example is an event on July 24th 2010, in the Varandey area in northern Russia where the oil treatment and storage terminal was flooded even if the terminal was located several kilometres away from the coast. Furthermore, the airport runway nearer the coastline was severely damaged, by the excessive flooding [11]. This event was caused by a combination of storm waves, surges and tides. Shoreline erosion occurred as the coastline permafrost is melting.

2.3. Permafrost melting effects; shoreline erosion

The permafrost is melting in the Arctic due to average increase in the air temperature. This melting exposes coastal soft sediment and sand fronts to increased erosion. The erosion will depend on the action from the sea and for every flooding situation caused by high seas, the sea will "take a bite" of the coast. In case of an increased number of the storm events, the erosion will increase. A model for the increased erosion is proposed in [17].

Several assumptions are made in this paper to estimate the amount of eroded soil during a period of one-year:

- Erosion is occurring between May and September only as the erosion process is negligible during the season of frozen soil (between October and April).
- At the end of each season (Spring, Summer, Autumn) a storm surge hits the shore, eroding all melted soil.
- A season is defined as a 50 days period

Between 2005 and 2007 the average erosion rate in Varandey area was $2.7m/yr$ [6]. Using these actual data and referring to the above assumptions, the amount of eroded soil could be estimated. As it is assumed that all melted material is being removed by a storm surge at the end of each "season", frozen soil is then exposed to heat and melting when the insulation layer is removed. The insulation layer decreases the melting processes and therefore, a single storm surge at the end of fall, influences the erosion rate much less than repeated storms.

To assess the effect of the number of storms in a year on the total erosion rate, a sensitivity of the erosion as function of the number of storms was carried out in [16]. The period between May and September was divided into sub-periods. It was, as discussed above, assumed that a storm surge hits the shore at the end of each sub-period, eroding all melted material, Figure 2.

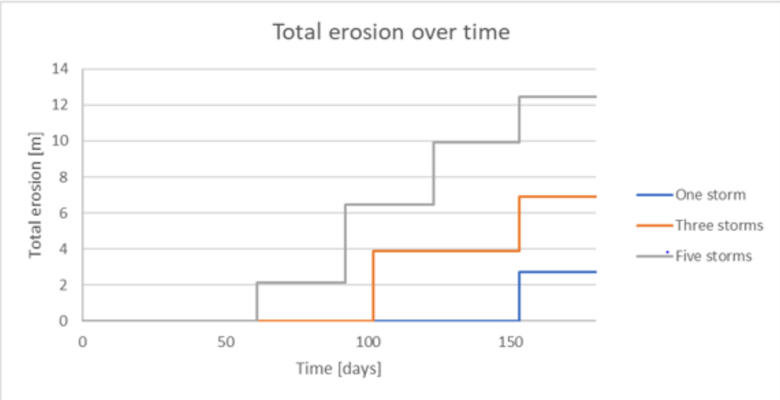

Figure 2. The total erosion as function of time as caused by the number of "storms" [17].

Figure 2 shows the erosion during the storms. These results are summarized in Figure 3 which shows the total erosion as number of storms/ storm surges.

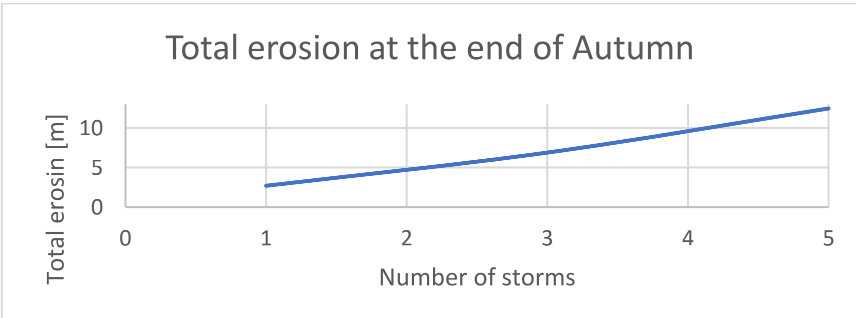

Figure 3. The total erosion given as function of the number of storm surges [17].

These suggested erosion rates are in line with measurements documented in [18] where actual erosion measured at Drew Point, Alaska was 15 m/year during the years 2008 to 2011.

A study of the effects of the coastal erosion in the Arctic due to breaking waves over a slope and a vertical bluff has recently been carried out [19]. The study shows a scour depth of approximately one meter near the toe of the bluff over a time of 300 s. This scour depth was within the range of actual scour depth observed at the Bjørndalen - Isfjorden coastline at Spitzbergen in September 2015. There is no doubt that scour can accelerate very rapidly during large wave attacks.

Onshore, melting permafrost causes landslides to occur and even offshore there are slices of permafrost which have not yet melted even if the permafrost was generated during the ice age when glaciers covered the location.

Onshore slides occur more frequently when the permafrost is melting. The Trans Alaskan Highway and the Trans-Alaskan Pipeline are threatened by slope failures [20], see Figure 4. Relocations may be necessary. For further reference, see also [21]. Similarly, areas with quick clay are very susceptible to huge slides when the weather becomes warmer and wetter. A recent (June 2020) quick clay slide in Alta, Northern Norway, took 8 houses (no fatalities) and was followed by a a hughly damaged road, Figure 5 [22].

Figure 4. A massive slow-moving avalanche made of thawing Alaskan soil is approaching the Trans Alaskan Highway and the Trans Alaskan Pipeline. Image by Eli Kintisch, Alaska, 2015 [20].

Figure 5. Quick Clay slide after a wet period. Photo Anders Bjordal / NVE / NTB Scanpix [23].

Melting of the underwater permafrost will take place as the water temperature heats up during the summer. In this respect we have to keep in mind that sea water with 2.5°/₀₀ salt will freeze up at -1.8°C. The fresh water moisture in the permafrost will, however, melt at 0^{O}C. In case of sloping seafloor, there is a certain probability of sea floor slides that will be followed by tsunami waves that could hit low-lying coastal settlements hard. On the morning of June 17, 2017 an Arctic tsunami destroyed the settlement Nuugaatsiaq on Greenland [24]. There were four fatalities. Due to the treats of further sea slides and tsunamis all 84 inhabitants were evacuated and moved to another location. Presently, only a handful of persons have dared to return to live at the location. It should be noted that the fjords on Western Greenland are deep and sea slides would not be unexpected.

2.4. Permafrost melting effects; built structures

During the warm summer months the upper layer of the permafrost is melting. As built structures are supported on the permafrost, the structures will settle in case the permafrost is melting more than predicted. These buildings will be dangerously damaged and concrete buidings will in particular be non-inhabitable. Even buildings made from wood will be unsitable for use.

Of particular concern is roads that will need annual huge repairs if the permafrost melts below the road foundation. Similarly, are the concerns for status of airports. Even the main airport on Greenland at Kangerlussuaq may be unsuitable for use from 2024 and the pavement is presently showing cracks [25]. The Arctic infrastructure is thus at risk [26].

Settlements close to the seafront face the challenge of having their fresh water supply infiltrated by salt water during flooding events. The situation could become critical for the inhabitants and it may be necessary to invest in de-salinity equipment to ensure back-up. The process of melting permafrost will also cause disturbance to the fresh water supply. At University of Oulu in Finland, projects are undertaken jointly with University of Anchorage to study the availability of fresh water in Arctic communities [27].

Figure 6. Kivalina is a remote Alaskan village that needs to be relocated due to climate change [25].

3. Management of coastal erosion and melting permafrost

Management strategies to limit coastal erosion are developed world wide for different types of sediments [28]. The very rapid erosion of the Arctic shorline caused by the melting permafrost and the worsening effects of increased storms, require expensive measures, such as ue of sandbags, protection by stones or concrete. The effects are, however uncertain due to the tawing permafrost and relocation are considered and even implemented as for Newtok. Similarly the settlement of Kivalina may need to relocate, see Figure 6, [29]. For a thorough discussion, see [30]

Specific problems are encountered for these relatively small Arctic settlements as the entire settlements are located close to the sea. The erosion affects, thus, the entire settlements, including the access airstrips that may have to be relocated further inland. This will also cause the needs to build new roads. An alternative would be to use helicopters more frequently with gathering airports located away from the exposed locations. A particular phenomenon for Utqiaġvik (formerly named Barrow, the most northern settlement in Alaska) is that the fresh water reservoirs of the settlement may soon be flooded due to the erosion and the high seas, Figure 7. A relocation may be needed with subsequent needs for piping of fresh water. The costs must be compared to investments in a de-salinity plant.

Figure 7. Utqiagvik, the city formerly known as Barrow, AK (File photo courtesy of Wikipedia).

A study of the use of "geo-bags" for shoreline protection was conducted at NTNU, Trondheim [31], Figure 8. The study concluded that the "textile must be sufficiently robust to withstand the actions to which they are exposed. Annual replacement of lost bags would be required".

To identify sustainable methods to protect Arctic Settlements from coastal erosion is a very challenging task, in particular where the coastal sediments are soft. The investments in protection may, however, prove very economical in comparison with relocation of the entire community.

The discussion presented in this paper should also be seen in view of the hydraulics of Arctic rivers as presented by the author in [32]. The riverbanks will erode due to the melting of permafrost and the river will widen. Further down the river, the eroded material will settle and cause generation of sand or silt banks causing problems for river traffic.

Regarding the melting of the permafrost, this is a matter of huge concern for all Arctic communities and infrastructure [26], [27]. However, the proximity to the sea enhances the problems associated with permafrost melting at coastal settlements due to the expected increased erosion of the shoreline.

4. Economic challenges associated with erosion and permafrost melting of the Arctic shoreline

The economy of relocation of a settlement is very large as relocation needs to come with all infrastructure. A cost of US$ 1M per person is quoted for the case of Kivalina [33]. The option to repair and protect will cause high “operational costs”, however, investments will be lesser until relocation or transfer to a larger cluster will be necessary.

The author is of the understanding, however, that most countries have as a policy to inhabit all their land for strategic reasons and a thorough economic/ strategic analysis is necessary to identify the way forward for the Arctic threatened settlements.

Figure 8. Use of “geo-bags” is tested for reducing erosion at Svea Mine, Spitsbergen (Reproduced from [31]).

5. Conclusions

From the above examples and discussions, it is concluded that the warmer climate causes large challenges to coastal Arctic settlements. The erosion of the shoreline represents a threat to the infrastructure, in particular to buildings located near to the shoreline or a cliff consisting of clay or sand close to the shoreline. Management strategies are implemented to reduce the erosion, however, in some cases relocation of the entire settlement seems to be the ultimate solution. In some situations, the expenses may not warrant the upkeeping of the settlement and those living at the location may have to move to larger and better protected communities.

In estimating the erosion, all factors influencing the erosion and the speed of the erosion must be taken into account. These include increased wave heights caused by the longer fetch when ice is retracting, lack of ice cover to protect against early fall storms, storm surge effects where increased surges are expected due to longer fetch when there is long distance from the shore to the ice edge. For longer perspective analysis, the possible sea level rise must in addition be taken into account. Furthermore, factors important for erosion include the accelerated melting of the permafrost of the shoreline due to increased temperatures in the Arctic, making the shoreline more susceptible to the attack of the waves riding on the surges.

The paper is prepared to ensure that all technical aspects causing erosion are implemented in evaluation of erosion potential and shoreline erosion management for Arctic settlements. The additional concerns related to melting of the permafrost are enhancing erosion of shoreline as well as causing problems for all built infrastructure in the area.

The technical and economic challenges for Arctic Coastal settlements/ villages are indeed huge. An increased understanding of the erosion processes is needed [34] for a sustainable policy to be developed by the authorities in charge.

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