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Impact of and solutions to effects of climate changes for Longyearbyen, Svalbard, Norway

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Abstract: Climate changes forces us to make significant mitigation and adaptation measures. As temperature rises and the environmental conditions changes, a variety of challenges occur. Across the whole globe, harming consequences are already being experienced. The Arctic region is particularly vulnerable to changes in Earth's climate system, especially because of the albedo effect, and the region is already heavily impacted. Primarily through the melting of ice, both sea ice and glaciers, permafrost thawing and changing precipitation patterns. Longyearbyen, Svalbard, is one examples of a society having to change as a direct result of global warming. This paper focuses on the challenges Longyearbyen will be facing and possible adaption methods and solutions. Because of environmental changes, the risk of natural hazards will increase, infrastructure will get damaged and traditional engineering methods will be impossible to implement. This is threatening to human lives as well as the habitat and survival of mammals, birds, and plants. It will be essential to find ways to predict and limit the effects of climate challenges, by protecting people and infrastructure from them. This will require innovation, adaption and risk-taking. By investigating the climate challenges facing Longyearbyen and possible ways to address them, this paper emphasizes the urgency of tackling the effects of climate changes in the Arctic in order to protect the communities in the Arctic region.

1. Introduction

The term climate change is used to describe the long-term variation of typical weather patterns, regionally or globally. Throughout the history, the Earth's climate has continually changed and gone through cycles with periods of warming and cooling [1, p. 81]. These climate variations are caused by various natural factors [2], and such processes occur slowly. However, large, and relatively rapid variations during the later decades are ongoing, indicating a change happening at a faster rate due to influence from human activities [1, p. 84]. The temperature is rising most rapidly in the Arctic, and Longyearbyen is one of the places on Earth where the average temperature is rising fastest. Further warming will amplify the melting of ice, thawing of permafrost and change of precipitation patterns, which will lead to severe consequences [3]. This paper will investigate how climate changes may affect the Arctic town Longyearbyen located at 78.25^{o} North and how solutions to these challenges possibly can be tackled. Firstly, it will discuss why an increasing risk of natural hazards such as avalanches, landslides, and floods, necessitates major measures. Then, several adaption challenges regarding infrastructure and technical solutions will be explored. Effects of climate change on terrestrial and marine ecosystems are not part of this study, however, these effects will also cause major changes to the landscape.

2. Climate change

2.1 The globe's energy budget

The Earth's average surface temperature is maintained by a balance in the energy budget. When incoming short-wave solar radiation reaches the Earth's atmosphere, some is absorbed by gases, some is reflected into space by clouds or aerosol particles, and the rest passes through to the surface where it again is either reflected or absorbed [4]. Bright surfaces such as snow and ice reflect solar radiation very efficiently. In addition, there is outgoing radiation. The Earth's surface emits long-wave radiation, and the atmosphere also emits radiation, however, because of greenhouse gases this radiation is emitted both towards space and the Earth's surface, which is what causes the greenhouse effect. If the incoming and outgoing radiation is not balanced, the temperature increases or decreases which in turn eventually affects the climate [1, p. 25].

Human activities influence the global surface temperature. Most significantly by adding to the natural concentration of greenhouse gases in the atmosphere, primarily through the burning of fossil fuels. Furthermore, emission of methane, either caused by human activities or by leakage of methane from melting permafrost is of large concern. The greenhouse gas effect of methane is suggested to be 25 times more powerful than the emission of CO_2 [5]. This creates an enhanced greenhouse effect where more heat is trapped in the lower atmosphere leading to warming of the surface [1, p. 28].

2.2 Amplification of climate changes in the Arctic

Arctic amplification refers to the Arctic being the fastest warming region on the planet. An analysis from 2022 shows that since 1979 the temperature in the Arctic has risen nearly four times faster compared to the rest of the planet [6], as shown in Figure 1.

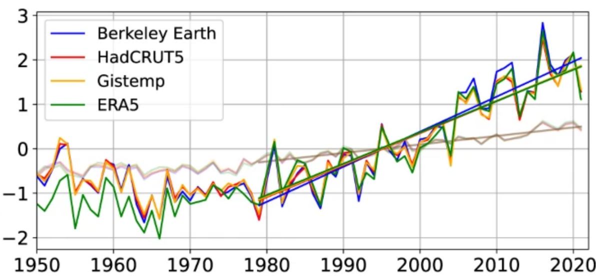

Figure 1. A comparison between the global mean (light colours) and the Arctic, 66.5 to 90º N (darker colours) average temperatures for the years 1950 to 2021 [6].

Legend: Berkeley Earth (non-profit research organization), Had CRUT5: the Met Office Hadley Centre/Climatic Research Unit version 5.0.1.0, Gistemp: NASA's Goddard Institute for Space Studies Surface Temperature version 4, ERA5: Data produced by the Copernicus Climate Change Service.

There are many processes contributing to the Arctic amplification. One of the main ones is the sea-ice albedo feedback. This process allows more heat to enter the Arctic system. As it gets warmer in the region, sea ice melts. When this happens, more of the Arctic Ocean gets exposed to solar radiation resulting in more warming as the dark ocean surface absorbs the radiation instead of reflecting it. This in turn leads to even more melting and warming. Another process involved in the Arctic amplification is the thawing of permafrost. When permafrost thaws, organic matter such as methane and carbon dioxide is released, leading to more greenhouse gases entering the atmosphere [7]. This in turn contributes to global warming, and permafrost thawing therefore makes up a feedback loop. What happens in the Arctic does not only lead to harming consequences locally, but it also affects the rest of the globe.

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3. Longyearbyen, Svalbard, Norway

Longyearbyen is the administrative centre of Svalbard. The town is on the main island Spitsbergen and has approximately 2400 citizens [8]. The geography of Longyearbyen is characterized by mountains, glaciers and fjords as can be seen in Figure 2. In addition, Arctic tundra with limited vegetation and permafrost soil is widespread. The Arctic wildlife is diverse and consists of species that have adapted to the harsh environment, and Longyearbyen has a large amount of rare and endangered plant species. The town also holds the location of the Global Seed Vault, a facility that serves as a backup storage for seeds from around the world. Currently, the vault holds over 1.2 million seed samples from more than 6000 plant species [9].

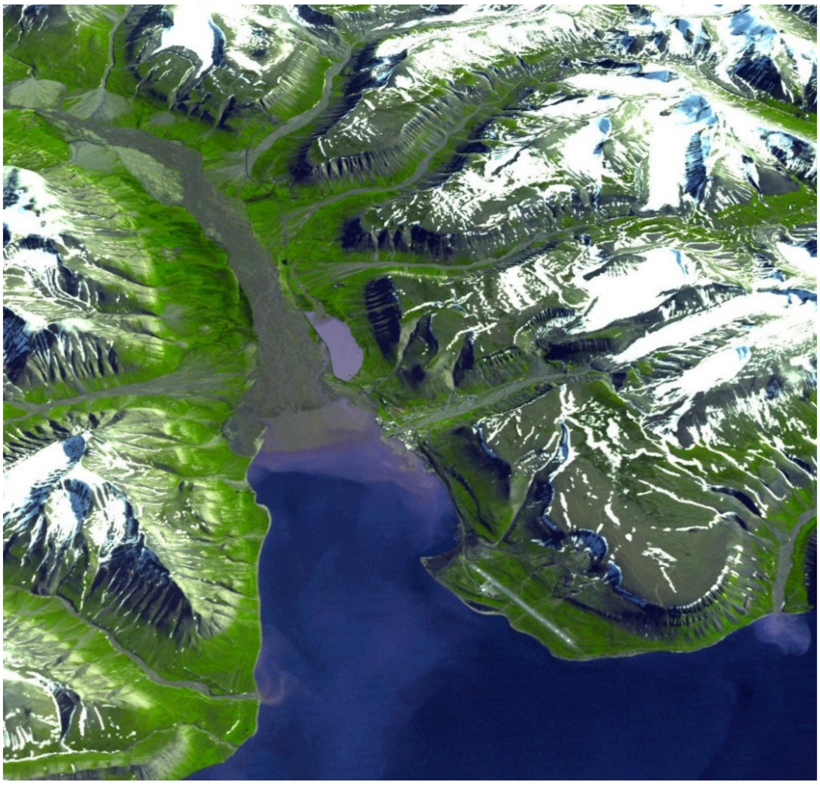

Figure 2. Image of part of Spitzbergen with Longyearbyen. Image from NASA [10].

3.1 Climate changes in Longyearbyen

Historical statistics from the weather station at Svalbard Airport give some insight in the weather trends Longyearbyen is experiencing. The station was established in 1964 and measures temperature, precipitation, snow depth and wind. Figure 3 illustrates the significant upward trend in temperature. This rapid warming causes increased melting of glaciers, permafrost thawing and precipitation, as well as more frequent extreme weather events.

When glaciers are melting in Longyearbyen, more water is added to the hydrological cycle. The most important effect of this in Longyearbyen is the increased wetness of the ground. Higher temperatures in Longyearbyen also increases the thawing of permafrost which makes the soil unstable. A monitoring station placed nearby Longyearbyen (at some higher location though) is indicating an increase in the ground temperature of about 1.8 ºC over the period from 1998 to 2023 [11]. The trend of the annual mean ground temperature in Longyearbyen is heading towards crossing the zero degrees mark. This would mean the end of permafrost in Longyearbyen. Over time, the permafrost will gradually thaw more and more until it all eventually is gone. The thawing will change the terrain drastically, with respect to the effects of landslides and vegetation.

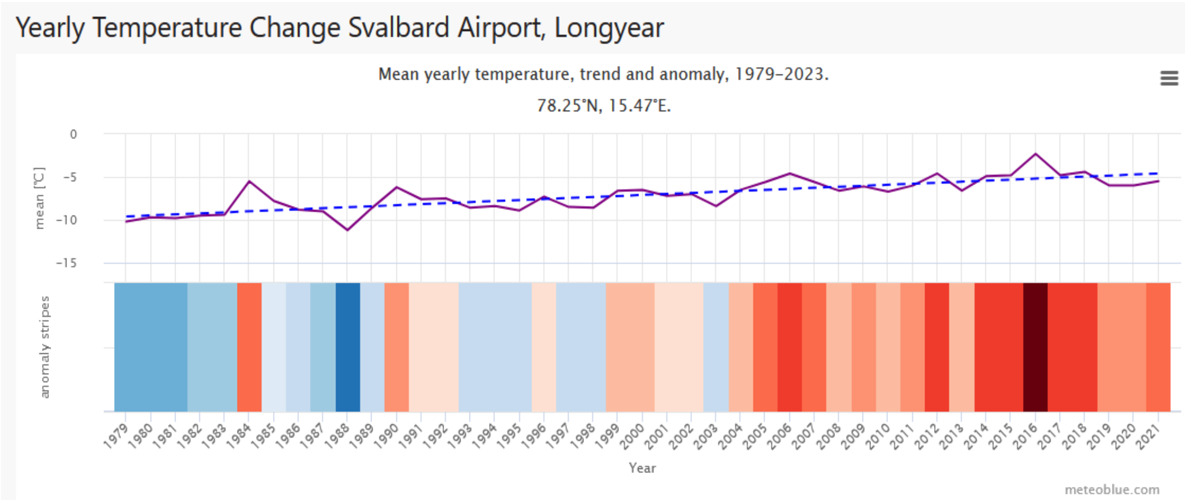

Figure 3. Yearly temperature change at Svalbard Airport, Longyearbyen, 1979 – 2021 [12].

The weather statistics also reveals that the amount of precipitation in Longyearbyen is increasing, which is an effect of the rising temperature [12]. Climate models predict that rain will be the dominating form of precipitation in the Arctic in the future. A larger part of snowfall will melt before reaching the surface because of the atmosphere being warmer. This will be particularly noticeable in autumn and spring when temperatures are close to zero degrees. It will get wetter also because warmer air has a higher capacity of holding moisture, leading to heavier rainfall [13]. Such changes in the weather pattern can lead to more permafrost thawing.

During recent years, temperature records and events of damaging avalanches and serious floodings have been linked to the changing climate. Other consequences concerning infrastructure are also present. Measures such as building of avalanche hindering barriers have been implemented to prevent and reduce damage of climate change in Longyearbyen [14].

4. Natural hazards caused by the effects of the warming climate

The changing climate in Longyearbyen will change the landscape as we know it, making it more likely to be affected by natural hazards such as avalanches, landslides, and floodings. Longyearbyen has experienced such situations in recent years. Mass movements (snow and ground slides) and accumulation of water are extremely dangerous and damaging. Therefore, it is important by the engineering society to identify ways to prevent, protect, and monitor these naturally triggered dangers.

4.1 Avalanches

In December 2015, eleven houses in Longyearbyen were taken by an avalanche that was released from the mountainside of Sukkertoppen. The incident resulted in several people getting injured and two people losing their lives [15], Figure 4. Because of Longyearbyen's isolated location, doctors and a surgical team had to be sent by plane from Tromsø to assist with the injuries, a trip that takes over an hour. Additionally, wounded people had to be transported to Tromsø. Homes and other buildings were left in ruins and the whole city contributed with search, rescue, and recovery. In 2017 another avalanche hit the town causing major damage. Both events have been linked to climate change as weather conditions were untypical for the season [14].

Figure 4. Damaged houses after the avalanche December 2015 [15] (photo: Geir Barstein)

The wetter climate and melting glaciers are huge avalanche triggers as the terrain becomes less stable. In order to understand the behaviour of snowpacks and avalanches, it is crucial to know what type of snow is present and its properties. However, this can be difficult, especially as the nature of avalanches have started changing due to global warming. As it gets milder and wetter, it is likely that the prevalence of wet-snow avalanches will increase in Longyearbyen. Such avalanches have a completely different dynamics than the dry avalanches that by far are the most common today. Higher levels of water in the snowpack makes it denser and weakens the bonds and layers, creating instability. Avalanches can also be very difficult to forecast and changes in weather patterns such as temperature, precipitation, and wind, expose new areas to avalanche risk [14]. For example, if wind direction and speed changes, that will affect where snow accumulates and thus potential avalanche risk areas.

4.2 Landslides

Permafrost thawing, more precipitation as rain and less sea ice contributes to more erosion and ground instability. This increases the probability of landslides. Due to the permafrost layer in Longyearbyen, the ground has the potential to become extremely wet. This is because the water does not have anywhere to escape as soon as it reaches down to the frozen ground. Therefore, the groundwater flow is highly restricted by permafrost. A higher amount of water increases the mass of the melted ground material and therefore also the gravitational driving force. Additionally, water can elevate pore-water pressures in the ground to the threshold of failure.

Another potential trigger for landslides is coastal erosion due to loss of the permafrost. Furthermore, as the sea level increases, more of the coast gets eroded, which in turn makes the terrain more vulnerable. So far, this has not been a significant issue in Longyearbyen, although a recent sea-cliff erosion failure occurred at Forkastningsfjellet northwest of Adventfjorden [16], see Figure 5. A larger failure could generate waves that would be of grave concern in Longyearbyen. Note that in other Arctic regions such as Siberia, coastal erosion represents a visible challenge [17].

Figure 5. Sea-cliff failure of approx. 300,000 m^3 of rock at Spitzbergen, not far from Longyearbyen, August 2016. (Photo: J. C. Nygaard [16]).

Figure 6 is a map showing Longyearbyen's risk picture, which considers landslides and floods. The red zones indicate the highest risk and shows areas where the probability of a landslide occurring is once every hundred years. However, keep in mind that the IPCC report [3] has signalled that extreme weather events have lower return intervals than thought, a more updated version would possibly suggest that the risks are somewhat more frequent than this figure says. While most of the infrastructure is placed outside the risk areas, we can find a few buildings and some roads even inside the red zones. A landslide will clearly have the potential to cause major destruction and threaten the safety of people.

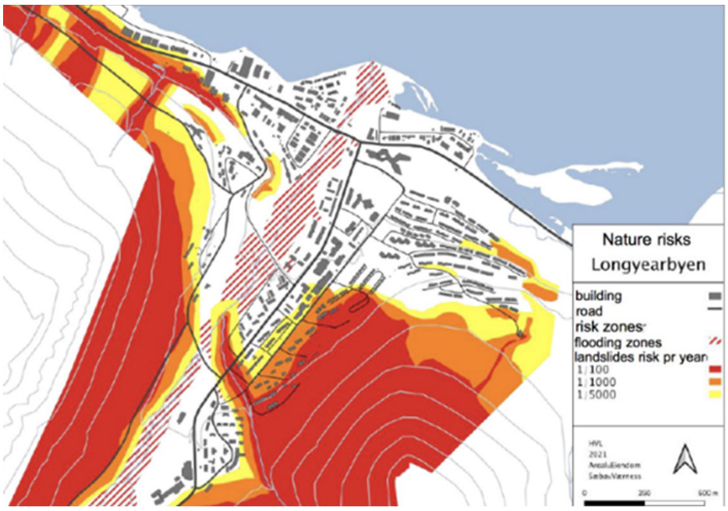

Figure 6. Areas of natural risk in Longyearbyen. Locations of highest flooding and landslide risk [18].

4.3 Flooding

Climate changes also increase the risk of flooding in Longyearbyen. When glaciers melt and permafrost thaws, large volumes of water get released. Additionally, it is expected that extreme weather events such as heavy rain or snowfall could become more frequent [14]. This will lead to increased runoff. It is most likely to happen in areas where permafrost and ice are close to the surface, and water cannot be absorbed into the ground or reach the river, resulting in the ground quickly getting fully saturated with water. If the amount of accumulated water is large enough, this can lead to flash floodings in downstream areas. One of the largest concerns is the Longyear River getting flooded. The river stretches through the Longyear valley, passing the town, before it runs out into Adventfjorden. Figure 6 reflects this risk of the river being flooded as water flow increases, by the marked flooding zones along the river.

Some years ago, the entrance to the Global Seed Vault (Figure 7), experienced several floodings mostly due to permafrost thawing, but also because of increased amounts of precipitation [19]. In the summer of 2020, Longyearbyen experienced record high temperatures which caused water from a melting glacier to flood a mine outside the town [20]. These events were reminders of how the climate change in Longyearbyen affects resources and societal functions.

Figure 7. The Svalbard Global Seed Vault [21] (Image Ambrosetti Tonatiuh)

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5. Solutions to mitigate the effects of climate change

Because of Longyearbyen's isolated location and limited population, it is important to take great measures to reduce the severity of events when they occur. When time is crucial, transportation to other cities and lack of necessary equipment or capacity can be fatal. As the risk of avalanches, landslides and floods increases, it also becomes important to prevent destruction because of financial reasons. Such events usually require major clean-up work and reconstruction. This is both time-consuming and expensive, meaning frequent occurrences would be less manageable in the long run. Additionally, areas that today are considered safe may in the future lie in the path of new potential run-out zones, which can be very difficult to anticipate and therefore weaken the safety.

5.1 Technical solutions

There has been taken various measures in Longyearbyen to protect the infrastructure from damage, and there are comprehensive building regulations for the town. New buildings in Longyearbyen are being built on steel pillars that are drilled far down in the ground, through the permafrost and into the underlying bedrock [17]. Today, facilities are also lifted higher above the ground than traditionally to further separate the permafrost from the warmth radiating out of the buildings. Additionally, there have been placed sensors to measure the temperature and moisture of the ground, so that it can be better monitored.

5.1.1 Avalanche barriers. Longyearbyen has an advanced alert system that updates citizens about the daily avalanche situation. This local warning system, that uses data from sensors and local observers, was a direct result of the avalanches in 2015 and 2017 [14]. Evacuations happens regularly and many people have been permanently relocated to avoid risk zones. There has also been placed massive protection barriers in many areas. For example, numerous avalanche fences have been built on Sukkertoppen to protect structures that lie nearby (Figure 8). The situation prior to building the barrier is clear from the photo in this figure, i.e. no protection existed against an avalanche. At the upper and lower foundation, piles made of steel are drilled into the ground before additional rock anchors are secured into the bedrock to make sure all tension forces are accounted for [20]. Avalanche fences reduces the speed and intensity of the flow, as well as it traps snow and debris from the avalanche.

Figure 8. Avalanche fence barrier, Longyearbyen. (Photo: Maria Philippa Rossi/UNIS [14].

5.1.2 Monitoring. In Longyearbyen the permafrost layer is being monitored to better assess the risk of landslides, and there has been taken measures to flood-proof the Longyear River [14]. After the floodings of the Global Seed Vault, a major reconstruction project was conducted outside the vault. A new waterproof entrance was built, drainage ditches was added to carry away meltwater, and the ground surrounding was stabilized by getting artificially frozen and protected by a 20 meters high frozen wall, [19], as shown in Figure 9, which can be compared with Figure 7 that was taken at the inauguration of the Vault. When the vault was first built, it was not anticipated that such efforts would be needed.

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Figure 9. For protection of the entrance to the Svalbard Seed Vault, a 20 m high frozen wall is created to stabilize the permafrost [19]. (Photo: Thomas Nilsen, Barents Observer)

As the conditions in Longyearbyen are getting warmer and wetter, it is crucial to be able to predict the behaviour of natural hazards. It will be important to further advance monitoring systems in the future, so they can give more precise information about when and where a potential avalanche or landslide will hit. Frequent evaluations and risk assessments should be done so that mitigation measures can be implemented [22], and the safety of the citizens can better be ensured.

5.1.3 The roads. Roads are highly exposed to the thawing permafrost. Potholes and cracks can become a frequent issue as the ground becomes unstable and shifts. Repairing or replacing are expensive processes, so there are strict regulations for road building in Longyearbyen. The roads are built on a specific fibre cloth that separates the masses from the underlying raised gravel bed, so that heat radiation which can further contribute to permafrost thawing is reduced [23]. The Svalbard Airport runway has experienced unevenness due to thaw subsidence. In 1998 a major, expensive reconstruction was carried out, however, it was only partly successful and is today regularly subject to re-pavement reparations.

5.1.4 Piping. In Longyearbyen, piping (water and sewage) that are buried in the ground are prone to break or rapture when the properties of the ground change. This can lead to leakage of pollutants and emissions of hazardous gases. Additionally, it is very costly and challenging to install pipelines in the ground in Longyearbyen because of the changing permafrost conditions. Because of the vulnerability of pipes running below the surface, the major piping systems in Longyearbyen are found above the ground. This includes water supply, sanitation, and district heating [23]. Above the ground, these systems can be made more flexible and adjustable. This reduces the risk of damage, as well as it makes repairing and maintaining easier. The pipes should be insulated to avoid freezing as well as avoiding outward radiation. It is important that there is no leakage leaving the pipes or the ground exposed. Additionally, the terrain must be levelled before construction can begin, Figure 10.

Figure 10. Piping over the ground on permafrost [24].

6. Conclusions

Climate change is drastically changing the Longyearbyen. The warming will impact the human communities, infrastructure, and landscape in the region. Retreating glaciers, changing weather patterns and permafrost thawing, as well as more frequent extreme weather events are all causing major challenges for Longyearbyen. For example, by increasing the risk of natural hazards such as avalanches, landslides, and floods. Additionally, essential structures and facilities, including buildings, roads, and pipelines, are getting more vulnerable. The survival of mammals, birds and plants will also be affected, as well as people's health and well-being. These challenges threaten the sustainability of the community. Extensive measures have already been taken. However, for the future of the town it will be important to continue coming up with new and improved ways to prevent, protect and restore. Because of Longyearbyen's isolated and northerly location, natural hazards are particularly critical. By reducing the severity of such events, we can make sure the consequences are restrained to a manageable level.

This can be done by relocating absolutely all structures to areas that are not at high risk, building more protection barriers and continuously improving monitoring systems to give early warnings. Infrastructure damage is also a concerning issue as buildings, roads and pipelines are particularly exposed to destruction when the ground loses its stability.

The mitigating effects of the activities undertaken to protect the buildings and the population of Longyearbyen are considered effective as improved safety against the effects of permafrost melting have been implemented in all building projects. The effects of increased precipitation are taken care of by ensuring drainage and use of material that can resist water and by constructing avalanche barriers that can resist large avalanches to form. There have been made many innovative improvements and solutions, however, we must make sure these can serve long-term and preferably permanent.

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