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Lessons learned from climate risk governance in the hotspot of climate change

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Understanding and adapting to climate change is one of the greatest ongoing challenges society faces. No other areas in the world experience climate changes as fast as the Arctic region. Longyearbyen, a settlement in the Norwegian archipelago Svalbard is located in the hotspot of the climate changes. This means that successful strategies for assessing and managing risks in response to climate change in Longyearbyen will serve as an important basis for future climate adaptation in other relevant parts of the world. This paper presents the main findings from the research project Arct-Risk (Risk governance of climate-related systemic risk in the Arctic), which aimed to develop knowledge and tools to understand and manage the effects of climate change on societal security. Five key lessons learned are identified: 1) Climate prognoses and data must be broken down into appropriate time and geographical units to make them applicable in risk assessments and planning work, 2) Methods for identifying and managing uncertainty will improve climate adaptation work and the handling of natural hazard events, 3) Utilizing local knowledge in various aspects of climate adaptation and natural hazard management systems will enhance risk understanding, thereby providing a stronger foundation for decision-making, 4) Use of sensor technology in warning systems to handle natural hazards and climate change as a flexible and low-cost solution for climate adapation and 5) Use of climate adaptation indicators at the municipal level for awareness and follow-up of systematic climate adaptation work

Keywords: climate adaptation, climate risk, risk governance, Arctic

1. Introduction

To understand and adapt to climate changes is one of the greatest challenges societies are facing today to maintain critical societal functions and infrastructures and to protect citizens' lives and health. Climate change will lead to more frequent, more severe and different patterns of natural hazard events which will impact societal security. The inseparable relationship between nature, technology and society in the context of climate-related risks is epitomized by the term "envirotechnical disasters" (Pritchard, 2012). The argument is that sociotechnical systems cannot be seen independent or as isolated from nature. This perspective is of high relevance to climate change adaptation, both in the Arctic and elsewhere.

Arctic communities play a key role in understanding and managing the climate adaptation challenge since the climate is changing much faster here than in other parts of the world. This means that successful strategies for assessing and managing risks in response to climate change in the Arctic will serve as an important basis for future climate adaptation in other relevant parts of the world.

Society's efforts to adapt to climate change are not keeping pace with the changes, (IPCC, 2023). The speed and intensity of climate change are more severe than previously thought, requiring both adaptation to the new climate conditions and a reduction in greenhouse gas emissions. Additionally, research on climate adaptation is lacking. The IPCC (2022, sec 16.3) points out gaps in knowledge regarding adaptation measures, such as early warning systems, and calls for research on the types of hazards that trigger adaptation, the responders, the documented responses, and the evidence of adaptation effectiveness. The 2023 IPCC report emphasizes that a key challenge is the limited research on the implementation, monitoring, and evaluation of adaptation measures.

The main purpose of the paper is to demonstrate essential lessons learned for both research and practice from climate change adaptation efforts in the Arctic. The paper presents the main findings from the research project Arct-Risk (Risk governance of climate-related systemic risk in the Arctic), conducted in the period 2021-24. The project was financed by the Norwegian Research Council's Polar Research Program (POLARPROG). The main purpose of the Arct-Risk project has been to develop knowledge and tools to understand and manage the effects of climate change on society's ability to protect citizens' lives and health and to maintain critical societal functions and infrastructures.

Management of snow avalanche risk in Longyearbyen, a town in the Arctic that is experiencing climate change faster than many other places in the world, has been the main case for the project.

2. Case: snow avalanche risk mitigation in Longyearbyen

Longyearbyen is located at 78 degrees North in the archipelago Svalbard. The town is situated on what was originally a river delta, bordered by steep mountainsides to the east and west of Longyeardalen (valley), Adventsfjorden to the north, and glaciers to the south. At the center of the valley flows the Longyear River. Since its establishment in 1905, Longyearbyen has been exposed to various natural hazards, including different types of avalanches, landslides, rockfalls, and flooding. With significant climate changes in the Arctic, the Longyearbyen community now faces new challenges in managing climate risks and evolving natural hazards.

The annual mean temperature in the Arctic has risen nearly four times faster than the global average since 1979 (Rantanen et al., 2022). No other place on Earth has experienced such a significant increase in annual average temperature as the part of the Arctic where Longyearbyen is located. Climate change, in addition to rising temperatures, brings more precipitation, both rain and snow, which is expected to alter several natural hazards present in Longyearbyen.

Expected changes in climate and natural hazards in Longyearbyen from the period 1971-2000 to the period 2071-2100 (Norsk klimaservicesenter, 2022) include:

- Increased air temperature
- Increased annual precipitation
- More frequent and intense heavy rainfall events
- Destabilization of near-surface permafrost
- Changes in glacier area and mass
- Increased frequency of various types of floods
- Increased frequency of various types of avalanches and landslides

For instance, the increased temperatures are already noticeable through a series of record-breaking summer temperatures that influence natural hazards and the community. An example of this occurred in the summer of 2020, when high temperatures led to melting and flooding in the then-operational coal mine, Mine 7. During the winter season, changes in weather conditions are evident through rain episodes and mild periods, leading to more frequent slush avalanches in the middle of winter—an avalanche type previously associated primarily with late winter on Svalbard.

These examples illustrate how Longyearbyen is already experiencing the impacts of climate change on natural hazards to a greater extent than most locations worldwide. This underscores the relevance of research on managing the impact of climate change on societal security in Longyearbyen, with significant potential for transferring experiences to locations that have not yet experienced climate change to the same extent.

While climate change affects various natural hazards in Longyearbyen, the Arct-Risk project has concentrated on risk governance related to avalanches. Nonetheless, the project's findings can be applied to other natural hazard management efforts in Longyearbyen, such as flood protection for the Longyear River and monitoring the active layer in the permafrost. Avalanches, including slush flow avalanches, have long been a part of life in Svalbard and Longyearbyen, with numerous occurrences in the surrounding mountains. Unfortunately, avalanches have resulted in fatalities in the town twice: a slush flow in Vannledningsdalen in 1953 that claimed three lives, and an avalanche from Sukkertoppen in December 2015 that killed two people and damaged eleven houses. Another avalanche from Sukkertoppen occurred in February 2017, causing material damage but no fatalities.

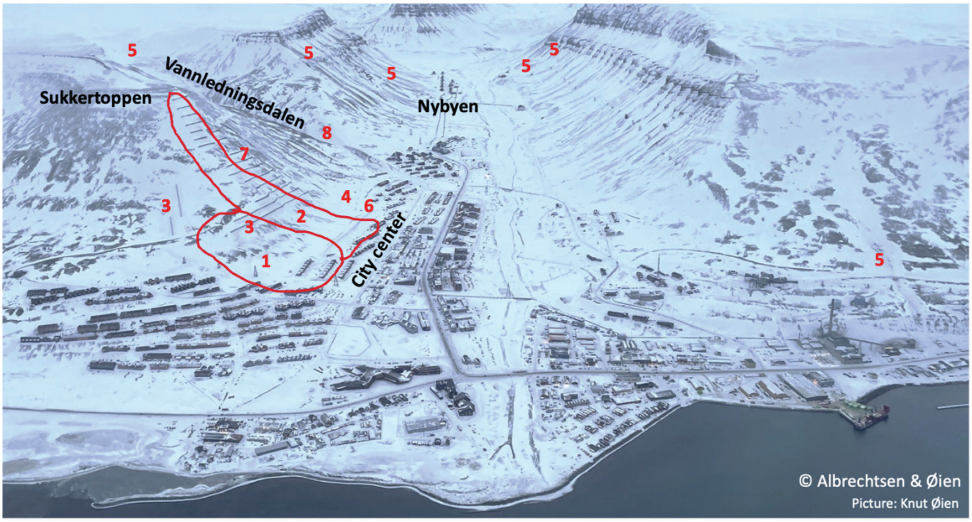

Fig.1. Overview of avalanches and mitigation measures in Longyearbyen (Albrechtsen et al., 2024)

Both the 2015 and 2017 avalanches were associated with extreme weather conditions (DSB, 2015; Landrø et al., 2017). The day before the 2015 avalanche, there were strong winds from the east, heavy snowfall, and a rapid temperature increase from -12 to -2 degrees Celsius within 24 hours (Jonsson and Jaedicke, 2017). Similarly, before the 2017 avalanche, a week of warm weather and heavy rain was followed by a week of cold weather, and in the days leading up to the avalanche, there was light snowfall and strong winds from the east (Jonsson and Jaedicke, 2017).

Before the 2015 avalanche, there was limited systematic work on avalanche risk in the town. However, following the 2015 event, a site-specific avalanche warning system was established (Hancock et al., 2024), which has been in place every winter season since then in areas not secured by physical measures. Planning and risk mapping to establish permanent safety measures began in 2016, with the first permanent measures, including snow fences and supporting structures, completed in 2018. Table 1 and Figure 1 provide an overview of the safety measures implemented since the 2015 avalanche (Albrechtsen et al., 2024). The avalanches in 2015 and 2017 have significantly impacted the town, leading to visible physical safety measures on the mountainside above the center. These permanent safety measures (snow fences, supporting structures, catching dams, and safety nets) secure the center of Longyearbyen. However, other parts of the town remain in avalanche-prone zones, including Nybyen, Sverdrupbyen/Huset (to the

Table 1. Chronological overview of avalanches and mitigation measures in Longyearbyen since 2015 (Albrechtsen et al., 2024)

No.	Year	Event/measure
1	Dec. 2015	Avalanche from Sukkertoppen hits buildings, 2 fatalities
2	2016-	Site-specific avalanche warning system established
3	Feb. 2017	Avalanche from Sukkertoppen hits buildings, no fatalities
4	2018	Completion of three supporting structures in the avalanche path of the 2015 avalanche, two snow fences, and a drainage ditch
5	2019-21	Relocation/removal of 140 housing units in avalanche zones, equivalent to 10% of the town
6	2019-	Stations with snow sensors established as part of the warning system, initially three sensors, later both five and six sensors in various locations
7	2022	Completion of a 400 m long and 5.5 m high catching dam
8	2022	Completion of a total of supporting structures in the avalanche path of the 2017 avalanche

right of Nybyen in the picture above), and Skjæringa/Burmadalen (in the bottom right corner of the picture), as well as the road sections under Gruvefjellet and Platåfjellet (roads on both sides of the river from the center to Nybyen/Huset). For these zones, site-specific avalanche warnings are still in place.

3. Research method

As detailed in the previous chapter, the Arct-Risk project has primarily focused on climate change adapation and mitigation of snow avalanche risk in Longyearbyen. This town has served as a "living laboratory" to: 1) understand the impact of climate change on societal safety and 2) develop and test technological and organizational solutions for climate adaptation

Arct-Risk has been an interdisciplinary project, integrating knowledge from safety science, engineering, meteorology, snow science, and sociology. This interdisciplinary approach has been crucial because effective risk management and adaptation to an uncertain future require more than just scientific knowledge about hazards. It also demands the ability to translate this knowledge into actionable strategies.

The methodological approach of Arct-Risk is inspired by action research (Greenwood and Levin, 2007), which involves collaboration between researchers and users to identify and solve problems, implement measures, and evaluate their effectiveness. This approach has proven successful, largely due to close cooperation with key stakeholders in Longyearbyen, including the Longyearbyen Local Council, the Governor of Svalbard, NVE Region North, Arctic Safety Centre, and Telenor Svalbard. Representatives from these organizations, along with those from Nordkapp Municipality, have formed a local user group. The effectiveness of this approach is evident in the practical application of various project results by these stakeholders, as will be discussed in the next chapter.

Data was collected through a series of workshops with the local user group, 38 interviews with various stakeholders related to avalanche management in Longyearbyen, observation studies of decision-making processes related to avalanche warnings, document studies, and seminars/webinars to present and discuss results with local stakeholders.

4. Five key findings from Arct-Risk for future climate adaptation

Longyearbyen is experiencing climate change faster than most other places in the world. Knowledge about how climate adaptation is planned and implemented in the town is therefore crucial for future climate adaptation both in Longyearbyen and elsewhere globally. The research results from Arct-Risk points to five main topics that are relevant for future practises and research on climate change adaptations and thus improved societal security:

- Climate prognoses and data with appropriate resolution
- Identification and management of uncertainty.
- The significance of local knowledge in different aspects of handling climate risk.
- Sensor-based warning systems for handling natural hazards and climate change
- Indicators for evaluation of climate adaption

4.1 *Climate prognoses and data with appropriate resolution*

Climate prognoses and data must be broken down into suitable temporal and geographical units to make them applicable in risk assessments and planning efforts. In Arct-Risk, we have demonstrated this by decomposing climate data for Svalbard into units that made them useful in risk assessments (Wickström and Jonassen, 2022).

For use in risk assessments, it is useful to have climate prognoses with high (fine-grained) geographical resolution and short time periods. Today, many climate prognoses are described for large geographical areas and over a long-time perspective up to the year 2100. In 2022, Arct-Risk collaborated with the mining company Store Norske on their climate risk assessment. An important contribution from Arct-Risk was to establish scenarios for climate change in Longyearbyen for short (0-5 years), medium (6-25 years), and long term (6-25 years), which were used to identify events and analyse the associated risks. This led to much better knowledge than applying a scenario for year 2100.

Another significant result has been knowledge-based descriptions and dissemination of how climate change impacts natural hazards and, in turn, society, in ways that make this information actionable for planners and decision-makers.

4.2 *Identification and management of uncertainty.*

Climate adaptation involves measures to handle future climate-related natural events that is associated with uncertainty regarding frequency, location, and magnitude. In Arct-Risk, we have identified uncertainties in various phases of risk governance and how these uncertainties can be handled (Albrechtsen and Holen, 2023; Albrechtsen, Holen and Wickström, 2023) . Methods for identifying and handling uncertainty will enhance climate adaptation work and the handling of natural hazard events. The topic of uncertainty has been a recurring theme in Arct-Risk. The studies demonstrate that better understanding, mapping, and communication of uncertainty can improve society's ability to manage risks related to climate change and natural hazards (Albrechtsen and Holen, 2023):

- Uncertainty can be reduced and managed by systematically mapping the sources of uncertainty (such as the checklists for avalanche warning), using multiple data sources and model runs to improve forecasts (e.g., ensemble forecasts in weather prediction), and/or designing measures with safety margins (such as the safety nets in Vannledningsdalen).
- Local knowledge is essential in both avalanche warning and climate adaptation. Uncertainty can be reduced with input from local actors to improve the relevance and accuracy of measures. This applies to observations, assessments of measures, and communication with the local population.
- Communication of uncertainty is key to building trust. Experiences from studied evacuation situations in the project show that clear communication about both risk and uncertainty strengthens understanding and acceptance among those affected.
- Need for continuous learning and adjustment. The climate profiles and projects in Vannledningsdalen illustrate how measures must be based on updated knowledge and adjusted as more information becomes available.
- Common language and tools strengthen the decision-making basis. The use of standardized methods, such as the risk matrix and checklists, makes it easier to communicate complex issues across disciplines and between experts and decision-makers.

An uncertainty model and an uncertainty checklist for use in site-specific avalanche forecasting was developed together with one of the user partners (Øien et al., 2023). This checklist is now used in practice by this company to identify and handle uncertainty.

4.3 *The significance of local knowledge in different aspects of handling climate risk.*

Utilizing local knowledge in various parts of climate adaptation and in systems for handling of natural hazard events will improve risk understanding and thereby greater ground for decision-making. In Arct-Risk we have research results which show the significance of:

- Use of local knowledge to understand the climate changes and their impact on society (Albrechtsen and Holen, 2023
- Local knowledge as one of the foundations for developing permanent mitigation measures (Holen, in review)
- Local knowledge as information for warning systems (forecasters on the mainland need «eyes in town», but also linked to local knowledge and history about avalanches) (Johannessen and Haavik, 2024)
- Local knowledge as a criterion of evaluation during contracting of critical societal functions (Størkersen et al., 2024).

4.4 *Sensor-based warning systems for handling natural hazards and climate change.*

Over the past decade, sensor technology has been developed and implemented to measure snow depth as part of the avalanche warning system in Longyearbyen. In Arct-Risk, we documented experiences with developing and using sensor-based warning systems as a flexible and cost-effective solution that can be implemented rapidly as an alternative before and during the establishment of permanent measures, as well as an alternative to permanent measures (Hancock et al. 2023).

In one of the research activities, we conducted a risk-scientific comparison of permanent safety measures (support structures, snow fences, catch dams, relocation of buildings) and organizational measures (warning systems based on sensor technology) using criteria for barrier performance (Albrechtsen et al., 2024). Permanent measures are reliable and effective for the risk scenarios they are designed for but may be less suitable for changing and uncertain conditions as a result of climate change. Organizational measures represent a flexible, cost-effective, and sustainable approach to risk management. With the impact of climate change on natural hazards and society, organizational measures based on sensor technology should be an important approach, as they can provide flexibility and adaptability to the dynamic and complex picture of natural hazards.

Increased use of sensor-based warning systems can be expected in the future, making Longyearbyen's experience valuable for developing and deploying warning systems elsewhere.

4.5 *Indicators for evaluation of climate adaption.*

In the project, we have developed a set of climate adaptation indicators in collaboration with Longyearbyen Local Government to provide local authorities with a status of the work with climate adaptation (Øien and Albrechtsen, 2024). Such systems for evaluating the status of climate adaptation work at local level are useful for raising awareness about and following up the systematic work with climate adaptation.

5. Conclusion

This paper has summarized key lessons learned for future climate change adaptation worldwide based on research on climate risk governance in the Arctic settlement Longyearbyen that is experiencing climate changes in a pace few other places in the world is experiencing today.

The research results contribute to closing gaps in the research frontier within climate adaptation and climate risk governance (Johannessen et al., 2024) by:

- Social science and interdisciplinary research on climate adaptation and natural hazard events
- Research on the importance of local knowledge as part of the knowledge base in risk co-management related to climate risk
- Research on identifying and managing uncertainties in risk co-management
- Research on temporary climate adaptation measures, including those based on sensor technology
- Research on climate change and adaptation in an Arctic context

Follow-up research should be to study how these experiences from the Arctic would contribute to improved climate change adaptation in local societies in other places in the world that is not experienced such climate changes.

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