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Identifying and managing uncertainty in governance of climate-related risk: Lessons from an Arctic society

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The Arctic experience climate changes at a much higher pace than the rest of the world which also impacts societal safety in the settlement in Longyearbyen. To deal with natural hazards in the age of climate change a range of measures have been implemented. Uncertainty, i.e. a state, even partial, of deficiency of information related to, understanding or knowledge of an event, its consequence, or likelihood (ISO31000), is predominant in dealing with natural hazards and societal safety in the age of climate change. Climate prognoses are uncertain by their inherent variability and by the choice of level of expected greenhouse gas emissions. Other uncertainties are related to lack of knowledge and experiences related to types of natural hazards and lack of knowledge of the effects of risk reducing measures. The paper 1) provides a categorization of sources to uncertainty in different steps in risk governance both for short-term climate disaster handling and long-term climate adaptation and 2) discusses approaches to manage the identified sources to uncertainty. A framework for risk governance is used in the categorization. Sources to and handling of uncertainty is found in all parts of risk governance: framing, assessment, decision-making and communication. The paper is based on a three-day workshop about uncertainty in risk governance of climate-related risk in Longyearbyen at the Norwegian archipelago Svalbard at 78 degrees North.

Keywords: uncertainty, Arctic, snow avalanche, risk governance, climate change, climate change adaptation

1. Introduction

The Arctic is experiencing climate changes at a much faster rate compared to other regions of the world. The warming observed in the Arctic is three times higher the global average (AMAP, 2021). This effect is particularly pronounced in Longyearbyen, a small Norwegian settlement at the archipelago Svalbard in the Arctic ocean. According to reports from the Norwegian Centre for Climate Services (NCCS, 2019), Svalbard has undergone significant changes since 1971, and projections for 2071-2100 indicate further increases in air temperature, annual precipitation, heavy rainfall, river flow, glacier area and mass changes, floods, and landslides. Near-surface permafrost is also expected to be destabilized. As a result, NCCS (2019) warns of increased risks of snow avalanches, landslides, flooding, and erosion that could impact the infrastructure and functioning of Longyearbyen society. The behaviour of snow avalanches is likely to change due to various factors, including wind direction, heavy snowfall, and an increased number of slush avalanches throughout the year.

Uncertainty, which can be defined as "the state, even partial, of deficiency of information related to, understanding or knowledge of an event, its consequence, or likelihood" (ISO31000:2009), is predominant in dealing with natural hazards and societal safety in the age of climate change. To govern risk in societies that experience climate change, such as in Longyearbyen, assessment and handling of uncertainty thus becomes essential. Future climate changes include considerable uncertainty, as the changes will lead to novel hazardous situations where there is lack of data and knowledge. This will also impact the establishment of risk pictures used for risk governance of societies.

The purpose of this paper is i) to provide a categorization of sources to uncertainty in different steps in risk governance both for short-term climate disaster handling and long-term climate adaptation and ii) discusses approaches to managing the identified sources to uncertainty. The paper is based on results of a three-day workshop about uncertainty in risk governance of climate-related risk in Longyearbyen.

1.1. Climate change and risk mitigation in Longyearbyen

Located at 78 degrees north latitude, Longyearbyen is a small settlement at the archipelago Svalbard in the Arctic ocean. The town is situated on the shores of Advent Fjord in the Longyear Valley, with steep mountainsides surrounding it. Being in this location, the town is prone to several natural hazards such as snow avalanches, landslides caused by melting permafrost, flooding from the river that runs through the valley and rock falls. Recent history shows that snow avalanches is the most frequent events to happen in town due to its geography and the positioning of houses and infrastructure. In 2015, a snow avalanche hit Longyearbyen resulting in the loss of two lives and the destruction of 11 houses. Two years later, in 2017, another avalanche hit the town, causing severe damage to several buildings, but thankfully without any loss of life. For both these avalanches, climate change has been pointed at as a contributing factor.

Following the 2015 avalanche, a system for avalanche forecasting was established to aid decisions about evacuating residents. However, despite this, another avalanche occurred in 2017 without evacuation of locals. While the forecasting system was intended to be temporary until permanent measures were implemented, it remains in operation for the parts of the town that lack permanent protection. Subsequent to the 2017 avalanche, the local government initiated measures to establish permanent physical safeguards for the town. The first permanent barriers for snow avalanches were installed in 2018, with the final barriers put in place in 2022. Additionally, land use planning has resulted in the abandonment and demolition of approximately 10% of the town's buildings. The recent years there has also been an increased number of slush avalanche events in mid-winter that have not happen previously. This is likely due to climate changes. To prevent the exposure of a significant portion of the town to slush avalanches in a side valley leading in to the Longyear valley, a decision was made in 2022 to commence the implementation of permanent measures against such avalanches.

2. Uncertainty in risk governance

Practitioners often define risk as a function of the probability and the consequences of undesirable incidents, expressed in quantitative or qualitative terms. One popular way of understanding risk is as an expression of the potential loss we anticipate but cannot predict with certainty. Risk is thus something that belongs to the future, and we have no knowledge of whether the loss actually will occur. Had the future been predetermined, there would have been no point talking about risk. In other words, there is a clear correlation between uncertainty in the form of a lack of knowledge and the concept of risk.

There has been increased attention to uncertainty in risk management the recent years. ISO31000:2018 Risk Management has defined risk as "the effect of uncertainty on objectives". A lot has also been written about uncertainty and risk in academia, particularly related to arguments about describing the strength of the knowledge we use to express risk (e.g. Flage et al., 2014, Aven, 2017) .

As a concept, we can express risk as the consequence of a situation/activity with associated uncertainty (Aven, 2017): 1) We have a situation/activity, 2) the situation/activity may lead to events, but we do not know if they will occur, 3) the events may lead to consequences, but we do not know what those consequences will be. This is still an expression of probability and consequence since we are talking about whether events might occur (probability) and their consequences. At the same time, it represents something new because the knowledge base comes into play. We look into the future to assess whether events and consequences may occur, but we do not know if they will. For example, there is uncertainty about what will happen (will there be an avalanche?), uncertainty about the consequences (will the avalanche hit buildings and to what extent?), and uncertainty about the probability of a given consequence.

The interesting innovation comes when Aven (2017) operationalizes risk to be characterized as a combination of 1) specific consequences, 2) a measure of uncertainty that can be probabilities and frequencies, and 3) the knowledge on which the consequences and the measure of uncertainty are based. It is the third part that brings something new to the table. In addition to expressing consequences and expected event frequency, knowledge strength is also expressed as an assessment of the basis for the evaluation of consequences and frequency. To express knowledge strength, Aven (2017) suggests classifying weak and strong knowledge based on whether assumptions appear reliable, data and information is relevant, experts agree, the analysis object is well understood and applied knowledge is found to be strong.

We can distinguish between two main types of sources of uncertainty (Rausand and Haugen, 2020). 1) Natural variation or randomness, often referred to as aleatory uncertainty, such as wind speed and rainfall. This type of uncertainty is often called non-reducible uncertainty. 2) Lack of knowledge or epistemic uncertainty. This uncertainty is referred to as subjective or reducible uncertainty and can be reduced by acquiring more knowledge. Uncertainty can be related to measurements, methods and models, but could also be about ambiguity (van Asselt, 2000). This means that uncertainty is not just about the strength of knowledge related to an event, its consequences, or the possibility of it occurring, but also about how data is collected, modeled, and interpreted for use in decision-making. Uncertainty affects all parts of risk management and risk governance (Cadena et al., 2020).

3. Method

The results in this paper are based on a 3-day workshop that was held in Longyearbyen, November 2022. Participants in the workshop were from the local authorities in Svalbard, avalanche forecasters, researchers and experts in different areas such meteorology, snow science, societal safety and risk management. The workshop consisted of presentations on topics within uncertainty of climate related natural hazards, avalanche warning and research within uncertainty and risk in other parts of society. Discussions were held both after the presentations and in groups where specific topics were given. The presentations and their discussions are the foundation for the results presented in sections 4-6.

4. Uncertainty in climate and weather prognosis

Both long-term and short-term prognosis of weather is important with regards to management of the consequences of the changing climate. Long-term prognosis are such as those presented by IPCC in global assessments and in national assessments. For Svalbard a local report was made in 2019 (NCCS, 2019) which gave projected values for the climate until 2100. These should be used as basis in climate adaption measures. Shorter -term prognosis, i.e., weather forecasts, are made for emergency preparedness purposes such as avalanche warnings.

4.1. *Long-term*

For long-term climate adaptation, climate profiles developed by the Norwegian Centre for Climate Services are important source and compilation of relevant information. These local climate profiles are made for all counties in Norway, as well as for Longyearbyen. The climate profiles are short versions of more in-depth reports that show how the changing climate factors affects the likelihood of weather-related natural hazard events. For Svalbard, the report Climate in Svalbard 2100 (NCCS, 2019) is the main basis for the profile. There are several uncertainties associated with the climate profiles:

- The models on which the climate profiles are based are coarse models, in the Arctic the finest resolution is 20 km. This is a type of model uncertainty.
- Local knowledge is not incorporated in the climate profiles. The cause for this is that the climate profiles are used for overall planning. For more detailed planning in time and space there is a need for local knowledge about for example shorter time development in weather aspects and particular challenges related to these.
- Knowledge strength about "today's climate" is a challenge in terms of what starting values should be set to add the projections to.

- There is uncertainty about which of the scenarios of greenhouse gas emissions that will become reality. In Norway this has been dealt with politically at the national level by selecting the "worst case" scenario.

4.2. *Short-term*

Weather forecasts are important information for short-term handling of emergency situations involving natural hazard. In particular, model uncertainties are prominent in weather forecasts:

- Uncertainties related to initial conditions.
- Uncertainty related to boundary values.
- Uncertainty related to simplifications of dynamic weather conditions and their relationships.

These uncertainties have consequences for knowledge about which areas are affected, the start and end time of the events, and the intensity and probability of emergency situations. Handling of uncertainties in the execution of the models is done through observations and measurements, and by running a model several times (ensemble forecasts) where different input data have been changed. Variability in these forecasts, can be visualized in different ways, which may be important for understanding the forecasts.

5 Uncertainty related to long-term climate change adaption and short-term disaster coping capacity

The discussions at the workshop pointed out that climate change leads to changes in the frequency and type of natural hazards that must be dealt with. Both long-term structural measures and short-time avalanche warnings are relevant measures to consider in relation to these hazards, and different types of uncertainties were identified in the development and operation of such measures.

5.1. *Long-term climate change adaption – design and implementation of structural barriers*

There is ongoing design of protection measures against slush avalanches close to Longyearbyen. This is an example of a long-term climate change adaptation measure. Slush avalanches are not a new natural hazard in Longyearbyen, but it is new that avalanches can occur throughout the winter season as a result of more water on snow events throughout the winter, which is a consequence of the climate changing. The risk of avalanches has previously been dealt with by dosing the valley late in the season, but this measure is not feasible throughout the winter season due to practicability and occupational safety. It is therefore planned to install a series of net barriers in the valley that will stop or reduce slush avalanches that might harm the town. Several uncertainties have been identified related to the net barriers:

- Uncertainty related to dynamics in slush avalanches as a phenomenon.
- Uncertainty on how the net barriers will affect snow conditions and accumulation of both wet and dry snow.
- Uncertainty related to which loads the net barriers can take up.
- Uncertainty related to future maintenance/ operation of the net barriers.

The uncertainties associated with design of the safety nets have been addressed through 1) obtaining more knowledge about slush avalanche properties and measures, 2) designing robust solutions and 3) a plan of following up assumptions in the future. The uncertainties in the design are largely related to a lack of knowledge about the type of avalanche and the mitigation measure, and work has been done to gather knowledge through the collection of literature for various avalanche events and to generate more knowledge through testing of models with data from known avalanche events, and through model experiments. The uncertainty has largely been dealt with by designing the net barriers with extra safety margins. In addition, it is recommended to follow up on assumptions made after the nets have been set up.

Development of and decisions on climate change adaptation measures in Longyearbyen are carried out through planning processes in the Local government of Longyearbyen. There are several sources of uncertainty in the planning process:

- Uncertainty in the decision-making process. Political decisions are made based on input from experts, but there are also other considerations that must be weighed against each other.
- To ensure appropriate knowledge is developed during the planning process, the competence of those ordering reports and investigations is relevant.
- Emphasis was placed on the importance of communication about plans and the knowledge base and facilitating the participation of the local population in planning processes.

5.2. Short-term disaster coping capacity – avalanche forecasting.

Avalanche forecasting and the process for gathering information for each forecast contain several sources of uncertainty. Øien and Albrechtsen (2022) have developed a checklist to identify uncertainty as part of the local forecasting. The development of the checklist identified the following uncertainty in the Longyearbyen local avalanche forecasting (Øien et al, 2000):

- Uncertainty related to the knowledge base for the report.
- Uncertainty related to snow observations.
- Uncertainty related to sensors and data about snow characteristics.
- Uncertainty about weather and snow conditions.
- Uncertainty related to assessment of probability and avalanche size.
- Uncertainty related to measures (decision and effect).

The uncertainties identified should be used as a tool for highlighting uncertainty for decision-makers (Øien and Albrechtsen, 2022). The uncertainty can be communicated in three ways: 1) clarify uncertainty by using the developed checklist and presenting it to decision-makers to show where there may be a weak knowledge 2) explain uncertainty to decision-makers through visualisation of information in maps, or 3) visualize uncertainty in a risk matrix by using an arrow indicating what the uncertainty is.

Avalanche forecasting for the public road sector in Norway uses physical avalanche protection and active avalanche protection (i.e. avalanche forecasting leading to action) and has the following uncertainties related to this, which is also relevant for avalanche protection and forecasting in Longyearbyen:

- Uncertainty related to the effect of physical avalanche barriers, in particular related to avalanche runout tracks.
- Uncertainty related to weather forecasting, snow cover and properties of the snow pack for active avalanche protection (warning and monitoring) which often leads to assumption on snow conditions.
- Uncertainty related to automatic avalanche detection in active avalanche protection. Here, data quality and data format are sources of uncertainty, for example, that sensors become available due to poor internet coverage, which is a new danger that must be considered.

In 2019, there was a large rock fall at the mountain "Mannen" in mid-Norway when parts of the mountainside collapsed after a long process including several evacuations of residents in the period 2014-2019. Although this is a different type of natural hazard than those most applicable to Longyearbyen today, there are some aspects related to uncertainties that can be transferred to Longyearbyen:

- Uncertainty in the geological models used. Little was known about the way in which the front rock would break.
- One could not calculate when the landslide would break, and this affected the communication of uncertainty to those involved.

The events at "Mannen" lasted for a period of 5 years, and gradually better knowledge of the situation was gained, including the installation of sensors that could measure mountain movements. These measurements became important inputs for communication with local people and other stakeholders. Communication with the evacuees was given priority when changes in the mountain was discovered. The evacuees have given the impression that they were satisfied with the handling.

An example from the discussions at the workshop about an evacuation situation in Longyearbyen showed that it is not only avalanche assessments that are important for a decision to evacuate, but also other considerations, such as previous experiences with avalanches and guidelines for how long to give before evacuation. Decision-making processes for societal safety are a complex problem with many considerations which introduce their own uncertainties. This applies to both short-term and long-term measures.

The group discussions also show that local knowledge is important in avalanche warning in Longyearbyen. This applies to knowledge of snow observers, but also information from local meteorologists who have expertise in the models and local knowledge.

5.3 Summary of results

Figure 1 shows types uncertainty that was identified and discussed in the workshop. The types of uncertainty are structured based on the conceptual framework for climate risk from IPCC (2012).

6. Management and communication of uncertainty

Based on presentations and discussions at the workshop, managing uncertainty can be categorized into four main types:

1. Raising awareness of uncertainty to decision-makers and other stakeholders. By emphasizing the presence of uncertainty, decision-makers and stakeholders can become more conscious of it when creating a basis for decision-making. Research into the integration of uncertainty in risk definitions within the petroleum industry has demonstrated increased awareness of uncertainty, leading to better communication and ultimately contributing to

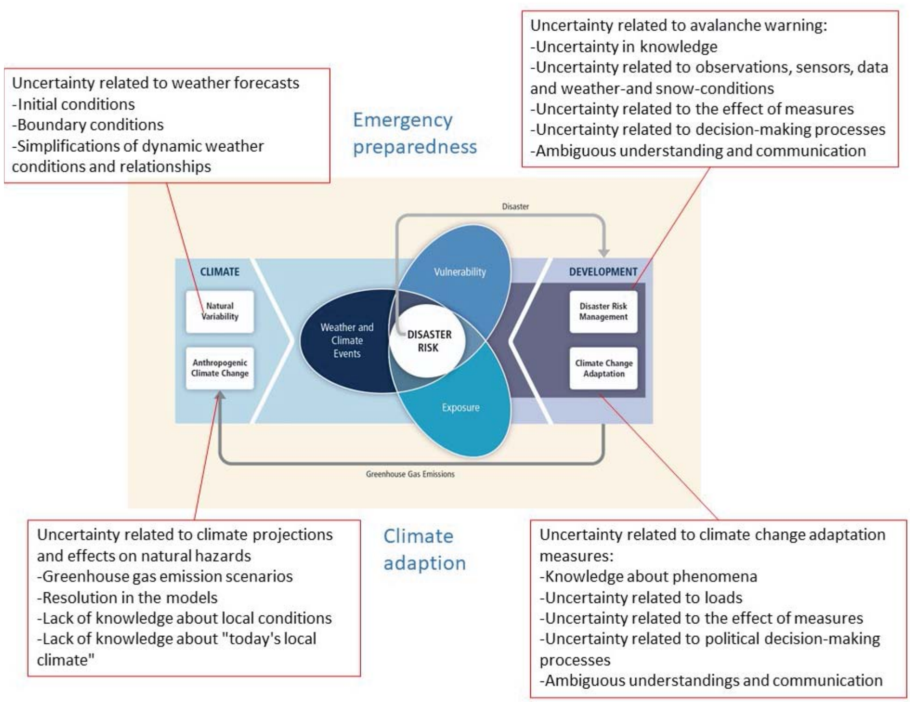

Figure 1 Summary of sources to uncertainty

improved risk management (Orvik and Valdernes, 2022; Haavik et al, unpubl). In a similar vein, studies of how the Norwegian authorities have handled the Covid-19 pandemic indicate a need for a shared vocabulary and greater comprehension of uncertainty (Antonsen et al, 2022).

Categorizing sources of uncertainty as done in section 4 and 5 is one method for emphasizing uncertainties, but there are various ways to do so. Figure 1 summary categorizes them based on climate conditions, natural hazards, society, and risk-reducing measures. Another approach is to categorize uncertainties according to steps in the avalanche forecasting process (Øien et al., 2022; Øien and Albrechtsen, 2022).

Uncertainties may also be categorized by their sources. For instance, uncertainties related to weather and climate models can be classified as model uncertainty, while uncertainties associated with the parameters used in those models are parameter uncertainty. The design of the slush avalanche barrier nets in a side valley to Longyearbyen highlights examples of model and parameter uncertainty.

2. Acquire more knowledge. The workshop discussed several proposals to reduce uncertainty by obtaining more and better knowledge. For example, by involving local actors for providing input to more adapted climate profiles and by facilitating more data collection related to natural hazards in Longyearbyen. It was emphasized that access to all background documents such as more complex versions of climate profiles is an important source of increasing knowledge strength for the development of climate adaptation measures.

For the design of slush avalanche barrier nets, more knowledge was obtained through a review of relevant literature and model experiments with data from known avalanche events. In the weather forecasts, the knowledge base can be strengthened through several observations and measurements and by running models several times. For the events at the mountain “Mannen” in mid-Norway sensors were set up to measure movements in the mountain to improve the knowledge base for evacuation decisions.

During the workshop, the group discussions highlighted the necessity for increased data collection on the impact of climate change on natural hazards. To incorporate this into the Local Council and Governor of Svalbard's work, it must be included in their planning for climate change adaptation and avalanche forecasting systems. There are several inhabitants in Longyearbyen who have knowledge on climate change, natural hazards, and their effects on the community, presenting ample opportunities for collaboration. The facilitation and systematization of local knowledge usage is crucial. Additionally, the need for detailed climate projections for different time periods, such as 10-20 years in the future, was emphasized. An example proposed was the creation of hazard zone maps based on climate projections, including uncertainty and regular updates.

3. Precautionary strategies. During the workshop, two precautionary strategies for managing uncertainty were presented. At the national level, political action has been taken to address uncertainty surrounding greenhouse gas emission projections and their effect on climate change by selecting the worst-case scenario with the highest emissions (RCP 8.5) from the IPCC's International Climate Report. This approach provides a precautionary strategy that accounts for the worst possible outcome.

Concerning the design of slush avalanche barrier nets, uncertainty related to the barriers' future performance concerning climate change has been managed by designing the nets with dimensioning values higher than what is currently observed or assumed to be necessary in todays environment.

4. Communication of uncertainty between subject matter experts and decision-makers and between decision-makers and affected persons. Communication of uncertainty, both between experts and decision-makers, and between decision-makers and affected persons, was also discussed in the workshop. For example, experiences from the rock fall at the mountain “Mannen” in Mid-Norway show advantages of being open about the knowledge foundation on which evacuation decisions were based. The example shows that in communication with those affected, it was useful to be specific about what information one had. The uncertainty checklist for avalanche forecasting was also discussed as an example of how uncertainty can be concretized and thus improve understanding between experts and decision makers for avalanche warnings. However, it was also pointed out that good contact and regular meetings were an important contribution to increased understanding between the parties.

7. Conclusion

Assessing and managing uncertainty, which includes both lack of knowledge and variability, is a crucial aspect of risk governance in the age of climate change. Climate change is inherently linked to an uncertain future concerning both climatic conditions and how they will affect natural hazards and societies.

This paper presents a categorization of various types of uncertainty that may arise regarding both long-term climate change adaptation and short-term coping and forecasting of climate-related disasters. Strategies for enhancing the management and communication of uncertainty are also presented. The findings are based on the current experience of managing climate-related risks in the Arctic community of Longyearbyen, which is experiencing climate change at a different rate than most other places in the world. Therefore, these results can be applied to other parts of the world that will encounter climate changes in the future

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