Impacts of the changing land-based cryosphere on Arctic society

The cross-cutting activity

The proposed cross-cutting activity on **"Impacts of the changing land-based cryosphere on Arctic society"** will be implemented in the next annual meeting of the IASC Network on Arctic Glaciology (NAG; http://nag.iasc.info) and "Workshop on the Dynamics and Mass Budget of Arctic Glaciers", to be held in January 2025, most likely in Hokkaido, Japan**.** The Network on Arctic Glaciology has a long history of implementing cross-cutting activities in the annual workshop, thereby fostering collaboration between glaciology and a range of other disciplines. The proposed activity can be regarded as a follow-up on our most recent activity on "Societal impacts of glacier and snow cover changes in a warming Arctic", in the upcoming IASC NAG meeting on 22-24 January 2024 in Obergurgl, Austria, for which 53 people have registered (15-20 direct contributions to the cross-cutting activity). In addition to the previously involved IASC Cryosphere, Atmosphere, and Social & Human WGs, the proposed activity newly includes the Terrestrial Working Group, stimulated by the **new additional focus on societal impacts of permafrost change in the Arctic**. The term "land-based cryosphere" above hence refers to glaciers, seasonal snow and permafrost. The main incentives are to stimulate increased collaboration of glaciologists, snow experts, permafrost researchers and social scientists, as well as to engage knowledge holders from Arctic communities. The cross-cutting activity will be in the form of oral and poster presentation sessions and a discussion session during one day of the 2.5-day meeting. A call for abstracts will open in September and close in November 2024. The meeting will be announced via mailing lists (e.g. the Cryolist), via the IASC and IASC NAG websites, and on social media.

Scientific background

The Arctic climate system has warmed at more than twice the average rate observed in the Northern Hemisphere between 1971 and 2017 (AMAP, 2019) as a result of Arctic Amplification. The increased moisture-holding capacity of the atmosphere induces an increase in Arctic precipitation, with increases in both averages and extremes of snowfall and even more so of rainfall (e.g. Bintanja, 2018).

The rapid warming has triggered an acceleration of Arctic glacier and ice sheet mass loss, which since the 1990s accounted for ~30% of total sea level rise. Increased melting and changes in precipitation amount and type affect glacier dynamics, primarily through basal sliding, which, together with changing fjord and ocean conditions also affect frontal ablation and calving of icebergs. Increased snowfall may partially offset melt increases, whereas more rainfall generally increases refreezing in seasonal snow and multi-year snow (firn) (e.g. Van Pelt et al. 2021). Extensive firn areas on Arctic ice caps can retain melt and rainwater in solid form (as refrozen ice layers) and in liquid form (as perennial firn aquifers), but this "buffer" is shrinking rapidly in many Arctic regions (e.g. Noël et al. 2020).

The duration of the snow season in the Arctic, both on- and off-glacier, is shortening (~3-5 days per decade; Bokhorst et al. 2016), yet with strong variations depending on region, latitude and study period (Barichivich et al. 2013). Arctic warming further induces an increase in rain-on-snow (ROS) events, as well as a general increase in precipitation, with significant impacts on snow depth, season length and stratigraphy (Serreze et al. 2021), thereby also affecting timing and rates of runoff.

A third component of the land-based cryosphere, permafrost, has undergone significant changes in the Arctic in recent decades. Rising temperatures have caused the top layer of permafrost to melt, leading to the destabilization of the ground. This thawing has resulted in changes to the landscape, causing land subsidence, sinking of infrastructure, and alterations in ecosystems. Furthermore, permafrost thawing is associated with the release of carbon dioxide and methane into the atmosphere. An estimated 2.5 million square miles of permafrost, equivalent to 40 percent of the world's total, could disappear by the end of the century (Chadburn et al. 2017).

Presentation and discussion topics

The traditional ways of life and well-being of many northern residents are affected by climate-induced changes in glaciers, seasonal snow conditions, and the state of permafrost. Below, we highlight some of the key societal impacts of trends in the three land-based cryosphere components.

Societal impacts of glacier retreat:

- **Coastal communities**: Glacier and ice sheet mass loss are major contributors to sea level rise, affecting societies worldwide. In the Arctic, sea level rise affects coastal communities, primarily due to coastal erosion, threats to infrastructure and permafrost thawing, potentially requiring relocation and having large impacts on traditional livelihoods (Nielsen et al. 2022).
- **Water resources**: Communities relying on glacier meltwater for drinking, agriculture, and hydropower face challenges as this water source diminishes, potentially leading to water shortages and affecting livelihoods (Instanes et al. 2015).
- **Natural hazards**: The retreat of glaciers can trigger various natural hazards. Glacier outburst floods (GLOFs), i.e. sudden catastrophic releases of water from glacial lakes, are common with glacier retreat, yet poorly studied (Emmer 2018). Other natural hazards include e.g. changes in river routes impacting infrastructure, such as bridges, that may need to be changed to fit the new rivers.
- **Tourism**: Changes in Arctic glacier landscapes and accessibility may affect income from tourism and dependent industries in the region (Varnajot et al. 2021).
- **Cultural impacts:** Indigenous communities often have deep connections to glaciers, considering them as an integral part of their cultural identity. Glacier retreat disrupts these cultural connections, affecting their traditional lifestyle (Hovelsrud et al. 2011).

Societal impacts of seasonal snow trends:

- **Rain-on-snow (ROS)**: During ROS events, rain falls on existing snow and due to refreezing hard crusts/ice layers form within or at the base of the snowpack. In the Arctic, such events can have profound immediate economic and environmental impacts (e.g. affecting travel and agriculture), as well as cumulative impacts, potentially resulting in starvation of reindeer, musk oxen and other grazing animals (Rosqvist et al. 2022).

- **Extreme precipitation events**: In a warmer Arctic climate, the frequency of extreme snow- and rainfall events are expected to increase (Loeb et al. 2022). Large unknowns however remain, primarily due to difficulties in observing precipitation in the Arctic. Extreme precipitation events may destabilize and damage e.g. infrastructure, buildings and forests (Lehtonen et al. 2016).
- **Hydropower potential:** Increasing precipitation and snowfall in the Arctic enhances hydropower potential in a future climate. While this may potentially yield economic benefits for Arctic communities, it does come with social costs, e.g. for indigenous communities, following changes in the natural environment (Engen et al. 2022).
- **Snow cover duration:** Shorter snow seasons in the Arctic are favorable for agriculture, yet other constraints, such as remoteness, lacking infrastructure and low population numbers persist (Hovelsrud et al. 2011). Furthermore, a shorter snow season reduces mobility in the Arctic, e.g. by limiting wintertime overland transport (Gädeke et al. 2021).
- **Avalanches**: In a warmer and wetter climate, the frequency and type of avalanches change, which has impacts on Arctic societies, e.g. through potential loss of life and the need for adaptation of infrastructure and buildings (e.g. Eckerstorfer et al. 2011).

Societal impacts of permafrost thaw:

- **Release of greenhouse gases (GHG)**: Permafrost holds large amounts of organic matter that have been preserved in a frozen state. Its thaw releases significant quantities of methane and carbon dioxide into the atmosphere (e.g. Knoblauch et al. 2018), leading to a feedback loop with amplified global warming and increased GHG release. Additionally, the development and implementation of methane budget policies for Arctic communities warrant attention and consideration.
- **Infrastructure challenges**: Thawing permafrost poses challenges for infrastructure built on these frozen grounds (e.g. Hjort et al. 2022). Roads, buildings, pipelines, and other structures are vulnerable to damage or collapse as the ground beneath them becomes less stable.
- **Ecosystem changes**: Permafrost thaw disrupts Arctic ecosystems. It alters vegetation patterns, affects wildlife habitats, and can lead to changes in the availability of water, impacting the delicate balance of these environments (Schuur & Mack 2018).
- **Coastal erosion**: Thawing permafrost contributes to coastal erosion in Arctic regions. The loss of permafrost stability along coastlines leads to the collapse of land masses, threatening communities and infrastructure (e.g. Ogorodnov et al. 2020). Among others, this poses a severe threat for many well-preserved archaeological sites in Greenland (Fenger-Nielsen et al. 2020).

Psychological impacts of the changing land-based cryosphere

Rapid changes in the Arctic climate cause traditional ways of life to become less viable for Arctic indigenous communities (Madden, 2021). This has a marked impact on mental health, affecting in particular the wellbeing of adolescents, resulting for example in increased suicide rates (Larsen et al. 2014). Climate change impacts and the changing environment have recently been found to not only restrict mobility and disrupt livelihoods but also affect mental health primarily through changes in culture, food access, housing, as well as interpersonal relations (Lebel et al. 2022). Increased information exchange between scientists and local communities may stimulate greater awareness of environmental changes and greater edngagement in conservation efforts.