PROJECT DESCRIPTION

The cross-cutting activity

The proposed cross-cutting activity on "Societal impacts of glacier and snow cover changes in a warming Arctic" 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 2024. 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 "Glacier – Atmosphere interactions in a warming and wetting Arctic", which was/is the theme of two short online meetings in 2021 and 2022, and an upcoming in person meeting in January 2023 in Obergurgl, Austria. The activity proposed here newly includes the Social & Human Working Group and shifts focus to the societal impacts of glacier and snow changes in the Arctic. Main incentives are to stimulate increased collaboration of glaciologists, atmospheric scientists and social scientists, as well as to engage indigenous knowledge holders. The cross-cutting activity will be in the form of presentation and discussion sessions.

Scientific background

Arctic glaciers and snow in a changing climate

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 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. Furthermore, the duration of the snow season in the Arctic, both on- and off-glacier, is shortening rapidly (~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.

Changes in Arctic sea ice cover and atmospheric flow patterns result in accelerated Arctic warming and will impact the amount and phase of precipitation with rainfall becoming increasingly prominent (Bintanja, 2018). Increased snowfall may partially offset melt increases, whereas more rainfall generally increases refreezing and ice-layer development 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 rain water in solid form (as refrozen ice layers) and in liquid form (as perennial firn aquifers), but this "buffer" is already in advanced stages of decline in many Arctic regions (e.g. Noël et al. 2020).

Both glaciers and seasonal snow are products of the climate system. They exist and evolve through a balance between mass gain by snowfall, riming and deposition, and mass loss from melting, wind erosion and sublimation. Tidewater glaciers additionally lose mass by calving and frontal ablation. Near-surface atmospheric conditions determine the surface energy balance, which in turn determines melt rates. Subsurface conditions may strongly affect surface melt and the amount of runoff, due to the potential for meltwater refreezing and liquid water storage. Numerical models are commonly used to assess long-term developments and trends in glacier surface and seasonal snow conditions. Two-way coupling of the subsurface, surface and overlying atmosphere in regional climate models (RCMs), general circulation models (GCMs) and Earth system models (ESMs) is critical for detailed assessments of weather and climate impacts on glaciers and seasonal snow. The quality of the model results, at all spatial scales, depends heavily on availability of observations to constrain model parameters and model process descriptions.

Societal impacts

The traditional ways of life and well-being of many northern residents are affected by climate-induced changes in glacier and seasonal snow conditions, with impacts on food sources, transportation and economic activities. In the two sections below, we highlight some of the key impacts, which will be at the basis for discussions in the cross-cutting activity.

Impacts of glacier retreat:

- Land-based glacier and ice sheet mass loss are major contributors to **sea level rise**, affecting societies worldwide. In the Arctic, local and regional sea level rise depend on glacial isostatic adjustment as well as halosteric and thermosteric ocean expansion, causing strong spatial variations. Sea level rise affects coastal communities, primarily due to coastal erosion and permafrost thawing, causing heritage data loss and the need for relocation of entire villages (Nielsen et al. 2022).
- The retreat of glaciers can result in **changes in river routes** that impact infrastructure, such as bridges, that may need to be changed to fit the new rivers. For example, in Iceland, the longest bridge in Southern Iceland, 880 m long, could be exchanged for a 68 m long bridge as most of the water that earlier ran into Skeiðará now runs into Gígjukvísl (Guðrún Nína Petersen, pers. commun.).
- **Glacier outburst floods** (GLOFs), i.e. sudden catastrophic releases of water from glacial lakes, are common with glacier retreat. GLOFs are low-frequency, high-impact events with severe societal impacts (Emmer et al. 2022). Research on GLOFs has seen a sharp increase in recent decades, with a primary focus on high-mountain Asia. However, GLOFs are very common in the Arctic, but remain severely understudied (e.g. Emmer 2018), despite increasing susceptibility of infrastructure and potential loss of lives.
- Similar to sea-ice reduction, glacier and ice sheet retreat increase accessibility of potentially large reserves of **raw materials** (e.g. Wenger 2022).
- Deposits of **pollutants in glacier ice**, in particular persistent organic pollutants (POPs), may be released, thereby reintroducing pollution from former emissions. The resulting polluted discharge may pose health risks and affect downstream fishing industry (Pawlak et al. 2021).
- Coastal marine ecosystems are influenced by **increased glacial freshwater runoff** affecting water salinity, which, in combination with changing ocean temperatures and

fjord circulation severely impact fishery resources in many Arctic fjords (Meire et al. 2017).

- **Tourism** is an important source of income for many Arctic communities. The changing Arctic landscape with, among others, diminishing glaciers, poses additional mobility challenges and limits opportunities to view glaciers and related wild-life (Orlove et al. 2008).

Impacts of seasonal snow trends:

- During **rain-on-snow (ROS)** events rain falls on existing snow and due to refreezing a hard crust/ice layer forms 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 in the Arctic. Trends in snow amount and the likelihood of winter melting/rainfall and refreezing induce trends in the likelihood of ROS events (Serreze et al. 2021).
- In a warmer Arctic climate, the frequency of **extreme snow- and rainfall events** is 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 damage among others infrastructure, buildings and forests (Lehtonen et al. 2016).
- With a rise in precipitation and runoff from glaciers and snow melt, **hydropower potential** in the Arctic increases 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).
- Shortening of the **snow cover duration** reduces one constraint for Arctic agriculture, yet other constraints, such as remoteness, lacking infrastructure and low population numbers remain in place (Hovelsrud et al. 2011). At the same time, a shorter snow season reduces mobility in the Arctic, e.g. by limiting wintertime overland transport (Gädeke et al. 2021).
- 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 lifes and need for adaptation of infrastructure and buildings (e.g. Eckerstorfer et al. 2011).

Rapid changes in 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 from, among others, changing snow conditions, 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).