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Editorial: Climate impacts on snowpack dynamics

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Editorial on the Research Topic
Climate impacts on snowpack dynamics

Snow plays a critical role in the global climate system and hydrological cycle by spatio-temporally interacting with land surface energy balance, atmospheric dynamics, and soil thermal conditions. Its albedo feedback generally balances surface air temperature, shapes atmospheric circulation, and thereby affects climatic conditions on Earth. From a hydrological point of view, the snowpack stores water during winter and gradually releases it as snowmelt into rivers and aquifers in the following spring or early summer. Hence, the snowpack substantially contributes to global sustainable development by providing over one billion people whose lives and livelihoods are directly and indirectly dependent on snowpack meltwater resources and ecosystem services.

In the era of global warming, significant changes in surface air temperature (SAT) and precipitation patterns have already influenced both the quantity and temporal characteristics of snowpack resources around the world. In general, substantial increases in SAT are associated with a reduced number of sub-zero (daily mean SAT <0°C) days in the cold months, less frequent snowfall events, more often rain-on-snow (ROS) during winters, and lower snowpack accumulation on the ground. Declining maximum water retention capacities of snowpack, such warmer SATs and less snow decrease the refreezing of water during the cold months. These alterations in both snowfall and snowpack dynamics reduce snow water equivalent (SWE) and springtime snowmelt, leading to the early summer freshwater shortage in cold climate regions. On the other hand, less SWE associated with decreases in snow cover area and duration would result in lower albedo and consequently global warming amplification. However, projected more wintertime precipitation can counteract such changes in snowpack accumulation and melt processes and their impacts on the global climate system and hydrological cycle. Hence, whether snowpacks decrease or increase under global warming depends on the balance between snowfall increase and wintertime melt.

This Research Topic brings together pure theoretical and applied scientific research on climate change impacts on snowpack dynamics in order to lay a foundation for acting toward achieving sustainable development goals (SDGs) in different cold climate environments on Earth.

Ackroyd et al. evaluated trends in monthly and annual snow cover durations, both binary (SCD) and fractional (fSCD), in different river basins (Amu Darya, Brahmaputra, Ganges, Indus, and Syr Darya) and 1,000 m elevation bands throughout the High Mountain Asia (HMA) during 2002–2017. Throughout the entire study area (HMA), both snow cover duration and extent significantly decreased over time. Substantial declines in snow cover were mostly detected in elevation bands in which snow is most likely present to sustain glaciers. The only increasing trend was found in the monthly fSCD in the Indus River Basin between the elevations of 2,000 and 5,000 m Generally speaking, fSCD and SCD showed different trends in HMA as the SCD analysis overestimated snow cover area relative to the fSCD. Finally, it was noted that such shortening of snow cover duration should continue to be monitored as millions of people are dependent upon freshwater resources provided by snowpack accumulation and melt processes throughout HMA.

Buomari et al. investigated the ability of MODIS to capture the spatial heterogeneity of snow cover induced by solar radiation. For this, they first examined the added value of different solar radiation treatments within empirical snowmelt models, and then, evaluated their performance to the snow cover area (SCA) estimated by MODIS. Three temperature index models including the potential clear-sky direct radiation, the incoming solar radiation, and the net solar radiation treatments were compared with a classical temperature-index (TI) model to simulate snow water equivalent (SWE), snowmelt rate, and SCA throughout the Rheraya River Basin in the Moroccan High Atlas Range during 2003–2016. In general, the models with net solar radiation treatment could better explain variations in historical SCA compared to the TI models. More heterogeneous snow cover conditions were also simulated by the models with different solar radiation treatments. However, aggregating the simulated SCA from the model resolution (100 m) towards the MODIS resolution (500 m) suppressed important spatial variability related to solar radiation, and thereby, lessened the differences between the radiative and TI models. In conclusion, hence, it was recommended to be cautious in applying medium resolution satellite products (e.g., MODIS) for calibrating and validating spatially distributed snow models.

There is still a lack of long-term *in situ* records representing the main snowpack traits throughout the Arctic circumpolar land area. This generally causes high uncertainty in modelling snowpack feedbacks on soil temperature regime particularly due to the impacts of climate change on Arctic snow cover insulating properties. Hence, Royer et al. employed new parameterizations of a few snowpack physical processes (e.g., the effects of Arctic low vegetation cover) in the SURFEX-Crocus (V 8.1) snow model to improve the simulation of Arctic snow properties and ground thermal regime evolution during 1979–2018, comparing with the standard (Std) version of the Crocus model. Accordingly, substantial improvements were primarily observed for a large set of *in situ* snow records throughout North America and Serbia. In the last 39 years, the Arctic snowpack significantly changed during the melt (April-June) and accumulation (September-October) periods, generating a wetter snowpack of higher density. Besides these changes in snowpack properties, surface air temperature warming has increased soil surface temperature in the Arctic circumpolar land area during the winter seasons in recent decades. Such warmer soil surface temperatures basically increase the estimated active layer thickness, with significant impacts on Arctic hydrology and erosion.

Nyamgerel et al. investigated the effects of snow cover and melt on spatio-temporal variability in soil moisture and temperature throughout both high (two sites) and low (two sites) elevation regions. For this, groundwater samples were collected from the Mt. Balwang area in Gangwon-do, South Korea, during September 2020-May 2021. In this area, spring snowmelt influencing soil moisture and temperature compromises not only natural snow cover but also artificial snowpacks produced in a ski resort during wintertime. Monitoring soil moisture and temperature indicated that the quantity and timing of snow cover and melt were different at the four sites depending on their characteristics such as snowfall, artificial snowpack intensity, vegetation cover, and windward direction. In general, the relatively steady and moist soil layers at both high elevation sites as well as at one of the low elevation sites were the influential points for groundwater recharging during warm months. The higher ionic concentrations were measured in the order of surface water, artificial snow, groundwater, and natural snow. Hence, the combination of *in situ* soil moisture and temperature measurements with hydro-chemical and isotope datasets will improve our knowledge about the role of snowpack dynamics in hydrological processes in such regions facing less snowfall and more artificial snow challenges imposed by global warming and climate change.

Brandt et al. reviewed the physical processes governing ROS and proposed the terms "active" and "passive" to describe different snowpack hydrological responses to ROS events. Accordingly, the active snowpack would readily contribute its meltwater to the TWI through the energy balance system and thereby increases rainfall-runoff totals. However, the passive snowpack does not melt and only conveys rainwater through the snow matrix. In both active and passive snowpacks, such preferential flow pathways improve water transmissivity. This classification scheme of active and passive snowpacks will help water researchers and managers to better communicate, interpret, and discuss the past and future changes in ROS events.

Snow is one of the key freshwater resources protecting both life and nature not only in cold regions but also in other snowmelt-dependent environments on Earth. However, global warming and climate change substantially influence snowpack dynamics and thereby implicate hydrological challenges, alter freshwater resources, and increase sustainability risks around the world, particularly in cold climate environments. Hence, improving our understanding of snowpack-hydrology- and sustainability interactions will significantly contribute to developing adaptation and mitigation strategies for saving our planet against undisputable global warming and climate change.

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