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Editorial

Role of Snow in the High-Mountain Hydrologic Cycle

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1. Introduction

Snow is a crucial component of the cryosphere and plays a vital role in the hydrological cycle, energy balance, and ecosystem function of mountainous regions [1,2]. However, snow cover in mountainous areas is undergoing significant changes due to climate warming and human activities, with important consequences for water resources, natural hazards, and socio-economic development [3,4]. Monitoring and modeling the spatiotemporal variability of snow cover and understanding its drivers and impacts remain major challenges, particularly in data-scarce and hard-to-access high mountain environments.

This Special Issue, "The Role of Snow in the High-Mountain Hydrologic Cycle", presents ten original research articles that advance our understanding of snow cover dynamics and hydrological impacts in mountainous regions across the world. These studies apply a variety of methods, including remote sensing, ground observations, isotope tracers, and hydrological modeling, to characterize snow cover patterns, investigate snow-climate-hydrology interactions, and assess snow-related hazards at different spatial and temporal scales. Here we summarize the key findings and implications of each study and discuss the future directions of snow cover research in mountain regions.

2. Summary of Contributions to This Special Issue

2.1. Remote Sensing of Snow Cover Change

Remote sensing has been widely used to map snow cover extent and snow properties over large areas. Li et al. (2022a) (Contribution 1) developed a novel snow cover classification method based on the persistence and variability of snow cover using a long-term AVHRR snow cover extent product. They found significant differences in the distribution and change of persistent, intermittent, and ephemeral snow cover across China, with persistent snow cover dominating northern Xinjiang, northeast China, and the high mountains of the Tibetan Plateau, while ephemeral snow cover increased dramatically in the eastern Tibetan Plateau in recent decades. This study provides a useful framework for characterizing snow cover stability and a valuable dataset for hydrological and ecological impact assessments.

Bishay et al. (2023) (Contribution 2) explored the potential of using the MODIS-derived snow disappearance date (SDD) as an indicator of seasonal water supply in high-mountain Asia. They found strong correlations between basin-averaged SDD and seasonal streamflow volume across the region. This suggests that SDD can serve as a promising predictor for seasonal water supply forecasting in ungauged basins, which are common in mountainous areas. However, the skill of SDD varies with elevation and climate, highlighting the need to consider the spatiotemporal variability of snow processes.

Snow albedo is another important parameter that affects the surface energy balance and snow melting. Bolaño-Ortiz et al. (2023) (Contribution 3) and Figueroa-Villanueva et al. (2023) (Contribution 4) quantified the impact of light-absorbing particles (LAPs), particularly dust and black carbon, on snow albedo reduction in the Colombian tropical

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glaciers and Chilean Central Andes, respectively. By combining remote sensing observations and radiative transfer modeling, they showed that LAPs can significantly accelerate snow melting and shorten snow duration, and the effects vary with LAP concentrations, snow conditions, and elevation. These studies underscore the importance of considering LAPs in snow process modeling and have implications for water resource management in these regions.

2.2. Ground Observations and Isotope Tracing of Snow Cover

While remote sensing provides spatially continuous snow cover information, ground observations offer more detailed and accurate measurements of snow properties and processes. Chen et al. (2021a) (Contribution 5) analyzed the variations of snow depth and duration at different elevations in the Changbai Mountains in northeast China, using meteorological station data from 1960 to 2018. They found significant decreasing trends in recent decades. The elevation-dependent changes in snow depth and duration have implications for the ecological and hydrological functions of the Changbai Mountains as an important water tower in northeast Asia.

Using observation data from the National Climate Reference Station for the period 1986–2005, Chen et al. (2021b) (Contribution 6) developed a backpropagation artificial neural network snow simulation model to simulate future daily snow depth in China under different representative concentration pathways.

Zhang et al. (2022) (Contribution 7) conducted a controlled field experiment in northeast China to quantify the contribution of snowmelt water to soil moisture at different depths, using stable isotopes of oxygen and hydrogen as tracers. They found that snowmelt water contributed 8–11% to the top 30 cm soil layer on average, with greater contributions from higher snow depths. The retention time of snowmelt water differed from surface to deep soil and was affected by both snow depth and subsequent precipitation. This study provides insights into the role of snowmelt in soil water dynamics and groundwater recharge and has implications for spring crop water management.

2.3. Hydrological Modeling of Snow Processes and Impacts

Hydrological modeling is an essential tool for understanding and predicting the hydrological impacts of snow cover change. Two studies in this Special Issue focused on improving the simulation of snow processes in hydrological models. Li et al. (2022b) (Contribution 8) introduced a frequency correction method for bias correction of reanalysis precipitation data in the Manas River basin and evaluated its effects on snow and glacier melt simulations using the reanalyzed precipitation dataset. They found that the corrected precipitation improved the model's performance in reproducing observed streamflow and snow cover area, especially in the cold season. This suggests that correcting the frequency bias of precipitation forcing is important for reducing the uncertainty in high-mountain hydrological modeling.

Tan et al. (2023) (Contribution 9) integrated a snowmelt module into the Xin'anjiang (XAJ) hydrological model and tested it in the Upper Heihe River basin in northwest China. By comparing the original XAJ model with a modified XAJ model with elevation bands, they demonstrated that the coupled snowmelt-XAJ model performed best in simulating streamflow in snow-dominated basins, particularly for capturing the timing and magnitude of snowmelt-induced flood peaks in spring. This study provides a useful tool for snowmelt runoff modeling and flood forecasting in mountainous watersheds.

2.4. Snow-Related Hazards and Risk Assessment

Snow cover change not only affects water resources but also alters the frequency and magnitude of snow-related hazards. Two studies in this Special Issue investigated the characteristics and drivers of snow avalanches. Medeu et al. (2022) (Contribution 10) analyzed the interannual variability and trends of snow depth and avalanche activity in the Ile Alatau Ridge in Northern Tien Shan from 1966 to 2022. They found a weak increasing trend in snowiness but a significant decreasing trend in the maximum avalanche volume, which may be related to changes in snow density, wind redistribution, and avalanche control measures.

Li et al. (2022a) (Contribution 1) further assessed the avalanche risk in different snow cover types across China. They showed that the persistent and intermittent snow cover areas in northern Xinjiang and northeast China have more predictable avalanche timing, while the ephemeral snow cover areas in the eastern Tibetan Plateau have a higher avalanche risk due to the unstable snow conditions. The study highlights the importance of considering snow cover stability in avalanche hazard mapping and risk management.

3. Conclusions and Future Perspectives

The studies in this Special Issue have advanced our understanding of snow cover dynamics and hydrological impacts in mountainous regions by developing new methods, collecting new data, and providing new insights at various scales. They have demonstrated the value of integrating remote sensing, ground observations, isotope tracers, and hydrological modeling to monitor and predict snow cover change and its hydrological consequences. However, significant challenges remain in snow cover research, including:

(1) Developing and validating high-resolution and long-term snow cover products that can capture the spatial heterogeneity and temporal variability of snow in complex terrain.
(2) Improving the representation of snow processes in Earth system models and hydrological models, particularly the interactions between snow, vegetation, soil, groundwater, and the atmosphere.
(3) Investigating the effects of snow cover change on water resources, ecosystem services, natural hazards, and human activities in a changing climate and socio-economic context.
(4) Strengthening the integration of multi-source data and multi-disciplinary knowledge to inform sustainable water resource management and adaptive risk reduction in snow-dominated regions.

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