

Monitoring Cold-Region Water Cycles Using Remote Sensing Big Data

Hongyi Li ^{1,*}, Xiaohua Hao ¹, Youhua Ran ¹ and Pengfeng Xiao ²

¹ Key Laboratory of Cryospheric Science and Frozen Soil Engineering, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China; haoxh@lzb.ac.cn (X.H.); ranyh@lzb.ac.cn (Y.R.)

² School of Geography and Ocean Science, Nanjing University, Nanjing 210023, China; xiaopf@nju.edu.cn

* Correspondence: lihongyi@lzb.ac.cn

1. Introduction

In recent years, under the backdrop of global warming and intensifying extreme climates, water cycle processes in cold regions have been undergoing profound changes. Glacier retreat, earlier snowmelt seasons, transformations in permafrost landscapes, and increasing uncertainties in various hydrological processes not only affect the sustainable supply of regional water resources, but also exert far-reaching impacts on downstream agriculture, energy, and ecosystems. In such settings, traditional ground-based monitoring faces challenges posed by sparse meteorological stations, complex terrain, and high observational costs, making it difficult to accurately quantify these rapidly changing conditions.

To address these issues, the application of Remote Sensing Big Data (RSBD) and data-driven machine learning methods in monitoring and modeling cold-region water cycles has become increasingly prominent. However, effectively integrating and utilizing diverse remote sensing data sources to produce meaningful information remains a challenge. Several technical and scientific gaps persist:

(1) How can we extract physically meaningful, high-accuracy snow, glacier, and precipitation information across various spatial-temporal scales and from different sensors (optical, microwave, reanalysis data, and satellite-based precipitation products)?

(2) How can we enhance the quantitative monitoring of land use/land cover (LULC), and lake changes through improved classification methods, feature optimization, and physical constraints, thereby supporting mechanistic exploration of cold-region eco-hydrological processes?

(3) How can we improve the accuracy and timeliness of cold-region hydrological modeling and runoff prediction using machine learning, super-resolution reconstruction, and data fusion methods?

The studies included in this Special Issue, “Monitoring Cold-Region Water Cycles Using Remote Sensing Big Data”, directly address these challenges and present a wide range of solutions, from data sources and methodological approaches to feature extraction and process modeling. Below, we summarize how each study fills existing knowledge gaps, discuss their interconnections and contributions, and suggest directions for future research.

2. Improving the Accuracy of Snow, Glacier, and Snowline Dynamics Monitoring in Cold Regions

High-precision snow and glacier information is fundamental for cold-region water cycle research. However, previous optical and passive microwave data approaches often suffered from limitations in spatial resolution and classification accuracy.

Kan et al. [1] tackled the low-resolution issue of FY-4A satellite imagery by proposing DSRSS-Net, which combines super-resolution and semantic segmentation. This job improves cloud–snow discrimination and snow distribution extraction, filling the fine-scale detection gap left by conventional geostationary meteorological satellites. It also



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paves the way for incorporating multiple data sources (e.g., optical and SAR) into snow detection frameworks.

Complementing this, Zhao et al. [2] developed MFPANet, which leverages multi-source (SAR and optical) and multi-scale feature fusion to achieve high-resolution snow depth estimates in high-latitude areas. This approach resolves the precision limitations arising from low-resolution passive microwave data. These studies are complementary; while DSRSS-Net focuses on super-resolution and semantic segmentation, MFPANet emphasizes feature aggregation from multiple data sources. Together, they give examples for enhancing snow parameter extraction over larger spatial extents and more complex terrains.

On longer time scales, snowline and glacier mass balance are key indicators. Wang et al. [3] reviewed three decades of end-of-melt-season snowline changes in the Himalayas using Landsat data, addressing the previous lack of long-term snowline trend monitoring, and providing insights into glacier retreat and regional water resource shifts. Concurrently, Ren et al. [4] compared various machine learning models for simulating glacier mass balance in High Mountain Asia, demonstrating that models such as GBDT can effectively capture the complex nonlinear relationships between climate and glaciers. These two studies complement each other; one focuses on long-term spatiotemporal trends, and the other on optimizing model prediction which, together, lay the groundwork for integrated “observation-model” frameworks that continuously improve glacier and snow monitoring.

Furthermore, Ma et al. [5] incorporated vegetation information into a snow-cover retrieval algorithm (BV-BLRM) to improve snow-cover fraction estimation in vegetated regions. More accurate snow parameters can then feed into runoff simulations, strengthening machine learning models in complex hydrological backgrounds.

In addition to these advances, understanding fine-scale snow physical properties, such as snow grain size, is crucial for assessing snow albedo feedbacks and water resource implications. Zhang et al. [6] made a contribution by using remote-sensing-based simulations to estimate snow grain size distributions and their spatial–temporal variations in Northeast China from 2001 to 2019. By capturing the decadal-scale changes in snow grain size, and identifying underlying spatial patterns, Zhang et al. [6] offer insights into how changing snow properties influence regional climate feedback, water availability, and ecosystem responses.

3. Improving Multi-Source Precipitation Products and Reducing Uncertainty

Scarce and biased precipitation data limit the accuracy of hydrological modeling in cold regions. Several studies in this Special Issue address this gap, offering insights into improving precipitation data and reanalysis model corrections.

Lei et al. [7] examined the performance of multiple precipitation products in mountainous watersheds, and used variance analysis (ANOVA) to quantify the contributions of precipitation products, model parameters, and their interactions to simulation uncertainty. This research helps future studies select and integrate suitable datasets.

In addition, Li et al. [8] applied XGBoost and other machine learning methods for bias correction of high-altitude precipitation measurements, exploring the feasibility of replacing in situ wind speed with remotely sensed precipitation data.

Future studies may integrate bias correction, data assimilation, and spatiotemporal interpolation to produce more reliable inputs for cold-region water cycle simulations.

4. Coupling Data-Driven and Physical Models: Precipitation and Runoff Simulation

Runoff processes in high-altitude and polar regions significantly influence regional water resources and cryosphere hydrology. Historically, models have been limited by data errors and inadequate parameterization. The studies in this Special Issue illustrate how combining data-driven machine learning models with physical models can effectively improve runoff simulation accuracy.

Wang et al. [9] integrated machine learning models (e.g., Random Forest and ANN) and multi-source datasets (reanalysis precipitation, MODIS snow cover, and meteorologi-

cal factors) to achieve high-accuracy snowmelt runoff simulations in high-altitude areas. Meanwhile, Tang et al. [10] integrated a glacier dynamics module into an improved SWAT model to evaluate multi-source precipitation data suitability, thereby enhancing the model's physical realism and achieving a more robust data-process coupling.

5. High-Resolution Land Cover Classification and Lake Monitoring as a Foundation for Eco-Hydrological Research

A comprehensive understanding of cold-region water cycles also requires accurate land cover data and information on lake dynamics.

Li et al. [11] developed a subregion ensemble learning framework for large-scale LULC mapping, improving classification accuracy and reducing computational costs. Shi et al. [12] utilized GF-7 high-resolution images and multiple ensemble learning strategies to achieve high-precision LULC classification in the complex terrain of the eastern Qinghai–Tibet Plateau. These two approaches complement each other. Li et al. [11]'s work emphasized overall integration and efficiency, while Shi et al. [12] focused on multi-temporal data and feature optimization. Together, they gave examples for generating high-quality LULC products across various terrain and climate conditions, supporting precipitation-runoff–evapotranspiration modeling.

In terms of lake dynamics, Liu et al. [13] used time-series remote sensing to detect thermokarst lake drainage events in Northeastern Siberia, revealing how permafrost changes affect water distribution. This case study offers insights into integrating subsurface hydrology into water cycle models.

The changes in cold-region water cycles affect not just water resources, but also vegetation growth and phenological patterns. Ren et al. [14] investigated how snow cover changes influence spring phenology in different vegetation types in Northeast China, identifying “temperature effects” and “moisture effects” associated with snow. Such insights are vital for understanding snow–vegetation–climate coupling. Future work could incorporate precise snow parameters, precipitation data, and LULC products into vegetation dynamics models for a more integrated analysis of cold-region eco-hydrological processes.

6. Sensor Calibration and Multi-Source Data Fusion Underpin High-Quality Analyses

High-quality remote sensing data are a prerequisite for all these studies. Zhang et al. [15] addressed radiometric imbalances in the blue band of BNU-1 satellite imagery through on-orbit relative sensor normalization, improving data quality. In the future, multi-source and multi-sensor data fusion and robust radiometric calibration will remain critical steps in ensuring data reliability.

7. Conclusions

This Special Issue advances cold-region water cycle monitoring through several significant contributions. The studies presented have improved data extraction and processing methods for snow, glacier and precipitation monitoring, developed novel machine learning and data fusion techniques, established physically coupled models integrating multiple data sources, and refined land cover classification approaches for complex terrains. Together, these advances form a comprehensive framework spanning from raw data processing to actionable insights for environmental management.

While these innovations represent important progress, several critical research gaps remain to be addressed. The first priority is strengthening uncertainty quantification and data assimilation capabilities. Future research could focus on implementing advanced optimization methods, such as Bayesian optimization and ensemble Kalman filters, to better quantify and reduce multi-dimensional uncertainties in monitoring systems.

A second challenge lies in enhancing the physical basis of machine learning approaches. This requires careful integration of domain knowledge into models while maintaining a balance between predictive accuracy and physical interpretability. Such physically constrained models will be essential for reliable long-term predictions.

The third area requiring attention is the validation and standardization of methods across broader spatial and temporal scales. This includes systematic cross-regional testing, the integration of data from multiple sensor generations, and the development of standardized workflows that can be applied globally. These efforts will help to establish robust, reproducible frameworks for cold-region monitoring.

Long-term forecasting capabilities also need significant enhancement. This involves extending time-series analyses for improved trend detection, developing more sophisticated climate scenario models for water resource projections, and creating practical applications for flood prediction and infrastructure planning. Such advances will directly support decision-making for climate adaptation.

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