remote sensing

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Editorial

Editorial: Applications of Remote Sensing in Glaciology

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Contemporary and significant spatiotemporal changes in glaciers are a result of rapidly evolving regional and global climate, and continuous monitoring is imperative for understanding the complexities of glacio–climatic interactions. Although the importance of glaciers as climate proxies was first recognized in the latter half of the 19th century, the awareness and efforts surrounding the glacier monitoring for climate change assessment have persistently improved since 1990s, after the Intergovernmental Panel on Climate Change (IPCC) started including glacier fluctuation data in their assessments. Large-scale shifts in the areal, altitudinal, and flow regimes of glaciers are bound to promote glacial disasters and hydrological irregularities, necessitating their worldwide monitoring. However, year-round, field-based glacier monitoring is limited by several factors, such as a hostile climate, poor approachability, inadequate skilled labor, and insufficient funding. In such scenarios, remote sensing is largely utilized as a practical alternative or a supporting technique to field studies, in order to meet the growing needs of glaciology research.

With the continuous advancements in imaging systems and remote sensing platforms, and enhancements in the computational efficiencies of hardware and related software programs, remote sensing applications in glaciology have considerably increased in the past decade. Many universities have started dedicated programs or courses in glaciology, and well-known environmental science and Earth observation journals have increased the frequency of special collections covering glaciology and cryosphere research. With this background, our topical collection was designed to invite multidisciplinary submissions pertaining to the use of remote sensing in assessing glacier changes and the associated impacts in high altitude and high latitude regions. This topical collection offered a wider scope to potential authors and encouraged contributions in all areas of contemporary or future glaciology research related (but not restricted) to the use of spaceborne/aerial/terrestrial remote sensing for glacier mapping, glacier area changes, volumetric estimations, glacio-hydrology, glacier flow dynamics, glacial or periglacial geomorphology, glacial lakes, glacial seismology, lithological mapping in a glacial environment, glacial hazards, and synergy between glacier field work and remote sensing.

After thorough review and revisions, all the accepted papers in our topical collection were novel, comprehensive, and informative with emphasis on the systematic and recent advances in our knowledge, tools, techniques, and methods for employing remote sensing in glaciology. In total, 14 papers were published, including 2 review articles, representing authors and study regions from across the globe. The first review article [1] covered a relevant topic of contemporary applications and prospects of unmanned aerial vehicles (UAVs) for cryosphere research. Since the publication of the first review article on UAV applications in glaciology in 2016, there was a significant gap, filled by the published review article [1] in this Special Issue. This holistic review [1] discussed the methodological advancements, hardware and software improvements, results, and future prospects of over hundred published studies, covering the most recent applications of UAVs within glaciology, snow, permafrost, and polar research. The authors also analyzed the UAV and sensor hardware, and data acquisition and processing software in terms of popularity. In addition, this review [1] revisited and compiled the existing UAV flying regulations in cold

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regions of the world to inform the readers on the key legal requirements before planning a field work. Of course, such requirements are rapidly evolving and often quite stringent. The visible impacts of climate change are understandably pronounced in Antarctica and the second review article [2] focused on past glaciological studies conducted on King George Island (KGI). This review [2] highlighted the spatiotemporal data discontinuity for the mass balance parameters of the KGI ice dome. A lack of sufficient and reliable data on glaciological parameters is the main reason behind large uncertainties in our understanding of the impact of climate change on ice reserves globally. The authors [2] also highlight the use of varying baseline datasets as a practice behind obtaining misleading trends in glacier fluctuations and dynamics.

Moving to the published research articles, they can broadly be classified into three categories: (1) estimating, mapping, and monitoring glacier parameters; (2) novel approaches in mapping and conservation; and (3) modelling glacial environs and hazards. In the first category, the article by Liao et al. [3] offers information on long-term estimation of the glacier surface temperature of Hailuogou Glacier in Southeastern Tibetan Plateau. The authors used 28 years (1990–2018) of Landsat data for this purpose. Their algorithm accounted for the emissivity of ice and snow, atmospheric transmittance, and effective mean atmospheric temperature, and the final results showed an increasing trend of 0.054 °C a^{-1} during the observation period, possibly due to atmospheric warming, expanding debris cover, and lowering albedo of debris-free accumulation area. Another article [4] in the glacier monitoring category focused on 30 years (1985–2015) of observational data to report the spatiotemporal dynamics of the termini of 17 marine-terminating glaciers in West Greenland. The authors [4] manually digitized the frontal positions to find a retreat in 15 of the glacier termini; ~80% of this retreat was post-2000. Additionally, the authors [4] performed frequent temporal analyses to identify 10 actively retreating glaciers, showing even seasonal variability in their retreat rates. These findings certainly have implications for the Arctic ice reserves in the wake of ongoing dramatic seasonal weather anomalies.

Ice thickness estimation, particularly for mountain glaciers, is tricky but equally important, and Liu et al. [5] performed a more localized analysis for Baishui River Glacier No. 1 of Yulong Snow Mountain, China, using a ground penetrating radar (GPR) to estimate the ice thickness and detect subglacial features. The authors [5] were able to identify and characterize various subglacial features such as water paths, ice caves, crevasses, small ice basins, and distributed ice steps and ice ridges. The authors [5] also listed several limitations of the technique, e.g., the lower sensitivity of amplitude and polarity changes of the reflected radar wave at the glacier bottom might lead to uncertainty on the real erosion situation of ice, water, and debris. Monitoring glacier dynamics is useful in better understanding the response of mountain glaciers to climate forcing and Zhang et al. [6] studied seasonal and interannual variability in surface velocity of four representative glaciers of the Parlung Zangbo Basin (PZB), Tibetan Plateau, using the Co-registration of Optically Sensed Images and Correlation (COSI-Corr) tool. Contrary to the findings of several other studies for the region, the authors reported that the glacier centerline velocity showed slight increase during 2017–2020. Glacier mass balance estimations are one of the most reliable parameters used to examine the health of a glacier, and Gharehchahi et al. [7] performed a regional-scale analysis to understand the impact of local and regional climate forcing on the glacier mass balance changes in the Swiss Alps. The results indicated the loss of equilibrium condition in recent decades for all the studied glaciers, with negative mass balance trends and decreasing accumulation areas, as a result of increasing air temperatures of $\geq$+0.45 °C decade^{-1}. Gharehchahi et al. [7] also reported considerable controls of the Atlantic multidecadal oscillation (AMO), Greenland blocking index (GBI), and East Atlantic (EA) teleconnections on the interannual variability of summer and winter mass balances. The authors [7] further corroborated their findings with the analysis of decadal frontal retreat using Landsat images from 1984 to 2014.

Moving to the next category of novel approaches in mapping and glacier conservation, the Special Issue received several interesting submissions. Huang et al. [8] successfully used airborne light detection and ranging (LiDAR) data for developing a semiautomated detection and mapping algorithm for glacier crevasses, further confirming the relevance and wide applicability of LiDAR data in glaciology. In their bidirectional analysis method, Huang et al. [8] first separated the crevasse points from non-crevasse points, and then adaptively delineated the crevasses through a local statistical analysis method. The effectiveness of digital elevation models (DEMs) in estimating geodetic glacier mass balances becomes impacted by the presence of voids in them, and Seehaus et al. [9] targeted this issue of void filling using several approaches for generating more reliable glacier elevation change datasets. They concluded that the bilinear void filling method was computationally most effective. Supraglacial surface features, particularly the lakes, are very dynamic and significant to monitor due to their role in enhancing melting and hazards. In this direction, Chen [10] employed GaoFen-3 synthetic aperture radar (SAR) data to find that the U-Net-based deep learning model worked best, not only in detecting and mapping supraglacial lakes but also supraglacial streams and ice crevasses. Another glacier parameter that has often been correlated with mass changes is glacier snow line altitude, prompting for its seasonal and annual monitoring. Prieur et al. [11] proposed machine learning methods to automatically detect the snow line on multispectral satellite imagery and quantify its average altitude. However, using such approaches to demarcate discontinuous snow lines or the ones exhibiting an abrupt change in elevation still presents various difficulties [11]. Artificial glacier melt reduction is gaining increasing attention as a glacier conservation strategy. Finally, in this category of novel approaches, Liu et al. [12] quantified the effectiveness of such approaches. They compared two high-resolution DEMs derived from terrestrial laser scanning and UAV, in addition to albedo and meteorological data to assess glacier ablation mitigation under three different cover materials. The results were encouraging as 32% of mass loss was preserved in the protected areas compared with that of the unprotected areas with the nanofiber material performing better than the geotextiles.

In the third category of this Special Issue, i.e., modelling glacial environs and hazards, two articles were published. The first paper by Gharehchahi et al. [13] focused on modelling glacier ice thickness estimation and future lake formation in Swiss Southwestern Alps. Glacial lakes can be extremely hazardous, and the need for their monitoring and modelling is imperative. The study by Gharehchahi et al. [13] integrated the glacier outlines and DEMs into the volume and topography automation (VOLTA) model to estimate ice thickness and identify overdeepenings. This timely information on future glacial lakes can help manage water resources and hazards, and better understand glacier dynamics, catchment ecology, and landscape evolution. The final article [14] in this category also focused on glacier hazards, i.e., rock–ice avalanches, which are being reported more frequently from across the globe. This work [14] focused on a flash flood triggered by a rock-ice avalanche on the 7 February 2021, causing significant damage to life and property in the Tapovan region of the Indian Himalaya. The main findings highlighted the relevance of studying the changes in surface velocity as a precursor to such events, and the need to consider the antecedent conditions, while making a holistic assessment of such hazards.

With these published articles, we observe a variety of research ideas and emerging trends in glaciology. This Special Issue was successful in providing a dedicated platform to the papers which used remote sensing for glaciology research, and we are considering to open another follow-up Special Issue on this topic.

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References

1. Gaffey, C.; Bhardwaj, A. Applications of unmanned aerial vehicles in cryosphere: Latest advances and prospects. *Remote Sens.* **2020**, *12*, 948. [CrossRef]
2. Dziembowski, M.; Bialik, R.J. The Remotely and Directly Obtained Results of Glaciological Studies on King George Island: A Review. *Remote Sens.* **2022**, *14*, 2736. [CrossRef]
3. Liao, H.; Liu, Q.; Zhong, Y.; Lu, X. Landsat-based estimation of the glacier surface temperature of Hailuogou glacier, Southeastern Tibetan Plateau, between 1990 and 2018. *Remote Sens.* **2020**, *12*, 2105. [CrossRef]
4. York, A.V.; Frey, K.E.; Jamali, S.; Das, S.B. Change Points Detected in Decadal and Seasonal Trends of Outlet Glacier Terminus Positions across West Greenland. *Remote Sens.* **2020**, *12*, 3651. [CrossRef]
5. Liu, J.; Wang, S.; He, Y.; Li, Y.; Wang, Y.; Wei, Y.; Che, Y. Estimation of ice thickness and the features of subglacial media detected by ground penetrating radar at the Baishui River Glacier no. 1 in Mt. Yulong, China. *Remote Sens.* **2020**, *12*, 4105. [CrossRef]
6. Zhang, J.; Jia, L.; Menenti, M.; Ren, S. Interannual and seasonal variability of glacier surface velocity in the parlung zangbo basin, tibetan plateau. *Remote Sens.* **2020**, *13*, 80. [CrossRef]
7. Gharehchahi, S.; Ballinger, T.J.; Jensen, J.L.; Bhardwaj, A.; Sam, L.; Weaver, R.C.; Butler, D.R. Local-and Regional-Scale Forcing of Glacier Mass Balance Changes in the Swiss Alps. *Remote Sens.* **2021**, *13*, 1949. [CrossRef]
8. Huang, R.; Jiang, L.; Wang, H.; Yang, B. A bidirectional analysis method for extracting glacier crevasses from airborne LiDAR point clouds. *Remote Sens.* **2019**, *11*, 2373. [CrossRef]
9. Seehaus, T.; Morgenshtern, V.I.; Hübner, F.; Bänsch, E.; Braun, M.H. Novel techniques for void filling in glacier elevation change data sets. *Remote Sens.* **2020**, *12*, 3917. [CrossRef]
10. Chen, F. Comparing Methods for Segmenting Supra-Glacial Lakes and Surface Features in the Mount Everest Region of the Himalayas Using Chinese GaoFen-3 SAR Images. *Remote Sens.* **2021**, *13*, 2429. [CrossRef]
11. Prieur, C.; Rabatel, A.; Thomas, J.B.; Farup, I.; Chanussot, J. Machine Learning Approaches to Automatically Detect Glacier Snow Lines on Multi-Spectral Satellite Images. *Remote Sens.* **2022**, *14*, 3868. [CrossRef]
12. Liu, S.; Wang, F.; Xie, Y.; Xu, C.; Xue, Y.; Yue, X.; Wang, L. Quantifying the Artificial Reduction of Glacial Ice Melt in a Mountain Glacier (Urumqi Glacier No. 1, Tien Shan, China). *Remote Sens.* **2022**, *14*, 2802. [CrossRef]
13. Gharehchahi, S.; James, W.H.; Bhardwaj, A.; Jensen, J.L.; Sam, L.; Ballinger, T.J.; Butler, D.R. Glacier Ice Thickness Estimation and Future Lake Formation in Swiss Southwestern Alps—The Upper Rhône Catchment: A VOLTA Application. *Remote Sens.* **2020**, *12*, 3443. [CrossRef]
14. Bhardwaj, A.; Sam, L. Reconstruction and characterisation of past and the most recent slope failure events at the 2021 rock-ice avalanche site in Chamoli, Indian Himalaya. *Remote Sens.* **2022**, *14*, 949. [CrossRef]