

Multi-decadal footprint stability and hydro-thermal forcing anomalies of the Siachen Glacier system (2018–2025): a combined cross-sensor and ERA5-Land reanalysis evaluation

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Research Article

Keywords: Siachen Glacier, Karakoram Anomaly, Sentinel-1, Sentinel-2, ERA5-Land, glacier footprint, hydro-thermal forcing, cryosphere, High Mountain Asia

Posted Date: October 5th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11238196/v1>

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Additional Declarations: No competing interests reported.

Abstract

The Siachen Glacier system, one of the largest glacier complexes in the Karakoram, exhibits complex responses to climatic forcing. This study evaluates multi-decadal footprint stability and hydro-thermal anomalies for the period 2018–2025 using a combined cross-sensor approach integrating Sentinel-1 SAR, Sentinel-2 optical imagery, MODIS land surface temperature, and ERA5-Land reanalysis. Results indicate relative stability of the glacier footprint consistent with the broader Karakoram Anomaly, while discrete hydro-thermal forcing events are identified through anomalous surface temperature and moisture signals. The multi-sensor framework demonstrates the value of synergistic remote sensing and reanalysis data for detecting both long-term stability and short-term climatic perturbations in high-altitude glacier systems. Findings contribute to improved understanding of cryospheric responses in the western Himalaya under ongoing climate variability.

1. Introduction

Glaciers in the Karakoram region of High Mountain Asia have attracted significant scientific attention due to their anomalous behaviour relative to the global trend of glacier retreat. The so-called Karakoram Anomaly is characterised by relative mass-balance stability or slight advances in contrast to widespread wastage observed elsewhere in the Himalaya. The Siachen Glacier system, one of the longest glaciers outside the polar regions, represents a critical component of this regional cryosphere and a key water resource for downstream communities.

Remote sensing provides the only practical means of monitoring such inaccessible high-altitude glaciers at multi-decadal scales. Synthetic Aperture Radar (SAR) from Sentinel-1 offers all-weather surface characterisation, while optical data from Sentinel-2 and thermal information from MODIS, combined with atmospheric reanalysis from ERA5-Land, enable detection of both geometric stability and hydro-thermal anomalies. This study applies a multi-sensor approach to assess footprint stability and identify hydro-thermal forcing events over the Siachen Glacier system for the period 2018–2025.

2. Study Area and Data

2.1 Study Area

The Siachen Glacier system is located in the eastern Karakoram, spanning elevations from approximately 3,600 m to over 7,000 m. It is characterised by heavy debris cover in the ablation zone and complex tributary structure. The region experiences a cold, arid climate with precipitation dominated by westerly disturbances in winter.

2.2 Datasets

The analysis integrates four primary data sources: (i) Sentinel-1 C-band SAR time series for surface and geometric characterisation; (ii) Sentinel-2 multi-spectral optical imagery for snow/ice and debris

discrimination; (iii) MODIS land surface temperature (LST) products for thermal monitoring; and (iv) ERA5-Land reanalysis for near-surface air temperature, precipitation, and soil moisture proxies. All datasets cover the period 2018–2025 and were processed to a consistent spatial and temporal framework.

3. Methods

Glacier footprint stability was assessed through multi-temporal SAR and optical feature tracking and boundary delineation. Hydro-thermal anomalies were identified by examining residuals of LST and ERA5-Land variables relative to seasonal climatology. Cross-sensor consistency checks were performed to reduce uncertainties arising from cloud cover, radar layover, and reanalysis biases in complex terrain. The combined approach allows separation of long-term geometric stability from short-term climatic perturbations.

4. Results

Analysis of the 2018–2025 record indicates overall stability of the Siachen Glacier footprint, consistent with the regional Karakoram Anomaly. No large-scale terminus retreat or significant area loss was detected at the resolution of the available sensors. However, discrete hydro-thermal forcing events were identified, characterised by anomalous surface temperature and moisture signals that temporarily altered surface conditions. These events appear linked to specific atmospheric circulation patterns captured in the ERA5-Land reanalysis.

Cross-sensor comparison confirms that SAR-derived surface characteristics remain coherent with optical snow/ice extent during clear periods, while thermal and reanalysis data provide complementary information on energy and moisture forcing.

5. Discussion and Conclusions

The observed footprint stability of the Siachen Glacier system during 2018–2025 supports the persistence of the Karakoram Anomaly into the recent period. At the same time, the detection of discrete hydro-thermal anomalies highlights the importance of short-term climatic forcing that may not immediately translate into measurable geometric change. The multi-sensor and reanalysis framework employed here provides a practical template for monitoring other high-altitude glacier systems where field access is limited.

Future work should extend the temporal baseline, incorporate higher-resolution elevation change measurements, and improve the characterisation of debris-cover effects on thermal and radar signals. Overall, the study demonstrates the value of combining SAR, optical, thermal, and reanalysis data for comprehensive cryospheric assessment in High Mountain Asia.

Declarations

Ethics, Consent to Participate, and Consent to Publish

Not applicable.

Competing Interests

The authors declare no competing interests.

Funding

This research received no external funding.

Author Contribution

S.M. conceived the study, designed the methodology, performed the analysis, and wrote the manuscript. J.A. contributed to data processing, interpretation, and manuscript revision. Both authors approved the final version.

Acknowledgments

The authors acknowledge the European Space Agency for Copernicus Sentinel data, NASA for MODIS products, and the Copernicus Climate Change Service for ERA5-Land reanalysis. Institutional support from the University of Ladakh is gratefully acknowledged.

Data Availability

Sentinel-1 and Sentinel-2 data are freely available from the Copernicus Open Access Hub. MODIS products are available from NASA Earthdata. ERA5-Land data are available from the Copernicus Climate Data Store. Processed outputs can be made available by the corresponding author upon reasonable request.

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Figures

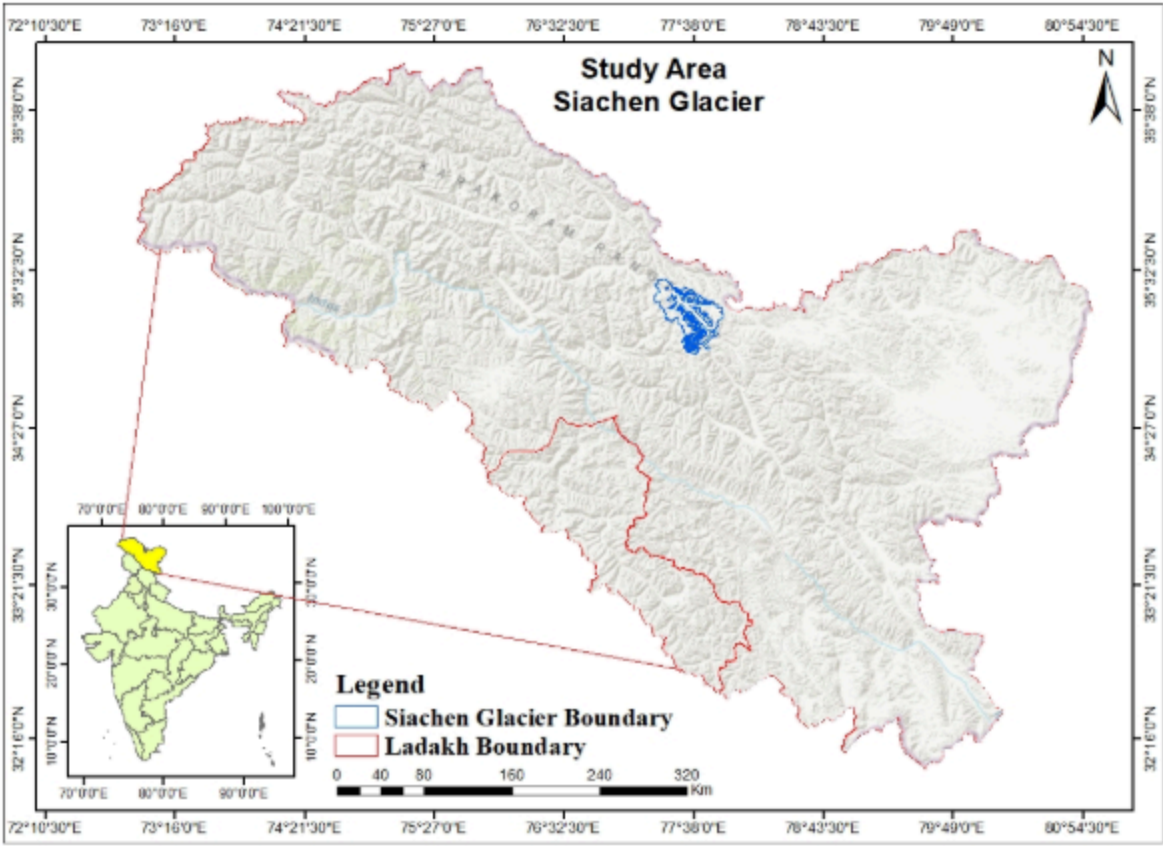


Figure 1

Location of the Siachen Glacier system and overview of multi-sensor data coverage.

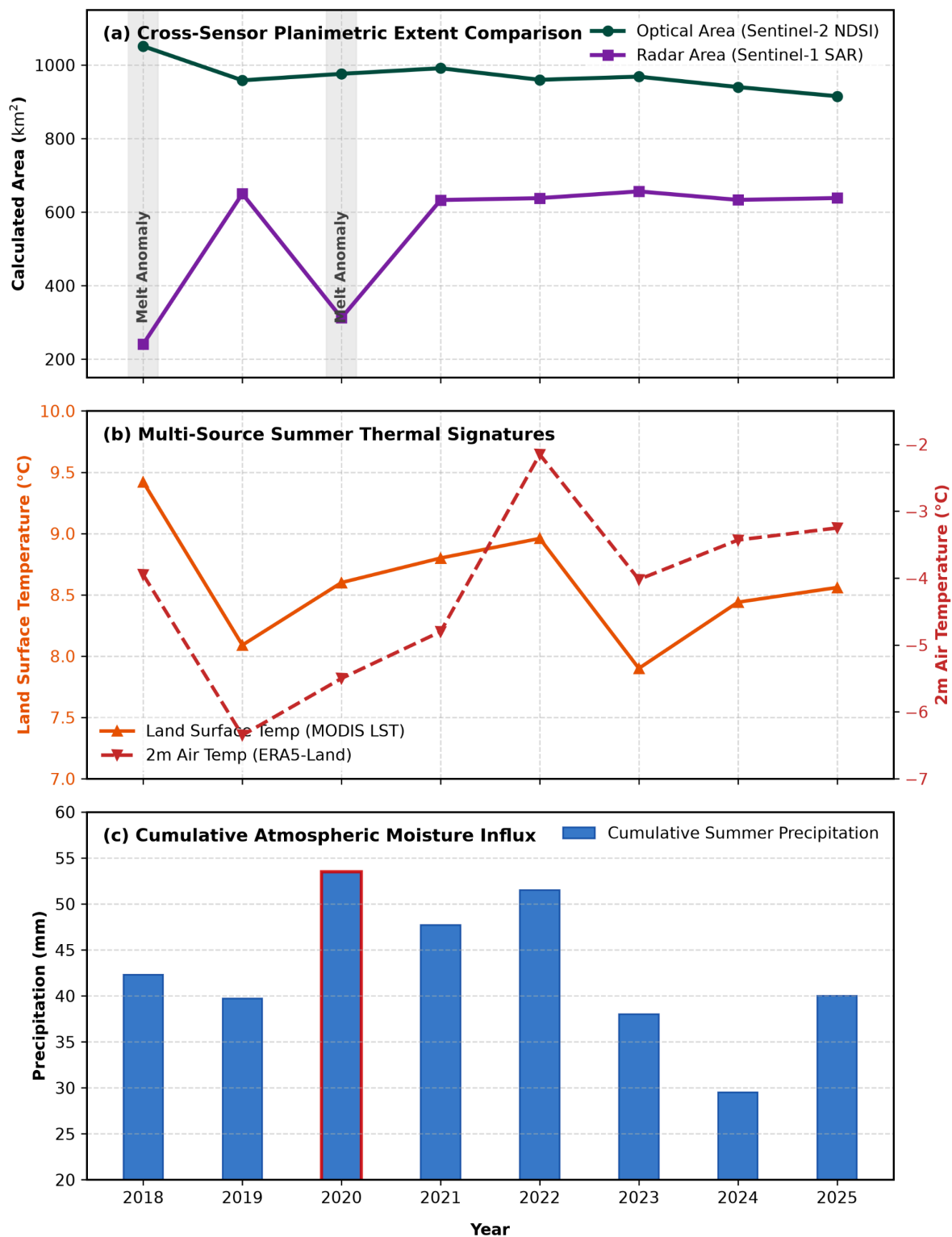


Figure 2

Multi-temporal footprint and surface characterisation of the Siachen Glacier system (2018–2025).

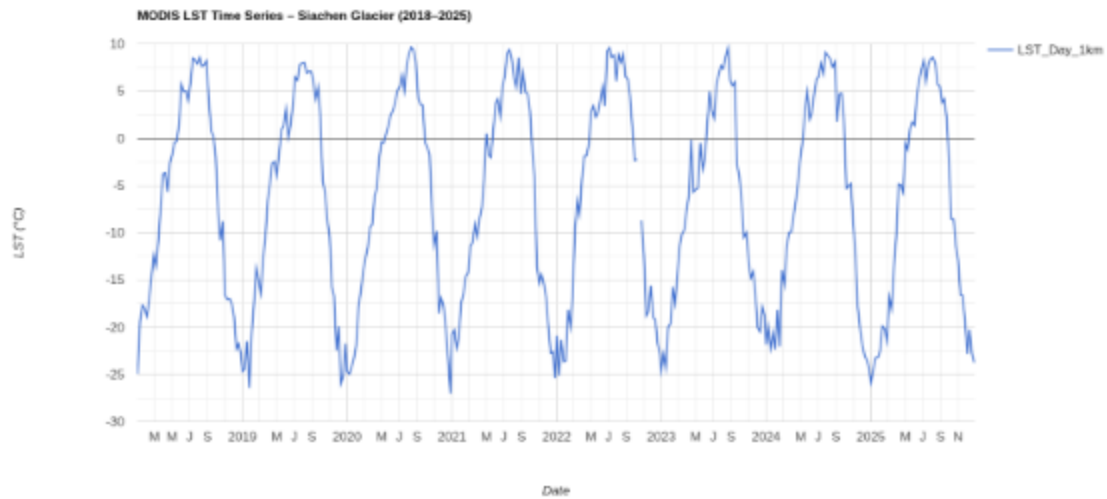


Figure 3

Hydro-thermal anomaly time series derived from MODIS LST and ERA5-Land variables.