

Remote sensing early supraglacial debris evolution on a mountain glacier using an energy balance model, thermal imagery, and climate reanalysis data

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Context

Supraglacial debris modifies glacier melt. Thick debris reduces ablation, while thin or sparse debris cover enhances ablation.

On Himalayan glaciers, debris-covered areas are expanding under climate change as rising equilibrium line altitudes (ELAs) increase debris meltout (Thakuri et al., 2014), but the **early development of debris cover remains poorly constrained**.

Current debris thickness datasets (e.g., Rounce et al., 2021) focus on near-stagnant areas, whereas dynamic regions remain flowing at higher elevations. Consequently, **debris evolution is poorly captured**.

Understanding how debris cover evolves as ELAs rise will enable better estimates of glacier longevity (Compagno et al., 2022).

This gap is especially critical on glaciers such as Rongbuk Glacier, in the Everest region, where debris is advancing up-glacier. We address this using **multi-temporal averaging** and **pixel-wise regression** to resolve debris evolution in flowing ice that previous datasets could not capture.

Case Study – Rongbuk Glacier, Everest Region

Landsat 7 satellite imagery shows debris cover advancing up-glacier between 2000-2021.

Global debris-thickness datasets (e.g., Rounce et al., 2021) omit much of this newly emerged debris because they focus on stagnant glacier tongues.

The Middle Rongbuk Glacier remains flowing, highlighting this limitation.

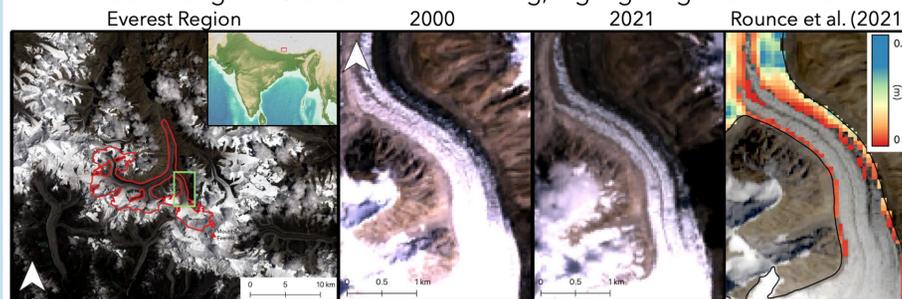


Figure 2. Study site in the Everest Region within the Himalaya. Rongbuk Glacier is outlined in red, with the transition zone of the Middle Rongbuk Glacier outlined in green. Landsat 7 imagery from 2000 and 2021 shows the advance of supraglacial debris cover. Comparison with Rounce et al.'s (2021) global debris-thickness dataset (right) demonstrates the omission of newly emerged medial moraines, as the dataset focuses on stagnant glacier tongues

Workflow

A time series of individual debris thickness maps (2000-2021), derived from cloud-free Landsat 7 thermal imagery, shows inconsistent results between maps, indicating unclear debris evolution.

To reduce this noise, we developed two approaches that emphasise longer-term signals and remove map-to-map variability:

- 1) **Five-year temporal averaging**, revealing clear debris evolution between maps
- 2) Pixel-wise linear regression to define a **debris accumulation rate**, capturing long-term debris thickening.

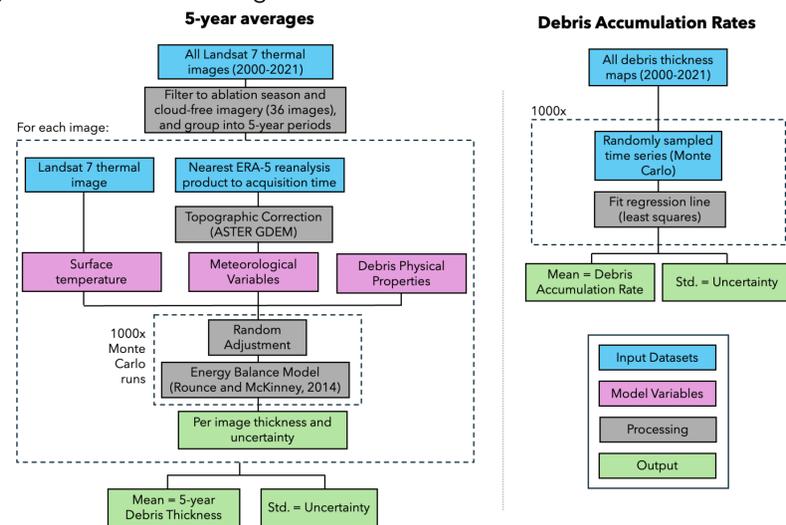


Figure 3. Workflows for deriving 5-year average debris thickness maps (left) and debris accumulation rates (right). Both methods reduce inconsistencies between individual thickness maps, revealing long-term debris trends. The workflow for deriving individual thickness and uncertainty maps is adapted from Stewart et al. (2021).

Results

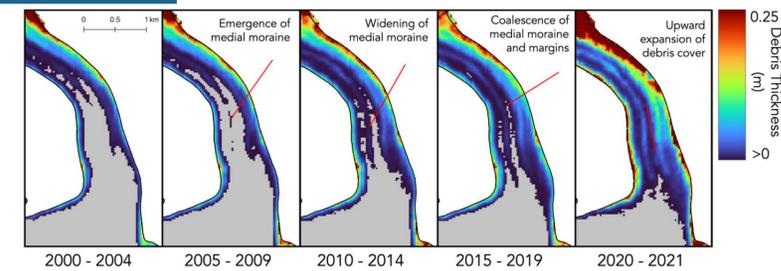


Figure 4. 5-year debris thickness maps between 2000 and 2021.

Temporally Averaged Maps: (above)

Progressive advance of debris cover up-glacier between 2000 and 2021.

Debris first emerges in lateral bands, then widens and coalesces into seemingly continuous debris cover.

Debris Accumulation Rates: (right)

Rates are **highest in lateral bands and margins**, consistent with debris delivery from englacial septa and mountainsides. Mean thickening in the transition zone is $1.3 \pm 0.4 \text{ mm yr}^{-1}$.

Multi-temporal methods reveal new debris evolution. By stacking maps and employing regression, we demonstrate clear debris evolution in the transition zone that previous datasets (e.g., Rounce et al., 2021) fail to capture.

However, interpreting these patterns requires caution. The apparent continuous debris cover in the maps may not reflect the true debris distribution, requiring careful interpretation.

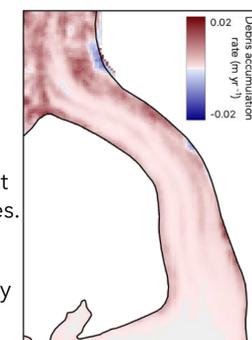


Figure 5. Debris accumulation rates (m yr^{-1}) along Rongbuk Glacier's transition zone.

Discussion

Apparent continuity of debris may be misleading. Drone imagery shows debris is concentrated in topographic lows between seracs.

Pixel-scale assumptions may introduce uncertainty in melt estimates. Treating debris cover as continuous within a pixel distorts melt estimates. The transition zone's thin and patchy debris alters melt in a non-linear way. Estimating a sub-pixel **'debris-covered fraction'** would improve accuracy.

Accurate ELAs are critical for diagnosing debris sources:

- Beneath ELA: debris accumulation indicates increased meltout or mountainside delivery.
- Above ELA: debris accumulation indicates increased mountainside delivery.
- Greater supply enhances englacial debris, driving **faster debris development beneath the ELA** and increasing glacier longevity.

Next Steps

We propose using high-resolution UAV imagery as ground truth for model training to estimate the sub-pixel debris-covered fraction of the transition zone.

Quantifying this fraction will enable a mixed-pixel melt model that better resolves the non-linear influence of patchy debris on ablation.

Early Debris Evolution

Debris cover emerges as patchy cover below the ELA as englacial septa melt out (e.g., from medial moraines).

This patchy cover then redistributes into continuous debris cover in the **transition zone** (Kirkbride and Deline, 2013). Our methods capture this development.

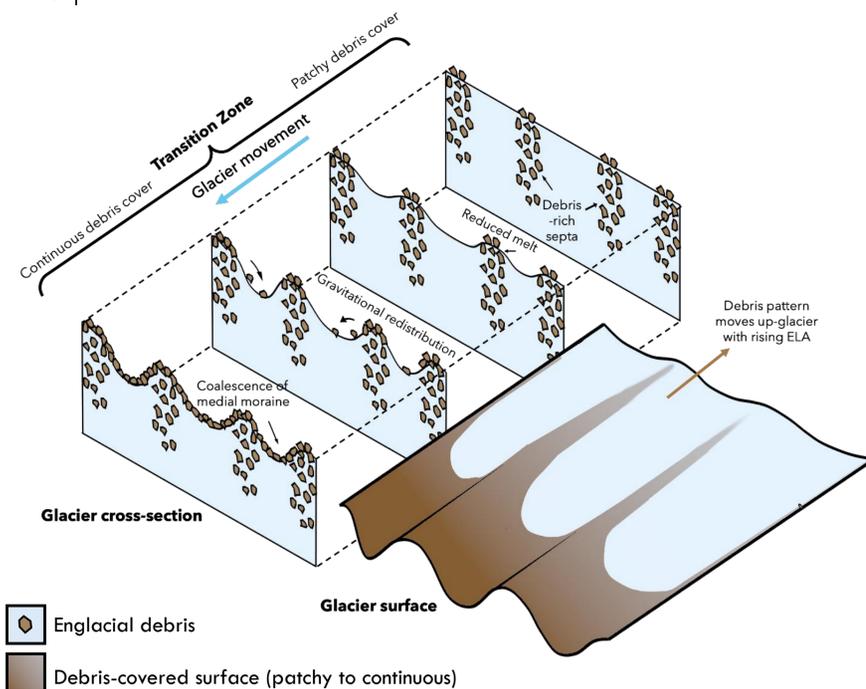


Figure 1. Schematic of early debris cover evolution showing how englacial debris (septa, medial moraines) melts out to form patchy supraglacial debris, which then redistributes into continuous cover within the transition zone. Rising temperatures are moving these processes further up-glacier.

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