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Understanding spatial patterns of mass loss of a debris-covered glacier

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Debris-covered glaciers make up a significant fraction of glacier surface (~15%) and ice volume (~30%, [1]) in High-Mountain Asia. To estimate melt from these glaciers and their contribution to stream flow remains difficult because of a lack of spatial data and the challenge to accurately reproduce the energy transfer through debris to the ice surface. Using high-resolution DEM data from 6 consecutive years in the Nepalese Himalaya, we are able to quantify mass loss and use it to constrain a new energy balance model and develop a simpler temperature based index model.

Research aim

- establish a **distributed energy balance** and simple **temperature index** model for sub-debris melt
- What is the **sensitivity** to debris properties?
- How does **debris effect** the melt **discharge**?

Study site + Model

Lirung Glacier (6.5 km², 17% debris-covered, 4044-6615 m a.s.l., 28.2N, 85.6E) in the Central Himalaya has been researched since many decades, including **recent studies** on turbulent fluxes, supraglacial ponds and cliffs as well as debris redistribution [2,3,4,5]. **Climate data** and concurrent **high-resolution DEMs** from nine UAV flights are available between 2012 and 2018. **Debris temperature** and **moisture** measurements as well as **depth measurements** are available from multiple locations (Figure 1).

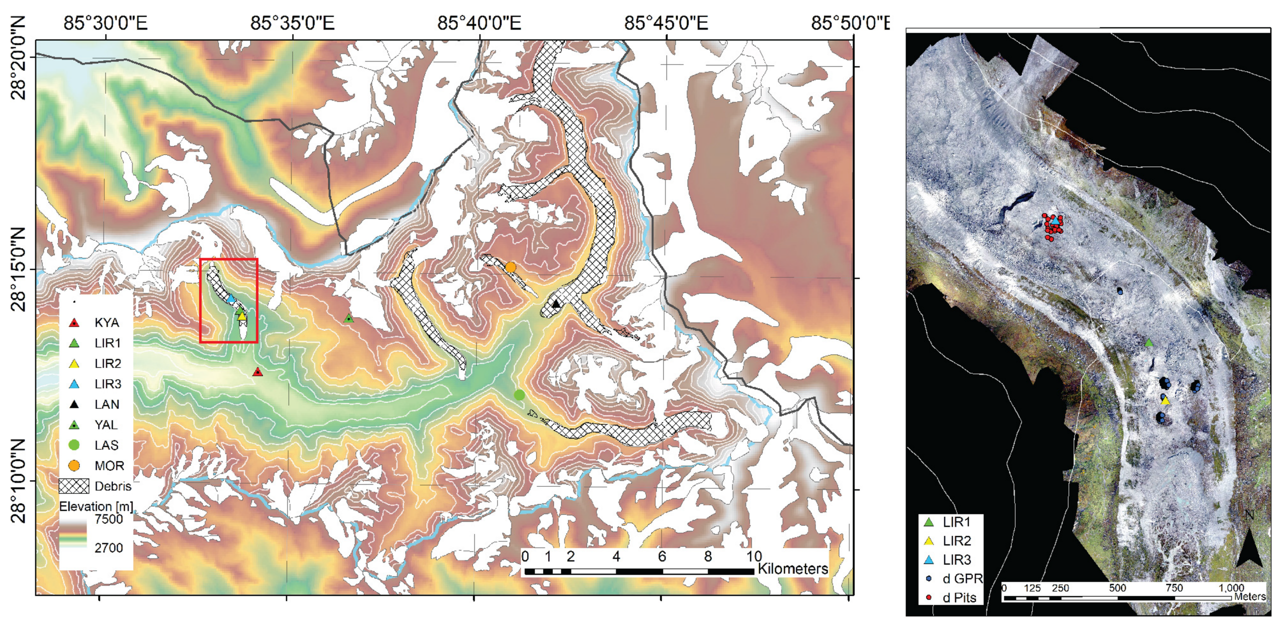
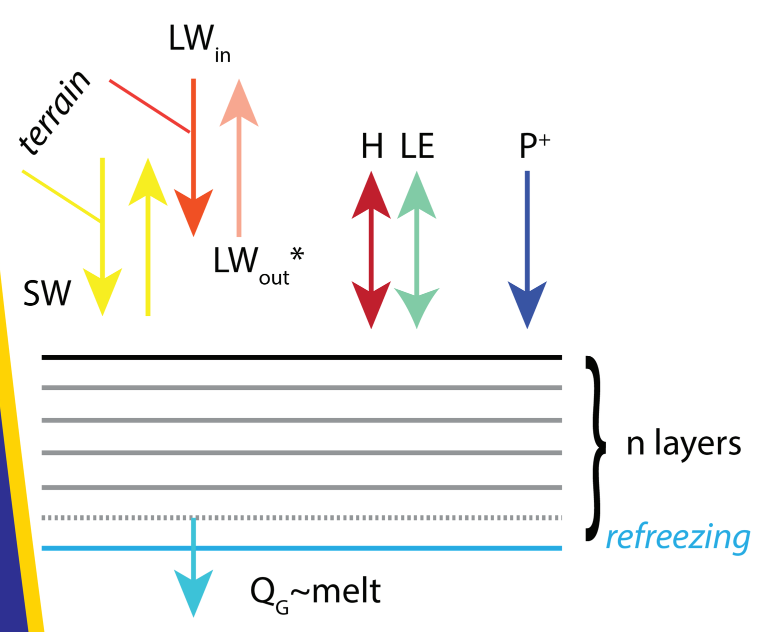


Figure 1: Lirung Glacier in the Central Himalaya has been heavily researched in recent decades and ample climatic data as well as observations of mass loss are available.



The energy balance model (see [6] for the point scale) uses climate data at **hourly resolution** and considers the effect of **shading from the surrounding topography**. Debris thickness in space is determined by solving an inversion of the balance against measured values, using a Monte Carlo approach for each cell.

Figure 2: The energy balance model uses all fluxes and resolves the energy transfer on multiple layers. Local topography is accounted for in radiation input.

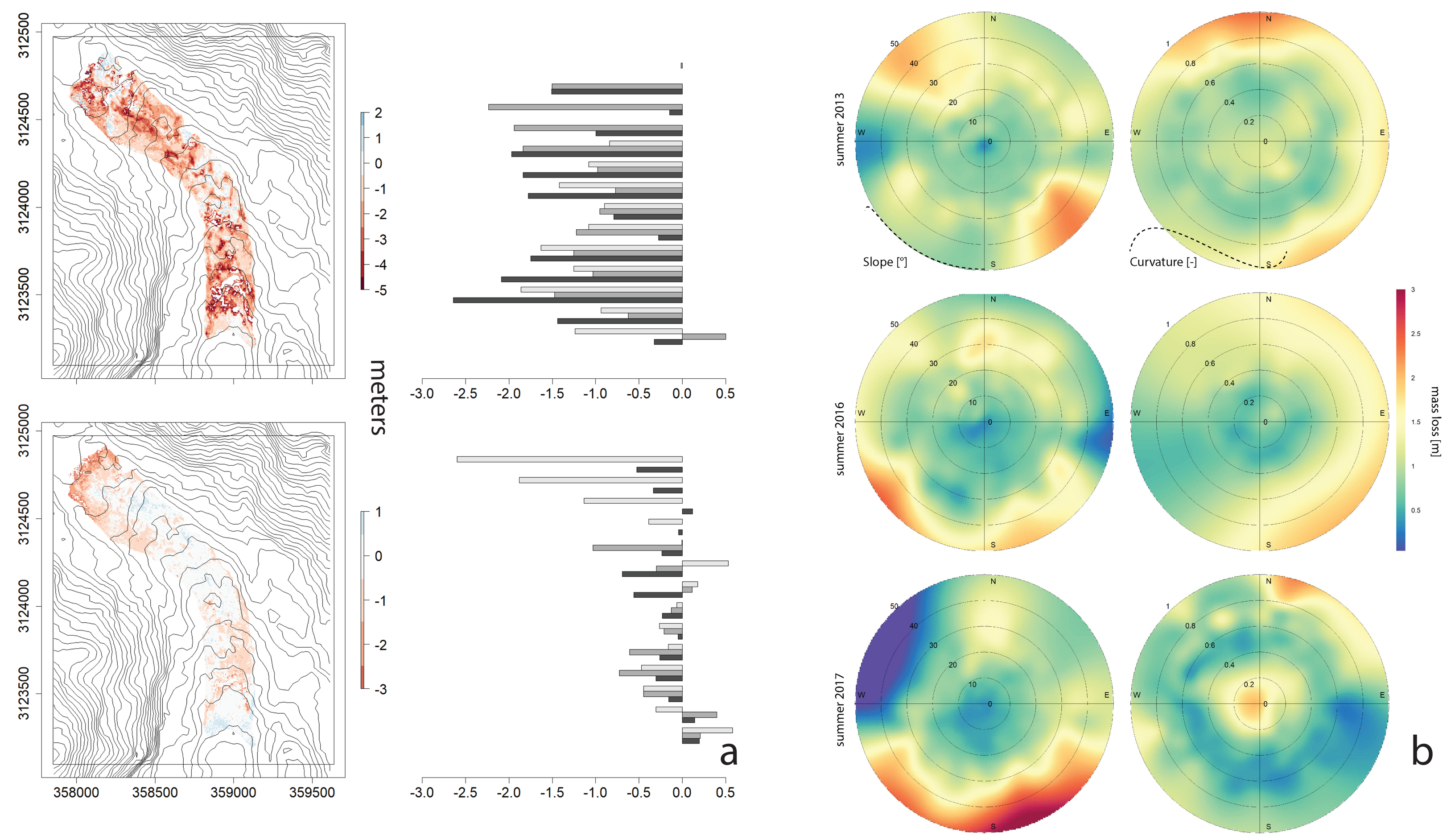


Figure 3: (a) Distributed mass loss in monsoon (top) and during winter (bottom), with distributions for 50m elevation bands shown right. (b) Mass loss against slope and curvature during three monsoon seasons.

Measured mass loss

- mass loss heterogeneities, **larger rates at terminus and higher elevations**
- high melt rates in monsoon (-0.5 to -2.5 m a^{-1})
- link to **topographic variables** difficult, more melt in depressions and on mounds

Debris properties

- **debris texture** varies in space and depth, making judgements from the surface difficult (Figure 5).

- **soil moisture** varies with depth (Figure 6, [7])

- as a result, thermal **conductivity** through debris varies strongly in space and time

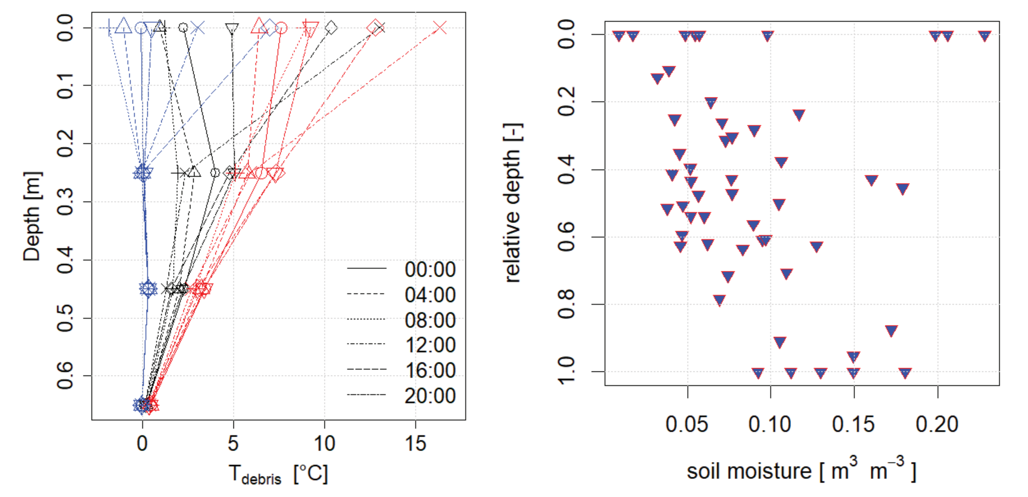


Figure 6: (left) Temperature profiles at LIR3 in 2017 in winter (blue), the dry seasons (black) and monsoon (red); (right) moisture measurements

Figure 5: Example of debris pits, showing a variability in debris properties (a - e); grain size distribution for all pits, normalized for depth (f)

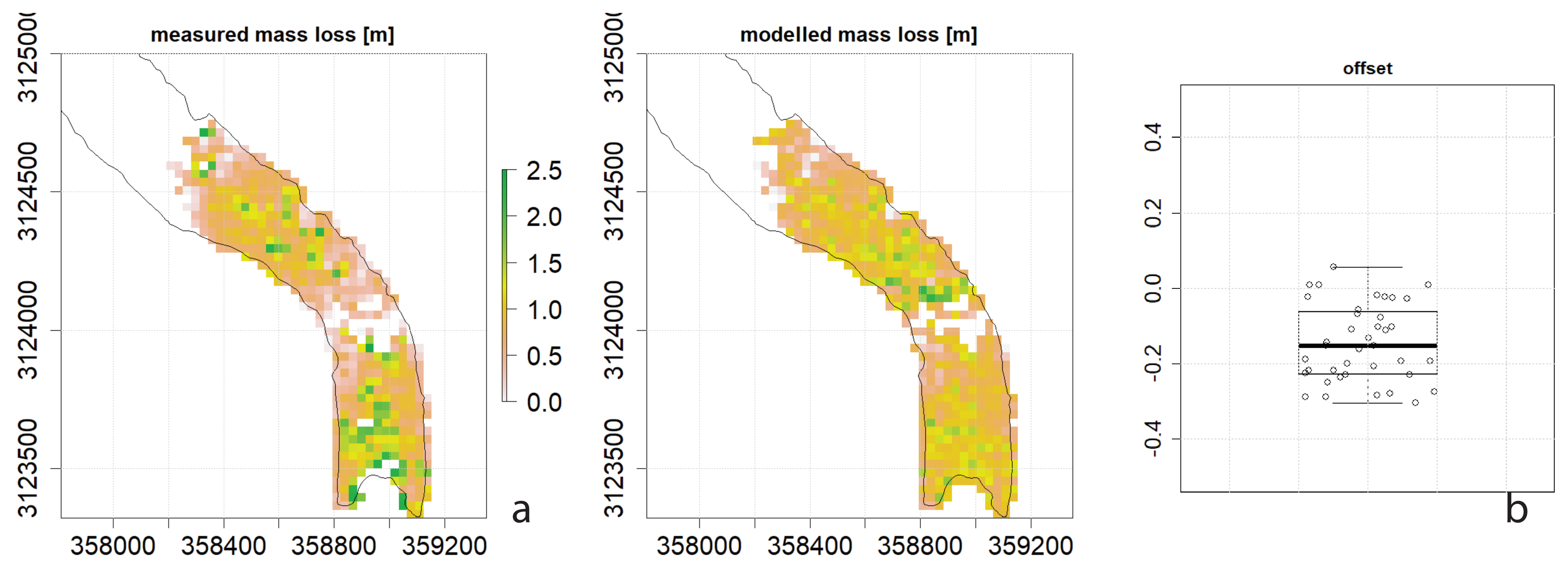


Figure 4: (a) Distributed measured and modelled mass loss at 15 m resolution. Total measured volume is 440 000 m³ vs a modelled volume of 435 000 m³. (b) Measured minus modelled debris thickness for available pits and GPR locations.

Modelled mass loss

- melt patterns on the large scale are well reproduced
- model remains **sensitive** to debris thickness and conductivity
- multi-layer solution of the debris pack is **computationally expensive** in space

Conclusions and outlook

1 refreezing: saturated water content freezes in the debris (~10^5 m³; 5-10% of the mass loss in monsoon) and is released only days after debris surface is above freezing

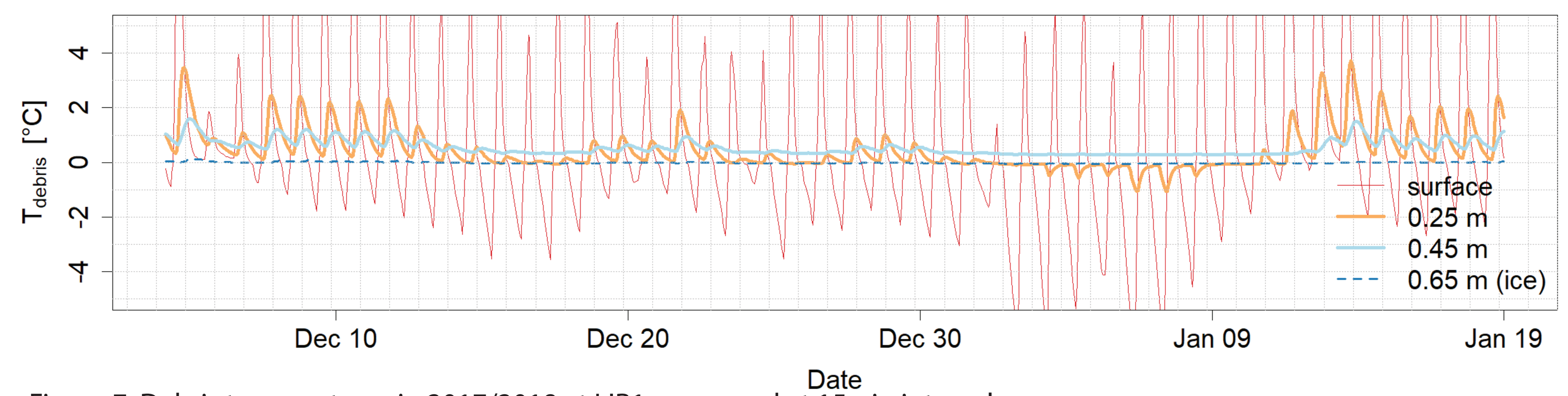


Figure 7: Debris temperatures in 2017/2018 at LIR1, measured at 15min intervals.

2 melt delay: debris delays the melt peak by ~ 18h / m debris and on the catchment scale buffers ice melt runoff

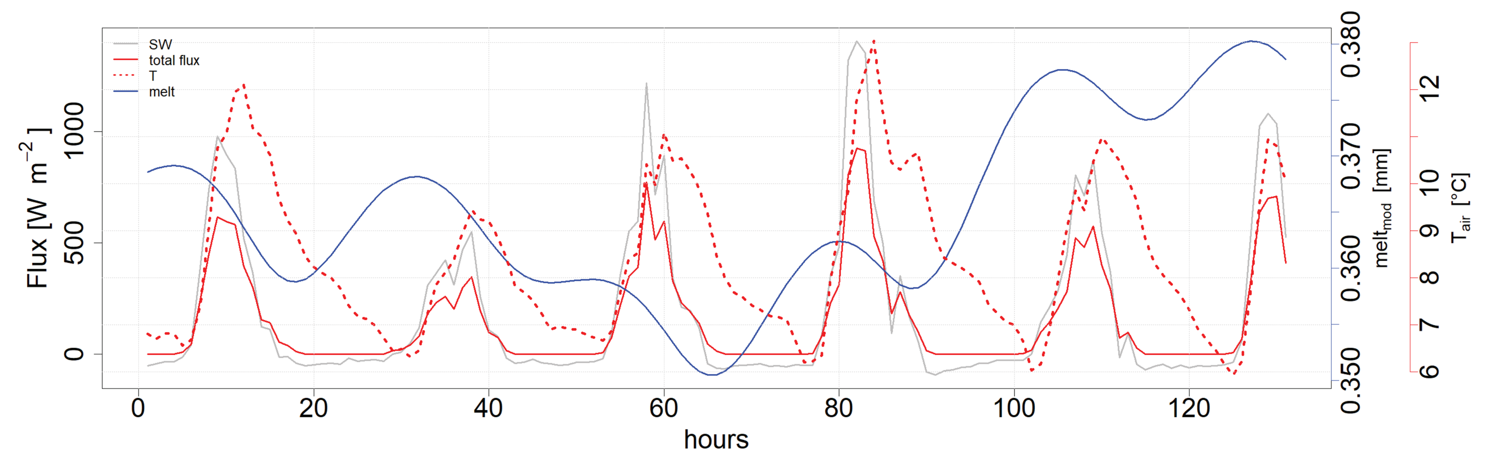


Figure 8: Surface fluxes (net shortwave radiation and total energy) and air temperature at the debris surface and resulting melt at the debris-ice interface at a random cell of the domain, showing the shift in peak melt.

3 temperature index: preliminary results show that a simple temperature index approach allows similar results at much less computational expense

$$M_d = \begin{cases} TF(d)\,T_{air}(t-lag(d)), & \text{if } T_{air}(t-lag(d)) > T_T \\ 0, & \text{otherwise} \end{cases}$$

$$TF = a\,d^b$$

$$lag = c\,d$$

References [1] **Kraaijenbrink et al. 2017**, Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers, Nature **[2] Steiner et al. 2018**, The Importance of Turbulent Fluxes in the Surface Energy Balance of a Debris-Covered Glacier in the Himalayas, FoES, **[3] Miles et al. 2016**, Refined energy-balance modelling of a supraglacial pond, Langtang Khola, Nepal, Annals of Glaciology, **[4] Steiner et al, 2015**, Modelling ice-cliff backwasting on a debris-covered glacier in the Nepalese Himalaya, JoG, **[5] Woerkom et al. 2019**, Sediment supply from lateral moraines to a debris-covered glacier in the Himalaya, Earth Surface Dynamics, **[6] Reid et al 2010**, An energy-balance model for debris-covered glaciers including heat conduction through the debris layer, JoG, **[7] Giese et al. [2019]**, Incorporating moisture content in surface energy balance modeling of a debris-covered glacier