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## Formation condition of debris-covered glaciers in the Bhutan Himalaya derived by satellite data

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Debris-covered glaciers are widely distributed along the Himalayas. It is well known that insulation effect of debris mantle and heterogeneous topography make response of the debris-covered glaciers to climate change complex. Furthermore, glacial lakes, which have often occurred outburst flood and thus threat Himalayan countries, are formed at the termini of debris-covered glaciers. It is little understood, however, what kinds of geomorphological and climatic environment determine the glacier termini as debris-covered or debris-free. In this study we describe geomorphological conditions which determine whether glacier termini are covered by debris as well as their shape in the Bhutan Himalaya using remotely sensed satellite data.

We first delineate glaciers and surrounding slopes using AVNIR2 visible ortho-rectified images obtained by ALOS. Debris-covered areas are defined by a normalized snow index derived by ASTER data. We secondly analyze slope angle and aspect of the glaciers and the surrounding slopes using ASTER-GDEM by assuming that the debris mantle is supplied from the slope steeper than 40°. We also estimate surface temperature distribution using thermal infrared data of ASTER because freeze-thaw activity at the bedrock should produce debris mantle.

We delineate more than 1000 glaciers in the Bhutan Himalaya including north facing glaciers on the Tibetan slope. Spatial analysis show that the debris-covered glaciers have five times larger area of steep slopes than the debris-free glaciers. Surface temperature distribution indicates that the surface exceeding 0 °C is found in the south-facing steep slopes even in winter season. We find a significant positive correlation between the area of steep slopes exceeding 0 °C and the area of debris-covered surface. In addition, ablation area of the south facing debris-covered glaciers is fully covered by debris mantle, which should be supplied from the widely distributed south-facing steep slopes, while the north-facing glaciers have an elongated debris-covered area along flow line of the glaciers, whose debris mantle seems to be supplied from very limited but south-facing steep slopes within the glacier catchment. Our analyses suggest that the spatial distribution of south-facing steep slopes determine the extent and shape of debris-covered area in the Bhutan Himalaya.

Keywords: Debris-covered glacier, Freeze-thaw activity, Bhutan, Himalaya, ALOS, ASTER