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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 the response of the debris-covered glaciers to climate change complex. Furthermore, glacial lakes, which have often caused outburst floods and thus threatened Himalayan countries, are formed at the termini of debris-covered glaciers. It is little understood, however, what kinds of geomorphological and climatic environments determine the glacier termini as debris-covered or debris-free. In this study we describe the geomorphological conditions which determine whether glacier termini are covered by debris as well as their shapes 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 angles and aspects of the glaciers and the surrounding slopes using ASTER-GDEM by assuming that the debris mantle is supplies 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 shows that the debris-covered glaciers have ten 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, the ablation areas of the south-facing debris-covered glaciers are fully covered by debris mantle, which should be supplied from the widely distributed south-facing steep slopes. On the other hand, the north-facing glaciers have elongated debris-covered areas along the flow lines of the glaciers, whose debris mantle seems to be supplied from very limited south-facing steep slopes within the glacier catchment. Our analyses suggest that the spatial distribution of south-facing steep slopes determines the extent and the shape of a debris-covered area in the Bhutan Himalaya.