Debris-covered glaciers are common in the Himalaya and an important source of melt water. However, they remain relatively unstudied because of the inaccessibility of the terrain and the difficulties in fieldwork. Here, we utilize unmanned aerial vehicles (UAVs) for debris-covered glacier monitoring. In three separate studies we have explored their potential by determination of elevation changes and surface velocities in great detail, and by automatic delineation of ice cliffs and supraglacial ponds using an object-based approach.

**1. Elevation change**
- Derive surface lowering using UAV data
- Evaluate melt patterns and dynamics
- May and Oct 2013 surveys of Lirung Glacier

**2. Surface velocity**
- Assess automated feature tracking for high-resolution UAV imagery
- Evaluate seasonal differences in surface velocity
- Additional May 2014 survey of Lirung

**3. Ice cliffs and ponds**
- Develop object-based method to automatically extract quantitative data on ice cliffs and supraglacial ponds.
- Evaluate the spatial distribution and characteristics of these surface features
- Survey in May 2014 of Langtang Glacier

**Study area**
- Focus of the studies are the debris-covered tongues of the Lirung and Langtang glaciers, located at above 4000 m in elevation in the Nepalese Himalaya.
- UAV survey of the glacier using the eBee, a fixed-wing UAV system. Imagery is captured by the mounted RGB compact camera.

**General UAV Methodology**
- Many overlapping 6 cm resolution images of the glacier surface
- Imagery processing in Agisoft Photoscan using the Structure from Motion algorithm, creating an accurate 3D point cloud
- Derive 10 cm resolution elevation model and orthorectified image mosaics
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**Conclusions**
- UAVs have high potential and may revolutionize methods of glacier monitoring
- Average surface lowering is limited, i.e. -1.09 m
- Highly heterogeneous melt patterns
- Mass loss near ice cliffs 10 times higher than average

**Conclusions**
- Frequency cross correlation useful for UAV imagery
- Optical input data provides best results
- UAV useful to determine seasonal differences
- Large difference between summer and winter
- Basal sliding (summer) vs deformation (winter) could be the mechanism

**Figure:** Surface velocity and flow direction as determined using frequency cross-correlation of UAV imagery for the summer and winter period. The plots show transverse surface velocity profiles at the indicated locations.

**Figure:** Heterogeneous patterns of elevation change observed over the 2013 monsoon season. Ice cliffs found on Lirung are highly dynamic and have considerable influence on total melt. Elevation gains in the bend because of emergence.

**Figure:** Cross-section of the UAV-derived point cloud of a cliff. The UAV is capable of capturing undercut morphology. Location of the cross-section is indicated in the map above.

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