Research internship report

Monitoring supra-glacial cliffs over debris covered glaciers using high resolution ground measurements

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Abstract

Being able to measure and model accurately Himalayan glacier mass balance is of critical importance in terms of assessing hydrological impacts and glacier related hazards. In area, about 10% of these glaciers are debris-covered and they counter-intuitively exhibit thinning rates similar to the clean-ice glaciers. A potential important contribution to melt could originate from the supra-glacial ice-cliffs forming on the debris-covered glaciers. Their total contribution to glacier melt is not yet known. In this study, we develop a method to estimate the ice-cliff volume loss based on high resolution topographic data. We apply our method to 3 to 6 cliffs between May 2013, October 2013, May 2014 and October 2014 using four different topographic datasets of Lirung Glacier, Nepalese Himalayas. In average, the cliffs melt at a rate of $3.7 \pm 0.7$ cm w.e./day between May and October, with larger variations between cliffs in the second season (May to October 2014), when the cliff geometry has changed more importantly. They melt at a rate of $1.3 \pm 0.2$ cm w.e./day between October and May. These results are consistent with energy balance modelling estimates of cliff ablation. They seem to confirm the non negligible contribution of ice-cliff to total glacier melt (Lirung Glacier melts at the rate of 0.6 cm w.e./day on average, according to previous studies), even if they account only for a small area of the glacier.

Résumé

Il est important de réussir à mesurer et modéliser le bilan de masse des glaciers himalayens en terme d’impacts hydrologiques et de risques glaciaires. Environ dix pourcents de ces glaciers sont couverts de débris, et, de façon surprenante, fondent à des taux comparables aux glaciers blancs. Les falaises supra-glaciaires, qui se forment à la surface des glaciers couverts de débris, pourraient avoir une contribution importante à la fonte. Pour le moment, leur contribution à l’ablation totale du glacier n’est pas connue. Au cours de cette étude, nous avons développé une méthode pour mesurer précisément la fonte provenant de ces structures à partir de données topographiques de haute résolution. Nous avons appliqué cette méthode sur 3 à 6 falaises du glacier du Lirung (Népal) entre mai 2013, octobre 2013, mai 2014 et octobre 2014. En moyenne les falaises fondent à un taux de $3.7 \pm 0.7$ cm w.e./jour entre mai et octobre. On observe une plus grande variabilité dans la fonte entre mai et octobre 2014 quand la géométrie des falaises est plus variable. Elles fondent à un taux de $1.3 \pm 0.2$ cm w.e./jour entre octobre et mai. Ces résultats sont cohérents avec ceux obtenus par modélisation du bilan d’énergie et semblent confirmer la contribution non-négligeable des falaises de glace à l’ablation totale (le glacier du Lirung fond de 0.6 cm w.e./jour en moyenne), même si elles ne couvrent qu’une petite surface du glacier.
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Preamble

This master internship was conducted in the framework of a larger project involving ETH Zurich (Switzerland), Utrecht University (the Netherlands) and ICIMOD (Nepal). The aim of this project is to understand the glacio-hydrological response of the Langtang catchment (Nepalese Himalayas) through extensive data collection and development of models. This project involves many actors, extensive field data acquisition and significant modelling efforts. It has lead to numerous publications (e.g., Immerzeel et al., 2014a,b; Pellicciotti et al., 2015; Steiner et al., 2015; Ragettli et al., 2015; Miles et al., 2015; Buri et al., 2015).

Part of this project focuses on understanding the processes controlling the melt of debris-covered glaciers and the role of supra-glacial ice-cliffs and lakes on their mass balance (e.g., Steiner et al., 2015; Miles et al., 2015; Buri et al., 2015). I was involved in this sub-project. As a consequence, I worked with some data that were already processed and with others that I processed myself. To make a clear distinction, I summarized the work I did on every type of data in table 2 on page 7.

1 Introduction

The Pamir – Karakoram – Himalaya (PKH) region, with more than 70 000 km² of glacierized areas including approximatively 10 % of debris-covered glaciers, is often referred to as the third pole (e.g., Bolch et al., 2012; Gardner et al., 2013). The Pamir and Karakoram glaciers did not experience significant mass changes over the last decade (Gardelle et al., 2012), whereas the Himalayan glaciers have been shrinking and wasting mass (e.g., Gardelle et al., 2013; Racoviteanu et al., 2015). These changes are likely to trigger modifications in the local hydrology (Immerzeel et al., 2013; Ragettli et al., 2015) and to enhance the glacial hazards (Richardson and Reynolds, 2000; Somos-Valenzuela et al., 2015).

It is therefore important to understand how debris-covered glaciers will respond to climate change (Scherler et al., 2011).

The processes governing the formation of debris-covered glaciers and the expansion of their debris coverage are not yet fully understood (Kirkbride and Deline, 2013). The increase of debris-covered areas since the 1960s has already been observed in some parts of the PKH region (Kirkbride and Deline, 2013; Thakuri et al., 2014; Racoviteanu et al., 2015). As the debris-covered areas of glaciers are located at the lowest elevations of every glacier, they have the potential to modify significantly the total ice loss across PKH in a changing climate (Scherler et al., 2011; Gardelle et al., 2013).

Since Østrem (1959), it is generally understood that the contrasting effects of debris (i.e. enhanced ablation due to reduced albedo or decreased ablation due to their insulating effect) compensate each
other for a given debris thickness called the critical debris thickness, below which ablation is enhanced
and above which it is decreased. This was confirmed by numerous studies that modelled energy fluxes
through a debris layer to calculate ice melt beneath debris (e.g., Han et al., 2006; Nicholson and Benn,
2006; Reid and Brock, 2010; Benn et al., 2012; Lejeune et al., 2013; Fujita and Sakai, 2014; Fyffe
et al., 2014; Juen et al., 2014). Nevertheless recent remote sensing studies (e.g., Kääb et al., 2012;
Naimura et al., 2012; Gardelle et al., 2013; Pellicciotti et al., 2015; Holzer et al., 2015) have suggested
that debris-covered glaciers experience similar thinning rates as clean ones (when in the same elevation
range; Gardelle et al. (2013)). According to the mass conservation equation, glacier elevation changes
at a specific location are the combined effect of surface mass balance (i.e. ablation) and ice flux budget
(i.e. emergence velocity). Thus, similar rates of elevation changes cannot readily be assumed to result
from differences in ablation rate. However, Kääb et al. (2012) suggested that ice dynamics effects are
probably small and, then, these similar trends in elevation changes on debris-covered and debris free
parts of glaciers are likely due to similar ablation rates on both surfaces. This is sometimes referred as
the debris-covered anomaly. It is critical to better understand this paradox if we want to be able to
predict debris-covered glacier response to climate change.

Some pioneering studies of the 2000s already pointed out the role of supraglacial features such as
ice-cliffs and ponds as potential hot spots for melt over debris-covered glaciers. This enhanced melt is
compensated by the reduced ablation experienced on thick debris-covered flat areas explaining why, on
average, clean and debris-covered glaciers have similar ablation rates at a given elevation (e.g., Sakai
et al., 1998, 2000, 2002). These features expose dirty bare ice or water directly to the atmosphere,
enhancing the radiative transfer and turbulent energy fluxes at the glacier surface (Miles et al., 2015;
Buri et al., 2015). Due to their steep slopes, the cliffs also receive longwave radiation from the sur-
rounding debris (Buri et al., 2015; Steiner et al., 2015). The ice-cliffs appear as areas of large elevation
lowering when differencing high resolution digital elevation models (DEMs) of a debris-covered glacier
(Immerzeel et al., 2014a).

Ice-cliff backwasting\footnote{ice-cliff backwasting originally refers to the cliff retreat (Han et al., 2010). In this study it refers either to a change in length or to a volume loss.} rate can be modelled based on an energy flux budget adapted to the cliff ge-
ometry (e.g., Han et al., 2010; Reid and Brock, 2014; Steiner et al., 2015; Buri et al., 2015). The energy
balance model was first developed at the point scale by Han et al. (2010), itself based on the pioneering
studies of Sakai et al. (1998, 2000), and then improved toward a more physically based model by Reid
and Brock (2014) and Steiner et al. (2015). They showed that for a given set of meteorological data the
backwasting rate was highly dependent on the slope and aspect of the ice-cliff. Consequently, Buri et al.
(2015) developed a distributed model that calculates each energy flux and resulting ablation for every grid cell of a DEM representing the cliff. This model requires less calibration than the previous models and was applied on two cliffs of Lirung Glacier, based on a 20 cm resolution DEM (Buri et al., 2015).

Nevertheless, these models were only validated against point scale measurements and over short periods of time given the difficulty of maintaining ablation stakes inserted in cliffs (Steiner et al., 2015) or against simple cliff retreat measurements (Han et al., 2010). This lack of validation comes from the difficulty to measure ice-cliff backwasting: it is not straightforward to assess the mass loss at cliff scale even with high resolution DEM differencing because of the ice flow and because of the cliff complex geometry (they often exhibit overhanging surfaces, Immerzeel et al., 2014a). To fill this measurement gap we developed a method to assess cliff backwasting based on differential global positioning satellite system (dGPS) and photogrammetric surveys.

In this report, we present the above mentioned method to measure cliff backwasting. We first describe the study area and the data used. We then develop the method’s principle and discuss the main results obtained on Lirung Glacier (Nepal) with this method.

2 Study area

Lirung Glacier (28.24 ° N, 85.56 ° E) is a debris-covered glacier located in the Upper Langtang Valley, Central Nepalese Himalayas (fig. 1 - inset). It flows from Langtang Lirung (7234 m a.s.l.) down to approximately 4000 m a.s.l. (e.g., Sakai et al., 1998; Immerzeel et al., 2014a; Buri et al., 2015). In this study we focus on the lower ablation zone (ranging between 4000 and 4450 m a.s.l.), which is entirely covered by a heterogeneous debris layer and detached from the main glacier upper body (Ragettli et al., 2015).

Ice-cliffs of Lirung Glacier have a height usually ranging between 10 and 30 m, a width ranging between 40 and 200 m and a mean slope around 45° (Table 1). Figure 2 shows a typical ice-cliff, which is one of those investigated in this study. Figures A.1, A.2, A.3, A.4 show the other cliffs investigated. The cliff outlines were accurately mapped by dGPS in May 2014 and October 2014 (fig. 1). For the rest of this study we focused on the following cliffs: cliff 01, cliff 02, cliff Cornelia, cliff Philly and cliff Edu (fig. 1).
Figure 1: Map of Lirung Glacier tongue showing the different cliffs surveyed in May 2014 (black polygons and dots) and in October 2014 (red polygons and dots). The crosses show the locations from where the pictures used to derive the overall DEM were taken. They are coloured according to which dataset they belong to. The blue areas show the location of the local surveys where the topography analysis is refined. The background is an orthophoto of October 2013 (Immerzeel et al., 2014a) and the glacier outline comes from the Randolph Glacier Inventory 4.0 (Pfeffer et al., 2014). All the coordinates are in WGS84/UTM 45N (in meters). The inset shows the general location of Langtang catchment.
Figure 2: Picture of cliff 02 taken in May 2014. The highest part of the cliff (not fully visible on the photograph) is approximately 20 m high. Note the overhanging and shaded part. Photo: ETHZ.

3 Data

All the field data used in this study were collected during four field trips: May 2013, October 2013, May 2014 and October 2014. The field work was carried out by the ETH team in collaboration with Utrecht University and Patrick Wagnon (May 2014). A field campaign was also scheduled for May 2015 but was cancelled because of the 7.8 Barpak earthquake which caused severe damages and many casualties in Langtang valley. All the data used in this study are summarized in table 2.

3.1 Photogrammetry

The topographic data were obtained from terrestrial or airborne (unmanned aerial vehicle; UAV) photogrammetry. Five different sets of data were used (Table 2). All the photographs were processed using the commercial Agisoft software (see section 4 for the methodological details). For the overall DEM (October 2014; Table 2), we processed a total of 682 pictures. For the local surveys (October and May 2014; Table 2), we processed between 10 and 200 pictures per survey.

3.2 Differential GPS data

The dGPS measurements are based on simultaneous use of two GPS devices: a base station and a rover. The relative accuracy between both devices is usually better than 5 cm, in horizontal and vertical. Different bases have been used in 2013 and 2014. After realizing it, we georeferenced both bases in the same absolute system afterwards, using post processing system. It was done using precise point
Table 1: Characteristics of the studied cliffs. The mean value is taken when multiple years of observations are available. The mean slope and aspects are calculated from DEMs and therefore are not totally realistic (because for an equal area a steep slope is represented by fewer pixels).

<table>
<thead>
<tr>
<th>Cliff ID</th>
<th>Height (m)</th>
<th>Width (m)</th>
<th>Area (m²)</th>
<th>Slope (degree)</th>
<th>Aspect (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cliff01</td>
<td>9</td>
<td>42</td>
<td>381</td>
<td>45</td>
<td>321 (NW)</td>
</tr>
<tr>
<td>Cliff02</td>
<td>21</td>
<td>102</td>
<td>1921</td>
<td>48</td>
<td>31 (NE)</td>
</tr>
<tr>
<td>Cliff Philly</td>
<td>11</td>
<td>72</td>
<td>1117</td>
<td>43</td>
<td>265 (W)</td>
</tr>
<tr>
<td>Cliff Philly - western part</td>
<td>32</td>
<td>65</td>
<td>1369</td>
<td>39</td>
<td>47 (NE)</td>
</tr>
<tr>
<td>Cliff Edu</td>
<td>21</td>
<td>245</td>
<td>6441</td>
<td>43</td>
<td>313 (NW)</td>
</tr>
<tr>
<td>Cliff Cornelia</td>
<td>21</td>
<td>80</td>
<td>1494</td>
<td>47</td>
<td>351 (N)</td>
</tr>
</tbody>
</table>

During the May 2014 field campaign, thirteen cliffs were mapped on Lirung Glacier (fig. 1), but in October 2014 only two cliffs were fully mapped and three of them were partially mapped (only the upper edge was mapped). To map the cliff edge, the surveyor records one dGPS point every 5 to 10 m. The cliff edge was measured as accurately as possible, but it is not always possible to map the exact edge because of the risk of falling. In case where a supra-glacial pond is present at the foot of the cliff, the cliff bottom is not surveyed (see fig. 2 for an example of a pond).

### 3.3 Velocity data

As the avalanche-fed and almost flat tongue of Lirung Glacier is disconnected from its steep accumulation zone, the ice flow is small. *Immerzeel et al.* (2014a) measured surface velocities ranging between almost 0 m/year (almost stagnant terminus) to 5 m/year. As the glacier thickness is not known, it is not possible to calculate the emergence velocity.

Since May 2014, taped rocks have been monitored with a dGPS to track the surface velocity. The surface velocity data used in this study are summarized in table A.2. For the rest of the study, all cliff outlines are translated down-glacier to compensate for the glacier displacement. The local velocity for each cliff is determined by taking the median of the measured velocities in a 50 m buffer around the cliff outlines.

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2http://webapp.geod.nrcan.gc.ca/geod/tools-styles/PPP.php
<table>
<thead>
<tr>
<th>Date</th>
<th>Type of data</th>
<th>Data format</th>
<th>Precision</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>18-19 May 2013</td>
<td>Topography</td>
<td>DEM and TIN</td>
<td>30 cm</td>
<td>Aerial photogrammetry (UAV)</td>
</tr>
<tr>
<td>15 May 2014</td>
<td>Topography</td>
<td>DEM and TIN</td>
<td>1 m</td>
<td>Aerial photogrammetry (UAV)</td>
</tr>
<tr>
<td>22 Oct. 2013</td>
<td>Topography</td>
<td>DEM and TIN</td>
<td>30 cm</td>
<td>Aerial photogrammetry (UAV)</td>
</tr>
<tr>
<td>26 Oct. - 31 Oct.2013</td>
<td>Topography</td>
<td>DEM and TIN</td>
<td>&gt; 1 m</td>
<td>Aerial photogrammetry (UAV)</td>
</tr>
<tr>
<td>02 Nov. 2014</td>
<td>dGPS points</td>
<td>X, Y, Z coord.</td>
<td>5 cm</td>
<td>Reprocessing of the raw base data with PPP</td>
</tr>
<tr>
<td>15-17 May 2014</td>
<td>dGPS points</td>
<td>X, Y, Z coord.</td>
<td>5 cm</td>
<td>Reprocessing of the raw base data with PPP</td>
</tr>
<tr>
<td>22 Oct. 2013</td>
<td>Pléiades images</td>
<td>GeoTiff</td>
<td>50 cm</td>
<td>Comparison with the Agisoft DEM</td>
</tr>
</tbody>
</table>

Table 2: Summary of the data used in the framework of this study.
3.4 Satellite images

Two Pléiades images were acquired on 02 November 2014 and 09 November 2014. They were processed by Etienne Berthier using the Ames Stereo Pipeline (http://ti.arc.nasa.gov/tech/asr/intelligent-robotics/ngt/stereo/) to obtain a 2 m resolution DEM (Berthier et al., 2014). Unfortunately the important change in snow cover between the two dates lead to a lack of correlation on some parts of the images, which ultimately lead to holes in the final DEM. The DEM was processed without ground control points (GCPs).

4 Method 1: Digital elevation model generation from terrestrial photographs

High resolution topographic data are required to study processes at fine scale (Buri et al., 2015) and to reveal the heterogeneous melt pattern (Immerzeel et al., 2014a). Hereafter we refer to two surveys: the overall DEM (also called Agisoft DEM later) and the local surveys. The overall DEM is generated from photographs taken from the lateral moraine (coloured crosses on fig. 1). The local DEMs and triangulated irregular networks (TINs) are generated from pictures taken on glacier and cover only the blue areas on fig. 1. A TIN is a 3D model of the topography (point cloud and oriented faces). Hereafter, we refer either to the TIN or the DEM when talking about the topographic data. They are two different ways to represent the same object and the DEM is derived from the TIN.

4.1 Processing

We used the commercial software Agisoft to reconstruct a TIN from the terrestrial photographs. The structure from motion workflow implemented in this software is detailed in Immerzeel et al. (2014a). We used the software as a black box, which is not without inconvenience. For instance, we realized that the software could not manage to match the pictures taken from the western moraine (datasets 1 and 3 on fig. 1) with the pictures taken from the eastern side (dataset 2 on fig. 1), because of the difference in the viewing angle and in the snow cover. Consequently, we processed the three datasets separately, and aligned them only in the last stage.

Photogrammetric based elevation models require GCPs to properly georeference the model and to avoid distortion (bowl effect for instance). As no specific GCPs (i.e. a painted cross which location is measured with a dGPS, for example) were taken during the field campaign, we had to use the monitored natural features as GCPs (cliff edges, lake outlines). The list of the 21 GCPs used in the overall DEM is shown in table A.3. This has two major drawbacks: the GCPs have a low accuracy (~1 m) and they are not homogeneously distributed on the glacier (black crosses on fig. 4). In particular they are all located on the central part of the glacier and therefore do not constrain the general tilt of
the DEM or do not constrain the topography of the lateral moraines.

The local DEMs were better constrained because more GCPs were visible on the pictures. For instance, for a given cliff we could identify more distinguishable features on the pictures taken on glacier than for the pictures taken from the moraine. Consequently, the geometry is better constrained for these local DEMs and TINs than for the overall DEM. Each local TIN/DEM was processed with 4 to 8 GCPs. We then realigned each of the local TIN on a 3D model of a surface interpolated from the dGPS outline (see section 5.4 for a description of how we interpolate this surface) after processing.

4.2 Validation of the local DEMs and TINs

To validate the local TINs, we manually extracted the cliff outlines from them and compared the extracted outlines with the dGPS data. We compared each dGPS point to the closest one on the TIN cliff outline (fig. 3). The median distance between dGPS points and the TIN cliff outline ranges between 0.16 and 1.53 m (Table 3). The discrepancies between the two data sources can have multiple origins:

- a poorly aligned TIN. For instance cliff Philly in October 2014 is not well aligned because it is only aligned on the cliff upper edge (the bottom edge was not mapped because of time constraints for field work). Therefore we could not constrain well the location of the TIN, which is probably tilted. This results in a large shift in the $z$ direction (fig. 3 and Table A.4).

- bad quality of the TIN. For cliff 02 in October 2014, the TIN is distorted on its northern side and on the south-eastern corner (fig. 3). This is a consequence of pictures that were taken from too short distance. For cliff Philly in May 2014, a part of the cliff was missing in the south-western corner.

- disagreement between the field mapped parts of the cliffs and the TIN cliff outline. For instance, for cliff Edu in May 2014 the dGPS outline is more complex on the north-eastern corner of the cliff than the TIN one. It is also noteworthy that the dGPS cliff outlines are often located 50 cm to 1 m away from the real edge to avoid falling.

The differences between the dGPS and the TIN outlines are summarized in table 3. On average we estimate that a given cliff is located with a 1.1 m error, which is calculated as the median of the median distance between dGPS points and TIN outlines for all the surveyed cliffs (Table 3).

4.3 Validation of the overall DEM

The overall DEM produced by photogrammetry is shown in figure 4. The first bias that needs to be corrected in a DEM is the horizontal shift, due to inexact georeferencing (Berthier et al., 2007). Unfortunately, this is not possible with our dataset because we used all the
Figure 3: Distance (horizontal + vertical) between the field dGPS mapped cliff outlines (dots) and the TIN cliff outlines (black line). The dots are coloured as a function of the distance to the closest point in the TIN outline. All the coordinates are in WGS84/UTM 45N. Note the difference in scale between the different cliffs. Note that cliff Philly October 2014 is poorly aligned. This is partially due to the lack of points at the bottom of the cliff which are very helpful to align the 3D models and constrain the photogrammetric processing.
Figure 4: Overall DEM of Lirung Glacier (Agisoft DEM; resolution = 25 cm) tongue. The dots are coloured as a function of their elevation difference with the dGPS points collected on glacier. The GCPs used to process the DEM are shown as black crosses.
| Cliff ID     | May 2014 | | | October 2014 | | |
|-------------|----------|---|---|----------------|---|
|             | n        | median dist. (m) | std (m) | n        | median dist. (m) | std (m) |
| Cliff 01    | 57       | 0.19            | 0.15    | 47       | 0.16            | 0.19    |
| Cliff 02    | 79       | 0.57            | 0.45    | 108      | 1.52            | 0.97    |
| Cliff Philly | 78       | 0.82            | 1.86    | 46       | 1.30            | 1.26    |
| Cliff Edu   | 170      | 1.53            | 2.76    | 76       | 0.65            | 1.13    |

Table 3: Summary of the distance between the dGPS outlines and the TIN outlines.

Figure 5: Zooms from the overall DEM showing the cliff 02 outlines (a) and an example of artifacts (b). The red crosses are the dGPS points. Inset shows the AB elevation profile.

GCPs available to process the DEM. Therefore we can expect a horizontal shift of 1 m, due to the uncertainties on GCPs. Nevertheless, visual inspection of the hillshade and orthophoto shows that the horizontal location of the dGPS cliff outlines is very good (fig. 5a). For the rest of the study, we assume the horizontal shift to be ±1 m in both x and y directions.

We then evaluated the vertical anomalies by comparing the elevation of the dGPS points with the elevation of the DEM (fig. 6 - A). The DEM shows a clear tilt in the y direction (fig. 6 - D; $R^2 = 0.71$), which can be approximated by a linear function. The anomalies in the x direction are not linearly distributed (fig. 6 - C) and are the consequences of the lack of constraints on the sides of the DEM and of probable misalignments when merging the different datasets. We therefore corrected only the elevation as a function of y. We corrected linearly by fitting a plane through the elevation difference (fig. 6 - B) and substracting the median elevation difference of the residuals to obtain a zero median elevation difference between the dGPS points and the DEM (fig. 4).

We then compared the Pléiades DEM to the Agisoft DEM (fig. 7). As the Pléiades DEM was pro-
cessed without GCPs it could be incorrectly georeferenced. To evaluate the horizontal shift between
the two DEMs we correlated the images using the COSI-Corr tool (Leprince et al., 2007). The two
orthoimages are shifted by less than one meter in $x$ and $y$ directions (fig. A.5), this is therefore within
the precision of the location of the Agisoft DEM. Even if it is small, the horizontal shift can explain
the heterogeneous pattern of elevation difference (Nuth and Kääb, 2011). The DEM differencing also
reveals a non homogeneous tilt of one of the DEM: the elevation difference decreases from east to west
in the northern part of the DEM, whereas it is rather constant in the southern part of the DEM (fig. 7).
This difference might originate from the merging of the different dataset when processing the Agisoft
DEM. As this tilt is non linear (also visible in fig. 6 - C), we cannot correct it easily.
It is also noteworthy that the Agisoft DEM has some artefacts. Some artificial ridges are visible on
the DEM (fig. 5b). They lead to the appearance of artificial steps of approximately 2 m.

As a conclusion, the Agisoft DEM (fig. 4) gives a quite accurate representation of the real topogra-
phy along the central part of the debris-covered tongue of Lirung Glacier. But it has some non-linear
deformation in the $x$ direction, and therefore should be used with caution, especially when used for
calculations requiring high precision in topography. The median absolute difference in elevation be-
tween the dGPS points and the DEM after correction is 0.5 m (fig. A.6), which is very low. In the rest
of this study we used only the local TINs to assess the cliff backwasting, the main goal of this study.
They are easier to manipulate, because they are smaller. However, the Agisoft DEM will be used for
other studies, such as elevation changes monitoring or to run distributed melt models.

5 Method 2: Precise measurement of cliff backwasting

5.1 Motivations

Recent and older studies stressed the need to evaluate the contribution of ice-cliffs to total debris-
covered glacier melt (e.g., Sakai et al., 1998, 2000; Han et al., 2010; Immerzeel et al., 2014a; Reid and
Brock, 2014; Buri et al., 2015). Nevertheless measuring the volume loss from cliffs is not straightfor-
ward. At least four points should be considered:

1. the ice-cliffs are relatively small on Lirung Glacier (10 to 30 m high and 40 to 300 m long). They
usually represent between 1 and 2 % of the glacier surface projected on an horizontal plane (Sakai
et al., 1998; Reid and Brock, 2014). Consequently, most of the usual satellite imageries (ASTER,
Landsat...) do not have a high enough resolution to monitor the cliffs. Even the very high
resolution images (such as Pléiades or SPOT 6/7) are on the edge in term of required resolution.

2. the glacier flow has to be taken into account. As the cliff backwasting is a local mass loss,
we cannot neglect the ice divergence term in the continuity equation. Therefore direct DEM
Figure 6: DEM validation - first correction applied. A- Elevation difference between the Agisoft DEM and the dGPS points (dots are coloured as a function of the elevation difference); B- Plane fitting the elevation difference between the Agisoft DEM and the dGPS points; C- Elevation difference as a function of easting; D- Elevation difference as a function of northing, the black solid line is the linear regression from which the correction is calculated.
differentiation is not suitable to measure ice-cliff backwasting.

3. the most popular approach so far is to extrapolate stake measurements (Reid and Brock, 2014; Steiner et al., 2015). Nevertheless, for a given set of meteorological variables, the melt rate is strongly affected by the cliff slope and aspect (Buri et al., 2015). Therefore it is not possible to extrapolate directly point measurements to the whole cliff. On Lirung Glacier, it is also not possible to measure ablation during monsoon season or over longer time spans due to the difficulties to access the glacier and to maintain stake reading measurements.

4. the cliffs have a rather complex geometry. They often exhibit overhanging faces. Therefore our usual topography analysis tools like DEMs are not suitable to represent the cliffs in a realistic way (Immerzeel et al., 2014a; Buri et al., 2015). We therefore need to use other tools like steep slope models (SSM; Kolecka, 2012) or TINs.

Hereafter we present a new method developed to fill this gap between modelling studies and measurements.

Figure 7: DEM differentiation between the overall Lirung DEM generated from photogrammetry (Agisoft DEM) and the Pléiades DEM. The grey regions correspond to holes in the Pléiades DEM.
5.2 Principle of the method

Figure 8: Idealized cross-section views of a retreating cliff between \( t_1 \) and \( t_5 \). The two methods presented hereafter aim to measure the cliff backwasting (grey shaded area on the left panel), and to assess whether the volume estimated by triangulation of the dGPS outline is a good proxy (right panel).

Figure 9: Chart of the workflow

The principle of the method is simple: ice-cliffs retreat fast with a rather constant geometry. This can be idealized as in figure 8. In this case the cliff backwasting can be seen as the volume sandwiched between the cliff surfaces at different times (assuming a stagnant ice tongue). We developed two methods to measure this volume. The "dGPS only" method triangulates the dGPS outline of the cliffs
to get two interpolated surfaces, and then the outlines of the two surfaces are triangulated to get a volume. The "full method" is based on the extraction of the cliff triangulated surface (TIN) obtained by photogrammetry. Then the outlines of the cliff at \( t_1 \) are triangulated with the ones of the cliff at \( t_5 \) to get a volume (fig. 9).

We correct the advection of cliffs by the ice flow (approximated by the 3D displacement of the glacier surface) by translating all the cliffs down-glacier in the October 2014 reference base (fig. 10).

5.3 Data needed

The method requires two types of input data: topographic data and displacement.

The topographic data can either be dGPS outlines of the cliffs (method dGPS only) or TINs of the cliffs (in our case the TINs were derived from terrestrial photographs). The dGPS outlines are taken with a point every 5 to 10 m approximately. Unfortunately the bottom of the cliff is not always accessible (lakes form at the bottom of cliffs). The TINs need to be calculated with a high resolution (one grid point approximately every 20 to 50 cm).

The 3D displacement of the glacier surface is needed.

All the data used in this study are summarized in table 2.

5.4 Step 1: surface reconstruction

Method dGPS only The main assumption to triangulate the surface from the outlines is that the cliff surface is mostly flat. Therefore it is consistent to link the upper edge of the cliff with the bottom one. As the dGPS points are not equally spaced (especially when there is a non reachable area like a lake on the outline), we interpolate different number of points between the original dGPS points to obtain an outline of each cliff edge made of 500 points. The number of points interpolated between two adjacent dGPS points is a function of the distance between those points normalized by the median distance between adjacent dGPS points along this cliff edge.

Once the outline is interpolated, we triangulate it according to the rule illustrated on figure 11a. The point number \( i-1 \) of the bottom edge \((y_{i-1})\) is linked with the point number \( i \) of the bottom edge \((y_i)\) and with the point number \( i \) of the upper edge \((x_i)\). Then \( x_i \) is linked with \( y_i \) and \( x_{i+1} \).

Full method For the full method the cliff surface is simply delineated and extracted based on visual inspection of the coloured TIN and of the photographs (the cliff has different color and texture than the surrounding terrain).

In both cases we obtain a TIN that contains only the cliff surface. This TIN is exported as a .ply file (Polygon File Format or Stanford Triangle Format). It consists of a binary or ASCII file (both
Figure 10: Cliff outlines evolution from May 2013 to October 2014. The light coloured outlines are the original ones and the darker ones are the cliff outlines shifted to correct for the glacier flow. All the coordinates are in UTM 45N/WGS 84 system (in meters).
(a) Schematic of the principle of triangulation for a given cliff outline (used in the "dGPS only" method). The dots represent the interpolated points defining the outline.

(b) Schematic of the principle of the triangulation between two cliffs outlines to measure the melted ice volume. For the sake of lisibility, the density of points is reduced. In real cases, the points are closer and more evenly distributed along each outline.

Figure 11

formats are supported) containing the coordinates of the vertices (X, Y, Z coordinates) and the faces defined as an ordered triplet of vertices. Additional information, such as color, orientation, flags and quality can be added. We choose this file format because it was readable by 3D visualisation and manipulation softwares (such as Agisoft or MeshLab) and modifiable with any programming language.

5.5 Step 2: surface(s) displacement

For this study, all the cliffs were linearly displaced downglacier to the position where they should have been in October 2014 if the glacier was motionless (fig.10). We used the data from table A.2. For the Oct. 13 to May 14 period the vertical displacement was not available. Consequently, we assumed a zero vertical displacement.

5.6 Step 3: triangulation of the final volume from the cliff outlines

The triangulation of the melted ice volume is quite similar to the triangulation of the surface from the dGPS outline. Figure 11b shows the rule used to triangulate the final volume.

5.7 Step 4: volume mesh calculation in MeshLab

The final three meshes (cliff at t1 and cliff at t2 displaced to October 2014 and the mesh obtained by joining the two cliff outlines) are exported into MeshLab (Cignoni et al., 2008) in form of .ply files. MeshLab reorients all the face normals consistently (i.e. all the normals of the faces point outside of the volume) and then merges the meshes into a single mesh (which is a closed volume).

MeshLab then automatically calculates the volume of this closed volume with an algorithm based on Mirtich (1996).
5.8 Uncertainty assessment

The main sources of uncertainties are:

1. the emergence velocity which is not taken into account
2. uncertainty on the cliff outlines (i.e. difficulties to discriminate between cliff and non-cliff in the TINs vertices)
3. uncertainty and variability of the glacier surface velocity
4. uncertainty on cliff location

For point 1 and 2, it is difficult to assess the uncertainty associated with these sources of errors. For the emergence velocity, it can be estimated by calculating the ice flow through a cross-section of the glacier. This can be done by measuring the ice surface velocity (and assuming a certain ice velocity profile) and the ice thickness along the cross-section. The surface velocity can be assessed from our data (either from the UAV or the dGPS data). The ice thickness is still not known, because the results of the ground penetrating radar surveys conducted in spring 2015 are not available yet. For the discrimination between cliff and non-cliff vertex (point 2), it is usually straightforward to distinguish between vertical bare ice and the surrounding rocks because they have very different colors and the cliff surface is very smooth and flat compared with the environment.

For point 3, the uncertainty on displacement is similar to the general uncertainty in term of georeferencing in the absolute system of coordinates (i.e. 30 cm). Nevertheless, we assume that the local velocity is homogeneous within the cliff. This is a reasonable assumption for small cliffs (e.g. cliff 01) but is more questionable for bigger cliffs, even if the cliffs mostly form perpendicular to the main flow direction, and are therefore in a quite homogeneous displacement field.

The main uncertainty remains the location of the cliff outlines (point 4). Even if the median distance between the TIN cliff outlines and the dGPS outlines can be quite high, the median distance between dGPS points and cliff contours in all the directions is lower (section 4.2, fig. 3 and Table A.4). We can therefore consider that the cliff is located with an accuracy of 1.1 m (median of the median distances between the dGPS and TIN outlines for each cliff; Table A.4).

Assuming that both errors in displacement and in location are independent, the overall uncertainty in the location is therefore 1.14 m, and is calculated as follow:

$$\Delta_{overall} = \sqrt{\Delta_{velocity}^2 + \Delta_{pos}^2} = 1.14\,\text{m}.$$  

We cannot really assess if this overall error in location has preferential directions. Therefore we can only give an estimate for the upper bound of the error on the cliff backwastening assuming that the error
in location has the same direction as the backwasting. Taking typical values of 6 m of backwasting \( (D_{\text{melt}}) \) over monsoon season and 3 m over winter obtained with our method (Table 4), we obtain the following relative uncertainties:

\[
\Delta_{\text{melt}} = \frac{\Delta_{\text{overall}}}{D_{\text{melt}}} = \begin{cases} 
19 \% & \text{between May and October} \\
38 \% & \text{between October and May}
\end{cases}
\]

The uncertainty on the cliff area is negligible compared with this one, consequently the relative uncertainty on volume is directly the above-mentioned one.

6 Results: a first precise assessment of cliff backwasting

We applied the full method to all possible cliffs (fig. 12 - lower panel and Table 4). The normalized volume loss (also called melting rate) is calculated as the volume loss between \( t_1 \) and \( t_2 \) divided by the average of the cliff areas at \( t_1 \) and at \( t_2 \). It is converted in centimeters water equivalent (cm w.e.) assuming a density of 900 kg/m\(^3\) for the ice. This normalization is useful to compare changes in cliffs with very different areas (fig. 12 - upper panel). Nevertheless, it might not be appropriate to normalize by the mean area when the area changes a lot between the two dates (for instance cliff 01 and the western side of cliff Philly change a lot between May 14 and October 14; fig. 12). On average cliffs melt at much faster rates between May and October \((3.7 \pm 0.7 \text{ cm w.e.}/\text{day})\) than between October and May \((1.3 \pm 0.2 \text{ cm w.e.}/\text{day}; \text{Table 4})\), which is expected. We suspect that a large part of the measured melt between October and May happens in October and April/May, but we cannot prove it. Cliffs have quite similar melting rates during monsoon season 2013 (between 3.5 and 4.5 cm w.e./day) and in winter\(^3\) (between 1.2 and 1.5 cm w.e./day). During monsoon 2014 cliffs melt is more variable (between 2.2 and 4.0 cm w.e./day). This is an interesting result because the cliffs studied have area spanning over two orders of magnitude (fig. 12). The difference in melting rates during the two monsoon seasons could also be explained by the source of data, which is more homogeneous in 2013 (Table 2). The reduced melting rate during winter can be explained by a reduction in the incoming shortwave and longwave radiation, which are the two main energy fluxes (Steiner et al., 2015). In winter, the incoming shortwave radiation is reduced because the solar elevation angle is lower. Therefore it is reduced on average, but it is even more reduced on the cliffs because they are mostly north facing (and consequently are mostly in the shade during winter). The incoming longwave radiation from the surrounding debris is lower because they have a lower temperature in winter. Refreezing might play a strong role in the reduction of melt in winter (Steiner et al., 2015).

\(^3\)October to May survey. We use \textit{winter} for convenience, even if it does not match the real winter season.
Figure 12: Area change (upper panel) and melt rate (lower panel) of all cliffs as a function of time. The melt rate is defined as the volume change between \( t_1 \) and \( t_2 \) divided by the number of days and the mean cliff area. Note that the y-axis for the upper panel has a logarithmic scale. Shaded areas in both panels stand for the monsoon period (15 June – 30 September).

We also compared the volume loss obtained by applying the dGPS only method (fig. A.7). The data were sufficient to apply it only for cliff 01 and cliff 02 between May and October 14. The cliff outlines were fully mapped for cliff Philly and Cornelia in May 2014 as well, but technical problems did not allow to repeat properly the survey in October 2014. Cliff Edu’s bottom edge is never accessible because of a large supra-glacial lake. For cliff 01 the agreement is very good and the volume loss estimated with the dGPS only method is less than 1.5 % lower than the one estimated with the full method. On the other hand for cliff 02 the agreement is not as good and the dGPS only method underestimates by 9 % the volume loss (fig. A.7). This could either be due to the complex geometry of cliff 02 (fig. 2) or to the non-complete dGPS outline of cliff 02 (fig. 3) which necessary lead to an underestimation of the volume loss. Our results are not sufficient to conclude on the relevance of the dGPS only method.

7 Discussion

7.1 Comparison with model results and other methods

Buri et al. (2015) developed a distributed energy balance model which calculates melt for each grid
Table 4: Volume loss obtained with the different methods for cliff 01 and 02 over the study period. The values in bracket for cliff 01 and cliff 02 in May 13 to October 13 are the estimates of Buri et al. (2015).

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<td>-</td>
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<td>-</td>
<td>-</td>
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</table>

cell of a DEM of the cliff. They applied the model to cliff 01 and 02 of Lirung Glacier and ran it from 8 May 2013 to 23 October 2013. The model is forced with an automatic weather station located on glacier which records meteorological variables. The spatial resolution of the model is 20 cm. They calculated average melt rates of 3.6 and 3.1 cm w.e./day for cliff 01 and 02, respectively. This is very consistent with our method results: we obtained $3.8 \pm 0.8$ and $3.7 \pm 0.7$ cm w.e./day, respectively (Table 4). It would be very interesting to compare the model’s results for the other season (October to May) to see to which extent the lower melt rate we measure is consistent with an energy balance model. We suspect that the refreezing of the melt water running along the cliff plays an important role in post-monsoon (October to November) and winter seasons (Steiner et al., 2015). A comparison between the model, which does not take it into account now, and the measured mass loss could be very insightful. From this study we created a database of mass loss from cliff backwasting which will be useful to validate different models.

These repeat topographic surveys are also useful to document cliff evolutions from a more qualitative point of view. For instance, the expansion of cliff Philly, with the apparition of a new cliff on its western side, or the shrinkage of cliff 01 are striking features. This questions how much we understand of cliff formation and evolution processes. For instance, cliff 02 and cliff Edu keep a very constant shape (fig.13b) whereas cliff 01 (fig. 13a) and cliff Philly change a lot (fig. 10).
Nevertheless our method requires a large amount of field data and can thus be applied only to a limited number of cliffs. One ultimate goal is to find the minimum of input data required to obtain a satisfying estimate of the cliff melt rate. To evaluate ice-cliff backwasting, Han et al. (2010) measured the distance between the cliff edge and a distinguishable fixed boulder at $t_1$ and measured it again at $t_2$ (one month later in their case). We adapted their method and measured the position of a distinguishable point of each cliff edge (e.g. a high point) on our different datasets. We corrected for glacier flow for the analysis and excluded the western part of cliff Philly from the analysis because it was not possible to link a point in the edge in May 2014 and October 2014. We then compared the horizontal distance between the points with our estimate of the perpendicular melt (fig. 14 - left panel). The perpendicular melt is simply the volume loss divided by the cliff average area (with no density correction; it is expressed in m). The horizontal distance is higher than the perpendicular melt (mean bias of 2.6 m). If we calculate the horizontal melt by projecting the perpendicular melt (i.e. by dividing the perpendicular melt by the cosine of the slope), the mean bias is reduced (0.51 m) and the correlation is slightly better ($R^2 = 0.59$ when correcting versus 0.55 without correction; fig. 14). Even if the agreement between both methods is not fully satisfying, as the cliff edges are visible on high resolution satellite imagery, it could be interesting to track them to give a comprehensive rough estimate of cliffs contribution to total mass loss of a debris-covered glacier.
Figure 14: Comparison of the cliff backwasting measured with our method (x-axis) and the horizontal displacement of the cliff edge (y-axis). The circles correspond to the period May 2013 to October 2013, the diamonds to the period October 2013 to May 2014 and the squares to the period May 2014 to October 2014. The dashed line is the 1:1 line. The melt distance is calculated as the volume loss divided by the cliff area. Note that the western side of cliff Philly is excluded from the analysis. The x errorbars are calculated assuming 20% of uncertainties and the y errorbars correspond to 1 m of error.

7.2 How valuable are the insights gained by this method?

This method has the potential to be used to validate melt models and/or to give an estimate of the cliff contribution to the total melt. Nevertheless, it requires high resolution data that are labour intensive to collect. Therefore, even for a small glacier such as Lirung Glacier, we could not collect enough data to estimate the volume loss of all the cliffs. We need to develop a simplified method, either based on field data that are easier to collect or on remote sensing data. This method has to be more sophisticated than the method developed by Han et al. (2010), which is not accurate enough (fig.14). This method also requires a lot of manual processing: delineating the cliff outlines, merging the different TINs and even calculating the volume of the mesh. This was not the limiting factor of this study, but it would be interesting to automatize some of these steps if we want to apply this method more systematically.
This method is also intrinsically limited by the accuracy of the topographic data we can collect. We can apply it to calculate melting rates only over long periods to measure changes that are significantly higher than the accuracy of the method.

Another limitation of the method is its unsuitability to assess melt rates when the geometry of the cliff changes a lot between two dates. For instance, cliff 01 shrinks between May 2014 and October 2014 (fig. 12 - upper panel). Depending on how we normalize the volume loss, we can obtain a melt rate of 0.7 or 3.8 cm w.e./days if we take the cliff area in May 2014 or in October 2014, respectively. The same phenomenon happens for cliff Philly, which expands a lot between May 2014 and October 2014. This also highlights the fact that the conversion between melt rate and volume or mass loss is not straightforward. One should be very careful when extrapolating a simple (or even a refined) melt model to assess volume loss from the cliffs for the whole glacier based on melt rate measurements and modelling (e.g., Han et al., 2010).

8 Conclusions

In this study we processed terrestrial photographs and dGPS measurements to generate high resolution topographic data of Lirung Glacier, Nepalese Himalayas. We then developed a method to assess volume loss due to ice-cliff backwasting. This method gave encouraging results and has the potential to be applied to other debris-covered glaciers which are also accessible, either in the Alps and in the PKH. This study stresses the importance of high resolution topographic data to validate process oriented models. The development of process oriented models is needed if we want to be able to predict the mass loss from debris-covered glaciers at a broader scale. Thanks to the development of UAVs and softwares which simplify the photogrammetric processing, high resolution topographic data are now easier to collect and process. It also demonstrates the interest of using more complex data, such as TINs, even if they are more complicated to manipulate than DEMs. The TINs are more realistic representation of the topography and they allow gaining insight into cliff evolution over time, which is not always possible with DEMs.

Nevertheless, this method has two main limitations, which prevent its broader application: it requires high resolution data, which can only be collected in the field now and it can only measure relatively large volume losses.

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References


Figure A.1: Cliff 01 in May 2013 and October 2014. Note the important change in shape. Note that the two pictures are not taken from the same point of view.

Figure A.2: Cliff Philly in October 2014. Note the two different parts of the cliff, with the western side appearing around May 2014.
Figure A.3: Cliff Cornelia in October 2014. The photograph is taken from the eastern moraine.

Figure A.4: Cliff Edu in October 2014. The photograph is taken from the eastern moraine.
Figure A.5: Distribution of the displacement between Pléiades and Agisoft orthoimages (1 m resolution) calculated by the software cosicorr. Only pixels with a SNR above 0.95 were retained for the analysis.

Figure A.6: Absolute difference between the elevation of the dGPS points and the Agisoft DEM.
Figure A.7: Volume loss calculated with the dGPS only and the full method. It was only possible to apply the dGPS only method between May 14 and October 14. For May 2014 to October 2014 cliff 01, the two curves overlap.

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Table A.1: Original locations of the different dGPS bases used to process the rover data and locations of the bases calculated by PPP. The correction factors were applied to translate the processed rover data in the same base. For the 2013 correction, the dZ does not correspond to the difference in elevation between the two bases because an additional correction due to the height of the antenna was added.
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Table A.2: Local glacier’s surface displacement. The data from May 14 to Oct. 14 are obtained by tracking painting rocks with dGPS. The other data come from feature tracking on UAV orthophotos and DEMs (Immerzeel et al., 2014a).
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Table A.3: List of the 21 GCPs used to generate the October 2014 DEM (Agisoft DEM).
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<th>Cliff ID</th>
<th>( \Delta x ) (m)</th>
<th>Median</th>
<th>Std</th>
<th>( \Delta y ) (m)</th>
<th>Median</th>
<th>Std</th>
<th>( \Delta z ) (m)</th>
<th>Median</th>
<th>Std</th>
<th>Distance (m)</th>
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<td>0.24</td>
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| Median | 0.02 | 0.97 | -0.175 | 0.99 | 0.03 | 0.765 | 1.105 | 1.05 |

Table A.4: Detailed differences between dGPS and TINs cliff outlines. Table based on the same data as fig. 3.