Response to anonymous referee 1

We thank anonymous referee 1 for the detailed review. In this response, the reviewer's comments are in black standard font. Our response is in standard blue font and the modifications to the manuscript are in blue bold font.

Brun et al combine several state-of-the-art observational datasets with a novel correction for glacier dynamics (based on unique field observations) to measure volume losses due to bare ice cliffs exposed on Changri Nup Glacier in Nepal. This is an important question, as recent studies have suggested that ice cliffs play an important role in bringing the thinning rates of debris covered glaciers to parity with those of clean ice glaciers (unexpectedly). The study finds that ice cliffs indeed account for a disproportionate amount of mass loss in the debris-covered ablation area of Changri Nup, but that emergence velocity has been neglected in assessments of the 'debris covered glacier anomaly'.

I am impressed with the careful processing of the field and remote-sensing observations, in particular with the correction of point clouds for glacier flow and the treatment of uncertainty in general, and I find this study to be an excellent combination of high-resolution topographic datasets and robust processing to measure changes of highly dynamic features. I am particularly pleased to see attention given to emergence velocity, an aspect of glacier dynamics and mass balance that is often neglected in contemporary studies due to the recent emphasis on remote sensing observations. I have concern with the strength of the authors' refutation of the 'debris covered glacier anomaly' based on observations from a single glacier; I rather think they have highlighted the (largely unacknowledged) importance of emergence velocity, but have not demonstrated that this is the dominant or general mechanism by which debris covered glaciers thin at rates comparable to clean ice glaciers in High Mountain Asia. I suggest the authors consider some textual revision in order to better balance the focus of their discussion and conclusions with the focus of their highly sophisticated processing.

We thank the anonymous referee 1 for her/his positive appreciation of our work and we understand her/his concern about the lack of balance in the focus of our discussion and the critics of the extrapolation of our findings based on a single case. We respond on the specific points raised hereafter.

Major points:

1. The manuscript is not balanced in terms of the focus of its methods, results, and discussion. The manuscript is mostly aimed at assessing the contribution of ice cliffs to mass balance; the gold-standard methods are targeted specifically to assess this using multiple (perhaps redundant) high-resolution datasets, yet once the authors have a number for the ice cliff net ablation, the discussion is nearly all about the importance of emergence velocity. This feels like an afterthought (i.e. determination of emergence velocity itself is not given much attention in the background and methods, but this is the main topic in the discussion, whereas ice cliffs received little attention); this disparity is awkward. In particular, additional attention needs to be paid to the uncertainty in both the original emergence velocity dataset (per Vincent et al 2016) and particularly with respect to the 'updated' estimate. For example, what about uncertainties in ice thickness retrieval and differences in emergence velocity due to profile orientation? What about the uncertainty of thermal regime and its effect on column-averaged ice velocity? If emergence velocity is to be a major outcome of the manuscript, its uncertainty needs to be more carefully assessed.

We agree with the reviewer. However, we think that many recent studies, based on DEM differences often neglected the ice dynamics. This article was an opportunity to stress the potential influence of the emergence velocity, and consequently to stress the fact that thinning rates and ablation rates are very different. We address the reviewer's comment by two developments in the text:

1- We changed the structure of the text in order to better emphasize the emergence velocity calculation. The section 3.4.2 is now titled "Ground penetrating radar" and we added more methodological development and background about the emergence velocity in a new subsection within the method section, which is now divided as: 4.1 Emergence velocity; 4.2 Ice cliff backwasting calculation; 4.3 Sources of uncertainty. We substantially enriched the 'update' estimate. We corrected the uncertainty of the GPR estimate (see below and thanks for pointing this out!) and tested different glacier thermal regime hypothesis.

Section 4.1 now reads: **"The emergence velocity refers to the upward flux of ice relative to the glacier surface in an Eulerian reference system (Cuffey and Paterson, 2010). For the case of a glacier in steady-state (i.e., no volume change at the annual scale), the emergence velocity balances exactly the net ablation for any point of the glacier ablation area (Hooke, 2005). For a glacier out of its steady state (as Changri Nup Glacier) the thinning rate observed in the ablation area is the sum of the net ablation and the emergence velocity (Hooke, 2005). On debris-covered glaciers, while the thinning rate is relatively straightforward to measure from DEM differences, for example, the ablation is highly spatially variable and difficult to measure (e.g., Vincent et al., 2016). In order to evaluate the mean net ablation of Changri Nup Glacier tongue from the thinning rate, we estimate the mean emergence velocity (w_e) for the period November 2015-November 2016 and for the period November 2016--November 2017 using the flux gate method of Vincent et al. (2016). As the ice flux at the glacier front is 0, the average emergence velocity downstream of a cross-section can we calculated as the ratio of the ice flux through the cross-section (Φ in m^3 a^{-1}), divided by the glacier area downstream of this cross-section (A_T in m^2):**

$$w_e = \frac{\Phi}{A_T}$$

This method requires an estimate of ice flux through a cross-section of the glacier, and is based here on measurements of ice depth and surface velocity along a profile upstream of the debris-covered tongue (Figs. 1 and 2). The ice flux is the product of the depth-averaged velocity ($\overline{u}$ in m a^{-1}) and the cross-sectional area. For the period November 2015-November 2016 (resp. November 2016-November 2017), the glacier slowed down compared with the 2011-2014 period and the centerline velocity was equal to 10.8 m a^{-1} (resp. 11.1 m a^{-1}), leading to an assumed mean surface velocity along the upstream profile of 8.1 ± 0.6 m a^{-1} (resp. 8.3 ± 0.6 m a^{-1}), as the centerline velocity is usually 70 to 80 % of the mean surface velocity along the cross-section (e.g., Azam et al., 2012; Berthier and Vincent, 2012). We used the relationship between the centerline velocity and the mean velocity, instead of an average of the velocity field along the cross section, because the image correlation was not successful on a relatively large fraction (~ 30 %) of the cross section. Converting the surface velocity into a depth-averaged velocity requires assumptions about e basal sliding and a flow law (Cuffey and Paterson, 2010). Little is known about the basal conditions of Changri Nup Glacier, but Vincent et al. (2016) assumed a cold base, and therefore no sliding. This leads to $\overline{u}$ being approximated as 80 % of the surface velocity, additionally assuming n = 3 in Glen's flow law (Cuffey and Paterson, 2010). As an end-member case, assuming that the motion is entirely by slip implies $\overline{u}$ equals to the surface velocity (Cuffey and Paterson, 2010). Consequently, we followed Vincent et al. (2016) and assumed no basal sliding, but we took the difference between the two above-mentioned cases as the uncertainty on $\overline{u}$. This leads to $\overline{u}$ = 6.5 ± 1.6 m a^{-1} (resp. 6.6 ± 1.7 m a^{-1}) for the period November 2015-November 2016 (resp. November 2016-November 2017).

Assuming independence for the cross-sectional area (σ_S) and the depth-averaged velocity ($\sigma_{\overline{u}}$), the uncertainty on the ice flux (σ_Φ) can be estimated as:

$$\frac{\sigma_\Phi}{\Phi} = \sqrt{\frac{\sigma_{\bar{u}}}{\bar{u}}^2 + \frac{\sigma_S}{S}^2}$$

Given the above mention values for the depth-averaged velocity, the cross-sectional area and the associated uncertainties, the relative uncertainty of the ice flux is ~30 %. As a result, for the period November 2015-November 2016 (resp. November 2016-November 2017), the incoming ice flux was thus 499 700 ± 150 000 $m^3\ a^{-1}$ (resp. 503 840 ± 150 000 $m^3\ a^{-1}$). The glacier tongue area was considered unchanged at 1.49 ± 0.16 km^2, corresponding to w_e = 0.33 ± 0.11 m a^{-1} (resp. 0.34 ± 0.11 m a^{-1}). It is notoriously difficult to delineate debris-covered glacier tongues (e.g., Frey et al., 2012). In this case, we assumed an uncertainty in the outline position of ± 20 m, leading to a relative uncertainty in the glacier area of 11 %, which is higher than the 5 % of Paul et al. (2013). In this case, the uncertainty on the glacier outline is not the main source of uncertainty in w_e, but for automatically delineated glacier outlines, this would be an important source of uncertainty. The updated emergence velocity is ~20 % lower than estimated for the 2011-2015 period (Vincent et al., 2016), due to both the thinning and deceleration of the glacier. As the difference in w_e between November 2015-November 2016 and November 2016-November 2017 is insignificant, we consider w_e to be constant and equal to w_e= 0.33 ± 0.11 m a^{-1} for the rest of this study. It is noteworthy that some spatial variability is expected for w_e, however, we have no means to assess it.”

2- We now describe in more detail the cliff evolution (number of cliffs, backwasting rates, area changes) in section 6.1 of the discussion and we shortened and substantially rewrote section 6.3. Section 6.1 is now entitled “**Cliff evolution and** comparison of two years of acquisition”, and the two first paragraphs read as:

“The total ice cliff covered area did not vary significantly from year to year, ranging from 70 ± 14 × 10^3 m^2 in November 2017 to 72 ± 14 × 10^3 m^2 in November 2016. The twelve individual cliffs surveyed showed large variations in area within the course of one year, with a maximum increase of 57 % for the large cliff 06 and a decrease of 34 % for cliff 03 and 09 (Table S2). The total area of these twelve cliffs increased by 8 % in one year. Interestingly, over the same period, Watson et al. (2017) observed only declining ice cliff areas on the tongue of Khumbu Glacier (~6 km away). All the large cliffs (most of them are included in the twelve cliffs surveyed with the terrestrial photogrammetry) persisted over these two years of survey, including the south or south-west facing ones (Table 1) , although south facing cliffs are known to persist less then non south facing ones (Buri and Pellicciotti, 2018). However, we observed the appearance and disappearance of small cliffs, and marginal areas became easier to classify as either ice cliff or debris-covered areas, highlighting the challenge in mapping regions covered by thin debris (e.g., Herreid and Pellicciotti, 2018).

We calculated backwasting rates for the twelve cliffs monitored with terrestrial photogrammetry for the period November 2015--November 2016 (Table 1). The backwasting rate is sensitive to cliff area changes (because it is calculated as the rate of volume change divided by the mean 3D area) and should be interpreted with caution for cliffs that underwent large area changes (e.g., cliffs 01, 02, 03, 06, 09 and 11; Table S2). The backwasting rates ranged from 1.2 ± 0.4 to 7.5 ± 0.6 m a^{-1}. The lowest backwasting rates are observed for cliffs 11 and 12, located on the upper part of the tongue, roughly 100 m higher than the other cliffs (Fig. 1 and Table 1). The largest backwasting rates were observed for cliff 01, which expanded significantly between November 2015 and November 2016. The backwasting rates are lower than those reported by Brun et al. (2016) on Lirung Glacier (Langtang catchment) for the period May 2013-October 2014, which ranged from 6.0 to 8.4 m a^{-1} and lower than those reported for surviving cliffs by Watson et al. (2017) on Khumbu Glacier for the period November 2015-October 2016, which ranged from 5.2 to 9.7 m a^{-1}. These

differences are likely due to temperature differences between sites. Indeed, the cliffs studied here are at higher elevation (5320-5470 m a.s.l.) than the two other studies (4050--4200 m a.s.l. for Lirung Glacier and 4923-4939 m a.s.l. for Khumbu Glacier)."

2. I think some adjustment to the title and latter discussion is necessary: I do not think the authors are able to answer the title question using data from Changri Nup alone.
We modified the title of the article, which now reads "Ice cliff contribution to the tongue-wide ablation of Changri Nup Glacier, Nepal, Central Himalaya"

First, the authors provide no evidence that Changri Nup fits within the 'debris cover anomaly' framework (that Changri Nup is thinning at a comparable rate to debris-free ice at a similar elevation). This is partly due to the hypsometric differences of debris-covered and debris-free ice in the Solukhumbu region, but this is largely why the debris-cover anomaly has been determined from numerable populations of glaciers, which will exhibit a variety of hypsometric distributions.
The "debris cover anomaly" (i.e. similar thinning rates over debris-covered and debris free glaciers at similar elevations, although ablation is expected to be reduced over debris covered glaciers compared with debris-free glaciers) is to our opinion an interesting but fuzzy concept, which has been used to motivate previous studies that looked for processes responsible for enhanced ablation on debris-covered tongues. Based on the data of Brun et al. (2017), we show that the thinning rates of debris-covered areas are comparable to thinning rates of debris-free areas for glaciers in the Khumbu region (Figure R1). The thinning rate of Changri Nup Glacier agrees well with this regional pattern and therefore we do conclude that the tongue of Changri Nup Glacier is a representative "debris-anomaly" glacier.

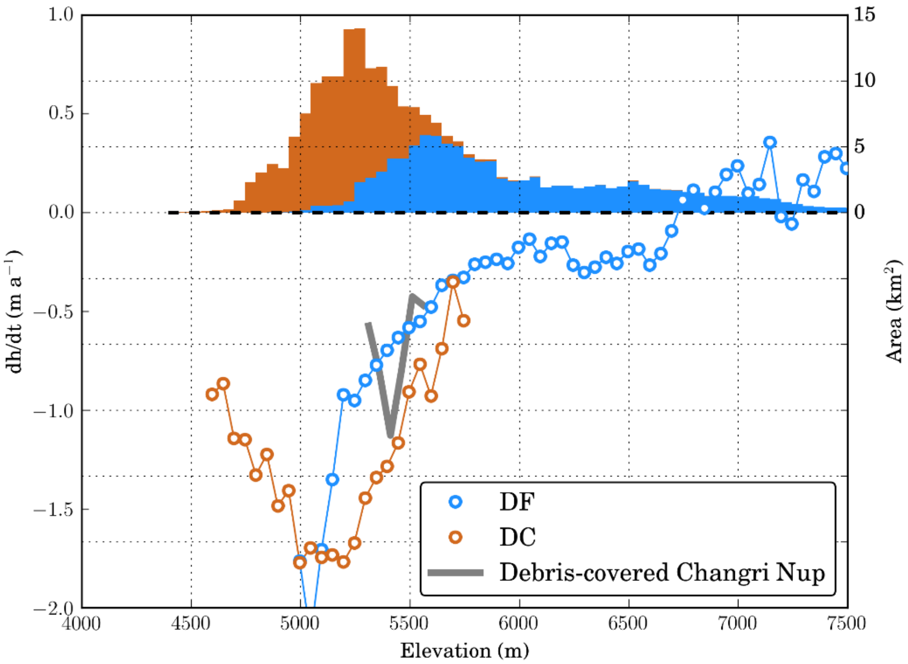

Figure R1: rate of elevation change for debris-free and debris-covered ice in the Khumbu region, based on Brun et al. (2017) data. The brown histogram represents the hypsometry of the debris-covered ice and it is stacked above the blue histogram, which represents the hypsometry of the debris-free ice. The thinning rate for the debris-covered part of Changri Nup is overlaid in grey.

It could be possible to assess the thinning rates (and melt rates) just below the GPR transect, where debris and ice surfaces exist at the same elevations – does Changri Nup actually show evidence of comparable thinning rates for debris and ice?
We do not think that comparing melt rate just beneath the GPR section to compare clean ice and debris covered ice is possible, because the transition between clean ice and debris-covered ice is very smooth and it is hard to distinguish between the two categories. Moreover, this area is very small and it is not representative of heavily debris-covered tongues.

However, I am doubtful that this would be satisfactory, as Vincent et al (2016) has already demonstrated that melt rates at Changri Nup would be very different beneath debris and clean ice; it seems that the hypsometric parity of thinning rates for debris-covered and debris-free ice does not hold for this particular location, but for larger regions.
Put differently, there is circular logic at play – it is already known that subdebris melt rates are not equivalent to clean-ice melt rates at this location, so no amount of ice cliff melt could bring the subdebris mass balance to the same level. A way forward is to emphasize that both processes are important: neglecting emergence velocity, one does underestimate melt rates, but similarly one does if neglecting ice cliffs. However, emergence velocity has been neglected, and the Changri Nup data is the first field data to demonstrate the effects theorized by Banerjee (2018). Thus, a meaningful question is how much are the competing hypotheses responsible for boosting the thinning rate of debris-covered glaciers? I.e. how much of a boost in lowering is due to cliffs vs how much is because of emergence velocity? Or, how much 'additional' melt would be needed from cliffs to lead to thinning (or b_dot) -equivalence? Twice as much? Three times?
The point raised by the reviewer is interesting but we believe that it is not possible to address it (at least using our data), for two main reasons: first, we do not know much about the emergence (of both categories of glaciers), and consequently it is not possible to answer directly the question "how much is because of emergence velocity" raised by the reviewer. Second, the cliff melt is highly localized, whereas the emergence velocity effect is spatially distributed. Consequently, we cannot really calculate the values suggested by the reviewer, as they are expected to be very different for each glacier, because they depend on the relative areas and they depend on the ice dynamics. Instead, we calculated the area covered by cliffs which produce ablation similar to a debris-free tongue (P12-L22-24).

Can you guess how much ablation ponds are responsible for (realising that this is just part of your non-cliff net ablation, and does not affect the role of emergence velocity)?
We tried to map the area occupied by ponds, but it turns out that this task was not straightforward. Based on the UAV orthomosaic, we could not distinguish between very shallow ponds/supraglacial river systems, which have a limited contribution to ablation, and ponds that are deep enough to develop vertical mixing and therefore enhanced ablation. We mapped approximately 20 000 m^2 of surface covered by ponds (i.e. approximately 1.5 % of the tongue area) on the November 2017 imagery. It is noteworthy that a single pond contributed to half of this total by itself (area of 9 600 m^2). This pond is located at the bottom of cliff 06 and triggered a large calving event between November 2015 and 2016. We cannot say much more about pond ablation with this dataset.

Minor points
Some nomenclature formality is needed for the cliff area terms. Variably through the manuscript there are 'planar' (cliffs are often considered inclined planes, so this is confusing), '2D' and '3D' areas of cliffs. Please clarify this early on in the manuscript, and ensure consistency.
We have removed "planar" from the manuscript and replaced it with "map view", following (Herreid and Pellicciotti, 2018). The cliff 2D area was defined as the cliff footprint (P5 L28).

P1 L20. Suggest 'have been found' in place of 'were found' for correct tense
Modified accordingly

P2 L5-11. It may be useful to use the same order for the hypotheses here as for the rest of the text, e.g. you first discuss how to test the cliff hypothesis before considering the role of emergence velocity.
Modified accordingly

P2 L6-8. This is the thesis of this paper (that emergence velocity is a major player), which it supports very well. Here, however, this is an hypothesis – that differences in emergence velocity 'can/could lead to comparable thinning rates despite differences in surface ablation. The two studies referenced are hypothetical, idealised flow-models.
We added "**could**"

P2 L10. This seems to refer to surface ablation only, yet Sakai et al 2000, Miles et al 2016, and Watson et al 2017 (ESPL) also indicate that ponds could potentially lead to significant internal ablation (which would also contribute to lowering as in Thompson et al 2016).
We separated this sentence into two parts: the first one mentions only the cliffs (we removed the reference to Miles et al 2016) and the second one mentions the supraglacial and englacial ablation due to water circulation: "**Other processes linked to supraglacial and englacial water circulation could lead to substantial ablation** (e.g., Benn et al., 2017; Miles et al., 2016; Sakai et al., 2000; Watson et al., 2018)."

P2 L12. It follows that you also need to determine the melt contribution of supraglacial ponds in order to resolve this
Modified accordingly. "**In order to partially test the first hypothesis, there is a need to calculate the total contribution of the additional melt processes to the tongue-wide surface mass balance. In this work, we focused on the ice cliff contribution, as the other processes are currently not quantifiable at the scale of a glacier tongue.**"

P2 L17. In the formulation of Equation 1, does the 'tongue' area include or exclude the ice cliff areas? That is, does p compare ice-cliff ablation to the overall surface mass balance, or to the non-cliff ablation? Is this consistent between the studies mentioned?
This point was also mentioned by other reviewers. The *p* factor is now named f_C factor to avoid a confusion with the "*p*-value" (comment from reviewer 3). The f_C factor has the same definition as *p*, but we added the definition of a new factor, named f_C^*, which is the ratio of the cliff ablation divided by the non-cliff terrain ablation (denoted by the subscript NC):

$$f_C^* = \frac{\Delta V_C}{A_C}\frac{A_{NC}}{\Delta V_{NC}} = f_c\,\frac{\Delta V_T}{\Delta V_T - \Delta V_C}\,\frac{A_T - A_C}{A_T}$$

Based on our data, for Changri Nup Glacier, $\frac{\Delta V_T}{\Delta V_T - \Delta V_C} = \frac{1}{1-0.23} = 1.30$ and $\frac{A_T - A_C}{A_T} = \frac{1-0.07}{1} = 0.93$, consequently $f_C^* = 1.2\, f_C$.

For the consistency between the studies mentioned, we interpreted the studies as follow:
- Juen et al. 2014 : "Although the ice cliffs occupy only 1.7% of the debris covered area, the melt amount accounts for approximately 12% of the total sub-debris ablation" -> $f_C^* = \frac{12}{1.7} = 7.1$
- Reid and Brock 2014: "Analysis of the DEM indicates that ice cliffs account for at most 1.3% of the 1m pixels in the glacier's debris-covered zone, but application of a distributed model indicates that ice cliffs account for ~7.4% of total ablation." -> $f_c = \frac{7.4}{1.3} = 5.7$

- Buri et al. 2016: "Although only representing 0.09% of the glacier tongue area, the total melt at the two cliffs over the measurement period is 2313 and 8282m^3, 1.23% of the total melt simulated by a glacio-hydrological model for the glacier's tongue. -> $f_c = \frac{1.23}{0.09} = 13.7$
- Sakai et al 1998: From the abstract: "The ice cliff melt amount reaches 69% of the total ablation at debris covered area, although the area of ice cliffs occupies less than 2% of the debris covered area" -> $f_c = \frac{69}{2} = 35$
- Sakai et al 2000: From their Table 2: ratio of the "absorbed heat at each type of surface during the observation period (167 days)", including the "whole debris-covered zone" -> $f_c = \frac{256}{26} = 9.8$ or looking only at the debris -> $f_C^* = \frac{256}{21} = 12.2$
- Brun et al 2016: "The ice cliffs lose mass at rates six times higher than estimates of glacier-wide melt under debris, which seems to confirm that ice cliffs provide a large contribution to total glacier melt." -> $f_c = 6$
- Thompson et al 2016: "Although ice cliffs cover only ~5% of the area of the lower tongue, they account for 40% of the ablation." -> $f_c = \frac{40}{5} = 8$

As most of the studies were already within the framework of the original definition of p/f_C, we decided to keep the focus on this factor, instead of f_C^*. This example demonstrates the importance of a consistent framework for comparing these studies.

P2 L24. Please also mention the source data and method for Brun et al 2016 if you are going to for Thompson et al 2016.
Modified accordingly

P2 L28. Suggest 'positive emergence velocities will increase the : : :' as it is more concrete than 'affect'
This paragraph has been reworked. It now reads: "**Neglecting the emergence velocities (i.e. comparing thinning rates instead of ablation rates) introduces a systematic overestimation of f_c. This is due to the fact that cliffs ablate at higher rate than the rest of the glacier tongue: ice cliff thinning rates are thus less influenced than the thinning rates of debris-covered ice when neglecting the emergence velocity. As a consequence, the ratio of the cliff thinning rate divided by the mean tongue thinning rate will overestimate f_c. To correctly estimate f_c and the fraction of total ice cliff net ablation, thinning rates need to be corrected with the emergence velocity.**"

P3 L5-10. It is necessary to make some mention of your emergence velocity correction in this paragraph.
Modified accordingly. "We introduce a new method based on DEM differencing, which takes into account geometric changes induced by glacier flow, **and in particular by the emergence**, and apply it to the UAV and Pléiades imagery."

P3 L28. 'GCPs' should be singular or possessive here.
Modified accordingly

P4 L15. 'equal' should be 'equivalent'
Modified accordingly

P5 L3. Incomplete sentence. 'This ensured our study/our analysis to: : :'
Modified accordingly

P6 L9. I don't believe the accuracy of this cross-sectional area. The uncertainty with respect to radar velocity in ice alone is greater than the stated value. The stated uncertainty equates to 10cm of uncertainty in ice thickness all along the cross section. Please ensure that your corrected uncertainty is propagated to your uncertainty in emergence velocity as well.

We apologize for this mistake and thank a lot the reviewer for pointing it out!

The section has been quite modified following the reviewer's major comments. The uncertainty on the GPR data is ± 15 m.

The new section 3.4.2 ("**Ground penetrating radar data**") now reads: "**A cross sectional profile of ice thickness has been measured upstream of the debris-covered tongue (Fig. 1) in October 2011, with a ground penetrating radar (GPR) working at a frequency of 4.2 MHz (Vincent et al., 2016). The original cross-sectional area was 79 300 m² in 2011 and 78 200 m² in 2015 (Vincent et al., 2016). Between November 2015-November 2016 and November 2016-November 2017, the cross sectional area decreased from $S_{2015\text{-}2016}$ = 76 900 m² to $S_{2016\text{-}2017}$ = 76 340 m² (with $S_{yr1\text{-}yr2}$ being the mean cross sectional area between the year 1 and year 2), based on the 0.86 m a^{-1} thinning rate measured over the November 2015-November 2017 period along the profile. The uncertainty on the ice thickness is ±15 m (Azam et al., 2012), which leads to an uncertainty (σ_S) of ± 10 000 m², as the length of the cross-section is 670 m.**"

P6 L19. Constant and equal over the lower glacier for both periods of study, you mean. As the flux gate method can only give you a mean emergence velocity for the lower glacier, but please mention how it is expected to vary in space, and how this might affect your results for ice cliffs and for the whole glacier.

We added: "**It is noteworthy that w_e is likely to be spatially variable, however, we have no means to assess its spatial variability.**"

P9 L2. Your kernel sizes are with units of pixels, correct?

It is in pixel, this is added in the text.

P11 L10. Can you calculate or estimate the 3D area of these cliffs in order to calculate a mean backwasting rate for comparison to other studies? As the rate of elevation change over a cliff-affected area is heavily influenced by, e.g. their height and slope, the backwasting rate is perhaps easier to compare between studies (or indeed between years, as your 2016-2017 data is quite different).

We added a supplementary table (Table S2), which shows the cliff 3D area in 2015 and 2016 and we calculated the backwasting distance in Table 1. We calculated the backwasting as individual cliff volume loss from terrestrial photogrammetry (i.e., only for the period Nov. 2015 – Nov. 2016), divided by the mean 3D area. The backwasting rate is compared with other studies in section 6.1.

P11 L18-19. For p, it makes sense to me that the comparison would be cliff area tonon-cliff area, rather than cliff area to the whole area. Please check what prior studies have used for this calculation.

For a comparison with previous studies, see our response above. We added the results for f_C^* as well.

P11 L25. Why the much higher melt rates in 2016-2017?

The difference in mass balance between 2015-16 and 2016-17 is also observable in the glacier-wide mass balance of the near-by debris-free West Changri Nup Glacier (-0.76 and -2.56 m w.e. yr^{-1}, for 2015-16 and 2016-17, respectively) (P. Wagnon, unpublished data). The exact reasons explaining such large differences need to be analyzed but are not related to air temperature almost similar between both years (-3.6°C measured at the AWS at 5360 m a.s.l. on West Changri Nup, in both years, from 1 November to 31 October). The mean summer temperatures (1 April – 30 September) are also very similar (0.3°C for 2016 versus 0.1°C for 2017). The difference might come from other meteorological variables, but this has not been analyzed in details yet, and it is not the scope of this present paper.

P12 L8. 'Mean tongue' is not a sensible term. Consider 'relative to the whole tongue'
Modified accordingly

P12 L10-18. Neglecting the emergence velocity, what portion of the glacier's total ablation would be accounted for by ice cliff melt? Perhaps it would likewise be useful to compare the area-averaged losses due to ice cliffs and emergence velocity – are they of comparable magnitude?
We added this calculation and calculated the f_C^* ratios when neglecting the emergence, the section now reads as:
"In this case, the factor f_c would be 4.5 ± 0.6 **(and f_C^*would be 5.4 ± 0.7)**, which is 50 % higher than the actual value. **The cliffs would be found to contribute to ~34 \% of the tongue ablation**. For the period November 2016--November 2017, the factor f_c would be 3.6 ± 0.6 **(and f_C^* would be 4.3 ± 0.7)**, which is 20 % higher than the actual value. **The cliffs would be found to contribute to ~29 % of the tongue ablation.** This might partially explain why previous studies found significantly higher values of f_c, and stresses the need to estimate and take into account the ice flow emergence, even for almost stagnant glacier tongues like Changri Nup Glacier (see Discussion below)."

P12 L19. Consider 'the' debris-cover anomaly
Modified accordingly

P12 L22. This emphasizes the problem with your p calculation – it is not comparing ice cliff to debris, but ice cliff to drbis-and-cliff mixtures. Your values of p will increase with this correction. I.e. total melt due to cliffs was 440000m3 for 2015-2016, and they covered an area of 113000m2. Total melt for the whole glacier was 1,918,000m3 over an area of 1.49 km2. Thus the non-cliff melt was 1478000m3 over an area of 1.377km2. And thus p is 3.6 (20% higher). Can you also calculate what p would be neglecting your emergence velocity estimation (for comparison to the studies mentioned?
As mentioned earlier in this response: $f_C^* = 1.2\ f_C$ for this year on Changri Nup (in agreement with the reviewer's calculation!). We added the influence of neglecting the emergence velocity on f_C^* as well.

P12 L29. This is a very good point, but highlights a key difficulty for the paper. The authors have not demonstrated that the 'debris-cover anomaly' is applicable to Changri Nup at all! That is to say – the authors have not demonstrated that Changri Nup's debris-covered area is indeed thinning at a rate comparable to clean ice glaciers at the same elevation (the point of the debris-cover anomaly). Vincent et al 2016 has already demonstrated that the surface mass balance of Changri Nup is lower than it would be if debris were not present. Here you demonstrate that ice cliffs cannot bring the debris area's mass balance to the same level, but does Changri Nup even fit the debris-cover anomaly in the first place? This is not so problematic for your analyses and paper, but for the generalisation of your results to other areas (P13 L1-2 especially)
We both agree and disagree with the reviewer. Figure R1 shows that Changri Nup Glacier fits within a regional pattern of "debris cover anomaly". Moreover, we think that our calculation related to the cliff area equivalent ablation is true independently of the debris-cover anomaly, as it is based only on field measured ablation rates (for the debris-free surface) and the ablation rates measured in this study. Consequently, we decided to keep the lines 20-26 of page 12 unchanged. However, we understand the reviewer's concern about the generalization to the debris-cover anomaly, which implies additional assumptions, such as the reduced emergence velocity for debris-covered tongues. That's why we substantially modified the rest of this section.

P13 L4. I think this section needs to be tidied up with respect to nomenclature, in particular replace 'tongue' with 'ablation area'.

We prefer to keep the word tongue, because the glacier tongue is not the same as the ablation area.

P13 L8. This hypothetical analysis is very worthwhile, but as stated in the text, 'has already been shown by Banerjee (2018)'. Please properly reference that study early in this section (you can state that you provide the first field evidence supporting this hypothesis) and reduce this text accordingly. I recommend that you expand the discussion of the responsibility of reduced emergence velocity vs enhanced ablation (how important are cliffs and ponds for mass balance, then?) or consider more fully how the mass balance and emergence velocity (thus thinning rates) of both systems will continue to evolve. Is the apparent parity of thinning rates a temporary feature in this evolution, or should we expect this to perpetuate?

This section has been substantially modified in the revised version of the article. It is challenging to discuss the enhanced ablation of ponds, because we know very little about them on Changri Nup Glacier. We tried to map them, but with limited success because we can't distinguish between the large ponds, that are deep enough to produce enough ablation and the shallow ponds, which play a much more minor role (see our response above). While we appreciate the suggestion to orient the discussion towards the future evolution of these processes, we definitively think that we do not have enough elements to discuss this. The revised section reads:

"6.3 Ice cliff ablation and **the** debris-cover anomaly

Between November 2011 and November 2015, Vincent et al. (2016) quantified the reduction of area-averaged net ablation over the glacier tongue due to debris-cover. They obtained a tongue-wide net ablation of -1.2 m w.e. a^{-1} and -3.0 m w.e. a^{-1} with and without debris, respectively. As ice cliffs ablate **at -3.5 m w.e. a^{-1}, ~3.6** times faster than **the non-cliff terrain of the debris-covered tongue for the period November 2015-November 2016**, and ~1.2 times faster than the tongue if it was entirely debris-free, **approximately** 75 \% of the tongue would have to be covered by ice cliffs to compensate for the lower ablation rate under debris and to achieve the same overall ablation rate as a clean ice glacier under similar conditions. **Since ice cliffs typically cover a very limited area (Herreid and Pellicciotti, 2018), it is unlikely that they can enhance the ablation of debris-covered tongues enough to reach the level of ablation of ice-free tongues.**

Other ablation-related processes such as supra-glacial ponds (Miles et al., 2016) or englacial **ablation** (Benn et al., 2012) may contribute to higher **ablation** rates than what can be expected on the basis of the Østrem curve. Yet this does not apply to the case of Changri Nup Glacier, as Vincent et al. (2016) already showed that the debris part as a whole is responsible for a significant reduction of ablation. As a consequence, **and based on this case study, we hypothesize** that the reason for similar thinning rates over debris-covered and debris-free areas, i.e. the "debris-cover anomaly" is largely related to a combination of surface mass balance change and dynamics.

This hypothesis currently applies to the Changri Nup Glacier tongue only, and it is unclear if it can be extended to the debris cover anomaly identified at larger scales. The high quality data available for Changri Nup Glacier are not available for other glaciers at the moment, and consequently we provide a theoretical discussion below.

The mass conservation equation (e.g., Cuffey and Paterson, 2010) gives the link between thinning rate ($\frac{\overline{\partial h}}{\partial t}$ in m a^{-1}), ablation rate and emergence velocity for a glacier tongue:

$$\frac{\overline{\partial h}}{\partial t} = -\frac{1}{\rho}\,\dot{b} + \frac{\Phi}{A}$$

where Φ (m^3 a^{-1}) is the ice flux entering in the tongue of area A (m^2), ρ is the ice density (kg m^{-3}), and $\dot{b}$ is the area-averaged tongue net ablation (kg m^{-2} a^{-1}). **Consider two glaciers with tongues that are either debris-covered (case 1- referred hereafter as "DC") or debris-free (case 2 – referred hereafter as "DF"), and similar ice fluxes entering at the ELA i.e., $\Phi_{DC} = \Phi_{DF}$. The ice flux at the ELA is expected to be driven by accumulation processes, and consequently it is reasonable to assume similarity for both debris-covered and debris-free glaciers. There is a clear link between the glacier tongue area and its mean emergence velocity: the larger the tongue, the lower the emergence velocity. These theoretical considerations have been developed by Banerjee (2017) and Anderson and Anderson (2016), the latter demonstrating that debris-covered glacier lengths could double, depending on the debris effect on ablation in their model. Real-world evidence for such differences in debris-covered and debris-free glacier geometry remain largely qualitative. For instance, Scherler et al. (2011) found lower accumulation-area ratios for debris-covered than debris-free glaciers. Based on the data of Kraaijenbrink et al. (2017), we found a negative correlation (R = -0.36, p < 0.01) between the glacier minimum elevation and the percentage of debris cover (Fig. 10), hinting at both reduced ablation and a larger tongue for debris-covered glaciers.**

Consequently, the qualitative picture we can draw is that debris-covered glacier ablation area **is usually** larger ($A_{DC} > A_{DF}$), leading to lower emergence velocity ($w_{e,DC} = \Phi/A_{DC} < w_{e,DF} = \Phi/A_{DF}$). If the glacier is in equilibrium, in both cases, the thinning rate at any elevation is 0, because the emergence velocity compensates the surface mass balance, but with lower magnitudes for both variables (w_e and $\dot{b}$) in case of a debris-covered tongue (Fig. 11). In an unbalanced regime with consistent negative mass balances**, as mostly observed in High Mountain Asia (Brun et al., 2017)**, similar thinning rates between debris-free and debris-covered tongues could be the combination of reduced emergence velocities and lower ablation **roughly summing** up to similar thinning rates as debris-free glaciers (Fig. 11). Additionally, there are evidences of slowing down of debris-covered tongues and detachment from their accumulations area, both leading to reduction in ice flux and consequently in w_e (Neckel et al., 2017).

In conclusion, our field evidence shows that enhanced ice cliff ablation alone could not lead to a similar level of ablation for debris-covered and debris-free tongues. While we acknowledge the existence of other processes which can substantially increase the debris-covered tongue ablation, we highlight the potential important share of the emergence velocity in the explanation of the so-called 'debris-cover anomaly', which partly originates from a confusion between thinning rates and net ablation rates."

P13 L22-23. The manuscript has demonstrated that emergence velocities (and the difference between emergence velocity for clean-ice and debris-covered areas) are a key part of the debris-cover anomaly, but the manuscript has certainly not demonstrated that this is always (or even generally!) the reason for the thinning rate parity. Consequently I respectfully but strongly think that your statement should be modified, e.g. 'In conclusion, we have demonstrated that emergence velocity differences are as important as ice cliffs and supraglacial ponds in the calculation of melt rates for debris covered glaciers, and that the 'debris cover anomaly' is in part due to the confusion of thinning rates and net ablation.'
We modified this sentence. See our modified version just above.

P13 L24. This section is very out of place with regards to the underlying theme of the manuscript, especially as your discussion up until now focuses on cliffs not being important. I suggest as a segue to emphasize that melt rates are substantially higher than without ice cliffs, and that the primary analysis of the study is thus of benefit for modelling studies (otherwise why automatically delineate cliffs at all?).

We removed this section

P14 L6. Please include a mention of where Brun et al (2016) falls in this spectrum.
Modified accordingly

P14 L7-10. This is an important consideration that should be expanded upon. Your analysis including flow correction is without a doubt more sophisticated and 'correct' than prior efforts, but it extremely limited in its transferability because of the field data requirements. While emergence velocity is clearly an important and neglected aspect of studies addressing debris-covered glacier mass balance, it is extremely difficult to assess (and thus also the reliance on overall thinning rates rather than mass balance). It is not enough to say 'more data would be helpful' when you advocate abandonment of an entire train of thought; rather, I think it is important to acknowledge why such data do not already exist (why debris thickness has prevented widespread ice thickness measurement through debris), and to address alternative methods of assessing emergence velocity (e.g. networks of ablation stakes combined with dGPS).
The new paragraph reads: "A significant obstacle to applying our method to other glaciers is the need to estimate the emergence velocity, which requires an accurate determination of the ice fluxes entering the glacier tongues. **The measurement of ice thickness with GPR systems is already challenging for debris-free glaciers, as it requires to drag emitter, receiver and antennas along transects of the glacier surface. It is even more challenging for debris-covered glaciers, as the hummocky surface prevent the operators from dragging a sledge.** More field campaigns dedicated to ice thickness and velocity measurements (Nuimura et al., 2011, 2017) or the development of airborne ice thickness retrievals through debris are recommended. **The precise retrieval of emergence velocity pattern using a network of ablation stakes combined with DGPS is a promising alternative, in particular if combined with detailed ice flow modeling (e.g., Gilbert et al., 2016).**"

P14 L24. There is no discussion of this point, but I think it would be useful to expand upon (briefly). What do we do with your results? How does this affect models of debris covered glacier mass balance and/or dynamics?
The revised sentence reads: "**The main limitation of our study is its short spatial and temporal extent. It would be very worthwhile to obtain longer-term and multiple sites quantification of the relative ice-cliff contribution to net ablation. Then a compilation of these data would allow to develop empirical relationships for cliff enhanced ablation, which could** be included into debris-covered glacier mass balance models."

Figure 6. These are normalised change in the volume change (rather than cliff volume), correct?

Modified accordingly

Figure 10. I like the simplicity of Figure 10, but it is deceptive in its simplicity (the scales are of course arbitrary). It would be worthwhile to emphasize that this is one hypothetical transient state (another would be to double b_dot for debris free glaciers, the end-member with no increase in w_e in either case). It also would be worthwhile to highlight here the fraction of b_dot due to ice cliffs (the focus of the study), and to emphasize that w_e is the least measured aspect of the chart.
Modified accordingly

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Response to anonymous referee 2

We thank referee 2 for the detailed review. In this response, the reviewer's comments are in black standard font. Our response is in standard blue font and the modifications to the manuscript are in blue bold font.

This study evaluated ablation at ice cliff of Changri, debris-covered glacier tongue using UAV-image and dem (and also Preades). They consider the emergence velocity and also evaluated several kinds of errors carefully. They concluded that recent elevation changes at tongue of Changri Glacier is mainly due to lower emergence velocities, not ablation at ice cliffs. In particular, Figure 4 and 5 are very impressive for me, because it's ideal data to analyze ablation process of debris-covered glaciers (Off course we have to consider distribution of emergence velocity). I think this result can be analyzed for other target. I'm looking forward to read other papers. I have some comments as follows. I hope my comments will help to improve your manuscript.

We thank the anonymous referee 2 for her/his positive appreciation of our work.

<Specific comments> Page2 L21 '35 (Sakai et al., 1998)' » Please refer Table 2 in Sakai et al.(2000) p = 256/26=9.8. The value 35 calculated from Sakai et al.(1998) is inaccurate value.
Modified accordingly

Page 2 L26 'but it has typically been neglected in the calculation of p.' » Which previous study neglected emergence velocity? Please address the references.
As this applies to all the studies listed in the beginning of the section, we added **", for all the above-mentioned studies."** at this sentence.

Page 2 L26 '5.7–6.4 _ 3.9 m a-1' » 6.4 _ 3.9 m a-1 is the value of mass balance in Nuimura et al.(2011)
Thanks for pointing out this mistake, it has been corrected and the correct values are now reported.

Page 2 L28-31 'Emergence velocities will affect the thinning rates of debris-covered ice and ice cliffs equally. But since the cliffs ablate at higher rate, their thinning rate is relatively less influenced than the thinning rate of debris-covered ice. As a consequence, the ratio of the cliff thinning rate divided by the mean tongue thinning rate will overestimate p.' » Those explanation is a little bit ambiguous expression. Please write more clearly.
We modified this paragraph, which now reads as: "**Neglecting the emergence velocities (i.e. comparing thinning rates instead of ablation rates) introduces a systematic overestimation of f_c. This is due to the fact that cliffs ablate at higher rate than the rest of the glacier tongue: ice cliff thinning rates are thus less influenced than the thinning rates of debris-covered ice when neglecting the emergence velocity. As a consequence, the ratio of the cliff thinning rate divided by the mean tongue thinning rate will overestimate f_c. To correctly estimate f_c and the fraction of total ice cliff net ablation, thinning rates need to be corrected with the emergence velocity.**"

Page 3 '2 Study area' »There are basic information of study area in Vincent et al.(2016). But, I recommend that ELA around the Changri glacier and altitudes (Max, min) information are necessary, here.
Modified accordingly

Page 6 L6 I cannot find out the location of cross section in Fig. 1 or 2.
We added them on the figures.

Page 7 section 4.2 and 4.3 Ice cliff is unstable. Sometimes they disappear or newly emerge in one melting season. Are there any ice cliffs diminished or emerged? And you have neglected those ice loss in this study?

The cliff outlines were updated for each year. Globally, we observed little change in the total area covered by ice cliffs (69 876, 71 826 and 69 357 ± 14 000 m² for Nov. 2015, 2016 and 2017, respectively). However, the reviewer is right and there were some substantial changes observed for individual cliffs. This is now discussed in details in section 6.1 ("**Cliff evolution and** comparison of two years of acquisition") and we added a table in the supplement (Table S2) showing the evolution of individual cliffs:

"**6.1- Cliff evolution and** comparison of two years of acquisition

The total area occupied by ice did not vary significantly from year to year, ranging from 70 ± 14 × 10^3 m^2 in November 2017 to 72 ± 14 × 10^3 m^2 in November 2016. The twelve individual cliffs surveyed showed large variations in area within the course of one year, with a maximum increase of 57 % for the large cliff 06 and a decrease of 34 % for cliff 03 and 09 (Table S2). The total area of these twelve cliffs increased by 8 % in one year. Interestingly, over the same period, Watson et al. (2017) observed only declining ice cliff area on the tongue of Khumbu Glacier (~6 km away). All the large cliffs (most of them are included in the twelve cliffs surveyed with the terrestrial photogrammetry) persisted over these two years of survey, including the south or south-west facing ones (Table 1) , although south facing cliffs are known to persist less then non south facing ones (e.g., Buri and Pellicciotti, 2018). However, we observed the appearance and disappearance of small cliffs, and marginal areas became easier to classify as either ice cliff or debris-covered areas, highlighting the challenge in mapping regions covered by thin debris (e.g., Herreid and Pellicciotti, 2018).

We calculated backwasting rates for the twelve cliffs monitored with terrestrial photogrammetry for the period November 2015-November 2016 (Table 1). The backwasting rate is sensitive to cliff area changes (because it is calculated as the rate of volume change divided by the mean 3D area) and should be interpreted with caution for cliffs that underwent large area changes (e.g., cliffs 01, 02, 03, 06, 09 and 11; Table S2). The backwasting rates ranged from 1.2 ± 0.4 to 7.5 ± 0.6 m a^{-1} , reflecting the variability in terms of ablation rates among the terrain classified as cliff (Fig. 9). The lowest backwasting rates are observed for cliffs 11 and 12, located on the upper part of the tongue, roughly 100 m higher than the other cliffs (Fig. 1 and Table 1). The largest backwasting rates were observed for cliff 01, which expanded significantly between November 2015 and November 2016. The backwasting rates are lower than those reported by Brun et al. (2016) on Lirung Glacier (Langtang catchment) for the period May 2013-October 2014, which ranged from 6.0 to 8.4 m a^{-1} and lower than those reported for surviving cliffs by Watson et al. (2017) on Khumbu Glacier for the period November 2015-October 2016, which ranged from 5.2 to 9.7 m a^{-1}. These differences are likely due to temperature differences between sites. Indeed, the cliffs studied here are at higher elevation (5320-5470 m a.s.l.) than the two other studies (4050-4200 m a.s.l. for Lirung Glacier and 4923-4939 m a.s.l. for Khumbu Glacier)."

Page 8 '4.4.1. Emergence velocity' 'The debris-covered part of the tongue has an area of 1.49 _ 0.16 km2'(Page3 line 16) The uncertainty is induced assuming that there are 20 m uncertainty in the glacier outline Vincent et al.(2016). I think estimation of the tongue area is difficult. I have never been to the Changri Glacier, therefore, I'm not sure the confidence of glacier outline at the terminus. But, in general, it is difficult to estimate outline of glacier terminus at debris-covered glacier. Then, we have to measure ice depths at two cross sections, and calculate emergence velocity between the two cross sections to avoid large error due to glacier area estimation. You can discuss.

This issue was extensively discussed in Vincent et al. (2016), who produced the glacier outline. We agree with the reviewer that debris-covered glacier outline mapping is a timely issue and consequently, we added: "**It is notoriously difficult to delineate debris-covered glacier tongues (e.g., Frey et al., 2012). In this case, we assumed an uncertainty in the outline position of ± 20 m, leading to a relative uncertainty in the glacier area of 11 %, which is higher than the 5 % of Paul et**

al. (2013). In this case, the uncertainty on the glacier outline is not the main source of uncertainty in w_e, but for automatically delineated glacier outlines, this would be an important source of uncertainty."

Page8 L13-14 ' The maximum net ablation measured with stakes within the period 2014–2016 on the tongue of Changri Nup was chosen as an upper limit equal to 2.22 m a-1' » Please explain why you can choose the maximum net ablation measured with stakes can be assumed to be the maximum emergence velocity.
For a glacier in imbalance, the ablation is higher than the emergence velocity and the glacier surface thins. Consequently, the ablation can be seen as an upper bound for the emergence velocity. In this case, we took a rather extreme value for the uncertainty on the emergence. We added:
"**For a thinning glacier, the net ablation is higher than the emergence velocity (Hooke, 2005), consequently, the net ablation can be used as a proxy for the upper bound for the emergence velocity.**"

P13 L3-23 and Fig. 10 ãˇAAˇ In this discussion, you have compared debris-covered and debris-free glaciers in equilibrium and transient (shrinking) regime. But, your target is ice loss at ice cliff. Almost assumptions are based on part of other studies. Further, I cannot accept some assumptions, Ex. ice flux is same at both debris-covered and debris-free glaciers. Usually, debris-covered glaciers are large, and debris-free glaciers is small. Further, each altitude are different. Then, I think we cannot discuss without the observation of debris-free glaciers.
The paragraph referred to by the reviewer has substantially been modified. We added the following sentence about this specific comment: **"The ice flux at the ELA is expected to be driven by accumulation processes, and consequently it is reasonable to assume similarity for both debris-covered and debris-free glaciers.**"

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Response to anonymous referee 3

We thank anonymous referee 3 for the detailed review. In this response, the reviewer's comments are in black standard font. Our response is in standard blue font and the modifications to the manuscript are in blue bold font.

— SUMMARY ———-

Brun et al. present an analysis aiming at determining the actual role of ice cliffs in the so-called "debris-cover anomaly". The analysis in performed on Changri Nup Glacier, Everest region, and combines both in-situ and remote-sensing data for a two-year period. The results are bold: The debris-cover anomaly - the authors say - does not exist, but is the result of confusion around the concepts of "thinning rates" and "net ablation". The "anomaly" – the authors explain – only comes to happen because past studies failed to account for emergence velocities. In reality, the similar thinning rates observed for debris-covered and debris-free glaciers are a result of the difference between net ablation and ice flow emergence being coincidentally similar for the two types of glaciers. As much as I agree with the first part of the interpretation, I do believe that the second part is too weakly backed-up: The authors try to generalize their field-based results in the discussion section, but the result is not convincing. Some general statements (e.g. debris covered glacier have smaller accumulation-area-ratio and are generally smaller) should be better corroborated (inventories for doing that exist by now).

A part from the above, the manuscript has a very high standard: The topic is of high relevance and actuality, the introduction is well written, the text is easy to follow, the technical analysis is clearly done by experts, the relevant literature is cited in an exemplarily manner, and the figures are illustrative. I am fully convinced that the manuscript will be an important addition to the glaciological literature once it is revised.

We thank the anonymous referee 3 for her/his positive appreciation of our work. We understand his/her concern about the disproportion between the strength of our conclusion and the weakness of the theoretical arguments we advanced. We addressed this concern by revising a large part of the discussion (see details in our response to the general comments below)

— GENERAL COMMENTS ———-

1) Sample size

The fact that all claims are built on one glacier (sample size = 1) is a clear handicap for the general conclusions the authors are aiming at. For making the point that much of the debris-cover anomaly is due to a confusion of concepts, the sample size is not an issue. This can be shown with one single example, and this is really the paper's merit. Where it becomes more difficult is when the authors stat arguing that "[for debris-covered glaciers,] the combination of reduced emergence velocities and lower ablation coincidently sum up to similar thinning rates as [for] debris-free glaciers" (p. 13, L. 19-20). Arguing for a regional-scale "coincidence" seems at least adventurous with the single data-point at hand.

I see two ways of solving this: Either (1) the authors try to get hold of published data that exist for other glaciers, or (2) they refine their theoretical argumentation (Sec. 6.3) and back up some of the as-yet little-supported claims (see next comment) with remote-sensing and inventory data.

We thank the reviewer for the two suggestions and respond to his/her comment together with the next comment.

2) "Theoretical considerations"

The "theoretical considerations" presented in Sec. 6.3 is the part of the manuscript that I found the least convincing. Unfortunately, it is the crucial one.

The problem is that the arguments seem to be much based on qualitative considerations, whilst the author's point is much focused on quantitative statements. Two examples: (1) "debris-covered glaciers have lower accumulation-area ratios than debris-free glaciers" (p. 13 L. 9). The claim is backed up with a reference (Scherler et al., 2011) but it would be ways more convincing to have some actual numbers corroborating this. These can either be re-presented from the original publication or re-compiled from inventory data and remote sensing products (I'm fully aware that the second option would be much more work-intensive). Ideally, a distribution of AARs would be shown for both debris-free and debris-covered glaciers, and the difference quantified. (2) "the glacier response time of a debris covered glacier is longer compared with a debris-free glacier (Rowan et al., 2015), therefore the clean tongue will shrink faster than the debris-covered tongue, further enhancing the difference between ADC and ADF." (p. 13 L. 15-16). Well, again, although a reference is given, it would be so much more convincing having two distributions shown, and a difference quantified. In this case, however, I'm not even sure whether this is necessary since what actually would matter are the present, actual sizes of the debris-free and debris-covered tongues – and not their response times. I think that fixing this section is the only major work that is in front of the authors.

We agree that some claims in this section 6.3 were supported only with qualitative considerations, preventing our conclusions from being convincing. We re-wrote a large part of this section 6.3 (see below) being more cautious and following the reviewer's suggestions, we also backed up our arguments with quantitative statements.
A distribution of AARs for debris-covered and debris-free glaciers could not be shown because ELAs are not available everywhere with enough accuracy. However, to quantify the fact that debris-covered tongues are most of the time larger than debris-free ones, we plotted the minimum elevation as a function of debris cover percentage for all glaciers in HMA larger than 2 km^2 (approx. 6500 glaciers) (new fig. 10, added in the revised manuscript). We can see that the larger the percentage of coverage by debris, the lower the glaciers flow, which is an indication that debris-covered glaciers have on average a larger ablation area than the debris-free glaciers. Concerning the response time, we agree that this was not backed up, and not really necessary in our analysis, and in turn it has been removed.

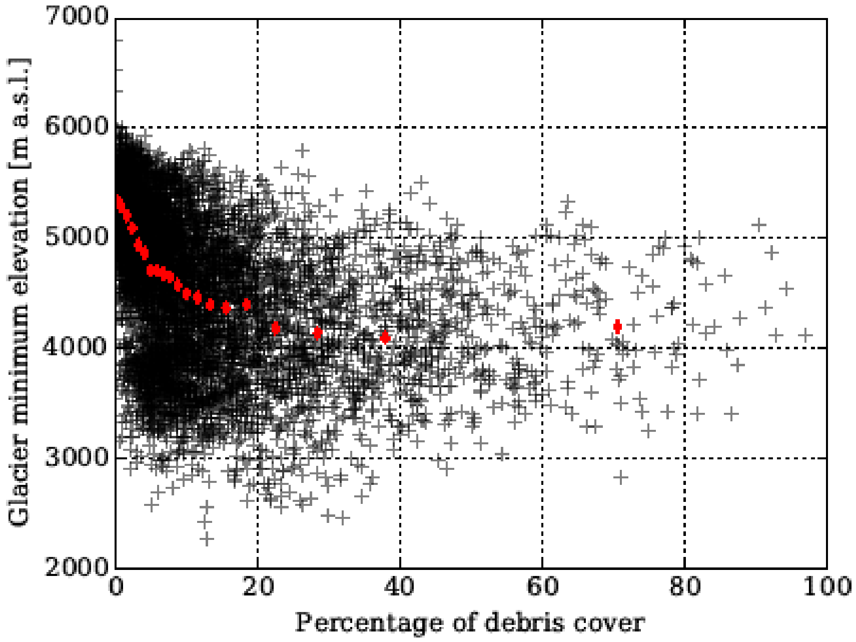

Figure 10 - Glacier minimum elevation as a function of the percentage of debris cover for the glaciers larger than 2 km^2 in High Mountain Asia (6571 glaciers in total). The black crosses represent individual glaciers and the red diamonds shows the mean of the glacier minimum elevation. For instance, the first diamond represents the mean of the glacier minimum elevation for glaciers with a percentage of debris cover between 0 (minimum) and 0.51 (5th percentile).

Revised section 6.3.:
"6.3 Ice cliff ablation and the debris-cover anomaly
Between November 2011 and November 2015, Vincent et al. (2016) quantified the reduction of area-averaged net ablation over the glacier tongue due to debris-cover. They obtained a tongue-wide net ablation of -1.2 m w.e. a^{-1} and -3.0 m w.e. a^{-1} with and without debris, respectively. As ice cliffs ablate **at -3.5 m w.e. a^{-1}, ~3.6** times faster than **the non-cliff terrain of the debris-covered tongue for the period November 2015-November 2016**, and ~1.2 times faster than the tongue if it was entirely debris-free, **approximately** 75 \% of the tongue would have to be covered by ice cliffs to compensate for the lower ablation rate under debris and to achieve the same overall ablation rate as a clean ice glacier under similar conditions. **Since ice cliffs typically cover a very limited area (Herreid and Pellicciotti, 2018), it is unlikely that they can enhance the ablation of debris-covered tongues enough to reach the level of ablation of ice-free tongues.**

Other ablation-related processes such as supra-glacial ponds (Miles et al., 2016) or englacial **ablation** (Benn et al., 2012) may contribute to higher **ablation** rates than what can be expected on the basis of the Østrem curve. Yet this does not apply to the case of Changri Nup Glacier, as Vincent et al. (2016) already showed that the debris part as a whole is responsible for a significant reduction of ablation. As a consequence, **and based on this case study, we hypothesize** that the reason for similar thinning rates over debris-covered and debris-free areas, i.e. the "debris-cover anomaly" is largely related to a combination of surface mass balance change and dynamics.

This hypothesis currently applies to the Changri Nup Glacier tongue only, and it is unclear if it can be extended to the debris cover anomaly identified at larger scales. The high quality data available for Changri Nup Glacier are not available for other glaciers at the moment, and consequently we provide a theoretical discussion below.

The mass conservation equation (e.g., Cuffey and Paterson, 2010) gives the link between thinning rate ($\frac{\overline{\partial h}}{\partial t}$ in m a^{-1}), ablation rate and emergence velocity for a glacier tongue:

$$\frac{\overline{\partial h}}{\partial t} = -\frac{1}{\rho}\dot{b} + \frac{\Phi}{A}$$

where Φ (m^3 a^{-1}) is the ice flux entering in the tongue of area A (m^2), ρ is the ice density (kg m^{-3}), and $\dot{b}$ is the area-averaged tongue net ablation (kg m^{-2} a^{-1}). **Consider two glaciers with tongues that are either debris-covered (case 1- referred hereafter as "DC") or debris-free (case 2 – referred hereafter as "DF"), and similar ice fluxes entering at the ELA i.e., $\Phi_{DC} = \Phi_{DF}$. The ice flux at the ELA is expected to be driven by accumulation processes, and consequently it is reasonable to assume similarity for both debris-covered and debris-free glaciers. There is a clear link between the glacier tongue area and its mean emergence velocity: the larger the tongue, the lower the emergence velocity. These theoretical considerations have been developed by Banerjee (2017) and Anderson and Anderson (2016), the latter demonstrating that debris-covered glacier lengths could double, depending on the debris effect on ablation in their model. Real-world evidence for such differences in debris-covered and debris-free glacier geometry remain largely qualitative. For instance, Scherler et al. (2011) found lower accumulation-area ratios for debris-covered than debris-free glaciers. Based on the data of Kraaijenbrink et al. (2017), we found a negative correlation (R = -0.36, p < 0.01) between the glacier minimum elevation and the percentage of debris cover (Fig. 10), hinting at both reduced ablation and a larger tongue for debris-covered glaciers.**

Consequently, the qualitative picture we can draw is that debris-covered glacier ablation area **is usually** larger ($\mathrm{A}_{DC} > \mathrm{A}_{DF}$), leading to lower emergence velocity ($w_{e,DC} = \Phi/\mathrm{A}_{DC} < w_{e,DF} = \Phi/\mathrm{A}_{DF}$). If the glacier is in equilibrium, in both cases, the thinning rate at any elevation is 0, because the emergence velocity compensates the surface mass balance, but with lower magnitudes for both variables (w_e and $\dot{b}$) in case of a debris-covered tongue (Fig. 11). In an unbalanced regime with consistent negative mass balances**, as mostly observed in High Mountain Asia (Brun et al., 2017)**, similar thinning rates between debris-free and debris-covered tongues could be the combination of reduced emergence velocities and lower ablation **roughly summing** up to similar thinning rates as debris-free glaciers (Fig. 11). Additionally, there are evidences of slowing down of debris-covered tongues and detachment from their accumulations area, both leading to reduction in ice flux and consequently in w_e (Neckel et al., 2017).

In conclusion, our field evidence shows that enhanced ice cliff ablation alone could not lead to a similar level of ablation for debris-covered and debris-free tongues. While we acknowledge the existence of other processes which can substantially increase the debris-covered tongue ablation, we highlight the potential important share of the emergence velocity in the explanation of the so-called 'debris-cover anomaly', which partly originates from a confusion between thinning rates and net ablation rates."

3) Introduction
A rather minor issue: The concept of "emergence velocity" is, obviously, of central importance to the paper. Since one of the main conclusions is that there is confusion around the term, I think it would make much sense to provide a clear definition in the introduction. Some indication on how the quantity is typically calculated from field data (or other types of data) may also be helpful for the one or the other reader.
We modified the method section to include a more detailed description of the emergence velocity in section 4.1. The alternative methods to measure the emergence velocity are mentioned in the discussion and in the conclusion.

— LINE-BY-LINE COMMENTS ————-
What follows is a series of line-by-line comments of various nature, ranging from comprehension questions to stylistic corrections and including some specific suggestions for issues the authors may want to think about or change.
P.2 L.14: Maybe a detail but I see a danger of the "p" being referred to as "p-value" at some stage. This would obviously be extremely misleading, since the term is reserved for something very specific in statistics.
We now name this quantity f_C and defined f_C^* which is the cliff ablation enhancement factor compared to non-cliff area (instead of the average glacier tongue).

P.2 L.15: I was confused by the mixture for plurals ("cliffs") an singulars ("cliff"). At that stage, I even briefly asked myself if "p" was something defined at the cliff-scale (i.e. one "p" for every cliff). Please avoid the confusion by using consistent wording.
Cliffs is plural, and cliff is singular. In some cases however it is necessary to use the singular to denote the singular sum of the plurals: e.g. *net ice cliff ablation* refers to ablation from all ice cliffs. We have attempted to clarify this and be consistent throughout the revised manuscript.

P.3, L15: Remove "in the same outline" (there is no danger of misunderstanding that)
Modified accordingly

P.4, L.7: "using a [not "the"] Structure from Motion algorithm"

Modified accordingly

P.5, L.13-14: I was wondering whether the relatively large offset determined for stable terrain (-7 or so meters) requires a short comment/explanation?

This offset is usual, and due to the fact that Pléiades DEMs are derived from orbital parameters only (i.e., without GCPs). Consequently, while the geometry of the DEM is robust it is somehow "floating" in the 3D space, with offsets on each components that can be up to ~10 m. We added: "**This vertical offset is expected, as the DEMs are derived from the orbital parameters only (Berthier et al., 2014)**"

P.5, L.30: "The velocities measured with Pléiades match well with the field data" –> I may have missed it, but I don't think any in-situ velocity measurements were described so far? (The only reference to such measurements seems to be at P.3 L.14, but I understood that info only to be a side note on how the glacier outline was derived in another publication?)

We clarified this point: "The velocities measured with Pléiades match well with the field data **(ablation stake displacements measured with a DGPS between November 2015 and November 2016)**, with the…"

P.6, L15-16: Can a word be spent in discussing the implication of assuming a homogeneous w_e? That quantity is a distributed field, and I have the impression that assuming a similar w_e for all ice-cliffs that are considered is an important assumption? Some discussion is found later, but here is where the question arises

We added: "**It is noteworthy that some spatial variability is expected for w_e, however, we have no means to assess it.**"

P.6, L.26: I'm not sure to understand what "deformed" means in this case. "Deformed" how?

"deformed" meant non homogeneous of the individual points of the PCs: "we deformed the PCs, **by displacing its individual points,** for…"

P.7, L.19-20. I found the concept of analogous points somewhat abstract. Would it make sense to provide a figure with a visual example?

We added a supplementary figure (fig. S5) showing this:

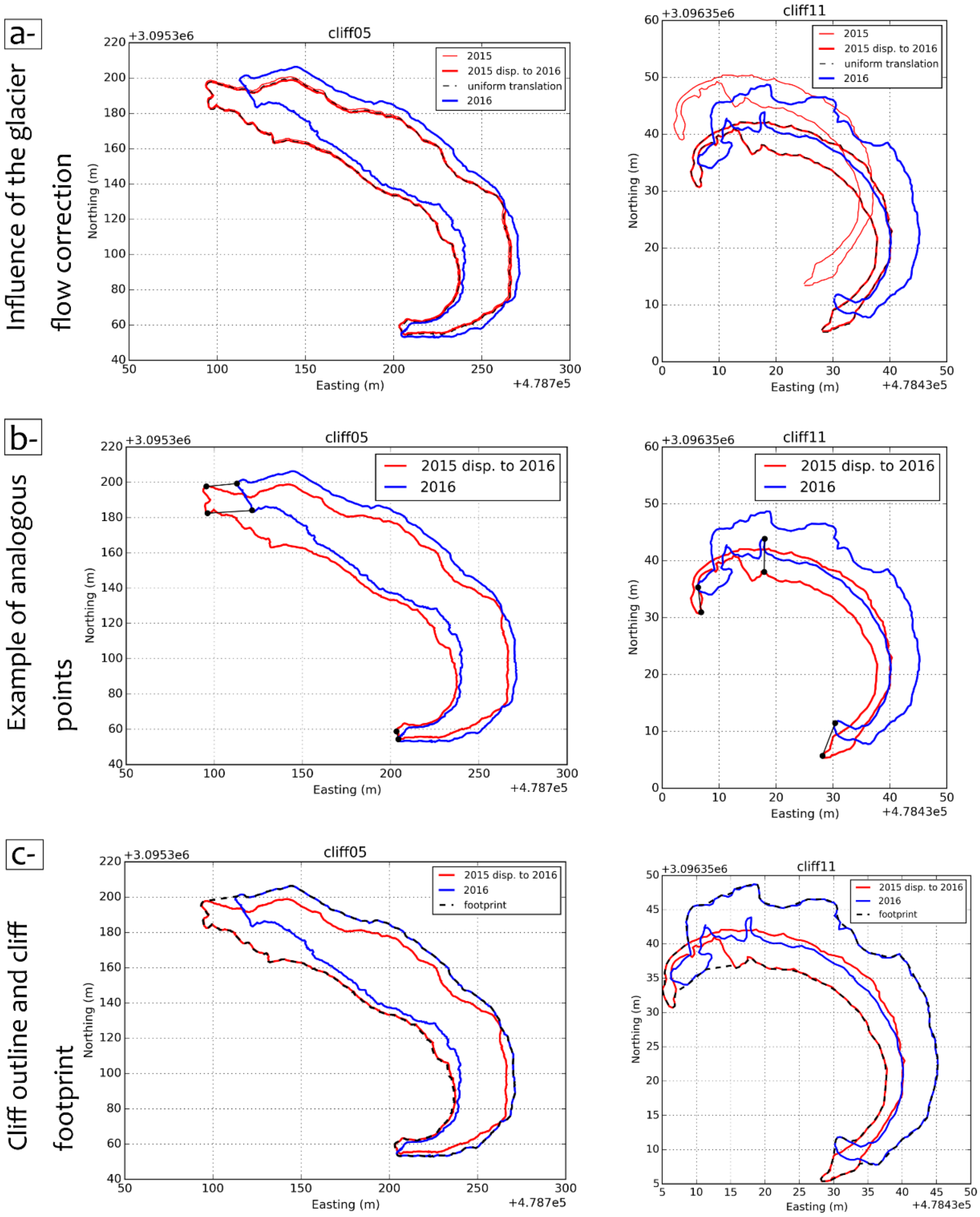

Fig. S5 - Examples of the methodological processing for cliff 05, located on a slow flowing area (left panels) and cliff 11, located in a fast flowing area (right panels). For all the panels the cliff outlines are represented in UTM45/WGS84. a- influence of the glacier flow correction, and comparison with a uniform translation. B- example of analogous points needed for the triangulation regularization. c- difference between the individual cliff outlines and the cliff footprint needed to calculate the cliff contribution for gridded data (DEMs).

P.8, L.2-3: Also in this case, a visualization would probably make it easier to understand what is meant exactly.

See the figure above

P.9, L.26-27: “We experimentally determined L = 150 m for the UAV and L = 150 m for the Pléiades data” –> “We experimentally determined L = 150 m for both the UAV and Pleiades data” (or should one of the two “150” read something else?)
Modified accordingly

P.11, L.9: The unit of -3.88+/-0.27 is missing
Modified accordingly

P.11, L.10: Here and elsewhere: In light of the estimated uncertainty, it would make sense to state 440+/-54 x 10ˆ3 m3/a (instead of 439 689 +/- 54 000 m3/a).
Modified accordingly

P.11, L.26: I’m not following: Is the stated value (1.51+/-0.21 m/a) already corrected for emergence?
Yes, we added: “**after correction for the emergence**”

P.12, L.7-8: The last part of the sentence is rather involved. Can’t you simply say that the cliffs seem to contribute a constant share to the total ablation?
Modified accordingly

P.12, L.14: Here and below: Consider replacing “original” with “actual”.
Modified accordingly

P.12, L.15: Remove “Doing the same”.
Modified accordingly

P.12, L.17: Replace “emergence velocity” with “ice flow emergence” (saying “the influence of velocity” sounds somewhat odd).
Modified accordingly

P.12, L.24-25 An alternative (simpler?) wording would be “Since ice cliffs typically cover a very limited area, thus, it is unlikely that they can explain the debris-cover anomaly."
The new sentence reads: “Since ice cliffs typically cover a very limited area (Herreid and Pellicciotti, 2018), it is unlikely that they can enhance the ablation of debris-covered tongues enough to reach the ablation of ice-free tongues.”

P.12, L.27: Check the wording: “englacial hydrology” is not an "ablation-related processes" (it’s rather a "discipline", as e.g. glaciology)
Modified accordingly

P.12, L.28, sentence starting with “.Yet this does not: : :” –> Split the sentence somewhere; it is very long.
Modified accordingly

P.13, L.1-23: This is the part that really needs revision.

P.13, L.7: The unit of “density” should be kg/m3 (not m2)
Modified accordingly

P.13,L.10: Well, the comparison is somewhat "cheated", as it should certainly include areas of the same size.
This section was largely modified, please refer to the new version at the beginning of this response.

P.13, L.12: Not entirely sure what “both variables” is referring to. To mass balance and emergence velocity?
This section was largely modified, please refer to the new version in the beginning of this response.

P.13, L.20: If I read this correctly, you imply that the similar thinning rates for debris-free and debris-covered glaciers are only observed now, and that this was different in the past and will be different in the future. Is this correct? If so, state that explicitly.
We do not claim this. We just try to reason within a transient framework that is somehow close to the recent situation (i.e., corresponding to the geodetic observations of the last decades).

P.13, L.30-31: I don’t understand the sentence. Especially the two "in" within the parenthesis create confusion.
This section was removed according to reviewer’s 1 comment.

P.13, L.32: Why "nevertheless"? What’s the logical link to the previous sentence?
This sentence has been moved to section 6.1 and “nevertheless” has been removed.

P.14, L.2: “i.e. the p factor defined in this study” should live in a parenthesis (the sentence is difficult to understand at the moment). Also try to split the sentence as it is very long.
Modified accordingly

P.14, L.5: “models [: : :] are not directly comparable with the observations” –> Explain (or at least give a hint) why not.
“For instance, the f_C values from models (Buri et al., 2016; Juen et al., 2014; Reid and Brock, 2014; Sakai et al., 1998) are not directly comparable with the observations (Brun et al., 2016; Thompson et al., 2016), **because they usually require additional assumptions about e.g., the sub-debris ablation or emergence velocity**.”

P.14, L.5: Not sure to understand what you mean with "flow components". Please clarify. In light of the claims provided above, moreover, I’m not sure to understand the latter part of the sentence (the one that “advocates for a more consistent framework”). This may be clearer after revision.
We removed this sentence.

P.14, L.10: As much as I agree with the statement, I don’t think it is appropriate making it “yours”: Geophysicists are working on that since years, after all.
“More field campaigns dedicated to ice thickness and velocity measurements (Nuimura et al., 2011, 2017) or the development of airborne ice thickness retrievals through debris **are needed, as stressed by the outcome of the Ice Thickness Models Intercomparison eXperiment (Farinotti et al., 2017).**”

P.14, L.16: “or englacial conduits” –> That’s a very speculative claim, isn’t it? I would suggest to flag it as such.
“Other contributions, such as ablation from supra-glacial lakes**, or even from englacial conduits**, are potentially…”

P.14, L.18: “we hypothesize that” –> In the last section (Sec. 6) the claims were stated in a much more decided way. Why this caution here? The text should be coherent in what the level of trust in the results is concerned.
We adjusted the rest of the manuscript on the level of confidence of the conclusion.

P.14, L.18-19: “the debris-cover anomaly could be a result of lower emergence velocities and reduced ablation” –> This is basically the main claim of the paper. Whether it is suitable of having it in the conclusion section or not very much depends on how convincing Sec. 6 will be after revision.

Ok

P.14, L.22: ": : :our suggested framework would inform estimates of ice cliff ablation: : :" –>not sure to understand how "inform" is used here. Can you reword?
"A comparison of f_C or f_C^* values calculated for other debris-covered glaciers under our suggested framework would be informative, in order to compare estimates of ice cliff ablation for other and potentially much larger debris-covered tongues."

P.14, L.24: "[: : : it] is required to include these results into debris-covered glacier mass balance models" –> I'm not entirely sure but it looks like you advocate for mass balance models to include a "p"-factor? If this is actually your message, please be more explicit in saying that.
This sentence was not really clear in the original manuscript. It is revised as: "**It would be very worthwhile to obtain longer-term and multiple sites quantification of the relative ice-cliff contribution to net ablation. Then a compilation of these data would allow developing empirical relationships for cliff enhanced ablation, which could be included into debris-covered glacier mass balance models.**"

P.14, L.28-29: If what I understood the message correctly, the sentence could be adjusted to "Two research directions could be (a) to extensively measure ice thicknesses and (b) to install networks of stake measurements to assess the spatial variability of ice flow emergence."
Modified accordingly

— COMMENTS TO FIGURES ————-
Fig. 1: (a) The red box in the upper-right inset is misleading, since it is not the part enlarged in the main figure. Consider replacing it with a red dot or similar. (b) Last parenthesis of the caption: Why "measured"? (The word can simply be removed.)
Modified accordingly

Fig. 2: Please tell what coordinates are used. The black line is the same as the red-dashed one in Fig. 1, I guess? (Readers shouldn't be guessing ;-))
Modified accordingly

Fig. 3: (a) In the caption, spell out what U_s, w_s, etc are. (b) "Local slope" is misleading; it looks more like the local tangent of the surface (and my guess is that "nalpha =local slope").
Modified accordingly

Fig. 4+5: (a) Can the colour-bar be stretched and more values be added? At the moment, it is difficult to tell what colour corresponds to, e.g. -2.5 m. (b) What is the meaning of "raw" in "raw elevation change"? (c) Please indicate the time span between the UAV surveys (or the dates of the surveys as such). (d) "from flow for" –> Do you mean "for iceflow from"? (e) For consistency, the last sentence should read "Zoom in the dashed rectangle of panel a (c,d)".
Modified accordingly

Fig. 6: (a) Please (re-) state what "normalized" means in this case. (b) State the period over which the changes refer to. (c) "In the latter" –> "In panel b" (d) "because it is more than 150%" –> "(since the value is >150%)"
Modified accordingly

Fig. 7: State the period over which the changes refer to.
Modified accordingly

Fig. 8: The red markers should be crosses (area), and not dots (volume).

Modified accordingly

Fig. 10: (a) Please simplify the third sentence (the one starting with “In the transient state,: : :”). As far as I understand, it simply means that all but the blue w_e are taken from Vincent et al (2016)? (b) “ratio of net ablation” –> Not sure to understand that. A “ratio” is between something and something else, I would say.

Modified accordingly

Tab. 1: (a) “A_SD” never shows up in the table. Thus, no need of introducing the symbol. (b) “The main aspects” –> Why plural? If there is a share of aspects implied in what the table shows, please state that.

The cliffs exhibit multiple aspects. We made this point clearer in the revised version.

Tab. 2: (a) I don’t understand the meaning of the reference. Just remove? (b) Please explain in the caption what "virtual" means. (c) In the caption, provide a hint for why some values are “N/A”.

This is clarified in the revised version.

Tab. 3: What is “B/H”? The caption should tell.

It means “base to height ratio”, it was added in the caption.

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Response to anonymous referee 4

We thank the referee 4 for the detailed review. In this response, the reviewer's comments are in black standard font. Our response is in standard blue font and the modifications to the manuscript are in blue bold font.

Summary:
The authors estimate the total ablation associated to supraglacial ice cliff melt on the debris-covered tongue of Changri Nup Glacier, Nepalese Himalaya, based on high resolution topographical data. They use terrestrial photogrammetry surveys on selected cliffs for validation and UAV- and satellite-imagery for the entire cliff population on that glacier for two consecutive years. They then derive the contribution of ice cliff melt relative to glacier melt on the tongue of Changri Nup Glacier by taking into account emergence velocity and estimate ice cliff melt to be ~3 times higher than the average melt of the glacier tongue. They conclude that ice cliffs cannot explain the debris-cover anomaly and that the anomaly in turn could be a result of lower emergence velocities and reduced ablation.

General comments:
The main outcome of this study is that UAV- and especially high-resolution satellite imagery can be used to estimate glacier-wide volume losses associated to ice cliff melt, as the authors showed by a sophisticated analysis of various topographic datasets. The second important conclusion of the study is the fact that emergence velocities have so far not been considered carefully enough in terms of glacier ablation estimates and should be investigated further. However, as much as I appreciate the topic of the paper including all its careful analysis, I think the authors' main conclusion of explaining the debris-cover anomaly with reduced emergence velocities in general is not appropriate and a bit out of the context of the paper, given the limited sample size of just one glacier tongue. I suggest the authors adapt the title accordingly and focus more on the nice outcome of the cliff volume loss estimates at the glacier scale, especially in the discussion of the manuscript. Further, I think the balance between ice cliffs and emergence velocity is not given, as the main part of the paper regarding methods description and results, is mostly about ice cliffs and in contrast the discussion/conclusion part is mostly about emergence velocities. The processing of the ice cliff data is well described in general and the results are elaborated carefully by taking into account uncertainties. I miss a better description of one of the key improvements compared to an earlier study, the correction for distortion. Further, I am not convinced that the calculation of the p-factor is feasible or should be done in a different way. All in all my impression of the paper in terms of quality, writing, and relevance in the context of the actual literature is good and it fits into the scope of The Cryosphere, but I have major comments that should be addressed. If these are addressed, I am sure the paper will be a useful contribution to the glaciological community. See further comments below.
We thank referee 4 for her/his positive appreciation of our work. See our response to the comments below.

Main issues:

1) Explanation of "debris-cover anomaly"

I like that you bring the emergence velocity component into the focus of the analysis and interpretation of debris-covered glaciers. It is clear that this upward movement of parts of the glacier tongue has been neglected so far in most of the studies related to debris-covered glaciers especially. In the case of Changri Nup Glacier the emergence velocity is, based on your observations, very small and thus similar downwasting rates of debris-free and debris-covered glacier surfaces might be explained by this differential emergence. However, I am not convinced by the reasoning of the authors to generalize this result and explain the debris-cover anomaly solely by the confusion of glacier elevation changes and net ablation. It is not clear if Changri Nup Glacier has ablation rates similar to that of debris-free glaciers (of the same elevation range) at all, but this would be the case for the debris-cover anomaly.

The "debris cover anomaly" (i.e. similar thinning rates over debris-covered and debris free glaciers at similar elevations, although ablation is expected to be reduced over debris covered glaciers compared with debris-free glaciers) is to our opinion an interesting but fuzzy concept, which has been used to motivate previous studies that looked for processes responsible for enhanced ablation on debris-covered tongues. Based on the data of Brun et al. (2017), we show that the thinning rates of debris-covered areas are comparable to thinning rates of debris-free areas for glaciers in the Khumbu region (Figure R1). The thinning rate of Changri Nup Glacier agrees well with this regional pattern and therefore we do conclude that the tongue of Changri Nup Glacier is a representative "debris-anomaly" glacier.

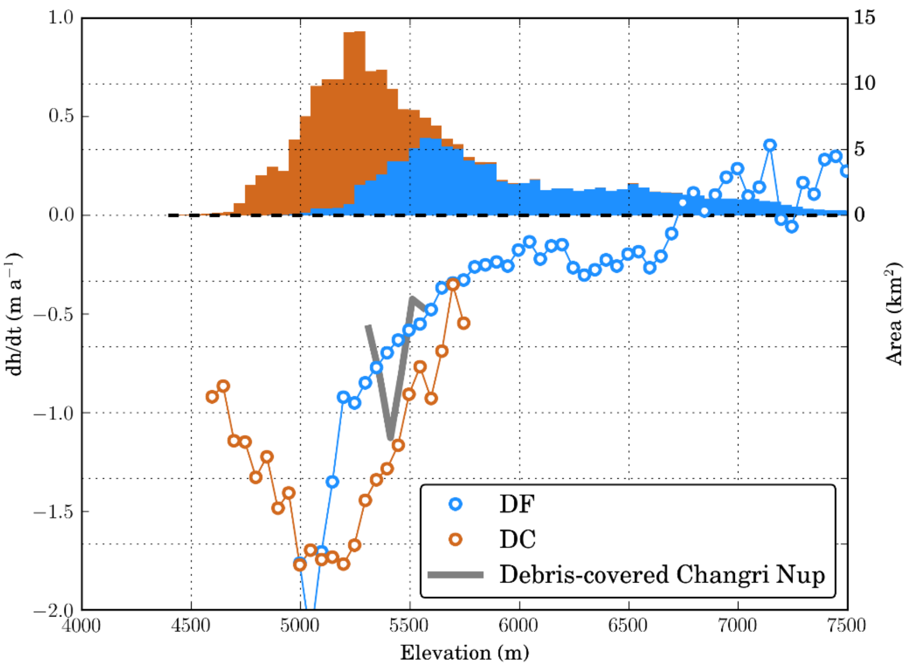

Figure R1: rate of elevation change for debris-free and debris-covered ice in the Khumbu region, based on Brun et al. (2017) data. . The brown histogram represents the hypsometry of the debris-covered ice and it is stacked above the blue histogram, which represents the hypsometry of the debris-free ice. The thinning rate for the debris-covered part of Changri Nup is overlaid in grey.

For sure emergence is an important component and might explain many issues related to this topic. But I think, just based on one single glacier making a general conclusion is too ambitious and therefore the title of the manuscript should be adapted accordingly, away from the debris-cover anomaly more towards the volume loss of the ice cliffs. The study still presents interesting points and provides nice results, such as: estimation of the volume loss associated to ice cliff melt at the glacier scale; incorporating rotational behavior of ice cliffs in volume loss estimates; sophisticated comparison to net ablation by taking into account also glacier emergence.

We agree with the reviewer's comment and now avoid unsupported generalization, as also recommended by other reviewers. Consequently, the title of the manuscript was revised and now reads: "**Ice cliff contribution to the tongue-wide ablation of Changri Nup Glacier, Nepal, Central Himalaya**". Additionally, section 6.3 regarding the debris-cover anomaly has been mostly rewritten, with much more caution regarding the generalization of our conclusions.

The manuscript now focuses more on the cliff evolution and contribution to tongue-wide ablation. Indeed, we extended the discussion section 6.1 (“**Cliff evolution and** comparison of two years of acquisition”) and we added a table in the supplement (Table S2) showing the evolution of individual cliffs:

“The total area occupied by ice did not vary significantly from year to year, ranging from 70 ± 14 × 10^3 m^2 in November 2017 to 72 ± 14 × 10^3 m^2 in November 2016. The twelve individual cliffs surveyed showed large variations in area within the course of one year, with a maximum increase of 57 % for the large cliff 06 and a decrease of 34 % for cliff 03 and 09 (Table S2). The total area of these twelve cliffs increased by 8 % in one year. Interestingly, over the same period, Watson et al. (2017) observed only declining ice cliff area on the tongue of Khumbu Glacier (~6 km away). All the large cliffs (most of them are included in the twelve cliffs surveyed with the terrestrial photogrammetry) persisted over these two years of survey, including the south or south-west facing ones (Table 1) , although south facing cliffs are known to persist less then non south facing ones (e.g., Buri and Pellicciotti, 2018). However, we observed the appearance and disappearance of small cliffs, and marginal areas became easier to classify as either ice cliff or debris-covered areas, highlighting the challenge in mapping regions covered by thin debris (e.g., Herreid and Pellicciotti, 2018).

We calculated backwasting rates for the twelve cliffs monitored with terrestrial photogrammetry for the period November 2015-November 2016 (Table 1). The backwasting rate is sensitive to cliff area changes (because it is calculated as the rate of volume change divided by the mean 3D area) and should be interpreted with caution for cliffs that underwent large area changes (e.g., cliffs 01, 02, 03, 06, 09 and 11; Table S2). The backwasting rates ranged from 1.2 ± 0.4 to 7.5 ± 0.6 m a^{-1} , reflecting the variability in terms of ablation rates among the terrain classified as cliff (Fig. 9). The lowest backwasting rates are observed for cliffs 11 and 12, located on the upper part of the tongue, roughly 100 m higher than the other cliffs (Fig. 1 and Table 1). The largest backwasting rates were observed for cliff 01, which expanded significantly between November 2015 and November 2016. The backwasting rates are lower than those reported by Brun et al. (2016) on Lirung Glacier (Langtang catchment) for the period May 2013-October 2014, which ranged from 6.0 to 8.4 m a^{-1} and lower than those reported for surviving cliffs by Watson et al. (2017) on Khumbu Glacier for the period November 2015-October 2016, which ranged from 5.2 to 9.7 m a^{-1}. These differences are likely due to temperature differences between sites. Indeed, the cliffs studied here are at higher elevation (5320-5470 m a.s.l.) than the two other studies (4050-4200 m a.s.l. for Lirung Glacier and 4923-4939 m a.s.l. for Khumbu Glacier).”

2) Calculation of p

I am not sure if your calculation of the p ratio makes much sense. Like this you compare ice cliff melt to the melt of the entire debris-covered glacier tongue. This means you compare ice cliff melt to a mixture of subdebris- and ice cliff melt (the glacier tongue). Wouldn’t it be more feasible to compare ice cliff melt to subdebris melt (i.e, exclude ice cliff areas)? In order to be comparable to the previous studies you cited, you should check if they also compared ice cliff melt to the ice cliff-subdebris mixture or to subdebris melt only.

This point was also mentioned by other reviewers, consequently the *p* factor is now named f_C factor to avoid a confusion with the “*p*-value”. The f_C factor has the same definition as *p*, but we added the definition of a new factor, named f_C^*, which is the ratio of the cliff ablation divided by the non-cliff ablation (denoted by the subscript NC):

$$f_C^* = \frac{\Delta V_C}{A_C}\frac{A_{NC}}{\Delta V_{NC}} = f_C\,\frac{\Delta V_T}{\Delta V_T - \Delta V_C}\,\frac{A_T - A_C}{A_T}$$

Based on our data, for Changri Nup Glacier, $\frac{\Delta V_T}{\Delta V_T - \Delta V_C} = \frac{1}{1-0.23} = 1.30$ and $\frac{A_T - A_C}{A_T} = \frac{1-0.07}{1} = 0.93$, consequently $f_C^* = 1.2\, f_C$.

For the consistency between the studies mentioned, we interpreted the studies as follow:

- Juen et al. 2014 : "Although the ice cliffs occupy only 1.7% of the debris covered area, the melt amount accounts for approximately 12% of the total sub-debris ablation" -> $f_C^* = \frac{12}{1.7} = 7.1$
- Reid and Brock 2014: "Analysis of the DEM indicates that ice cliffs account for at most 1.3% of the 1m pixels in the glacier's debris-covered zone, but application of a distributed model indicates that ice cliffs account for ~7.4% of total ablation." -> $f_c = \frac{7.4}{1.3} = 5.7$
- Buri et al. 2016: "Although only representing 0.09% of the glacier tongue area, the total melt at the two cliffs over the measurement period is 2313 and 8282m3, 1.23% of the total melt simulated by a glacio-hydrological model for the glacier's tongue. -> $f_c = \frac{1.23}{0.09} = 13.7$
- Sakai et al 1998: From the abstract: "The ice cliff melt amount reaches 69% of the total ablation at debris covered area, although the area of ice cliffs occupies less than 2% of the debris covered area" -> $f_c = \frac{69}{2} = 35$
- Sakai et al 2000: From their Table 2: ratio of the "absorbed heat at each type of surface during the observation period (167 days)", including the "whole debris-covered zone" -> $f_c = \frac{256}{26} = 9.8$ or looking only at the debris -> $f_C^* = \frac{256}{21} = 12.2$
- Brun et al 2016: "The ice cliffs lose mass at rates six times higher than estimates of glacier-wide melt under debris, which seems to confirm that ice cliffs provide a large contribution to total glacier melt." -> $f_c = 6$
- Thompson et al 2016: "Although ice cliffs cover only ~5% of the area of the lower tongue, they account for 40% of the ablation." -> $f_c = \frac{40}{5} = 8$

As most of the studies were already within the framework of the original definition of p/f_C, we decided to keep the focus on this factor, instead of f_C^*. This example demonstrates the importance of a consistent framework for comparing these studies.

Consequently, we decided to present both factors f_C and f_C* in the revised manuscript, in order to avoid any confusion.

Also, it is not clear how many ice cliffs you detected on the entire debris-covered glacier tongue in both seasons, does this number vary? Did you observe the formation of new features over time or disappearance of them? This might also affect the p ratio, in case the cliff areas are not excluded in its calculation.
We added some information regarding the year-to-year evolution of the cliffs, in section 6.1 (see above). For the calculation of the factors f_C and f_C* we used the cliff footprint. Consequently, the dynamic changes in the cliff areas are taken into account.

Additionally, could you derive melt rates for the cliff surface (perpendicular to their surface) instead of pure elevation change rates? This would be helpful in order to compare your results to previous studies.
We added the backwasting distance in Table 1. We calculated it as individual cliff volume loss from terrestrial photogrammetry (i.e., only for the period Nov. 2015 – Nov. 2016), because this is the acquisition for which we know the mean cliff 3D area. The backwasting rate is compared with other studies in section 6.1.

3) Correction with local field of displacement

From the text I cannot follow how the rotational component of the ice cliffs/glacier surface are implemented in the calculations of the ice cliff volume changes (Section. 4.2). Since this is a main improvement of this study compared to an earlier one using a similar method, much more emphasis should be given to explain this implementation. How do you use the local field of displacement? Where does the 3D flow field that you use for the correction come from? This is a key comment that should be addressed for the paper clarity. A schematic figure would be helpful. Also, can you estimate how much the difference is compared to the previous method used in Brun et al. 2016? More importantly, can you validate the new method to show that it is appropriate and sound? From the short description provided: i) the method cannot be reproduced; ii) there is no evidence that it is the correct approach. You should discuss this new method in the discussion part of the manuscript, as it seems to be a clear advancement from previous studies, where a simple homogeneous direction of displacement was assumed.

Actually, taking into account the heterogeneity in the field of displacement has only little effect on the outcomes, because finally in our case study of Changri Nup Glacier, the rotational effect is limited. We added a supplementary figure (Fig. S5, see below) showing this. We added: "**This would be an important methodological refinement for ice cliffs on fast flowing glaciers with a rotational component, but has minor influence for the cliffs of interest in this study (Fig. S5)**". The main interest on this new method is its ability to handle gridded data, while the method of Brun et al. (2016) worked only with 3D (TINs) data. Taking into account the rotational effect is still an important improvement compared with Brun et al. (2016) especially if the method is used on fast moving and turning glaciers, which is not the case on Changri Nup or on Lirung glaciers (this study and Brun et al., 2016). Figure S5 helps also to visualize the method's development as well.

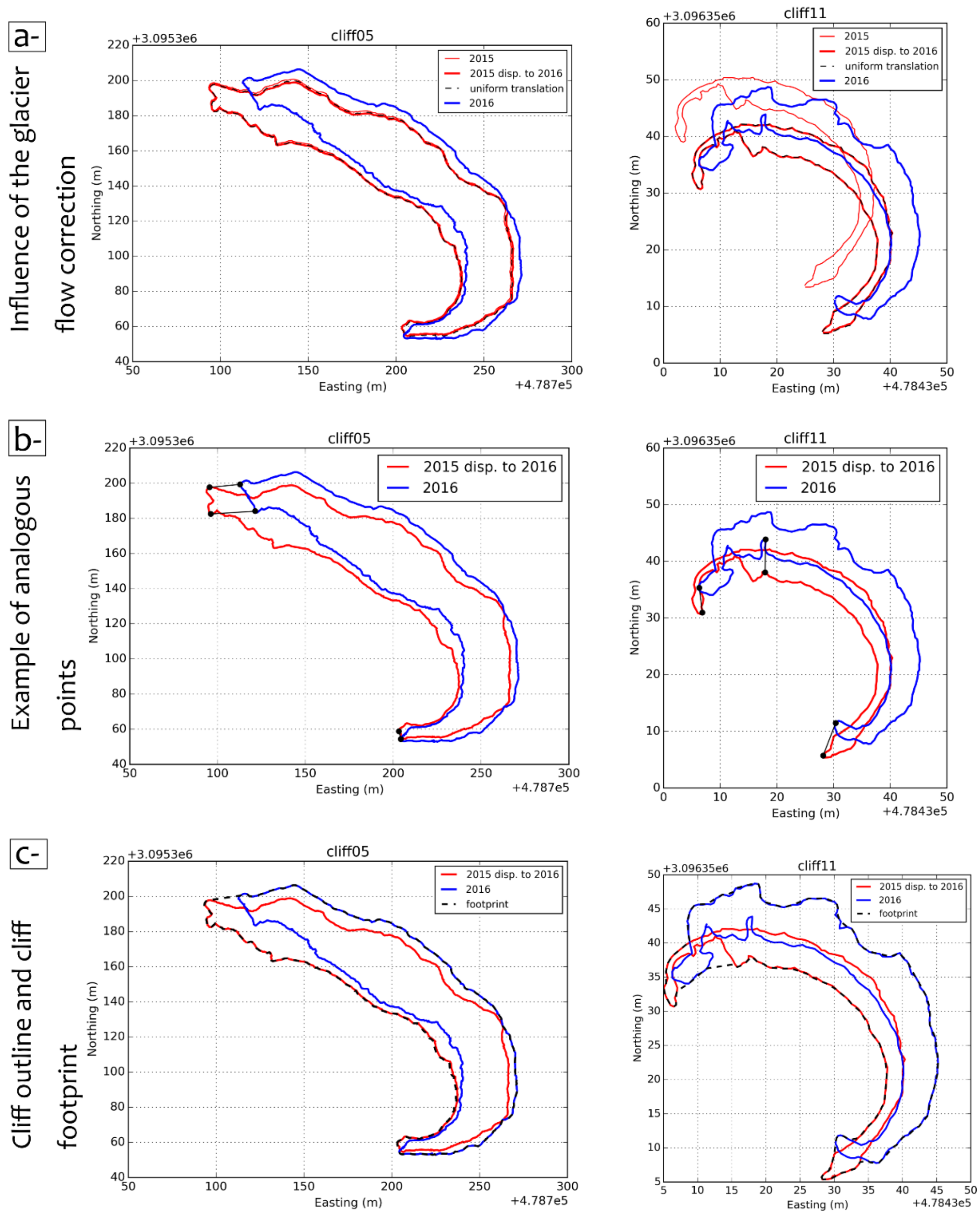

Fig. S5 - Examples of the methodological processing for cliff 05, located on a slow flowing area (left panels) and cliff 11, located in a fast flowing area (right panels). For all the panels the cliff outlines are represented in UTM45/WGS84. a- influence of the glacier flow correction, and comparison with a uniform translation. B- example of analogous points needed for the triangulation regularization. c- difference between the individual cliff outlines and the cliff footprint needed to calculate the cliff contribution for gridded data (DEMs).

4) Uncertainty of emergence velocity assumptions

As mentioned above in the general comments, the balance between ice cliff associated melt estimates and emergence velocity assumptions is not well elaborated in the manuscript. E.g. I miss a more in depth discussion of the uncertainties related to the calculation of the emergence velocities in the methods section, such as the one associated with having only one cross section profile for glacier thickness estimates, or general uncertainties in ice flux assumptions (glacier thickness measurements, bed topography, subglacial conditions, distribution of emergence etc.). As stated in line 19, p.10, “the main source of uncertainty on the cliff volume change is the uncertainty on the emergence velocity”, but this is not discussed later on in the text.

We added a paragraph about the uncertainty in the calculation for the emergence velocity (section 4.1):

“The emergence velocity refers to the upward flux of ice relative to the glacier surface in an Eulerian reference system (Cuffey and Paterson, 2010). For the case of a glacier in steady-state (i.e., no volume change at the annual scale), the emergence velocity balances exactly the net ablation for any point of the glacier ablation area (Hooke, 2005). For a glacier out of its steady state (as Changri Nup Glacier) the thinning rate observed in the ablation area is the sum of the net ablation and the emergence velocity (Hooke, 2005). On debris-covered glaciers, while the thinning rate is relatively straightforward to measure from DEM differences, for example, the ablation is highly spatially variable and difficult to measure (e.g., Vincent et al., 2016). In order to evaluate the mean net ablation of Changri Nup Glacier tongue from the thinning rate, we estimate the mean emergence velocity (w_e) for the period November 2015-November 2016 and for the period November 2016--November 2017 using the flux gate method of Vincent et al. (2016). As the ice flux at the glacier front is 0, the average emergence velocity downstream of a cross-section can we calculated as the ratio of the ice flux through the cross-section (Φ in m^3 a^{-1}), divided by the glacier area downstream of this cross-section (A_T in m^2):

$$w_e = \frac{\Phi}{A_T}$$

This method requires an estimate of ice flux through a cross-section of the glacier, and is based here on measurements of ice depth and surface velocity along a profile upstream of the debris-covered tongue (Figs. 1 and 2). The ice flux is the product of the depth-averaged velocity ($\bar{u}$ in m a^{-1}) and the cross-sectional area. For the period November 2015-November 2016 (resp. November 2016-November 2017), the glacier slowed down compared with the 2011-2014 period and the centerline velocity was equal to 10.8 m a^{-1} (resp. 11.1 m a^{-1}), leading to an assumed mean surface velocity along the upstream profile of 8.1 ± 0.6 m a^{-1} (resp. 8.3 ± 0.6 m a^{-1}), as the centerline velocity is usually 70 to 80 % of the mean surface velocity along the cross-section (e.g., Azam et al., 2012; Berthier and Vincent, 2012). We used the relationship between the centerline velocity and the mean velocity, instead of an average of the velocity field along the cross section, because the image correlation was not successful on a relatively large fraction (~ 30 %) of the cross section. Converting the surface velocity into a depth-averaged velocity requires assumptions about e basal sliding and a flow law (Cuffey and Paterson, 2010). Little is known about the basal conditions of Changri Nup Glacier, but Vincent et al. (2016) assumed a cold base, and therefore no sliding. This leads to $\bar{u}$ being approximated as 80 % of the surface velocity, additionally assuming n = 3 in Glen's flow law (Cuffey and Paterson, 2010). As an end-member case, assuming that the motion is entirely by slip implies $\bar{u}$ equals to the surface velocity (Cuffey and Paterson, 2010). Consequently, we followed Vincent et al. (2016) and assumed no basal sliding, but we took the difference between the two above-mentioned cases as the uncertainty on $\bar{u}$. This leads to $\bar{u}$ = 6.5 ± 1.6 m a^{-1} (resp. 6.6 ± 1.7 m a^{-1}) for the period November 2015-November 2016 (resp. November 2016-November 2017).

Assuming independence for the cross-sectional area (σ_S) and the depth-averaged velocity ($\sigma_{\bar{u}}$), the uncertainty on the ice flux (σ_Φ) can be estimated as:

$$\frac{\sigma_\Phi}{\Phi} = \sqrt{\frac{\sigma_{\bar{u}}}{\bar{u}}^2 + \frac{\sigma_S}{S}^2}$$

Given the above mention values for the depth-averaged velocity, the cross-sectional area and the associated uncertainties, the relative uncertainty of the ice flux is ~30 %. As a result, for the period

November 2015-November 2016 (resp. November 2016-November 2017), the incoming ice flux was thus 499 700 ± 150 000 m^3 a^{-1} (resp. 503 840 ± 150 000 m^3 a^{-1}). The glacier tongue area was considered unchanged at 1.49 ± 0.16 km^2, corresponding to w_e = 0.33 ± 0.11 m a^{-1} (resp. 0.34 ± 0.11 m a^{-1}). It is notoriously difficult to delineate debris-covered glacier tongues (e.g., Frey et al., 2012). In this case, we assumed an uncertainty in the outline position of ± 20 m, leading to a relative uncertainty in the glacier area of 11 %, which is higher than the 5 % of Paul et al. (2013). In this case, the uncertainty on the glacier outline is not the main source of uncertainty in w_e, but for automatically delineated glacier outlines, this would be an important source of uncertainty. The updated emergence velocity is ~20 % lower than estimated for the 2011-2015 period (Vincent et al., 2016), due to both the thinning and deceleration of the glacier. As the difference in w_e between November 2015-November 2016 and November 2016-November 2017 is insignificant, we consider $w_e$to be constant and equal to w_e= 0.33 ± 0.11 m a^{-1} for the rest of this study. It is noteworthy that some spatial variability is expected for w_e, however, we have no means to assess it."

Also, the reduction in emergence velocity of _20% compared to the period 2010-2015 (line 16, p. 6) is striking, isn't it? Can you try to explain it more convincingly? If glacier emergence is so (relatively) variable, this might also have implications on your assumption of generally explaining the debris-cover anomaly by lower emergence velocities.

This reduction in emergence velocity is likely due to negative mass balances over this 2010-2017 period. Indeed, over the period 2010-17, we observe a strongly continuous negative glacier-wide mass balance of the debris-free West Changri Nup glacier of -1.36 m w.e. yr^{-1} (-1.24 m w.e. yr^{-1} between 2010 and 2015 from Sherpa et al., 2017; and unpublished data from P. Wagnon, for the period 2015-2017). Since Changri Nup and West Changri Nup glaciers are located near-by and since the time lag between negative surface mass balances and decreasing velocities is expected to be short (Vincent et al., 2000), the reduction in velocity between 2010-15 and 2015-17, and as a consequence in emergence velocity, is not surprising on Changri Nup glacier.
Nevertheless, we agree that the emergence velocity is likely to be variable both in time and space over Changri Nup Glacier (and elsewhere), but we do not have any clue to quantify this variability. That is the reason why we performed a sensitivity test over this emergence velocity, using a very large range of possible values (section 4.3.1 and fig. 6).

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Summary of the response to the four reviewers' comments

We thank the scientific editor and the four reviewers for their detailed reviews of our article submitted to The Cryosphere. The main improvements in the manuscript are:

- As suggested by reviewer 3, we processed additional data in order to improve the discussion section about the debris cover anomaly (section 6.3). The discussion section 6.3 has been substantially modified (see below and see the detailed responses to each of the reviewers' comments), in particular we are now more careful about the generalization of our findings. However, we added a figure (fig. 10) showing the minimum glacier elevation as a function of the debris cover percentage (based on the data of Kraaijenbrink et al., 2017). The minimum glacier elevation decreases with the percentage of debris cover. We interpret this relationship as an indirect hint that debris-covered tongues are larger than debris-free tongues and that the ablation is reduced on these debris-covered tongues, because they can exist at lower elevation than the debris-free tongues.

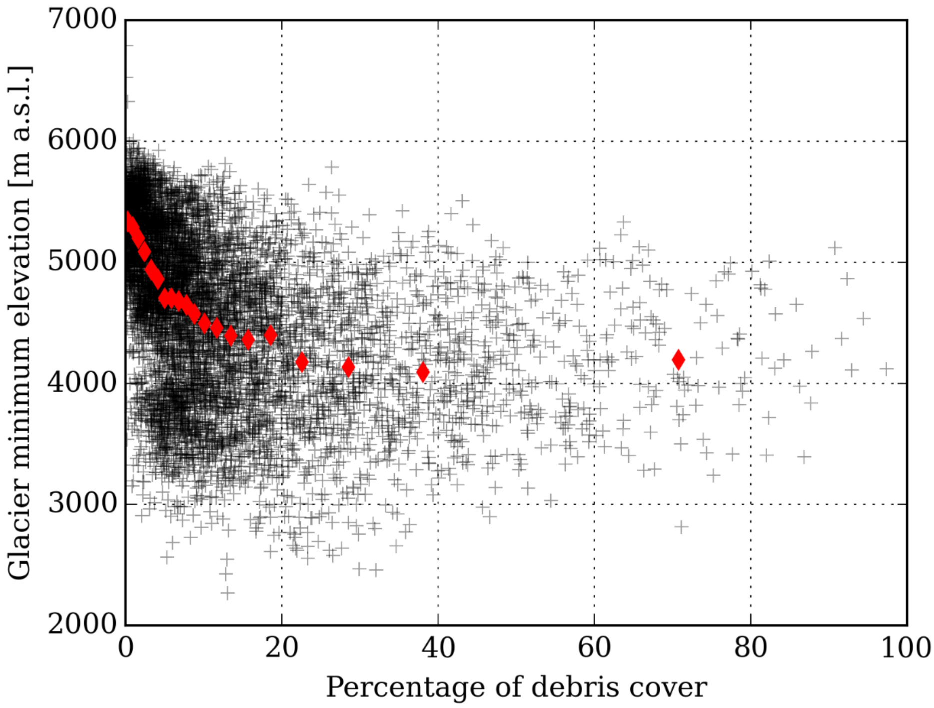

Figure 10: Glacier minimum elevation as a function of the percentage of debris cover for the glaciers larger than 2 km² in High Mountain Asia. The black crosses represent individual glaciers and the red diamonds shows the mean of the glacier minimum elevation. For instance, the first diamond represent the mean of the glacier minimum elevation for glaciers with a percentage of debris cover between 0 and 0.51% (5th percentile).

- We added a supplementary figure S5, illustrating some specific aspects of our new methodological developments

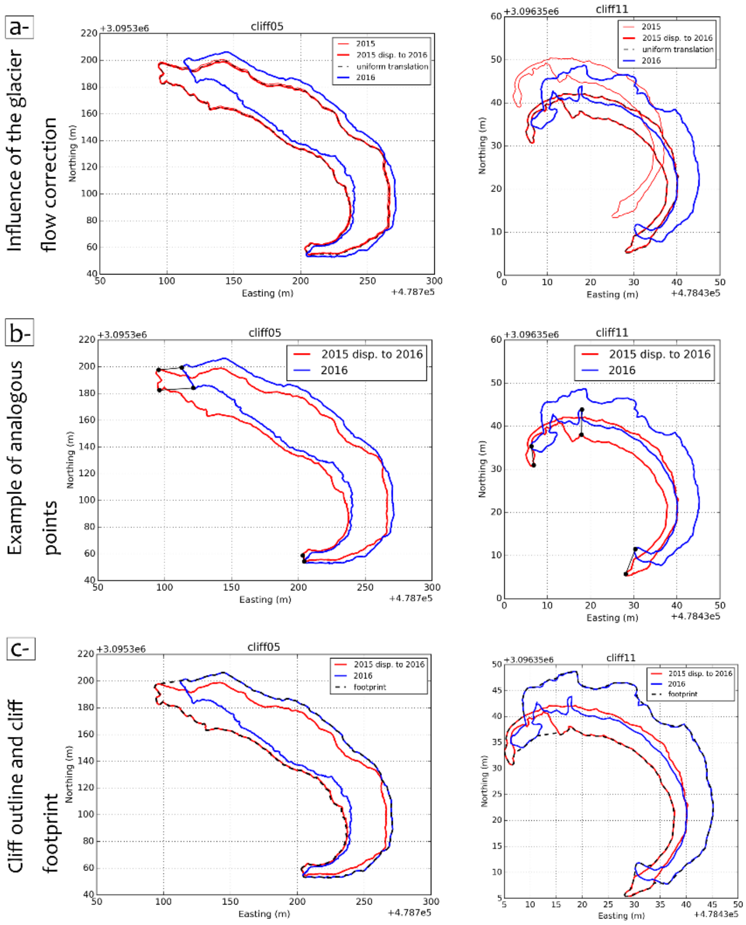

Figure S5 - Examples of the methodological processing for cliff 05, located on a slow flowing area (left panels) and cliff 11, located in a fast flowing area (right panels). For all the panels the cliff outlines are represented in UTM45/WGS84. a- influence of the glacier flow correction, and comparison with a uniform translation. B- example of analogous points needed for the triangulation regularization. c- difference between the individual cliff outlines and the cliff footprint needed to calculate the cliff contribution for gridded data (DEMs).

- We added a supplementary table S2, showing the changes in area between Nov. 2015 and Nov. 2016 for the twelve cliffs surveyed with the terrestrial photogrammetry

Tab. S2 – 3D area changes of the twelve field monitored cliffs

Cliff ID	3D area 2015 [m²]	3D area 2016 [m²]	Relative area change (%)
Cliff 01	6126	8961	46
Cliff 02	1135	1496	32
Cliff 03	3650	2415	-34
Cliff 04	1915	1788	-7
Cliff 05	11323	11265	-1
Cliff 06	4099	6435	57
Cliff 07	749	756	1
Cliff 08	1286	1278	-1
Cliff 09	2897	1918	-34
Cliff 10	2659	2192	-18
Cliff 11	466	707	52
Cliff 12	818	732	-11
Total	**37124**	**39942**	**8**

- The cliff ablation enhancement factor, named *p* in our original submission is now named f_c to avoid any confusion with the "p-value" as suggested by reviewer 3. Following, the suggestion of reviewer 1 and 4, we added the definition and computation of the f_C^* factor, which compares the cliff and non cliff ablation (instead of the cliff and whole glacier tongue).
- We changed the structure of parts of the data and method sections. Section 3.4.2 is now entitled "Ground penetrating radar data", and the method section is now separated into three main subsections: 4.1-Emergence velocity; 4.2-Ice cliff backwasting calculation; 4.3-Sources of uncertainty on the ice cliff backwasting.
- In order to better balance the focus of the paper (comments from reviewers 1, 2 and 4), we extended the section 6.1 with a description of the cliff evolution and compared backwasting rates with published values. We extended Table 1 with values of mean elevation and backwasting rates for individual cliffs.
- Reviewers 1, 3 and 4 legitimately criticized the extrapolation we made based on a single glacier. We substantially modified section 6.3 ("Ice cliff ablation and the debris-cover anomaly"), in order to modify our previous statements, which were probably too strong with regards to the small sample studied here (n=1, as pointed out by reviewer 3). We changed the title of the paper, which is now "Ice cliff contribution to the tongue-wide ablation of Changri Nup Glacier, Nepal, Central Himalaya". Moreover, we backed up some of our theoretical arguments, based on a compilation of data from Kraaijenbrink et al. (2017) shown in figure 10.

Additional changes:

- The family name of Dibas Shrestha was misspelled (missing "h") in the original submission

- Silvan Raggetli brought to our attention that the “debris-cover anomaly” was never observed in the Langtang catchment, due to insufficient hypsometric overlap between debris-free and debris-covered ice. We modified the text accordingly.
- The signs greater than and smaller than were inverted in equation 5. It is corrected in the revised version.

~~Can ice-cliffs explain "debris-cover anomaly"? New insights from~~ Ice cliff contribution to the tongue-wide ablation of Changri Nup Glacier, Nepal, Central Himalaya

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Abstract. Ice cliff backwasting on debris-covered glaciers is recognized as an important process, potentially responsible for the so-called "debris-cover anomaly", i.e. the fact that debris-covered and debris-free glacier tongues appear to have similar thinning rates in Himalaya. In this study, we assess the total contribution of ice cliff backwasting to the net ablation of the tongue of the Changri Nup Glacier over two years. Detailed terrestrial photogrammetry surveys were conducted on select ice cliffs in November 2015 and 2016, and the entire glacier tongue was surveyed with unmanned air vehicles (UAVs) and Pléiades tri-stereo imagery in November 2015, November 2016, and November 2017. The total difference between the volume loss from ice cliffs measured with the terrestrial photogrammetry, considered as the reference data, and the UAV and Pléiades was less than 3 % and 7 %, respectively, demonstrating the ability of these datasets to measure volume loss from ice cliffs. For the period November 2015–November 2016 (resp. November 2016–November 2017), using UAV and Pléiades over the entire glacier tongue, we found that ice cliffs, which cover 7 % (resp. 8 %) of the ~~planar~~ map view area, contribute to 23 $\pm$ 5 % (resp. 24 $\pm$ 5 %) of the total net ablation of Changri Nup Glacier tongue. Ice cliffs have a net ablation rate 3.1 $\pm$ 0.6 (resp. 3.0 $\pm$ 0.6) times higher than the average glacier tongue surface. However, on Changri Nup Glacier, ice cliffs cannot compensate for the reduction of ablation due to debris-cover. Reduced ablation and lower emergence velocities on debris-covered glacier tongues could be responsible for the debris-cover anomaly.

1 Introduction

Ablation areas in High Mountain Asia (HMA) are heavily debris-covered, meaning that a potentially large part of melt water originates from ice ablation of debris-covered glacier tongues (Kraaijenbrink et al., 2017). Numerous studies have demonstrated that a debris layer thicker than 5–10 cm has a dominant insulating effect and dampens the ablation of ice beneath it (e.g., Østrem, 1959; Nicholson and Benn, 2006; Reid and Brock, 2010; Reznichenko et al., 2010; Lejeune et al., 2013). Yet counter-intuitively, similar thinning rates (change in glacier surface elevation over time) ~~were~~ have been observed for clean ice and debris-covered ice at similar elevations across HMA (Gardelle et al., 2013; Kääb et al., 2012), in the Khumbu region (Nuimura et al., 2012), the ~~Langtang catchment (Pellicciotti et al., 2015), the~~ Kangri Karpo Mountains (Wu et al., 2018), for the Kanchenjunga Glacier (Lamsal et al., 2017) and the Siachen Glacier (Agarwal et al., 2017). This has been referred to as the “debris-cover anomaly” (Pellicciotti et al., 2015).

Two main hypotheses have been proposed to explain this anomaly. First, while ablation rates are reduced by thick debris, ice cliffs could be "hot spots" of ablation and thus contribute disproportionally to the tongue-averaged ablation (Sakai et al., 1998, 2002; Reid and Brock, 2014; Immerzeel et al., 2014; Pellicciotti et al., 2015; Steiner et al., 2015; Buri et al., 2016a). Other processes linked to supraglacial and englacial water systems could lead to substantial ablation(e.g., Sakai et al., 2000; Miles et al., 2016; Watson et al., 2018; Benn et al., 2017). Alternatively, debris-covered tongues could have a lower emergence velocity compared with debris-free tongues (Anderson and Anderson, 2016; Banerjee, 2017). As a result, even though debris-covered tongues could have less negative surface mass balance compared to clean ice glaciers, their thinning rates (surface mass balance rate minus emergence velocity) ~~are similar. Alternatively, while ablation rates are reduced by thick debris, supra-glacial features such as ice cliffs and ponds could be “hot spots” of ablation and thus contribute disproportionally to the tongue-averaged ablation (Sakai et al., 1998, 2002; Reid and Brock, 2014; Immerzeel et al., 2014; Pellicciotti et al., 2015; Steiner et al., 2015).~~ would be similar.

In order to ~~test the second~~ partially test the first hypothesis, there is a need to calculate the total contribution of ~~ice cliffs~~ the additional melt processes to the tongue-wide surface mass balance. In this work, we focus on the ice cliff contributions, as the processes related to the glacial water system are currently not quantifiable at the scale of a glacier tongue. For simplicity, hereafter we ~~abusively~~ use the term ~~net ablation~~ *net ablation* instead of surface mass balance as we focus only on the ablation areas. We introduce ~~a variable, noted hereafter p, to quantify the enhanced ablation at ice cliffs. The variable p~~the variable f_C, defined as the spatially integrated ratio between the ~~cliff net ablation~~ net ablation from all ice cliffs and the glacier tongue net ablation, ~~is used to quantify~~ to quantify the enhanced ablation due to the presence of ice cliffs:

$$\cancel{p} f_C = \frac{\dot{b}_C}{\dot{b}_T} = \frac{\Delta V_C}{A_C} \times \frac{A_T}{\Delta V_T} \tag{1}$$

where $\dot{b}$ is the net ablation, ΔV is the volume loss and A is the area, in each case the subscript refers to the ~~cliff~~ cliffs (C) or the glacier tongue (T). Additionally, we define the quantity f_C^*, which is the spatially integrated ratio between net ablation from all ice cliffs, and the net ablation on all non-cliff areas on the glacier tongue (noted with the subscript NC):

$$f_C^* = \frac{\dot{b}_C}{\dot{b}_{NC}} = \frac{\Delta V_C}{A_C} \times \frac{A_{NC}}{\Delta V_{NC}} = \frac{\Delta V_C}{A_C} \times \frac{A_T - A_C}{\Delta V_T - \Delta V_C} = f_C \frac{\Delta V_T}{\Delta V_T - \Delta V_C} \frac{A_T - A_C}{A_T} \tag{2}$$

f_C^* has the advantage of not including the total ice cliff contributions in the total tongue ablation, whereas f_C has the advantage of being directly linked to the total ice cliff contributions to ablation. f_C^* is expected to be larger than f_C, and both terms refer to a glacier-wide value.

Most previous attempts to estimate the value of ~~p~~ f_C were based on modelling and found values ~~to be between 5 to 7 (Juen et al., 2014; Reid and Brock, 2014),~~ of ∼6 (Reid and Brock, 2014), ∼10 (Sakai et al., 2000), and around 14 (Buri et al., 2016b)~~or even more than 35 (Sakai et al., 1998).~~. Fewer studies assessed f_C^* and found values of $\sim$7 (Juen et al., 2014) and $\sim$12 (Sakai et al., 2000). Two studies have quantified ~~p~~ f_C using direct observations: Brun et al. (2016) found ~~$p = 6$~~ $f_C = 6$ over Lirung Glacier by extrapolating volume losses measured from very high resolution photogrammetry on a limited number of cliffs and Thompson et al. (2016) found a value of 8 by digital elevation model (DEM) differencing at Ngozumpa Glacier in the Nepalese Himalaya.

The emergence velocity (w_e) of ice for debris-covered glaciers has been found to be significantly different from zero for some cases, but it has typically been neglected in the calculation of ~~p~~f_C, for all the above-mentioned studies. Values of w_e equal to ~~5.7–6.4~~ 5.1–5.9 $\pm$ ~~3.9~~ 0.28 m a^{-1} (Nuimura et al., 2011), 0.41 $\pm$ 0.05 m a^{-1} (Vincent et al., 2016) and 0.00–0.35 $\pm$ 0.10 m a^{-1} (Nuimura et al., 2017) have been found for, respectively, the debris-covered tongues of Khumbu, Changri Nup and Lirung glaciers in Nepal. ~~Emergence velocities will affect the thinning rates of debris-covered ice and ice cliffs equally. But since the~~ Neglecting the emergence velocities (i.e. comparing thinning rates instead of ablation rates) introduces a systematic overestimation of f_C. This is due to the fact that cliffs ablate at higher rate ~~, their thinning rate is relatively~~ than the rest of the glacier tongue: ice cliff thinning rates are thus less influenced than the thinning ~~rate~~ rates of debris-covered ice when neglecting the emergence velocity. As a consequence, the ratio of the cliff thinning rate divided by the mean tongue thinning rate will overestimate ~~p~~f_C. To correctly estimate ~~p~~ f_C and the fraction of total ice cliff net ablation, ~~it is therefore needed to correct the thinning rates~~ thinning rates need to be corrected with the emergence velocity~~in order to calculate net ablation rates~~.

Recent studies advocate the use of terrestrial photogrammetry to understand patterns of ice cliff retreat (e.g., Watson et al., 2017). Nevertheless, these data can only be collected in the field with some difficulty, and can only be acquired on a limited number of cliffs. Remote sensing platforms (unmanned ~~air~~ aerial vehicles [UAVs], satellites) offer the potential to provide high resolution topographic data with a glacier-wide or region-wide coverage but have not yet been evaluated for detailed multi-temporal monitoring of ice cliffs. Here we test the possibility to use gridded elevation data (i.e. DEMs) obtained from both UAV and Pléiades imagery to assess the total ice cliff contribution to the tongue-wide net ablation.

In this study, we use three very high resolution topographic datasets based on terrestrial photogrammetry, UAV imagery, and Pléiades imagery collected over the tongue of Changri Nup Glacier, Nepal between 2015 and 2017. From the terrestrial photogrammetry, 3D models of 12 cliffs are created to calculate reference ice cliff volume losses ~~(~~from 2015 to ~~2016).~~ 2016. We introduce a new method based on DEM differencing, which takes into account geometric changes induced by glacier flow~~and~~, and in particular by emergence velocity, and apply it to the UAV and Pléiades imagery. The new method is validated with the terrestrial photogrammetric estimates and applied to the entire Changri Nup Glacier tongue in order to evaluate the fraction of the tongue-wide net ablation due to ice cliffs.

2 Study area

This study focuses on the debris-covered part of the tongue of the Changri Nup Glacier, Everest region, Nepal (Fig. 1). The glacier accumulates partly through avalanche falling from the surrounding steep slopes (up to $\sim$6700 m a.s.l.) and flows down to 5250 m a.s.l. The local equilibrium line altitude (ELA) was evaluated around 5600 m for the nearby debris-free West Changri

Nup Glacier (Sherpa et al., 2017). We use the same glacier tongue outline as Vincent et al. (2016), which was derived from a combination of UAV imagery, field measured velocity fields and field expertise. It is different from the outline available in the Randolph Glacier Inventory 6.0 (Pfeffer et al., 2014), which includes the nearby West Changri Nup Glacier ~~in the same outline~~ (Sherpa et al., 2017). The debris-covered part of the tongue has an area of 1.49 ± 0.16 km^2 (Fig. 1). We focus first on 12 ice cliffs that were ~~ground surveyed~~ ground-surveyed (Table 1 and Fig. 1), before extending the analysis to more than 140 ice cliffs of various sizes (Fig. 1). The ~~planar~~ map view area of these cliffs were ~~69 876 ± 14 000~~ $70 \pm 14 \times 10^3$ m^2, ~~71 826 ± 14 000~~ $72 \pm 14 \times 10^3$ m^2 and ~~69 537 ± 14 000~~ $70 \pm 14 \times 10^3$ m^2 in November 2015, in November 2016 and in November 2017, respectively (see section 4.4.4 for the uncertainty assessment ~~for the cliff planar area~~of the cliff map view areas).

3 Data

3.1 Terrestrial photogrammetry

We collected terrestrial photographs during two field campaigns: 24–28 November 2015 and 9–12 November 2016. We surveyed a total of 12 cliffs (Table 1) with methods similar to Brun et al. (2016) and Watson et al. (2017). Between 200 and 400 photographs of each cliff were taken from various camera positions using a Canon EOS5D Mark II digital reflex camera with a Canon 50 mm f/2.8 fixed focal length lens (Vincent et al., 2016). For each cliff, we derive point clouds (PCs) and triangulated irregular networks (TINs) with Agisoft Photoscan 1.3.4 professional edition (Agisoft, 2017). In order to align the photographs and georeference the final point clouds and derived products, between 7 and 17 ground control points (GCPs) made of pink fabric were spread around each cliff. ~~GCPs~~ GCP positions were surveyed with a Topcon differential global positioning system (DGPS) unit with a precision of ∼10 cm. All markers were used as GCPs and therefore no independent markers were available for validation. After optimization of the photographs alignment, the marker residuals were on average 27 cm for the 2015 campaign and 18 cm for the 2016 campaign. The 3D area of the surveyed cliffs ranged from 600 m^2 to more than 11 000 m^2 (Table 1).

3.2 UAV photogrammetry

UAV imagery of Changri Nup Glacier was obtained in November 2015, November 2016, and November 2017 using the Sony Cyber-shot WX DSC-WX220 mounted on the fixed-wing eBee UAV manufactured by senseFly (Table 2). The Structure from Motion (SfM) procedure that we implemented in Agisoft Photoscan Professional version 1.2.6 to process the imagery is equivalent to the procedure used in Vincent et al. (2016) and Kraaijenbrink et al. (2016a). From the PCs, we produced a 10 cm resolution orthomosaic and a 20 cm DEM for each year.

In 2015, five separate flights with the eBee were performed to cover the surface of the glacier over the course of 3 days, i.e. 22–24 November. The ~~imagery was processed into a dense point cloud using the Structure from Motion (SfM) algorithm (Agisoft, 2017), which was subsequently used to produce a 10 cm resolution orthomosaic and a 20 cm DEM. The~~ data was georeferenced using a set of 24 GCPs that were well spatially distributed and measured using the Topcon DGPS (Fig. S1).

Based on 10 additional independent GCPs, the error of the UAV products was ~~measured independently and~~ determined to be 4 cm horizontal and 10 cm vertical, which is in the range of expected accuracy (Gindraux et al., 2017). For a detailed description of the data processing refer to Vincent et al. (2016) and Kraaijenbrink et al. (2016a).

On 10 November 2016 we surveyed Changri Nup in three successful flights with the eBee UAV. ~~In the three flights the eBee captured a total of 475 images using the mounted Sony Cyber-shot WX DSC-WX220. The SfM procedure that we implemented in Agisoft Photoscan Professional version 1.2.6 to process the imagery is equal to the procedure that we used for the 2015 data (Vincent et al., 2016; Kraaijenbrink et al., 2016a) to enable an optimal comparison. Also for this dataset, an orthomosaic and a gridded DEM were produced from the generated dense point cloud with 10 cm and 20 cm resolution, respectively.~~ To georeference the 2016 UAV imagery, we distributed a total of 17 markers on the glacier and measured their coordinates with the Topcon DGPS. Unfortunately, due to time constraints, the resulting spatial distribution of the markers was suboptimal (Fig. S1). Using only these markers as GCPs had considerable consequences for processing accuracy, and we therefore defined 16 additional virtual tie points for which we sampled the coordinates from the November 2015 UAV orthomosaic and DEM (Fig. S1). For the tie points, we selected specific features on boulders that were clearly identifiable on both the 2015 and 2016 image sets. The use of virtual tie points requires stable terrain (Immerzeel et al., 2014), i.e. the coordinates of the features should not change over time. We have therefore only selected points in stable areas in the vicinity of the glacier, which we determined from visual inspection of the Pléiades orthoimages and DEMs.

In 2017, we performed the same measurements as in 2015 in three separate flights on 23 November, using 30 GCPs (Fig. S1). The residuals, based on 6 independent check points were 10 cm in horizontal and 14 cm in vertical .

3.3 Pléiades tri-stereo photogrammetry

Three triplets of Pléiades images were acquired over the study area on 22 November 2015, on 13 November 2016 and on 24 October 2017 (Table 3). The along track angles of the acquisitions gave base to height ratios ensuring suitable stereo capabilities (e.g., Belart et al., 2017). For each acquisition, we derived a 2 m ~~resolution~~ DEM and a 0.5 m ~~resolution~~ orthoimage using the Ames Stereo Pipeline (ASP; Shean et al., 2016) using only the rational polynomial coefficients (RPCs) provided with the imagery (no GCP) and the same processing parameters as Marti et al. (2016). We used the *stereo* routine of ASP to derive one PC from each triplet of images, which was gridded into a single 2 m DEM using the *point2dem* routine. The orthoimages were generated from the image closest to the nadir using the *mapproject* function and a 2 m resolution DEM, which was gap-filled with 4 and 8 m DEM resolutions derived similarly. This ensured ~~to obtain~~ sharp and gap-free images.

Each Pléiades orthoimage was co-registered to the corresponding UAV orthomosaic, by matching boulders on stable ground visually. We check the accuracy of this co-registration by calculating the median displacement on a 2.4 km^2 stable area off-glacier. An east to west residual displacement of 0.05 m and a north to south residual displacement of -0.09 m was identified after co-registration. This absolute co-registration was needed to compare the UAV and Pléiades datasets, but would not be necessary while working with Pléiades data only. In the latter case, the robustness of the Pléiades processing based on RPCs only would be sufficient to co-register the images and DEMs relatively using automatic co-registration methods. Each Pléiades DEM was shifted with the same horizontal displacement as the corresponding orthoimage (Table 3). Automatic co-registration methods applied to the manually-shifted DEMs (Berthier et al., 2007; Nuth and Kääb, 2011) resulted in no improvement of the standard deviation of elevation changes on stable terrain. Thus, no further horizontal shift was applied. The vertical shift between the two Pléiades DEMs was calculated as the median elevation change on stable terrain and was equal to -7.43 m and -3.31 m for the periods November 2015–November 2016 and November 2016–November 2017, respectively. ~~We corrected this vertical median bias by subtracting this value to~~ These vertical offsets are quite large but expected, as the DEMs are derived from the orbital parameters only (Berthier et al., 2014). We corrected these offsets by subtracting them from the elevation difference map. We tested the dependency of the elevation changes over stable terrain to the slope, aspect and curvature and found no dependency to these parameters (Fig. S2).

For these three datasets, the duration between acquisition dates were 350 to 381 days. All displacements and volumes have been linearly adjusted (divided by the number of days between the acquisition dates and multiplying by the total number of days in a year) to obtain annual velocities and change rates.

3.4 Update of existing datasets

We updated two datasets from Vincent et al. (2016): the glacier surface velocity and the cross sectional ice thickness data.

3.4.1 Surface velocity fields

Surface velocity fields were derived from the correlation of the Pléiades orthoimages and UAV orthomosaics using COSI-corr (Leprince et al., 2007). The UAV orthomosaics were resampled to a resolution of 0.5 m to match one of the Pléiades orthoimages. For both data sets we choose an initial correlation window size of 256 pixels and a final size of 16 pixels (Kraaijenbrink et al., 2016a). The step was set to 16 pixels, leading to a final grid spacing of 8 m.

The raw correlation outputs were filtered to ~~maintain~~ retain pixels with a signal to noise ratio larger than 0.9. We manually removed pixels at ice cliff locations, as cliff retreat lead to large geometric changes and therefore poor correlation. These outputs were filtered with a 9×9 pixel window moving median filter and then gap-filled with a bilinear interpolation (Fig. 2). The patterns of displacement from UAV and Pléiades are in very good agreement. The velocities measured with Pléiades match well with the field data (ablation stake displacements measured with a DGPS between November 2015 and November 2016), with the notable exception of a stake located where the velocity gradient is high and for which the correlation between the Pléiades images could not work due to snow, leading to a poor bilinear interpolation (Fig. S3). Nevertheless, the maximum displacement is lower in the remote sensing data (around 11 m a^{-1}), than the 2011–2015 field data (around 12 m a^{-1}; Vincent et al., 2016). This is due to a slowdown of the glacier observed also in the 2015–2016 field data.

3.4.2 ~~Emergence velocity~~Ground penetrating radar data

A cross sectional profile of ice thickness has been measured upstream of the debris-covered tongue (Fig. 1) in October 2011, with a ground penetrating radar (GPR) working at a frequency of 4.2 MHz (Vincent et al., 2016). The original cross-sectional area was 79 300 m^2 in 2011 and 78 200 m^2 in 2015 (Vincent et al., 2016). Between November 2015–November 2016 and November 2016–November 2017, the cross sectional area decreased from $S_{2015-2016}$ = 76 900 m^2 to $S_{2016-2017}$ = 76 340 m^2 (with $S_{\mathrm{yr1-yr2}}$ being the mean cross sectional area between the year 1 and year 2), based on the 0.86 m a^{-1} thinning rate measured over the November 2015–November 2017 period along the profile. The uncertainty on the ice thickness is ± 15 m (Azam et al., 2012), which leads to an uncertainty on the cross sectional area (σ_S) of ± 10 000 m^2, as the length of the cross-section is 670 m.

4 Methods

4.1 Emergence velocity

The emergence velocity refers to the upward flux of ice relatively to the glacier surface in an Eulerian reference system (Cuffey and Paterson, 2010). For the case of a glacier in steady-state (i.e., no volume change at the annual scale), the emergence velocity balances exactly the net ablation for any point of the glacier ablation area (Hooke, 2005). For a glacier out of its steady state (as Changri Nup Glacier) the thinning rate in the ablation area is the sum of the net ablation and the emergence velocity (Hooke, 2005). On debris-covered glaciers, while the thinning rate is relatively straightforward to measure from DEM differences, for example, the ablation is highly spatially variable and difficult to measure (e.g., Vincent et al., 2016). In order to evaluate the mean net ablation of ~~the~~ Changri Nup Glacier tongue from the ~~rate of elevation change~~thinning rate, we estimate the mean emergence velocity (w_e) for the period November 2015–November 2016 and for the period November 2016–November 2017 using the flux gate method of Vincent et al. (2016). As the ice flux at the glacier front is 0, the average emergence velocity downstream of a cross-section can be calculated as the ratio of the ice flux through the cross-section (Φ in m^3 a^{-1}), divided by the glacier area downstream of this cross-section (A_T in m^2):

$$w_e = \frac{\Phi}{A_T} \tag{3}$$

This method requires an estimate of ice flux through a cross-section of the glacier, and is based here on measurements of ice depth and surface velocity along a profile upstream of the debris-covered tongue (Figs. 1 and 2). ~~Between November 2015–November 2016 and November 2016–November 2017, the cross sectional area was reduced from 76 900 ± 100~~ The ice flux is the product of the depth-averaged velocity ($\bar{u}$ in m ~~^{2} to 76 340 ± 100 m^2, based on the 0.86 m~~ a^{-1}~~thinning rate measured for the November 2015–November 2017 period along the profile. The glacier tongue areawas considered unchanged at 1.49 ± 0.16 km^2~~) and the cross-sectional area. For the period November 2015–November 2016 (resp. November 2016–November 2017), the glacier slowed down compared with the ~~2011–2014~~ 2011–2015 period and the centerline velocity was equal to 10.8 m a^{-1} (resp. 11.1 m a^{-1}), leading to an assumed mean surface velocity along the upstream profile of 8.1 ± 0.6 m a^{-1} (resp. 8.3 ± 0.6 m a^{-1})~~and a~~, as the mean surface velocity along the cross-section is usually 70 to 80 % of the centerline velocity (e.g., Azam et al., 2012; Berthier and Vincent, 2012). We used the relationship between the centerline velocity and the mean velocity, instead of an average of the velocity field along the cross section, because the image correlation was not successful on a relatively large fraction (∼ 30 %) of the cross section. Converting the surface velocity into a depth-averaged velocity ~~of~~ requires assumption the basal sliding and a flow law (Cuffey and Paterson, 2010). Little is known about the basal conditions of Changri Nup Glacier, but Vincent et al. (2016) assumed a cold base, and therefore no sliding. This leads to $\bar{u}$ being approximated as 80 % of the surface velocity, additionally assuming $n = 3$ in Glen's flow law (Cuffey and Paterson, 2010). As an end-member case, assuming that the motion is entirely by slip implies $\bar{u}$ equals to the surface velocity (Cuffey and Paterson, 2010). Consequently, we followed Vincent et al. (2016) and assumed no basal sliding, but we took the difference between the two above-mentioned cases as the uncertainty on $\bar{u}$. This leads to $\bar{u}$ = 6.5 ± ~~0.6~~ 1.6 m a^{-1} (resp. 6.6 ± ~~0.6~~ 1.7 m a^{-1}) ~~(Vincent et al., 2016). The incoming ice flux for the period~~ for the period November 2015–November 2016 (resp. November 2016–November 2017).

Assuming independence for the cross-sectional area (σ_S) and the depth-averaged velocity ($\sigma_{\bar{u}}$), the uncertainty on the ice flux (σ_Φ) can be estimated as:

$$\frac{\sigma_\Phi}{\Phi} = \sqrt{\frac{\sigma_{\bar{u}}}{\bar{u}}^2 + \frac{\sigma_S}{S}^2} \tag{4}$$

Given the above mentioned values for the depth-averaged velocity, the cross-sectional area and the associated uncertainties, the relative uncertainty of the ice flux is ∼30 %. As a result, for the period November 2015–November 2016 (resp. November 2016–November 2017), the incoming ice flux was thus 499 700 ± ~~46 130~~ 150 000 m^3 a^{-1} (resp. 503 840 ± ~~45 800~~ 150 000 m^3 a^{-1}). The glacier tongue area was considered unchanged at 1.49 ± 0.16 km^2, corresponding to w_e = 0.33 ± ~~0.05~~ 0.11 m a^{-1} (resp. 0.34 ± ~~0.05~~ 0.11 m a^{-1})~~, when distributed over the ablation area . This~~ . It is notoriously difficult to delineate debris-covered glacier tongues (e.g., Frey et al., 2012). In this case, we assumed an uncertainty in the outline position of ± 20 m, leading to a relative uncertainty in the glacier area of 11 %, which is higher than the 5 % of Paul et al. (2013). In this case, the uncertainty on the glacier outline is not the main source of uncertainty in w_e, but, if we had used automatically delineated outlines, this would be an important source of uncertainty. The updated emergence velocity is ∼20 % lower than estimated for the 2011-2015 period (Vincent et al., 2016), due to both the thinning and deceleration of the glacier at the cross-section. As the difference in w_e between ~~the two periods~~ November 2015–November 2016 and November 2016–November 2017 is insignificant, we consider w_e to be constant and equal to w_e = 0.33 ± ~~0.05~~ 0.11 m a^{-1} for the rest of this study. It is noteworthy that w_e is likely to be spatially variable, however, we have no means to assess its spatial variability.

4.2 Ice cliff backwasting calculation

4.2.1 Point cloud deformation

Every point on the glacier surface moves with a horizontal velocity u_s, along a surface slope α and is advected upwards following the vertical velocity w_s (Fig. 3; Hooke, 2005; Cuffey and Paterson, 2010):

$$w_s = u_s \tan\alpha + w_e \tag{5}$$

When DEM differencing is applied, observed thinning rates at every point on the glacier surface is a combination of net ablation and displacement caused by glacier flow. In order to measure only the volume loss associated with the net ablation, we deformed the PCs~~of~~ , by displacing its individual points, for the datasets acquired in November 2015 and in November 2016, in order to account for three-dimensional glacier flow between November 2015 and November 2016 and between November 2016 and November 2017, respectively. For the terrestrial photogrammetry and UAV data, we applied these deformations directly to each point of the PCs. For the Pléiades data, we artificially oversampled the DEM on a 0.5 m resolution grid and converted this DEM to a PC, using the *gdal_translate* function. All the points of the PCs were displaced in x, y and z direction:

$$\begin{cases} x_{t+dt} = x_t + u_{s,x} dt \\ y_{t+dt} = y_t + u_{s,y} dt \\ z_{t+dt} = z_t + w_s dt \end{cases} \tag{6}$$

where $u_{s,x}$ and $u_{s,y}$ are the x and y components of the horizontal velocity, dt is the duration between the two acquisitions and z is the glacier surface elevation.

Even though w_e is likely to be spatially variable, we consider it to be homogeneous over the whole ablation tongue. The horizontal velocity u_s was directly taken from the bilinear interpolation of the Pléiades velocity field (Fig. 2). The term $u_s \tan\alpha$, can be expressed as:

$$u_s \tan\alpha = \frac{z(x + u_{s,x}dt, y + u_{s,y}dt) - z(x,y)}{dt} \tag{7}$$

As the ice flows along the glacier mean slope instead of the rough local surface slope, we extracted z from a ~~smoothed~~ version of the Shuttle Radar Topography Mission (SRTM) DEM ~~. In order to smooth the SRTM DEM, we filtered it~~ smoothed with a Gaussian ~~function~~ filter using a 30 pixel kernel size ~~to calculate $u_s \tan\alpha$~~ (Fig. S4).

For the Pléiades and UAV data, we then gridded the deformed PCs using the *point2dem* ASP function (Shean et al., 2016) and derived the associated maps of elevation changes (Figs. 4 and 5).

4.2.2 Ice cliff volume change from TINs

In order to measure the volume changes due to cliff retreat from the TINs derived from terrestrial photos, we applied the method from Brun et al. (2016) with some methodological improvements. First, the field of displacement was assumed to be ~~homogenous~~ homogeneous at the cliff scale in Brun et al. (2016). In this study, we use interpolated values of the local field of displacement with a resolution of 8 m. This ~~is~~ would be an important methodological refinement for ~~cliffs over~~ ice cliffs on fast flowing glaciers with a rotational component~~.~~ , but has minor influence for the cliffs of interest in this study (Fig. S5a). Second, we added more analogous points in the cliff edge triangulation method. Analogous points are points that are assumed to match in the two acquisitions (e.g. the corners of cliffs; Fig. S5b). Brun et al. (2016) discretized the triangulation problem assuming that the final number of points was equal on the upper and on the lower side of the cliff outline (i.e. implicitly assuming that the two corners of the cliffs were the only analogous points). In this study, the operator can choose how many analogous points are needed to link the two cliff outlines. Consequently, the method is now able to handle larger geometry changes than previously, under the assumption that some analogous parts of the cliffs are identifiable on both cliff outlines.

4.2.3 Ice cliff volume change from DEMs

We measured the cliff volume change from DEMs simply as the mean elevation change corrected from glacier flow below a cliff mask multiplied by the projected ~~planar~~ map view area of the mask. The cliff mask was defined as the union of the shapefiles of the cliff outlines, and is called the cliff footprint and noted A_{2D} hereafter. The cliff outlines were manually delineated both on the Pléiades and UAV orthoimages for November 2015, November 2016 and November 2017. For each acquisition, we used deformed outlines of November 2015 and November 2016 cliffs when working with the corresponding deformed DEM difference. We manually edited the cliff mask to make sure we included the terrain along which the cliff retreated. In particular, this implied linking the corners of the cliff outlines of the two acquisitions in many cases ~~.~~ (Fig. S5c).

4.3 Sources of uncertainty on the ice cliff backwasting

The main sources of uncertainties on the volume loss estimates are (1) the uncertainty on the spatial distribution of the ~~vertical~~ emergence velocity (σ_e); (2) uncertainties of the horizontal surface displacement (σ_d); (3) uncertainty introduced by the displacement along the slope (σ_w); (4) uncertainties of the cliff outlines delineation (σ_m) and (5) uncertainties of the various representations of the glacier surface in TINs and DEMs (σ_z). The first, second and third sources of uncertainties are common to the three datasets and the third and fourth ones are specific to each dataset. We assume these five sources of uncertainty to be independent.

4.3.1 Emergence velocity

We calculated a mean emergence velocity for the tongue of 0.33 $\pm$ ~~0.05~~ 0.11 m a^{-1}, but as the spatial variability was unknown extreme values of emergence velocities were tested to estimate σ_e. We choose 0.00 m a^{-1} as a lower limit because the emergence velocity is positive in the ablation area (Hooke, 2005; Cuffey and Paterson, 2010). For a thinning glacier, the net ablation is higher than the emergence velocity (e.g., Hooke, 2005), consequently, the net ablation can be used as a proxy for the upper bound for the emergence velocity. The maximum net ablation measured with stakes within the period 2014–2016 on the tongue of Changri Nup was chosen as an upper limit equal to 2.22 m a^{-1} (Vincent et al., 2016). We tested these values on the terrestrial photogrammetry-based volume change estimate of each cliff (Fig. 6a). Except for cliff 11, the relative volume change that resulted from the test was always below +40 % for an increase in the emergence velocity and -5 % for a decrease in the emergence velocity. Cliff 11 likely exhibits a high sensitivity to the emergence velocity due to its relatively shallow slope and its very small volume loss (Table 1 and S1). The tested range of values of emergence velocities ~~are~~ is rather extreme for the case of Changri Nup Glacier, and we therefore assumed that the uncertainty due to the emergence velocity was equal to the median of the relative volume change for an increase in the emergence velocity (23 %). As a consequence, $\sigma_e = 0.23V$, where V is the cliff volume change.

4.3.2 Horizontal displacement

The quality of the horizontal surface displacement derived from Pléiades orthoimages was evaluated by comparison with field measurements of the surface displacement. The median of the absolute difference between the 16 field measurements (stakes and marked rocks) and the corresponding Pléiades measurements was 30.8 cm. We therefore assumed that the uncertainty introduced by the horizontal displacement (σ_d) is 30 cm. The conversion into volumetric uncertainty, σ_d, was made by multiplying this uncertainty by the cliff 3D area (A_{3D}) for the terrestrial photogrammetry and by the cliff footprint area (A_{2D}) for the UAV and Pléiades (Table 1).

4.3.3 Displacement along the glacier slope

The uncertainty on $u_s \tan\alpha$ depends mostly on the uncertainty on the mean slope of the surrounding glacierized surface (Hooke, 2005). We evaluated kernel sizes of 5 and 60 pixels to filter the SRTM DEM and found respective mean elevation changes on the cliff mask of -0.51 and -0.33 m a^{-1}. As these values correspond to relatively sharp and very smooth DEMs, half of the difference between these two values (10 cm) is a good proxy for the uncertainty due to this correction. We converted this uncertainty into a volumetric uncertainty (σ_w) by multiplying it by the cliff 3D area (A_{3D}) for the terrestrial photogrammetry and by the cliff footprint area (A_{2D}) for the UAV and Pléiades.

4.3.4 Cliff mapping

The uncertainty on the cliff mapping from Pléiades orthoimages was empirically assessed by asking eight different operators (most of the co-authors of this study) to map six cliffs for which we had reference outlines from the terrestrial photogrammetry. The operators had access to the Pléiades orthoimage of November 2016 and to the corresponding slope map. We calculated a normalized length difference defined as the difference between the area mapped by the operator and the reference area divided by the outline perimeter. The median normalized length difference ranged between -0.7 and 1.7 m, and was on average equal to 0.6 m, meaning that the operators systematically overestimated the cliff area. The mean of the absolute value of the median normalized length difference was 0.8 m, which was used as an estimate for the cliff area delineation uncertainty. We conservatively assumed the same value for the Pléiades orthoimages and UAV orthomosaics, even though it should be lower for the UAV orthomosaics because of their higher resolution. For the terrestrial photogrammetry data, we assumed no uncertainty on the cliff area. The volumetric uncertainty σ_m was obtained by multiplying this value by the perimeter of cliff footprint and by the mean elevation change from DEM differences for UAV and Pléiades.

4.3.5 Accuracy of the topographic data

The uncertainty on the vertical accuracy of the terrestrial photogrammetry was directly estimated as the mean of the GCPs residual of all cliffs (0.21 m). For the UAV and Pléiades orthoimages we followed the classical assumption of partially correlated errors (Fischer et al., 2015; Rolstad et al., 2009) and therefore σ_z is given by:

$$\sigma_z = \begin{cases} A_{2D}\sigma_{\Delta h}\sqrt{\frac{A_{cor}}{5A_{2D}}} & ; A_{2D} \geq A_{cor} \\ A_{2D}\sigma_{\Delta h} & ; A_{2D} < A_{cor} \end{cases} \tag{8}$$

where $A_{cor} = \pi L^2$, with L being the decorrelation length and $\sigma_{\Delta h}$ being the normalized median of absolute difference (NMAD; Höhle and Höhle, 2009) of the elevation difference on stable ground. We experimentally determined L = 150 m for both the UAV and ~~L = 150 m for the~~ Pléiades data, even though the spherical model was not fitting the Pléiades semi-variogram very well. We found $\sigma_{\Delta h}$ = 0.27 m for the UAV and 0.36 m for Pléiades.

Under the assumption that the different sources of uncertainty are independent, the final uncertainty on the volume estimate σ_V is:

$$\sigma_V = \sqrt{\sigma_e^2 + \sigma_d^2 + \sigma_w^2 + \sigma_m^2 + \sigma_z^2} \tag{9}$$

5 Results

5.1 Comparison of TIN based and DEM based estimates

The volume changes estimated from terrestrial photogrammetry (our reference) and from UAV / Pléiades data are in good agreement and within error bars (Table ~~S1~~ S2 and Fig. 7). The total volume loss estimated for these twelve cliffs for the period November 2015–November 2016 is 193 453 $\pm$ 19 647 m^3 a^{-1} using terrestrial photogrammetry and 188 270 $\pm$ 20 417 m^3 a^{-1} and 181 744 $\pm$ 19 436 m^3 a^{-1} using UAV and Pléiades, respectively. The total relative difference is therefore -3 % for the UAV and -7 % for Pléiades, which is smaller than the uncertainty on each estimate ($\sim$10 %, calculated as the quadratic sum of the twelve individual cliff uncertainty estimates, assumed to be independent). The total Pléiades and UAV estimates are lower than the reference estimate, nevertheless, this is probably due to the estimate of the largest cliff (cliff 01), as there is no systematic under estimation of the volume for individual cliffs (Fig. 7).

5.2 Sensitivity to the emergence velocity

As Changri Nup Glacier is a slow flowing glacier, the emergence velocity is small and the associated uncertainty is low (Fig. 6a). Nevertheless, with our dataset it is possible to explore more extreme emergence velocities up to 5 m a^{-1}, which is a value inferred for a part of the Khumbu Glacier tongue and which is also the maximum emergence velocity measured on a debris-covered tongue, to our knowledge (Nuimura et al., 2011). Our results show that, as a rule of thumb, every 1 m a^{-1} error on the emergence velocity would increase the one-year volume change estimate by 10 % (Fig. 6b). It is noteworthy that the main source of uncertainty on the cliff volume change is the uncertainty on the emergence velocity.

5.3 Importance of the glacier flow corrections

In order to check the internal consistency of the glacier flow correction, we calculated the mean glacier tongue net ablation (calculated as the mean rate of elevation change minus the emergence velocity) before and after corrections. For the period November 2015–November 2016, without flow correction the mean tongue net ablation was equal to -1.07 $\pm$ 0.27 m a^{-1} and -1.18 $\pm$ 0.36 m a^{-1} for the UAV and Pléiades DEM differences, respectively. After the glacier flow correction (Eq. 3), the mean tongue net ablation was equal to -1.10 $\pm$ 0.27 m a^{-1} and -1.20 $\pm$ 0.36 m a^{-1} for the UAV and Pléiades data, respectively. The very good consistency between each estimate gave confidence in the fact that our glacier flow correction conserves mass. The same consistency was found for the period November 2016–November 2017.

For individual cliffs, the contribution of the glacier flow corrections were small relative to the uncertainties (Fig. 7), except for cliff 11 and 12 that ~~have~~ experienced a small volume ~~contribution~~change. These two cliffs are also located in the fastest flowing part of the glacier tongue. The low magnitude of the glacier flow corrections is a result of (1) the small displacements of most of the cliffs and (2) the vertical displacement due to slope, which tended to compensate for the emergence velocity (Fig. ~~3~~3). Nevertheless, for the two smallest and fast moving cliffs (cliffs 11 and 12), these corrections were much larger and resulted in improved estimates of volume change for both Pléiades and UAV data (Fig. 7).

5.4 Total contribution of ice cliffs to the glacier tongue net ablation for the period November 2015–November 2016

In addition to the 12 cliffs mapped in the field, we manually mapped 132 additional ice cliffs from the Pléiades and UAV orthoimages and slope maps. The total ~~planar~~ map view cliff footprint area from November 2015 and November 2016 was ~~113 007 ± 20 800~~ $113 \pm 21 \times 10^3$ m^2, i.e. 7.4 % of the total tongue ~~planar~~ map view area. Averaged over this cliff mask, the UAV (respectively Pléiades) rate of elevation change corrected from glacier flow and emergence was -3.88 $\pm$ 0.27 m a^{-1} (respectively -3.91 $\pm$ 0.36 m a^{-1}). This corresponds to a total average volume loss at ice cliffs of ~~439 689 ± 54 000~~ $440 \pm 54 \times 10^3$ m^3 a^{-1}.

The three largest cliffs contribute to almost 40 % of the total net ablation from cliffs (Fig. 8). As there is some variability in the rate of cliff thinning, the volume change of each cliff is not always directly related to its area (Figs. 8 and 9). Nevertheless, the largest cliffs dominate the volume loss, as 80 % of the total cliff contribution originates from the 20 largest cliffs in our study and all the cliffs below 2 000 m^2 (i.e., the 120 smallest cliffs) contribute to less than 20 % of the total volume loss (Fig. 8).

For the same period the tongue-averaged rate of elevation change was -0.79 $\pm$ 0.21 m a^{-1} (average of the UAV and Pléiades thinning rates) which, after adding the emergence velocity, corresponds to a net glacier tongue ablation of 1.12 $\pm$ 0.21 m a^{-1} or a volume loss of ~~1 918 172 ± 196 431~~ $1.9 \pm 0.2 \times 10^6$ m^3 a^{-1}. Consequently, the fraction of total net glacier tongue ablation due to cliffs was found to be 23 $\pm$ 5 % for both methods although ~~they cover~~ these cliffs covered only 7.4 % of the tongue area. The ~~factor p was~~ factors f_C and f_C^* were thus equal to 3.1 $\pm$ 0.6 and 3.7 $\pm$ 0.7, respectively.

5.5 Total contribution of ice cliffs to the glacier tongue net ablation for the period November 2016–November 2017

For the period November 2016–November 2017, we relied on the Pléiades and UAV data only. The cliff footprint area from November 2016 and November 2017 was ~~119 600 ± 20 800~~ $120 \pm 21 \times 10^3$ m^2, i.e. 7.8 % of the total tongue area. Averaged over this cliff mask, the UAV (respectively Pléiades) rate of elevation change corrected for glacier flow and emergence was -4.76 ± 0.27 m a^{-1} (respectively -4.43 ± 0.36 m a^{-1}). ~~For the two elevation products this corresponds to an average~~ The average from the Pléiades and UAV data gives a total ice cliff volume loss of ~~549 943 ± 66 000~~ $550 \pm 66 \times 10^3$ m^3 a^{-1}. In the meantime the tongue-average rate of elevation change was -1.18 ± 0.21 m a^{-1} (average of the UAV and Pléiades thinning rates), corresponding to a net glacier tongue ablation of 1.51 ± 0.21 m a^{-1}, after correction for the emergence, or a total volume loss of ~~2 308 596 ± 235 000~~ $2.3 \pm 0.2 \times 10^6$ m^3 a^{-1}. Consequently, the ice cliffs contributed to 24 ± 5 % of the net glacier tongue ablation and the ~~p factor was~~ factors f_C and f_C^* were thus equal to 3.0 ± 0.6 ~~for the period November 2016–November 2017.~~ and 3.6 ± 0.7, respectively.

6 Discussion

6.1 ~~Comparison of two years of acquisition~~

6.1 Cliff evolution and comparison of two years of acquisition

The total ice cliff covered area did not vary significantly from year to year, ranging from $70 \pm 14 \times 10^3$ m^2 in November 2015 and 2017 to $71 \pm 14 \times 10^3$ m^2 in November 2016. The twelve individual cliffs surveyed showed substantial variations in area within the course of one year, with a maximum increase of 57 % for the large cliff 06 and a decrease of 34 % for cliffs 03 and 09 (Table S2). The total area of these twelve cliffs increased by 8 % in one year. Interestingly, over the same period, Watson et al. (2017) observed only declining ice cliff area on the tongue of Khumbu Glacier (∼6 km away), suggesting a lack of regional consistency. All the large cliffs (most of them are included in the twelve cliffs surveyed with the terrestrial photogrammetry) persisted over two years of survey, including the south or south-west facing ones (Table 1), although south facing cliffs are known to persist less then non south facing ones (Buri and Pellicciotti, 2018). However, we observed the appearance and disappearance of small cliffs, and marginal areas became easier to classify as either ice cliff or debris-covered areas, highlighting the challenge in mapping regions covered by thin debris (e.g., Herreid and Pellicciotti, 2018).

We calculated backwasting rates for the twelve cliffs monitored with terrestrial photogrammetry for the period November 2015–November 2016 (Table 1). The backwasting rate is sensitive to cliff area changes (because it is calculated as the rate of volume change divided by the mean 3D area) and should be interpreted with caution for cliffs that underwent large area changes (e.g., cliffs 01, 02, 03, 06, 09 and 11; Table S2). The backwasting rates ranged from 1.2 ± 0.4 to 7.5 ± 0.6 m a^{-1}, reflecting the variability in terms of ablation rates among the terrain classified as cliff (Fig. 9). The lowest backwasting rates are observed for cliffs 11 and 12, located on the upper part of the tongue, roughly 100 m higher than the other cliffs (Fig. 1 and Table 1). The largest backwasting rates were observed for cliff 01, which expanded significantly between November 2015 and November 2016. The backwasting rates are lower than those reported by Brun et al. (2016) on Lirung Glacier (Langtang catchment) for the period May 2013–October 2014, which ranged from 6.0 to 8.4 m a^{-1} and lower than those reported by Watson et al. (2017) on Khumbu Glacier for the period November 2015–October 2016, which ranged from 5.2 to 9.7 m a^{-1} (we reported the values for cliffs which survived over their entire study period only). These differences are likely due to temperature differences between sites. Indeed, the cliffs studied here are at higher elevation (5320–5470 m a.s.l.) than the two other studies (4050–4200 m a.s.l. for Lirung Glacier and 4923–4939 m a.s.l. for Khumbu Glacier).

While a comparison between only two years of data cannot be used to extrapolate our results in time, we note the similarity between the total ice cliff contribution to net ablation (23 $\pm$ 5 % and 24 $\pm$ 5 % in November 2015–November 2016 and November 2016–November 2017, respectively). In contrast, total net ablation of the Changri Nup Glacier tongue was $\sim$25 % higher for the period November 2016–November 2017 than for the period November 2015–November 2016. While a difference in meteorological conditions between these two years is a likely cause of the greater ablation totals, the ice cliffs ~~ablate at a temporally constant rate relative to the mean tongue~~seem to contribute a constant share to the total ablation.

6.2 Influence of the emergence velocity and glacier flow correction on ~~p~~ f_C and f_C^*

In most studies quantifying ice cliff ablation (Immerzeel et al., 2014; Brun et al., 2016; Thompson et al., 2016), the glacier thinning rate was assumed to be directly equal to the net ablation rate, i.e. emergence velocity was assumed to be zero. If we make the same assumption (but include the corrections for horizontal displacement and the vertical displacement due to the slope), we find a mean thinning rate of 0.80 $\pm$ 0.10 m a^{-1} for the tongue and of 3.59 $\pm$ 0.17 m a^{-1} for the cliffs (average of UAV and Pléiades data) for the period November 2015–November 2016. In this case, the factor ~~p~~ f_C would be 4.5 $\pm$ 0.6 (and f_C^* would be 5.4 $\pm$ 0.7), which is 50 % higher than the ~~original value. Doing the same for~~ actual value. The cliffs would be found to contribute to $\sim$34 % of the tongue ablation. For the period November 2016–November 2017, the factor ~~p~~ f_C would be 3.6 $\pm$ 0.6 (and f_C^* would be 4.3 $\pm$ 0.7), which is 20 % higher than the ~~original value.~~ actual value. The cliffs would be found to contribute to $\sim$29 % of the tongue ablation. This might partially explain why previous studies found significantly higher values of ~~p~~ f_C, and stresses the need to estimate and take into account the ~~influence of emergencevelocity~~ice flow emergence, even for almost stagnant glacier tongues like Changri Nup Glacier (see Discussion below).

6.3 Ice cliff ablation and the debris-cover anomaly

Between November 2011 and November 2015, Vincent et al. (2016) quantified the reduction of area-averaged net ablation over the glacier tongue due to debris-cover. They obtained a tongue-wide net ablation of -1.2 m w.e. a^{-1} and -3.0 m w.e. a^{-1} with and without debris, respectively. As ice cliffs ablate at -3.5 m w.e. a^{-1}, $\sim$~~3~~ 3.6 times faster than the non-cliff terrain of the debris-covered tongue ~~, and only~~ for the period November 2015–November 2016, and $\sim$1.2 times faster than the tongue if it was entirely debris-free, approximately 75 % of the tongue would have to be covered by ice cliffs to compensate for the lower ablation rate under debris and to achieve the same overall ablation rate as a clean ice glacier under similar conditions. ~~As a consequence, it is unlikely that ice cliffs can explain the "debris-cover anomaly" as they~~ Since ice cliffs typically cover a very limited area ~~(Sakai et al., 1998; Buri et al., 2016b; Reid and Brock, 2014)~~(Herreid and Pellicciotti, 2018), it is unlikely that they can enhance the ablation of debris-covered tongues enough to reach the level of ablation of ice-free tongues.

Other ablation-related processes such as supra-glacial ponds (Miles et al., 2016) or englacial ~~hydrology~~ ablation (Benn et al., 2012) may contribute to higher ~~thinning~~ ablation rates than what can be expected on the basis of the Østrem curve. Yet this does not apply to the case of Changri Nup Glacier, as Vincent et al. (2016) already showed that the debris part as a whole is responsible for a significant reduction of ablation~~on debris-covered tongues and that the insulating effect of the debris surpasses the enhanced ablation processes~~. As a consequence, and based on this case study, we hypothesize that the reason for similar thinning rates over debris-covered and debris-free areas, i.e. the "debris-cover anomaly"~~can only be~~ , is largely related to a ~~combination of surface mass balance change and dynamics~~reduced emergence velocity compensating for a reduced ablation due to the debris mantle.

~~Indeed, let us consider theoretically one glacier with a tongue that is either debris-covered (case 1- referred hereafter as "DC") or debris-free (case 2 – referred hereafter as "DF"). In both cases, the mean glacier tongue thinning rate $\overline{\partial h/\partial t}$, follows the equation of mass conservation (Cuffey and Paterson, 2010)~~ This hypothesis currently applies to the Changri Nup Glacier tongue only, and it is unclear if it can be extended to the debris cover anomaly identified at larger scales. The high quality data available for Changri Nup Glacier are not available for other glaciers at the moment, and consequently we provide a theoretical discussion below.

The mass conservation equation (e.g., Cuffey and Paterson, 2010) gives the link between thinning rate ($\overline{\frac{\partial h}{\partial t}}$ in m a^{-1}), ablation rate and emergence velocity for a glacier tongue:

$$\overline{\frac{\partial h}{\partial t}} = -\frac{1}{\rho}\dot{b} + \frac{\Phi}{A} \qquad (10)$$

where Φ (m^3 a^{-1}) is the ice flux entering in the tongue of area A (m^2), ρ is the ice density (kg $m^{\cancel{-2}-3}$), and $\dot{b}$ is the area-averaged tongue net ablation (kg m^{-2} a^{-1} ~~). In the upper part of this glacier above the tongue, the ice flux is similar in both cases~~ or m w.e. a^{-1}). Consider two glaciers with tongues that are either debris-covered (case 1- referred hereafter as "DC") or debris-free (case 2 – referred hereafter as "DF"), and similar ice fluxes entering at the ELA i.e., $\Phi_{DC} = \Phi_{DF}$. ~~But~~ The ice flux at the ELA is expected to be driven by accumulation processes, and consequently it is reasonable to assume similarity for both debris-covered ~~glaciers have~~ and debris-free glaciers. There is a clear link between the glacier tongue area and its mean emergence velocity: the larger the tongue, the lower the emergence velocity. These theoretical considerations have been developed by Banerjee (2017) and Anderson and Anderson (2016), the latter demonstrating that debris-covered glacier lengths could double, depending on the debris effect on ablation in their model. Real-world evidence for such differences in debris-covered and debris-free glacier geometry remain largely qualitative. For instance, Scherler et al. (2011) found lower accumulation-area ratios for debris-covered than debris-free glaciers~~(Scherler et al., 2011). Their ablation area is thus expected to be~~ . Based on the data of Kraaijenbrink et al. (2017), we found a negative correlation (R = -0.36, p < 0.01) between the glacier minimum elevation and the percentage of debris cover (Fig. 10), hinting at both reduced ablation and a larger tongue for debris-covered glaciers.

Consequently, the qualitative picture we can draw is that debris-covered glacier ablation area is usually larger ($A_{\mathrm{DC}} > A_{\mathrm{DF}}$), leading to lower emergence velocity ($w_{e,\mathrm{DC}} = \Phi/A_{\mathrm{DC}} < \Phi/A_{\mathrm{DF}} = w_{e,\mathrm{DF}}$). If the glacier is in equilibrium, in both cases, the thinning rate at any elevation is 0, because the emergence velocity compensates the surface mass balance, but with lower magnitudes for both variables (w_e and $\dot{b}$) in case of a debris-covered tongue (Fig. 11).

~~In a transient~~ In an unbalanced regime with consistent negative mass balances, ~~the glacier response time of a debris covered glacier is longer compared with a debris-free glacier (Rowan et al., 2015), therefore the clean tongue will shrink faster than the debris-covered tongue, further enhancing the difference between A_{DC} and A_{DF}. The difference between emergence velocities will increase accordingly, with an enhanced emergence velocity over debris-free tongue and almost unchanged velocity over debris-covered tongue (Fig. 11). As a result and as already shown by Banerjee (2017) using a modelling approach~~as mostly observed in High Mountain Asia (Brun et al., 2017), similar thinning rates between debris-free and debris-covered tongues ~~are due to the fact that the~~ could be the combination of reduced emergence velocities and lower ablation ~~coincidently sum~~ roughly summing up to similar thinning rates as debris-free glaciers (Fig. 11). Additionally, there are evidences of slowing down of debris-covered tongues and detachment from their accumulations area, both leading to reduction in ice flux and consequently in w_e (Neckel et al., 2017).

In conclusion, ~~this term "debris-cover anomaly" comes from a confusion between thinning rates and net ablation and in turn we recommend to abandon the term.~~our field evidence shows that enhanced ice cliff ablation alone could not lead to a similar level of ablation for debris-covered and debris-free tongues. While we acknowledge the existence of other processes which can substantially increase the ablation of debris-covered tongues, we highlight the potential important share of emergence velocity in the explanation of the so-called 'debris-cover anomaly', which partly originates from a confusion between thinning rates and net ablation rates.

6.4 ~~Automatic delineation of cliffs~~

~~Previous studies automatically digitized cliff outlines using object-based analysis workflows (Kraaijenbrink et al., 2016b), or by identifying area of large elevation change (Thompson et al., 2016). The first methodology was not applicable to Changri Nup Glacier (neither on the UAV imagery, nor on the Pléiades imagery) due to the presence of shadows and the wide range of appearances of ice cliffs on the debris-covered tongue. Lower resolution datasets would not be suitable for object-based image analysis. The automatic delineation of cliffs as areas of large elevation change may not be reliable as the elevation change distributions of cliff and off-cliff overlap (Fig. 9). A combination of these two methods (i.e. including in the elevation change component in the object-based classification) might be a promising alternative in the automatic mapping of cliff outlines.~~

~~Nevertheless, 80 % of the total cliff contribution originates from the 20 largest cliffs in our study (Fig. 8), which are less challenging to map than the smaller cliffs.~~

6.4 Applicability to other glaciers

Determining the total ice cliff contribution to the net ablation of the tongue ~~,~~ (i.e.~~the p~~, the f_C factor defined in this study~~,~~) of a single glacier has limited value by itself, because we do not know the glacier-to-glacier variability. In particular, it is too early to conclude if the ~~differences~~ spread of f_C in the literature reflect the inconsistencies amongst the different methods used or the glacier-to-glacier variability. For instance, the f_C values from models (Sakai et al., 1998; Juen et al., 2014; Buri et al., 2016b; Reid and Brock, 2014) are not directly comparable with the observations ~~(Thompson et al., 2016; Watson et al., 2017).Up to now both neglected the flow components, and we advocate for a more consistent framework.~~ (Brun et al., 2016; Thompson et al., 2016) , because they usually require additional assumptions about e.g., the sub-debris ablation or emergence velocity.

A significant obstacle to applying our method to other glaciers is the need to estimate the emergence velocity, which requires an accurate determination of the ice fluxes entering the glacier tongues. The measurement of ice thickness with GPR systems is already challenging for debris-free glaciers, as it requires to drag emitter, receiver and antennas along transects of the glacier surface. It is even more challenging for debris-covered glaciers, as the hummocky surface prevents the operators from dragging a sledge. More field campaigns dedicated to ice thickness and velocity measurements (Nuimura et al., 2011, 2017) or the development of airborne ice thickness retrievals through debris are ~~recommended.~~ needed, as stressed by the outcome of the Ice Thickness Models Intercomparison eXperiment (Farinotti et al., 2017). The precise retrieval of emergence velocity pattern using a network of ablation stakes combined with DGPS is a promising alternative, in particular if combined with detailed ice flow modeling (e.g., Gilbert et al., 2016).

7 Conclusions

In this study, we estimate the total contribution of ice cliff to the total net ablation of a debris-covered glacier tongue for two consecutive years, taking into account the emergence velocity. Ice cliffs are responsible for 23-24 $\pm$ 5 % of the total net ablation for both years, despite a tongue-wide net ablation approximately 25 % higher for the second year. ~~For the case of~~ On Changri Nup Glacier, the fraction of total net ablation from ice cliffs is too low to explain by itself the so-called "debris-cover anomaly". Other contributions, such as ablation from supra-glacial lakes~~or englacial conduits~~, or even from englacial conduits, are potentially large and have to be quantified, but for the specific case of Changri Nup Glacier they are not large enough to compensate for the reduced ablation (Vincent et al., 2016). Consequently, we hypothesize that the "debris-cover anomaly" could be a result of lower emergence velocities and reduced ablation, which leads to *thinning rates* comparable to those observed on clean ice glaciers.

Our method requires high-resolution UAV or satellite stereo imagery, and is restricted to glaciers where thickness estimates at a cross section upstream of the debris-covered tongue are available and emergence velocity can be estimated. A comparison of ~~p~~ cliff ablation enhancement factor (f_C or f_C^*) values calculated for other debris-covered glaciers under our suggested framework would ~~inform~~ be informative, in order to compare estimates of ice cliff ablation for other and potentially much larger debris-covered tongues. Though our results cover only two years of data, the ~~p value remains constant for different~~ f_C value remained almost constant for net ablation totals ~~. A~~ differing by 25%. The main limitation of our study is its short spatial and temporal extent. It would be very worthwhile to obtain longer-term and multiple sites quantification of the relative ice-cliff contribution to net ablation~~is required to include these results~~. Then a compilation of these data would allow to develop empirical relationships for cliff enhanced ablation, which could be included into debris-covered glacier mass balance models.

In line with a previous study (Vincent et al., 2016), we advocate for the abandonment of the term "debris-cover anomaly", which is based on a confusion between thinning rate and net ablation, and we stress the need for more research about the emergence velocity of debris-covered (and nearby debris-free) tongues. Two research directions could be ~~extensive measurements of ice thicknesses and networks of stake measurements~~ (a) to measure cross sectional ice thicknesses for multiple debris-covered glaciers and (b) to install dense networks of ablation stakes to assess the spatial variability of ~~the~~ ice flow emergence.

Data availability. Data are available upon request to F.B.

Author contributions. F.B., P.W. and E.B. designed the study. F.B. and C.R. processed the terrestrial photogrammetry data, F.B. and E.B. the Pléiades data, P.K., W.I. and F.B. the UAV data. P.W., E.B., C.V., J.S., D.S. and F.B. collected the field data. All authors interpreted the results. F.B. led the writing of the paper and all other co-authors contributed to it.

Competing interests. The authors declare no competing interest.

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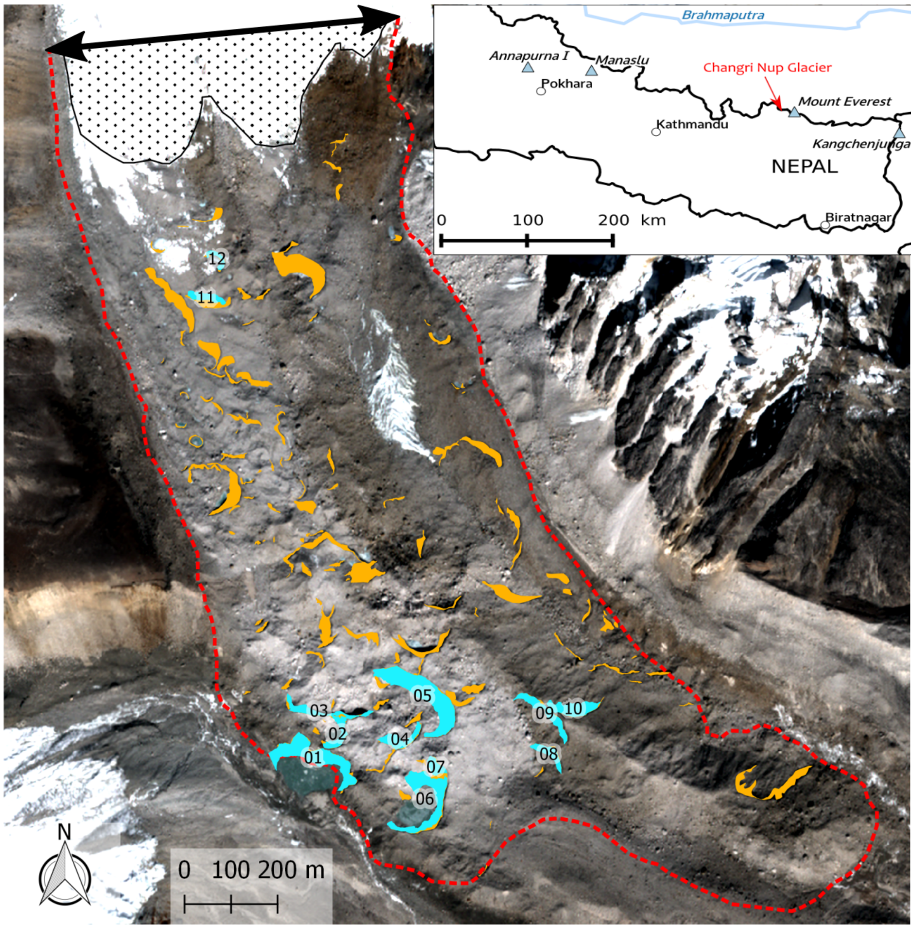

Figure 1. Map of Changri Nup Glacier tongue (red outline). The light blue shapes are the twelve cliffs surveyed with the terrestrial photogrammetry and the orange shapes are all the cliffs of the tongue. The background image is the Pléiades images of November 2016 (copyright: CNES 2016, Distribution Airbus D&S). The ice thickness was measured along the ~~upper line of the glacier tongue outline~~ black double-headed arrow in 2011 (Vincent et al., 2016). The dotted area is the debris-free part of the tongue (~~measured on~~ November 2017).

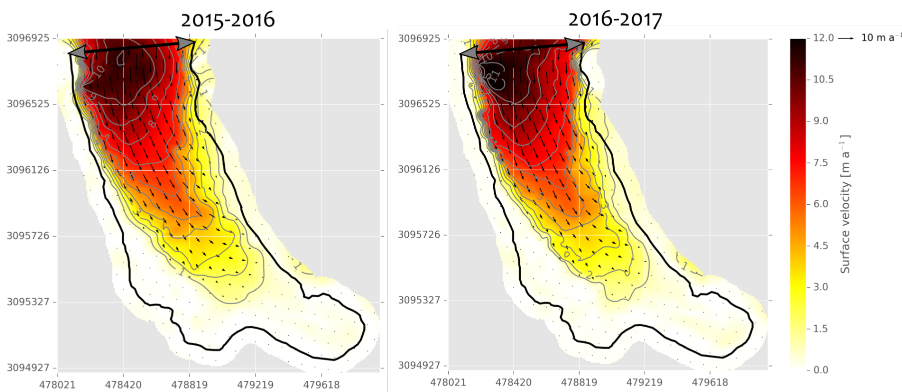

Figure 2. Annual horizontal velocity fields deduced from the correlation of Pléiades orthoimages. Coordinates are in UTM 45/WGS 84. The ~~field~~ black line is ~~linearly interpolated in~~ the ~~area of~~ tongue outline. The missing data in the velocity fields were filled using linear interpolation.

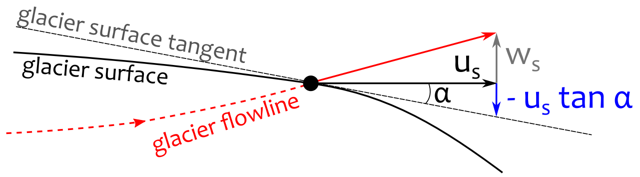

Figure 3. Definition of the different flow components, u_s is the horizontal velocity, w_s the vertical velocity and α the angle of the glacier surface tangent; adapted from Hooke (2005).

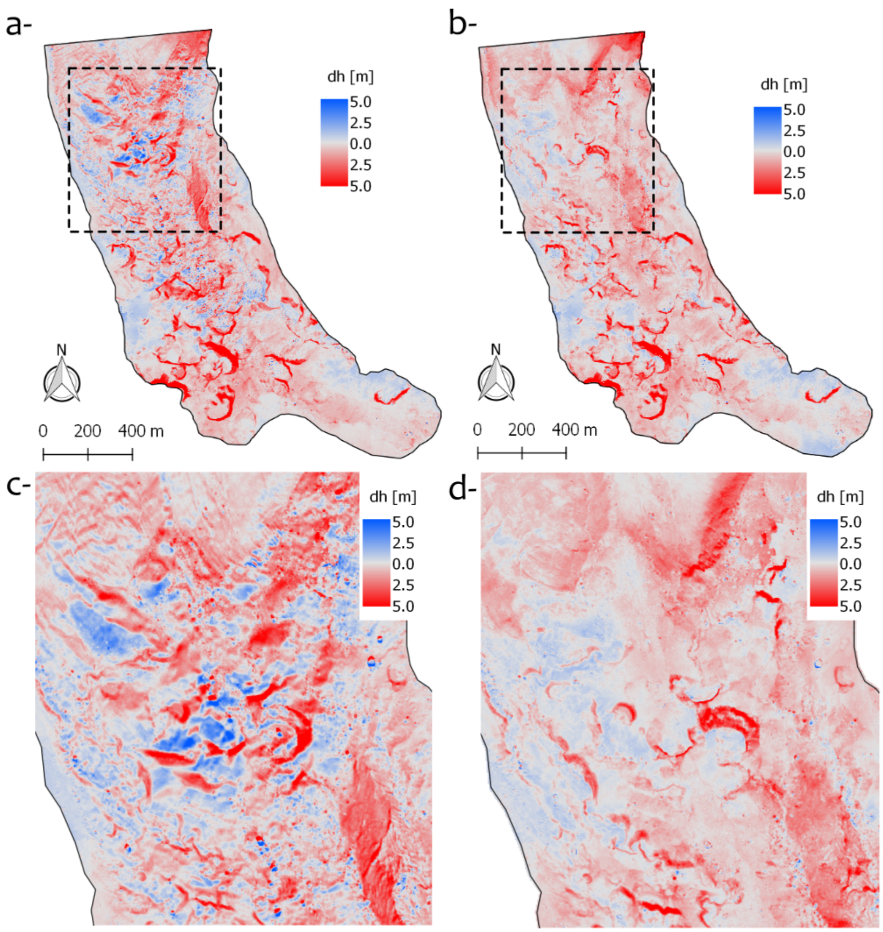

Figure 4. Panels showing maps of ~~: raw~~ elevation change ~~for~~ from UAV (a, c) ~~, elevation change corrected from~~ before flow ~~for UAV~~ correction and (b, d) ~~. The panels~~ after flow correction over the period 23/11/2015–16/11/2016. Panels c and d ~~correspond to a zoom in~~ are zooms of the ~~dashed rectangle (~~panels a ~~)~~and b, respectively.

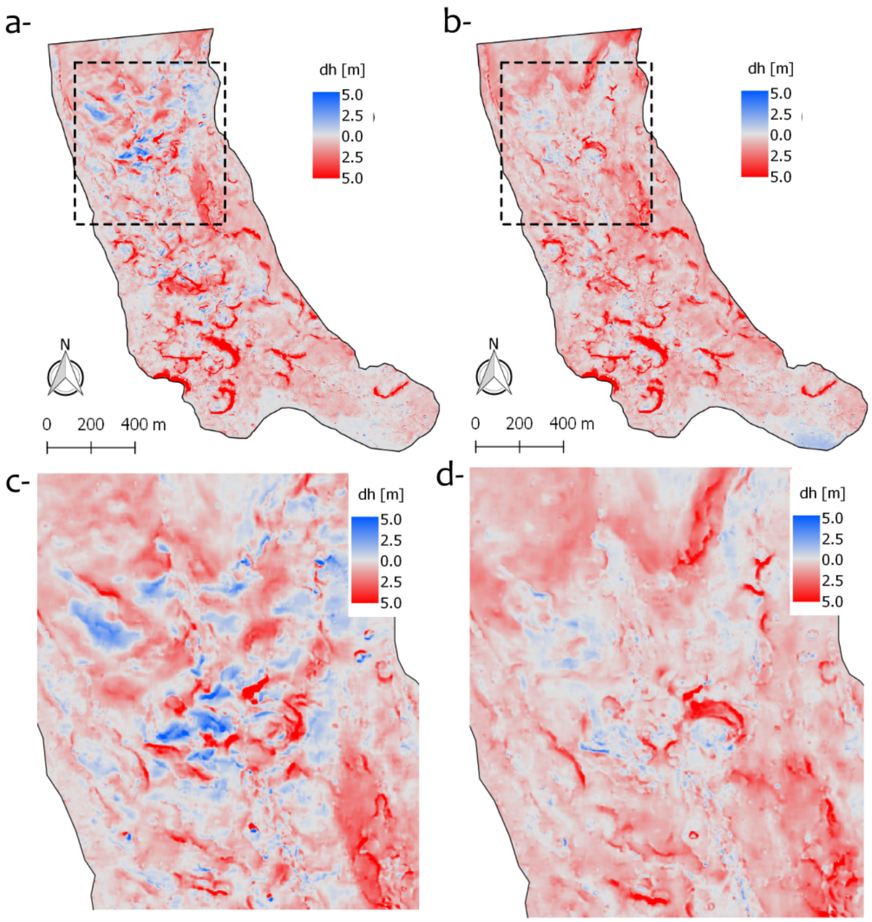

Figure 5. Panels showing maps of ~~: raw~~ elevation change ~~for~~ from Pléiades (a, c) ~~, elevation change corrected from~~ before flow ~~for Pléiades~~ correction and (b, d) ~~. The panels~~ after flow correction over the period 22/11/2015–13/11/2016. Panels c and d ~~correspond to a zoom in~~ are zooms of the ~~dashed rectangle (~~panels a ~~)~~and b, respectively.

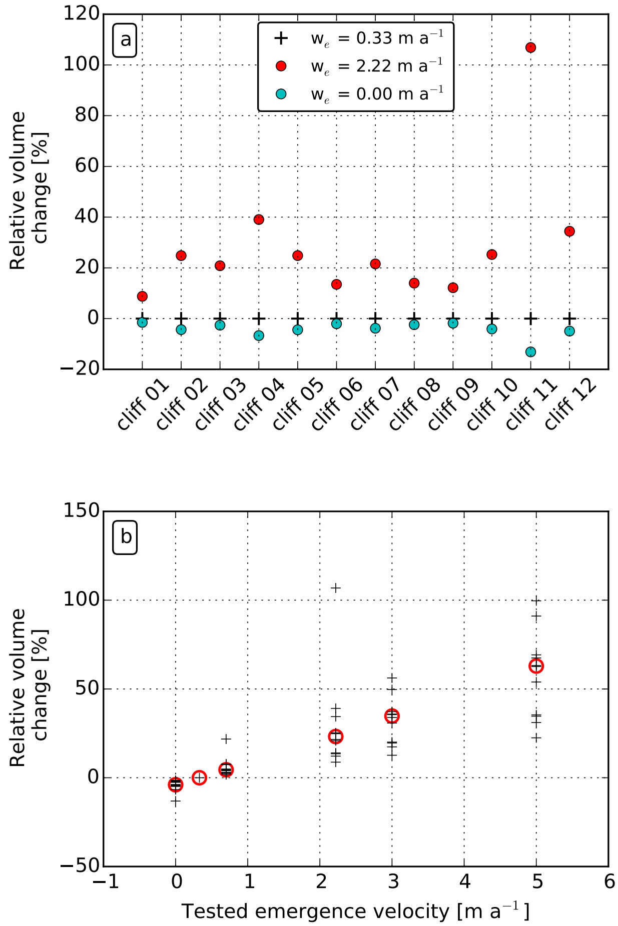

Figure 6. Sensitivity of the ~~normalized~~ volume change estimate to the emergence velocity for each cliff with two tested emergence velocities (a) and for all cliffs with various emergence velocities tested (b). The relative volume change is the tested volume change minus the reference volume change (obtained for $w_e = 0.33$ m a^{-1}), divided by the reference volume change and multiplied by 100. In the ~~latter~~lower panel, each cross ~~represent~~ represents a cliff and the open circles represent the median, note that cliff 11 relative volume change is not visible for emergence velocities ~~higher than 2.2~~ of 3.0 and 5.0 m a^{-1}, because it is ~~more than 150~~ equal to 153 and 255 %, respectively. The volume estimates are from terrestrial photogrammetry data~~.~~, for the period November 2015–November 2016.

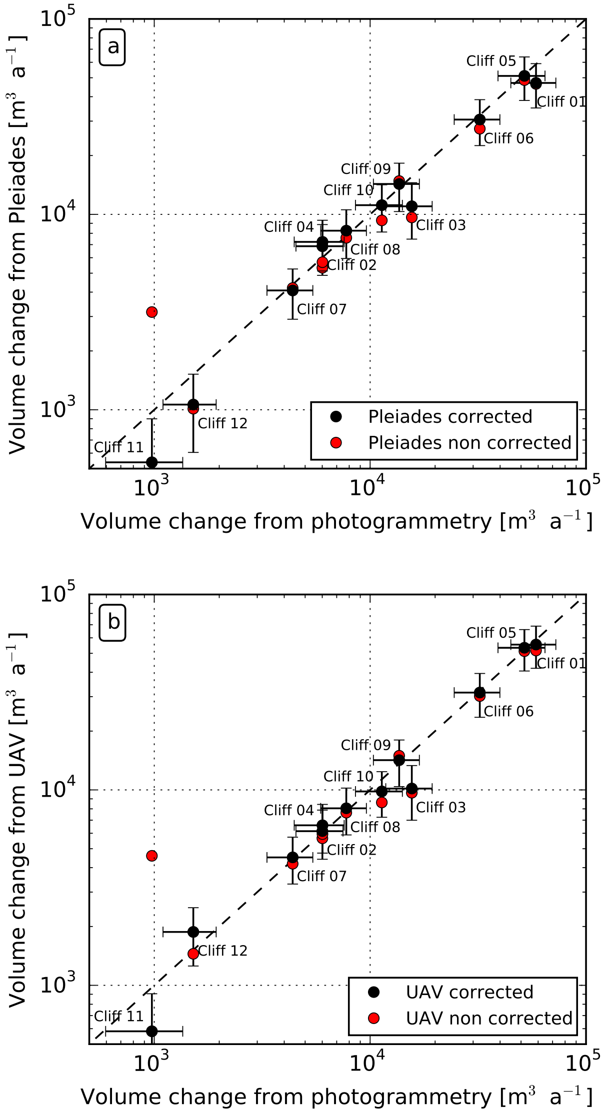

Figure 7. Comparison of the ice cliff volume changes estimated from DEM differences between UAV (a) or Pléiades (b) and terrestrial photogrammetry~~.~~, for the period November 2015–November 2016. Note the log scale. For each panel, "corrected" means taking into account the geometric corrections due to glacier flow and "non corrected" means neglecting them.

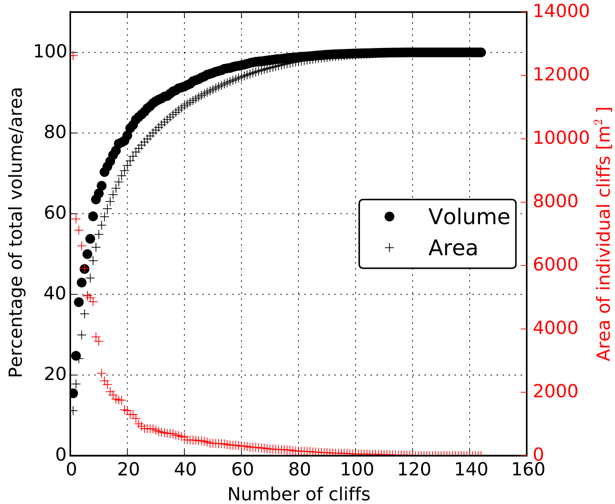

Figure 8. Individual ice cliff contributions for the period November 2015–November 2016 based on the UAV data. The left axis shows the cumulative volume (black dots) and area (black crosses), expressed as a percentage of the total volume or area, respectively.

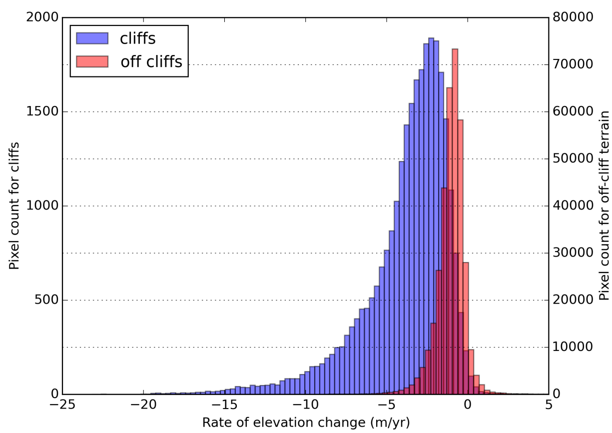

Figure 9. Rate of glacier surface elevation change for cliff and off-cliff terrain (Pléiades DEM difference November 2015–November 2016, corrected from flow). Note the strongly different Y axis.

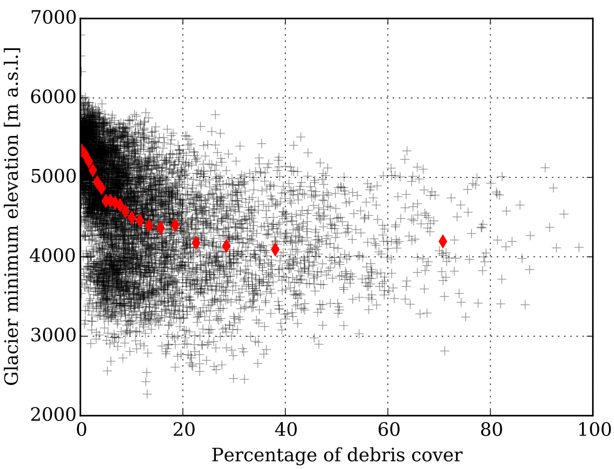

Figure 10. Glacier minimum elevation as a function of the percentage of debris cover for the glaciers larger than 2 km^2 in High Mountain Asia. The black crosses represent individual glaciers and the red diamonds shows the mean of the glacier minimum elevation. For instance, the first diamond represent the mean of the glacier minimum elevation for glaciers with a percentage of debris cover between 0 and 0.51% (5th percentile).

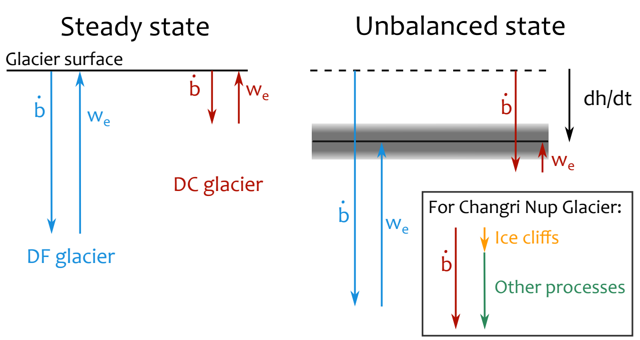

Figure 11. Conceptual representation of the interplay of net ablation ($\dot{b}$) and emergence velocity (w_e) for debris-free (DF, blue color) and debris-covered (DC, brown color) glacier tongues. In the left panel both glaciers are at equilibrium (no thinning) and in the right panel their tongues are thinning at roughly the same rate $\overline{\partial h/\partial t}$, shown by the grey shaded area. In the unbalanced state, the values are scaled according to Vincent et al. (2016). For the steady state, we assumed a similar emergence velocity for the debris-free tongue. The inset shows the share of the ice cliffs versus the other processes for the tongue-wide ablation on Changri Nup Glacier tongue. It is noteworthy that this representation is only conceptual, that it is based on our current understanding of the interplay of ablation and ice dynamics of a single, small glacier tongue (Changri Nup), and that the emergence velocity values are very poorly constrained.

Table 1. Characteristics of the 12 surveyed cliffs. The 3D mean area ~~(A_{3D})~~ was calculated as the mean of the November 2015 and 2016 areas, which were measured from the PCs obtained with the terrestrial photogrammetry on CloudCompare. The perimeter was calculated from the cliff footprint of November 2015 and 2016. The backwasting rate was calculated as the ratio between the cliff backwasting volume obtained from terrestrial photogrammetry and the 3D mean area, for the period November 2015–November 2016. The cliffs are usually not perfectly planar and they exhibit multiple aspects. The main aspects were calculated by fitting a plan through the cliff PC or through parts of the PC in CloudCompare, the main aspect is in bold when it was possible to determine it.

Cliff ID	3D mean area [m^2]	Cliff footprint [m^2]	Footprint perimeter [m]	Elevation [m a.s.l.]	Backwasting rate [m a^{-1}]	Main aspects (slope [degree])
Cliff 01	7543	6575	711	5330	7.5 ± 0.6	**SW** (44°) / S (46°) / W (39°) / NE (59°)
Cliff 02	1315	1406	260	5343	4.4 ± 0.5	SW (25°) / NW (29°)
Cliff 03	3033	1821	479	5347	4.9 ± 0.5	**N** (69°)
Cliff 04	1851	1774	286	5352	3.1 ± 0.4	**N** (42°) / NW (57°) / E (36°)
Cliff 05	11294	8592	607	5353	4.4 ± 0.5	**SW** (44°) / NW (51°)
Cliff 06	5267	5064	639	5331	5.9 ± 0.5	N (60°) / W (52°) / S (45°) / SW (86°)
Cliff 07	752	979	153	5350	5.6 ± 0.5	**SW** (41°)
Cliff 08	1282	1307	227	5325	5.8 ± 0.5	S (58°) / SW (59°)
Cliff 09	2408	2263	386	5350	5.4 ± 0.5	**SW** (60°) / S (46°)
Cliff 10	2426	2521	284	5338	4.5 ± 0.5	**N** (35°)
Cliff 11	775	630	194	5452	1.2 ± 0.4	**N** (38°)
Cliff 12	587	653	165	5464	2.5 ± 0.4	W (58°) / SW (50°) / S (40°)

Table 2. Characteristics of the three UAV flights. The horizontal and vertical residuals are assessed on independent additional GCPs~~(Agisoft, 2017)~~. The virtual GCPs are reference points taken in stable ground from the 2015 UAV DEM and orthomosaic, and used as GCPs to derive the 2016 UAV DEM and orthomosaic. For the 2015 and 2017 campaigns, the GCPs were in sufficient number and consequently we did not use virtual GCPs. For the 2016 campaign, we used all the available GCPs to derive the DEM, and consequently could not evaluate the residuals.

Date of acquisition	Number of images	Number of GCPs	Number of virtual GCPs	Horizontal residuals (cm)	Vertical residuals (cm)
22–24/11/2015	582	24	0	4	10
16/11/2016	475	17	16	N/A	N/A
23/11/2017	390	30	0	11	14

Table 3. Characteristics and IDs of the Pléiades images. Horizontal shifts relative to the UAV ortho-images are also given.

Date of acquisition	~~B/H~~ Base to height ratio (B/H)	Shift eastward (m)	Shift northward (m)
22/11/2015	0.36;0.26;0.10	-4.3	0.3
13/11/2016	0.47;0.28; 0.20	6.6	3.7
24/10/2017	0.34;0.25;0.09	1.0	4.2