**Dear Editor and Reviewers,**

We thank the reviewers for their valuable comments. Here we address how we will revise the manuscript. The comments are in italic font, which are followed by our replies in bold font.

## Reply to Anonymous Referee #1

*The conclusions of the paper are not very surprising, as the relationships between rockwall area (and orientation) and supraglacial debris are well known (e.g. Benn 1989, Journal of Quaternary Science). The present paper does go far beyond that early work in terms of the size and quality of the dataset, however.*

**Response: We will add Benn (1989) to the references cited in P1676L7 as:**

**"On the other hand, it has been pointed out that asymmetric shape of terminal moraines were strongly correlated with aspects of source walls (Benn, 1989). In the Kangchenjunga Valley of the Nepal Himalaya, frequency of rockfall events….".**

*I am unsure whether The Cryosphere is the most appropriate home for this paper. The findings will be of interest to geomorphologists, although perhaps not to the glaciological community. Perhaps it would be better suited to one of the specialist geomorphological journals such as Earth Surface Processes and Landforms or Geomorphology. But that is an editorial decision.*

**Response: We selected The Cryosphere because of its open-access policy while those proposed journals are not.**

## Reply to D. Shugar

*Generally speaking, the manuscript is well-written although there are some confusing passages that should be clarified, and some comparisons to other mountain ranges (e.g. Akaishi Range, Japan) that seem out of place.*

**Response: At the sentence beginning from P1685L12, we do not compare those regions but describe the actual scale of freeze-thaw cycles and depth. Anyhow, we will delete this sentence "The frequency of…" to avoid confusion.**

*Two factors that I would have thought would play a big role in debris production – geological setting and post-Little Ice Age glacier thinning (by debuttressing on north vs south slopes) are not discussed at all, and should at least be mentioned.*

**Response: In terms of LIA, we will add the following description after P1688L17:**

**"In longer term, degradation of glaciers since the Little Ice Age (LIA) should have released PDS slopes, and thus caused more preferable condition for debris supply.".**

**And we will change the following sentence beginning from P1689L5 as:**

**"On the Bhutanese side, however, sufficient precipitation might explain the lack of a latitudinal gradient in**

**debris production. In this region, local relief of the PDS slopes, which has been exposed since the LIA would be the primary control of debris supply to the glaciers.".**

**In terms of geological settings, we will add the following paragraph after P1688L3:**

**"In addition, lithological settings in the study region are categorized into metamorphic rocks in the southern area and sedimentary rocks in the northern area divided by the main Himalayan ridge (Long et al., 2012). Although their hardness is difficult to be evaluated quantitatively, more distribution of shattered zones formed by the Himalayan uplift is expected in the southern area supported by the complex geological features shown in Long et al. (2012).".**

*Last, it is not clear how the authors know which are the potential debris supply (PDS) slopes in the first place.*

**Response: We included any possible slopes continuously inclining toward individual glaciers as the PDS slopes because the remotely-sensed snapshot cannot provide the activity of rockfall. We will revise the description and a figure corresponding to your following comment on P1677L25. Please see below.**

*P1675 L4 – See also Shugar et al. (2012, JGR doi:10.1029/2011jf002011).*

**Response: We will add the description in P1675L5 as:**

**"For instance, thick debris coverage induced by a landslide drastically changed glacier mass balance and flow velocity (Shugar et al., 2012).".**

*P1675 L6 – It is unclear why ponds should be considered rugged topography.*

**Response: Supraglacial ponds are formed in rugged topography of debris-covered area. Even though a thick debris layer disturbs heat transfer between ice and the atmosphere, the ponds absorb the solar radiation and provide heat energy to the ice when the pond water drains through englacial water paths. Detail description was written in Sakai et al. (2000; 2002). The sentence beginning from P1675L5 will be changed as:**

**"However, topographically rugged surfaces are also known to cause considerable ice melting in debris-covered areas, where numerous ice cliffs and supra-glacial ponds effectively absorb and transport the solar radiation for ice melting such as hotspots (Sakai et al., 2000, 2002).".**

*P1675 L16 – The paragraph describing implications for glacier lake outburst floods, while important, is perhaps a little long. Since glacier lakes are not the focus of the paper, and indeed hardly appear in it at all except for here, I suggest shortening this paragraph.*

**Response: We will make it shorter as:**

**"Spatially heterogeneous debris cover also has potentially important implications for risk assessment of glacial lake outburst floods. Glacial lakes are larger and more numerous in the eastern Himalaya, such as Nepal and Bhutan, compared with the western Himalaya (Gardelle et al., 2011). In the Nepal Himalaya, glaciers with thinner debris cover typically have lakes at their termini (Suzuki et al., 2007). Inclination and surface lowering of the debris-covered areas are probably associated with lake formation (Sakai and Fujita, 2010; Salerno et al., 2012). In Bhutan Himalaya, glacial lakes on the southern side expanded faster than**

**those on the northern side (Komori, 2008), which is probably associated with topography (Kääb, 2005).".**

*P1677 L25 – It is unclear what is meant by "…delineation error was modified." Please clarify. Further, it is unclear why the authors overlaid the 2.5-m PRISM- and 10-m AVNIR-derived glacier outlines onto Google Earth imagery. Is the Google Earth data higher resolution?*

*P1678 L1 – I don't understand what "topographic contour lines" used to delineate glacier outlines are. Do the authors mean they looked at the inflection point in the lateral slopes?*

*P1679 L14 – As above, what role does Google Earth play in the analysis?*

*P1679 L19 – The description of the potential Debris supply slopes is somewhat confusing. A figure might help to clarify.*

*P1679 L25 – Why were the lateral and terminal moraines included?*

**Response: We will add a new figure (attached below) and revise the description of glacier delineation (Chapter 2.3, P1679) as:**

**"No promising algorithm has yet been developed for automated mapping of debris-covered glaciers (Racoviteanu et al., 2009; Paul et al., 2013), and although the Global Land Ice Measurements from Space (GLIMS) provides a global glacier database, its use of relatively low-resolution ASTER VNIR sensors (15 m) has resulted in identification of incorrect boundaries between glacier ice and ice-free surfaces covered by snow in the Bhutan Himalaya. As such, it was necessary to manually delineate glaciers on PRISM and AVNIR-2 images using the standard definition of glacier outlines, following Raup and Khalsa (2007) and Rastner et al. (2012). Visual interpretation of higher resolution PRISM images enabled exclusion of snow-covered terrain, whilst gradational shading and crevasses were used to identify glacier ice. In the uppermost snowfield, where less contrast made difficult to identify glacier boundary, contour lines derived from ASTER GDEM-2 were utilized to divide glaciers.**

**Debris-covered areas were identified using PRISM images (2.5-m resolution) and Google Earth™ high-resolution images. Rugged, small-relief supra-glacial ponds and ice cliffs are typical features for a relatively thick debris cover and are not found on lateral moraines or bedrock terrains around glaciers. Upper boundary of debris cover often varies in several PRISM images taken on different dates. In such case, we adopted the most spread outline by considering temporal snow cover.**

**We define potential debris-supply (PDS) slopes that could supply the debris mantle. Such slopes were manually extracted as the continuous slope between the glacier margin and mountain ridges, downward to the glacier, using contour lines at a 20-m interval and a slope map derived from ASTER GDEM-2 (Fig. R1). More precise interpretation is given by the PRISM images. Rockfall- or avalanche-induced scars and traces are identified as rockfall possibility (Fig. R1). Slopes intercepted by hills or lateral moraines were excluded from the PDS slopes because rockfall would be prevented. Slopes with ephemeral snow cover were included to account for debris-supply induced by snow avalanches (e.g. Scherler et al., 2011b). Lateral and terminal moraines, which consist of allochthonous glacially transported sediment, were also included because we had no reliable threshold to separate them. Their area is, however, expected to be quite smaller than that of the headwalls which is the dominant part of PDS slopes.**

**For further quality check, we imported delineated glacier polygons onto Google Earth™ with the 0.8-m Quickbird-derived images taken in different dates.".**

*P1680 L21 – It is surprising that the melting point was exceeded at elevations of up to 7500 m asl in winter! Wow.*
*P1681 L8 – I found it very interesting that north-flowing glaciers had smaller debris-covered areas than south-flowing glaciers.*
**Response: Thanks.**

*P1682 L17 – I like the idea of the geometric shape index. It is similar to what we did in Shugar and Clague (2011), where we calculated adimensionless spreading index as the quotient of the landslide deposit's maximum and initial widths.*
**Response: We will refer to Shugar and Clague (2011) after P1682L19 as: "This is a similar concept to an index proposed by Shugar and Clague (2011). ".**

*P1683 L14 - I don't understand how the authors know which particular slope(s) failed in any particular case. For example, in Figure 6, which slope failed (or both?), to provide all the debris on the south-facing glacier? Part of the headwall is also north-facing. This is an important point that is not discussed in the manuscript.*
*P1683 L 22 – Some large leaps of faith are required for this last sentence.*
**Response: We do not identify vulnerability of particular slopes. We will modify the sentences after P1683L13, and add a new sentence and a new paragraph as:**
**"…. of the Bhutan Himalaya overall.**

**Comparing the shapes of debris-covered area and the spatial distributions of south- and north-facing PDS slopes for these two glaciers (Fig. 6), dominant debris supply is expected from the south-facing PDS slopes rather than the north-facing PDS slopes. The south-flowing glacier has a south-facing PDS slope with a wide headwall immediately above the accumulation area (Fig. 6). Debris-covered areas are separated by debris-free surfaces on this slope, and the mantle in the accumulation zone is likely to be entrained and transported down the glacier, re-appearing in the ablation zone (e.g. Hambrey et al., 1999). On the other hand, the northflowing glacier has south-facing PDS slopes on either side of glacier tributaries, with debris-covered areas starting at the foot of these slopes. The debris mantle appears to be primarily transported on the surface of the glacier, with less entrainment than that of the south-flowing glacier. The contribution of the southwest-facing PDS slope to debris supply suggested here is well consistent with the result in Fig. 5a even though the approach is different. These differences suggest that the shape of debris-covered areas is also controlled by the spatial distribution of south-facing PDS slopes around a glacier, which is in turn coupled with the ice flow direction.".**

*P1685 L11 – As described above in the general comments, I think the authors need to discuss other possible mechanisms for debris transfer from the slopes to the glaciers. The two most obvious are geological setting (both lithology and tectonic setting) and magnitude of post-LIA glacier thinning and debuttressing.*

**Response: We replied these possibilities above.**

*P1686 L20 – Another relevant study is by Shugar et al. (2012, JGR).*

**Response: We will add this paper.**

*P1687 L6 – I suggest the authors cite any number of Ken Hewitt's papers in which he describes avalanche-fed glaciers in the Karakoram.*

**Response: We will refer to Hewitt (2011) as a following paragraph added after P1687L12:**

**"In the Karakoram, on the other hand, avalanche-fed glaciers are well developed hosting the large area of debris cover, and their nourishment occurs in winter and summer simultaneously (Hewitt, 2011). Less possibility of freeze-thaw activity on the surrounding slopes is thus expected due to constant snow cover. In this region, therefore, snow avalanche is expected to have larger portions of debris supply comparing with that in the Himalayas, where arid winter climate could cause the exposure of headwall. Comparison of the glaciers located in the Himalayas and the Karakoram with the PDS-slope analysis will reveal regional difference of the debris-supplying mechanisms.".**

*P1701 Fig 4 – In the figure, r values are given (e.g. r=0.81) but in the caption, R^2 values are given (e.g. R^2=0.80). Are these typos or intentionally different?*

**Response: Those are not typos. The R^2 values are given for the regression lines. On the other hand, r values are given for correlation coefficients among PDS slope and debris-covered area.**

*P1702 Fig 5 – I'm not sure this figure is necessary.*

**Response: We think that is necessary for our discussion because it strongly shows the aspect (and gradient) dependency of debris-supply probability. Our discussion on debris-supply mechanism is based on these findings.**

**Technical Corrections**

*P1676 L15 – The sentence beginning "In this study…" should begin a new paragraph.*

**Response: We will correct this.**

*P1684 L17 – Do the authors mean decimetres rather than deca-centimetres?*

**Response: We will correct this.**

*P1686 L17 – The sentence beginning "In the course of our research…" should begin a new paragraph.*

**Response: We will correct here.**

P1694 L14 – GJ Young's last name is misplaced. Instead of after GJ, it is before the word 'Edited', on L13.

**Response: We will correct this as: Mattson, L. E., Gardner, J. S., and Young, G. J.: Ablation on debris**

**covered glaciers: an example from the Rakhiot Glacier, Punjab, Himalaya, in: Snow and Glacier Hydrology, edited by: Young, G. J., IAHS Publ., 218, 289–296, 1993.**

**Additional references:**

Benn, D. I.: Debris transport by Loch Lomond Readvance glaciers in Northern Scotland: Basin form and the within-valley asymmetry of lateral moraines, J. Quat. Sci., 243–254, doi:10.1002/jqs.3390040305, 1989.

Hewwit, K.: Glacier change, concentration, and elevation effects in the Karakoram Himalaya, upper Indus basin, Mt. Res. Dev., 31(3): 188–200, doi:10.1659/MRD-JOURNAL-D-11-00020.1, 2011.

Long, S., McQuarrie, N., Tobgay, T., Grujic, D., and Hollister, L.: Geologic map of Bhutan, J. Maps, 184–192, doi:10.4113/jom.2011.1159., 2011.

Shugar, D. H., Rabus, B. T., Clague, J. J., and Capps, D. M.: The response of Black Rapids Glacier, Alaska, to the Denali earthquake rock avalanches, J. Geophys. Res., 117, F01006, doi:10.1029/2011JF002011, 2012.

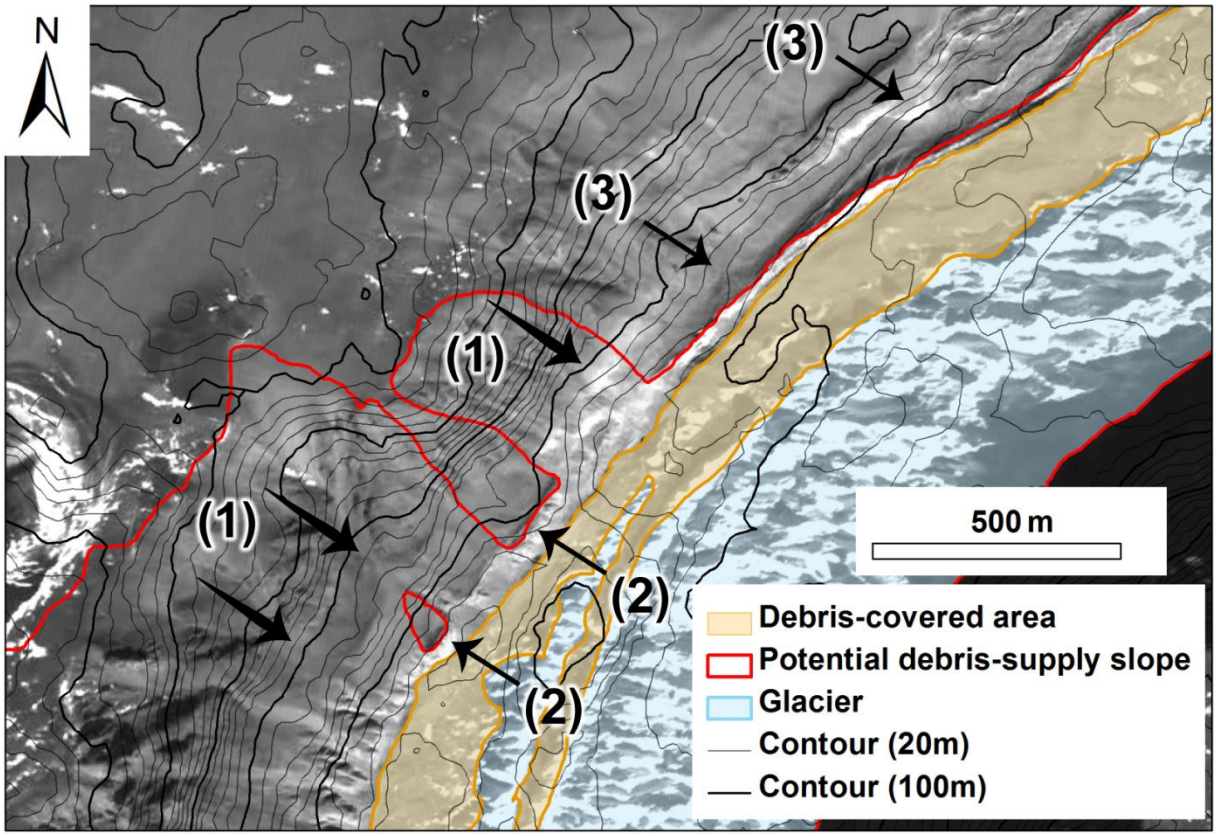


Fig. R1) Visual interpretation of potential debris-supply slopes on a PRISM image. (1) Traces or scars show the possibility of debris supply. (2) Small hills identified by shadings and (3) depressions outside lateral moraine may prevent debris supply.