+ Dear Adina Racoviteanu, (corresponding to tcd-8-C666-2014)

We thank you for your valuable comments. Here we address how we will revise the manuscript corresponding to your general and specific comments. The comments are in italic font, which are followed by our replies in bold font.

The study by Nagai et al aims at providing topographic and climatic influences on the distribution of glaciers in the Bhutan Himalaya. This is a relevant objective, since 1) little is known on the distribution of glaciers, and their characteristics in this part of the Himalaya and 2)more research is needed on the debris-covered glaciers across the Himalaya, particularly their characteristics. Combining topographic and climatic factors to characterize thèse glaciers is whorthwile; however, at this point it seems that the paper lacks a rigurous statistical analysis to justify this.

I would suggest revising the objectives, and the results/discussion and re-‐submit at a later time. I think this can still be a valuable contribution, but needs to be thoroughly revised.

Here we will change our manuscript substantially. We will remove the analysis on PMS slope and precipitation data. Instead, more detail explanation of glacier delineation method, results of basic topographic analysis, and discussion of delineation accuracy through comparison with other glacier inventories will be added. We aim to revise this manuscript to the following frame.

Temporary tittle: Comparison of glacier inventories in the Bhutan Himalaya

Introduction

- **Introduction of present glacier inventories and their delineation methods**
- **Introduction of the outlines of glaciers in the Bhutan Himalaya generated by Nagai et al. (2013)**
- **Issue: The quality of the inventories in the Bhutan Himalaya is not validated.**
- **Purpose: This study aims to compare the qualities of manual delineation (i.e. our inventory) and semi-automatic delineation (i.e. the ICIMOD inventory, GLIMS database, and the RGI), and show sensitive and insensitive variables of glacier distribution in the Bhutan Himalaya.**

Data sets

- **Description of the Bhutan Himalaya**
- **Data and processing of ALOS PRISM/AVNIR2 images**
- **Data and processing of ASTER GDEM2 data**

Methods

- **Description of manual glacier delineation**
- **Flowchart of delineation process**
- **Figures of delineation process**

Results

- **Basic statistic and topographic variables obtained by our outlines**
- **Characteristics of the glaciers in the Bhutan Himalaya focusing on north-to-south contrast**

Discussion

- **Quality comparison between pre-revised and revised outlines of ours.**
- **Quality comparison between our revised inventory and other inventories**

- **Analysis of sensitive and insensitive variables among these different inventories**

Conclusion

- **Largely different values and similar values of glacier distribution variables among the different glacier inventories**

General comments

- *I am not convinced by the emphasis on the contribution of PMS to debris cover distribution. The authors assume that this is one of the key controlling factors, and a particular focus is placed on this. Is there really a need to place a focus on this, particularly when this is approached in a rather simplistic way? Rather than this, I would suggest using a rigorous statistical analysis to explore the contribution of all topographic variables, or just focus on the debris cover and its characteristics, which would be a good contribution.*

A rigorous statistical analysis of PMS slope for debris supply has been done by Nagai et al. (2013). This manuscript was built on it and discussed elevation deviation caused by the PMS slope, which contribute as avalanche accumulation. Anyway, we will remove further description of the PMS slope at this stage to avoid misunderstanding.

- *Similarly, I do not see the need for an emphasis on ELA (as derived from median elevation) here. There is no need to point out obvious facts such as ELA decreases in humid climates or with increased accumulation etc…, and decidate a whole section on proving this point.*

Another reviewer also suggested the flaws of analysis for ELA, therefore we will remove the analysis of ELA and precipitation data in the revised manuscript.

- *I do not fully agree with the glacier delineation method chosen, ie the authors state that automatic glacier delineation is not possible in this area. Almost no remote sensing studies in this area (or other) claim to be using a fully automated method for glacier delineation, but rather a semi-automated one (band ratios for clean ice with some manual corrections, and more manual methods for debris cover). Thus, the approach is not fully justified, and also makes it difficult to compare with other inventories (ie ICIMOD), which rely on semi-automated methods.*

Manual delineation by PRISM panchromatic image enables delineation of small glaciers which semi-automated methods by Landsat image and its manual modification cannot identify. An example is shown in the reply to the specific comment by F. Paul for P1309, L9/10 (Fig. AC7). Fortunately the ICIMOD inventory was updated recently and its quality seems fine. In the revised manuscript, therefore, we will compare and evaluate our inventory and other inventories to clarify how glacier topographic variables are affected by the quality difference of these outlines.

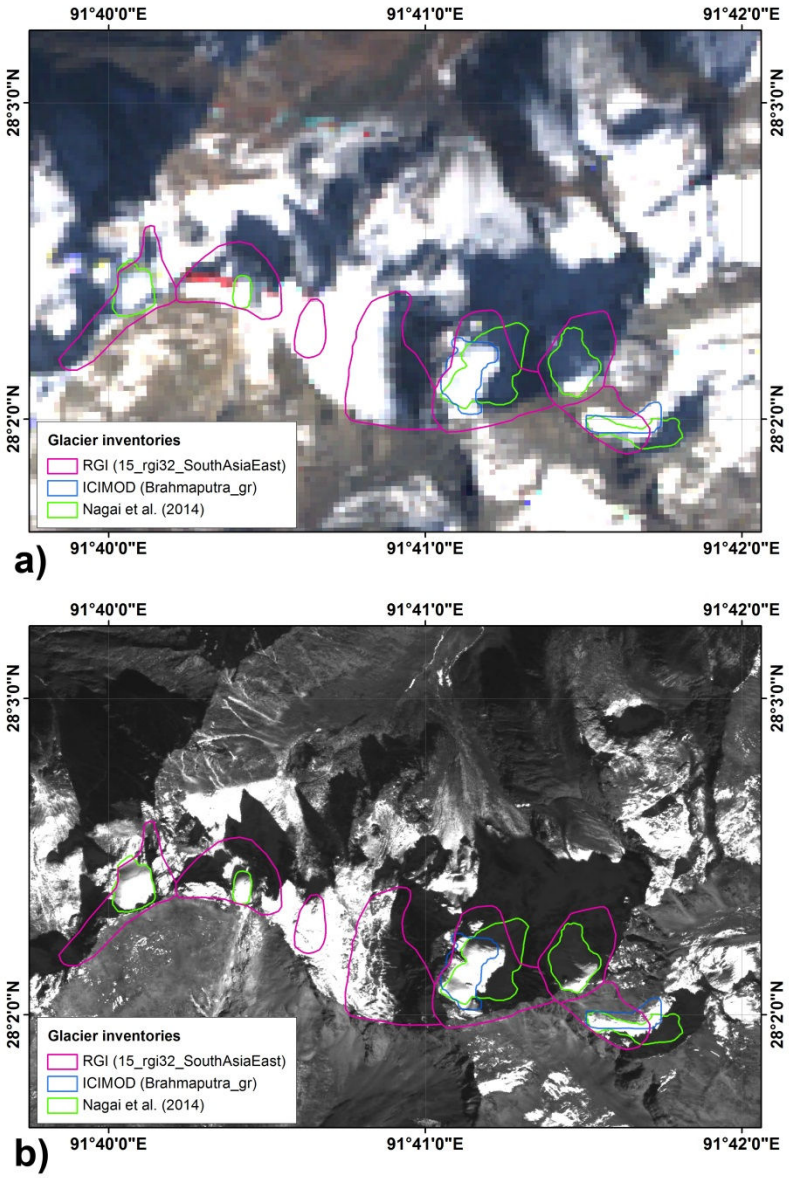

Fig. AC7. Comparison of (a) a Landsat ETM+ image and (b) an ALOS/PRISM image. Outlines of the RGI, ICIMOD inventory, and our inventories are overlaid.

- *The objectives of the studies should be re-considered. I think it is first worthwhile presenting a detailed glacier inventory for Bhutan, before attempting to explain the role of topographic factors. While this has been published before by ICIMOD, in this area it is worthwhile to continue updating these inventories with new analysis. Therefore, I think there can be a meaningful contribution in presenting an updated glacier inventory, with a thorough analysis on the distribution of debris cover. The methods need to be expanded, in general they lack much needed detail, eg how where the ice divides delineated, how were the topographic factors chosen and derived, the pixel size, accuracy of the image orhorectification, GIS methods and other small details such as this. A short literature review of previous glacier inventories is needed, ie previous work of Mool et al, Karma et al, etc… and note what the research gap is. Also, a discussion of data scarcity in this region would be useful, ie lack of adequate topographic maps, limitations in satellite imagery due to frequent cloud cover, etc… (this discussion is in lines 85—92 currently), but it would be more appropriate in the introduction. The separation of debris vs dirty ice do not seem appropriate to me. I suggest the authors revise GLIMS methods carefully, see (Raup and*

Khalsa 2007; Racoviteanu et al. 2009; Paul et al. in press) and follow the same classification so that comparison with other studies is possible.

We appreciate your suggestions. We think that we have to clarify our method more in detail and visually. Including those references which you introduced us, we will reconstruct the manuscript focusing on glacier inventory itself. The outline is shown at the beginning of this reply.

- *Results are hard to follow since they contain a mix of glacier inventory results, PMS slope analysis, precipitation influences, and some uncertainty analysis. There are no clear glacier inventory results, and the focus on only those two variables seems subjective. Also, the statistic significance is not given, in most cases. Results contain a large number of assumptions which are not supported by the data, ie the solar radiation control on debris cover, the influence of aspect, glacier size, etc… I am not sure about the meaningfulness of some of the results, ie what does it mean that the hypsometry of debris cover vs debris free glaciers is different, or that median elevations are different? These are valid types of analysis, often done in a glacier inventory, but they need to be put in context, ie either present glacier inventory results, or compare and contrast the two types of glaciers, or use this information to explain some differences in the behavior of the two types.*

We apologize for the inconvenience. Description and analysis of PMS slope will be removed. Then simpler analysis of glacier statistical facts and topographic characteristics will be done, referencing to what previous papers were done on glacier inventories in other regions.

- *The discussion section needs much work, as the focus on PMS and ppt gradient is not justified. What does it mean that « terminus elevation and median elevations appear stable? » , and other statements such as this ?*

Again, we will remove PMS slope and precipitation data in the revised manuscript. 'Terminus elevation and…' means that relatively lower minimum elevation of the debris-covered glaciers than those of debris-free glaciers (Fig. 6) and median elevation which is lower for heavily debris-covered glaciers (Fig. 8) suggest slower retreat of the debris-covered glaciers. We will modify our English sentence to be more specific expression.

Specific comments;
Line numbers 'L xx' which you noted do not matched the original line number, suggesting that the line number was changed while you were reviewing the manuscript. Therefore we added original line as (PyyLzz) at the beginning of your comments for convenience.

(PL1307L13–L22) *L46-54 The ELA discussion in the introduction is a bit simplistic, and I am not sure of its utility here (ie ELA is lower in larger snow accumulation). I suggest revising this paragraph, or better integrate in the presentation of the objectives.*

We will not analyze ELA and precipitation data in the revised manuscript.

(P1307L24) *L 56 « which potentially prevents ice melting if the debris layer is sufficiently thick'" This statement is not sufficient, nor the references A thorough discussion of the role of thin vs thick debris cover, the critical thickness, as well as reference some more recent studies, would be needed, ie. (Mihalcea et al. 2008a; Mihalcea et al. 2008b; Brock et al. 2010; Zhang et al. 2011; Foster et al. 2012).*

We will refer to those papers and reconstruct this paragraph, thank you.

(P1307L25) *L 57 "..which stabilizes their termini surrounded by their equivocal boundary" Misleading. A glacier terminus with thick debris can be stable in length but can change in thickness, as shown by various studies in the Karakoram, eg (Gardelle et al. 2012; Gardelle et al. 2013). Need to cite these studies, based on recent work, and also expand on the variable role of debris cover on glacier length/thickness.*

We will modify 'stabilize their termini' to 'stabilize the horizontal positions of their termini' and refer to those papers, thank you.

(P130L27) *L 58 "massive"- please quantify this. Is it meters, cm? Again, here, a discussion of critical thickness is needed.*

We will change the sentence as 'a debris mantle with thickness exceeding 5 cm can decrease the melting rate of ice (Matsson et al., 1993),…'.

(P130L29) *L 60 reference?*

This sentence is our assumption as is described with 'can' and 'possibly'.

(P1308L3) *L 64 "Avalanche-fed accumulation is also another influence of topography on the extent of glaciers" How so? Need to expand on this statement if this is considered important.*

The next sentence explains it in detail.

(P1308L9–L13) *L 69 – 72 "Some previous studies have reported on the spatial distribution of precipitation (Eguchi, 1991), changes in terminus locations of glaciers (Karma et al., 2003), topographic asymmetries affecting dynamic regimes (Kääb, 2005), and the formation of debris-covered areas (Nagai et al., 2013) in relation to glaciers in the Bhutan Himalaya" Please be more specific here, is it not clear what kind of relation to glaciers: area, elevation, or both? And also, what do these studies show, and what is missing from them and how does the current study complement this?*

We will change this sentence as 'In the Bhutan Himalaya, significant precipitation gradient from 500 mm (at the northwestern side) to 2500 mm (at the southeastern side) per year was observed (Eguchi, 1991), faster glacier retreat in the southeastern side was recognized (Karma et al., 2003), a contrast of faster glacier flow to the north-facing gentle slope and slower flow with debris cover to the

south-facing slope was distinguished (Kääb, 2005), and southwest-facing slope has the highest potential of debris supply (Nagai et al., 2013). These sensitive glaciers in the complicated topography should be monitored with updating satellite-derived inventories.'

(P1309L13) *L99 debris covered area are part of the glacier itself, phrase need to be revised or separated from PMS concepts*

We will delete any mention of PMS slope in the revised manuscript.

(P1309L15–17) *L 102 -103 "We defined debris-covered areas as zones where ice cannot be seen on account of debris mantles in glacier ablation zones, but which does not include dirty glacier ice" Why this definition and not the standard definition used for ex by GLIMS, ie glacier ice covered by any amount of debris? In any case the distinction b/w "dirty" and "debris covered" is not clear here, how is the boundary drawn?*

We specified the definition by GLIMS and made it clear that those glaciers such as one in Fig. AC13 were not defined as 'debris-covered'. Therefore, in the revised manuscript, a statement that the definition of a glacier and a debris-covered area by GLIMS is utilized will be added with several figures and explanation of such unclear cases.

Fig. AC13. Google Earth image of a dirty but not debris covered area of a glacier.

(P1309L27–P1310L6) *L 109 – 120 please check verb tense here, some are in the past, some in the present. I*

suggest using the past tense.

OK. We will modify it, thanks.

(P1310L10) *L 124- 125 "the National Aeronautics and Space Administration, United States, and the Ministry of Economy, Trade, and Industry, Japan."*
This is not needed here, just cite the reference

Yes. We will modify it.

(P1310L14) *L 128 Hayakawa et al. (2008) reported that accuracy of ASTER GDEM2 was better than that of SRTM DEM in steep terrain" Please give some numbers here, ie what is the accuracy of the GDEM2 in this area?*

This sentence mentioned frequency of missing data in terms of which data is preferable for steep slopes. Hayakawa et al. (2008) reported that 2-3 % of SRTM data was missed at the elevation of 2000 to 2500m, whereas no point was missed in GDEM2 data there. Also, more number of missing SRTM data than the GDEM2 data was found especially in slopes with the gradient steeper than 25 degrees and gentler than 10 degrees. (Fig. 2 in Hayakawa et al. 2008). In the Bhutan Himalaya, such difference has not yet evaluated.

(P1310L20) *L134 The outline polygons of features were overlain on bird's-eye view images in Google Earth™ to check delineation quality. Do you mean 3D perspectives? Was this visual? Please specify*

Yes, visual 3D perspectives by Google Earth. We chose (a) a PRISM image with less snow cover rather than (b) that with much snow cover, but ambiguous outlines still remain. Then we used (c) AVNIR-2 image and (d) Google Earth image, outlines were revised (orange to green outlines) to the most preferable shape (Fig. AC8 corresponding to a Dr. F. Paul's comment and shown below again).

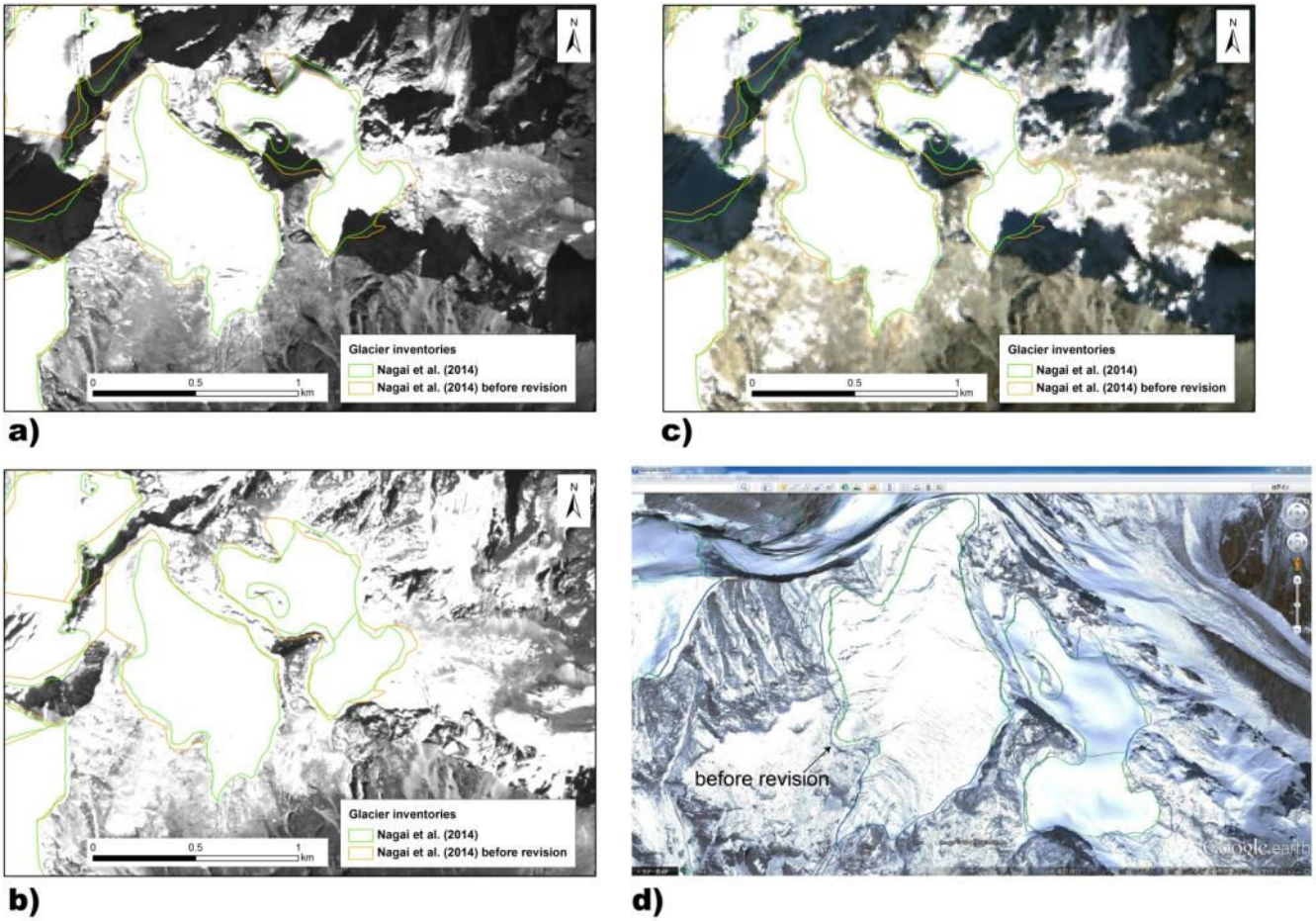

Fig. AC8. Comparison of (a) a less snow-covered, (b) a much snow-covered PRISM image, (c) AVNIR-2 image, and (d) Google Earth image of three glaciers in the Bhutan Himalaya.

(P131L25) *L 141: "In terms of accuracy in high mountains, monthly mean precipitation of the TRMM data showed better consistency with an in-situ measurement in the Nepal Himalaya than the other precipitation products (Yamamoto et al., 2011)." I am not sure what you mean by consistency. Other work needs to be cited, such as the work of (Bookhagen in review),*

It means that TRMM data showed the most similar seasonal pattern and amounts of monthly precipitation versus a ground-truth data, whereas other data showed very lower values or an irregular high value.

(P1311L26) *L 167 was this done visually as well, or were spectral methods attempted (ie texture, shape etc?). You could also reference some potential methods explored in (Racoviteanu and Williams 2012).*

Completely visual interpretation. We will refer to the method by Racoviteanu and Williams (2012), but in realistic cases of ICIMOD and GLIMS, visual interpretation and manual modification have been done to distinguish debris-covered area and other terrains.

(P1312L2) *L 169 "In such cases, the outline of the maximum area was adopted" Unclear. Is this the area of debris cover (I assume) or the snow- should be the former.*

That means 'In such cases, the outline of the maximum area of debris cover was adopted', correctly.

(P1312L5) *L 172 .."slopes if they tilted towards the glacier" Sounds qualitative. Is this assessed visually? An aspect analysis would be needed, was this done? Similar for the remainder of the paragraph, how were these variables determined?*

Completely visual interpretation was done for PMS slope (renamed to 'P-M slope' due to other reviewers' suggestions) with the combination of contour lines and PRISM image (Fig. AC11 corresponding to a Dr. F. Paul's comment and shown below again). Surface features including traces of something fallen and steep edge of mountain ridges appear in the PRISM image, which enable further precise judgment for the division comparing with aspect analysis within the spatial resolution of GDEM2 (~30 m). These qualitative but detail ways of interpretation will be noted with figures in the revised manuscript.

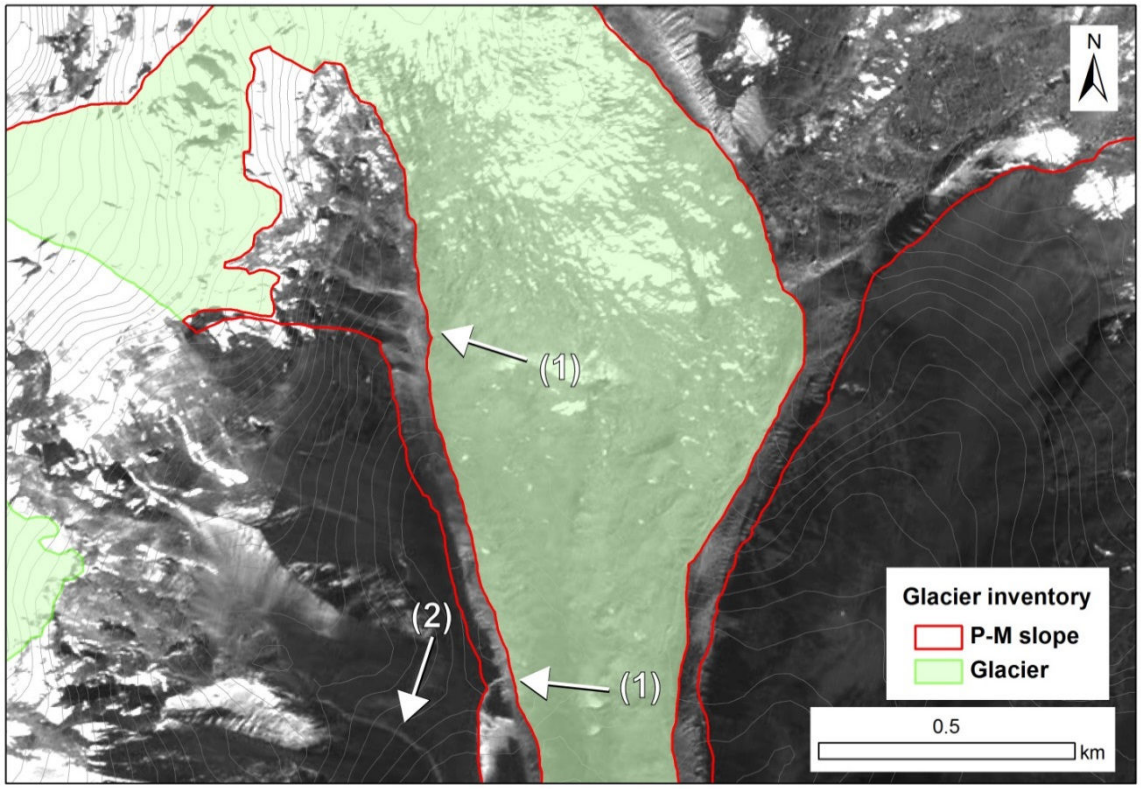

Fig. AC11. A PRISM image of a glacier and its P-M slope. Several traces which are (1) flowing into the glacier and (2) flowing outside of the glacier are recognized.

Results

(P1312L12) *L 180 Are these all glaciers in Bhutan Himalaya, or just a part (study area) ? Please specify.*

We set the domain as [27°36'–28°31'N, 89°12'–92°00'E] (see P1308L23) and delineated all identified glaciers in this. The latitudes and longitudes will be noted after '1579 glaciers in the Bhutan Himalaya'.

(P1312L26) *L 194 "The PMS slope area is highly correlated with debris-covered area," What does this mean, what is the Pearson's coefficient (or other?) I am not convinced by this result.*

That intended to mean the significant positive correlation ($r = 0.83$, $p < 0.001$) between the area of PMS slope and debris-covered area shown by Fig. 5a in Nagai et al. (2013).

(P1313L14) *L 207 "Paul et al. (2013) demonstrated that debris-cover could lead to large interpretation differences" Phrasing like this should be checked throughout the manuscript. It is not debris cover that leads to large uncertainties- it is the type of analysis. Also, high resolution imagery does not necessary mean very high accuracy- it depends how it is used. In the case of debris covered glaciers it is hard to see where ice terminates even when high resolution imagery is used.*

This is incorrect, sorry. Glacier topographic variables affected by the interpretation difference will be analyzed in the revised version using out inventory and the ICIMOD inventory.

(P1313L24) *L 217 "The numbers and mean areas of debris-covered and debris-free glaciers are summarized by aspect, which is averaged over each individual glacier using ASTER GDEM2 images" Again, the language does not make much sense here, what does this mean?*

Sorry, that is because how to estimate glacier flow aspect was not described and 'images' was correctly 'data'. The analysis method was written below.

- **Mean slope aspect of the pixels on each glacier surface was obtained using ASTER GDEM2 data.**
- **It was regarded as glacier flow direction.**
- **Glaciers were classified by their flow direction into eight groups.**
- **Numbers of the glaciers were accumulated in the groups (Fig. 3a).**
- **Mean area of the glaciers were obtained in the groups (Fig. 3b).**

(P1313L27) *L 220 "directional preferences for debris-covered glaciers are uncertain" Another example of a qualitative statement – this does not say much*

OK. We will modify it as 'any significant difference (or no difference exceeding xx%) was found among them'.

(P1313L28) *L 221 south- and north-facing debris-covered glaciers tend to be large*
This is a generalization and should be shown with statistics. This is misleading since on the north side of the divide, there is much less debris than on the S facing slopes. How was the delimitation done?

We understand '*on the north side of the divide, there is much less debris than on the S facing slopes*'. When we identify any of debris-covered area which covers ice-or-snow surface, we define it as a debris-covered glacier. Therefore this analysis will be modified considering debris-covered ratio.

(P1314L2) *L 223 "These aspect dependencies suggest that solar radiation controls the development of debris-free glaciers" Speculative phase. Solar radiation was not considered as one of the variables, and*

cannot be assumed to be a control. Besides, how can solar radiation control the development of debris covered glaciers?

Since no information of solar radiation is available in this study, this description will be removed.

(P1314L14) *L 234 This trend is similar to glaciers located around Greenland (Rastner et al., 2012)*
This is not a valid comparison since the glacier types are different.

We will refer to Pan et al. (2012) and Bolch et al. (2010) instead of Rastner et al. (2012) for the comparison in the revised manuscript.

(P1315L4) *L 252 Why plot mix vs max rather than compute the elevation range, to be able to compare with other regions?*

That is because the values of maximum/minimum elevation were needed for comparison in this region. An elevation range would not point out whether a debris-covered glacier terminus reaches lower elevation than that of debris-free glaciers.

(P1315L11) *L 259 terminus elevations of debris-covered glaciers are substantially lower than those of debris-free glaciers*
Again, this needs to be supported with statistics

OK, several numbers of statistics will be added.

Discussion
(P1316 L7) *L 281 ELA might be lower in areas of increased precipitation (accumulation)*
Generalization, and obvious fact- needs to be shown for this area.
(P1316L4) *Section 4.1 I do not see the point here, in estimating the PPT-Temp relationship*

We will remove analysis of precipitation and ELA from this manuscript.

(P1317L17) *L 310 – 313 The estimated precipitation–air temperature gradient in the Bhutan Himalaya (234–377 mm/degC) covers the range of empirical values of ELAs worldwide (287–344 m/deg C). This result supports the assumption that the median elevation is an applicable proxy for the ELA*
This seems circular, what is the use of proving that the assumption of median elevation as an ELA proxy is valid, using other, arger PPT-Temp gradients? The discussion section is dispersed, and this does not add much. References would be sufficient here.
(P136L18) *L311 how can ppt-temp gradient cover an ELA range? Please revise such statements throughout the manuscript.*

We intended to note that the plots shown Fig. 7 were consistent with the results by Ohmura et al. (1992). Analysis of precipitation and ELA from this manuscript will be removed.

Sections 4.2 and 4.3- language is confusing, there is a mix of climatic and topographic factors which is not well organized and hard to follow.

Sorry. We will substantially change the discussion as describe above.

Reference

Bolch, T., Yao, T., Kang, S., Buchroithner, M. F., Scherer, D., Maussion, F., Huintjes, E., and Schneider, C.: A glacier inventory for the western Nyainqentanglha Range and the Nam Co Basin, Tibet, and glacier changes 1976–2009, The Cryosphere, 4, 419-433, doi:10.5194/tc-4-419-2010, 2010.

Nagai, H., Fujita, K., Nuimura, T., and Sakai, A.: Southwest-facing slopes control the formation of debris-covered glaciers in the Bhutan Himalaya, The Cryosphere, 7, 1303–1314, doi:10.5194/tc-7-1303-2013, 2013.

Pan, B. T., Zhang, G. L., Wang, J., Cao, B., Geng, H. P., Wang, J., Zhang, C., and Ji, Y. P.: Glacier changes from 1966–2009 in the Gongga Mountains, on the south-eastern margin of the Qinghai-Tibetan Plateau and their climatic forcing, The Cryosphere, 6, 1087-1101, doi:10.5194/tc-6-1087-2012, 2012.