Review of the study by Nagai et al.

A. General comments

The study by Nagai et al. aims at presenting how climatic and topographic influences impacts on the glacier distribution for Bhutan as derived from a new inventory. In my opinion this is a worthwhile topic to present, but I have difficulties to find such an analysis in this ms. Instead, it is rather repetitive of what is already reported in Nagai et al. (2013) (N13 in the following) and has several further shortcomings that need to be addressed. My key objections are:

1. there is too much overlap with N13 (e.g. most of the text on P1320 is copy/paste)
2. there are more topographic influences on glacier distribution than PMS slopes
3. there are more climatic influences than precipitation
4. a real discussion is missing (mostly further results are presented in Ch. 4) and the overall structure is a little bit confusing
5. I also miss a visualization of glacier outlines in challenging regions (close-ups)
6. though already published, the PMS concept (or PDS in N13) is not convincing to me
7. the missing separation of regions supplying debris and avalanches is in my opinion unfortunate, these are different processes acting at different time scales
8. nothing is said about the special characteristics of the glaciers in the regions north and south of the divide (e.g. valley glaciers vs. Firnkessel type)
9. with the focus on statistics and correlations the process understanding is getting lost

I provide details to each of the above objections in the next section. Further issues that need to be addressed are listed in section C. Based on point 6, I strongly recommend removing the analysis of PMS slopes in a revised ms, which will likely substantially alter its contents. Based on this, the other points above and the details provided below, I recommend rejection of the ms at this stage. However, I would strongly recommend performing the suggested revisions and resubmit the study.

B. Details to the general comments

1. Please do not copy/paste larger text sections from N13 into this study (e.g. L3-20 on P1320). This is never a good idea and also supporting the impression that the same story is sold twice. With the strong focus on the PMS slopes in the topographic analysis and the use of the same datasets and their description on page 1309-10, the repetition of large parts from N13 is unavoidable. So please make something new here to better distinguish it from N13.

2. There are abundant topographic factors that can be analysed when glacier outlines are combined with a DEM. This study only shows the overall hypsography, area and number histograms (sorted for aspect or slopes) and mean/maximum elevations, most of them in a non-standard way (making them incomparable to other studies). Just to give a few examples for further topographic indices:
- hypsographies can be compared for a couple of individual glaciers (e.g. larger than a certain size) for N vs S side, with or without debris
- glacier types (e.g. valley, mountain, cirque, firnkessel) should be assigned for a more detailed analysis of the characteristics of subsets
- mean slopes of ablation areas can be plotted against the mean values for accumulation areas using different symbols for glaciers on the N vs S side of the main divide
- potential global radiation can be calculated for all grid cells (e.g. for the melting season) and compared for the ablation and accumulation regions and the N vs S side glaciers

- glacier size can be plotted against minimum/maximum elevation, and mean slope / aspect
- mean elevation can be plotted against aspect (with different symbols for N vs S side and different colours for glacier type)
- the median elevation can be shown on a map (hill shade with outlines overlay?) as colour-coded filled circles (for glaciers larger than a certain size), or the grid-based precipitation from the climate data an be shown in the background (maybe using a greyscale coding?). Both would be more illustrative than Fig. 7
- maximum elevation, precipitation and maybe further terrain parameters should be used to explain the glaciers distribution
- some comments on how to calculate a median elevation for a glacier with an interrupted profile (e.g. nourished by snow/ice avalanches from higher elevations) would be worthwhile

The in-depth analysis of the respective plots should allow for results that are sufficiently different from the N13 paper.

3. When 'climatic influences on glacier distribution' is mentioned in the title as a key topic of this study, I expect a little bit more than precipitation only and Fig. 7. For example, the Ohmura et al. 1992 curve could be repeated for the glaciers in the study region, colour and symbol coded for glacier type, debris-free/covered glaciers and/or located in the N vs S. I also expect to see a map with the precipitation distribution (see point 2) and how this can explain median elevations (and their geographic trends), and where other factors play a role (e.g. snow redistribution by wind and avalanches, preferred nourishment for certain glacier types, etc.). For example, one can calculate precipitation amounts from median elevations and compare them to the climate data. This might be followed by an analysis of the degree of imbalance for the heavily debris-covered glaciers which might only exist due to the debris cover. In short, please add some climate data analysis or remove the topic from the title.

4. Ch. 4 is in my opinion not really a discussion. It is presenting several further results related to this study. In a discussion I expect to see a comparison with results from other studies, a critical evaluation of the results, maybe including an error analysis, what has been missed and learned, and what future studies should investigate. I would also suggest to better distinguish data, methods and results and reduce repetition of N13 to a minimum. At first, I suggest introducing separate Chapters for the description of the data sets and the methods. The study site might be described as a part of the datasets. Then introduce sub-headings for glacier outlines, DEMs and climate data. Section 2.2 is basically methods, and should be separated into glacier outlines (please remove the PMS slopes), drainage divides (why have they not been derived from watershed analysis?), DEM-related calculations (hypsometry, statistics), preparation of climate data, and accuracy assessment (this has to be added, you cannot just adopt the uncertainty from another study!). P1313, L14-23 and P1314, L8-15 belongs to the discussion. The first 11 lines in Ch. 4 is a repetition of results, please remove. Sections 4.1, 4.2 and 4.3 should be rewritten (see details in the other comments) and moved to the results.

5. P1309, L11: This is not a good motivation. The errorrs of the RGI described in Pfeffer et al. (2014) belong to another region (and have been corrected in the meantime) and the glacier outlines from ICIMOD should be fine for Bhutan. Why do it again? Why have your outlines not been compared to those from ICIMOD? Why is the use of panchromatic imagery 'advanced' (L12). As far as I remember, bare ice and rock are often difficult to distinguish (due to poor contrast) and high spatial resolution does not help at all when it comes to seasonal snow cover, in particular in the accumulation region and with panchromatic imagery. I can

thus not see why new inventory has an improved quality over what has been available from ICIMOD. If a different interpretation of the accumulation area has been applied, fine. But please show the differences and use this as a motivation to digitize everything again. As I do not remember a specific publication for the ALOS derived inventory (?), please describe its details for Bhutan here. This means a full description of the snow conditions in the satellite images, how seasonal snow and debris cover has been mapped (outline overlay in close-ups), and how low-contrast regions (e.g. shadow) and clouds have been handled. This information is required when a topographic analysis of the glacier distribution is presented afterwards.

6. The PDS concept presented in N13 has in my opinion some flaws. I apologize for not having mentioned this earlier. However, as this study is rather repetitive in this regard, I take the opportunity to point out some of the issues. In N13 it is basically concluded that SW facing slopes and diurnal freeze-taw cycles provide the debris for the debris-covered glaciers in Bhutan. As far as I know, the debris on the surface of a glacier appears in the ablation region due to emergent flow rather than deposition from above. It is a mixture of internal/basal material (e.g. forming a medial moraine) and material that has fallen on the glacier in the accumulation region (near the bergschrund). This can happen when the accumulation region is surrounded by some ice-free rock walls (as is the case for the glaciers south of the main ridge). Without these debris providing ice-free rock walls (e.g. as common for ice caps and the glaciers north of the main divide), glaciers are debris free apart from medial moraines resulting from basal/internal material.

Debris that is falling on the glacier from rock walls surrounding the ablation region must be large to get the entire way down to the glacier surface and maybe also jump over a lateral moraine. As far as I know, this is not possible for material resulting from diurnal freeze-thaw cycles as its size is too small. On the other hand, larger rock fall events leave debris of a particular lobate shape that is gradually stretched with glacier flow (as shown in Fig. S1 of N13). To get a homogenous cover, such rock fall events reaching the glacier tongue in the ablation area must be very frequent (is this the case in Bhutan?). The loose material from exposed lateral moraines can only accumulate locally and will likely never provide sufficient material to cover the entire surface. A good example is the glacier Pasterzenkees in Austria (below Grossglockner) where the related processes have been studied and documented in detail (e.g. Kellerer-Pirklbauer et al., 2008). The glacier is only partly debris-covered on its western side as there are no ice-free rock walls in the upper part of the accumulation area but steep slopes with frequent rockfall above its ablation area. There is in general no dependence on the aspect of the rock wall to be expected, neither when the material is entrained in the accumulation region nor when it falls on the glacier in the ablation region. For the Pasterzenkees the rockwalls are facing NE, for the neighbouring Ödenwinkelkees the rock walls are facing N. In the latter case they surround the entire accumulation area so the tongue is completely debris-covered.

To some extent also the lithology of the material should play a role for weathering processes, at least compared to terrain aspect. But I think the point is made. I would strongly recommend removing the PMS analysis from this study (see also next point). By the way, PMS is an unfortunate abbreviation that has also a very different meaning.

7. By extending the former PDS (from N13) to PMS including avalanches, completely different processes are mixed up. Snow avalanches might be a major source of accumulation for the glaciers in this region and they do not depend on the availability of ice-free rock walls

and likely occur much more frequent. The amount of snow that can accumulate depends (among others) on wind direction and requires low slopes while rock avalanches might preferably occur at steep slopes and depend on lithology rather than wind direction. So when explaining why glaciers are where they are these processes should be distinguished.

8. When explaining the glacier distribution from topographic and/or climatic characteristics, please consider to separate glaciers of different type. Apart from debris covered or not and being located N vs S of the main ridge, it would make sense to classify glaciers by type (valley, mountain, cirque, firnkessel type, calving, etc.). These types have likely distinct topographic characteristics that could be analysed separately (or for sub-samples, see point 2).

9. In my opinion too much of the governing process is 'hidden' in statistics (Figs. 6 to 9) and selected to be relevant based on correlation coefficients. However, there is in general very little that can be derived from r and p values alone, e.g. the glaciological meaning is getting little attention. For example, why show Fig. 8 when there is no correlation to be expected? Median elevation might depend on glacier aspect and precipitation amounts, but not on glacier size (the PMS slope ratio is auto-correlated with size). I have given some examples for correlations under point 2 and hope that these can be evaluated in a revised ms.

C. Specific comments

P1306, L22: Are you sure that glacier melt water is directly used for human consumption? At some point I assume is a filter to remove the sediment?

P1307, L7: What does 'highly sensitive' mean? The change in mass balance (or length?) due to a change in temperature or precipitation or some other climate variable? And why 'highly' what does change more than elsewhere.

P1307, L8ff: This argument is difficult to follow: The Randolph Glacier Inventory is available for some years now and combined with the also available SRTM or GDEM we already have the complete information about glacier distribution (spatially and in elevation) and their relation with topography. 'Largely unknown' is something different. Please add and explain what this study is providing compared to what we already have.

P1307, L14ff: Please be sure to refer here to the ELA_0 (for a balanced budget) rather than the highly variable ELA of a specific year.

P1307, L20: How does the median elevation as a proxy for the ELA_0 work for glaciers with an interrupted profile?

P1307, L22: Why is debris cover a matter of concern? Please explain. It is certainly a key challenge for mapping glacier extents, but what is the problem when it protects the ice from melting?

P1307, L25: How can a thick debris mantle 'stabilize their termini' and at the same time 'enhance the expansion of debris-covered ablation areas, thus lowering the median elevation'? I see the point that glaciers with debris-cover could become larger than debris-free glaciers during their formation, but afterwards the debris is just keeping the glacier out of balance with climate for some time. So these ice bodies should have much too low median elevations compared to what precipitation and temperature is providing. Please show this imbalance.

P1307, L29: Debris supply is only one factor with a potential influence on glacier extent among many others. There is also topographic shading, elevation and shape of the surrounding topography compared to wind direction, snow deposition and solar radiation, the hypsometry of the glacier surface, etc. Please investigate these!

P1308, L7/8: Indeed, little is known but their influence might be large. Please show what the local depression of the median elevation due to topography and debris cover is

P1308, L14/5. Yes indeed. Please investigate this.

P1309, L1: Raup and Khalsa (2007) are practical guidelines for digitizing of glaciers. Please cite Kargel et al. (2005) or Raup et al. (2007) as a reference for GLIMS.

P1309, L2-6: These shortcomings in RGI quality were related to glaciers in the Andes (seasonal snow) and the Tien Shan. For Bhutan, the RGI/ICIMOD inventories are fine

P1309, L9/10: Why does complex topography and snow cover not influence the high spatial resolution imagery from ALOS? The ALOS satellite has a much shorter archive than Landsat so that it is likely much more difficult to find appropriate ALOS scenes. You have thus to make very clear (and visualize!) what the advantages of the ALOS inventory are (or publish the inventory paper first and explain it there).

P1309, L22: I would not do this under the same name. These are very different processes.

P1310, L1: Taking the image with the least snow cover is fine, but this is different from an image without snow cover (outside of glaciers). So please show examples of such images and hw you have corrected the outlines (overlay).

P1310, L7: How have drainage divides in the accumulation area been derived from 20 m contour lines, by manual digitization? Please explain this, as for normal (automated) watershed analysis is applied (providing more consistent results).

P1310, L14/15: Two things are wrong here: First, because of the higher resolution (artifacts!) of the GDEM2, its accuracy is often worse than the SRTM DEM. Please also consider that the details resolved in the GDEM are closer to what SRTM is providing than to 30 m. Secondly, the cited Hayakawa study has not analysed glaciers. Regarding stereo-photogrammetry from optical imagery, glaciers are very different from other terrain. They are much more gentle sloped, have often zero contrast over snow-covered regions and the spatial pattern of debris cover can interfere with the image matching algorithm, both resulting in low correlations and poor DEM quality over glaciers (despite their gentle slope). Overall, SRTM has often superior quality over glaciers and other reasons for using the GDEM2 in this study should be provided (e.g. the data voids issue).

P1310, L21: Please explain why this is possible and maybe show an example illustrating the quality of the digitizing. The images in GE are sometimes heavily snow covered, i.e. please provide evidence that this was not an issue in this study. Please explain the process of correcting an obviously wrong delineation after visual inspection (repeat overlay?).

P1311, L7: What are these surface features of unstable steep slopes?

P1311, L15/16: This external control is fine, but it also worries me. When outlines need to be corrected three times I would conclude that the analyst has problems with the digitizing.

P1311, L23/4: Deriving watersheds from contour lines only, seems rather inaccurate to me. What about using a flowdirection grid or any of the other available algorithms?

P1311, L26: It is not possible to apply automatic methods with panchromatic imagery, you need a SWIR band for this

P1312, L1/2: This sounds like serious impacts from seasonal snow. Can you please demonstrate that your glacier outlines do not suffer from misinterpretation of snow?

P1312, L5/6: I would restrict the term 'slope instability' to slopes that are instable. An avalanche that comes down a slope does not mean that the slope is instable. These are completely different processes (see point 7).

P1312, L14/15: How is debris covered vs debris free defined? I assume that only completely covered tongues are counted here? This needs clarification as a glacier with a medial or lateral moraine would also be considered as debris covered.
P1312, L17: That's all fine, but what is now the debris-covered area and the percentage of coverage per glacier (min/mean/max/std)?

P1313, L5-13: The hypsometric analysis should be better resolved, e.g. for glaciers of the same size class, N and S of the main divide and/or by glacier type. Just lumping all debris free and debris-covered glaciers in one graph gives little insight to the 'topographic influence on glacier distribution' (see also point2).
P1313, L16: Please perform an uncertainty assessment here as well, independent of the results of earlier studies. Take about 10-20 glaciers of different size (with and without debris cover) and digitize them 3 times independently (with one day in between). The standard deviation of the derived glacier areas will be a good measure of the accuracy.
P1313, L25/26: What are ASTER GDEM2 images? Do you mean that aspect has been derived from the GDEM2? If yes, please add the information their.
P1314, L2: I think this statement about the influence of solar radiation on the development of debris-free glaciers cannot be made here. It requires at least some investigations about (potential) solar radiation.

P1315, L17-21: I see no point for this statement in such a generalized form. Glaciers develop where sufficient solid precipitation (snow) survives summer temperatures. So elevation and precipitation amounts are responsible for glacier development. Aspect (and topographic shading!) or debris cover only modify their general distribution.
P1317, L3: I do not understand the meaning of Eq. (1). Please explain its physical base.
P1317, L21: Please show this on a colour-coded map as described above.
P1318, L5: There are several papers that have already shown this (e.g. Kuhn 2003)
P1318, L8: This sounds like a very active process. Please consider that current glacier extents are likely only relicts of better times and that might vanish under current climate conditions. The debris protection is just extending their existence.
P1319, L1: The entire section 4.3 reads like a self-fulfilling prophecy for the N13 paper. Please write about something different in this study.
P1320, L3-13: Please remove this copy/paste section from N13 (cf. P1675 in the TCD ms).

D. Terminology

Please use region instead of area when reference is made to a geographic region and please use glacier / glacierized instead of glacial / glaciated when referring to contemporary glaciers

E. Figures and Tables

I have already provided some suggestions for improvements above (e.g. close-ups, outline overlays, other plots), so I will not repeat this here. In general: Please add tick marks on both sides of the plot (such as Figs. 2 and 6-8) and maybe even dotted grid lines (Figs. 2 and 6).

F. References

Kargel, J. et al. 2005. Remote Sensing of Environment, 99, 187-219.
Kellerer-Pirklbauer, A. et al. 2008. Geogr. Ann., 90A (4), 269-285.
Kuhn, M. 2003. J. Hydrology, 282, 95-103.
Nagai, H. et al. 2013. TCD, 7, 1673-1705.
Raup, B.H. et al 2007. Computers & Geosciences 33, 104-125.