

Nagai et al, the Cryosphere Discuss
Climatic and topographic influences on glacier distribution in the Bhutan Himalaya

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 débris-covered glaciers across the Himalaya, particularly their characteristics. Combining topographic and climatic factors to characterize these glaciers is worthwhile; however, at this point it seems that the paper lacks a rigorous 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.

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 débris cover and its characteristics, which would be a good contribution.
- 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 decide a whole section on proving this point.
- 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 débris 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.
- 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 orthorectification, 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.
- 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.
- 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 ?

Specific comments

L 46 -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 it in the présentation of the objectives.

L 56 « which potentially prevents ice melting if the debris layer is sufficiently thick”” This statement is not sufficient, nor the referencesA 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).

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.

L 58 “massive”- please quantify this. Is it meters, cm? Again, here, a discussion of critical thickness is needed.

L 60 reference?

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.

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 (K..b, 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?

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

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?

L 109 – 120 please check verb tense here, some are in the past, some in the present. I suggest using the past tense.

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

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?

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

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),

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).

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.

1172 ..”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?

Results

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

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.

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.

L 217 “The numbers and mean areas of debris-covered and debris-free glaciers 217 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?

L 220 “directional preferences for debris-covered glaciers are uncertain” Another example of a qualitative statement – this does not say much

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?

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?

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.

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

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

Discussion

L 281 ELA might be lower in areas of increased precipitation (accumulation) Generalization, and obvious fact- needs to be shown for this area.

Section 4.1 I do not see the point here, in estimating the PPT-Temp relationship
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.

L 311 how can ppt-temp gradient cover an ELA range? Please revise such statements throughout the manuscript.

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.

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