

## ***Interactive comment on “Characterization of glacier debris cover via in situ and optical remote sensing methods: a case study in the Khumbu Himalaya, Nepal” by K. A. Casey et al.***

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### General comments

This paper focuses on characterizing the debris cover on two glaciers in the Nepal Himalaya using field spectrometry. This aspect is an important contribution, since there are very few measurements of spectral reflectance on debris-covered glaciers in this region. Furthermore, quantifying role of debris cover on glaciers and mapping of debris-covered glaciers remain significant challenges. So, the motivation of this study is appropriate and timely. The analysis is very detailed and thorough, based on extensive fieldwork and remote sensing data analysis. Some of the methods are novel.

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The authors' main goal seems to be to provide background material for satellite image analysis techniques.

However, the manuscript in its current form is very dense and hard to follow. The section on geology is quite technical and in my opinion too detailed for a glaciologic audience. I find it hard to extract the relevant information, especially related to the remote sensing techniques that were explored in this study. My main concerns about this manuscript, and suggestions for improving it, are as follows:

1. Goal of the paper should be better defined. What remote sensing applications is the study targeting? Is the goal is to validate remote sensing methods for estimating melt under the debris cover, debris cover mapping, debris temperature, or all of these? It is unclear of the focus is on the field results, or on the remote sensing techniques.
2. Content: There is a wealth of good material, and thorough analysis here. Some of it, though, it too detailed – the technical details on mineralogy and sensors could be put in an appendix to make the paper more concise.
3. Organization of the paper: A major re-organization is needed. A clearer distinction of methods, results and discussion would greatly improve the manuscript. In particular, the results sections contain a large amount of background and methodology, which diverge from the main points being made.
4. Writing: While the use of the English language is appropriate, and mostly correct, in many cases the phrases are very long, with various ideas in the same phrase. It would help the reader a lot to revise such sentences and make them more concise.
5. Length: The paper is quite long. It would help removing some of the material in the sections as suggested in the specific comments (for example, the discussion on sensors). Some of the material is redundant.

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6. Glaciologic application: This is the key part of the paper, but it is not emphasized in the results and discussion. In particular, debris cover temperature, thickness and velocity would need to be discussed in more detail in light of the findings. It is of great interest to the glaciologic community to use these spectral reflectance measurements to explain the different behavior of debris covered glaciers in the same area, for example, Khumbu vs Imja Glacier. While these are referred to in the text, this link is not being made.
7. Overall, the results presented here provide a good basis for discussion- this discussion needs to be taken a step further, and the results should be thinned to the key ones which would help this goal.

My recommendation is a major review of the paper with emphasis on tailoring the results presented to the goal of the paper, and taking into consideration the comments below.

Specific comments

Abstract:

L5: “for comparison with satellite optical remote sensing data” – mention what exactly is being validated using the field data.

P 500 | 25:

If referring to Hall et al papers, then spectral reflectance of snow and ice should be mentioned as basis

L 26: Please include other references on semi-automated glacier mapping from other parts of the world including the Himalaya, such as .....(Bolch 2007; Bhambri et al. 2010) or review papers such as ..(Racoviteanu et al. 2009)

L 26 “;” after citation should be “,”

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P 501 | 11.

Break phrase after “in development”- phrase is too long

P 501 paragraph 2:

The critical debris cover thickness should be mentioned here; for example, what is “minimal” debris cover? Also, papers dealing with melt rates under debris cover should be mentioned: ...(Mattson et al. 1993; Nakawo et al. 1999; Kayastha et al. 2000; Singh et al. 2000) at least.

L 17 – 20: phrase is too long. Not sure what is the main point here. Please clarify the discussion of glacier dynamics here.

P 502 | 3 Starting with “Colloquially referred to as 3<sup>rd</sup> pole. . . .”

I suggest a new paragraph since it’s a new idea; also, this phrase has been overused and the original reference is often not used. I suggest removing since it is not particularly relevant here. The following phrase (discussion of sea level rise and crustal uplift) is confusing- here the discussion is global again. I suggest either referring to the Himalaya or removing since it is distracting here.

L 21 Section 2 “glacier debris”

this should be consistent throughout the manuscript, ie. Debris cover glaciers etc.

P 502 – 504 :

the section of optical sensors is way too long and general. Most readers are familiar with Landsat and ASTER; this could be shortened to 1 paragraph.

P 505 this section can be shortened and more to the point

L 17 – 20: “In this paper, we utilize XRD and XRF analysis of glacier debris samples to qualitatively and quantitatively and investigate lithology(which we de?ne as the description of rock composition and texture) via remote sensing data in light of glacier

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dynamics. . . . .”

Phrase is long; also, it is buried in the midst of literature review. I suggest shortening it and merging with the last phrase of that section (p. 506 l 9 -10), which is redundant.

p. 506, l 13-15:

I see the intro phrase unnecessary, and it's also been used too many times, based on extrapolations mainly. I would suggest omitting and getting directly to the study area.

L 15: “unpublished initial Himalaya”

A reference is needed, such as a paper in preparation

L 17-19: “Focusing on the Khumbu Himalaya study area (Fig. 2, 3), the gozumpa glacier is the longest glacier in Nepal at approximately 25 km (Benn et al., 2001) with Khumbu glacier measuring 17 km in length (Hambrey et al., 2008).

Sentence is awkward and needs to be rephrased (change the continuous tense to simple present tense); “at” should be “with”; same for “measuring”- change to simple present tense

L 21 “ranging from 15 – 90 m

Put this comment about the pixel size separately

L 27: “Glaciologically” is awkward; remove or replace with “Commonly”. Check grammar (subject-verb)

P 507, l2 “as was observed at Khumbu glacier in December 2009”

Is this from this study, or a previous study? Please mention.

L 7 “extreme topographic relief are characteristics that differentiate Himalayan glaciers from polar and other alpine glaciers.”

I do not agree. The Karakorum are more extreme. Unless you include the Karakorum

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in your definition of the Himalaya (which I do not recommend), please revise this.

L 15 – 19 is really long. Split into 2 sentences according to the different ideas.

L 26 “Fushimi et al (1980) field based maps. . .

Check the grammar here (subject is Fushimi not the field based maps.

L 29 check grammar (“Khumbu glacier longitudinal supraglacier bands” should be “longitudinal supraglacier bands on Khumbu..”

P 508 l3: insert “which” before “glacial flow”

L 18 insert “The” before “Instrumental”

L 2: “in excess of” is unclear. Do you mean “more than”?

Passive voice used excessively “were collected” repeated many times on p 509, and elsewhere in the manuscript.

L 19 “determination” is awkward.

p.510 l 25-26. Point already made in the intro and not needed here. I suggest removing the first phrase for conciseness.

P 511 l 1- 5: numbering the methods would help the reader here

L 5 – 10 Long. You could refer to table 2 to save some space

L 10 – 12 These are lit review (background material) and belong to section 2.1 where the sensors are discussed. The whole discussion of sensors is redundant with section 2.1. I suggest removing or merging that info, and starting the section with l 13.

P 511 l 20 to p 512 line 9: confusing. Were the corrections applied to ASTER? Again, too much background here for a methods section.

P 512 l 20-22 I do not see this phrase necessary.

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L 23: you are mentioning the results (“3360 plus visible ..”) before introducing them to the reader. I’d first introduce the results. It reads awkward as it is.

P 513 | – 27: Here you are mixing results with discussion. I suggest splitting this two.

It is tiring to read “Ngozumpa glacier snow” and “Khumbu bare ice” over and over. The important thing here is the signal, so I would just refer to ice vs snow, and then comment on where the samples are in the figures. Or present Ngozumpa and Khumbu results separately. Right now it is very hard to read and sort through these results.

“Reduction” is not used correctly- I think you mean “difference” , Please revise.

L3-4 Rather than describe the plot (“overplotted”, say what it means and put the phrase in the figure caption.

L 10 -15: This can be argued differently. The differences with the results from Qunzhu et al can also be due to different characteristics of snow in the two regions. What is the time of the year of the measurements in Qunzhu paper?

P 514 | 9 – 15: Long phrase, please revise and make it more concise.

L 15- 17: these belong to methods.

L 25 “spectral signature was calculated at 0.013”

Confusing phrasing. Do you mean the spectral signature was 0.013?

Again, long phrases.

P 515 | 9- awkward “Fig 7 of visually dry and wet mud”- please revise (first refer to the figure then interpret it)

L 15 – 18: This is an important point, but it needs to be moved to the discussion section (6) or to the conclusions.

P 516: section 5.2 is too sense and hard to follow for non-geology audience. Consider revising this and keep the main points which are of relevance here.

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### Section 5.3 “Optical satellite data”

It is confusing here to have another section called “data”- which gets mixed up with the methodology. I suggest rephrasing to “analysis”, or “results”

Also, this section has mixed analysis and results.

L 15 – 25 seem almost entirely methods material

P 517 section 5.3.1 | 1 -14 these are methods, and they belong to the methods section. The rest of the paragraph until end of line 19 on p 518 is also not results, but background/methods- please revise accordingly and move this entire section to previous section on satellite data.

Section 5.3.3 “Mineralogic mapping” – again, this sounds like methods. I suggest calling it “composition”

All the material from section 5.3.3 to 5.3.4 is background material on remote sensing techniques; these do not belong to a results section. The results are hard to extract from here. I suggest carefully revising this section, shorten the discussion on RS techniques. You could create a sub-section under “Methods” that explains these RS techniques.

P 523, | 18- 20: you mention SAM analysis on Khumbu glaciers, but no results are presented.

### Section 5.3.4 Land Surface temperature

L 1 – 9 – these are again methods

L 10: explain that the increase in temperature towards the glacier termini relates to the increase in debris cover thickness. I have found a very similar result on Zemu glacier in Sikkim. In the discussion, provide the explanation why debris cover increases at the terminus (glacier dynamics).

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L 24 -25: Again,, this is a crucial point and should not be buried in the results, but brought up in the discussion section.

This section has a lot of potential, but needs to be developed. There is no mention on thermal resistance/conductivity, which is key to understanding debris cover thickness, and consequently ablation rates. You mention the application to glacier melt models (line 24), but this link is not made.

Section 5.3.5:

L 1 – 5 are methods

L 20: remove parentheses in the last sentence. Clarify “all other listed references”- which studies are you referring to?

L 23 remove “were calculate”- since you are showing results here

P 526 l 1 – 15 most of this paragraph belongs to section 6, summary and outlook.

L 10 -15 – it is unclear if you refer to the results here or whether these are broad theoretical statements. Please clarify.

6. Synthesis

I do not see it necessary to go back to the figures here; rather, summarize the findings.

The five points could be numbered, or use bullets to make them more evident.

7. Conclusion

p 529 line 2: Here you refer to HKH region, but previously in the manuscript, the Himalaya range is discussed. There is often confusion in the literature on these boundaries. Please specify clearly how you define “Himalaya” and give references to support this.

Tables and figures:

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Table 3: This may be too much material on geology. Maybe put in an appendix?

Same for table B1

Fig 2: Difficult to see the study are. I suggest zooming into Asia and combine with Fig 3 as a subset image.

Fig 6 It would be useful to have this graph side by side, or part of a figure showing Ngozumpa glacier. The figure caption on Fig 6 has a lot of the methodology already covered. The last sentence is confusing- the 4x4 and 2x2 pixel sizes are unnecessary.

Fig 8: This is misleading. You show Imja glacier, which is a fast retreating glacier with the pro-glacier lake, but the text refers mostly to the mineral composition. There is no mention that I see on how the mineral composition might inform the behavior of Imja glacier (ie. maybe helping to confirm the hypothesis that Imja has a thin debris cover, which enhances ablation). This deserves some further thoughts.

Fig 9: Capture is way too long

Reference suggested:

.Bhambri, R., et al. (2010). "Glacier changes in the Garhwal Himalayas, India during the last 40 years based on remote sensing data." *Journal of Glaciology* **54**.

Bolch, T. (2007). "Climate change and glacier retreat in northern Tien Shan (Kazakhstan/Kyrgyzstan) using remote sensing data." *Global Planet Change* **56**(1-2): 1-12.

Kayastha, R. B., et al. (2000). Practical prediction of ice melting beneath various thickness of debris cover on Khumbu Glacier, Nepal, using a positive degree-day factor. *Debris-Covered Glaciers*. C. F. Raymond, Nakawo, M., Fountain, A. Wallingford, UK, IAHS. **264**: 71 - 81.

Mattson, L. E., et al. (1993). Ablation on debris covered glaciers: an example from the Rakhiot Glacier, Panjab, Himalaya. *Snow and Glacier Hydrology*. Proceedings of the International Symposium, Kathmandu, Nepal, 16-21 November 1992. G. J. Young,

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IAHS Publication. **218**.

Nakawo, M., et al. (1999). "Characteristics of Khumbu Glacier, Nepal Himalaya: recent change in the debris-covered area." *Ann Glaciol* **28**: 118-122.

Racoviteanu, A., et al. (2009). "Challenges and recommendations in mapping of glacier parameters from space: results of the 2008 Global Land Ice Measurements from Space (GLIMS) workshop, Boulder, Colorado, USA." *Annals of Glaciology* **50**(53).

Singh, P., et al. (2000). Influence of a fine debris layer on the melting of snow and ice on a Himalayan glacier. *Debris-covered glaciers*. M. Nakawo, C. F. Raymond and A. Fountain. Wallingsford, IAHS. **264**: 63 - 69.

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Interactive comment on *The Cryosphere Discuss.*, 5, 499, 2011.