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The Cryosphere Discussions

Interactive comment on "Monitoring Tropical Debris Covered Glacier Dynamics from High Resolution Unmanned Aerial Vehicle Photogrammetry, Cordillera Blanca, Peru" *by* Oliver Wigmore and Bryan Mark

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The authors would like to thank the anonymous reviewer who took the time to provide a detailed review of this manuscript. Their constructive comments and suggestions will greatly improve the quality and impact of the manuscript. Our responses can be found below a reiteration of the reviewers comment.

The paper presents UAV survey results from the Cordillera Blanca, Peru. The data are novel, in that they provide information on a comparatively little-studied area and add

to the limited number of UAV surveys on high-altitude glaciers. However, for me, the study does not really address its objectives. It measures changes over a portion of the glacier, but does not capture the full volume change. I also question why the velocities were determined manually and for 72 points, rather than using more spatially comprehensive feature tracking. For objective three, the study does not explicitly investigate the role of debris thickness and its links to melt: it identifies debris as a secondary control, because it is thick at the terminus, but does not look at smaller scale variations or assess its impact on melt rates at higher elevations. It also does not consider that the debris may well be the reason for the tongues existence and characteristics (e.g. presence of ice cliffs). Overall, the discussion of debris cover is a little simplistic. Similarly, I felt Objective 4 was not properly addressed, and was a more limited discussion of the expansion of melt pools between two surveys, with some speculation about the potential for rapid drainage and lake expansion. I'm not sure how much this section extends our understanding of the interaction between the glacier and the lake. Overall, the paper has some valuable and interesting data, but it needs to be more specific about what the data can actually tell us (in terms of glacier dynamics, ice loss, lake interactions etc.) and the objectives should be re-focused accordingly. It would be good to see more comparison of these processes (e.g. melt cliffs, pools, lake formation) with analogues in the Himalaya: we have quite a bit of data and process knowledge from there, so it would be could to link these results to this literature and to make the comparison between different regions and sizes of glacier.

Response: While we agree this study would be improved by surveying the entire glacier, this was unfortunately not possible given access, elevation and flight time constraints. We have elaborated on this in response to your specific comments below. We will specifically address these constraints and the limitations it places on our findings in the revised manuscript. We will revisit our list of objectives and ensure that they are appropriate for the data, and that they are comprehensively addressed. We will separate the results and discussion sections, and expand the discussion to incorporate a broader comparison of our results with the existing literature. To the extent that it is

beneficial we may include reference to Himalayan glaciers, given the larger volume of literature. However, we feel that direct comparison to this region is of limited benefit given the considerable differences in the hydrologic and climatic regimes of these two regions.

My detailed comments are below. Page 1 Line 10: What about thinning, as well as retreat?

Response: We will correct this statement to include both retreat and thinning.

Also, altering THE timing.

Response: Agreed.

Line 19: Why the only the tongue and not the whole glacier? This would be important for water resources.

Response: It would be great to survey the entire glacier, and we agree that to derive and accurate mass balance using this method it is imperative. However, the main accumulation zone is almost 3km horizontally and 1000-1500m higher (topping out at $\sim$6000m) in elevation than the calving face – and the nearest safe, accessible launch point. Covering these distances with our multirotor drone was not feasible given the serious limitations on total flight time at these elevations. Furthermore, to produce reliable DEM's using structure from motion accurate ground control targets/control points are required. Accessing these upper parts of the glacier is extremely difficult and was not possible for this study.

Line 23: I don't follow how this shows a continued connection to the glacier tongue: the pieces of detached ice could just be melting away in-situ, completely dynamically detached from the glacier.

Response: We will improve this statement. Basically, we measured low (1-4m/yr) velocities over the sediments below the glacier calving face. Suggesting that the glacier is still pushing these sediments down valley. This suggests at least some connection

with the glacier above. However, you are correct that this does not necessarily mean a direct continuation of ice within these sections. We agree that the changes observed here are likely due to pieces of ice melting away insitu within a sediment and ice matrix.

Line 27: First statement needs a reference and give % for the Cordillera Blanca.

Response: We will include this value.

Page 2 Line 1: Rise in glacier terminus elevation sounds odd.

Response: We will edit accordingly.

Line 8: is>are

Response: Agreed.

Line 13: what is meant by 'geomorphic change for a debris covered glacier'? Do you mean glacier change, e.g. shrinkage / retreat?

Response: We will more clearly define this statement.

Line 19: I'm not sure this paragraph is needed. It's pretty general. I think it would be better to just say which approach was used and why, maybe at the start of the methods. I feel like all of section 1.1. is stepping too far back in terms of explanation and would be much better if it cut out the general material about each method, and focused specifically on its previous application to the study area (or relevant comparison glaciers, e.g. debris-covered glaciers) or why it hasn't been used previously. The paper does link to the study area at points, but it would benefit from a tighter, more focused argument throughout.

Response: We agree with these statements and will consolidate the introductory sections of the manuscript accordingly. These issues were raised by the other reviewers and the editor and are discussed more fully in the general response.

Page 5 Line 4: I like that the objectives are clearly stated.

Line 15 & 16. Reference if possible.

Response: We can probably find a suitable reference for this, but it's fairly general at this point.

Line 26: How was this determined? By this study or previous work? Needs to be cited if it is the latter.

Response: This is from general knowledge and experience in the region, however there is likely a reference somewhere to support it. If not I can provide specific terminal elevations for a couple of nearby glaciers.

Page 7 Line 22: dated for use?

Response: We can improve the wording of this statement. Basically the SRTM data is too coarse and in some instances too old (dated) to provide accurate elevation data for planning autonomous flight paths close to the ground surface (i.e. under $\sim$40m). If we had access to a higher resolution and more recent DEM we could be more confident the drone would not hit anything and therefore fly it closer to the ground and increase the spatial resolution.

Line 28: Was this why only the lower portion of the glacier was surveyed?

Response: See above re flight time, distance and access constraints.

Page 8 Line 16: DEMs (remove the ')

Response: Agreed.

Page 9 Line 1: Why do this manually? Why not use e.g. Cosi-Corr or Imgraft? This should give you a much more spatially extensive velocity field, so you don't need to interpolate. The glacier is quite small, but 72 points does not seem a lot when you have a heterogenous surface (pools, cliffs, debris cover). Based on Line 5, I'm not clear if these offsets were then used to calculate the distance the cliffs were advected by the flow or to determine how much they had melted back (i.e. by taking out the

velocity component and then subtracting the two DEMs). If the data are being used to estimate ice cliff melt rates, then can we really accurately separate out the local flow velocity from the melt rates (which are likely to be a few tens of cm, to a couple of meters) using just 72 points?

Response: We initially attempted to use Cosi-Corr for this but experienced difficulty in obtaining a good result. This may be due to the significant changes occurring within the scene and a limited number of identified matching points by the algorithm. In the interests of time we decided it was best to proceed with a manual feature tracking approach. We arrived at 72 points after iteratively adding more points and determining only minor changes in the velocity field after $\sim$60 points were included. Obviously minor velocity variations are likely missed using this approach and a continuous velocity field would be preferable. We hope to explore the application of Cosi-Corr and Imgraft in our ongoing work in the area but do not plan to address this in this manuscript.

Clarification per line 5. We used the velocity vectors to shift (polynomial georectification) the 2015 orthomosaic to match the 2014 location, thereby removing the down valley motion that took place between the two dates. Measurements of ice cliff back wasting were then made manually by measuring offset distances between the two dates – i.e. we calculated how much they melted back between the two dates from the orthomosaics. There are obviously some errors involved in this method (likely much less than 1m), which could be reduced by better deriving the flow velocity (either with Cosi-Corr/Imgraft or by using more points). We agree that with ice cliff melt rates of tens of cms to a couple of meters this error could be particularly problematic. However, in this case measured ice cliff melt rates were 2-25m which is considerably greater than the potential error of using this method.

Page 10 Line 12: For me, this shows a limitation to addressing objective 2 (and 4, to a lesser extent). We can't assess total volume changes or its potential future evolution, without accounting for the entire glacier.

Response: Given the limitations discussed above it was not possible to survey the entire glacier. However, we agree that this does limit to some extent the ability to address objective 2. We plan to revisit the list of objectives and specifically address them – see general response.

Line 23: As noted above, how confident can we be of removing the horizontal velocities local to the ice cliff, when 72 points were used across the glacier?

Response: See above.

Line 27: Needs a reference.

Response: We will include one.

Line 31: Quite vague and speculative. Do you have any data on debris thickness?

Response: We do not have quantitative data on debris thickness, but from our visual observations it is extremely variable. In some areas it is well over 1m thick and in others less than 5cm. Generally debris thickness exceeds 50cm and is thus likely to provide and insulation for the ice beneath. Indeed insulation from this thick debris cover (along with a relatively large accumulation zone) is likely the reason this glacier extends to a much lower terminal elevations than others in the Cordillera Blanca.

Page 11 Line 6: I don't think you can say debris cover is secondary here. First, the differential melt associated with ice cliffs is at least partly due to the removal of the debris layer. Second, the presence of the thick debris layer may well be why this tongue still exists at these altitudes (you note earlier in the paper this is a comparatively low altitude for the region), so although it doesn't increase melt rates, it is still an important control on them. There are no in-situ measurements of melt versus debris thickness, so I think it is hard to make this statement, particularly as the study only focuses on the tongue where the debris cover is thick. Debris may well be important here for supressing melt, then accelerate melt further up.

Response: We agree with these statements. The role of variable debris thickness will

be more clearly discussed in the expanded (and separated) discussion section.

Line 10: I'm unclear how much of the change discussed earlier in 5.2. is due to this movement of large objects, versus net change. We need to distinguish the two for e.g. forecasting water resources.

Response: Correct, however without completing a survey of the entire glacier it is impossible to quantify this.

Line 32: How? It would be tricky for the lake water to get very far up glacier. Could also relate to basal topography.

Response: We will clarify this statement in the expanded discussion. The basal topography is unknown, however it is likely similar to other glaciers in the Cordillera Blanca. For these glaciers we have observed the rapid expansion of proglacial lakes as their glaciers have receded up valley. By looking at the local topography of Llaca and comparing to others in the area it appears there is about 600-900m of the Llaca glacier tongue that lies within the depression of its future lake bed. As Llaca continues to thin and retreat up valley the lake will expand bringing it in closer proximity to the steeper faces of the mountains above, which is likely to increase the risk of an outburst flood, as has been observed and studied elsewhere in the range.

Figure 4: I would make the dots bigger, so they are easier to see. A black outline would help.

Response: We can make these changes.

Figure 7: Make the scale bards categorised, rather than stretched, as it's easier to read of individual values.

Response: We agree categorized is easier to read values, however stretched provides a clearer indication of the spatial variability. We will see how it looks with categorized bars and change if appropriate/beneficial to data display.

Figures 9-12. It would be useful to have some context about where these sites are, e.g. using extentboxes on Fig. 1 or 2.

Response: Agreed, we will add these.

Finally, we would like to thank you again for your time and constructive comments on this manuscript.

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