<u>Response to Reviewer 2</u>

This is an interesting and well put-together study. It presents some interesting insights into supraglacial drainage networks on a large number of Swiss glaciers, which must be one of the first such studies that takes advantage of modern remote sensing/photogrammetric approaches. Supraglacial drainage networks on the Greenland Ice Sheet are a popular focus of research, but such networks on valley glaciers are understudied. I thus welcome the efforts of this paper. I would also like to congratulate the authors on their attention to detail. I think I came across just one typo throughout, and the formatting, presentation, writing style and all other such aspects are top class. I very much appreciate the care taken to ensure this. It makes the job of reviewers much easier, and indeed makes the work far more accessible to a readership. We thank the reviewer for highlighting the value of our manuscript, and we are grateful for their positive comments on its presentation. We appreciate the feedback and address each point in turn below, with our responses indicated in blue text.

Whilst I see value in the paper and welcome the efforts of the authors, I do have some concerns as follows:

1) One of the key issues I have is that I am not 100% certain of the broader aims of the work. The authors very clearly state on lines 91-92 that our 'aim is to characterise the morphometry of supraglacial channels on mountain glaciers, providing insight into where and why they form'. Whilst this is clear, I would like the authors to go further, and say why this matters – why, glaciologically speaking, should we be doing this? Why is it important for us to gain these new insights? I suspect the authors can address this relatively easily, but I would like to see clear statement as to the value of this work. It's worth saying that I think a lot of text that could contribute to such a statement already exists in the Introduction, so it's just a matter of coalescing the key points. Amended – We have added an additional statement of the importance of supraglacial channels, after the aims. In the first paragraph of the introduction we have added in information about the importance of supraglacial channels that route meltwater to the bed, and the implications that has for ice motion.

2) Perhaps my main concerns are about the subjectivity of the mapping of channels, and the assumption that not seeing channels of a certain size means there are no channels. I don't believe this is correct. I believe that the approach is more about resolution rather than presence. I go into some detail in my line-by-line comments below, and indeed the authors themselves actually raise this in the very last sentence of the paper! However, I believe this deserves more attention. Please see my comments below.

Mapping accuracy:

We acknowledge that there is a subjective element to channel delineation and have now tested the accuracy of the mapping by repeat mapping of the Rhone Glacier (Fig. 2a) which contains >100 streams (>0.5 m). We find a difference in drainage density of 2.6% and a 0.21% decrease in total channel length which we deem acceptable for providing a good representation of glacier drainage density, and have added this into section 3.1 in the methods. In addition, we have added an additional figure to the appendix that shows a comparison of our repeat mapping. The primary source of error was found to be determining where to stop mapping up-channel, which we explain in the methods. However, we aimed to take a conservative approach in when to stop making to reduce our chances of overinterpreting channel pathways.

Mapping resolution:

It is outlined throughout the manuscript that we only delineate channels that are around >0.5 m wide as we cannot clearly delineate channels below this resolution. We have amended the manuscript to clearly state 'no visible channels' when referring to glaciers where channels are not identifiable below our resolution. We have also added our justification for not mapping or quantifying small channel networks, which is simply that we cannot do this reliably enough for each glacier. We could perhaps denote the presence of channels below our mapping resolution for our study area, however it is likely that these dense networks are only visible on large glaciers where there is more surface melt. Hence, we do not do this because it raises the same issue identified by the reviewer about our mapping threshold. Unfortunately, there is no consistent way for us to map the accurate distribution of all channels on every glacier in Valais, but we believe that the most consistent way for us to do this is to choose a clear threshold that we can confidently map above, whilst acknowledging that this may create a bias towards larger glaciers (section 5.1). We too agree that these smaller channels may be important, but they are simply outside of the scope of and data products available for this current paper. Hence, we our focus is on larger channels that carry the bulk of the meltwater.

3) Another key concern is about the timing of the analysis. The imagery for the analysis was gathered in the early part of the summer. Lower altitude glaciers in early summer will have more melt and thus more channels than those at higher altitude. This could be the main or even sole driver of the differences observed in channel density. I believe it is dangerous to use a single snapshot in time, particularly when it is this early in the melt season, to assess overall drainage density. I appreciate that the authors are constrained by data availability, but this is an important point that needs careful consideration.

We agree with the reviewer that imagery obtained at the end of the melt season would be preferable, but we are limited by the fact that the orthophotos were only available in mid-July. We have since quantified snow-cover at different elevations to reinforce the point that there are still sufficiently large snow-free areas in mid-July at all elevations. We find on average that 39.6% of each glacier was snow-free, which is slightly higher (45.0%) where a glacier has a lower mean elevation (2500 – 2800 m.a.s.l), although this is not a particularly large difference compared to the snow free area (39.5%) of the highest mean elevation band (>3700). We agree that glacier mean elevation is one of the main drivers of glacier drainage density ($\rho = -0.66$, Fig. 6). However, this relationship would be anticipated to be a strong control on drainage density regardless of when the imagery was acquired in July or late August, and our imagery does contain snow-free glacier areas at all elevations. We have now added information into the methods to provide better context on the year of imagery acquisition, and have acknowledged the impact of our imagery acquisition timings in the discussion.

I have a significant number of other comments which I relate to specific locations in the text. These are detailed below.

Line	Issue
13	It seems odd to state that your investigations explore '<2000 supraglacial channels'. This seems rather vague to me. '<2000 could mean anything from 1 to 1999. Can you be a bit more precise? Are you looking at a few tens, a few hundreds or nearly 2000? Amended – We have altered the abstract to reflect the exact number of channels (n = 1890).
13	I must confess to being quite surprised that only 85 of your studied 285 glaciers have supraglacial channels. What time of year did you carry out your investigations, since I think this would be significant. The orthophoto images are from mid-July 2020 which is mentioned in the methods. The 85 glaciers contain channels above our threshold of 0.5 m at this specific time. However,

	we acknowledge that channel networks become more developed at the end of the melt season, but no orthophotos are available at the end of August or early September.
34	You state here that glaciers and ice caps 'are anticipated to contribute to sea level rise throughout the 21st century and beyond'. It would be worth stating that they have indeed already been contributing too. Amended.
90	With reference to my point above, here you mention that you create an inventory of 'almost 2000 supraglacial channels'. This is a much clearer indication of the numbers involved than the <2000 referred to previously. We have modified this to be the exact number, in line with the abstract.
162	I'm pretty astonished by the manual effort that must have gone into mapping these channels. This is an impressive feat, so very well done! However, I have a couple of concerns. Firstly, how did you assess and quantify the accuracy of your manual approach? The channels you indicate as being mapped in Figure 2 are quite clear and relatively straightforward to delineate and map I would imagine. However, I would guess that some of the images you were using were less clear and the channels less well-defined. In such circumstances I suspect there's a degree of uncertainty and error in your mapping. How do you quantify this, and can you put some numbers on this? We have quantified the repeatability of our mapping by repeating the mapping (using the same mapper) for the Rhone Glacier (shown in Figure 2a) which contains >100 channels (>0.5 m), some of which are more complex to delineate. We find a 2.6% difference in the drainage density for the glacier and a 0.21% decrease in total channel length, when comparing our original to our repeat mapping, which is now detailed in section 3.1. We have added a figure in the appendix (Figure A3) that shows a comparison between the original mapping in this study, and the mapping completed as part of the accuracy assessment. This error acknowledges there is some subjectivity involved in mapping the channels, but it is low enough to ensure that the drainage density for each glacier is still a reliable reflection of the drainage network, and glaciers can clearly be grouped into low, medium and high drainage densities (for channels >0.5 m).
Figure 2	Following on from the point above, and particularly relating Figure 2, I am curious about how you determine what to include in your delineation. I can definitely identify several channels in part (a) that you do not choose to delineate in part (b). This causes me concern, since it suggests an (inevitable) degree of subjectivity is integral in this study, and there are clear consequences of this when it comes to considering metrics such as drainage density. Some of the channels not mapped by the authors are only just visible as they are quite fine and thus presumably smaller (in parts (c) and (d) for example, there are numerous very small channels, which would be very hard to map, but are worth being aware of). As a result, there is, I guess, a size- threshold element as to which channels are included. However, to me, there are some channels that I would consider to be of similar size (and clarity) to those which have been delineated but which the authors have chosen not to map. I think this issue is of considerable concern, and needs consideration

	and arguably, more channels need mapping. We agree that there is a degree of subjectivity and human error in the mapping (as quantified above). However, as mentioned in the methods we only map channels that can be clearly delineated at a 1:1000 scale, and whilst some small channels can be seen at this resolution, they cannot be clearly mapped and we focus on streams >0.5 m to prioritize accuracy and because they carry the bulk of the meltwater. We have now modified Figure 2 so that all images are shown at a 1:1000 scale so it is easier to see what is and is not visible at this resolution. We have modified panels a & b to an example that shows more small channels so it is more apparent where small channels exist but haven't been mapped.
218	This concept of the mapping resolution and the fact that you are mapping channels above this threshold, is important. However, in the imagery, it looks to me that there are hazy, grey areas which most likely indicate a dense network of small channels. Whilst you can't map these individually, they are areas of channels and so I wonder if this needs to be considered (particularly in your drainage density calculations). We agree with the reviewer that there are dense areas of very small channels that can be seen below the imagery on many glaciers but are too small to map clearly. Whilst we could identify the number of glaciers these occur on, this would not be a fair comparison between glaciers as it would be harder to define a cut-off resolution and as the reviewer notes, we are likely to only see these dense networks on larger glaciers. Thus, we take a conservative approach by only mapping channels we can clearly identify >0.5 m to avoid additional interpretation and to keep our focus on the larger channels that carry the bulk of the meltwater.
219	As a consequence of the threshold mapping resolution, I am uneasy about this differentiation between glaciers with and without channels. More accurately, those without are simply those without channels above the threshold mapping resolution. It seems likely to me that they do have supraglacial water flowing in channels, but these are in smaller networks that are not easily identifiable as discrete channels. We have added clearer language, i.e., 'glaciers without large channels (> 0.5 m)' when discussing glaciers without visible channels.
221	I am concerned about the observation that all glaciers above 5.6km^2 have channels, and the insights being drawn about bigger glaciers having channels. Could it not be simply that bigger glaciers have bigger channels while smaller glaciers have smaller channels. As a result, we don't see the smaller channels as easily (due to the image resolution), and so are swayed into seeing these as lacking channels? We agree that glacier area likely controls the size of the channels, which may affect drainage density because we only map large channels above our threshold (0.5 m). However, our research reveals that glacier area is not the primary control on drainage density, which is evident by the fairly weak but still significant Spearman's rank correlation (ρ = -0.10) between glacier drainage density and glacier area. This means

	that whilst the size of the glacier probably does affect the amount of channels we detect, there are other factors such as slope and glacier mean elevation that are more important for determining the density of channels.
231	I've said it previously, but I am very concerned about the distinction that is being made between glaciers where channels are/aren't present. It's about resolution and not presence to my mind. If glaciers experience melt, unless all surface water immediately enters the englacial region of a glacier, there must be some surface water and to my mind, this must (at least in part) be in the form of channels. I think the distinction is between the size of the channels and not their presence. I would also argue that given your imagery was gathered in mid-July, it is highly likely that the amount of generated melt is not at its maximum, particularly on glaciers at higher elevation. The impact of altitude could be fundamental, since at this point in the melt season, glaciers at lower elevation may well have much more melt occurring than those at higher elevations. This may thus be the driver of there being more, larger, and denser channels on these lower elevation glaciers. We have strengthened the language surrounding where glaciers do not have large (0.5 m) channels and mentioned why we use the resolution that we do in the methodology but acknowledge that the channels below our mapping resolution are present and may also be important. The imagery acquisition date will affect channel development, and we find that glacier mean elevation affects drainage density (ρ = -0.66) (Figure 6). However, we also find that other factors, e.g., slope, clearly affect drainage density. Hence elevation is not the sole driver of drainage density. It would be expected that elevation is an important control on channel distribution regardless of the date of imagery acquisition, as less melt will occur at higher elevations, resulting in smaller and fewer channels.
255	It is a little odd that some channels disappear 'below the mapping resolution'. I am assuming you mean that they disappear as they head downglacier, since the phraseology of the various ways channels terminate in this passage implies this. However, I would have imagined that as channels flow downslope, they get bigger (as they carry more water) rather than disappearing under the threshold resolution for mapping. Amended - The reviewer is right in that this terminology refers to channels that disappear downglacier, which seems counterintuitive as channels widen downglacier. However, there are many instances where a channel may have terminated in a crevasse or moulin, but the channel terminus location is obscured by debris/snow, or the imagery resolution is not sufficient for identifying the terminus. There are also instances where the channel disappears below the resolution down-channel, which may be because a crevasse has captured some meltwater up-channel, which we cannot pinpoint. In response to this comment, we have added a new sentence in paragraph 2 of section 3.1

	to expand upon our terminus categories.
266	I'm a little uneasy about the statement: 'large channels often occur at the interface between debris-covered and bare ice'. Firstly, what do you mean by 'large'? Do you mean in terms of diameter or length, and what criteria do you use to designate a channel as large? Furthermore, this seems to be quite a significant statement. Like your other metrics, you should quantify this – what proportion occur at such a boundary? Does the statement really hold true, when the channels in Figures 4a, c, d and e do not seem to be controlled by debris presence, and nor do those in Figure 2. We have removed the size descriptive element from this sentence. The statement still holds true, however, as topographic depressions between medial and lateral moraines often capture this meltwater due to streams logically flowing into lower elevation areas. The reviewer notes that this isn't visible in much of Figure 4, but this is simply because not all of these show the described environment. Figure 4b does show a channel on the interface between clean ice and debris cover, and whilst panel 4e doesn't show a channel along this interface, it does show meltwater running off into the depressions between the lateral moraine and the glacier surface, which would likely be channelized if not for the thick debris and undulating topography.
278	In drawing conclusions about the relationship between, for example, sinuosity and slope, I think you need to express some measure of statistical significance so that we know whether these relationships are real. Spearman's rank values have been added to Figure 5, and the caption now specifies that each value displayed on the plots has a significance value of at least $p = <0.05$.
300-306	I am very uneasy about the statements made here. To simply state, for example, that 'a relationship between drainage density and glacier slope exists' needs statistical support. Looking at the graphs is Figure 5 (particularly e, f and g), I do not see a strong relationship, and so to back up your statements, you need to use some statistics to prove your point. Following suggestions from Reviewer 1, we have added in the spearman's rank values to Figure 5. Hence, when citing relationships in Figure 5, there are now statistics to support these relationships which resolves this comment.
308	I am not a statistician at all, so can't offer a lot of insight here. However, you make several statements prior to this point regarding relationships in your data, yet it is only here, towards the end of your results, that you directly address statistical relationships. I wonder if things need reordering slightly. We have now addressed this issue by adding Spearman's rank values (all statistically significant) onto Figure 5 so there is a quantitative measure of the relationships we refer to in section 4.3.

313-314	I come back to my concern raised above, that the relationship between drainage density and glacier altitude. I don't think this is surprising, particularly given the timing of the imagery used to explore drainage density. I feel that this is likely to be the most significant control. There is a relationship between glacier altitude and drainage density as noted by the reviewer (Fig. 6), but this relationship would likely exist regardless of imagery acquisition date because channels would be expected to be more prevalent at elevations characterised by higher surface melt. We are less concerned by the potential over-exaggeration of the impact of glacier elevation because Figure 6 shows that many relationships exist between our metrics and drainage density, and this is not solely dominated by elevation metrics. Hence, despite the date of imagery acquisition it was still possible to establish a range of controls on drainage density. We now acknowledge in the methods that our date of imagery acquisition means that we are unlikely to capture the peak extent of channel distribution and provide further detail on the climatic conditions that precede imagery acquisition. We also acknowledge the impact that our imagery acquisition date has on how extensive channel distribution is in section 5.1.
359-360	Whilst I rather like the schematics you provide in Figure 7, there is a degree of conjecture here, particularly in relation to the proposed hydrographs. I'd like it to be made clearer that these are not measured or calculated at all, but rather assumed. Even then, I am wary of them, since in reality, these hydrographs and their shape are strongly influenced by time of year, air temperatures, ease and speed with which channels are formed, diurnal temperature range etc. Amended – We have added a sentence to the figure caption to clarify that these hydrographs are conceptual and do not reflect measured proglacial stream discharge. In response to the concern about the time of year/air temperatures, we now note that these will change throughout the melt season due to increased subglacial drainage network efficiency.
369-371	Interesting point, but I'd also point out that higher temperatures will mean more melt is generated and thus there's more water available to incise deeply. We discuss this in lines 517 to 519 (in the pre-print version) and we deem this to be a valid point. However, we have now added an additional sentence that follows on from lines 369-371 (pre-print version) to ensure that this point is also included here.
391-393	Need a reference here to support the statement about lake drainage. Amended – an example from Gornergletscher has been included (Huss et al., 2007).
399-400	I am very wary of the statement: 'Our dataset provides new insight into meltwater transport across a large range of glaciers, allowing simple inferences to be made about connectivity and lag times'. Your data is all about channel mapping. Water transport and lag times are assumed based on this knowledge, so I would prefer that this is toned down a little. Amended – this has been toned down.
411	One thing we can't tell is whether the channels you are mapping are currently active. So, it is possible that the crevasse identified in Figure 8 has appeared relatively recently, thus intersecting the channel shown, and halting the flow of water in this

	channel further downglacier. I don't know how likely this is, but it should at least be considered, alongside the proposed idea that the crevasse is water-filled and thus flowing water overtops it. Without fieldwork observation, we are both speculating, so due caution in the interpretation needs to be exercised. The role of crevasses in intercepting and transporting meltwater has been expanded upon in the last paragraph of page 18 in the revised version.
416-417	Similar to the previous comments, I am wary of the statement: 'the delay between surface melt and proglacial discharge will be larger due to longer pathways and the potential for supraglacial and subglacial storage'. This is true, IF storage takes place. However, you don't know if this is the case. There could be highly efficient englacial/subglacial channels. Again, I think that it needs to be made clearer that these are suggestions rather than based on direct observations. We have modified the language in line 416 (pre-print version) to change 'will be' to 'may be', and we believe that the other text already reflects that we do not have in situ measurements, so these statements are speculative.
448	Throughout, you make reference to 'larger' channels, but this is never quantified. What do you mean by larger? Here, for the first time (I think) you indicate that by 'larger' you mean higher discharge. Is this what you have meant throughout? This needs making clear since to me, I had assumed you meant the physical dimensions of the channels. Regardless of what 'larger' means, I do think you need to quantify the criteria somewhat. We mean physical dimensions and we have now stated this more clearly, i.e. >0.5 m wide. We had mentioned discharge to indicate that channels with larger physical dimensions are typically accompanied by higher discharge, but this is a qualitative assumption as we did not systematically measure width because our channels were manually mapped as a centerline, and this would be too data collection intensive.
480-512	I'm not convinced of the need for this section comparing supraglacial drainage on glaciers and ice-sheets. I feel that the paper is drifting away from its focus a little by including this passage. I'm not suggesting that this section MUST be removed, but rather simply suggesting that its value to the wider paper is not terribly clear, and thus this could be considered. We think this section has value because most of the research on supraglacial channels has been conducted in an ice sheet setting. Hence it is useful to know how comparable channels on mountain glaciers and on ice sheets are, especially if there are some important differences that advance understanding beyond the body of knowledge gleaned only from ice sheet settings. We have added an extra sentence to state this at the beginning of section 5.3.
518-519	Presumably you mean an increase in the SIZE of the ablation area, but when referring to a 'reduction in area for smaller glaciers' you are referring to the entire glacier rather than the ablation area? A bit of clarity needed here. Amended – we have reworded line 518 (pre-print version) to instead say 'rising equilibrium lines' to avoid confusion regarding the mention of both ablation area and overall glacier

	area.
545	‘off the glacier’ rather than ‘of the glacier’. Amended.
557-560	This last statement is the first such mention of the existence of other channels beneath the mapping resolution. I believe this is important (see my earlier comments) and so for it to only appear as the final sentence in the conclusions is rather late. I would prefer to see this discussed earlier, and the importance considered more. We agree that it is important to acknowledge the presence of channels below our mapping resolution and have now mentioned this in the methods section. Please see our response to the second general comment on this topic for a more detailed response.