

# Variability of glacier albedo and links to annual mass balance for the Gardens of Eden and Allah, Southern Alps, New Zealand

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**Status:** final response

**RC1: Interactive comment on “Variability of glacier albedo and links to annual mass balance for the Gardens of Eden and Allah, Southern Alps, New Zealand” by Angus J. Dowson et al.”, Anonymous Referee #1, 30 Jan 2020**

*This is a welcome contribution that provides details of an alternative remotely sensed method for monitoring glacier albedo as a potential mass balance proxy. Direct measurement of mass balance on mountain glaciers is resource intensive and often only provides a small number of point data that still require interpolation. Improving remote monitoring methods is essential as this will enable a more comprehensive and sustainable approach to mass balance monitoring. This is a key rationale present for this project. Increased use of remote sensing techniques is a key way scientists can reduce the carbon footprint of their climate-science. Research that progresses such techniques is timely.*

**Response:** We thank the anonymous reviewer for his/her very positive review of our manuscript.

*However, despite the authors making a strong case for the benefit of remote sensing over on-site measurement it is noted in the acknowledgments (and in a media campaign) that the authors did undertake field work at this remote, protected site. The strength of this method will lie in it being able to be robustly applied to any glacier without the need for onsite calibration. So some questions arise;*

**Response:** It is true that the team completed a 2-day fieldwork trip on the study site at the end of January 2018. The data collected on this trip were not directly linked to the study of albedo presented in this paper. The paper did not suggest otherwise but, for the sake of clarification, we provide an answer to each of the referee's specific questions below:

1. *What data was gathered at the site and was this used to tune processing?*

**Response:** As explained in the manuscript, the only data originating from the field trip that were used to inform this study were oblique aerial and terrestrial photographs that we found useful to refine glacier outlines. At the early stages of this study, glacier outlines were derived from Sentinel-2 imagery until we were fortunate enough to receive very high-resolution Pleiades imagery. Based on this, we decided to refine some glacier outlines and used photos captured during the trip to help inform this process. No data collected during the fieldwork were used to calibrate or validate the processing of MODIS albedo data.

2. *Could the method calibration have been done at an already high-use glacier site (e.g. Franz, Fox, Tasman Glaciers), thereby providing more support for using RS at sensitive sites,*

**Response:** The albedo retrieval method presented in this study does not need field observations for calibration. The albedo retrieval implemented in Modimlab has already been validated on multiple sites around the world, including on New Zealand glaciers, as can be found in the bibliographic references provided in the manuscript. Given the principle by which the albedo is retrieved by Modimlab and its previous validation in a New Zealand glacier environment, it did not require calibration for this study. Therefore, our method can be applied to other high-use and/or sensitive glaciers sites.

and 3. What confidence do the authors have that this method can be applied to sensitive, protected sites without the need for onsite measurement?

**Response:** As noted above, this study did not require site-specific calibration, and no onsite measurements were used other than some additional photos to help refine a number of specific glacier outlines. The photos and on-site field observations were of course very helpful in our efforts to refine the glacier outlines from a quality standpoint. Nonetheless, they were not essential to the method per say. Given the relatively coarse resolution of MODIS data, the interpretation of glacier outlines from high to very high resolution imagery remains sufficient to derive the albedo series. Importantly, there is no significant improvement on the albedo retrieval solely arising from the use of the photos. Given the new insight this study reveals about a poorly documented protected site, we are now much more confident that this method can be applied more widely. This confidence is matched by a reviewer of one of the validation studies of this method, who noted this *“powerful observation-based approach begs to be applied elsewhere”* (Interactive comment on The Cryosphere Discuss., doi:10.5194/tc-2016-98, 2016).

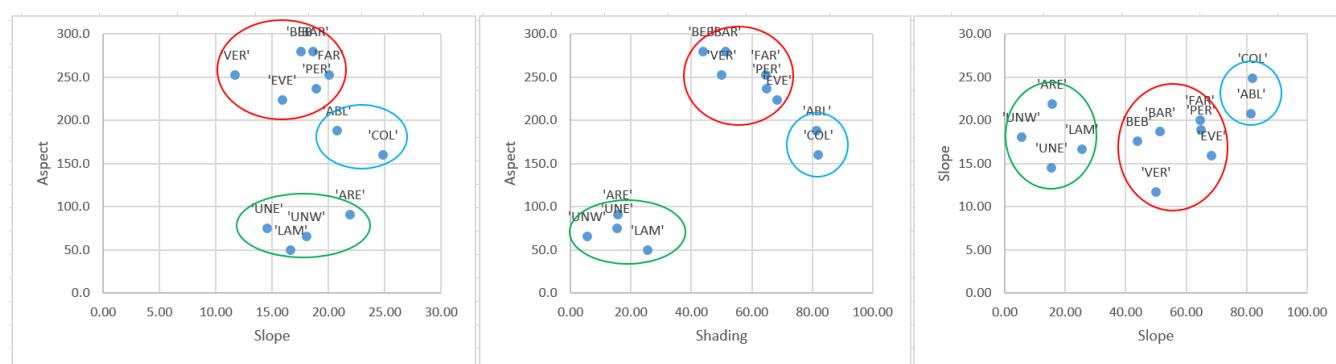
Please note that as we addressed this comment we noted a mistake in the reported date of the fieldwork in the original manuscript, which has been corrected (27-28 January 2018 instead of 20-21 January 2018.)

Generally the paper is well written and contains sufficient background information and detailed (RS) methods section. However, the interpretation of results is compromised by inadequate information (Figure 1) of the actual glaciers used in analysis. Figure 1, the location map, does not make clear the locations of all the individual glaciers contained in the text. This becomes rather frustrating when reading results and attempting to consider them in a spatial context. Consultation of the official topographic map for the area provided some assistance, but it was still unclear exactly what ice bodies the authors were referring to for the two unnamed glaciers, and for a glacier like Colin Campbell, which has multiple branches, it is not clear what branch has been used for analysis.

**Response:** We thank the reviewer for this constructive comment. We agree that Figure 1 is a good place to show the names of each glacier mentioned in the study. We have modified Figure 1 and added a panel showing the glacier outlines and names, and also display the cluster to which they belong.

The decision to separate the 12 glaciers into 3 classes would benefit from a little more explanation. For example Eve Glacier appears more topographically similar to Abel and Colin Campbell (when one makes some assumptions about which branch has been used for the Colin Campbell).

**Response:** We have clarified how we determine the 3 glacier classes in Section 4.2, which is based on the interpretation of glacier characteristics from clusters identified in scatter plots. Those scatter plots are reproduced below for the reviewer and other readers (class 1: green; class 2: red; class 3: blue). While such a classification involves a trade-off between generalisation and retaining some formal structure, we believe there is enough evidence to justify having three classes. The updated Figure 1 and scatter plots below also provide clear evidence that the class of Eve Glacier is appropriate.



*It is also unclear whether statistics for elevation and slope include the upper accumulation zones or just focus on the more defined glacier trunks.*

**Response:** We have clarified that the statistics for the features used to support the classification are “derived from the mapped outlines of each glacier”.

*Having all 12 glaciers clearly defined on a map would benefit result interpretation.*

**Response:** We modified Figure 1 to display glacier outlines and names as well as clusters.

*Figure 5 is a key Figure, but I found myself looking for a third panel showing the average albedo over time, which could potentially be added to Figure 5 (right). If the timing of the ablation minimum is getting later, does this mean that the minimum albedo is also decreasing due to a longer ablation season? Or Not?*

**Response:** We thank the reviewer for this constructive comment. We added a panel showing the evolution of the minimum glacier-wide minimum albedo alongside the evolution of its timing. As we revised this figure, we decided to also display yearly values to help visualise the variability better, while maintaining the 3-year rolling average as a dotted line. Furthermore, we added a scatter plot that shows the relationship between  $\alpha_{yr}^{min}$  and its timing and assessed its correlation to inform the hypothesis of the reviewer. We find a weak correlation when all clusters are considered together ( $R^2=0.26$ ,  $p<0.001$ ) and an even weaker correlation when all glaciers are considered separately ( $R^2=0.11$ ,  $p<0.001$ ). However, within an individual cluster, the value of  $\alpha_{yr}^{min}$  does not exhibit a significant correlation with its timing (cluster 1:  $R^2=0.2$ ,  $p=0.058$ ; cluster 2:  $R^2=0.08$ ,  $p=0.248$ ; cluster 3:  $R^2=0.03$ ,  $p=0.472$ ). We have added some further insights in Section 4.4 to report on this new result, updated references to this figure in the text where appropriate, and added a glaciological interpretation and significance of these findings in a new discussion section (5.2 Implications of variability of albedo on mass balance).

*As noted above, the lack of a detailed location map hinders spatial thinking, as does the organisation of Figure 6. While clearly the authors have opted to organise both graphs in Figure 6 by the scale of the x-axis values in doing so the reader is left with no clues as to how these glaciers are actually related in space, again is there a spatial influence on the data presented? It is very difficult to compare results of the left and right graph for an individual glacier as the order of the y-axis (by giving priority to the x-axis value) are different for each graph. While it is appreciated that a 'progressional' x-axis approach might be the 'neatest' presentation, something is lost in regards to the actually physical process or characteristics that might be driving the patterns being presented. For example can something more be said about W/E or N/S trends? If one colour-codes the class sizes some patterns appear, for example class 1 glaciers tend to have lower albedo and a later minimum timing, whereas class 2 (n=2, should potentially include Eve) have higher albedo and earlier minimum timing.*

**Response:** Thanks for the constructive comment. We found the suggestion of colour coding glaciers by class in Figure 6 very helpful and well-thought out. Section 4.4 in the original manuscript did characterize the contrast in magnitude and timing of minimum albedo between glaciers of class 1 and 2 that now becomes more obvious with the colour coding. The reference to Fig. 6 has also been added to the point made in Section 4.4. As noted above, we have added a new section in the discussion that adds to the interpretation of our results by assessing how topography modulates the response and possible fate of the GoEA glaciers.

*While it is appreciated that this paper is 'methods' focused there is missed opportunity to engage more fully with some of the glaciological findings.*

**Response:** Our paper makes use of the albedo method to produce a comprehensive set of new glaciological observations in an area where very little data exist. The principles of this method are described for completeness, yet this section remains limited to echoing the body of literature where it was developed and validated. In particular, Sirguey et al. (2016) provides a very useful 'methods focused paper' that is in part focused on describing, calibrating and validating the albedo method.

In contrast, this study is very much an application of the method rather than a paper about the method. It provides a large amount of new glaciological observations unavailable to date, and characterizes glacier behaviour of largely undocumented icefields. It is true that this new application of the albedo method provides an opportunity to incrementally refine it, for example by testing the use of glacier outlines to facilitate masking and the opportunity to use MODIS Aqua data. Nevertheless, results associated with these "methodological" steps only involve three out of the now eleven sections of the results and discussion. All other results present new insights about the behaviour of glaciers in the study area. This paper also provides a discussion of the implications of the new findings regarding the variability of the glacier surface compared to results from the EOSS methodology traditionally used in New Zealand. We have also explored the validity of the "unified climatic unit" theory about the response of New Zealand glaciers. In response to comments from both reviewers, we have added a new discussion section (5.2 Implications of variability of albedo on mass balance) that we hope builds knowledge about the glaciology of this remote but important region in the Southern Alps.

*In particular, the finding that the timing of the minimum albedo is occurring later in the summer, which could signal a later onset of the first winter snowfall (i.e. lengthening of the ablation season). This result also makes one wonder if there is any*

*trend (across all the glaciers measured) of a decreasing minimum albedo over time, for if the ablation season is becoming more protracted then the snow surface would likely become more discoloured. Or alternatively, is the minimum albedo the same and the trend is associated with a later start to the ablation season (i.e. more spring snow delaying the onset of melting). It would be great to see a little more discussion of these important mass balance feedbacks.*

**Response:** We thank the reviewer for this input. We found the suggestion very useful as a prompt for us to explore this issue more deeply as our data challenges this hypothesis. As demonstrated above, the comparison between the magnitude of  $\alpha_{yr}^{min}$  and its timing shows that a delayed minimum albedo does not necessarily lead to a lower albedo. We have added elements of our interpretation of this result in the new discussion section.

*Should the authors wish to include a reference for the Rolleston Glacier mass balance programme, they could cite Purdie, H., Rack, W., Anderson, B., Kerr, T., Chinn, T.J., Owens, I. and Linton, M. 2015: The impact of extreme summer melt on net accumulation of an avalanche fed glacier, as determined by ground-penetrating radar. Geografiska Annaler, Series A: Physical Geography 97, 779-791.*

**Response:** We thank the reviewer for this suggestion and have added the citation to support the statement made in the introduction about the Rolleston Glacier mass balance programme.

**RC2: 'Interactive comment on "Variability of glacier albedo and links to annual mass balance for the Gardens of Eden and Allah, Southern Alps, New Zealand" by Angus J. Dowson et al.', Anonymous Referee #2, 05 February 2020**

*The paper proposes to use minimum MODIS albedo to approximate snow line altitudes (SLA). The paper requires a substantial effort to improve the clarity and organisation. The authors need to clearly define the objectives of the paper then use the results to support the objectives.*

**Response:** We thank the reviewer for his/her comprehensive review of our manuscript.

*General comments: A clearly stated set of objectives is required. The authors need to put some significant thought into this as no surface mass balance (smb) records are presented. The authors need to find a way to make a better connection to smb, otherwise the analysis compares a proxy for smb to another proxy for smb.\|*

**Response:** We have refined the aim and provided three specific objectives to meet this aim. We have clarified how this research provides another important step towards developing a robust and comprehensive approach to remotely monitoring glaciers in the Southern Alps. We have clarified in the introduction and elsewhere in the manuscript how the albedo method can be used, even when not calibrated, to assess the spatial and temporal variability of glacier mass balance. Finally, in the context of having limited direct measurements of mass balance in the Southern Alps, the albedo method provides the opportunity of having a second proxy to supplement the 40-year record of the EOSS programme. There is merit in making this comparison as it produces new insights and enabled us to revisit an important conclusion inferred from the EOSS programme.

*The manuscript requires substantial editing for clarity and organisation.*

**Response:** We have made major revisions of the manuscript. The changes we have made, as suggested by the reviewers, have improved the clarity and organisation of the manuscript as detailed in our response to each comment and the track-changes version of the new manuscript.

*The error analysis of MODIS albedo and the potential for sensor degradation (post 2016 on the Terra bus) need to be addressed.*

**Response:** The reviewer reiterated this point in another specific comment – please see our full response below.

*Please use continuous line numbers and do not restart the line numbers at every page.*

**Response:** Done.

*A series of paper citations are listed at the end of this review for you to consider.*

**Response:** We thank the reviewer for those suggestions. We used some of these citations in the revised manuscript as indicated in our response to the reviewer's comments.

*Please remove the words "important", "meaningful", "arguably", etc. from the manuscript. Let the readers decide for themselves.*

**Response:** Accepted, we have removed or replaced all instances of the words.

*Julian Day should probably be referred to as Day of Year.*

**Response:** We appreciate that Julian Day is initially defined as a datation system with an origin on 1 January 4713 BC. However, it is generally accepted that in context, a Julian Day is often understood and unambiguously defined as the number of days since an alternative origin. For example, CNES uses 1 January 1950, while NASA uses 24 May 1968 to define their Julian date. In fact, without historical context, Julian Day is often used to refer to the day of year number as we use it here. NASA provides a Julian Day Calendar that can be found at <https://landweb.modaps.eosdis.nasa.gov/browse/calendar.html>. In

view of this, we don't think that our use of "Julian Day" creates an ambiguity that warrants a change as suggested by the reviewer.

*A substantial amount of effort is required to understand the errors in SLA, and minimum albedo related to their temporal mismatch. The figures are not used to full effect in the text. A clearer description and analysis of the figures in the text is required.*

**Response:** We clarified the methodology used by the EOSS program to derive SLA and expanded Section 4.6 with reference to Figures 8, 9 & 10 to stress this point, as well as providing a new discussion section that reflects on these differences. We hope these substantial revisions have provided more clarity.

*The word significant should be reserved to describe statistical significance, otherwise words like substantial should be used to describe a large change.*

**Response:** We agree with the reviewer about the use of "significant". We replaced the word "significant" if it was not being used to describe, or supported by, a statistical test, except when the word was unambiguously referring to its alternate meaning as "*indicative of something sufficiently great or important to be worthy of attention*".

*If the authors are going to invoke the 50 EOSS glaciers, then a much stronger analysis of how the 12 glaciers in this study compare to the 50 is required.*

**Response:** We have updated and provided a detailed comparison between the response of the glaciers on the GoEA and the EOSS observations from the same region. See Sections 4.6-7 and the discussion in Section 5.1 for these analyses.

*Specific comments:*

*Line 10: Using the whole glacier minimum albedo the dynamics of the glacier are somewhat smoothed over. Perhaps define what is meant by dynamics in this instance. Is it annual minimum albedo that was used, or melt season?*

**Response:** We thank the reviewer for this input. The use of the word *dynamics* was ambiguous as it suggests mechanical behaviour. We implied a more general definition of *dynamics*, namely "*a characteristic in relation to the constant change of a process or a system*". This has been removed as part of our reworking of the abstract.

*Line 13: briefly define new approach*

**Response:** We believe that describing the approach we tested and used for masking would be unnecessarily complicated and lengthen the abstract. We decided to remove this part of the sentence.

*Line 14: provide the evidence in brief*

**Response:** We rephrased the sentence to clarify this.

*Line 12: Was surface mass balance measured, or was EOSS SLA measured – the two are not the same thing?*

**Response:** We have refined and updated the abstract. Surface mass balance was not measured in this study. This sentence referred to the fact that the albedo method used in this study has been shown in earlier work to be an efficient proxy for glacier mass balance. The question raised by the reviewer is legitimate as the sentence may have been misleading given we are not in a position to provide a quantitative estimate, as there has not been a calibration of mass balance in this study.

*Line 16: Define "high snow line"*

**Response:** We added that "high snow line altitude" is defined as "relative to the long-term average"

*p-value should be p<0.001, etc. depending on level of significance.*

**Response:** Accepted, we expressed the actual p value unless  $p < 0.001$ , in which case we only used the statement of inequality.

*The results section of the Abstract need to be rewritten to present all of the results.*

**Response:** We have refined and updated the abstract.

*Furthermore, a statement of why you have done this analysis is required.*

**Response:** This comment echoes the need for clearer objectives that was highlighted in the first general comment. We have modified the abstract and other parts of the manuscript to ensure the aim and objectives of this research are more explicit.

*Lines 26-27: Define climate units.*

**Response:** We are referring to the theory of the Southern Alps glaciers behaving as a “*unified climatic unit*” as proposed by Chinn et al. (2012). This is one of the main outcomes of the EOSS monitoring programme inferred from the high degree of intra-correlation found in the variability of snowline elevation between any index glacier and the average of the group. In the introduction where the term “*unified climatic unit*” is directly quoted from Chinn et al. (2012), we have clarified that this is referring to a “consistent response to climate variability inferred from the EOSS record”. We have also reworded the abstract to clarify the origins and meaning of this term.

*Introduction:*

*P2,Line 17: The minimum albedo method does not infer mass balance. It scales to ELA and AAR, which in turn scale to mass balance. Without measurements of mass balance to quantify the relationship to minimum albedo, ELA, or AAR, mass balance should not really enter into the discussion.*

**Response:** We agree that the word “infer” was not appropriate in this sentence. We replaced it by “estimate”. We however respectfully disagree with the reviewer that mass balance should not enter into the discussion. This paragraph is introducing the general concepts of remote sensing approaches for the very purpose of capturing glacier mass balance, whether its relative variability, or its absolute value when calibration data can be provided. The statement made remains factually correct in view of the supporting literature provided in the paragraph.

*P2,Line 20: Define “relationships”.*

**Response:** We have rephrased this sentence as “The annual minimum glacier-wide albedo ( $\alpha_{\text{yr}}^{\text{min}}$ ) retrieved from MODIS imagery has been found to scale to annual glacier mass balance...”

*P2,Line 20-23: There are more citations for this method – see below.*

**Response:** We thank the reviewer for these suggestions. Among those, we find that only Zhang et al. (2018) is directly relevant and added it to the Introduction section.

*P2,Line 25: why is the glacier contribution “globally significant” and define (i.e., X m sea level increase).*

**Response:** We must stress to the reviewer that the meaning and definition of *significant* is not unique and solely reserved to characterise a quantitative value subject to statistical significance testing. In context, *significant* means “*Sufficiently great or important to be worthy of attention; noteworthy*” (Oxford Dictionary). As such, New Zealand is invariably represented in global studies as its own glacier region. In view of this we maintain that our statement that New Zealand Glaciers “*are regarded as globally significant*” is factually correct and has adequate context to suggest the meaning of significant in this sentence as “*noteworthy*”. The alternative would be that New Zealand glaciers would be otherwise ignored in such global studies, which is clearly not the case. We respectfully disagree with the reviewer that using *significant* in this context necessarily calls for a specific quantified statement.

P2,Line 29: Air temperature is important in controlling glacier mass balance – but on line 19 you said shortwave radiation played a governing role on smb. Which is it? Both I gather, so this section should be expanded to detail the nuanced nature of the controls on glacier smb.

**Response:** We have changed the wording in this paragraph to ensure readers understand the relative importance of solar radiation, air temperature and precipitation. Our review of these governing processes are consistent to those that are well established in the literature.

P2,Line 31: define cloud properties and how they influence smb. What is the role of longwave forcing?

**Response:** We have provided a benchmark reference for readers and return to the importance of clouds in the results and discussion.

P2,Line 32: “global warming in the Southern Alps” is nonsensical.

**Response:** We have changed the wording of this sentence. However, we respectfully disagree with the reviewer about this comment. In this paragraph we clearly provide context in reference to the findings of Mackintosh et al. (2017). The title and content of the latter is unambiguous about the regional impacts of a “*period of global warming*” on New Zealand. The abstract itself reads “*The exceptional terminus advance of some glaciers during recent global warming is thought to relate to locally specific climate conditions, such as increased precipitation.*” As such, we maintain that our statement is factually correct in reference to the point being made to the supporting literature.

P3,Line 1: define “fast-responding glaciers” what does this mean and why is it important?

**Response:** This is again a context statement that we believe unambiguously paraphrases Mackintosh et al. (2017) where the reviewer can read “*This combination of large mass balance gradients and steep, relatively thin and fast-moving ice makes them adjust rapidly to climate forcing. Very few glaciers on Earth are capable of responding this quickly.*”

P3,Line 3: Why was minimum albedo method not used on these two glaciers? If that analysis has already been conducted, then provide an analysis of ELA, AAR and minimum albedo for these two glaciers in reference to smb. Once completed then the analysis presented on the other glaciers without smb will be on a better footing.

**Response:** We provide information two paragraphs earlier that the albedo method has been used and related to glacier mass balance in the Southern Alps, with citations to relevant work by Sirguey et al. (2016) and Rabatel et al. (2017). In order to further address this, comment, we have specifically named the glaciers on which the albedo method was used, namely Brewster Glacier (direct calibration with in-situ mass balance) and Park Pass Glacier (indirect assessment via correlation to EOSS record, itself scaling to mass balance) to ensure readers are aware that this method has been used on glaciers in New Zealand. We hope readers who require further information will consult the cited literature. We have also provided further details about how the albedo method was calibrated using in situ mass balance data from Brewster Glacier. The albedo method has not been used on Rolleston Glacier as it is too small to be captured by MODIS imagery (0.11 km<sup>2</sup> in 2012), with the area and reasoning provided.

P3,Line 4: Define what was measured then tell me why it is important.

**Response:** We reworked this paragraph to state specifically that the mass balance campaign on Ivory Glacier in the 1970s was the first comprehensive glaciological mass balance study conducted in New Zealand’s Southern Alps. We removed the word “important” as part of addressing an earlier comment from the reviewer.

P3,Line 10: There is going to be a large problem using MODIS grids on very small glaciers because of the grid size to glacier area mismatch - discuss.

**Response:** The reviewer is right about this limitation to using MODIS for the albedo method. We did stress this point in Section 4.7 of the initial manuscript with a supporting citation. Noting that albedo is mapped with MODImLab at the improved 250m resolution, Davaze et al. (2018) show that  $\alpha_{yr}^{min}$  could be successfully retrieved for glaciers down to 0.5 km<sup>2</sup> (7 pixels) with good correlation to annual mass balance. The agreement we obtained between  $\alpha_{yr}^{min}$  and EOSS using the 0.7 km<sup>2</sup> Vertebræ Col 25 is consistent with this assessment. In response to an earlier comment, we emphasised this limitation when introducing

Rolleston Glacier. In order to address the reviewer's comment further, we also added a discussion about this limitation in Section 5.3.

*P3,Line 11: have meant – means*

**Response:** We have modified the sentence.

*P3,Line 13-21: this sounds like the missing research question that should have been addressed in the end of the Abstract.*

**Response:** This sentence does provide in part the background and motivation for the aim and three objectives that we have refined as part of our revision of the manuscript.

*P3,Line 22-27: Provide better links to the tables and figures detailing the study site. The last paragraph of the Introduction is redundant and should be removed.*

**Response:** We added a reference to Figure 1. We accepted the suggestion of the reviewer to remove the last paragraph of the introduction.

*Page 4: Site description: P4,Line 20: Provide climate normals.*

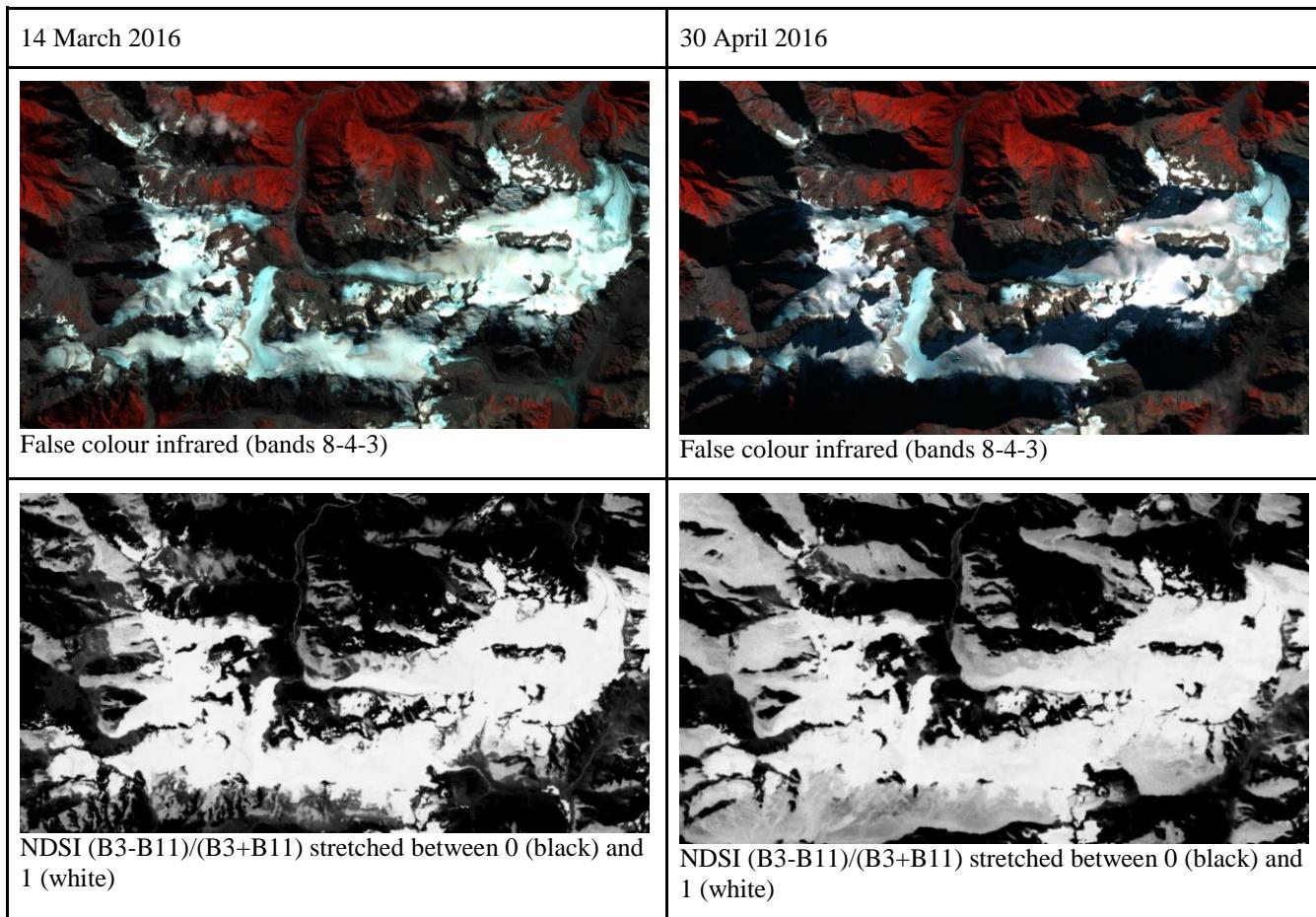
**Response:** Accepted. Marcara (2017) estimated a long-term mean annual rainfall surface for New Zealand for the period 1972-2016 from which we retrieved a range for precipitation over the area. We used normal temperature at surrounding weather stations over the period 1980-2010 and a lapse rate of  $-5.7^{\circ}\text{C km}^{-1}$  determined from the data to interpolate a mean normal temperature surface over the area, and a range over the glaciated region. We stress however that this estimate remains only indicative given the distance of the GoEA from established weather stations (closest weather station on the West Coast is 22km away, while the nearest to the east is  $>60\text{km}$ ) and the uncertainty associated with the interpolation.

*P5,Line 3: How is this a sensitive climate situation? Sensitivity means that there is a glacier response (dynamic, or mass loss etc.) for temperature or precipitation change. A case for neither of these scenarios has been presented.*

**Response:** We have removed reference to the “sensitive climate situation” to avoid confusion.

*P5,Line 10: How do you know that the 14 March corresponds to the minimum ELA?*

**Response:** The point the reviewer is raising is not clear, nor what she/he means by “minimum ELA” in this context. We understand ELA stands for Equilibrium Line Altitude, which has meaning in surface mass balance. Braithwaite & Raper (2009) define “minimum ELA values corresponding to balance years with *highly (...)* positive mass balances”. In view of this, we believe the reviewer's use of “minimum ELA” seems misplaced and makes a connection between ELA and glacier outlines that is irrelevant in our context. Nonetheless, we assume the reviewer is trying to say that glacier outlines should be derived from imagery timed precisely at the maximum ablation. If so, we dispute this strict requirement because glacier outlines are not a direct consequence of the surface mass balance for that year due to glacier response time. In practice, one aims for late summer imagery mostly because it corresponds to the melting of as much transient snow as possible to facilitate interpretation of glacier boundaries. At the same time, tradeoffs must be made given the availability of imagery, and mapping glacier outlines remains often heavily reliant on photo interpretation and experience. We indicated that we used the NDSI from the S2 image on 14 March as a base to derive glacier outlines. We then refined them manually (e.g., NDSI cannot map debris-covered parts and transient snow needs to be removed) using the additional data mentioned in the text. We believe this is a very common and valid approach, yet it is not within the scope of this manuscript to discuss this in more detail. For the reviewer's information, the Sentinel-2 image from 30 April 2016 shown in Figure 9 in the original manuscript would be closer to the end of ablation and the latest before winter snowfall that year. On the one hand it exhibits less residual snow, which may help. On the other hand, it can be seen in the comparison below, how topographic shading affects the image on 30 April compared to 14 March. Mapping solely from this image is not making the task easier nor more accurate. The NDSI is sensitive to shadow with high values in the shade greatly complicating the snow/ice segmentation. We maintain that the mid-March image is a better compromise despite the remaining snow patches, to derive suitable glacier outlines for this study. The consistency between snow patches with the late April image and across a few years with other Sentinel images (e.g., those shown in Fig. 9) and Pleiades 2017 images help discriminate them from glaciers at the refinement stage.

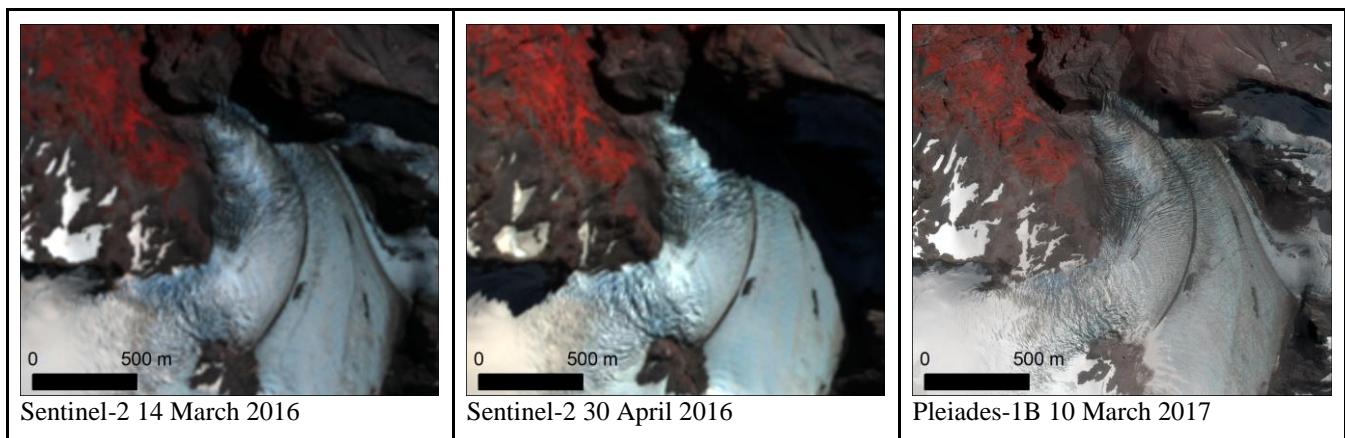


*P5, Line 12: What is ‘field knowledge’? Actually the whole section should be rewritten. What are the NDSI wavelengths used?*

**Response:** We have modified this section and specified the wavelength used for the NDSI. As explained, we took advantage of a two-day field trip to take close-up aerial photos of the glacier. This provided us with valuable direct evidence of this remote area that supplemented our interpretation of satellite imagery used to refine some glacier outlines. To avoid any confusion, we removed “field knowledge” from the revised manuscript.

*There is almost two months difference between image capture dates. How is this reconciled?*

**Response:** We have reworked this section to ensure there is no confusion for readers, and we hope this addresses the reviewer's concerns about our approach to mapping glacier outlines in this study. To respond to the specific question, we acknowledge that we did not specifically mention in the manuscript that we used the 29 April 2016 image to refine our mapping, which we understand the reviewer is referring rather than the 14 March 2016 image. It should also be noted that we used 0.5m imagery from Pleiades in March 2017, as well as photos from our field work in 2018. Thus, we compiled images across two years to help interpret glacier outlines from the March 2016 Sentinel-2 imagery. For example, the Pleiades imagery and high resolution surface supported much better interpretation of debris-covered glaciers. It is also important to keep in mind that the glacier boundaries used for this study are derived to extract 250-m resolution pixels from the MODIS albedo map and that glaciers are not expected to retreat hundreds of meters per year in this region (it would need calving in terminal lakes to achieve such rates). The mapping also compounds uncertainties in the order of tens of meters due to the geolocation of Sentinel-2 imagery and the variable interpretation at pixel level. In this regard, we don't believe the two-year period between these sources of information and our approach to mapping are any cause for concern. Further evidence of the benefit of exploiting all of these data are shown below, which provides a sequence of the terminus of Lambert Glacier from 14 March 2016, 30 April 2016 (Sentinel-2), and March 2017 (Pleiades).



P5, Line 27: What is the superscript T on MODIS? The standard usage is MOD for Terra and MYD for Aqua.

**Response:** T (resp. A) superscripts indeed stands for MODIS Terra (resp. Aqua). We believed this was self-explanatory. We are aware of the MOD/MYD convention for naming MODIS products, and we did refer to this usage in P6L9 of the original manuscript. In context, when clearly referring to either sensor rather than the products from them, we do not believe that using the acronyms of MOD or MYD are appropriate. We therefore maintain our use of the superscript to refer to either one or the other sensor, and clarified this convention in Section 2.2 to avoid confusion.

P5, Section 2.2: You should read: [https://nsidc.org/data/modis/terra\\_aqua\\_differences](https://nsidc.org/data/modis/terra_aqua_differences) There is some speculation that the Terra MODIS sensor is degrading. This degradation is largely correct for in the collection 6 data. There are several citations that should be considered in relation to this issue. These citations have been listed at the end of the review.

**Response:** We thank the reviewer for this reading suggestion. This also echoes the general comment made earlier about “*The error analysis of MODIS albedo and the potential for sensor degradation (post 2016 on the Terra bus) need to be addressed.*”

We have provided further information about MODIS calibration issues in Section 4.8.1. However, we raise two important points about this issue in response to the reviewer’s comments.

First, the main point being made on webpage given by the reviewer is about the differences in processing MODIS snow products between Terra and Aqua sensors due to the band 6 failed detectors of Aqua. There is no mention about the degradation of MODIS detectors. We are very aware of the differences in processing MOD10/MTD10 C6 products. However, these are not relevant for our study as we are not relying on MOD10 data. Instead, we complete all processing and albedo retrieval directly from L1B data, as is clearly explained in the manuscript, and in even more detail in the cited literature about our processing technique. As far as we know, the Quantitative Image Restoration (QIR) technique to restore Aqua band 6 is only used in production of MYD10 products but not in the production of the MOD03/MOD02 C6 products we are using. Thus, it does not apply to our data (see MODIS L1B Product User’s Guide for L1B Version 6.2.2 (Terra) and Version 6.2.1 (Aqua): [https://mcst.gsfc.nasa.gov/sites/default/files/file\\_attachments/M1054E\\_PUG\\_2017\\_0901\\_V6.2.2\\_Terra\\_V6.2.1\\_Aqua.pdf](https://mcst.gsfc.nasa.gov/sites/default/files/file_attachments/M1054E_PUG_2017_0901_V6.2.2_Terra_V6.2.1_Aqua.pdf)).

Please also note that we have acknowledged the failed detector of band 6 and demonstrate that it does not significantly affect our retrieval, which we believe is a valuable outcome of our study. This was expected as band 6 in the SWIR is an absorption band for snow and ice, and therefore contributes only marginally to the albedo signal.

Second, we are aware of the sensor calibration degradation in MODIS C5 data as demonstrated by Lyapustin et al. (2014). The latter concludes very clearly that “*The new C6 calibration approach removes major calibrations trends in MODIS Level 1B data.*”. From the citations suggested by the reviewer, Casey et al. (2017) and Polashenski et al. (2015) both point out and document calibration issues with C5 data and conclude that the use of C6 data is preferable, if not necessary. Sayer et al. (2015) also confirmed the better performance of the C6 calibration. The reviewer points out that the degradation is largely corrected for in the C6 data. As we use the C6 data, which are the highest quality data available and do not have any severe calibration issues, we are of the view that further justification for using them is not necessary.

In this context, we shall stress Figure 8 and 10 to the reviewer which show albedo time series. The reviewer can assess a lack of visible trends in winter albedo which we believe should lift concerns about the existence (speculated or not) of any major

calibration issue with C6 affecting our study and results. The alternative hypothesis would be that winter albedo has a trend that is precisely matched by a calibration issue. We do not believe that this hypothesis is likely.

Lyapustin, A., Wang, Y., Xiong, X., Meister, G., Platnick, S., Levy, R., Franz, B., Korkin, S., Hilker, T., Tucker, J., Hall, F., Sellers, P., Wu, A. & Angal, A. (2014). Science impact of MODIS C5 calibration degradation and C6+ improvements. *Atmospheric Measurement Techniques* 7 (12), 4353-4565. (Doi: 10.5194/amt-7-4353-2014.)

Sayer, A. M., Hsu, N. C., Bettenhausen, C., Jeong, M.-J. & Meister, G. (2015). Effect of MODIS Terra radiometric calibration improvements on Collection 6 Deep Blue aerosol products: Validation and Terra/Aqua consistency. *Journal of Geophysical Research: Atmospheres* 120 (23). (Doi: 10.1002/2015jd023878.)

*P5, Line 29: orbits are usually described as ascending and descending.*

**Response:** Agreed, we modified the revised manuscript accordingly.

*P6, Line 2: What does “exceptionally cloudy” mean? Provide a description with statistics.*

**Response:** We replaced “exceptionally” by “extraordinary” as described by Wardle (1986), and we reworked the sentence to make the origin of this statement unambiguous and invite the reader to consult the citation for more information. We also agreed with the reviewer and added specific statistics from Wardle (1986) that are specific to two sites surrounding our region of study. It should be noted that Cropp River, west from the GoEA, exhibits the most frequent cloud cover of all sites examined by Wardle (1986).

*Why were only four days used for comparison between Terra and Aqua? Provide justification.*

**Response:** We clarified that in addition to clear sky acquisition on the same day, such comparison needed similar sensor zenith to minimise the effect of contrasting panoramic distortion on pixel footprint. As our assessment of cloud cover below demonstrates, there are not many opportunities to get clear-sky conditions for both Terra and Aqua. This opportunity is further reduced when adding the limitation of sensor zenith. We also stated the number of samples provided by the four images amounts to 2196 pixel pairs, which we believe is a sufficient sample size to complete this comparison.

*The MODIS methods section does not indicate which albedo product was used, or how albedo was produced at 250 m. A much more clear description of data processing is required. O.k., I see the following section on albedo processing. Perhaps a sentence here to indicate that MODImLab will be detailed (and why) later in the paper.*

**Response:** We added a sentence in the previous paragraph that the albedo retrieval is described in the methods section.

*Section 2.3 requires a much better description of what exactly was done.*

**Response:** This comment suggests to us the reviewer is assuming we completed the mapping of the EOSS snowlines and generated the EOSS SLA records for Vertebrea Col 25 as part of this study. This is not the case. The EOSS programme is a national programme run by the National Institute of Water and Atmospheric Research or NIWA. An annual report with SLA values for each index glacier is normally published sometime after the observations are taken. Appendices about the method used to map SLA on each year are also provided on request. They indicate what method was used to derive SLA for any particular year. We have clarified that the EOSS record was obtained rather than generated by this study, summarised the methodology used by the programme to derive SLA and supported it with relevant citations in Section 2.3. We also substantially reworked the section to stress the outcome of the EOSS programme that led to the “climatic unit” theory that our study is testing.

*P6, Line 21: Sentinel was used to “approximate” the timing and elevation of SLA. A great deal of effort should be spent on what approximate means in this instance.*

**Response:** We considerably reworked this paragraph to clarify how we used additional Sentinel-2 images to observe the evolution of the glacier surface and assess its consistency with relative variations of EOSS and albedo in those years. We also revised Section 4.6 to stress the consistency of these observations with the measured evolution of the minimum surface albedo, and related those variations to documented heatwaves that affected New Zealand glaciers.

P8, Line 30: why was 50% used? How was this value determined? Should 100% be used if you want to remove debris-covered glaciers?

**Response:** We agree that in theory 100% snow/ice cover should be used. This however assumes that the spectral unmixing is perfect. This is not the case and relying only on pixels truly achieving 100% snow and ice membership from unmixing excludes too many to retrieve a useful albedo signal. We use the 50% threshold because it is the one generally used for binary discrimination of snow/ice pixels (see Hall et al. 2002; Hall & Riggs, 2007; Sirguey et al., 2009; Masson et al., 2018), while being conservative enough to preserve a sufficient amount of pixels. It is true that it may include mixed pixels into the signal and it is the reason why we tested this approach with the conservative masking technique (M2). We did report and discuss in Section 4.1 that the albedo signal with the objective masking (with 50% threshold) was slightly darker on average by 1.2%, likely due to some mixing in the debris-covered pixels. The differences between both approaches however demonstrated sufficient agreement to accept this choice. We added justification for the choice of this threshold and added a citation in support.

Masson, T., Dumont, M., Mura, M., Sirguey, P., Gascoin, S., Dedieu, J.-P. & Chanussot, J. (2018). An Assessment of Existing Methodologies to Retrieve Snow Cover Fraction from MODIS Data. *Remote Sensing* 10 (4), 619. (Doi: 10.3390/rs10040619.)

Hall, D. K. & Riggs, G. A. (2007). Accuracy assessment of the MODIS snow products. *Hydrological Processes* 21 (12), 1534--1547.

Hall, D. K., Riggs, G., Salomonson, V. V., DiGirolamo, N. E. & Bayr, K. J. (2002). MODIS snow-cover products. *Remote Sensing of Environment* 83, 181--194.

Page 9, Section 3.3: *The requirement of using only cloud free glaciers is very restrictive and substantially reduces the amount of data used in the analysis. Provide statistics on the amount and duration of cloud cover. When there is cloud cover will likely be as important as where there is cloud cover.*

**Response:** Accepted, we included that the cloud-free criteria excluded about 66% of images.

*Pixel is a picture element found on a display screen. Grid cell is a better usage.*

**Response:** We respectfully disagree with the reviewer on such a strict use of “pixel”. The use of “pixel” to denote image data is widespread in the literature and remote sensing textbooks. For example, Richards (2013) defines *“We talk about the recorded imagery as image data, since it is the primary data source from which we extract usable information. One of the important characteristics of the image data acquired by sensors on aircraft or spacecraft platforms is that it is readily available in digital format. Spatially it is composed of discrete picture elements, or pixels. Radiometrically—that is in brightness—it is quantised into discrete levels.”*

Richards, J. (2013). *Remote Sensing Digital Image Analysis. An Introduction*. Springer-Vertag.

Page 10, L1: Artefact should be replaced by error.

**Response:** Accepted.

*Section 4.3 should be presented in the Introduction section. Typical values for the different glacier states should be provided. This is an example of the systematic problem with this paper, in that there really aren't that much in terms of reportable results.*

**Response:** As noted earlier we have clarified the atmospheric controls on mass balance in the Introduction, and have removed and changed some of the text in this section to provide clarity. As suggested by the reviewer, we also moved two sections of discussion (5.2.1 & 2) to the results, which now contains 9 sections of results (4.1-4.8a,b). Thus, we are of the view there is no shortage of reportable results.

*Page 11, L5: The classification of glaciers into four groups is accomplished by geographical variables. Without providing climate data, it is a mystery to me how the authors determine the glaciers are not behaving as a single climate unit.*

**Response:** We classified glaciers into three groups, rather than four as suggested. We have responded to an earlier comment to clarify that the “unified climatic unit” refers to the theory proposed by Chinn et al. (2012) in reference to the consistent

response of glaciers inferred from the EOSS record. This is based on the high degree of intra-correlation between EOSS SLA across the Southern Alps, not on the study of climate data. Since the snowline and albedo methods aim to capture a similar glacier response, our study can apply a similar approach to test this hypothesis by assessing the degree of intra-correlation between minimum albedo across the GoEA. The outcome of this test and our conclusion that it challenges the “unified climatic unit” inferred by EOSS, is unrelated to the clustering of glaciers. The classification provides additional insights that help characterise what may control the consistency or contrasts in glacier responses across this area. It does not preclude the existence of local contrasts in climate that ultimately govern glacier mass balance. Our results do raise the question about the extent of local climate variability, which itself may be complicated by the complex terrain, but can hardly be answered without reliable climate data that are not available in this area.

*Page 11, L28: Either the declines are monotonic or they are not.*

**Response:** We respectfully disagree with the reviewer, “*monotonic decreasing*” has mathematical meaning that “*decreasing*” alone has not. A signal can be decreasing over a period albeit punctuated by increases. This is the definition of an increasing or decreasing function. A monotonic decreasing function however shall not exhibit any increase within a period of decrease. We have replaced decline by decrease to better fit the mathematical definition.

*Page 13, L15 (and elsewhere) R^2 values should be presented with significance values.*

**Response:** We added the significance value.

*Page 13, L29-30. What is a maximum summer snow line? When exactly was this observed within the summer period?*

**Response:** We added the word “altitude” and the years when those observations were made. The exact date can be found in the figure caption.

*P14,L10: Citation required.*

**Response:** Done.

*P14,L23: Using only 12 glaciers, which are argued to occupy different climactic regions, can size and elevation be reasonably discounted as predictors of the min albedo and SLA?*

**Response:** Indeed, this is what our results show. We have added the correlation analyses and significance of these as part of an earlier comment, which should help clarify and avoid any further confusion.

*P15,L7: define effective, precisely.*

**Response:** We reworked this sentence to be more factual with reference to supporting citations.

*P15,L23: I wouldn't have characterised the R^2 values found in the Results section as strong to moderate.*

**Response:** To reiterate here, the R2 value between EOSS and  $\alpha_{yr}^{min}$  for Vertebrae Col is 0.43, while for Angel glacier it is 0.69. Overall, Class 1 glaciers yield an average R2=0.51, while Class 3 glaciers yield R2=0.36. While we appreciate that there is no unique approach to qualifying the strength of the relationship, Akoglu (2018) compiled the following with all approaches compatible with a qualification of those R2 as indicative of moderate to strong relationship.

Adapted from Table 1 in Akoglu, H. (2018). Users guide to correlation coefficients. Turkish Journal of Emergency Medicine 18 (3), 91--93. (Doi: 10.1016/j.tjem.2018.08.001.)

Coefficient of Determination	Dancey & Reidy (Psychology)	Quinnipiac University (Politics)	Chan YH (Medicine)
1	Perfect	Perfect	Perfect

0.81	Strong	Very Strong	Very Strong
0.64	Strong	Very Strong	Very Strong
0.49	Strong	Very Strong	Moderate
0.36	Moderate	Strong	Moderate
0.25	Moderate	Strong	Fair
0.16	Moderate	Strong	Fair
0.09	Weak	Moderate	Fair
0.04	Weak	Weak	Poor
0.01	Weak	Negligible	Poor
0	Zero	None	None

Dancey C.P., Reidy J. Pearson Education; 2007. Statistics without Maths for Psychology; Chan Y.H. Biostatistics 104: correlational analysis. Singap Med J. 2003;44(12):614–619.

*Section 5.2 is results and should not be presented in the discussion section.*

**Response:** Accepted. We moved these sections to results. In relation to characterising cloud cover frequency, we added a statement in Section 2.2 that explicitly indicates that we re-used the classification of clouds from the albedo processing chain of the complete inventory of MODIS imagery for this purpose. The new discussion section (5.2) maintains key points relevant to the control of clouds on the spatial variability of glacier response.

*P18,L7: “likely having as significant influence” means you don’t know if it is significant or not.*

**Response:** We replaced “significant” with “substantial”.

*Section 5.3. This section should be expanded. Is the correlations between minimum albedo to SLA related to the amount of cloud cover?*

**Response:** In response to an earlier comment we added a discussion about the limitation of MODIS spatial resolution with respect to the size of glaciers. The section referred to has been moved to results and we have created a new section to address in part the potential role clouds have played on albedo and SLA.

*Figure 12 (left panel) There are obvious difference between MODIS Terra and Aqua related to Class. Why is this? Might this be related to the systematic increase in cloud cover in Aqua vs. Terra (Figure 14)?*

**Response:** We did indicate in Section 2.2 that this comparison used 4 pairs of clear-sky imagery for the purpose of testing the consistency of the albedo retrieval between Aqua and Terra, it is therefore unrelated to cloud cover. We must stress to the reviewer that this point is discussed in detail in Section 4.8.1 (former 5.2.1). This is related to the contrasting shadowing configuration between the morning and afternoon image acquisitions and the difficulty of retrieving an accurate observation of albedo in the shade.

*Citations to consider:*

Casey, K. A., Polashenski, C. M., Chen, J., & Tedesco, M., 2017. Impact of MODIS sensor calibration updates on Greenland ice sheet surface reflectance and albedo trends. *The Cryosphere*, 11, 1781–1795.

Polashenski, C.M., Dibb, J. E., Flanner, M. G., Chen, J. Y., Courville, Z. R., Lai, A. M., et al., 2015) Neither dust nor black carbon causing apparent albedo decline in Greenland’s dry snow zone Implications for MODIS C5 surface reflectance. *Geophys. Res. Lett.*, 42, 9319–9327.

Van Tricht, K. et al., 2016. Clouds enhance Greenland ice sheet meltwater runoff. *Nat. Commun.* 7:10266 doi: 10.1038/ncomms10266.

Williamson, S.N., Copland, L., Hik, D.S., 2016. The accuracy of satellite-derived albedo for northern alpine and glaciated land covers. *Polar Sci.* 10, 262-269.

Bahr, D.B., Radic, V., 2012. Significant contribution to total mass from very small glaciers. *The Cryosphere*, 6, 763-770.

Bennartz, R., Shupe, M., Turner, D. et al., 2013. July 2012 Greenland melt extent enhanced by low-level liquid clouds. *Nature*, 496, 83–86. doi:10.1038/nature12002

Zhang, Z., Jiang, L., Liu, L., Sun, Y., Wang, H., 2018. Annual Glacier-Wide Mass Balance (2000-2016) of the Interior Tibetan Plateau Reconstructed from MODIS Albedo Products. *Remote Sens.*, 10, 1031, <https://doi.org/10.3390/rs10071031>.

# Variability of glacier albedo and links to annual mass balance for the Gardens of Eden and Allah, Southern Alps, New Zealand

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**Abstract.** The Gardens of Eden and Allah (GoEA) are two of New Zealand's largest icefields. However, their remote location and protected conservation status has limited access and complicated monitoring and research efforts. As a result, the behaviour and dynamics of these unique glaciers are poorly understood. We use annual minimum glacier wide albedo ( $\bar{\alpha}_{\text{yr}}^{\text{min}}$ ) derived from icefields, observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensors aboard the Terra and Aqua satellites to assess linkages between the spatial and temporal variability of  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  and glacier mass balance. The  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  for 12 individual glaciers, identified using a new objective glacier masking approach, ranges between 0.42 and 0.70, and can occur as early as mid-January and as late as the end of April. There is evidence that the timing of  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  has shifted to later in the summer over the 19-year period on 10 of the 12 glaciers. However, there is only a weak relationship between the delay in timing and the magnitude of  $\bar{\alpha}_{\text{yr}}^{\text{min}}$ , which implies that albedo is not necessarily lower if it is delayed. The largest negative departures in  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  (lower than average albedo) are consistent with high snow line altitudes (SLA) relative to the long-term average as determined from the End-of-Summer Snowline (EOSS) survey, which has monitored glaciers in the Southern Alps for over 40 years. While the record of  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  for Vertebrae Col 25, an index glacier of the EOSS survey and one of the GoEA glaciers, explains less than half of the variability observed in the corresponding EOSS SLA ( $R^2 = 0.43$ ,  $p = 0.003$ ), the relationship is stronger when compared to other GoEA glaciers. Angel Glacier has the strongest relationship with EOSS observations at Vertebrae Col 25, accounting for 69% of its variance ( $p = 1.8 \times 10^{-5} < 0.001$ ). A key advantage in using the  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  approach is that it enables the variability in the response of individual glaciers to be explored, revealing that topographic setting plays an important role in addition to the regional climate signal. The observed variability of individual glacier response at the scale of the GoEA contrasts with the high consistency of responses found by the EOSS record across the Southern Alps, and challenges the suggestion that New Zealand glaciers behave as a "unified climatic unit". MODIS imagery acquired from the Terra and Aqua platforms also provide insights about the spatial and temporal variability of clouds. The frequency of clouds in pixels west of the Main Divide is as high as 90% during summer months, and reach a minimum of 35% in some locations in winter. These complex cloud interactions deserve further attention as they are likely a contributing factor in controlling the spatial and temporal variability of glacier response observed in the GoEA. The observed variability of individual glacier response on the GoEA demonstrate that glaciers in the Southern Alps do not behave as a single climatic unit.

**Keywords.** MODIS, albedo, glacier mass balance, remote sensing, New Zealand.

## 1 Introduction

The retreat of mountain glaciers during periods of the 20<sup>th</sup> and 21<sup>st</sup> centuries has been widespread and unprecedented (Zemp et al., 2015, 2019). One approach to document this change is to monitor glaciological mass balance, which enables the response of glaciers to climate forcing to be assessed (Hock et al., 2019; Zemp et al., 2019). However, global records of mass balance are sparse, as traditional *in situ* glaciological measurements are resource intensive (Cogley et al., 2011), with only 260 glacier-wide results available from an estimated 200,000 glaciers worldwide (Pfeffer et al., 2014; Zemp et al., 2015). In addition, the ongoing cost of maintaining the repetitive measurements means that few long-term records exist, with only 30 of the world's 40 glaciers having an uninterrupted series dating back to 1976 (Zemp et al., 2009). Mass balance records are therefore biased towards the more accessible glaciers in the Northern Hemisphere, while remote and relatively inaccessible glaciers in South America and New Zealand have remained largely out of reach. In this context, there is a need to monitor the state of more 45 mountain glaciers to capture their response to changes in regional and large-scale climate.

Recent developments in the capabilities of satellite and airborne sensors, and improved processing techniques, have provided 50 several alternatives to the *in situ* glaciological approach, to derive individual or regional mass balance signals for ~~out of reach~~remote glaciers (Rabatel et al., 2017). For example, mapping the end-of-summer snowline altitude (SLA) provides an estimate of the glacier equilibrium-line altitude (ELA) and accumulation area ratio (AAR). These glacier properties have been used as proxies for annual mass balance and are often less resource intensive to monitor (Chinn et al., 2012; Rabatel et al., 2016; Salinger et al., 2019b). Alternatively, the 'albedo method' uses glacier surface albedo, for example retrieved from 55 satellite imagery captured by the Moderate Resolution Imaging Spectroradiometer (MODIS), to ~~infer~~estimate glacier mass balance ~~and/or monitor its variations~~ (Rabatel et al., 2017). Surface albedo plays a governing role in the mass balance of glaciers due to its control on absorbed short-wave radiation (Klok and Oerlemans, 2004; Oerlemans et al., 2009; Pope et al., 2016). Importantly, relationships have been found between the ~~The~~ annual minimum glacier-wide albedo ( $\bar{\alpha}_{\text{yr}}^{\min}$ ) retrieved from 60 MODIS imagery ~~and has been found to scale to~~ annual glacier mass balance in the French Alps (Dumont et al., 2012; Davaze et al., 2018), the Arctic (Greuell et al., 2007), the Himalayas (Brun et al., 2015; [Zhang et al., 2018](#)) and New Zealand's Southern Alps ~~on Brewster and Park Pass glaciers~~ (Sirguey et al., 2016; Rabatel et al., 2017).

The mountain glaciers of the Southern Alps of New Zealand comprise the largest ice mass in the Southern Hemisphere outside 65 of Antarctica and South America, and are regarded as globally significant (Chinn et al., 2012; Zemp et al., 2016~~2015~~). The Southern Alps are unique as they are surrounded by vast areas of ocean and ~~are~~ subject to both subtropical and polar air masses that are embedded in a prevailing westerly airflow. This unique setting contributes to the humid, maritime climate that influences the glaciers in the Southern Alps, which is reflected ~~most starkly~~ by the exceptionally high precipitation rates ~~that exceed~~exceeding  $10 \text{ m a}^{-1}$  in many alpine regions (Fitzharris et al., 1999). However, ~~it~~Meteorological experiments on glaciers in the Southern Alps have shown the main source for melt energy is net radiation, driven primarily by net shortwave radiation (e.g. Gillett and Cullen, 2011; Cullen and Conway, 2015), but fluctuations in mass balance over time are sensitive to changes in air temperature that plays the most important role ~~and~~ precipitation. Given the importance of air temperature in controlling 70 mass balance variability in the Southern Alps ~~both melt and the phase of precipitation, the advance and retreat of glaciers in the wet climate of the Southern Alps are particularly sensitive to changes in air temperature~~ (Oerlemans, 1997; Mackintosh et al., 2017), though the ~~For example, the advance of some fast-responding glaciers in the Southern Alps between 1983 and 2008, during three of the warmest decades in the instrumental record, have been attributed to regional cooling controlled by changes in large-scale atmospheric circulation in the Southern Hemisphere (Mackintosh et al., 2017). The influence of synoptic scale circulation on air mass variability and changes in cloud properties remains important~~have also been shown to influence mass balance in the Southern Alps (Conway and Cullen, 2016; Cullen et al., 2019). Changes in large scale circulation have the potential to enhance or suppress the effects of global warming in the Southern Alps, which has been most recently demonstrated by the advance of some fast responding glaciers between 1983 and 2008 (Mackintosh et al., 2017).

Comprehensive [The first comprehensive glaciological mass balance study in New Zealand's Southern Alps was completed on Ivory Glacier between 1969 and 1975 \(Anderton and Chinn, 1973; 1978\)](#). Today, comprehensive [glaciological mass balance programmes exist on Brewster Glacier \(e.g. Cullen et al., 2017\) and Rolleston Glacier \(Purdie et al., 2015\)](#), extending back to 2004 and 2010, respectively. Important glaciological measurements were also made on Ivory [The size of Brewster Glacier between 1969 \(ca. 2 km<sup>2</sup>\) and 1975 \(Anderton\)](#) [its comprehensive in-situ record enabled the albedo method with MODIS to be assessed](#) and Chinn, 1973; 1978) [calibrated to estimate mass balance \(Sirguey et al., 2016\)](#). With only 0.11 km<sup>2</sup> in 2012, [Rolleston Glacier is however too small to be captured by MODIS imagery](#). In addition, the End-of-Summer Snowline (EOSS) survey, [which has been the benchmark for monitoring glaciers in the Southern Alps for over 40 years](#), has used aerial photography to map [and retrieve the altitude of](#) the annual [snowline at the end of the ablation season \(SLA-on\)](#) of 50 'index' glaciers across the Southern Alps since 1977 (Chinn et al., 2012). The SLA is used as a surrogate of the Equilibrium Line Altitude (ELA) whose annual variations inform about changes in the annual balance of the glaciers (Rabatel et al., 2017).

Despite is longevity, the EOSS survey continues to face two main challenges: (1) the temporal resolution is limited to a single observation per year in late-summer; the success of which is dependent on transient conditions such as snowfall prior to a flight, and (2) limited resources constrain the total number of index glaciers that can be mapped. Furthermore, the focus on relatively small glaciers in the Southern Alps has meant that only three index glaciers exceed 2 km<sup>2</sup>. These challenges, combined with the difficulty of establishing a network of glaciological programmes, have [meant that resulted in](#) the vast majority of glaciers in New Zealand [remain remaining](#) out of reach of current observation methods.

The EOSS programme indicates that the yearly response of the transient snowline for each of the index glaciers is consistent with the average of the group, with strong to very strong intra-correlations between SLA departures across index glaciers. [This consistent response to climate variability inferred from the EOSS record](#) has led to the suggestion that glaciers in the Southern Alps behave as a "single unified climatic unit" (Chinn et al., 2012, p. 115). Arguably, the [The](#) linear models corresponding to this hypothesis have led to observations from single glaciers, such as Tasman or Brewster Glacier, being used to estimate fluctuations in ice volume for the entire Southern Alps (Salinger et al., 2019a; 2019b). To further explore the validity of this approach, more long-term continuous signals of glacier mass balance are required across a broader topographical range of glaciers, particularly those larger than 2 km<sup>2</sup>. Given the available approaches to monitor glaciers and the lack of *in situ* data, the albedo method is a desirable alternative to objectively resolve mass balance variability and trends on large, un-monitored New Zealand glaciers [at near daily temporal resolution](#).

The Gardens of Eden and Allah (GoEA), located on the Main Divide of the Southern Alps, northeast of Aoraki/Mt Cook National Park, comprise two of the largest icefields in New Zealand [\(Fig. 1\)](#). They form an interesting target to test the climatic unit hypothesis, as the icefields consist of a network of smaller, interconnected glaciers, placed in a critical climatic zone straddling the Main Divide. Their position on the Main Divide, combined with their protected conservation status has greatly constrained the possible methods for data collection and extraction. As a result, these glaciers are yet to be the target of focused research, and their behaviour over the past decades is largely undocumented and poorly understood.

To address this gap in knowledge, the aim of this paper is to characterise the spatial and temporal variability of glacier-wide surface albedo on the GoEA, and to investigate the linkages between this variability and glacier mass balance. [By resolving and documenting spatial patterns in the evolution of glacier surface albedo across two of New Zealand's largest icefields, the single climatic unit hypothesis for glaciers in the Southern Alps can be tested, and the governing physical processes controlling mass balance explored in more detail.](#) [To achieve this aim, this research has the following objectives: \(1\) to determine the timing and magnitude of glacier-wide surface albedo on 12 different outlet glaciers on the GoEA; \(2\) to compare the spatial and temporal changes in surface albedo to variability in SLA as determined from the EOSS programme; and \(3\) to characterise variability in cloud cover using MODIS imagery acquired by the Terra and Aqua platforms.](#) Remote sensing with the albedo method provides an opportunity to examine the significant, yet remote and protected GoEA icefields, and provides an

opportunity to further assess the skill of the albedo method to remotely monitor the physical processes governing glacier mass balance ~~of~~ glaciers in the Southern Alps.

The next section describes the location and significance of the icefields in the New Zealand context. The methods section provides a description of the remote sensing datasets and processing techniques used to derive glacier wide surface albedo. 125 Two developments to the albedo method are proposed, namely (1) a new objective way to define glacier boundaries for albedo analysis, and (2) the processing and assessment of albedo from MODIS imagery acquired by the Aqua platform to increase the temporal resolution of albedo monitoring. The results section presents the records and analysis of glacier wide surface albedo for the GoEA, including a comparison to results from the EOSS programme. Finally, the discussion compares the results to the EOSS survey, examines the contribution of MODIS Aqua to resolve albedo and its usefulness in combination with Terra to characterise cloud cover variability, and describes the limitations and future opportunities of the albedo method. 130

## 2 Site description and data

### 2.1 The Gardens of Eden and Allah

#### 2.1.1 Situation

The Garden of Eden and Garden of Allah (referred to collectively as the GoEA) are two of New Zealand's largest icefields 135 (Fig. 1), situated in the Adams Range of the Southern Alps/Kā Tiritiri-o-te-Moana (43°18'S, 170°43'E). The icefields are aligned east to west, spanning across the Main Divide, 56 km northeast of Aoraki/Mt Cook. In this context, the GoEA are considered the perennial ice mass (ca. 36 km<sup>2</sup>) of the region, bordered by Outram Peak (2399 m), Mt Barlow (2100 m), Mt Kensington (2444 m) and Mt Stoddart (2223 m). The glaciers extend from a maximum elevation of 2543 m a.s.l. (Newton Peak) to ca. 1100 m a.s.l. at the terminus of Colin Campbell Glacier (southeast of Newton Peak).

140 The icefields are centred on two large rock plateaus (ca. 1900 m a.s.l), with ice flowing down into broad valley glaciers or terminating in dramatic icefalls over the incised valley walls. These outlets provide meltwater to the catchments of the Rangitata River on the east coast, and the Whataroa and Wanganui on the west coast. The positioning of the GoEA across the Main Divide places the icefields in a complex climatic setting. A prevailing westerly airflow combines with strong orographic lifting to generate a significant~~large~~ precipitation gradient from west to east across the Main Divide (Henderson and Thompson, 145 1999). The estimated mean annual rainfall in the area over the period 1972-2016 ranges from 6,000 to 8,500 mm yr<sup>-1</sup> (Macara, 2017). The mean annual temperature over the glaciated region for the period 1980-2010 is estimated to range from -1.0 to 2.5°C based on an interpolation of mean normal temperature from distant surrounding weather stations and a lapse rate determined from the data of -5.7°C km<sup>-1</sup>. Given the important role~~contribution~~ of snow and ice ~~into~~ New Zealand's water resources, changes in the volume of these icefields have the potential to impact the hydrology of these rivers under future 150 climate change (Chinn, 2001).

Despite their significance, research on the GoEA is limited by the remote location of the glaciers, and direct access has been further complicated in recent years by their inclusion in the 466 km<sup>2</sup> Adams Wilderness Area (est. 11 February 2014). Helicopter landings are now largely prohibited, effectively ruling out a number of *in situ* monitoring methods. As a result, the 155 most significant~~only~~ comprehensive data obtained from the area to date are EOSS SLA records for the two Vertebrae glaciers at the western margin of the GoEA (Willsman et al., 2018), which are described in more detail below. (Section 2.3). The Garden of Eden was also briefly included in an attempt to detect changes in the ELA of New Zealand glaciers from 15 m-resolution ASTER satellite imagery (Mathieu et al., 2009). The absence of data ~~contrasting with~~~~and~~ the large~~notable~~ extent and volume of ice locked in ~~a potentially sensitive climatic situation~~the GoEA make the GoEA~~region~~ a compelling target for research among the more than 2500 glaciers in the Southern Alps.

## 2.1.2 Glacier outlines and surface topography

As part of this research, the boundaries of the icefield outlets were redefined, updating the existing New Zealand Glacier Inventory outlines derived during the 1970s (Chinn, 1991), and refining the 2017 Randolph Glacier Inventory (RGI) version 6.0 outlines (Pfeffer et al., 2014). ~~The full extent of We used a 10 m-resolution Sentinel-2A image captured on 14 March 2016, in late-summer and cloud-free conditions, as the perennial base of our mapping. This image provided a suitable tradeoff between glacier exposure and illumination to define glacier outlines. Perennial~~ snow and ice in the GoEA ~~was~~<sup>were</sup> initially defined by ~~segmented using~~ the Normalised Difference Snow Index (NDSI) band ratio, ~~calculated for a 10 m-resolution Sentinel 2A image captured during late summer cloud free conditions on 14 March 2016, derived from bands 3 (Green) and 11 (Shortwave Infrared) of Sentinel-2, with a threshold of 0.8. Despite strong shadowing, a later Sentinel-2 image on 30 April 2016, which appears close to the maximum ablation, provided a visual reference to refine glacier outlines and exclude transient snow patches.~~ Manual edits were ~~then~~ made to refine the classification, specifically to correct shaded or debris-covered areas, where detection of snow and ice is impaired. These edits were aided by the interpretation of ~~high resolution imagery and field knowledge. These supplementary data included a 0.5 m-resolution orthorectified pan-sharpened Pléiades-1B satellite image acquired on 10 March 2017 as part of the Pleiades~~<sup>Pléiades</sup> Glacier Observatory programme (PGO), and a range of oblique aerial and terrestrial photographs captured during fieldwork on ~~20/21~~<sup>27/28</sup> January 2018.

The outlet glaciers were then delineated from the wider icefields using topographic divides identified from 20 m elevation contour vectors surveyed by Land Information New Zealand (LINZ), with refinements based on the interpretation of a preliminary high-resolution surface model derived from the Pleiades stereo acquisition. A total of 17 outlet glaciers were identified in the GoEA. However, this was reduced to 12, as: (1) some small adjacent glaciers (< ca. 0.5 km<sup>2</sup>) were amalgamated into larger units (if the direction of flow was consistent) to create a more suitable target for the MODIS analysis (i.e. O’Neil, Serpent and Cain glaciers), or (2) discrete glaciers < ca. 0.5 km<sup>2</sup> were excluded from further analysis (i.e. Vertebrae Col 12 and Wee McGregor Glacier). Elevation, slope and aspect data for these 12 outlet glaciers were then derived from the national 15 m-resolution digital elevation model (DEM, NZSoSDEM v1.0; Columbus et al., 2011).

## 2.2 MODIS products

This study relies primarily on a record of glacier surface albedo retrieved from a time-series of MODIS images. MODIS is one of the key sensors aboard the Terra (EOS/AM-1) and Aqua (EOS/PM-1) satellite platforms, ~~hereafter referred to as MODIS<sup>T</sup> and MODIS<sup>A</sup>, respectively.~~ Terra was launched on 18 December 1999 as the flagship of NASA’s Earth Observing System (EOS), allowing MODIS<sup>T</sup> to capture near daily, moderate-resolution images of Earth’s surface since 25 February 2000. Aqua was launched in May 2002, creating a second daily opportunity to capture MODIS<sup>A</sup> images. Terra ~~passes north to south over~~<sup>descending node crosses</sup> the equator at approximately 10:30 am, while Aqua ~~completes the reverse journey with~~<sup>ascending node is crossing</sup> at approximately 1:30 pm. Historically, MODIS<sup>T</sup> imagery has been preferred for the albedo method due to the longer record of imagery, as well as failed detectors with MODIS<sup>A</sup> Band 6.

~~Following Sirguey et al. (2009) and Dumont et al. (2012), the albedo retrieval was completed with the MODImLab software as described in Section 3.1.~~ As yet, the use of MODISA imagery to supplement the MODIST record for snow and ice albedo retrieval has not been explored. ~~Wardle (1986) demonstrated the extraordinary cloudy sky conditions that dominate~~ New Zealand’s Southern Alps ~~tend to be dominated by exceptionally cloudy sky conditions (Wardle, 1986),~~ greatly reducing the data available to space-borne remote sensors. ~~Wardle (1986) specifically reported that the western flanks of the study area near Cropp River exhibited the highest frequency of days with some clouds (92%), as well as days with heavy clouds (72%). The frequency of cloudy days tends to decrease towards the east, with some or heavy clouds occurring on 72% and 38% of days, respectively.~~ The consideration of MODISA data in this study provides an opportunity to compare surface albedo derived from each sensor, and to inform on key climate variables such as cloud frequency and variability over the Southern Alps. If the

albedo derived from MODIS<sup>A</sup> is suitable, despite the degraded Band 6, it can be used to increase the temporal resolution of the albedo method to two observations per day, or to fill gaps in the MODIST record.

We~~Following Sirguey et al. (2009) and Dumont et al. (2012), we~~ use MODIS Level-1B Collection 6 (C6) swath data products that contain calibrated and geolocated top-of-atmosphere (TOA) radiance counts for all 36 spectral bands. The products include bands 1 and 2 supplied at 250 m nadir resolution (MxD02QKM files, x=O/Y for Terra/Aqua, respectively). Bands 3 to 7 are provided at 500 m spatial resolution (MxD02HKM files), along with an aggregated 500 m version of bands 1 and 2. All 36 spectral bands are provided at 1000 m resolution (MxD021KM files), including the aggregated bands 1-7 at 1000 m. The accompanying MxD03 file contains the geolocation information and relative geometry parameters such as solar zenith ( $\theta_s$ ), solar azimuth ( $\phi_s$ ), sensor zenith ( $\theta_v$ ) and sensor azimuth ( $\phi_v$ ), required to take into account sun-target-sensor geometry in the albedo retrieval (Dumont et al., 2012; Sirguey et al., 2016).

The MODIS<sup>T</sup> record over the GoEA consists of 7067 ~~unique~~ granules between 25 February 2000 and 30 April 2018~~- captured on 6416 unique days~~. In addition, ~~four pairs of~~ MODIS images were selected to compare the surface albedo products from MODIST and MODISA over the GoEA. ~~Each of the~~ ~~Image~~ pairs ~~were~~ ~~needed to be~~ captured on the same day, under clear sky conditions, ~~and with similar near-nadir sensor zenith to mitigate the effect of different panoramic distortion on pixel footprint between MODIS<sup>T</sup> and MODIS<sup>A</sup>.~~ ~~Four suitable image pairs~~ across ~~four~~ separate years near the end of summer ~~were identified as suitable to assess the consistency of albedo retrieval between both sensors~~, namely 3 March 2009, 9 March 2010, 8 March 2012 and 10 March 2013. ~~The albedo products were compared at~~ ~~At~~ 250 m resolution, ~~with the~~ ~~this provided a sufficient sample size of 2196 pairs of albedo from matching pixels that were compared with linear regression and the~~ coefficient of determination ( $R^2$ ) ~~used to compare the albedo values of matching pixels.~~ Finally, a full year of MODIS<sup>A</sup> Level-1B images was downloaded between 1 January and 31 December 2012 (448 granules) to assess data loss compared to the MODIS<sup>T</sup> record.

### 2.3 EOSS survey programme

The national EOSS programme is run by National Institute of Water and Atmospheric Research (NIWA). Aerial photos are captured on the first suitable weather window following 1 March. The mapping of SLA for each of the index glaciers implements three methods summarised hereafter (see Willsman, 2018). (1) When the snowline is clearly visible, it is sketched from the oblique photograph onto 1:50,000 topographic contour maps of each glacier, or digitized readily from rectified photos to map the accumulation or ablation zones. The snowline elevation is derived from the ablation area and the hypsometric curve of the glacier. (2) The SLA is often determined by applying an “interpolation method” whereby all EOSS photographs of a glacier are arranged into a sequence of increasing area of snow cover (descending order of SLAs); the SLA value is interpolated from that of the adjacent years. (3) When the snowline is obscured, it is interpolated from an interpretation of the degree of snow cover surrounding the glacier compared to previous years on record.

For each year  $i$ , ~~EOSS~~ SLA <sub>$i$</sub>  records ~~delivered by the EOSS programme~~ for the two Vertebrae glaciers in the GoEA provide an independent dataset to make a comparison with the retrieved albedo signal. Vertebrae Col 25 is a 0.7 km<sup>2</sup> mountain glacier facing southwest at the western tip of the Garden of Eden (Fig. 1). Vertebrae Col 12 is a smaller cirque glacier (0.21 km<sup>2</sup>) located directly adjacent, to the north. The SLA was first recorded for the Vertebrae glaciers in 1978, despite the EOSS survey beginning in 1977, and has been recorded every year since, with the exception of 1979 (no flight), 1984 (no visit), 1987 (no visit), 1990 (no flight) and 1991 (no flight). Of the 35 observations in the 40-year period since 1978, the SLA was digitised eleven times (Fig. 2). In digitised years, the snowline is sketched onto the oblique aerial photographs and then digitised to derive its elevation from 1:50,000 topographic contour maps. In the remaining years, SLA <sub>$i$</sub>  is estimated by comparing the visible extent of the summer snowline to photographs from previous years~~. method 1 and interpolated (method 2 and 3) all other times (Fig. 2).~~

245 The SLA for each year (i.e.  $SLA_i$ )As part of the EOSS programme methodology (Chinn et al., 2012; Willsman et al., 2018),  
the SLA<sub>i</sub> for each glacier is compared against the long-term or ‘steady-state’ SLA, termed ‘ELA<sub>0</sub>’, which as determined by the EOSS survey is 1864 m a.s.l. and 1840 m a.s.l. for the Vertebrae Col 12 and 25 glaciers, respectively. Vertebrae Col 12 is not considered in this study, as it is not of sufficient size for albedo retrieval with MODIS, however the annual SLA departures from ELA<sub>0</sub> for the two glaciers are strongly correlated ( $R^2 = 0.95$ ). The SLA<sub>i</sub> departures for Vertebrae Col 25 show eight years with particularly high seasonal snowlines since 1999, indicative of a negative glacier mass balance (in particular 1999, 2008, 2011, 2012 and 2016), preceded by a majority of years with snowlines located near or below ELA<sub>0</sub>, indicative of a positive mass balance.

250 Both SLA departure records from Vertebrae Col 12 and 25 correlate strongly to the SLA departures averaged over the remaining index glaciers photographed in a particular year (EOSS<sub>Alps</sub>;  $R^2 = 0.86$  and 0.92, respectively), see Willsman et al., 2018. These very strong correlations between individual glacier responses to EOSS<sub>Alps</sub> suggest that the Vertebrae Col glaciers, like other index glaciers in the EOSS programme, respond uniformly to climate variability (or act as a climatic unit). This high degree of intra-correlation in the EOSS record has led to the theory that glaciers in the Southern Alps behave as a “unified climatic unit” (Chinn et al., 2012). However, we hypothesise that changes in the climate system are likely to result in greater variability in glacier response in the Southern Alps, which ~~is arguably~~may not ~~be~~be resolved and/or detected by the EOSS programme. The ability to derive and discriminate a mass balance signal from a large number of glaciers in the GoEA using the albedo method, which has a high temporal resolution, provides us with a ~~unique~~new opportunity to further characterize the spatial variability of glacier behaviour in the GoEA, as well as test the consistency in glacier response predicted by the EOSS programme.

## 260 2.4 Sentinel-2 data

265 As EOSS SLA<sub>i</sub> records only exist on two of the smaller glaciers in the GoEA, high-resolution Sentinel-2 data are also used to support the MODIS analysis by mappingobserving the evolution of the summer snowline across the icefields. Launched on 23 June 2015, Sentinel-2 imagery are available for the 2016, 2017 and 2018 summers, and provide ~~a second~~an independent means to assess the consistency of the albedo products and EOSS survey results. For the three summer periods (1 January - 30 April), sequences of cloud-free 10 m-resolution Sentinel-2A and 2B Level-1C images are used to identify the approximate elevation and timing of the SLA<sub>i</sub> over observe the evolution of the GoEA- surface until seasonal snow ends the ablation season. There is an expectation that the discolouration of the glacier surface and elevation and timing of the SLA<sub>i</sub>snowline in the Sentinel-2 images depicting maximum ablation will closely reflect the results from compare and be consistent with relative changes determined by the EOSS survey and ~~the summer minimum~~ glacier-wide albedo measured across the glaciers due to the relationship between the transient snowline and glacier wide albedo (Sirguey et al., 2016). Qualitative results of these observations are presented and discussed for Lambert Glacier, with the elevation of the snowline determined from LINZ 20 m topographic contours.

## 270 3 Methods

### 3.1 Retrieving snow and ice albedo

275 Terra and Aqua MODIS C6 Level-1B products were processed using the MODImLab toolbox (Sirguey et al., 2009). MODImLab has been widely employed to perform a series of image processing techniques on MODIS time-series data, yielding snow and ice albedo products at 250 m-resolution (Dumont et al., 2011, 2012; Brun et al., 2015; Sirguey et al., 2016; Rabatel et al., 2017; Davaze et al., 2018). The operations and processes of MODImLab are described by Sirguey et al. (2009) and Dumont et al. (2012), and ~~as such~~, are only covered here in brief.

280 First, image fusion combines the higher resolution MxD02QKM bands 1 and 2 (250 m) with the lower resolution MxD02HKM bands 3 to 7 (500 m) to produce seven spectral bands at 250 m spatial resolution (Sirguey et al., 2008). As a result, MODIS bands ~~important~~used for mapping snow cover (band 4 at 555 nm and 6 at 1640 nm) have a higher spatial resolution than other common MODIS products (e.g. MxD10 - 500 m). The atmospheric and topographic correction module (ATOPCOR) then corrects images containing TOA radiance counts into values of ground surface reflectance (Sirguey, 2009). Topographic corrections are calculated from the NZSoSDEM along with the MxD03 product to account for the relative illumination and viewing geometry. The DEM is also used to pre-process the sky-view and terrain factor to account for diffuse and terrain-reflected irradiance over rugged terrain, and the effects of both self and cast shadow.

285 The MODImLab algorithm has the ability to resolve the sub-pixel snow cover fraction in mountainous terrain (Sirguey et al., 2009). Spectral unmixing estimates the relative contributions of specific land cover types to the radiometry of each individual pixel (Masson et al., 2018). Values of spectral albedo (narrowband albedo) for each pixel measured from five MODIS bands are compared against a Look-Up Table (LUT) generated with DISORT (Stamnes et al., 1988). The LUT contains an array of spectral albedo values simulated for snow and ice surfaces with varying snow grain size, impurity type and content, and incident zenith angle (Dumont et al., 2011). The best match of spectral albedo can then be integrated to yield the Blue-Sky (BS) and White-Sky (WS) broadband albedo for a pixel. BS albedo is the value of broadband albedo corresponding to the specific ground irradiance. However, diffuse, or WS albedo is preferred in this research, as it allows the surface albedo to be studied with reduced sensitivity to seasonal changes in illumination conditions (Dumont et al., 2012). Given the small reflectance of snow and ice targets at 1600 nm and marginal contribution to broadband albedo, the performance of albedo retrieval from ~~MODIS~~MODIS Aqua data is not expected to be compromised despite the degraded Aqua band 6.

### 3.2 Glacier masks

300 Having processed the MODIS granules with MODImLab, we then create 250-m raster glacier masks using the glacier outlines from Section 2.1.2 under which albedo is averaged. Glacier masks are defined from glacier outlines to avoid debris-covered areas or mixed land-cover pixels (e.g. containing a combination of snow/ice and rock) so as to preserve the integrity of the snow and ice albedo retrieval. In previous studies, this has been achieved subjectively (e.g. Dumont et al., 2012; Brun et al., 2015; Davaze et al., 2018), but takes time and introduces variability between users. As a result, we consider an alternative 305 approach to masking that can be more objectively deployed across a large number of glaciers.

310 From all pixels within the glacier outlines, we use the sub-pixel snow classification produced by spectral unmixing in MODImLab to exclude those with snow-covered-area less than 50% snow, as this threshold is generally used to segment snow from snow-free pixels (Sirguey et al., 2009). This excludes most non-glaciated surfaces from the overall glacier outlines (e.g. ~~debris~~-covered) and mitigates the effect of mixed-pixels in the glacier-wide albedo. We assess the effectiveness of this masking approach (Mask 1) against a conservative glacier mask created manually (Mask 2) by comparing the glacier-wide albedo  $\bar{\alpha}(t)$  from each mask and outlet glacier over the full sequence of MODIS<sup>T</sup> imagery. The mean surface albedo series retrieved from each mask,  $\bar{\alpha}(t)_{M1}$  and  $\bar{\alpha}(t)_{M2}$ , are compared using the linear coefficient of determination ( $R^2$ ), root mean square difference (RMSD) and mean difference (MD).

### 3.3 Filtering the MODIS-albedo record

315 Despite the near-daily capture of MODIS images over the GoEA, cloud cover in the Southern Alps ~~significantly~~greatly reduces the quantity of available data. Following Sirguey et al. (2016), only MODIS images with no cloud present in any pixels within the glacier mask are retained in the analysis. Cloudy pixels were determined using MODImLab's cloud detection algorithm, based on the original MODIS MOD35 Cloud Product described by Ackerman et al. (1998). Using these products, Brun et al. (2015) and Davaze et al. (2018) demonstrated the successful application of a cloud threshold, whereby images are retained so

320 long as a certain proportion of the glacier surface is cloud-free in the image (>20% and >30% clear surface, respectively). While there is merit in this approach for larger glaciers (e.g. Chhota Shigri Glacier: 15.7 km<sup>2</sup> and Mera Glacier: 5.1 km<sup>2</sup>), the outlet glaciers of the GoEA identified in this analysis are much smaller (average ca. 2.8 km<sup>2</sup>). On small glaciers, there is a higher probability that large parts of the accumulation or ablation areas will be obscured by ~~cloud~~clouds, and therefore the surface albedo across the glacier may be misrepresented. Relying on cloud-free conditions over the glacier excluded ca. 66% of the images, resulting in an average of one clear-sky image every 3 days. The classification of clouds in the complete 19-year long inventory of near-daily MODIS images was then leveraged to characterise the spatial variability in cloud frequency of occurrence around the GoEA.

325 An increase in sensor viewing zenith angle ( $\theta_v$ ) distorts MODIS pixels due to the panoramic effect. The ground sampling distance of MODIS pixels increases from 2- to 5-fold from  $\theta_v = 45^\circ$  to  $66^\circ$ , respectively (Wolfe et al., 1998). Albedo retrieval of mountain glaciers with MODIS is most accurate with  $\theta_v < 30^\circ$  (Sirguey et al., 2016). However, Brun et al. (2015) and Sirguey et al. (2016) accepted  $\theta_v < 40^\circ$  and  $< 45^\circ$ , respectively, to increase the number of images available for retrieval. Davaze et al. (2018) confirmed that, while albedo retrieval was most accurate with view angle  $\theta_v < 30^\circ$ , it performed well until  $\theta_v < 45^\circ$ . In this study, and given the various configurations and size of glaciers in GoEA, we found that this threshold remained suitable to optimise the number of images and quality of the albedo retrieval.

### 335 3.4 Calculating glacier-wide albedo

Glacier-wide albedo  $\bar{\alpha}(t)$  was then calculated for each MODIS image (at time  $t$ ) as an average of all pixel values within each outlet glacier mask. Following Dumont et al. (2011),  $\bar{\alpha}(t)$  was calculated using the WS albedo product, under the anisotropic reflectance model. To reduce the noise of the  $\bar{\alpha}(t)$  signal and smooth the time-series, a three-period rolling average was applied (Sirguey et al., 2016), and was preferred to a fixed-day average, which is heavily influenced by large gaps in the series, driven 340 by persistent cloud cover. The  $\bar{\alpha}_{\text{yr}}^{\min}$  was then extracted as the annual minimum glacier-wide value of smoothed  $\bar{\alpha}(t)$ , from the period corresponding to the end of the ablation season (1 January - 30 April). Due to complex topography and cast shadows in the GoEA, visual confirmation revealed that when  $\bar{\alpha}_{\text{yr}}^{\min}$  is reached outside of this period, it is always due to incorrect albedo retrieval (underestimated) due to inaccurate topographic correction in the shade, as identified by Davaze et al. (2018).

### 3.5 Characterising topographic shading

345 Shading at the glacier surfaces complicates the topographic correction and has the potential to create ~~artefacts~~errors in the albedo retrieval algorithm. This typically occurs at low sun zenith angles, outside of the late-summer period when  $\bar{\alpha}_{\text{yr}}^{\min}$  is reached. Nonetheless, ~~it is important to understand how a change~~changes in the distribution of shortwave radiation being received at the glacier surface affects processes such as the evolution of surface albedo. Net shortwave radiation is one of the key components of the glacier surface energy balance (SEB). The intensity of solar radiation received at the surface is a 350 function of the time of year (season) and global position (latitude). At a local scale, this relationship is complicated by topography, slope and aspect. Olson and Rupper (2018) show shading from topography (both cast- and self-shading) is ~~an important~~a key factor contributing to the SEB. Therefore, in addition to quantifying glacier slope and aspect (Section 2.1.2), the ATOPCOR module from MODImLab is used to calculate fractional shading at 250 m resolution across the glacier surface at the time of image capture. We use the maximum proportion of surface shading (occurring during the winter solstice, when 355 the solar zenith angle is at its maximum) as a simple metric to compare shading between glaciers. A high maximum percentage of topographic shading indicates a topographically confined glacier, while a low maximum percentage indicates an open, unconfined surface that receives radiation year round (e.g. Fig. 3).

## 4 Results

### 4.1 Assessing the mask performance

360 Between February 2000 and April 2018, the difference between derived glacier-wide albedo  $\bar{\alpha}(t)_{M1}$  and  $\bar{\alpha}(t)_{M2}$  derived is small (RMSD = 0.037; Table 1), with Mask 1 (objective masking approach) typically yielding smaller albedo compared to Mask 2 (MD = -0.012). Importantly, the The linear agreement between the masks is highest during the critical summer period (1 October-31 March), when the  $\bar{\alpha}_{yr}^{\min}$   $\bar{\alpha}_{yr}^{\min}$  is expected to be reached. The increased difference during winter months is likely a result of debris-covered pixels (not considered by Mask 2) that become snow-covered beyond 50%, thus included in Mask 365 1 and raising  $\bar{\alpha}(t)$ . The relatively small difference between the two methods, particularly during summer, is confirmation of the suitability of the objective glacier masking approach, and is therefore used to produce the following results over the GoEA.

### 4.2 Glacier characteristics

370 Despite the two icefields being an interconnected ice mass, the glaciers of the GoEA exhibit large differences in their hypsometry (Table 2). The majority of the ice resides slightly above 1900 m a.s.l., close to the average elevation of the plateaus.

375 As with many other glaciers in the Southern Alps, the average surface gradient is steep, with a number of glaciers approaching 20°. In addition, glacier size is relatively small, ranging between 0.44 km<sup>2</sup> and 4.44 km<sup>2</sup>. Lambert Glacier is an exception (9.44 km<sup>2</sup>), comprising over one quarter of the total surface area (33.89 km<sup>2</sup>). The glaciers also occupy a range of aspects with variable topographic shading. As expected, glaciers with mean north-facing aspectaspects display lower values of topographic shading than south-facing glaciers (e.g. Angel Glacier, east-northeast, 5.4%; Colin Campbell, south, 82%).

380 385 It is anticipated that the large topographic differences between outlet glaciers may drive significantlya large variability in the temporal evolution of glacier surface albedo. To further characterise the contrasting topography of these glaciers, we perform a K-mean cluster analysis based on mean aspect, mean slope and maximum topographic shading. Three clusters are identified derived from the mapped outlines of each glacier. The glacier characteristics (Table 2) when viewed in scatter plots revealed that the 12 outlet glaciers grouped in three identifiable clusters, with the contrasting hypsometry indicated in Fig. 4. ClassCluster membership for each glacier is provided in Table 2. Glaciers in ClassCluster 2 are characterised by southerly aspects, steep slopes and incised topography (indicated by topographic shading exceeding 80%). These glaciers contrast to the north- and east-facing, unconfined glaciers in ClassCluster 1. ClassCluster 3 shares similar topographical attributes to ClassCluster 1, although the aspect is primarily west-facing. Importantly, the glaciers in Clusters 1 and 3 account for 81% of the total surface area of the GoEA , while the two south-facing glaciers in Cluster 2 occupy the remaining 19%.

### 4.3 Annual evolution of MODIS-derived glacier-wide albedo

390 All 12 glaciers in the GoEA exhibit a marked seasonal evolution of MODIS-derived glacier-wide albedo  $\bar{\alpha}(t)$  when averaged within-cluster (Fig. 5). As air temperatures rise and incident solar radiation increases following 5a), characterised by a decrease in  $\bar{\alpha}(t)$  at the end of the austral winter (1 September), as controlled by the onset of melt. The lowering of  $\bar{\alpha}(t)$  decreases. This is primarily due to the melting of snow from the previous winter, exposing the underlying glacier ice and firn. To compound this process, snow and ice that remain through the summer undergoes metamorphism. This process drives an increase in grain size, liquid water content and impurity concentration, which all act to decrease surface albedo. As a result, glacier-wide albedo continues to fall through the summer, until fresh snow begins to fall (accumulate in late summer and early March), autumn. The duration of exposure of discoloured glacier ice and firn across the glacier during summer is a critical part of the physical processes controlling surface ablation. Although each of the three clusters follows a typical pattern of seasonal evolution, the timing and magnitude of key events, such as the  $\bar{\alpha}_{yr}^{\min}$  and the rate of change of  $\bar{\alpha}(t)$ , appears to varyvaries between glaciers.

On some glaciers, the seasonality of the albedo signal is complicated by a ~~significant~~substantial decrease in  $\bar{\alpha}(t)$  centred around the winter solstice (21/22 June). This trend is not unique to the GoEA, and has been identified to be an artefact of widespread surface shading when the sun is at its lowest that compromises the radiometric correction by MODImLab, resulting in incorrect surface albedo (Rabatel et al., 2017; Davaze et al., 2018). This issue affects both glaciers in ~~class~~cluster 2 (observable in Fig. 5a), and some in ~~class~~cluster 3 (namely, Eve Icefall and Perth Glacier). These glaciers all exhibit a south/southwest aspect and topographic shading greater than 60% (Table 2). Importantly, as ~~As~~ this pitfall develops in winter, it has little or no impact on the summer albedo signal and the identification of  $\bar{\alpha}_{\text{yr}}^{\min}$ . We therefore disregard much of the winter signal from these glaciers, and focus on the summer ablation period.

During the ablation period, all three classes share consistent patterns over the 19-year albedo record that deviate from a monotonic ~~decline~~decrease. Short-lived increases in  $\bar{\alpha}(t)$  occur in mid-October and December, suggesting synoptic-scale atmospheric processes result in late snowfall events, which temporarily change the albedo signal over the glaciers. A similar pattern of late spring or early summer snowfall events were also observed on Brewster Glacier between November and December (Sirguey et al., 2016), which have a strong and coherent weather-system scale signature (Cullen et al., 2019). The occurrence of these snow events likely play ~~an important~~a considerable role in the evolution of albedo through the summer period and in turn, glacier mass balance. Large events have the potential to deposit enough fresh snow at the surface to provide prolonged protection of the otherwise exposed glacier ice during the height of summer.

#### 4.4 Annual minimum glacier-wide albedo ( $\bar{\alpha}_{\text{yr}}^{\min}$ )

Figure 6 demonstrates the variability of the  $\bar{\alpha}_{\text{yr}}^{\min}$  observed over the 19-year period between individual glaciers. The average magnitude of  $\bar{\alpha}_{\text{yr}}^{\min}$  varies between 0.50 (Arethusa Glacier) and 0.62 (Eve Icefall), but ranges between 0.42 and 0.70. The  $\bar{\alpha}_{\text{yr}}^{\min}$  is typically reached between early-February (Abel Glacier: 37 Julian Days (JD)) and mid-March (Barlow Glacier: 75 JD), but can occur as early as mid-January and as late as the end of April. In addition to a large range in timing between glaciers, the variability in the arrival of  $\bar{\alpha}_{\text{yr}}^{\min}$  on certain glaciers is also large (e.g.  $\sigma = 29.5$  days for Barlow Glacier).

The Spearman's rank coefficient is used to determine the topographic controls on the median value and timing of  $\bar{\alpha}_{\text{yr}}^{\min}$  across the outlet glaciers (Table 3). To avoid the circular nature of aspect data (i.e. where  $0^\circ$  and  $360^\circ$  are equal), values of mean aspect (in degrees) are converted into Cartesian coordinates and correlated independently. A strong and significant association is found between the magnitude of  $\bar{\alpha}_{\text{yr}}^{\min}$  and the proportion of topographic shading ( $r = 0.741$ ,  $p = 0.008$ ). Similarly, strong and significant associations are also found with the timing of  $\bar{\alpha}_{\text{yr}}^{\min}$  (north/south component of glacier aspect:  $r = 0.805$ ,  $p < 0.002$ ; proportion of topographic shading:  $r = -0.782$ ,  $p = 0.003$ ). These ~~correlation results~~correlations, as well as Fig. 6, suggest that glaciers with northerly aspects and low topographic shading (cluster 1) exhibit a lower and delayed  $\bar{\alpha}_{\text{yr}}^{\min}$ . Conversely, glaciers with southerly aspects and heavy topographic shading (cluster 2) typically have a higher  $\bar{\alpha}_{\text{yr}}^{\min}$ , which occurs earlier in the year. Interestingly, Fig. 5 shows that the timing of  $\bar{\alpha}_{\text{yr}}^{\min}$  over the period of the study appears to have evolved towards late summer for class 1 and 3, while this timing is unchanged for the two glaciers in class 2.

Interestingly, Fig. 5d shows that despite a large interannual variability, the timing of  $\bar{\alpha}_{\text{yr}}^{\min}$  appears to have evolved over the period 2010-2018 towards late summer for clusters 1 and 3, while this timing remained relatively unchanged for the two glaciers in cluster 2. However, Figure 5b reveals no significant temporal trend for  $\bar{\alpha}_{\text{yr}}^{\min}$  within each cluster (the Pearson correlation coefficient between  $\bar{\alpha}_{\text{yr}}^{\min}$  and the year yielded  $p = 0.20$ ,  $0.70$  and  $0.52$  for clusters 1, 2 and 3, respectively). A delayed  $\bar{\alpha}_{\text{yr}}^{\min}$  could indicate a longer ablation duration, and consequently correspond to a lower  $\bar{\alpha}_{\text{yr}}^{\min}$ . However, we only find a weak relationship between  $\bar{\alpha}_{\text{yr}}^{\min}$  and its timing when aggregating the three clusters ( $R^2=0.26$ ,  $p < 0.001$ , see Fig. 5c). This correlation proves to be weaker when considering all glaciers individually, with the Julian Day of the minimum albedo only

explaining 11% ( $p < 0.001$ ) of the variability of  $\bar{\alpha}_{\text{yr}}^{\text{min}}$ . Furthermore, this relationship loses significance within clusters (cluster 1:  $R^2=0.20$ ,  $p = 0.058$ ; cluster 2:  $R^2=0.08$ ,  $p = 0.248$ ; cluster 3:  $R^2=0.03$ ,  $p = 0.472$ ).

#### 4.5 Gardens of Eden and Allah (2000 – 2018)

We use the same methodology as the EOSS survey to characterise and compare the variability of  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  across the 12 outlet glaciers. The  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  across the 12 outlet glaciers are averaged to establish  $\bar{\alpha}_0^{\text{min}}$  (56.5%), from which yearly departures are calculated. The combined 19-year record of  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  variability averaged across the 12 outlet glaciers of the GoEA is shown in Fig. 7. The use of  $\bar{\alpha}_0^{\text{min}}$  follows the theory outlined by the EOSS survey, where the long-term average elevation of the SLA is assumed to approximate a glacier in its equilibrium state. The main limitation of  $\bar{\alpha}_0^{\text{min}}$  is that the record only consists of 19 years of data, as opposed to almost 40-years for the EOSS survey. In addition, there is no compelling proof that glaciers in the Southern Alps have been in equilibrium during either period. Therefore, it is possible that the value of  $\bar{\alpha}_0^{\text{min}}$  proposed here actually represents the GoEA in a state that is not in equilibrium. In this instance,  $\bar{\alpha}_0^{\text{min}}$  is arguably limited to describing relative change over the observation period, as opposed to providing a measure for quantitative mass balance in absolute terms.

Negative departures from  $\bar{\alpha}_0^{\text{min}}$  correspond to years where glacier-wide minimum albedo is lower than average, and in turn a more negative mass balance than average is expected. The opposite is expected for positive departures. Therefore, based on the relationship between  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  and annual mass balance, it can be inferred that these shifts broadly correspond to relative shifts in glacier mass balance. In general, the glaciers of the GoEA appear to have undergone four changes to  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  since 2000. For the first three years of the record (2000-2002),  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  across the GoEA was close to, or below average, followed by a positive shift for 2003-2007, with a maximum positive departure in 2004 (5.11%). Between 2008 and 2013, departures were largely negative, notably in 2008, 2011 and 2013. However, since 2014 the fluctuation in  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  has increased significantly substantially, highlighted by the very positive year in 2017 and very negative years of 2016 and 2018. The departure in 2018 is particularly significant as it is the most negative departure across the entire MODIS record (4.21% below  $\bar{\alpha}_0^{\text{min}}$ ). This value is also consistent with observations at Brewster Glacier and confirms the widespread effect of the 2018 summer heatwave on New Zealand glaciers (Salinger et al., 2019a).

The behaviour of the glacier-wide surface albedo anomaly on the GoEA over this 19-year period couples reasonably well with EOSS<sub>Alps</sub>, with about half of the variability explained ( $R^2 = 0.55$ ,  $p < 0.001$ ). Notably, the largest negative departures in  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  are in general consistent with high snowlines observed across the index glaciers of the Southern Alps in 2000, 2008, 2011, 2016 and 2018. Despite the relatively limited length of the series, the agreement between the two methods in years where the snowline departure is positive ( $R^2 = 0.68$ ;  $n = 9$ ,  $p = 0.006$ ) is much stronger than in years with a negative departure ( $R^2 = 0.22$ ;  $n = 9$ ,  $p = 0.201$ ). Salinger et al. (2019a) also highlight the overwhelmingly positive departures of the transient snowline during the 2018 summer, with EOSS<sub>Alps</sub> estimated to be 386 m above the long-term average from linear regression with the EOSS of Tasman Glacier alone. Since this estimate is derived with a very different methodology than the traditional EOSS survey, it is not included in the current analysis. Nonetheless, such a large positive departure is supported by widespread reports of exceptional ablation of glaciers in the Southern Alps. The effect of this extreme summer on the GoEA glaciers is now also supported by results in this study using the MODIS driven albedo method.

#### 4.6 Assessment of $\bar{\alpha}_{\text{yr}}^{\text{min}}$ on Lambert Glacier (2016-2018)

The full 19-year time-series of  $\bar{\alpha}(t)$  retrieved from Lambert Glacier exemplifies the annual variability in  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  (Fig. 8). The raw MODIS-derived values of  $\bar{\alpha}(t)$  are indicated in red, along with the three-period rolling average used to illustrate the seasonality of the albedo signal. In lieu of the glaciological mass balance data needed to relate the  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  to quantitative mass

balance, we use Sentinel-2 data to independently support the MODIS record. The images in Fig. 9 show the end of the ablation season and maximum altitude reached by the summer snowline observed on Lambert Glacier observed in cloud free Sentinel-2 images during the 2016, 2017, and 2018 summer periodperiods. Figure 9a shows the snowline captured on 2930 April 2016, 1112 days later than the  $\bar{\alpha}_{\text{yr}}^{\min}$  observed inestimated from the MODIS imagesrecord (18 April). The snowline can be distinguished by the separation between the bright white snow and discoloured ice and firn, visible above ca. 1900 m and up to 2000 m in partsat some locations. The snowline in the 29 March 2017 image is located at ca. 1820 m, slightly above the large icefall that separates the upper and lower glacier. A much higher proportion of snow covering the glacier surface corresponds to a 6% increase in the  $\bar{\alpha}_{\text{yr}}^{\min}$  during the 2017 summer, and is found to be 10 days later using the albedo method (8 April). This is consistent with the lower ablation reported by the EOSS programme in 2017 (Willsman et al., 2018). Despite a relatively large snowfall event brought by cyclone Gita in mid-February 2018, the image from 2829 March 2018 reveals high ablation and a similar snowline to 2016, although the proportion of exposed ice and firn appears to be slightly larger. These events are captured in the albedo record, with a short-lived rise in  $\bar{\alpha}(t)$  corresponding to Gita during February, followed by a  $\bar{\alpha}_{\text{yr}}^{\min}$  that is reached 19 days earlier (10 March) than the chosen Sentinel-2 image, with its magnitude lower than in 2018 compared to 2016. These images not only act to illustrate the variability The Sentinel-2 observations are consistent with the relative changes of  $\bar{\alpha}_{\text{yr}}^{\min}$ , but captured by the albedo method, as well as the effects of heatwaves on New Zealand glaciers in 2016 and 2018 (Salinger et al., 2019a; 2019b; Willsman et al., 2017).

The Sentinel-2 images shown in Fig. 9 also demonstrateillustrate the complexity of defining the summer snowline elevation on topographically complex glaciers such as Lambert. Despite the limited number of cloud-free images, the sequence of Sentinel-2 images obtained during the summer and through to the arrival of seasonal snow proved to be key in interpreting the evolution of the snowline. They were found to be available within a period of less than three weeks from  $\bar{\alpha}_{\text{yr}}^{\min}$  determined using the albedo method, while the 2016 and 2017 EOSS surveys captured Vertebrae Col glacier on 11 and 9 March, or 40 and 38 days earlier than  $\bar{\alpha}_{\text{yr}}^{\min}$ , respectively (see the albedo record for Vertebrae Col glacier in Fig. 10; note that reports from the EOSS 2018 campaign have not been released to date).

#### 4.7 Links between $\bar{\alpha}_{\text{yr}}^{\min}$ and EOSS

Previous applications of the albedo method to New Zealand glaciers have developed strong relationships ( $R^2 = 0.89$  and  $R^2 = 0.87$ , see Sirguey et al., 2016 and Rabatel et al., 2017) between the MODIS-derived  $\bar{\alpha}_{\text{yr}}^{\min}$  and EOSS SLA<sub>i</sub>. Across the GoEA, SLA records only exist for both Vertebrae Col glaciers. However, with 0.7 km<sup>2</sup> surface area, Vertebrae Col 25 is substantially smaller than the 2 km<sup>2</sup> recommended to develop a reliable glacier-wide albedo average with enough MODIS pixels (Sirguey et al., 2016). Although the albedo signal for Vertebrae Col 25 is obtained from only six11 250-m resolution pixels, the time-series appears to reflect the typical seasonal cycle of albedo, albeit with a larger range in the maximum and minimum albedos than those observed from Lambert Glacier (Fig. 10).

Between 2000 and 2017, the MODIS record of  $\bar{\alpha}_{\text{yr}}^{\min}$  for Vertebrae Col 25 explains nearly half of the variability observed in the EOSS SLA<sub>i</sub> (Fig. 11;  $R^2 = 0.43$ ,  $p = 0.003$ ). Alternatively,  $\bar{\alpha}_{\text{yr}}^{\min}$  of Angel Glacier exhibits the strongest relationship with EOSS observations at Vertebrae Col 25, accounting for 69% of its variance ( $p = 1.8 \times 10^{-5} < 0.001$ ). Other glaciers in the GoEA, namely Lambert, East Lambert, and Eve, each capture half or more of this variance as well (52%, 50%, and 55%, respectively). Overall, it appears that the relationship between EOSS observations at Vertebrae Col 25 and  $\bar{\alpha}_{\text{yr}}^{\min}$  of each glacier is related to topographic shading ( $R^2 = 0.48$ ,  $p_{\text{value}} = 0.012$ ), slope ( $R^2 = 0.42$ ,  $p_{\text{value}} = 0.022$ ), and the north/south component of glacier aspect ( $R^2 = 0.34$ ,  $p_{\text{value}} = 0.045$ ). In contrast, glacier size ( $R^2 = 0.03$ ,  $p = 0.609$ ) and elevation ( $R^2 = 0.20$ ,  $p = 0.142$ ) exhibit no significant role in determining this relationship. From the clustering analysis of the 12 glaciers in the GoEA, it is evident that changes in  $\bar{\alpha}_{\text{yr}}^{\min}$  over the unconfined glaciers in classcluster 1 are consistent to EOSS observations (mean  $R^2 = 0.51$ ). More

515 confined west-facing glaciers of classcluster 3 exhibit a weaker, yet still significant relationship (mean  $R^2 = 0.36$ ). Finally,  $\bar{\alpha}_{yr}^{min}$  of the two most confined south-facing glaciers in classcluster 2 do not have a strong relationship to the EOSS record (mean  $R^2 = 0.19$ ).

## 5 Discussion

### 5.1 Comparison to the EOSS survey

520 The EOSS survey provides a well documented and invaluable record of the changes to glaciers in the Southern Alps over the past 40 years. Importantly, the data collected by the survey bridges the gap in glaciological mass balance records between the termination of the Ivory Glacier programme in 1975 and commencement of the Brewster Glacier programme in 2004. In addition, the correlation between the snowline record and recently developed monitoring methods has allowed past mass balance trends to be reconstructed (e.g. Sirguey et al., 2016). At a larger scale, the use of EOSS<sub>Alps</sub> has proven to be an effective measure for broadly characterising the annual variability of glacier mass balance in the Southern Alps.

525 Published relationships developed between the MODIS derived  $\bar{\alpha}_{yr}^{min}$  and the EOSS SLA<sub>yr</sub> departures on Brewster Glacier and Park Pass Glacier were found to be strong (Sirguey et al., 2016; Rabatel et al., 2017). Although albedo and snowline methodologies differ significantly, both aim to remotely capture the point of maximum ablation at the glacier surface and use it as a proxy for mass balance. SLA<sub>yr</sub> used as an estimate of the ELA<sub>yr</sub> provides an effective measure of glacier mass balance (Rabatel et al., 2005), and should therefore be closely related to  $\bar{\alpha}_{yr}^{min}$  (Dumont et al., 2012).

530 However, measuring SLA<sub>yr</sub> remains difficult, in particular due to uncertainties associated with the method used to identify snowlines from oblique photos. Complex topography, avalanching, fresh snow, and cloud cover all present additional challenges for deriving consistent results of SLA<sub>yr</sub>. To compound these challenges, limited resources mean that the EOSS survey is required to assume that SLA<sub>yr</sub> occurs annually in early March, which involves careful timing of the observation flights (Willsman et al., 2018). In most cases, SLA<sub>yr</sub> is estimated manually based on the overall appearance of the glacier and snow patches compared to previous years. When SLA<sub>yr</sub> is digitized, photographs are compared to historical topographic maps or from orthorectified images. Furthermore, the methodology often involves an interpretation and assessment of the appearance of an individual glacier in relation to other glaciers in the programme, observed during the same or from different surveys.

540 Despite the coarse resolution of the MODIS sensor, it has been demonstrated in this study that the albedo method is capable of retrieving robust time series of  $\bar{\alpha}_{yr}^{min}$  that show strong to moderate relationships to EOSS signals (glaciers of Class 1 and 3, respectively). There are some clear advantages in using the albedo method over an EOSS approach, which include the approach being repeatable and not being temporally constrained. While the EOSS programme yields an archive of invaluable images, a number of photos are impacted by transient snow that impact the quality of the SLA<sub>yr</sub> estimates. The timing of the surveys also mean that some SLA<sub>yr</sub> estimates might not fully capture late summer melt (Sirguey et al., 2016). Monitoring albedo until the onset of the accumulation season (winter) allows sustained late season ablation to be recorded. The large variability in timing of  $\bar{\alpha}_{yr}^{min}$ , as well as the apparent trend towards a delayed occurrence for most glaciers in the GoEA (Fig. 5 and 6), demonstrates the benefit of systematically monitoring glacier surface albedo. Thus, the albedo method provides unique insights about glaciers in the Southern Alps that are arguably not captured by the EOSS programme.

545 The EOSS programme reports significantly high intra correlations across the 50 index glaciers that sample the Southern Alps, with pair wise  $R^2$  ranging 0.22 to 0.96 and averaging 0.69. Overall, our systematic application of the albedo method on the limited geographical extent of the GoEA reveals a degree of variability in glacier response that challenges the highly consistent behaviour suggested by the EOSS programme across the Southern Alps. Strong and significant intra correlations in  $\bar{\alpha}_{yr}^{min}$  across glaciers of the GoEA exist but do not dominate, with pair wise  $R^2$  ranging from 0.12 to 0.88 and averaging only 0.52. Similarly,

555 the correlation between the average GoEA albedo signal to EOSS<sub>Alps</sub> is only  $R^2 = 0.55$  (see Fig. 7), while the average correlation between SLA<sub>s</sub> and EOSS<sub>Alps</sub> is reported at 0.81. These contrasting results suggest the EOSS approach may have led to spatial and temporal auto correlation of the SLA records, which in turn build very strong correlations across SLA records of EOSS index glaciers and to EOSS<sub>Alps</sub>. The outcome of this is that it may have damped or concealed the variability of mass balance response of glaciers in the Southern Alps.

### 5.24.8 The contribution of Aqua MODIS

#### 5.24.8.1 MODIS albedo

560 Figure 12a illustrates the agreement between the MODImLab 250 m WS albedo retrieved from Terra and Aqua MODIS images across four days (3 March 2009, 9 March 2010, 8 March 2012, 10 March 2013). To account for the role of shadows during the albedo retrieval process, each pixel within the GoEA was assigned to one of four “shading classes:” depending on the presence of shade in each image. Pixels in Class 1 were unshaded in both images, Class 2 and Class 3 pixels were only shaded in the Aqua or Terra image respectively, and Class 4 pixels were shaded in both images. Of the total 2196 matching pixels from these 565 image pairs, 83.5% belonged to Class 1. The linear regression for these 1834 pixels is significant ( $p < 0.01$ ), and strong ( $R^2 = 0.58$ ), although slightly askew to a linear 1:1 relationship (Fig. 12a). Individually, each of the four days displays a similar trend and distribution, with  $R^2$  values ranging between 0.51 and 0.71, and gradients between 0.75 and 0.85.

570 Figure 12a also shows an increase in the variability of albedo between the sensors at higher values. Overall, this agreement is consistent with the expected 10% accuracy of the albedo retrieval method (Dumont et al., 2011, 2012; Sirguey et al., 2016). The increased variability coincides with the highest density of points; where 83% of pixel albedo values fall between 0.4 and 575 0.8. Due to the uneven distribution of albedo across the spectrum, a second linear regression was run on a stratified random sample of 150 Class 1 pixels (Fig. 12b). The linear regression of these resampled data show a much-improved fit ( $R^2 = 0.88$ ,  $p < 0.001$ ) that closely approximates the 1:1 relationship, and demonstrates that the degraded band 6 of MODIS<sup>A</sup> does not compromise MODImLab albedo retrieval. The slightly lower albedo found in Aqua images compared to Terra may also be explained by the timing, as snow and ice surfaces would undergo transformation compatible with a decrease in albedo from morning to afternoon.

580 To characterise the variability between the sensors in more detail, we present the spatial distribution of averaged residuals between maps of glacier surface albedo from MODIS<sup>T</sup> and MODIS<sup>A</sup> across the GoEA (Fig. 13). Although Fig. 13 confirms the good agreement between the sensors over large parts of the GoEA, it shows large departures around the fringes and near 585 rock outcrops (+0.23/-0.38), often close to steep, complex terrain and involving mixed pixels. In particular, two large steep-sided rock outcrops in the south of Lambert Glacier and West the west icefall of Angel Glacier corresponds descending from Mt Farrar correspond to MODIS<sup>A</sup> albedo being substantially larger than MODIS<sup>T</sup>. Close inspection of imagery before and after correction, as well as shadow maps reveal the larger extent of cast shadows produced by outcrops in the afternoon and affecting MODIS<sup>A</sup> imagery. Issues of overcorrecting spectral reflectance in cast shadows is known to challenge MODImLab (Davaze et al., 2018), and appears again to cause overestimations overestimates of MODIS<sup>A</sup> albedo. Figure 12 also demonstrates this effect with overestimation of albedo by MODIS<sup>A</sup> relative to MODIS<sup>T</sup> for Class 2 pixels (MODIS<sup>A</sup> pixels in the shade) and conversely for Class 3 pixels (MODIS<sup>T</sup> pixels in the shade).

590 MODIS<sup>A</sup> involves a delay in image capture from 10:30 am to 1:30 pm. Towards the winter solstice, this decreases the proportion of shaded pixels in the steep terrain of the Southern Alps. The change in the solar zenith angle caused by the delayed timing of the image capture means pixels on south- and southwest-facing slopes have a higher chance of receiving incident radiation. This effect was seen across the GoEA, where a much lower proportion of the total pixels in the GoEA were shaded in MODIS<sup>A</sup> images captured near the winter solstice, compared to MODIS<sup>T</sup> (34.5% and 49.8%, respectively). However, in

summer and toward April, steep rock outcrops cast large shadows in the afternoon that challenge albedo retrieval with MODIS<sup>A</sup>. By May, low sun zenith angles cast longer shadows that are not accurately modelled due to the resolution and accuracy of the DEM. Unpredicted shadows ~~yields~~yield severe underestimations of surface albedo, in particular affecting confined glaciers of ~~class~~cluster 3. Although MODIS<sup>A</sup> images could help capture a better albedo ~~signals~~signal in such cases, Figure 5 (left) 5a demonstrates that, over the period of this study, imagery from MODIS<sup>T</sup> remained suitable to capture  $\bar{\alpha}_{\text{yr}}^{\min}$  before this issue becomes problematic by May. Nevertheless, despite the computational burden, the systematic processing of MODIS<sup>A</sup> imagery may gain merit as the timing of  $\bar{\alpha}_{\text{yr}}^{\min}$  -appears to be more often delayed ~~into~~to late summer or early autumn ~~more often~~ (Fig. 5).

#### 5.2.2 MODIS cloud cover

Finally, Lyapustin et al. (2014) documented calibration issues with MODIS Collection 5 data, and concluded that major calibration trends were removed in C6. The stability of the C6 calibration was confirmed by Sayer et al. (2015). In the context of retrieving time series of snow and ice albedo with MODIS, Casey et al. (2017) stressed how C5 data could compromise the detection and interpretation of trends, and concluded that C6 is preferable. In the case of MODIS Terra, albedo time series derived from C6 data by MODImLab shown in Fig. 8 and 10 reveal no visible trend in winter albedo. It seems unlikely, if a trend in winter snow albedo existed, that it would be matched and concealed by a calibration issue of exactly the opposite magnitude. Our results therefore support the alternative hypothesis that there is no detectable trend in winter albedo nor calibration issue over the length of the record produced by this study. This is further supported by the cross-platform agreement shown in Fig. 12.

#### 4.8.2 MODIS cloud cover

While MODIS<sup>A</sup> potentially ~~provide~~provides a means to capture more shadow-free pixels across the GoEA, its use is inhibited by daily development of cloud cover over the Southern Alps. Figure 14 shows MODIS<sup>A</sup> images display a consistently higher proportion of cloudy pixels over the GoEA than MODIS<sup>T</sup> images over the course of a year. While this trend is consistent throughout the year, it is pronounced through the summer ablation period, at the critical time when the  $\bar{\alpha}_{\text{yr}}^{\min}$  is likely to be observed. A likely driver of this pattern is ~~the increased surface~~daytime heating of the atmosphere through the warmer summer months, ~~driving free~~resulting in convection and aiding cloud development over the course of the day. Ultimately, while MODIS<sup>A</sup> shows some promise in its ability to supplement the MODIS<sup>T</sup> dataset as discussed above, the high variability of albedo from mixed-pixels, and the daily increase in cloud cover means that its application is limited in New Zealand.

Interestingly, the cloud cover results from both MODIS<sup>A</sup> and MODIS<sup>T</sup> images are still of use, as the spatial characterisation of cloud cover over the Southern Alps is very limited- (Wardle, 1986). Current research is largely limited to point based cloud data from automatic weather stations (e.g. Conway et al. 2015). Cloud cover patterns and dynamics are important for glaciers, as clouds play a key role in influencing incident solar radiation at the glacier surface (Conway and Cullen, 2016). Figure 15 displays the non-uniform distribution of monthly average cloud cover across the processed area. The Over the period of study, the frequency of ~~cloud~~clouds in pixels west of the Main Divide is as high as 90% during summer months, and reaches a minimum of 35% in some areas during winter, reflecting Fig. 14. During summer, cloud spill-over is limited to within a few ~~kilometers~~kilometres east of the Main Divide, contrasting to relatively uniform conditions through winter. It is also possible to identify the presence of 'cloud hot-spots' that persist through the 19 year record. The spatial complexity of cloud cover is likely having a significant influence on the SEB, which would suggest the physical processes controlling glacier behaviour will be different from one individual glacier to another, which is apparent by the contrasting albedo records for glaciers of the GoEA. 'cloud hot-spots' that persist through the 19-year record.

## 5 Discussion

### 5.1 Comparison to the EOSS survey

The EOSS survey provides a well-documented and invaluable record of the changes to glaciers in the Southern Alps over the past 40 years. The data collected by the survey bridges the gap in glaciological mass balance records between the termination of the Ivory Glacier programme in 1975 and commencement of the Brewster Glacier programme in 2004. In addition, the correlation between the snowline record and recently developed monitoring methods has allowed past mass balance trends to be reconstructed (e.g. Sirguey et al., 2016). At a larger scale, the use of EOSS<sub>Alps</sub> has allowed the annual variability of glacier mass balance in the Southern Alps to be broadly characterised (Chinn et al., 2012; Willsman et al., 2018).

Published relationships developed between the MODIS-derived  $\bar{\alpha}_{\text{yr}}^{\min}$  and the EOSS SLA<sub>i</sub> departures on Brewster Glacier and Park Pass Glacier were found to be strong (Sirguey et al., 2016; Rabatel et al., 2017). Despite the large differences between the albedo and snowline methodologies, both aim to remotely capture the point of maximum ablation at the glacier surface and use it as a proxy for mass balance. SLA<sub>i</sub> – used as an estimate of the ELA – provides an effective measure of glacier mass balance (Rabatel et al., 2005), and should therefore be closely related to  $\bar{\alpha}_{\text{yr}}^{\min}$  (Dumont et al., 2012).

However, measuring SLA<sub>i</sub> remains difficult, in particular due to uncertainties associated with the method used to identify snowlines from oblique photos. Complex topography, avalanching, fresh snow, and cloud cover all present additional challenges for deriving consistent results of SLA<sub>i</sub>. To compound these challenges, limited resources mean that the EOSS survey is required to assume that SLA<sub>i</sub> occurs annually in early-March, which involves careful timing of the observation flights (Willsman et al., 2018). In most cases, SLA<sub>i</sub> is estimated manually based on the overall appearance of the glacier and snow patches compared to previous years. When SLA<sub>i</sub> is digitized, photographs are compared to historical topographic maps or from orthorectified images. Furthermore, the methodology often involves an interpretation and assessment of the appearance of an individual glacier in relation to other glaciers in the programme, observed during the same or from different surveys.

Despite the coarse resolution of the MODIS sensor, it has been demonstrated in this study that the albedo method is capable of retrieving robust time series of  $\bar{\alpha}_{\text{yr}}^{\min}$  that show strong to moderate relationships to EOSS signals (glaciers of clusters 1 and 3, respectively). There are some clear advantages in using the albedo method over an EOSS approach, which include the approach being repeatable and not being temporally constrained. While the EOSS programme yields an archive of invaluable images, a number of photos are impacted by transient snow that impact the quality of the SLA<sub>i</sub> estimates. The timing of the surveys also mean that some SLA<sub>i</sub> estimates might not fully capture late summer melt (Sirguey et al., 2016). Monitoring albedo until the onset of the accumulation season (winter) allows sustained late season ablation to be recorded. The large variability in timing of  $\bar{\alpha}_{\text{yr}}^{\min}$ , as well as the apparent trend towards a delayed occurrence for most glaciers in the GoEA (Fig. 5 and 6), demonstrates the benefit of systematically monitoring glacier surface albedo. Thus, the albedo method provides new insights about glaciers in the Southern Alps that are not captured by the EOSS programme.

The EOSS programme reports considerably high intra-correlations across the 50 index glaciers that sample the Southern Alps, with pair-wise R<sup>2</sup> ranging 0.22 to 0.96 and averaging 0.69. Overall, our systematic application of the albedo method on the limited geographical extent of the GoEA reveals a degree of variability in glacier response that challenges the highly consistent behaviour suggested by the EOSS programme across the Southern Alps. Strong and significant intra-correlations in  $\bar{\alpha}_{\text{yr}}^{\min}$  across glaciers of the GoEA exist but do not dominate, with pair-wise R<sup>2</sup> ranging from 0.12 to 0.88 and averaging only 0.52. Similarly, the correlation between the average GoEA albedo signal to EOSS<sub>Alps</sub> is only R<sup>2</sup> = 0.55 (see Fig. 7), while the average correlation between SLA<sub>i</sub> and EOSS<sub>Alps</sub> is reported at 0.81. These contrasting results suggest the EOSS approach may have led to spatial and temporal auto-correlation of the SLA records, which in turn build very strong correlations across SLA records of EOSS

index glaciers and to EOSS<sub>Alps</sub>. The outcome of this is that it may have damped or concealed the variability of mass balance response of glaciers in the Southern Alps.

## 5.2 Implications of variability of albedo on mass balance

Given the scarcity of surface mass balance measurements in the Southern Alps, and the spatial and temporal limitations of obtaining imagery from observational flights, satellite remote sensing provides a powerful tool to increase the number of glaciers being currently monitored in New Zealand. To relate the observed variability of albedo to changes in annual mass balance, the relationship between the magnitude and timing of  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  in each of the three glacier clusters identified on the GoEA (Table 2) needs to be further examined. There is evidence that the occurrence of  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  has been delayed in time (later in the year) on all glaciers other than those located on steep, south-facing slopes (Cluster 2) (Fig. 5d). Intuitively, a delay in the timing of  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  on 10 of the 12 glaciers (Clusters 1 and 3) might be expected to result in a more negative summer mass balance by virtue of the ablation season being extended. However, there is no visible trend in the magnitude of  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  in any of the clusters during the observation period (2000-2018). Also, there is only a weak relationship between a delay in timing and the magnitude of  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  (Fig. 5c), suggesting that glacier-wide albedo is not necessarily lower if it is delayed. We interpret this dichotomy as evidence that the atmospheric controls on mass balance are complex, and that the magnitude of ablation is in part sensitive to discrete weather events (Cullen et al., 2019), which either bring snowfall (increase albedo) or enhance ablation (decrease albedo) in summer. There is also compelling evidence that clouds play an important role in modulating the energy available for ablation over glaciers in the Southern Alps (Conway and Cullen, 2016), and are likely to influence both the timing and magnitude of  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  in the GoEA, thus confounding the relationship. In particular, clouds are very common to the west of the Main Divide in the GoEA region during summer (Fig. 15), and their spatial and temporal variability elsewhere may be an underlying factor in controlling the observed variability in  $\bar{\alpha}_{\text{yr}}^{\text{min}}$ . We believe there is a risk that some of this complexity is being missed using the single snapshot approach of the traditional EOSS programme. Arguably, the albedo method provides more certainty of the atmospheric controls on mass balance, as it provides a platform of continuous observations of albedo and cloud cover over a large number of glaciers throughout the ablation season.

Despite the observed complexity between the timing and magnitude of  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  over the observation period, there is evidence of a shift towards more negative annual departures of the mean  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  since 2008 (Fig. 7), which is consistent with the EOSS record, implying cumulative losses in mass balance for the glaciers of the GoEA. This mass loss is consistent with glaciological observations of mass balance from Brewster Glacier (Cullen et al., 2017) and the modelling of glacier response to changes in climate in the Southern Alps (Mackintosh et al., 2017; Salinger et al., 2019a, b). This shift towards mass loss appears to be widespread, with the 2018 summer heatwave reportedly the most damaging for glaciers in the Southern Alps over the last half century (Salinger et al., 2019a). We anticipate that the GoEA are particularly vulnerable to a warming climate, as the average elevation of the icefields is close to the regional snowline, which is estimated to be 1950 m a.s.l. (Chinn, 2001). Cullen and Conway (2015) showed that the majority of precipitation at the altitude of Brewster Glacier falls at an air temperature that is very close to the threshold between snow and rain. Thus, small increases in air temperature controlled by warming is likely to impact the amount of precipitation falling as snow on the GoEA, which in turn will impact surface albedo and mass balance, potentially driving a rapid decline under a sustained warming trend. While the observations we have obtained using the albedo method suggest that most glaciers are vulnerable, the contrasting response of glaciers contained on steep, south-facing slopes (Cluster 2) indicates they are likely to survive this demise longer.

Lastly, the positioning of the GoEA across the Main Divide of the Southern Alps is particularly important from a management perspective. Because the icefields straddle the Main Divide, they contribute meltwater to the catchments of the Rangitata River

on the east coast, and the Wanganui and Whataroa rivers to the west. Given the important role of snow and ice in New Zealand's water resources, changes in the volume of these icefields have the potential to impact the hydrology of these rivers in the future.

### 5.3 Limitations and developments of the albedo method

715 The results presented in this study rely on the inherent accuracy of MODImLab. The specific error associated with the MODImLab retrieval over the GoEA is uncertain due to the lack of *in situ* data. However, Dumont et al. (2012) quantified the relative error between field measurements and the MODImLab 250 m broadband albedo to be approximately  $\pm 10\%$  (RMSE = 0.052), confirmed by Sirguey et al. (2016). This value is an average estimate, with error recognised to be up to twice as high around the mixed-pixel margins of glaciers compared to the clear snow/ice pixels near the centre (Dumont et al., 2012). As a 720 result, it is expected the uncertainty will be variable between glaciers, where estimates of  $\bar{\alpha}(t)$  on large glaciers (i.e. Lambert Glacier) may be more reliable than those of small glaciers with high edge effects (i.e. East Lambert Icefall) (Brun et al., 2015).

725 Supporting Rabatel et al. (2017) and Davaze et al. (2018), we find that the ~~artefact~~error in the albedo retrieval caused by surface shading does not affect the identification of the summer  $\bar{\alpha}_{\text{yr}}^{\text{min}}$ . On glaciers where shading is most prominent (steep sloping, south-facing, topographically incised), we show the  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  is typically reached much earlier than early-April (when the shading-induced decrease in  $\bar{\alpha}(t)$  begins). Importantly, this This means that while New Zealand has a large number of glaciers that exhibit similar hypsometry to those glaciers in Cluster 2, in most cases, the albedo retrieval will still yield reliable values of  $\bar{\alpha}_{\text{yr}}^{\text{min}}$ .

730 The masking technique proposed in this study should simplify the process of objectively converting glacier outlines to glacier masks. As we show in Sect. 3.2 and 4.1, the new approach to masking glacier boundaries over the GoEA yields values of  $\bar{\alpha}(t)$  over the ~~important~~ ablation period within 3% of the more subjective method employed by previous studies. The success of this technique may support the rapid application of the albedo method to new glaciers using existing outlines, regardless of whether they are made up of mixed-pixels and/or debris-cover. In addition, the snow-covered-area filter may help to reduce some of the problems of using a static glacier mask (e.g. the glacier extent changing ~~significantly~~substantially over the observation period).

735 Finally, the use of MODIS imagery to apply the albedo method remains applicable only for glaciers that are large enough to allow albedo to be retrieved and averaged over a number of pixels. Davaze et al. (2018) show that  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  can be successfully retrieved on glaciers covering as little as  $0.5 \text{ km}^2$  with good correlation to annual mass balance. This is consistent with the agreement we obtained between  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  and EOSS on Vertebrae Col 25 ( $0.7 \text{ km}^2$  or 11 pixels), although it is believed to stretch the reliance on MODIS for the albedo method. The temporal resolution achievable by combining multi-spectral imaging from higher resolution sensors such as Sentinel-2 and Landsat 8 OLI justifies the development of snow and ice albedo products to resolve  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  on smaller glaciers. Such development is desirable to advance the albedo method and support the widespread monitoring of New Zealand glaciers.

## 6 Conclusion

745 The results from this study represent the next ~~meaningful~~ step towards the use of the albedo method for widespread monitoring of glaciers in the Southern Alps. Following the successful application to Brewster Glacier and Park Pass Glacier, we have produced ~~an~~a 19-year long coherent seasonal signal of glacier-wide albedo on the previously unstudied Gardens of Eden and Allah (GoEA). These results have supported and advanced key aspects of the methodology that will ~~be important for~~inform future applications in the Southern Alps and beyond. The key findings can be summarised as:

750 1. A new objective glacier masking approach has been developed that compares favourably to a more traditional manual method of identifying suitable pixels to calculate glacier-wide albedo.

755 2. The annual minimum glacier-wide albedo ( $\bar{\alpha}_{\text{yr}}^{\text{min}}$ ) for individual glaciers ranges between 0.42 and 0.70, and can occur as early as mid-January and as late as the end of April. The timing of  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  appears to have shifted to later in the year over the 19-year period on ~~glaciers that are not steep or south facing~~ all glaciers other than those located on steep, south-facing slopes. However, there is only a weak relationship between the delay in timing and the magnitude of  $\bar{\alpha}_{\text{yr}}^{\text{min}}$ , which suggests that glacier-wide albedo is not necessarily lower if it is delayed.

760 3. The glacier-wide surface albedo anomaly for the 19-year period explains 55% of the variability in the average annual departure of the 50 index glaciers from the EOSS programme (EOSS<sub>Alps</sub>). The largest negative departures in  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  (lower than average albedo) are consistent with high snowlines, with the 2018 departure the most negative on record. This is consistent with Brewster Glacier and was caused by a marine and terrestrial heatwave over New Zealand (Salinger et al., 2019a).

765 4. The MODIS record of  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  for Vertebrae Col 25 explains less than half of the variability observed in the EOSS SLA record ( $R^2 = 0.43$ ,  $p = 0.003$ ). However, the relationship is stronger when compared to other GoEA glaciers, with Angel Glacier having the strongest relationship with EOSS observations at Vertebrae Col 25, accounting for 69% of its variance ( $p = 1.8 \times 10^{-5} < 0.001$ ). Lambert, East Lambert, and Eve glaciers each capture half or more of the variance (52%, 50%, and 55%, respectively). The relationship between EOSS observations at Vertebrae Col 25 and  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  of each glacier is related in order of importance to topographic shading, slope and aspect.

770 5. The EOSS programme has reported on how strongly each of the 50 index glaciers behaviour is related to the mean of all remaining glaciers (known as EOSS<sub>Alps</sub>), and pair-wise regression shows there is high intra-correlation between glaciers. However, the albedo method enables the variability in response of individual glaciers to be explored in more detail, revealing that topographic setting plays ~~an important~~ a second order ~~role~~ control in addition to the regional climate signal (first order control). The albedo method captures enough individual glacier variability on the GoEA to firmly question the validity of the hypothesis that glaciers in the Southern Alps behave as a single climatic unit.

775 6. For the first time, MODIS imagery acquired by the Aqua platform (MODIS<sup>A</sup>) has been used successfully to increase the temporal resolution of albedo monitoring using the MODImLab algorithm. There is some evidence to suggest it is capable of capturing diurnal variability in albedo as controlled by changes to snow and ice properties during daytime. Despite cloud being more frequent during the afternoon, especially in summer, there are advantages in using MODIS<sup>A</sup> due to higher incident radiation (less shading) on some slopes at certain times of the year.

780 7. Cloud cover results from MODIS imagery acquired by the Terra (MODIS<sup>T</sup>) and Aqua (MODIS<sup>A</sup>) platforms show the spatial and temporal variability of clouds. The frequency of cloud in pixels west of the Main Divide is as high as 90% during summer months, and reaches a minimum of 35% in some locations in winter. There is a strong gradient in cloud cover frequency between regions west and east of the Main Divide, and specific areas appear to be consistently ~~more cloudy~~ cloudier than others. These complex cloud interactions deserve further attention as they are likely to play ~~an important~~ a considerable role in glacier surface energy and mass balance.

785 The key findings presented in this research have provided a platform to further develop and extend the application of the albedo method to monitor glacier behaviour in the Southern Alps. The next logical step will be to attempt ~~to resolve spatial and temporal patterns in glacier behaviour in~~ an assessment of all of the main glaciated areas of the Southern Alps together at a high temporal resolution, which will complement observations made by the EOSS programme, and expand our understanding of the linkages between glaciers and the climate system. There is some urgency to do this as our observations of the GoEA,

790 and those obtained from traditional glaciological observations elsewhere, suggest that glaciers in the Southern Alps are undergoing an unprecedented decline at present.

*Data and code availability.* MODIS data used in this research are freely available from the Level 1 and Atmosphere Archive and Distribution System (LAADS) Web. NZSoSDEM is freely available from the koordinates.com geographical data repository. The MODImLab software is available upon request from PS.

795 *Author contributions.* PS and NC initiated and coordinated the study. NC and PS obtained funding for the research. AD and PS processed and analysed the MODIS data. AD ~~led~~wrote the ~~writing~~first draft of the manuscript ~~with inputs,~~while PS and support from co-authors. NC were responsible for the submission and revision of the final research.

800 *Competing interests.* The authors declare that they have no conflict of interest.

*Acknowledgements.* This research received funding support from the Brian Mason Scientific and Technical Trust and University of Otago Research Grants (ORG0112-0313; ORG0118-0319). The field component of this research was supported by the Department of Conservation under the concession 52174-RES. A. Dowson was funded by a postgraduate scholarship 805 from the University of Otago, while N. Cullen received support from the Alexander von Humboldt Foundation, Germany to help support the completion of this research. The MODIS Level-1B data were processed by the MODIS Adaptive Processing System (MODAPS) and the Goddard Distributed Active Archive Center (DAAC), and are archived and distributed by the Goddard DAAC. We thank E. Berthier for enabling the acquisition of Airbus DS Pléiades imagery within the Pléiades Glaciers Observatory (PGO) initiative of the ISIS-CNES programme. The authors also thank both referees for their reviews and 810 constructive comments.

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Tables

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**Table 1: Comparison of  $\bar{\alpha}(t)$  between Mask 1 and Mask 2 from Terra MODIS images between 25 February 2000 and 30 April 2018. Statistics are calculated as average values from the 12 outlet glaciers.**

	R <sup>2</sup>	RMSD	MD
Annual	0.902	0.037	-0.012
Winter (April – September)	0.899	0.040	-0.010
Summer (October – March)	0.910	0.030	-0.013

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**Table 2: Physical characteristics of the 12 outlet glaciers in the GoEA identified for MODIS-albedo retrieval, calculated from the 15-m resolution NZSoSDEM. Cluster membership is defined by K-mean cluster analysis of aspect, slope and topographic shading. An estimate of the number of 250 m raster pixels in each individual glacier mask can be found by dividing the total area by 0.0625 km<sup>2</sup>.**

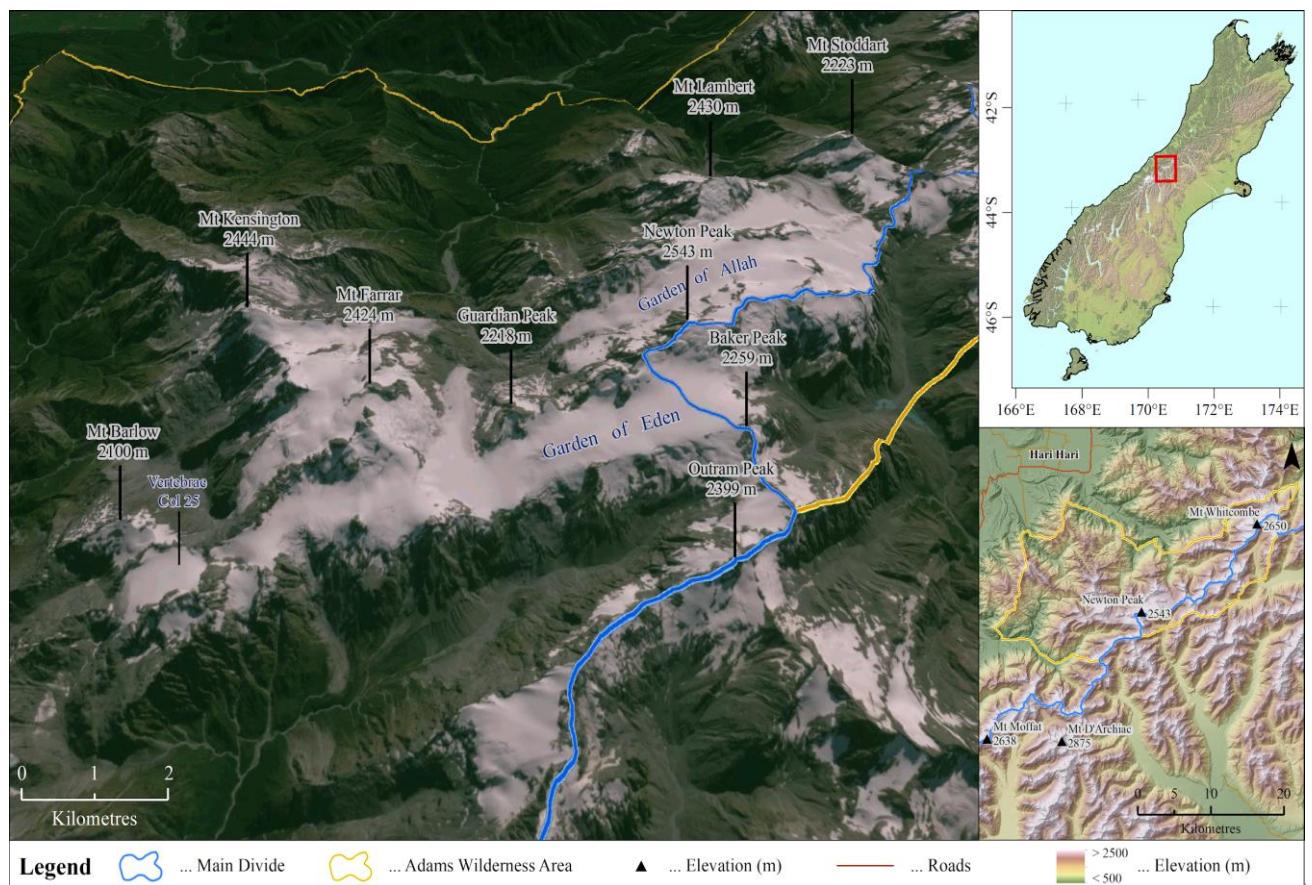
Glacier Name	Area (km <sup>2</sup> )	Aspect	Elevation (m)	Slope (°)	Topographic Shading (%)	Cluster
Abel	2.57	S	1918.7	20.7	81.5	2
Arethusa	2.57	E	1950.3	21.9	15.6	1
Barlow	1.09	W	2027.1	18.7	51.4	3
Beelzebub	4.44	W	2045.5	17.5	43.8	3
Colin Campbell	3.95	S	2008.7	24.8	82.0	2
Eve	2.73	SW	1918.1	15.9	68.4	3
Farrar	0.86	W	1986.2	20.0	64.5	3
Lambert	9.44	NE	1921.4	16.7	25.5	1
Perth	2.56	SW	1985.2	18.9	64.9	3
Unnamed East (East Lambert)	0.44	ENE	1971.0	14.5	15.4	1
Unnamed West (Angel Gl.)	2.54	ENE	1874.3	18.0	5.4	1
Vertebrae Col 25	0.70	SW	1882.7	11.7	50.0	3

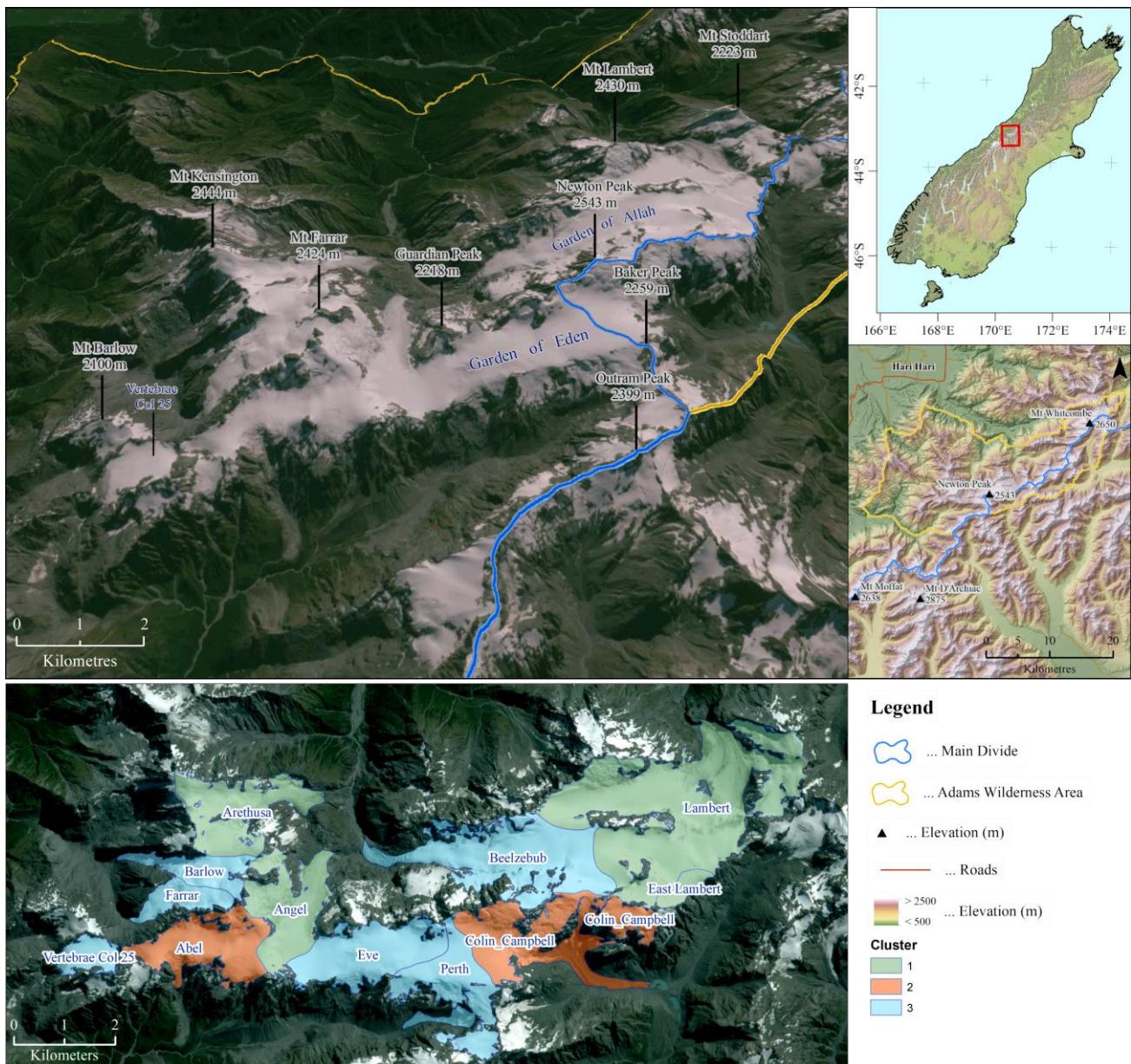
**Table 3: Correlation between the median timing and magnitude of the  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  and glacier hypsometry using the Spearman's rank coefficient (r) for the 12 outlet glaciers of the GoEA. 2-tailed correlation is significant at the 0.05 level (\*) and the 0.01 level (\*\*).**

	Elevation (m)	Slope (°)	Aspect cos(θ)	Aspect sin(θ)	Area (km <sup>2</sup> )	Topographic Shading (%)
$\bar{\alpha}_{\text{yr}}^{\text{min}} (\%)$	0.406	0.196	-0.489	-0.555	0.251	0.741**
$\bar{\alpha}_{\text{yr}}^{\text{min}} (t)$	0.049	-0.319	0.805**	0.225	-0.361	-0.782**

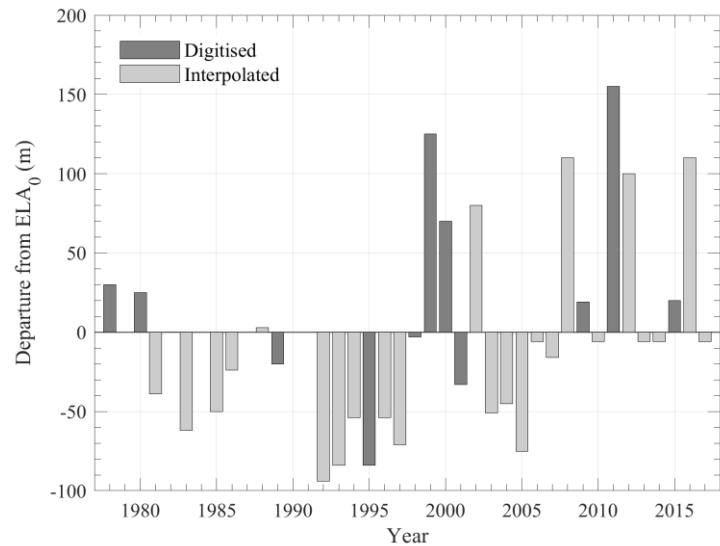
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## Figures



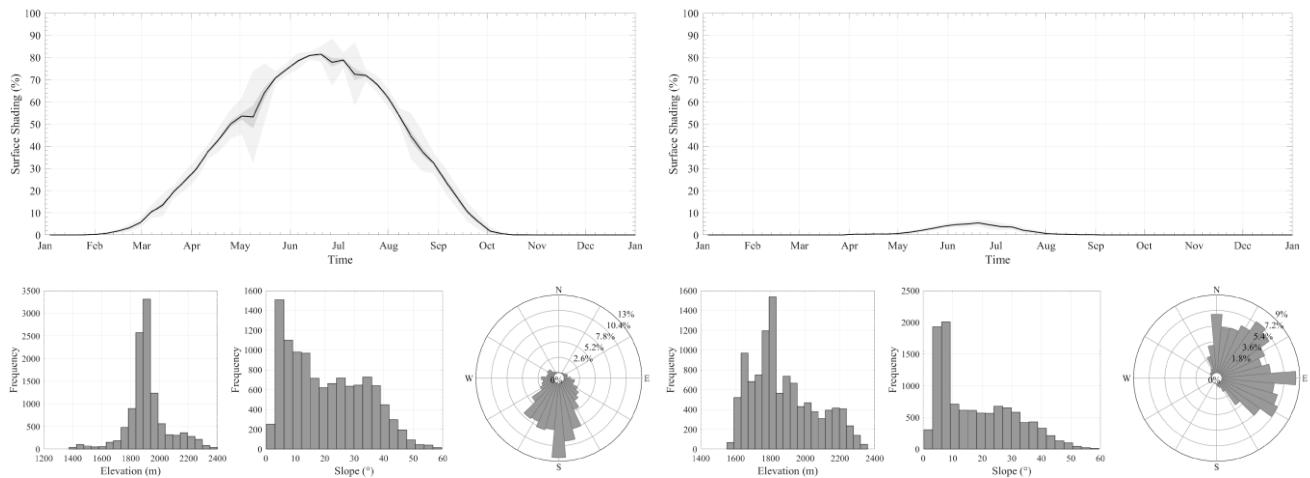


**Figure 1:** (top) Location of the Garden of Eden and Garden of Allah within the Adams Wilderness Area, straddling the Main Divide of New Zealand's Southern Alps. Sentinel-2A image from 9 March 2017 draped onto a 15 m-resolution NZSoSDEM (Columbus et al., 2011). (bottom) Outlines of glaciers considered in this study coloured by clusters.

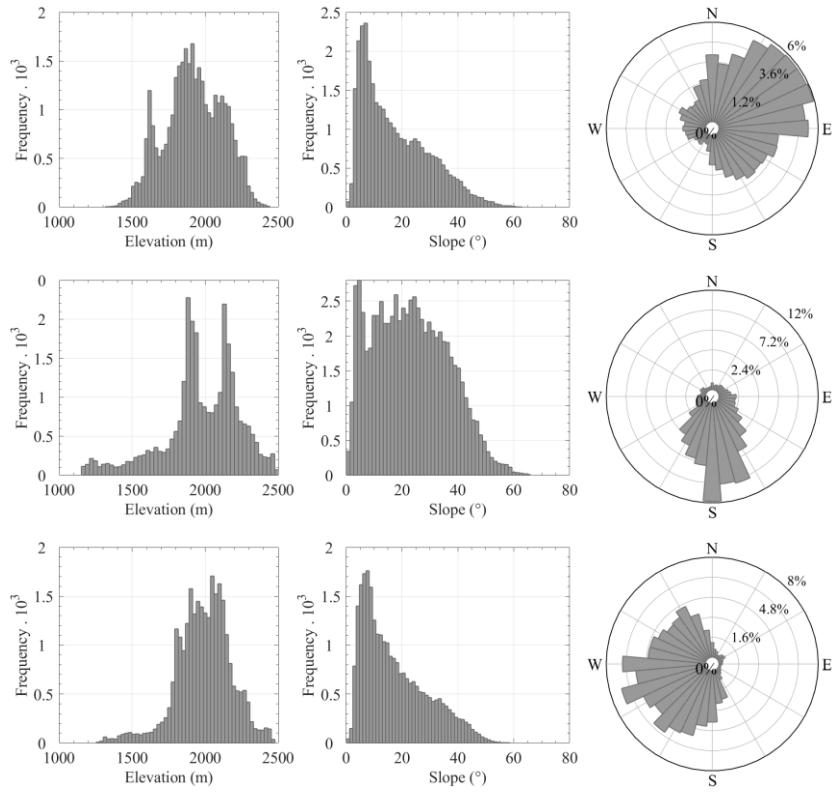


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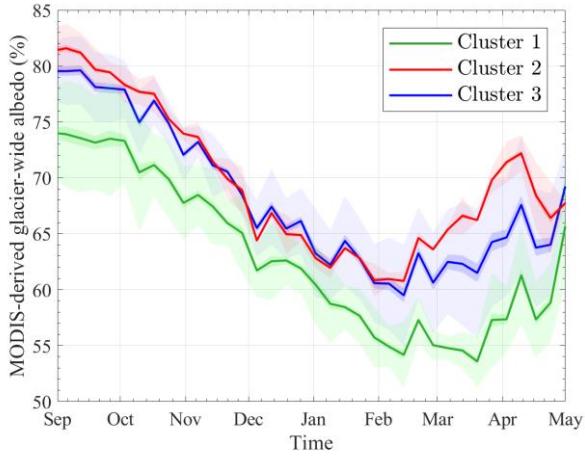
**Figure 2: Record of  $SLA_i$  departure for Vertebrae Col 25 from  $ELA_0$  (1840 m a.s.l.) between 1977 and 2017 (Willsman et al., 2018).**



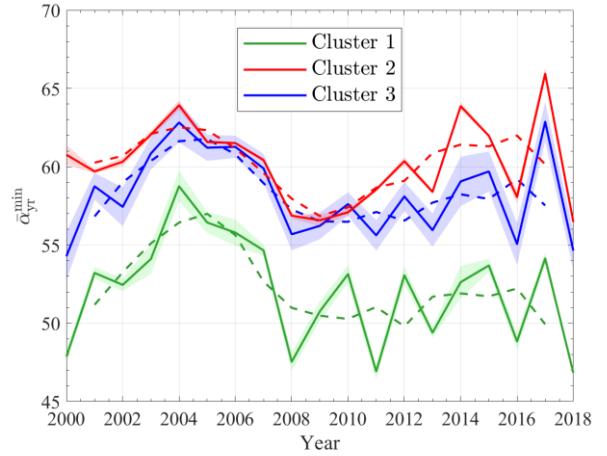
**Figure 3: Surface shading and hypsometry of (left) Abel Glacier and (right) Angel Glacier in the GoEA. Shading is displayed over one year, calculated as a weekly average between 2000 and 2018, used to indicate the nature of the surrounding topography. Topographic measures of (a) elevation, (b) slope and (c) aspect are calculated at 15 m-resolution from the NZSoSDEM.**



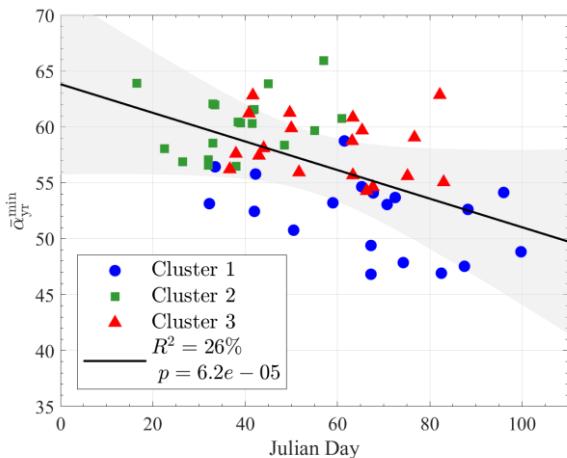
**Figure 4: Topographic measures of (a) elevation, (b) slope and (c) aspect are calculated at 15 m-resolution from the NZSoSDEM for each of the three [classes](#) [clusters](#) of glaciers in the GoEA (clockwise from top-left).**



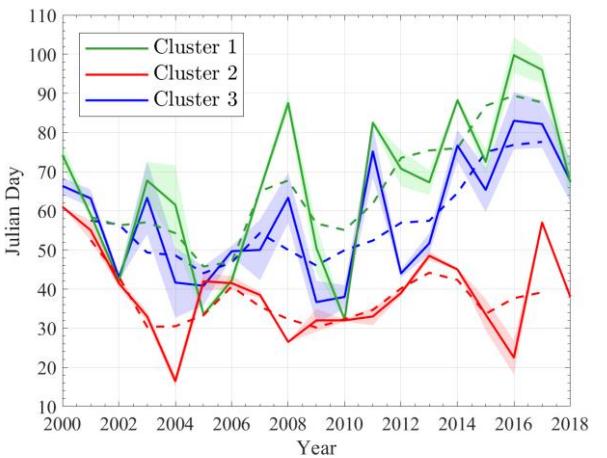
(a)



(b)



(c)



(d)

1005 **Figure 5:** (left a) MODIS-derived glacier-wide albedo  $\bar{\alpha}(t)$  between September and May of the outlet glacier averaged within-cluster. Values are calculated between February 2000 and April 2018 as a mean weekly average. The dark and light shaded envelopes show the standard error and standard deviation of the mean, respectively. (right b) Temporal changes by Julian Day of the  $\bar{\alpha}_{\text{yr}}^{\text{min}}$   $\bar{\alpha}_{\text{yr}}^{\text{max}}$  averaged within-cluster. (c) Correlation between  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  and its timing in Julian Day; the grey envelope shows the 95% confidence interval for the linear regression model. (d) Temporal changes of the timing of  $\bar{\alpha}_{\text{yr}}^{\text{min}}$  in Julian Day averaged within-cluster. Dotted lines show 3-year moving average.

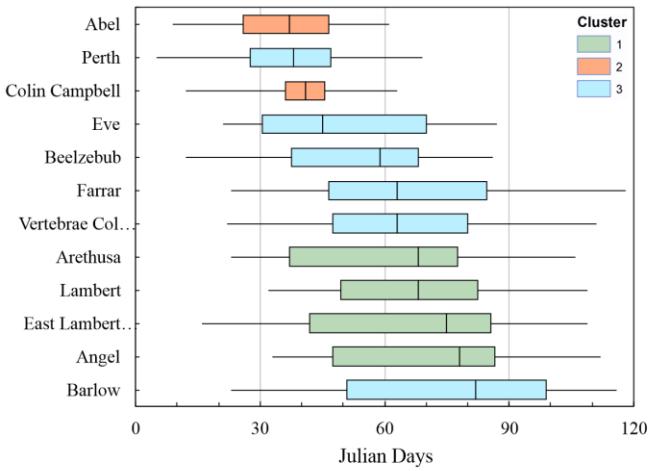
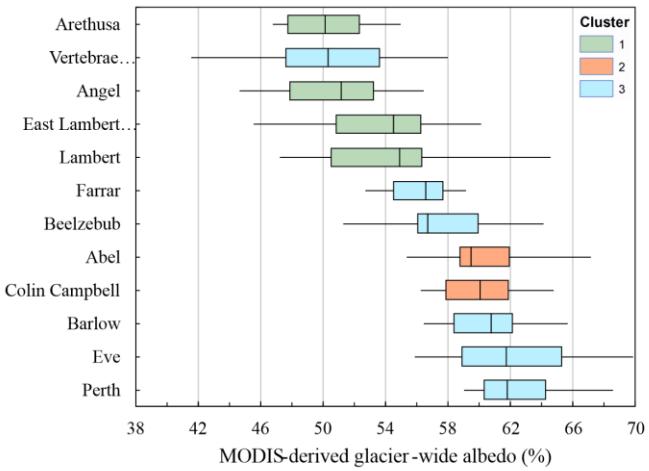
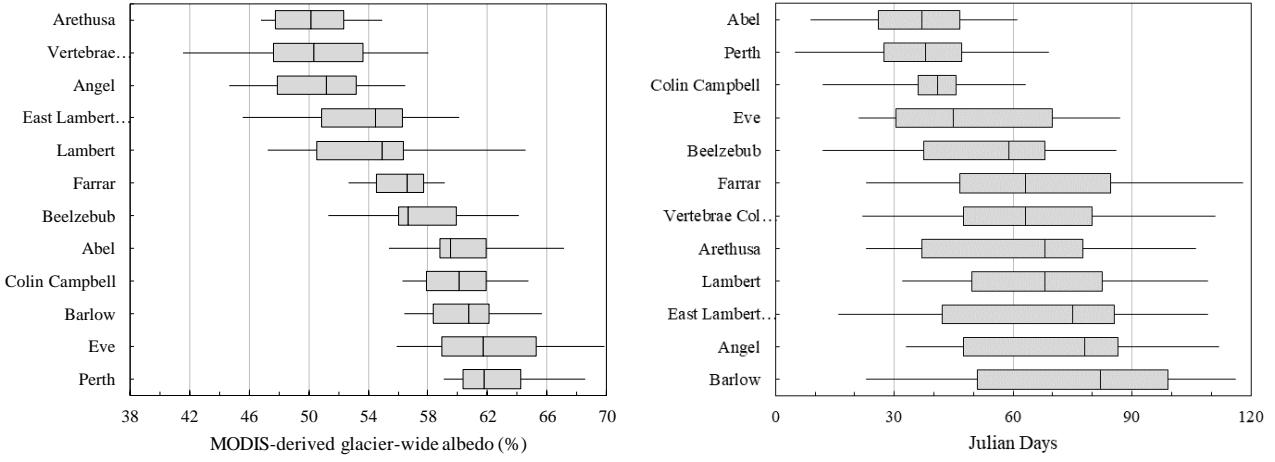
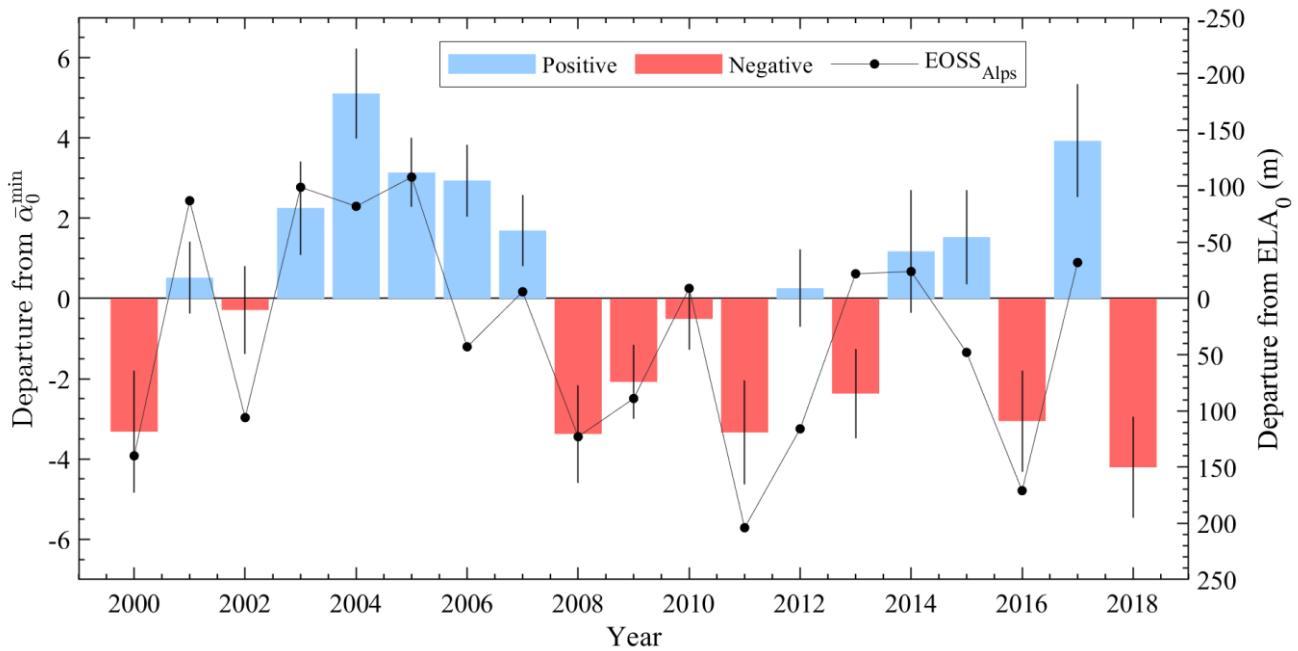
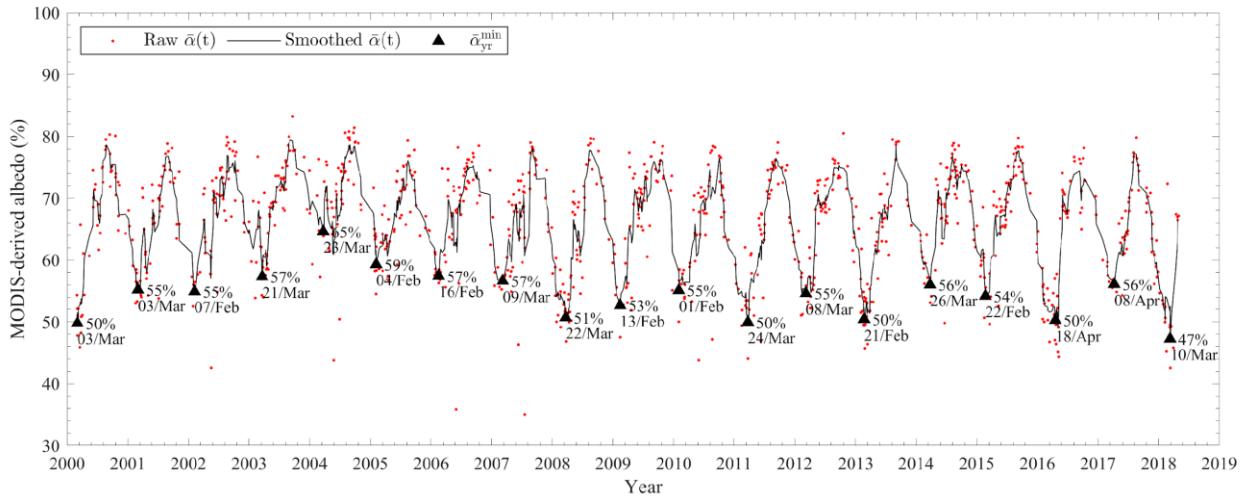


Figure 6: The (left) magnitude and (right) timing of the  $\bar{\alpha}_{\text{yr}}^{\min}$  over the 12 outlet glaciers of the GoEA between 2000 and 2018. The box plots represent the 19-year median, minimum, maximum and interquartile range of each of the glaciers.

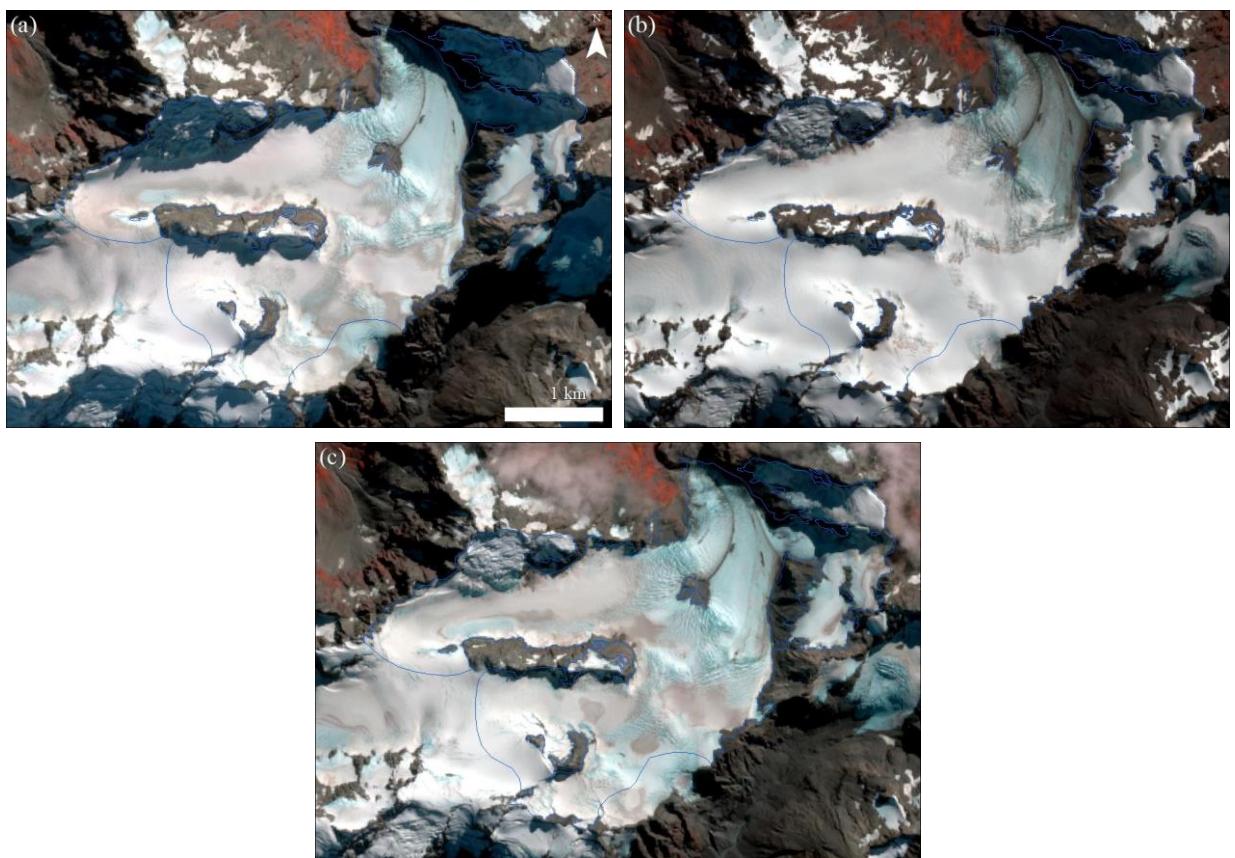


**Figure 7: Annual departure and standard error of the mean  $\bar{\alpha}_{\text{yr}}^{\min}$  across the 12 outlet glaciers from the long-term average  $\bar{\alpha}_0^{\min}$  ( $\bar{\alpha}_0^{\min}$ ; 56.5%) between 2000 and 2018. The average annual departure of the EOSS index glaciers from their respective  $\text{ELA}_0$  ( $\text{EOSS}_{\text{Alps}}$ ) is also included. Linear agreement between the records is  $R^2 = 0.55$ .**

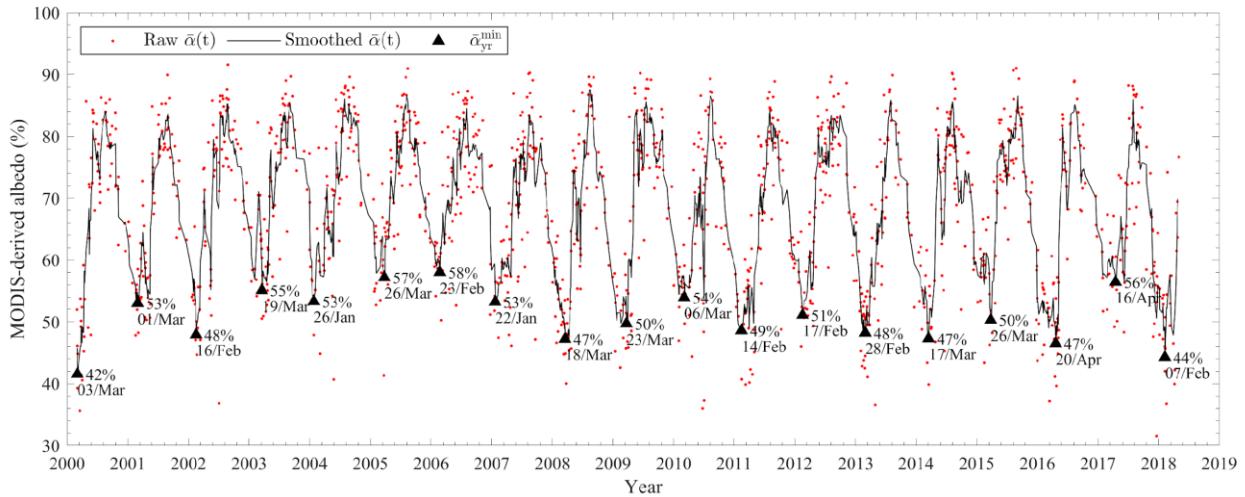


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**Figure 8: Near-daily MODIS-derived glacier-wide surface albedo  $\bar{\alpha}(t)$  on Lambert Glacier between February 2000 and April 2018, with the 3-period rolling average and annual minimum glacier-wide albedo  $\bar{\alpha}_{\text{yr}}^{\min}$  indicated in black.**

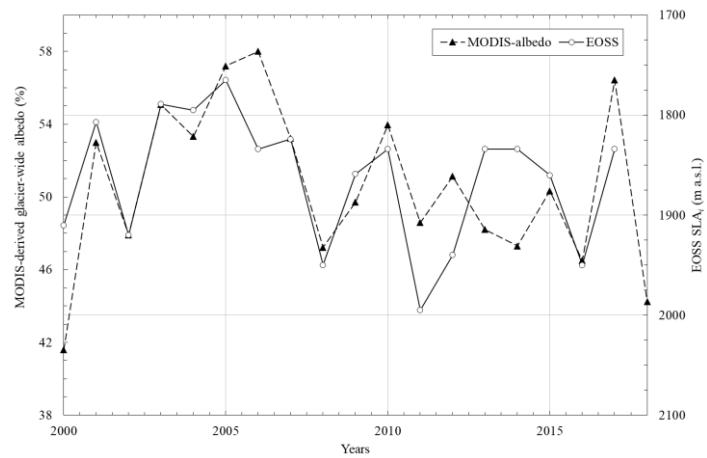


1040 **Figure 9: Maximum elevation of the seasonal snowline (approximating the point of maximum ablation) on Lambert Glacier (outlined in blue) observable in cloud-free Sentinel-2A and 2B images from (a) 30 April 2016, (b) 29 March 2017 and (c) 29 March 2018.**

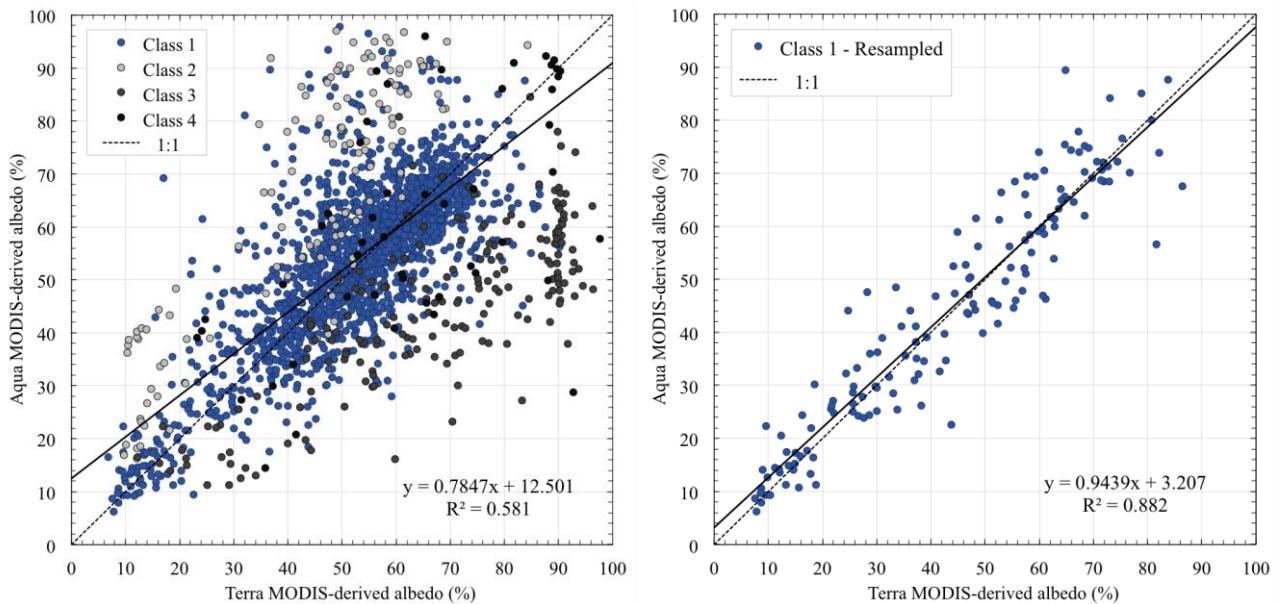


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**Figure 10: MODIS-derived glacier-wide surface albedo  $\bar{\alpha}(t)$  on Vertebrae Col 25 between February 2000 and April 2018, with the 3-period rolling average and annual minimum glacier-wide albedo  $\bar{\alpha}_{\text{yr}}^{\min}$  indicated in black.**



**Figure 11: Comparison of MODIS-derived  $\bar{\alpha}_{\text{yr}}^{\min}$  and EOSS SLA<sub>i</sub> on Vertebrae Col 25 between 2000 and 2018 ( $R^2 = 0.43$ ).**



**Figure 12:** Pixel-by-pixel comparison of MODIS-derived glacier surface albedo across the GoEA, from four pairs of cloud-free Terra and Aqua MODIS images (4 March 2009, 10 March 2010, 9 March 2012, 11 March 2013). Linear regression analysis was performed on (left) all Class 1 pixels ( $R^2 = 0.58$ ,  $p < 0.01$ ) and (right) a stratified random sample of 150 Class 1 pixels ( $R^2 = 0.88$ ,  $p < 0.01$ ). The dotted line represents the ideal 1:1 relationship.

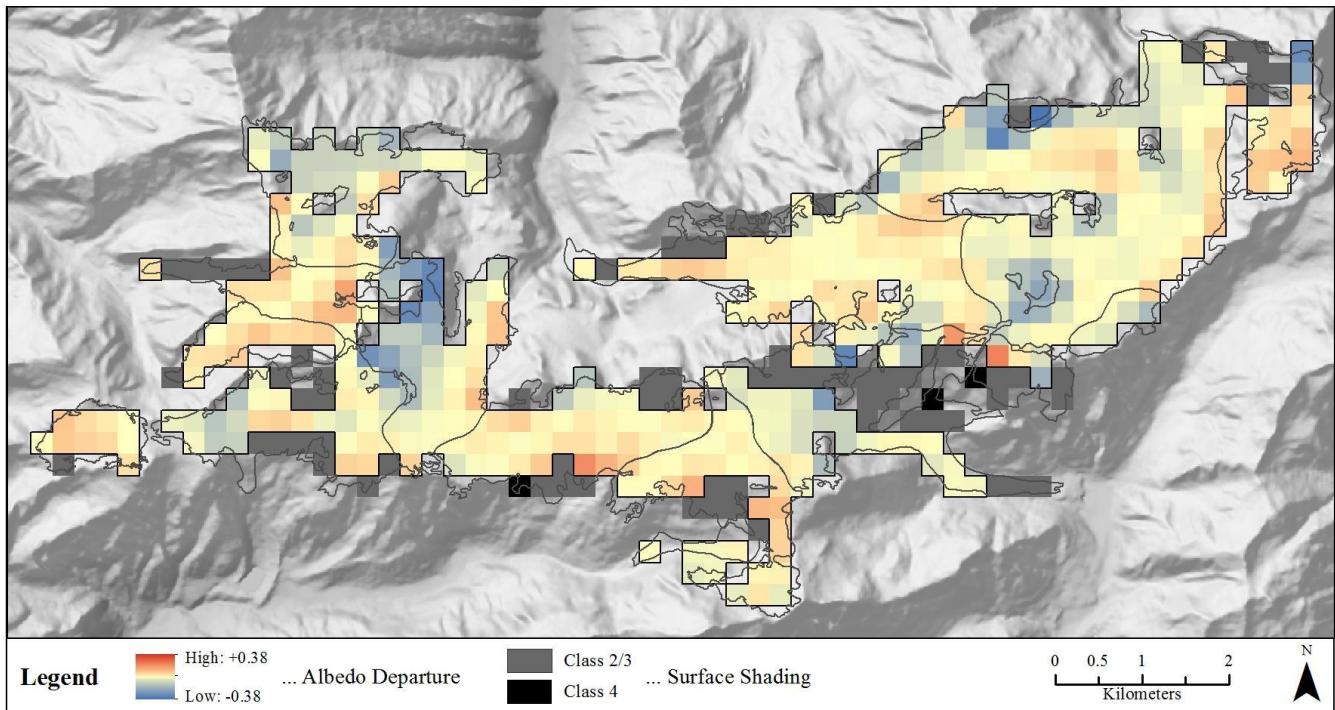
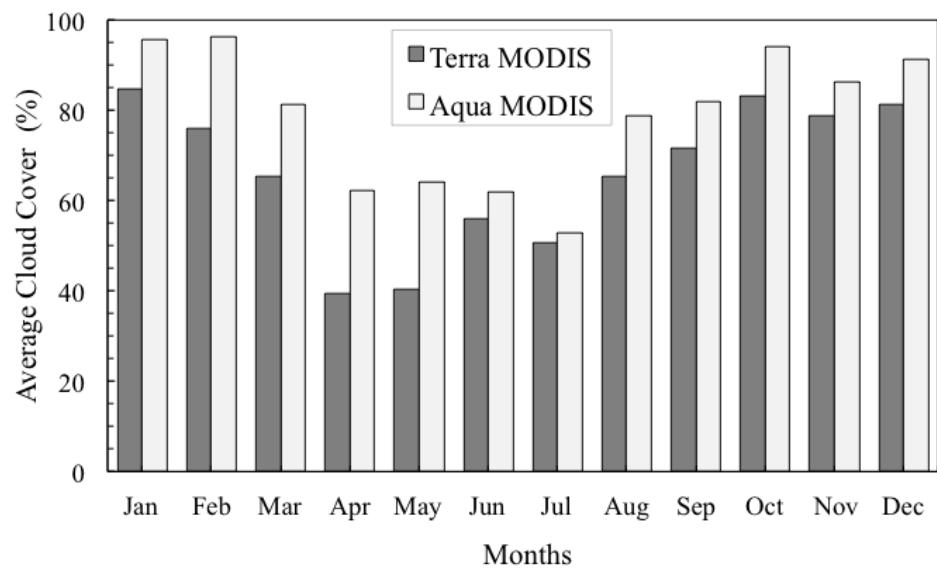


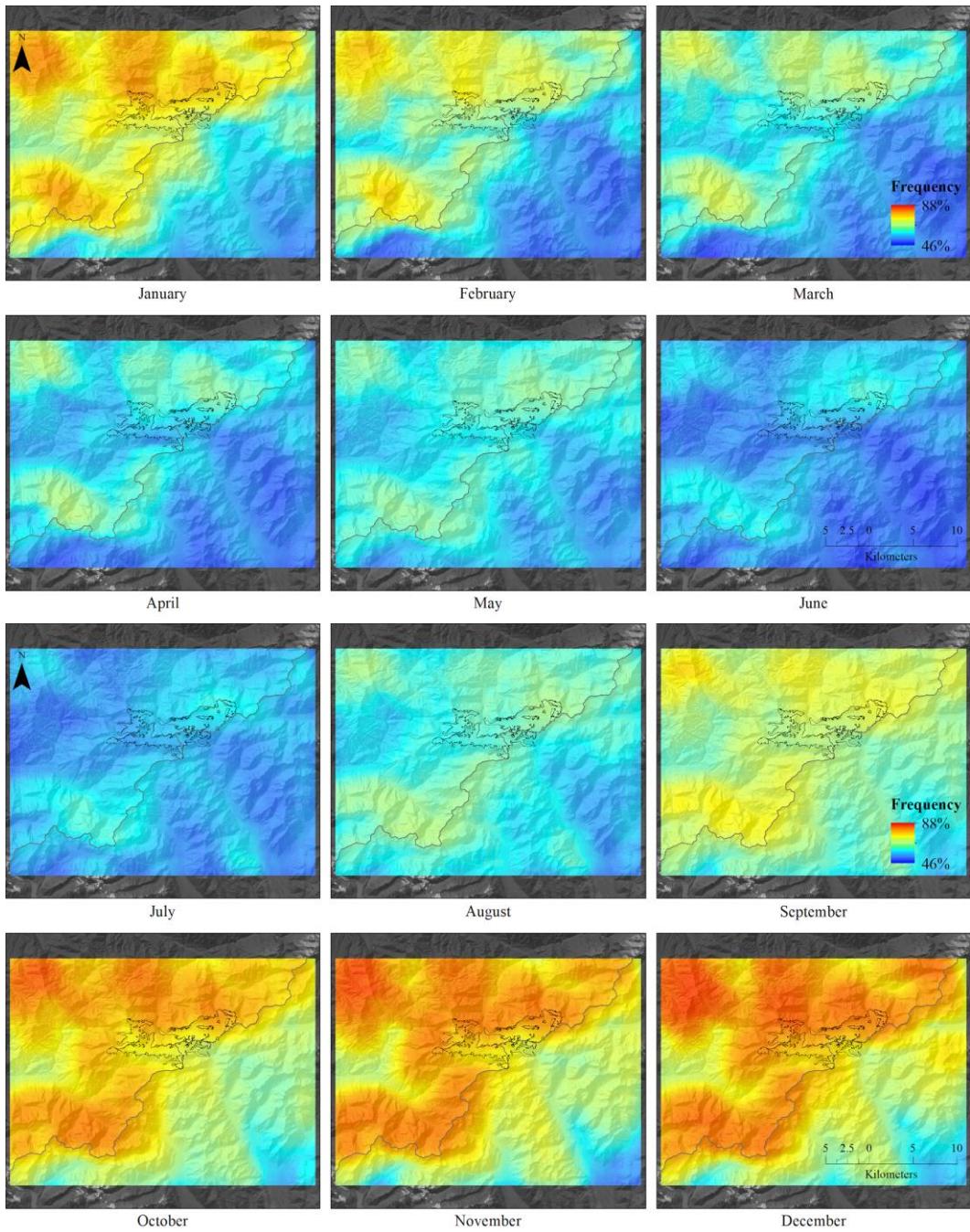
Figure 13: Average departure of MODIS-derived glacier surface albedo for Class 1 pixels between Terra and Aqua images from the 4 March 2009, 10 March 2010, 9 March 2012 and 11 March 2013. A positive departure (red pixels) indicates a higher value of albedo in the Terra image. Pixels with shadows have been displayed in grey/black.

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**Figure 14: Proportion of pixels over the GoEA obscured by cloud in Terra (10:30 am) and Aqua (1:30 pm) MODIS images. Monthly averages calculated from 1 January 2012 to 31 December 2012.**



**Figure 15: Frequency of monthly cloud cover per pixel in Terra MODIS images over the Southern Alps from 2000 to 2017 (frequent cloud cover is displayed in red). The Main Divide of the Southern Alps is shown running southwest to northeast, with the position of the GoEA marked in black.**