Reconstructing the mass balance of Brewster Glacier, New Zealand, using MODIS-derived glacier-wide albedo

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Status: final response

EC1: 'Editor Comment', Chris R. Stokes, 10 Aug 2016

I would like to thank the referees for their constructive reviews of this manuscript. Given their positive comments, and based on my own reading of the manuscript, I would certainly encourage the authors to submit a revised manuscript.

Response: We thank Prof Stokes for his very positive comment on our manuscript. We hereby submit a revised manuscript addressing the comments of all referees.

RC1: 'full manuscript review', Jason Box, 12 Jun 2016

The study makes application of NASA MODIS optical radiances to estimate broadband surface albedo an using original approach, here applied to Brewster Glacier, Southern Alps, New Zealand. Concurrent winter and summer mass balance from field surveys correlate strongly with cumulative winter albedo and minimum ablation season albedo, respectively. The empirical relationship is used to ad 50% (5 years) to the existing the Brewster Glacier labor intensive field mass balance series. The MODIS retrievals are aided in identifying cloud artifacts by surface albedo measurements from a Brewster Glacier AWS.

The study elegantly makes mass balance inferences using the a-priori satellite data and conclude among other things that over "the 2000-2013 period, the extended record shows that Brewster Glacier exhibited an overall shift from positive mass balance from 2000 to 2007 to negative mass balances from 2008 to 2013 (0.74 to -0.69 m w.e. 10 on average, respectively)." The study further extends the MODIS-assisted mass balance series with a mass balance record before 2000 to 1977. The study interprets periods of positive and negative mass balance tendency resulting from shifts in the Pacific (Inter-) Decadal Oscillation (PDO/IPO).

Critique The study is not only very clearly written and illustrated and free from obvious methodological problems, it drives forward a powerful observation-based approach that begs to be applied elsewhere.

Response: We thank Prof Jason Box for his very positive review of our manuscript.

The study mentions "minimum glacier-wide albedo is an appropriate proxy for mass balance in this maritime environment", while no explicit framing of appropriateness for the maritime environment is argued, presumably vs. continental or polar environments. Discussion of the appropriateness vs continental, maritime, polar, etc. is warranted and would add depth to the study.

Response: This statement was made due to the acknowledged maritime setting of Brewster Glacier as discussed by Anderson et al. (2010) (cited in the paper), and in contrast to the two other areas where this method was tested with arguably contrasting climate setting, namely the French Alps (Dumont et al., 2012) and two Himalayan glaciers (Brun et al., 2015). Although we agree that a discussion about how this method could be expected and proved to be appropriate or not in view of a broad classification of climate settings may find merit, we believe it would be premature and probably speculative to do so in view of the (very) limited sample size we have available. Arguably such discussion would equally apply to consideration of AAR relationship with mass balance. In their meta-analysis of AAR vs mass balance, Dyurgerov et al. (2009) only note that some degree of non-linearity has been observed for some glaciers in maritime climates, but without any attempt to generalize this results in view of the climate settings alone.

In view of this and despite the potential merit of the discussion suggested by the reviewer, we prefer to adjust the statement in a way that it does not mislead the reader into thinking that we claim the method to be appropriate for glaciers in a maritime setting, but rather that it “can be appropriate”.

Briefly describe the "glaciological method" referred to used to obtain field-based mass balance

Response: Agreed. We have clarified the description of the glaciological method referred to in the section 2.3.1 “Glaciological observations”.

Consider replacing "shows" with "illustrates" when referring to figures and "lists" instead of "shows" when referring to tables

Response: Thanks for this editorial improvement. Where applicable, we replaced “shows” by “illustrates” and “lists” when used in relation to figures and tables, respectively.

pg. 12 sentences beginning with "This" are less easy to follow

Response: We adjusted the sentences accordingly.

pg. 12 lines 19-20 define difference between standard error and standard deviation

Response: We reformulated the sentence to clarify the distinction between the standard deviation of the weekly population of albedo and the standard error of the mean (which is the standard deviation of the sample-mean’s estimate).

pg. 12 line 21 remove "highly" and other ambiguous adverbs

Response: Agreed. We removed “highly”.

pg. 12 line 25 not just metamorphism but surface accumulation of light absorbing impurities will contribute to albedo decline

Response: Agreed. We added the accumulation of light absorbing impurities as a reason of the albedo decline.

pg. 12 line 27 define "It"

Response: Agreed, we replaced “It” by “The glacier-wide surface albedo”.

pg 15 line 11 "the glacier gained up to 14.5 ± 2.7 m w.e" in average thickness? Please specify.

Response: Agreed, we added that the gain indicated is indicative of an average thickness (measured in m w.e.) gained by the glacier over the period.

Fig 7. is problematic, e.g. with solid circles obscuring something? use colored open symbols to reduce coalescence? Further,

Response: We agree that the coalescence of Fig. 7 is problematic. We changed the symbology to display open symbols only. For both sub-figures (a) and (b) we tried the use of colour to convey residuals but did not find it convincing. We kept the size of the symbols as an indication of the magnitude of the error with squares and circles to reveal over- and under-estimations, respectively and adjusted the legend to convey unambiguously the shape and scaling of the symbols in respect to the sign and magnitude of the error.

Fig. 7 did not add much. Even the authors state "This does not reveal any substantial relationship to the solar zenith s." so why not just remove the graphic?

Response: It is true that the relationship between error and solar zenith is not evident. However, the increasing over-estimation with incearsing view zenith is marked and discussed in the text. Although the reviewer suggests to remove the figure, we believe that it is necessary to illustrate fully the performance of the albedo retrieval method in view of the relative illumination/viewing geometry.

RC2: 'Review of "Reconstructing the mass balance of Brewster Glacier, New Zealand, using MODIS-derived glacier-wide albedo"', Edward Bair, 02 Aug 2016

In “Reconstructing the mass balance of Brewster Glacier, New Zealand, using MODIS-derived glacier-wide albedo”, remotely-sensed annual minima of snow and ice albedo are found and correlated with in situ measurements of albedo and mass balance at a well observed glacier. This is a strong paper and I couldn’t find much wrong with it. I recommend the paper be published as is, or pending some minor corrections at the authors’ discretion.

Response: We thank Dr Edward Bair for his very positive review of our manuscript.

I have one question. The presence of mixed pixels is not discussed at all. My understanding from a brief review of the authors' previous work, is that the broadband albedo reported here is a whole pixel albedo. In Dumont et al. (2012), which this work is based on, it is conceded that mixed pixels are not adequately dealt with: "To address the problem of mixed pixels, it would be interesting to apply the albedo retrieval method only to the part of the pixel reflectance which is attributed to snow and ice by linear unmixing." As far as I can tell, this suggestion was not followed here. In Dumont et al. (2012), mixed pixels of rock and snow were suggested to be one cause of higher errors around the glacier perimeter in the remotely-sensed albedos from MODIS. My worry with the albedo approach here to estimate mass balance is that an increasing fraction of some other endmember and a decreasing fraction of snowcover could be inferred as a change in snow/ice surface albedo, when in fact, it is the result of changing endmember fractions. This could result in an incorrect assessment of mass balance, especially over longer time periods. I suggest that authors at least acknowledge and discuss this source of error. Other comments are included as an annotated PDF.

Response: The reviewer is correct that the albedo values reported here correspond to the whole pixel. This is a very relevant point that is raised and we appreciate the reviewer comprehensive approach in consulting our related work in this regard. At this stage, we have not yet implemented nor tested the proposed approach to retrieve albedo from a modified pixel radiometry that would account for the sub-pixel fraction for snow/ice endmembers only.

The increasing underestimation of pixel albedo when the view zenith increases as shown in Figure 7 (top) suggests this effect becomes dominant at view zenith greater than 45˚. This is one of the reason why we limited the retrieval to images with viewing geometry that would mitigate this effect. Furthermore, since the context of the present study was, similarly to Dumont et al. (2012), to compute glacier-wide surface albedo from multiple pixels over a relatively short period of study with limited areal changes, and given that pixels were selected to be those consistently and near fully covered by snow and ice, we believed it was not yet imperative to consider such refinement.

Nevertheless, we fully agree with the reviewer that this method needs to be explored to improve the accuracy of albedo retrieval for single pixels as well as making it easier to monitor smaller glaciers whereby the relative number of pixels exposed to this effect may be large. We also agree that on the longer term, when the glacier extent may change and reveal increased exposure of darker surfaces at the margin, a trend in minimum glacier-wide albedo may emerge due to this short-coming that could compromise the mass balance model.

As suggested by the reviewer, we have emphasized this source of error and discussed its limitation in the revised manuscript (Section 4.1).

P4L13: There is no hyphen in "in situ." See http://www.economist.com/style-guide/italics

Response: We corrected this.

P5L2: Consider a citation here:Heucke, E. (1999), A Light Portable Steam-driven Ice Drill Suitable for Drilling Holes in Ice and Firn. Geografiska Annaler: Series A, Physical Geography, 81: 603–609. doi:10.1111/1468-0459.00088

Response: Agreed. We included the recommended citation.

P10L1: o_1,o_2,and o_3 need to be defined

Response: Agreed. We added the following statement after the equations: "where s_i and o_i are the slope and offset of each linear regression, respectively".

P34: which axis is a_mod and which is a_aws?Is it view zenith - 60 deg or view zenith = 60 deg? There are too many filled and unfilled symbols, making it difficult to understand. What is 0.05 and 0.5 in reference to?

Response: We clarified the figure caption to remove ambiguities about axis labels. The figure shows view zenith = 60 deg. We have increased the font to avoid misleading the reader. In response to both reviewers comment on the symbology of this figure, we have changed the symbology and the legend to convey unambiguously the shape and scaling of the symbols in respect to the sign and magnitude of the error.

P36 Please label, either in the legend or in the caption, the different shades around the mean.

Response: Agreed. We added the following statement in the figure caption: "The darker and lighter envelopes around the mean indicate the standard error and standard deviation, respectively, of the set of observations used to compute the mean."