Interactive comment on "*Annual and interannual variability and trends of albedo for Icelandic glaciers"* by Andri Gunnarsson et al.

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This paper presents the application of MODIS snow albedo products to characterize the spatial-temporal variability and trends of glacier albedo in Iceland. The albedo data are derived from the M*D10A1 products after interpolating missing data due to the frequent cloud cover. The topic is interesting since Icelandic glaciers are frequently exposed to volcanic ashes deposition causing large albedo changes and thereby modulating their response to climate forcing (Schmidt et al. 2017). A strength of the study is the extensive in situ dataset that was used to evaluate the MODIS products (20 AWS).

My main concern regarding this study is the apparent lack of novelty with respect to previous works by Möller et al. (2014) and Gascoin et al. (2017) who also studied the albedo changes over Icelandic glaciers. Some figures in the manuscript provide similar information as Gascoin et al. (2017).

In particular the introduction does not clearly state why it was needed to go beyond previous studies by Möller et al. (2014) and Gascoin et al. (2017). I see some differences that could indeed justify this new study.

The authors used M*D10A1, while the latter studies used MCD43A3. However, the authors should strengthen this part of the manuscript by providing a detailed comparison of both products. As it stands, the results cannot be compared to those reported by Gascoin et al. (2017) mainly because the authors computed the RMSE and correlations at the monthly time step whereas we used daily values (see L245 "The comparison presented here is in fact similar to previous work on Icelandic glaciers by Gascoin et al. (2017) where the MCD43A3 was evaluated with RMS errors ranging from 8–21%.").

Author response:

First, we would like to thank reviewer 1 (RC1) for useful comments and feedback about our submitted manuscript.

The original scope of the work was to quantify and assess the influence of volcanic activity and dust deposits on the surface mass balance of Icelandic glaciers using MC43A3 remotely sensed albedo, following in many aspects the work done by Gascoin et al. (2017). During this work, limitations of MCD43A3 for Icelandic glaciers where exposed. Below we hope to address those limitations.

Schmidt (et al. 2017) highlighted the importance of accurate glacier albedo for estimates of surface mass balance for Icelandic glaciers and similarly, this has also been observed in various hydrological models' efforts by the National Power Company in Iceland for many years.

Work done by Schmidt et al. 2017 used average values of MCD43A3 albedo as a background information for bare ice albedo to further improve the lowest albedo expected per pixel. It does not attempt to model the impact of dust deposit events, neither originated from exposed erosive surfaces in the proglacial areas nor the influence of volcanic eruptions while this is what we strive to do eventually.

As detailed in Gascoin et al. (2017) and Gunnarsson et al. (2019) a major challenge for remote sensing in Iceland is cloud cover, even though data from both Aqua and Terra are used cloud cover/no data pixels is still high. In addition to this, the strict processing criteria of the multi-look product from MCD43 reduces usable pixels even further, especially at higher elevations for Vatnajökull. An example of this is clearly shown in Figure 1 (below) where the pixel density for the melt season in 2019 (MJJA) is shown, for the combination of pixels available from MOD10A1 and MYD10A1. In comparison, Figure 2 (below) shows the pixel density for the melt season in 2019 (MJJA) for the MCD43A3 product. Essentially, this is the main reason we developed a new processing pipeline utilizing all data that is available, but also allowing for more tailored methodology to filter and reject pixels which is limited for MCD43.

It is hard to see how the indicated lack of novelty in our manuscript relates to the work done by Möller et al. (2014). Möller et al. (2014) investigate a single event (2004 Grímsvötn eruption) compared to an ash-dispersal dataset obtained from in situ measurements on the ice cap to develop a empirically based modelling approach to describe the albedo decrease across the glacier surface caused by the deposited tephra. The work done by Möller et al. (2014) is cited in our submitted manuscript.

Note must also be taken that MCD43A3 and MOD10A1 albedos are differently processed although obtained from the same sensor/daily surface reflectance product.

The scope of the paper is not to compare M*D10A1 or MCD11 to MCD43 albedo. It is aimed to develop a method to provide gap filled spatial-temporal continuous products to model near real time surface ablation and runoff in glacier fed rivers by direct albedo assimilation. That is the novelty of the paper.

A few key points highlighting the difference from our submitted manuscript and Gascoin et al. (2017).

- Melt increase from dust/ash deposit events are mostly observed to extend the active melt area of the glaciers, due to light absorbing impurities deposited in the accumulation area. This is why it is also important to represent albedo in the accumulation area better than MCD43 is able to.

- We have an albedo product that has a 2-5 day lag compared to the 14-16 day lag by MCD43A3. This is probably as close to "real time" as possible allowing usage of the albedo data in operational context.

- A much more detailed study is provided in our manuscript analyzing patterns and spatial trends of albedo than provided in Gascoin et al. (2017). Relations to elevation, monthly statistics and trends over time as well as temporal properties are reported. Individual dust events from documented erosive surfaces are identified and speculations relating the influence of the newly Holuhraun lava flow in 2015 are set forth among various other details.

- Seven year record for comparison and analysis for Icelandic glaciers are added including the cold summer of 2015, resulting in the first positive mass balance in 20 years at the time, and also the extreme dust deposit summer of 2019, is a good addition to the range of data in Gascoin et al. (2017) which spans 2000 - 2012.

We realize that MCD11 data is not perfect and there is a reason for the strict filtering criteria in MCD43. While MCD43 allows very limited improvement as it is a ready-made product the processing pipeline for MCD11 allows for more detailed filtering and rejection of cloud misclassified pixels. This methodology also allows for future improvements in the filtering criteria.

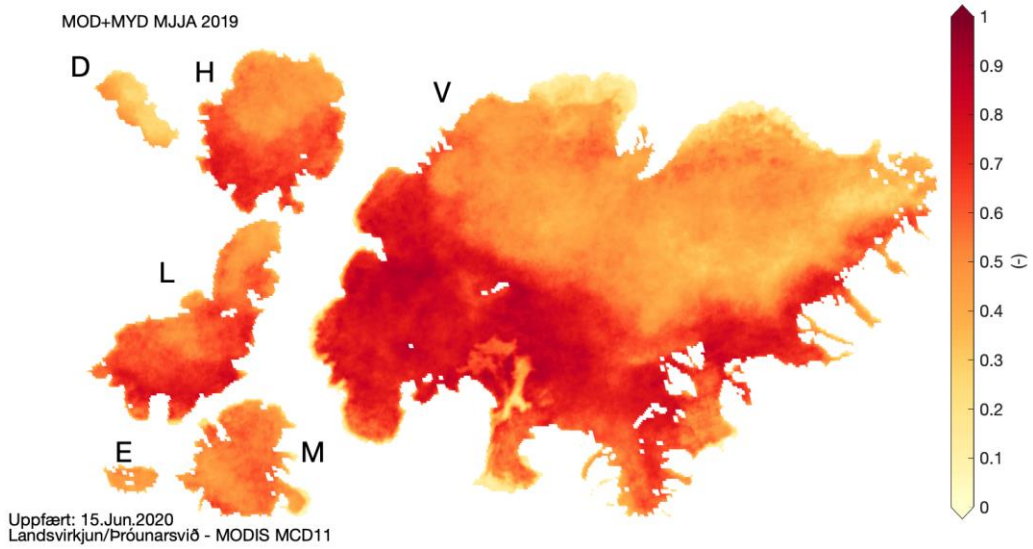

Figure 1 – MOD10A1 and MYD10A1 available pixels for MJJA 2019 for the largest Icelandic glaciers

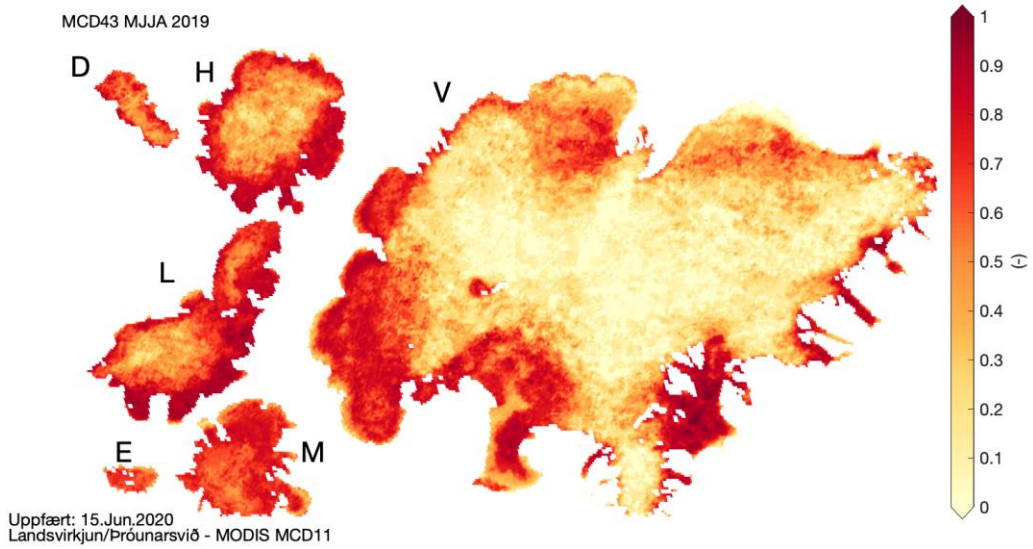

Figure 2 - MCD43 available pixels for MJJA 2019 for the largest Icelandic glaciers.

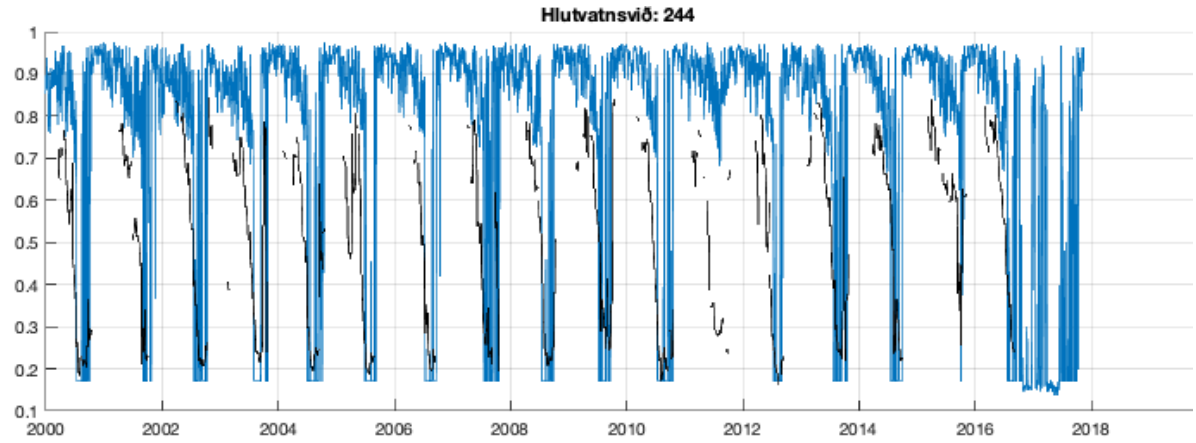

Figure 3 – Snapshot of calculated albedo and MCD43A3 MODIS albedo for a sub catchment at Brúarjökull glacier in Vatnajökull.

Looking at Tab B1 it seems that M*D10 products are more accurate than MCD43?

Author response:

There are some cases where the R^2 is better for MOD10A1 as well as lower RMSE values. Overall though, MCD43A3 albedo has better or equal R2 performance, in 15 out of 20 sites compared.

Also, an important aspect is that MCD43 provides albedo over all land masses, whereas M*D10A1 provides only albedo of the pixels that are detected as snow covered. This can be an issue in Iceland where large regions of glaciers may not be detected as snow due to the tephra layer. This issue should be investigated to make sure that the MCD11 product is not interpolating the albedo of clear-sky, snow-free pixels.

Author response:

Yes, correct, this is a very good comment. This has been visually investigated near the eruption sites at Grímsvötn for 2004, 2011 and Eyjafjallajökull eruption in 2010. In general, the random forest model is capable to estimate reasonable values for the thick tephra covered areas when they are not detected as snow, especially near the eruption site in 2011 in Vatnajökull.

To ensure less misclassification from clouds or tephra plumes during the eruption in these areas the local outlier thresholds applied are relieved allowing more range of expected values, especially lower values at higher elevations.

One weakness in our method is that during an eruption it might be hard to know the active extent of a tephra fallout that provides isolation to the surface. In a similar way tephra plumes discharged into the atmosphere with high tephra concentrations might further induce misclassifications. This is partially solved by Möller et al. (2014) fusing MOD10A1 and MCD43A3 albedos which might be a better future solution during eruptions and production of large thick tephra covered areas.

To highlight these problems, we will add the following sentence in L182:

In areas near the eruption sites in 2010 and 2011 the local outlier thresholds applied are adjusted allowing more range of expected values, especially lower values, to include the effect for tephra deposits to the glacier surface.

The trends should be masked or marked where MK test is not significant (Figure 10).

Author response:
We will add this to Figure 10

The improvements in MCD11 albedo with respect to the original product are very small (about 0.01 RMSE, Tab.2). In addition, it is indicated (L181) that the thresholds for outliers rejection were manually adjusted so the conclusions remain limited to this study. The main benefit of MCD11 is rather that it is a gap-free product which facilitates the utilization of the data.

Author response:
This is true and the main scope of the work. This is similar to Box et al. 2012 where local outlier thresholds are applied to improve the albedo retrieval for Greenland. We aim at improving the albedo retrievals for Icelandic glaciers, not glaciers worldwide.

The authors indicate that a motivation of their work is the integration of this albedo product in operational snow melt runoff model. It would be useful to have more background information on this aspect. What albedo is currently used by Landsvirkjun or other agencies? Is the developed product compliant with operational context if there is a lag of at least 5 days before updating the albedo (since temporal interpolation is based on a 10 days window)?

Author response:
Currently, albedo is calculated by a recent physically based broadband albedo parameterization (Gardner and Sharp, 2010). It is dependent on the five variables; specific surface area of snow (SSA), concentration profile of light absorbing carbon (or equivalent dirt) within the snow pack, cloud optical thickness, solar zenith angle and snow depth.

An example of calculated albedo results is provided in Figure 3 where MCD43A3 albedo is compared to glaciated sub-catchment on Brúarjökull. The room for improvement is very visible.

Availability for near real-time data is also important in operational context. MCD43 generally has a longer lag time, 12-14 days while M*D10A1 data is available with a 1-2-day lag. In the manuscript data is processed from a center date using data from 5 days into the past and future resulting in a 5-day lag from the current day. Currently the MCD11 product runs operationally daily with a 2-day lag. To do that, a modification of the process pipeline uses all available data 11 days back in time bridging from the conventional MCD11 to MCD11OPER which is then

overwritten when sufficient data is available to process with the pipeline as outlined in the manuscript. This is not a perfect solution but aims at having near real time estimations of albedo and albedo changes. Especially in the case of volcanic eruptions response times can be reduced to model the possibilities of floods due to melt enhancement and operational strategies for reservoir operation.

Minor comments

L31 in an maritime climate

Author response:

Will be fixed

L34: Seasonal glacier melt : what does it mean: seasonal snow and ice melt from the glacier area

Author response:

Yes, it is the amount the glacier melts seasonally.

L41: are

Author response:

Sentence is:

For Icelandic glaciers, surface albedo are the dominating factors governing surface melt annual variability…

Rewrite:

For Icelandic glaciers, surface albedo is the dominating factor governing surface melt annual variability…

L93: this paragraph gives me the impression to come out of the blue. The objective should be more clearly linked to the literature review and identified knowledge gaps.

Author response:

This paragraph summarizes the main objectives of the study based on the introduction for the convenience of the reader.

L153: "Daily averages" is not the correct wording if it refers to of hourly albedo values. I understand from the above paragraph that the daily albedo was in fact calculated from daily sums of incoming and reflected radiation (which is recommended to reduce measurement noise).

Author response:

For validation and comparison in the manuscript we calculated as the running 24-hour sum of upward shortwave divided by the running 24-hour sum of the downward shortwave as detailed in L135-137.

We will remove the following sentence from L153 as is originates from a version of the paper where we had modelling results to not create confusion:

Daily averages were calculated from hourly averages if at least 20 hourly values were available and monthly averages were calculated from daily averages if 24 values or more were available.

L168: what is a "median based statistical rejection of outliers."

Author response:
L177 explains better what median based statistical rejection of outliers does. Essentially this is to remove noise from the stacked pixels. Points that are larger or smaller than the median value of a given pixel stack are removed as outliers.

L173: I don't think you need these references to justify this general statement.

Author response:
References will be removed

L184: these pixels are not unclassified, since they are classified as cloud.

Author response:
Correct, *unclassified pixels* will be changed to *pixels classified as clouds*

L185: this approach is very similar to our algorithm for cloud pixels interpolation in MOD10 products (Gascoin et al. 2015). We used the same predictors. It should be cited if it has inspired your own algorithm.

Author response:
These are quite common predictors used in various studies we have researched and cited in the study. Indeed Gascoin et al. 2015 uses similar methodology.

L188 Correspondingly reads a bit odd here

Author response:
Correspondingly will be changed

L191 "monthly, basis"

Author response:
We will move the comma

L204: The calculations were

Author response:
Were will be changed to are

L215-220 the whole paragraph should be removed (it is method, not results)

Author response:
We will remove the paragraph

L246: results are not directly comparable (daily vs. monthly) (see my main comments)

Author response:

Sentence is:
The comparison presented here is in fact similar to previous work on Icelandic glaciers by Gascoin et al. (2017) where the MCD43A3 was evaluated with RMS errors ranging from 8–21%.

Rewrite:
The comparison presented here is in fact similar to previous work on Icelandic glaciers by Gascoin et al. (2017) where the MCD43A3 was evaluated with RMS errors ranging from 8–21%, although the results from Gascoin et al. (2017) are based on daily values.

L253: "indicating high sub-pixel albedo variability" This is a bit vague and unexpected comment since large areas of Icelandic ice caps have a rather homogeneous surface (in comparison with Alpine glaciers for example). We studied albedo subpixel variability from Landsat data to explain the discrepancy between AWS measurements and MODIS retrieval.

Author response:
Yes, more details are needed here. We will make the following change:

Sentence is:
Sub-pixel variability has been investigated by Reijmer et al. (1999) and Gascoin et al. (2017) for the Icelandic glaciers indicating high sub-pixel albedo variability.

Rewrite:
Sub-pixel variability has been investigated by Reijmer et al. (1999), Pope et al. (2016), and Gascoin et al. (2017) for the Icelandic glaciers. Results indicate higher sub-pixel albedo variability in the bare-ice areas, especially where stratified dirt bands and debris is observed while less variability is reported in the flat surroundings at higher elevations.

L273 experienced as an smoothing

Author response:
Fixed

Fig 3: a similar figure can be found in Gascoin et al 2017

Author response:
These figures show similar patterns. We suggest keeping this figure in the manuscript as it illustrates the cloud cover during the active melt season (MJJA) in Iceland not the whole data period (Feb to Nov).

The figure in Gascoin et al 2017 shows data availability for the whole year including the period during polar darkness when no data are available providing different information related to cloud cover. It also does not detail the cloud cover over the bare ice areas that form as the winter snow is melted from the dirty ice-covered surface and its development into the melt period.

Fig 4, 6, 7: rainbow colormaps are not recommended (see e.g. https://www.nature.com/articles/519291d)

Author response:
This is a good point and we spent a considerable amount of time selecting colormaps. Our conclusion was to highlight patterns in the data, bare ice areas, estimations of ELA and accumulation areas, a rainbow colormap is the best way to do so. This follows the examples by Box et al. 2012, Stroeve at al. 2013 and Riihelä et al. 2019.

Fig 6: the figure does not display correctly on my computer, I suggest to replace it by a bitmap (raster) version

Author response:
A final manuscript will have all figures as a raster

L440: this sentence should be removed or reformulated since there is no information on glacier mass balance in this study
Author response:
Correct, this will be removed as data regarding mass balance has been removed.

L462: Do you mean when MODIS will stop operating? Note that the successor of MODIS is rather VIIRS.
Author response:

We realize that VIIRS has operational data but look also towards using data from the SICE project (http://snow.geus.dk/) to take full potential of the twice per day overpass over Iceland.

We suggest modifying the sentence to:
... such as Sentinel 3 and VIIRS, to extend...