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

Referee 1 (RC1): Simon Gascoin, simon.gascoin@cesbio.cnes.fr
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Author response: 12.06.2020
Updated author response: 28.09.2020

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 surface mass balance of Icelandic glaciers using MC43A3 remotely sensed albedo, following in many aspects the work done by Gascoin et al. (2017). Also, in an operational context for hydropower generation, MCD43A3 has been used in relative comparison to qualitatively assess near future (days/weeks) melt potential, similar to data for Greenland by DMI, DTU and GEUS (http://polarportal.dk/en/greenland/surface-conditions/). Note that Polar Portal uses MOD10A1. During this work, limitations of MCD43A3 for Icelandic glaciers where exposed. Below we hope to address those limitations.

Schmidt et al. 2017 has highlighted the importance of accurate glacier albedo for estimates of surface mass balance for Icelandic glaciers and similarly, these challenges have 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 about bare ice albedo to further improve the lowest albedo expected per pixel. It does not include efforts to model the impact of dust deposit events, either 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 pixel 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 singular event (2004 Grímsvötn eruption) liked 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 to develop a method to provide gap filled spatial-temporal continuous products to model near real time influences of inflows to 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 extent the active melt area of the glaciers, i.e. light absorbing impurities deposit in the accumulation area. This is why it is also important to represent the accumulation area better than MCD43 is able to.

- We have a 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 we will get to be able to use the 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 other various details.

- Seven years of comparison and analytics for Icelandic glaciers are added including the very cold summer of 2015 resulting in the first positive mass balance in 20 years at the time but as well the extreme dust deposit year in 2019 compared 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 limiting 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.

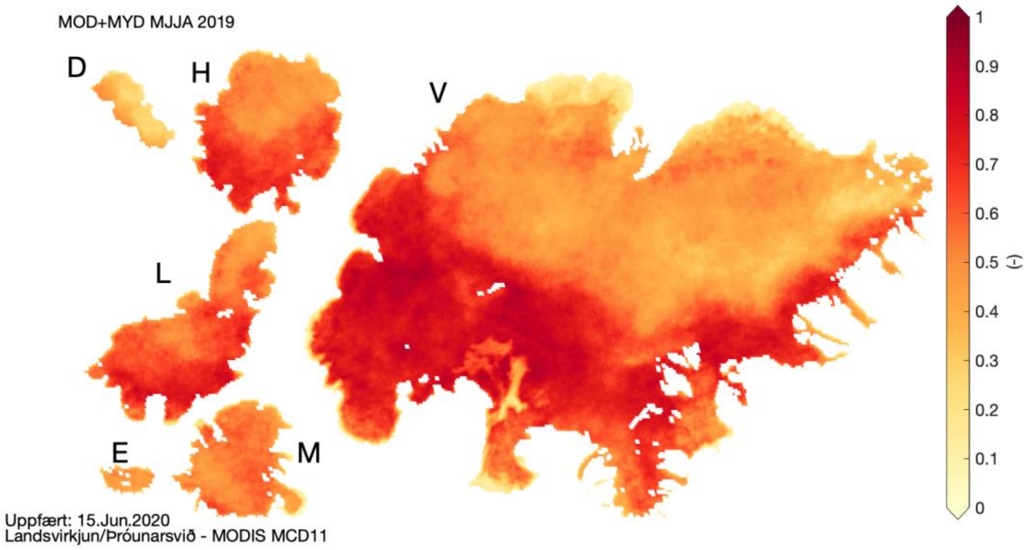

Figure 1 – MOD10A1 and MYD10A1 available pixels for MJJA 2019 for the largest Icelandic glaciers

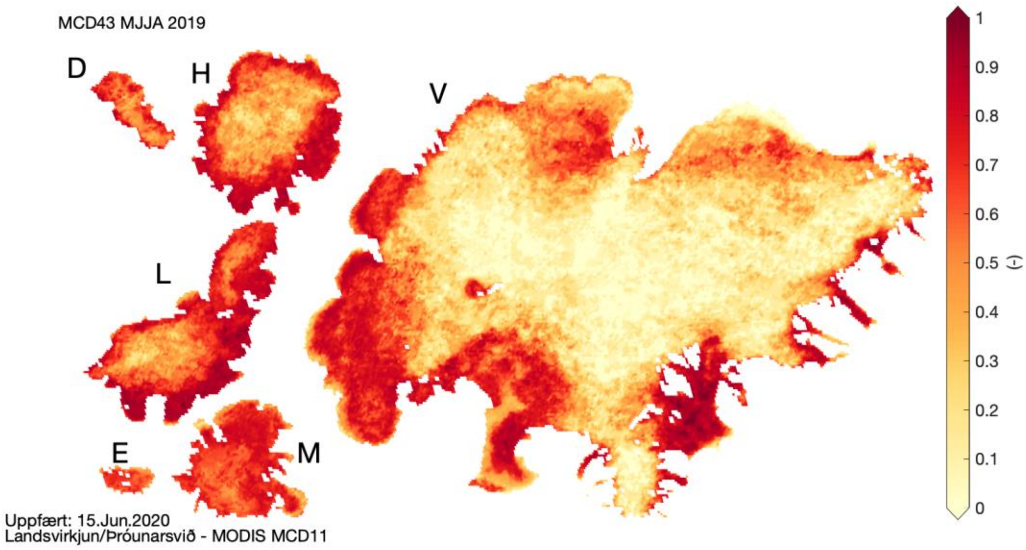

Figure 2 - MCD43 available pixels for MJJA 2019 for the largest Icelandic glaciers.

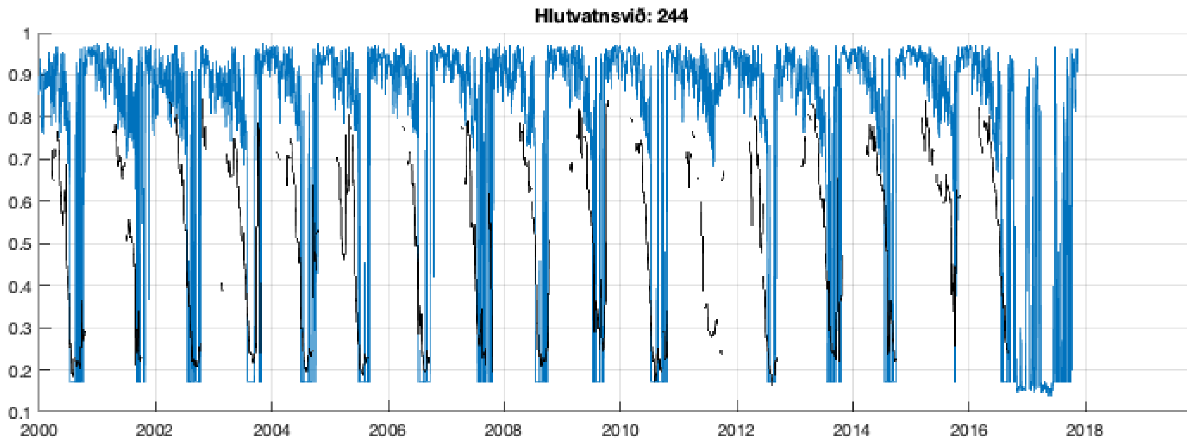

Figure 3 – Snapshot of calculated albedo and MCD43A3 MODIS albedo for a sub catchment at Brúarjökull glacier in Vatnajökull.

To accommodate the above comments from RC1 we have made the following changes to the manuscript:

L89:
Cloud cover is a major challenge for remote sensing in Iceland, even though data from both Aqua and Terra are used, the amount of cloud-covered pixels is still high. For albedo derived from the MODIS MCD43A3 product, the strict processing criteria of the multi-look product reduce the number of usable pixels even further than collected by Aqua and Terra. This is especially true at higher elevations for Vatnajökull where persistent cloud cover is frequently observed, resulting in fewer valid albedo pixels during the melt season. Melt increase from dust and ash deposit events is observed to extend the active melt area of the glaciers, i.e. LAP deposit in the accumulation area, increasing melting. Therefore data from these areas are very important for monitoring and forecasting runoff from glaciers in Iceland. Lag times of MCD43A3 (14--16 days) make this less feasible for near-real-time monitoring and operational modelling, for example, in the case of a major dust deposit or volcanic eruption. Additionally, MCD43A3 is not gap-filled, requiring some post-processing prior to monitoring or hydrological modelling efforts

Also in L100 when writing the studies objectives:

*This study aims to address some of the shortcomings of the MCD43A3 product for glaciers in Iceland and derive an albedo data set suitable for operational use as well as a scientific study of spatial and temporal variations in albedo. The daily M*D10A1 products were chosen to increase temporal resolution, allowing for more flexibility in post-processing, statistical filtering and near-real-time data posting. There are two main objectives of the study. First, to create a gap-filled MODIS-based surface-albedo product for glaciers in Iceland for this time period from 2000 to 2019 validated with in-situ data suitable for the monitoring and modelling of glaciers in an operational context. Second, the resulting gap-filled product was used to analyse and quantify spatio-temporal patterns of albedo for Icelandic glaciers for the time period, with monthly statistics and a detailed interpretation of the variation of albedo with elevation and trends over time.*

And in the conclusion of the paper in L 463:

Details are provided regarding spatial patterns and temporal trends, relations to elevation and monthly statistics adding to previous work by Gascoin et al. (2017) for 2000 to 2012.

In addition to the information provided in this document, we hope to have provided enough insights into these two different studies.

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. The outlier rejection of M*D10A1 data shows in many cases successful cloud rejection which is not rejected for MCD43A3.

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 project 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 relived 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 these eruptions and production of large thick tephra covered areas.

To highlight these problems, we will add the following sentence in L194:

During periods effected volcanic eruptions the outlier thresholds are not applied, allowing a greater range of expected values, especially lower values at higher elevations where tephra deposits were observed. In this study, this applies in melt seasons 2010 and 2011.

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

Author response:
Figure 10 now shows masked areas where significant trends are observed

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.

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 artificial 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.

We have added discussion to this end in L479:
The methodology allows for predictive and retrospective modes (Dozier et al. 2008), depending on the application. To use the albedo data for runoff forecasting for example, surface albedo

estimations using only data until the present (newest MODIS data) can be provided by applying the statistical filtering and gap-filling routines from today and backwards. Alternatively, in retrospective mode, best estimations can be provided for every day in a period.

Minor comments

L31 in an maritime climate

Author response:

This paragraph has been remove to shorten the article a bit.

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. This paragraph has been remove to shorten the article a bit.

L41: are

Author response:

Fixed

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. We have updated them with more details.

See L100:

This study aims to address some of the shortcomings of the MCD43A3 product for glaciers in Iceland and derive an albedo data set suitable for operational use as well as a scientific study of spatial and temporal variations in albedo. The daily M*D10A1 products were chosen to increase temporal resolution, allowing for more flexibility in post-processing, statistical filtering and near-real-time data posting. There are two main objectives of the study. First, to create a gap-filled MODIS-based surface-albedo product for glaciers in Iceland for this time period from 2000 to 2019 validated with in-situ data suitable for the monitoring and modelling of glaciers in an operational context. Second, the resulting gap-filled product was used to analyse and quantify spatio-temporal patterns of albedo for Icelandic glaciers for the time period, with monthly statistics and a detailed interpretation of the variation of albedo with elevation and trends over time.

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.

We have merged and updated these sentences to: see L189

On a pixel-by-pixel basis, the method Box et al. 2012 was applied to reject values exceeding 2 standard deviations from the 11 day temporally aggregated data stack. The method is only applied if 4 or more pixels in the data stack have valid albedo data. To prevent rejection of valid data, values within a certain threshold of the median were not rejected. The outlier thresholds were manually adjusted, mostly related to the elevation of the glaciers, ranging from 1 to 4\%, for higher to lower elevation, respectively. From the 22 potentially available values, the mean is calculated to represent the surface-albedo, after median-based statistical rejection of outliers. During periods effected volcanic eruptions the outlier thresholds are not applied, allowing a greater range of expected values, especially lower values at higher elevations where tephra deposits were observed. In this study, this applies in melt seasons 2010 and 2011.

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

Author response:
References is 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,* see L 198

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 is changed to *Aspect was then calculated for each pixel* see L202

L191 "monthly, basis"

Author response:
Fixed

L204: The calculations were

Author response:
Fixed

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

Author response:
Agreed, paragraph is removed

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: see L253
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: see L 262
Sub-pixel variability has been investigated by Reijmer et al. (1999), Pope et al. (2016), and Gascoin et al. (2017) for Icelandic glaciers. The study by Reijmer et al. (1999), using AVHRR and Landsat TM data at Vatnajökull reported large systematic differences for some of the automatic weather stations on the ice, attributed to sub-pixel-scale variations in the albedo. Results implied that the scale of the albedo variations was smaller than the scale of the AVHRR and TM pixels. Pope et al. (2016) studied high-resolution (5 m) airborne multi-spectral data collected over Langjökull in 2007, with comparison to near-contemporaneous Landsat ETM+ and MODIS imagery showing albedo to be highly variable at small spatial scales. Work by Gascoin et al. (2017) suggested that the RMSE of the difference between the in-situ automatic weather station data and MODIS data tends to increase when the corresponding Landsat sub-pixel spatial variability is higher. Lower standard deviation values were consistently obtained where the surface was less heterogeneous (accumulation areas).

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 which we want to highlight.

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

Author response:
Relevant colormaps have been updated

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

Author response:
All figure are pdfs and eps now

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.

L485 has been update to:
Finally, it is noted that the methodology applied in the study, based on MODIS data, can be applied to other satellite albedo products, such as VIIRS and Sentinel-3 as well as future missions, to extend the temporal range beyond the MODIS mission, allowing for short-term as well as long-term monitoring of albedo variations for glaciers in Iceland.

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

Referee 2 (RC2): Pavla Dagsson Waldhauserova, pavla@lbhi.is
Received and published: 26 May 2020

Original author response: 26.06.2020
Updated author response: 29.09.2020

The authors provide well-written detailed study on albedo changes of all Icelandic major glaciers using a comparison of MODIS snow albedo products and in situ measurements. This study could also serve as a comprehensive review of rapidly changing glaciers in Iceland with focus on impacts on their changing albedo. It brings insights into albedo analysis in problematic cloud-obscured region while providing novel findings on linear albedo gradients and dust plume shape patterns on snow and ice. Direct impacts of explosive volcanic eruptions as well as severe and moderate dust storms on the glaciers are evaluated. Additionally, possible indirect impacts of effusive eruptions such as Holuhraun 2014-2015 are suggested. It is clear that the authors know perfectly the local environment and its past. The data from the MODIS products were carefully screened during extensive manual quality control and results were evaluated with valuable data from in situ ICE-GAWS network. The greatest contribution of this study is that the data set does not only include major explosive eruptions and cold years, but it includes extremely rare year 2019, dry and dusty in the southern part of Iceland. This allows the authors to compare the impacts of volcanic ash and general volcanic/glacial dust on the albedo at the same level. There are minor errors in references that should be stated in ascending order and several references could be added. I would recommend publication after minor revisions.

Author response:

First, we would like to thank reviewer 2 (RC2) for very useful comments and a general positive feedback about our submitted manuscript. Your summary of the paper matches very well with our intended scope and deliverables.

Specific comments:

L18-95 – Introduction

Consider to add studies on snow albedo reductions due to volcanic dust, eg. **Meinander et al., 2014**, Peltoniemi et al., 2015**, Dagsson-Waldhauserova et al**., 2015, Zubko et al., 2019).

Kylling et al., 2018 calculated the instantaneous radiative forcing of the bottom of the atmosphere due to mineral dust deposited on snow as 0.135 W m-2.

Kylling A., Groot Zwaaftink, C. D., Stohl, A., 2018. Mineral dust instantaneous radiative forcing in the Arctic. Geophysical Research Letters, 45. doi: 10.1029/2018GL077346.

Peltoniemi, J. I., Gritsevich, M., Hakala, T., Dagsson-Waldhauserová, P., Arnalds, Ó., Anttila, K., Hannula, H.-R., Kivekäs, N., Lihavainen, H., Meinander, O., Svensson, J., Virkkula, A., de Leeuw, G., 2015. Soot on snow experiment: bidirectional reflectance factor measurements of contaminated snow. The Cryosphere 9, 3075-3111.

Dagsson-Waldhauserova, P., Arnalds, O., Olafsson, H., Hladil, J., Skala, R., Navratil, T., Chadimova, L., Meinander, O., 2015. Snow-dust storm A case study from Iceland, March 7th 2013. Aeolian Research 16, 69–74.

Meinander, O., Kontu, A., Virkkula, A., Arola, A., Backman, L., DagssonWaldhauserová, P., Järvinen, O., Manninen, T., Svensson, J., de Leeuw, G., and LepC2 päranta, M., 2014. Brief Communication: Light-absorbing impurities can reduce the density of melting snow. The Cryosphere 8, 991-995.

Zubko, N., Muñoz, O., Zubko, E., Gritsevich, M., Escobar-Cerezo, J., and Berg, J., 2019. Light scattering from volcanic-sand particles in deposited and aerosol form. Atmos. Env. 215, 116813. doi: 10.1016/j.atmosenv.2019.06.051

Author response:
The following references are added to introduction on impacts of dust and sand to snow covered surfaces. Meinander et al., 2014, Dagsson-Waldhauserova et al., 2015, Zubko et al., 2019, Peltoniemi et al., 2015 in L26 and onwards

L40 and L85 remove 'a' in Wittmann et al., 2017a. Consider to add Gascoin at al., 2017 here.

Author response:
We have fixed the 2017 Wittmann reference.

L40-41 – 'surface albedo IS the dominating factors' - change ARE->IS, FACTORS- >FACTOR

Author response:
For major revisions this paragraph was removed to account for the paper length.

In L1 in the abstract a similar sentence can be found:

During the melt season, absorbed solar energy, modulated at the surface predominantly by albedo, is one of the main governing factors controlling surface-melt variability for glaciers in Iceland

L44-45 – ..but it IS limited. . .

Author response:
Fixed.
L30: Optical satellite remote sensing offers a way to observe surface albedo continuously at large spatio-temporal scales but is limited to times of clear-sky overpasses.

L47 – Stroeve et al. 2001? As in reference, not 2002.

Author response:
These are two separated references, Stroeve, 2001 and Klein and Stroeve, 2002. No modifications have been made but references double checked.

(Stroeve et al., 1997; Reijmer et al., 1999; Stroeve, 2001; Klein and Stroeve, 2002; Liang et al., 2005; Stroeve et al., 2005, 2013).

L70-72 – Can you please rephrase the sentence or cut into two sentences. It is difficult to understand.

Author response:

Sentence was:
To confirm this hypothesis, in-situ data and higher resolution data from Landsat 5 Thematic Mapper (TM) sensor were compared as well showing greater variability in surface albedo implying that the scale of the albedo variations is larger than the AVHHR pixel (1.1 km) could resolve.

Rewrite: (L66)
To confirm this hypothesis, Reijmer et al. (1999) compared in-situ data and higher spatial resolution remote sensing data from the Landsat 5 Thematic Mapper (TM) sensor. The results

showed greater variability in surface albedo, implying that the scale of the albedo variations is larger than the AVHRR pixel (1.1 km) could resolve.

L144 – Van Den Broeke et al., 2004 a,b?

Author response:
Updated accordingly, see L156

L164 – Table 1 – What do you mean by 'average location'?

Author response:
Annually when the GAWS stations are installed in the field they are not in the exact same location from on year to another. This can vary between a few tens to hundred meters. Stations can also move during the melt season due to ice flow. We calculate the average locations, mean value of these locations for pixel data extraction instead of posting annual values.

An explanation is added in the caption text with Table 1:

Location and elevation is based on the average location of the site for the observation period, i.e. mean location values for multi-year installations which might not be the exact same location from on year to another

L192-193 – opening brackets are missing

Author response:
Fixed, see L 209

L229-230 – Do you mean annual melt rates here?

Author response:
…high melt rates… refers to summer melt rates indicating that large elevation changes can be expected during summer resulting in tilting of the instruments.

L230 – Sand particles have certain size resolution, maybe 'dust' is better here. Or 'sand and dust'.

Author response:
Sentence was:
Large sand and tephra covered areas have been observed…

Rewrite:
Large sand, dust and tephra covered areas have been observed… see L236

L253– Small scale spatial variability of albedo could be also discussed here. See Hartl et al., 2020. Hartl, L., Felbauer, L., Schwaizer, G., and Fischer, A.: Small scale spatial variability of bare-ice albedo at Jamtalferner, Austria, The Cryosphere Discuss., https://doi.org/10.5194/tc-2020-92, in review, 2020.

Author response:
The study reports a very detailed study on an small alpine glacier. The reference could fit well in an introduction or a literature review but we would question if this can be applied for Icelandic glaciers as no similar work has taken place.

L289-308 – Linear albedo gradients are really important and well discussed here. However, the role of local impurities should be also mentioned here. General lower albedo values at certain parts of Hofsjökull, Langjökull and Myrdalsjökull coincides well with location of dust source areas described in Arnalds et al., 2016, and classified as severe or extremely severe erosion areas. This should be also included here in the discussion. There is also work from Antarctica showing the vertical gradient of local dust impurities on glacier that could be discussed here. See Kavan et al., 2020.

Kavan, J., Nyvlt, D., Láska, K., Engel, Z., and Knazková, M. (2020) High latitude dust deposition in snow on the glaciers of James Ross Island, Antarctica. Earth Surf. Process. Landforms, https://doi.org/10.1002/esp.4831

Author response:
Correct, the following sentence is added in L 323

Local lower albedo gradients at Hofsjökull (SE), Langjökull (S) and Mýrdalsjökull (S) coincide with documented locations of severe or extremely severe dust source areas described in Arnalds et al., 2016.

L319-321 – General trends in annual albedo (lowest values vs. highest values) correspond to the long-term dust storm frequency studies in Iceland. For evaluation, consider these three studies:

Nakashima, M. and Dagsson-Waldhauserová, P., 2019. A 60 Year Examination of Dust Day Activity and Its Contributing Factors From Ten Icelandic Weather Stations From 1950 to 2009. Frontiers in Earth Science 6, 245-252. DOI:10.3389/feart.2018.00245

Butwin, M.K., von Löwis, S., Pfeffer, M., and Thorsteinsson, Th., 2019. The Effects of Volcanic Eruptions on the Frequency of Particulate Matter Suspension Events in Iceland. Journal of Aerosol Science 128, 99-113.

Dagsson-Waldhauserova, P., Arnalds, O., Olafsson, H., 2014. Long-term variability of dust events in Iceland. Atmospheric Chemistry and Physics 14, 13411-13422. DOI:10.5194/acp-14-13411-2014.

Author response:
For the cluster of glaciers (L319-321 old version) () refers to (South coast glaciers) there is no significant trend in annual values within in our study period (2000-2019), especially if the influence of the volcanic eruptions in 2010, 2011 and the residual effect in 2012 is removed.

There is a trend/pattern w.r.t. latitude generally with lower values in southern Iceland. With respect to the references provided there are discussion about longer term trends than our paper scopes.

We have added the Dagsson-Waldhauserova et al. 2014 paper in L340 and Butwin et al. 2019 in L401 to further support our findings.

L322-323 – Such unstable erosive surfaces are defined as 'dust hot spots' and it has been shown that dust events occur frequently in southern parts of Iceland in winter. Examples here:

Dagsson-Waldhauserova, P., Arnalds, O., Olafsson, H., 2014. Long-term variability of dust events in Iceland. Atmospheric Chemistry and Physics 14, 13411-13422. DOI:10.5194/acp-14-13411-2014

Dagsson-Waldhauserova, P., Renard, J.-B., Olafsson, H., Vignelles, D., Berthet, G., Verdier, N., Duverger, V., 2019. Vertical distribution of aerosols in dust storms during the Arctic winter. Scientific Reports 6, 1-11.

Dagsson-Waldhauserova, P., Arnalds, O., Olafsson, H., Hladil, J., Skala, R., Navratil, T., Chadimova, L., Meinander, O., 2015. Snow-dust storm A case study from Iceland, March 7th 2013. Aeolian Research 16, 69–74.

Author response:
We have added the following sentence in L340 :

Dagsson-Waldhauserova et al., 2014, 2015, 2019 has also shown that dust events can occur frequently in southern parts of Iceland during winter given the right surface and meteorological conditions for dust transport.

L329 – delete 'r' in severer

Author response:
Fixed

L329-332 – Just to comment. There are few cases when Drangajökull and Westfjords receive dust from the dust hot spots in central and South Iceland. Such events were captured by satellite or by dust model frequently in 2019.

Author response:
Figure 7 and 8 reflects this showing lower annual albedo values for 2019 for Drangajökull. In general, we would still consider Drangajökull to be "closest" of the Icelandic glaciers to have albedo driven by snow metamorphism even though dust events can take place. We have also add a sentence (See RC2 comment on L427 – Conclusions) that highlights this.

L353 – '>30%' Did you mean < 30%

Author response:
Yes. This has been fixed, see L373

L375 – Liu et al. (2014) do not really refer to volcanic ash from eruption, but dust event with maybe some relicts of ash. Their sample was collected in 2013 and they describe a dust event in 2013. I would suggest removing this from the references here.

Author response:
Yes, agreed. We have removed the reference.

L380-381 – It was also induced by high dust storm activity in that area, see Möller et al., 2019. Volcanic ash is usually being removed fast from surfaces in Iceland, in < 1 year. See Butwin et al., 2019 or Arnalds et al., 2013.

Butwin, M.K., von Löwis, S., Pfeffer, M., and Thorsteinsson, Th., 2019. The Effects of Volcanic Eruptions on the Frequency of Particulate Matter Suspension Events in Iceland. Journal of Aerosol Science 128, 99-113.

Arnalds, O., Thorarinsdottir, E.F., Thorsson, J., Dagsson-Waldhauserova, P., Agustsdottir, A.M., 2013. An extreme wind erosion event of the fresh Eyjafjallajokull 2010 volcanic ash. Nature Scientific Reports 3, 1257.

Author response:

Sentence was:
No eruption occurred in 2012 but residual effects were observed as ash deposits from previous eruptions were carried with the prevailing wind directions, enhancing melt due to the lowering of albedo.

Rewrite: see L 399
No eruption occurred in 2012 but residual effects were observed as ash deposits from previous eruptions were carried with the prevailing wind directions and high dust storm activity reported in the area, enhancing melt due to the lowering of albedo (Butwin er al. 2019, Möller et al., 2019).

L382 – Wittmann et al. (2017a). Why 'a'?

Author response:
Duplicate in the reference list produced this, has been fixed.

Figure 8 – Correct the title – delete 'for the'?

Author response:
Typographical error, fixed

L400 – 1999 Hekla – Are you talking about 26th Feb 2000 Hekla eruption here?

Author response:
Yes, 1999 should be 2000, fixed

L386-398 – When discussing dust influence on the albedos, you can also include that not only volcanic ash can be lifted to high altitudes and transported long distances. It is also Icelandic volcanic dust that can reach several km heights and travel long distances of thousands of km:

Dagsson-Waldhauserova, P., Renard, J.-B., Olafsson, H., Vignelles, D., Berthet, G., Verdier, N., Duverger, V., 2019. Vertical distribution of aerosols in dust storms during the Arctic winter. Scientific Reports 6, 1-11.

Djordjevic D., Toši ´ c I., Sakan S., Petrovi ´ c S., Ä ´ Ruri ˇ ci ˇ c-Milankovi ´ c J., Finger D.C. and ´ Dagsson-Waldhauserová P. 2019. Can Volcanic Dust Suspended From Surface Soil and Deserts of Iceland Be Transferred to Central Balkan Similarly to African Dust (Sahara)? Frontiers in Earth Sciences 7, 142-154.

Moroni B., Ólafur Arnalds, Pavla Dagsson Waldhauserová, Crocchianti, S., Vivani R., and Cappelletti, D. 2018. Mineralogical and chemical records of Icelandic dust sources upon Ny-Ålesund (Svalbard Islands). Frontiers in Earth Science 6, 187-219.

Beckett, F., Kylling, A., SigurÃˇrardóttir, G., von Löwis, S., and Witham, C., 2017. Quantifying the mass loading of particles in an ash cloud remobilized from tephra deposits on Iceland, Atmos. Chem. Phys., 17, 4401-4418.

Ovadnevaite J., Ceburnis D., Plauskaite-Sukiene K., Modini R., Dupuy R., Rimselyte I., Ramonet R., Kvietkus K., Ristovski Z., Berresheim H., O'Dowd C.D., 2009. Volcanic sulphate and arctic dust plumes over the North Atlantic Ocean. Atmospheric Environment 43, 4968-4974

Author response:
This is mentioned in the manuscript, we have modified in the discussion section the following:

Sentence was.
Airborne tephra can be transported by high plumes that can extend several

kilometres into the atmosphere and be transported great distances, up to several hundred kilometers (Guðmundsson, Magnús T. et al., 2012; Watson et al., 2016)

Changed to: see L395
Airborne tephra and dust can be transported by high plumes that can extend several kilometres into the atmosphere and be transported great distances, up to several hundred kilometers (Guðmundsson, et al., 2012; Watson et al., 2016; Đordevic et al., 2019; Dagsson-Waldhauserova et al., 2019).

L405-417 – Can you explain better why Dyngjujökull shows positive albedo trend? Is it after the Holuhraun eruption and reduction of dust events from Dyngjusandur towards the glacier?

Author response:
Various influencing factors could contribute to a positive Dyngjujökull albedo trend. One of those possibly the changes due to the Holuhraun eruption as mentioned in L392-396 in the manuscript:

"In 2014–15, the lava flow field of the Holuhraun non-explosive eruption covered about 84 km2 of volcaniclastic sandy desert and proglacial areas north of Vatnajökull. Since then, similar plume shaped albedo anomalies were not observed in the data. It is probable that the extent of the lava flow field reduces the dust production of this area significantly, although this cannot be quantified at this point in time, more data over a range of climatologies are needed to fully understand the impact of the Holuhraun eruption on dust production"

But it could also be related to other climatological variables such as the variability in winter precipitation, melt onset and snowfall during late summer. The figure below shows the most recent mass balance values for Dyngjujökull among others. Since 2004-05 net mass balance has a mild upwards trend although non-significant constrained by high summer melt years for 2004 (Gjálp), 2010 (Eyjafjallajökull) and 2012 and low melt in 2015.

This is a very interesting question to discriminate the actual influencing factors driving this trend but we feel it needs a more detailed investigation than the scope of the study to be able to state anything definite.

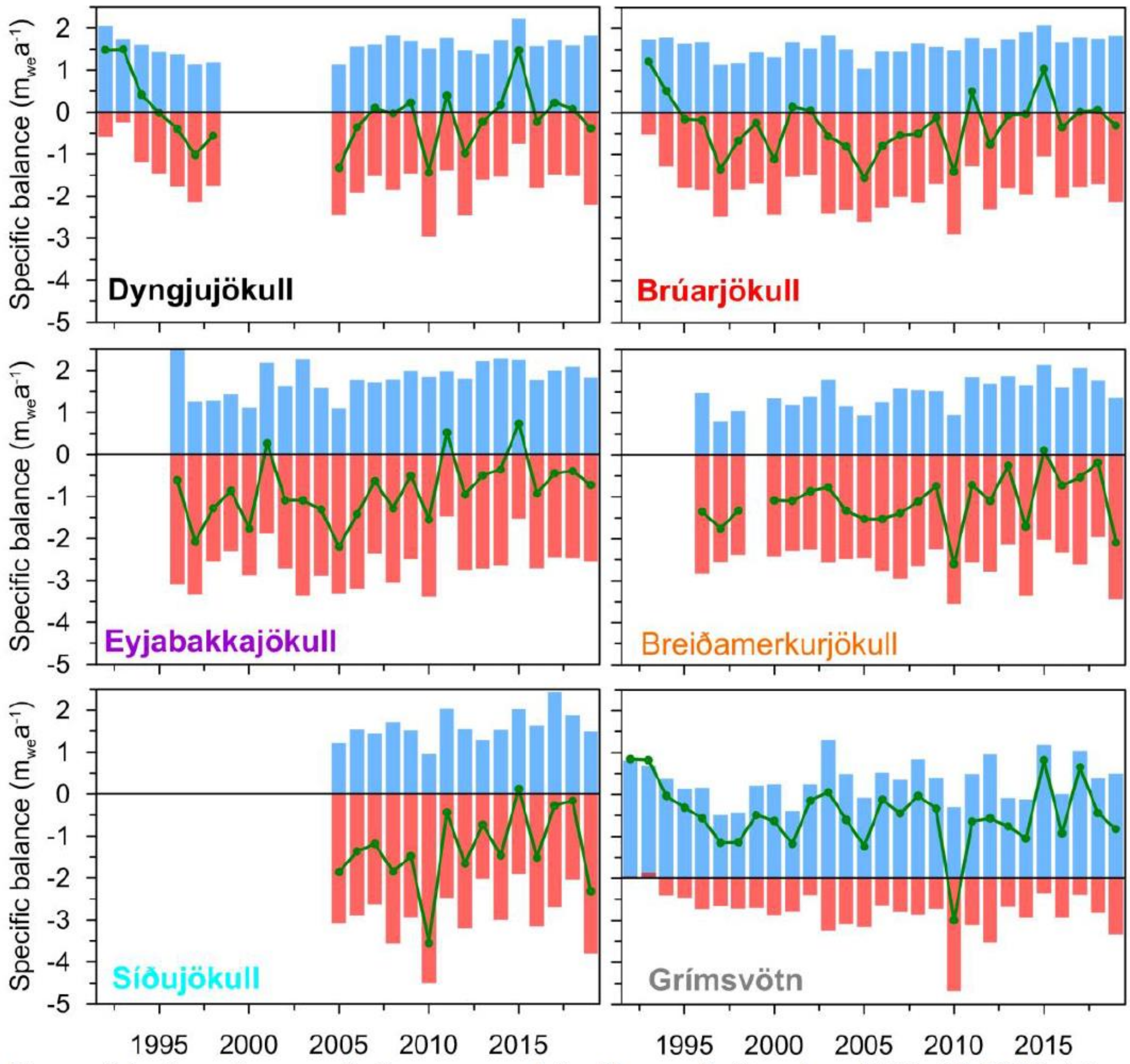

Figure 16. Specific mass balance record for Vatnajökull outlets 1991_92-2018_19.

L419-426 – Figure 11 and discussion. Doesn't this show that warm, dry and dusty year as 2019 have similar impacts on albedo as volcanic eruption years?

Author response:

Depending on the timing of the deposits and extent this is true. In the cases where the active melting area (ablation zone) is extended significantly as happens during eruptions, more melt is expected. A key factor in the 2019 melt enhancement is how early seasonal snow is melted exposing these erosive surfaces and how early in Spring dust transport starts. Similar events are seen, although less extensive as in 2019 in 2020 but they occur mid-August, not creating a lot of melt potential for the remaining of the melt season.

L427 – Conclusions – It would be beneficial to conclude in one sentence also the difference in influence of tephra after eruption and dust during dusty year as 2019 on albedo.

Author response:
L436 says:
Icelandic glacier albedo was observed to be influenced by variability in climate, tephra deposits from volcanic eruptions, and airborne dust from widespread unstable sandy surfaces which are subject to frequent wind erosion and dust production.

We suggest adding the following to L447 with the discussion about Figure 11:

Extensive dust transport to the glacier surface, as seen in 2019 melt season, had similar overall albedo lowering effect to that in the eruption years 2010 and 2011 for Vatnajökull, Langjökull, Eyjafjallajökull and Drangajökull specifically. It is, however, noted that following volcanic eruptions albedo lowering is generally more localized while extensive dust transport tends to affect larger areas.

L472- References should be ordered in ascending order (Palsson et al., Schmidt et al., Stroeve et al, need to be corrected).

Author response:
Yes, reference list is reviewed and updated accoringly

L549-551 – Liu is not relevant reference in the text. They do not refer to volcanic ash from eruption, but general dust event. Consider to remove this from the reference list.

Author response:
The reference to his work was removed in an earlier comment

L554 – remove 'a' in Matlab, 2017a

Author response:
The "a" refers to a version number of Matlab, not multiple same year publications.

L566 – Thorsteinsson et al., 2017 should be under T in the reference list, not under P

Author response:
Corrected.

Annual and ~~interannual~~ inter-annual variability and trends of albedo ~~for~~ of Icelandic glaciers~~.~~

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Abstract.

During the melt season, absorbed solar energy, modulated at the surface predominantly by albedo, is ~~the governing factor~~ one of the main governing factors controlling surface-melt variability for glaciers in Iceland. Using MODIS satellite-derived daily surface albedo, a gap-filled temporally continuous albedo product is derived for the melt season (~~MJJA~~May to August (MJJA)) for the period 2000–2019. The albedo data are thoroughly validated against available in-situ observations from 20 glacier automatic weather stations for the period 2000–2018. The results show that spatio-temporal patterns for the melt season have generally high annual and inter-annual variability for Icelandic glaciers, ranging from high ~~fresh- snow~~ fresh-snow albedo of about 85–90% in spring, decreasing to 5–10% in the impurity-rich bare-ice area during the peak melt season. The analysis shows that the volcanic eruptions in 2010 and 2011 had significant impact on albedo and also had a residual effect in the following years. Furthermore, airborne dust, from unstable sandy surfaces close to the glaciers, is shown to enhance radiative forcing and decrease albedo. A significant positive albedo trend is observed for northern Vatnajökull while other glaciers have non-significant trends for the study period. The results indicate that the high variability in albedo for Icelandic glaciers is driven by climatology, i.e. snow metamorphosis; tephra fall-out during volcanic eruptions and their residual effects in the post-eruption years; and dust loading from widespread unstable sandy surfaces outside the glaciers. This illustrates the challenges in albedo ~~parametrization~~ parameterization for glacier surface-melt modelling for Icelandic glaciers as albedo development is driven by various complex phenomena, which may not be correctly captured in conventional energy-balance models.

1 Introduction

Surface albedo is defined as the unitless ratio of radiant flux reflected from the Earth's surface to the incident flux. It is a controlling parameter, which governs the portioning of the shortwave radiative energy between the atmosphere and the surface and, therefore, a control of the surface energy balance modulated by the solar zenith angle, cloud optical thickness, cloud cover and transmission properties of the atmosphere (?Klein and Stroeve, 2002; Donohoe and Battisti, 2011)(Klein and Stroeve, 2002; Gardner and S

. The evolution of albedo for impurity-free snow and ice is controlled by the snow metamorphism process where snow-grain size increases with time and lowers albedo at all wavelengths while fresh new snow increases albedo (Warren, 1982). Light Absorbing Particles Light-absorbing particles (LAP), such as sand, mineral and volcanic dust/tephra, black carbonand algae , soot and algae, in the near-surface layers of the snow and ice further lower the albedo, enhancing the energy absorbed by the surface (Warren and Wiscombe, 1980; Box et al., 2012; Painter et al., 2012; Stibal et al., 2017; Skiles et al., 2018)(Warren and Wiscombe, 19

.

Iceland is located in the North-Atlantic Ocean on the mid-Atlantic Ridge, close to the Arctic Circle (between 63° and 66° N) with an area of 103.100 km^2. At present, about 10% (10.344 km^2) of Iceland is glaciated (Fig. 1) (Björnsson and Pálsson, 2008) . Icelandic glaciers span an elevation range from sea level up to 2110 m a.s.l. in an maritime climate, with large mass throughput and high variability in annual mass balance (Björnsson and Pálsson, 2008; **?**; **?**; **?**).

Glacier research is important in Iceland for multiple reasons. Seasonal glacier melt is vital for hydropower production and melt water storage in reservoirs as the energy system is strongly dependent on glacier and snow melt providing over 72% of the total average energy produced in Iceland (Hjaltason et al., 2018). The system isolation and high natural climate variability can pose a risk to the reliability of the energy system as drought conditions, low-flow periods and years with low summer mass balance are challenging to foresee. Activity in glacier-covered volcanoes can cause volcanic ash and tephra fall-outs on glaciers during explosive eruptions leading to enhanced melt or in some cases glacier surface isolation reducing melt significantly (Möller et al., 2014; **?**, 2019). For Icelandic glaciers, surface albedo are the dominating factors governing surface melt annual variability (De Ruyter De Wildt et al., 2002; Guðmundsson et al., 2009) and the importance of correct representation of surface albedo for glacier melt modelling is critical (Schmidt et al., 2017).

Optical satellite remote sensing offers a way to observe surface albedo continuously at large spatio-temporal scales but are is limited to times of clear-sky overpasses. Various studies have shown that surface albedo over snow and ice can be successfully derived from visible and near-infra red satellite sensors (Stroeve et al., 1997; Reijmer et al., 1999; Stroeve, 2001; Klein and Stroeve, 2002; (Stroeve et al., 1997; Reijmer et al., 1999; Stroeve, 2001; Klein and Stroeve, 2002; Liang et al., 2005; Stroeve et al., 2005, 2013)

. Since October 1978, regular polar coverage has been provided by the National Oceanographic and Atmospheric Administration (NOAA) satellites carrying the advanced very high-resolution (AVHHRAVHRR) radiometers (Stroeve et al., 1997; Xiong et al., 2018). The AVHHR AVHRR sensor has visible, near-infrared and thermal channels that observes the top of the atmosphere (TOA) radiances under clear-sky conditions, which allows for conversions of narrow-band reflectance measurements to broadband albedo by applying an atmospheric correction and using an radiative transfer model with successful results over snow- and ice-covered surfaces (Lindsay and Rothrock, 1994; de Abreu et al., 1994; Stroeve et al., 1997; Reijmer et al., 1999). Spatial resolution is 4 and 1.1 km depending of on the collection mode (global or local), allowing for sufficient representation of surface albedo for larger ice caps or sheets that encompass large areas such as Greenland (Steffen et al., 1993; Zhou et al., 2019) and the main ice caps of Iceland. Higher spatial-resolution optical data have been obtained from the Landsat constellation (30 m spatial resolution) for albedo retrievals with capabilities to further resolve smaller-scale patterns, more detailed variability of albedo and sub-pixel variability of large-footprint satellite sensors (Winther, 1993; Reijmer et al., 1999; Gascoin et al., 2017; Naegeli et al., 2017, 2019) . Higher spatial-resolution satellite data generally have the disadvantage of lower temporal resolution, which excludes the possibility of daily albedo observations.

Since February 2000, the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument, on board the NASA ~~TERRA~~ Terra satellite, has collected daily multi-spectral radiance data (36 spectral bands) viewing the entire Earth's surface every 1 to 2 days at ~~a~~ 500 m spatial resolution. Followed by the NASA ~~AQUA~~ Aqua satellite launch in July 2002, also carrying the MODIS sensors~~as well~~, MODIS data have significantly improved understanding of global-earth and lower-atmosphere processes and dynamics. Various albedo products for snow- and ice-covered surfaces have been developed and analysed to further understand the inter-annual and seasonal variability ~~in~~ of albedo for glaciers and ice sheets (Stroeve et al., 2005; Box et al., 2012; Möller et al., 2014; Gascoin et al., 2017).

Glacier research is important in Iceland for several reasons. Seasonal glacier melt is essential for hydropower production and melt water storage in reservoirs as the energy system is strongly dependent on glacier and snow melt, which provides over 72% of the total average energy produced in Iceland (Hjaltason et al., 2018). The system isolation and high natural climate variability can pose a risk to the reliability of the energy system as drought conditions, low-flow periods and years with low summer melt are difficult to predict. Volcanic activity in glacier-covered volcanoes can cause volcanic ash and tephra fall out on glaciers during explosive eruptions, leading to enhanced melt or in some cases isolation of the glacier surface reducing melt significantly (Möller et al., 2014; Wittmann et al., 2017; Möller et al., 2019). For Icelandic glaciers, surface albedo is the dominant factor governing the annual variability of surface melt (De Ruyter De Wildt et al., 2002; Guðmundsson et al., 2009) and the correct representation of surface albedo is critical for glacier melt modelling (Schmidt et al., 2017).

Reijmer et al. (1999) found that the temporal and spatial variations in the surface albedo of the Vatnajökull ice cap ~~was~~ were reproduced fairly well by using AVHRR data for the ~~melt season in 1996.~~ 1996 melt season. To confirm this hypothesis, Reijmer et al. (1999) compared in-situ data and higher ~~resolution data from~~ spatial resolution remote sensing data from the Landsat 5 Thematic Mapper (TM) sensor~~were compared as well showing~~. The results showed greater variability in surface albedo, implying that the scale of the albedo variations is larger than the ~~AVHHR~~ AVHRR pixel (1.1 km) could resolve. De Ruyter De Wildt et al. (2002) assessed Vatnajökull glacier albedo using AVHRR images and found a strong correlation (R^2: 0.87–0.94) between the mean albedo of the entire ice cap through the melting season ~~to~~ and observed specific mass balance for the period ~~from~~ 1991–99. In the accumulation area, average albedo was found to decrease from 80% down to 60%, with a gradual decrease during the melt season, while in the ablation area, values as low as 10% ranging up to 35%, with considerable variation, were found. Gascoin et al. (2017) indicate a good ability of the MODIS MCD43A3 multi-look product to characterize seasonal and ~~interannual albedo changes~~inter-annual albedo changes, with correlation coefficients ranging from 0.47 to 0.90~~but high RMS errors~~, but high RMSE values in comparison with in-situ data. ~~Subpixel~~ Sub-pixel variability was also investigated using Landsat 5 and 7 data similar to Reijmer et al. (1999) with generally better results. Möller et al. (2014) investigated the influence of tephra depositions from the 2004 Grímsvötn eruption in Vatnajökull glacier ~~by~~ using the MODIS MCD43A3 multi-look product in combination with daily observations from the MOD10A1 product. By developing an empirically-based model to describe the albedo decrease across the glacier surface caused by the deposited tephra, they ~~concluded~~ found that the tephra-induced albedo changes were largest and most widely distributed over the glacier surface during the ~~summer season 2005~~ 2005 summer season, when the observed albedo decrease reached 35% as compared with modelled undisturbed conditions. A study by ~~?~~ Wittmann et al. (2017) for the 2012 melt season, states that the positive radiative forcing of airborne dust on Brúarjökull can add up to an additional 1.1 m w.e. (water equivalent) of snowmelt (42%) compared with a hypothetical clean glacier surface. This represents the influence of volcanic eruptions and airborne dust deposits on the mass balance of Icelandic glaciers. In most cases, dust and tephra will amplify surface melt due to additional radiative forcing during the melt season, but in some cases, ash layers exceeding a certain critical thickness can cause insulation of the underlying snow and ice. Results by Dragosics et al. (2016) ~~found~~ showed that this critical thickness to ~~range from 9–15 mm dependant~~ ranged from 9 to 15 mm depending on grain size and material type.

~~The aim of this study was to~~ Cloud cover is a major challenge for remote sensing in Iceland, even though data from both Aqua and Terra are used, the amount of cloud-covered pixels is still high (Gunnarsson et al., 2019). For albedo derived from the MODIS MCD43A3 product, the strict processing criteria of the multi-look product reduce the number of usable pixels even further than collected by Aqua and Terra. This is especially true at higher elevations for Vatnajökull where persistent cloud cover is frequently observed, resulting in fewer valid albedo pixels during the melt season. Melt increase from dust and ash deposit events is observed to extend the active melt area of the glaciers, i.e. LAP deposit in the accumulation area, increasing melting. Therefore data from these areas are very important for monitoring and forecasting runoff from glaciers in Iceland. Lag times of MCD43A3 (14–16 days) make this less feasible for near-real-time monitoring and operational modelling, for example, in the case of a major dust deposit or volcanic eruption. Additionally, MCD43A3 is not gap-filled, requiring some post-processing prior to monitoring or hydrological modelling efforts.

This study aims to address some of the shortcomings of the MCD43A3 product for glaciers in Iceland and derive an albedo data set suitable for operational use as well as a scientific study of spatial and temporal variations in albedo. The daily M*D10A1 products were chosen to increase temporal resolution, allowing for more flexibility in post-processing, statistical filtering and near-real-time data posting. There are two main objectives of the study. First, to create a gap-filled MODIS-based surface-albedo product for glaciers in Iceland for ~~the~~ this time period from 2000 to 2019 ~~,~~ validated with in-situ data ~~. The~~ suitable for the monitoring and modelling of glaciers in an operational context. Second, the resulting gap-filled product was ~~then~~ used to analyse and quantify ~~,~~ spatio-temporal patterns of albedo for Icelandic glaciers for the time period~~.~~, with monthly statistics and a detailed interpretation of the variation of albedo with elevation and trends over time.

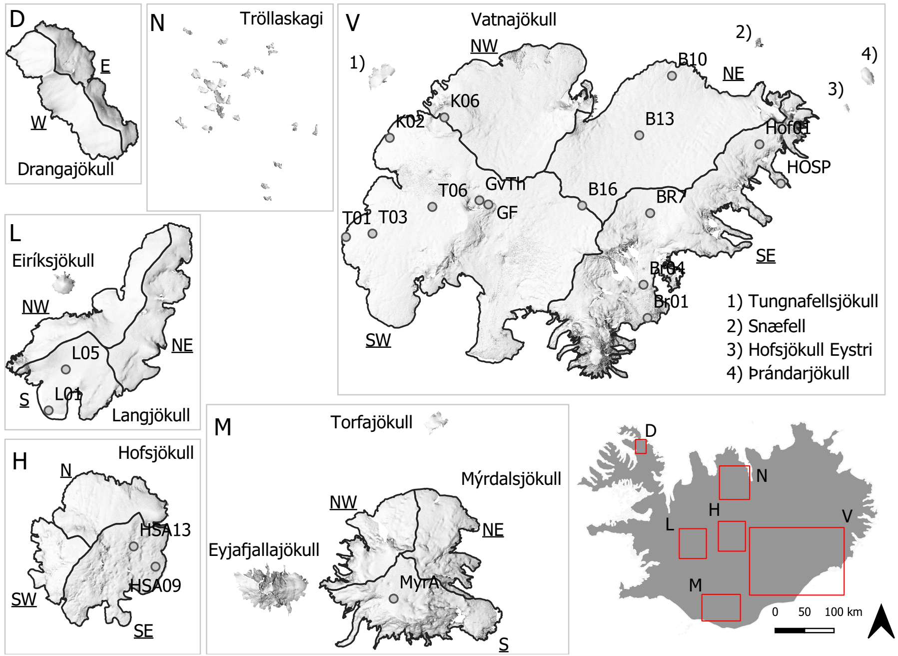

Figure 1. Location map of Icelandic glaciers used in the study. These ~~are~~ were glaciers that were at least 2 km^2 or eight unmixed MODIS pixels. For the larger glaciers, Vatnajökull, Langjökull, Hofsjökull, Mýrdalsjökull and Drangajökull, smaller areas are defined to the main ice flow basins of the glaciers for further analysis. These delineated areas are annotated with underlined text (e.g. NW for northwest). In total, 28 areas are processed, including the sub-areas, but small mountain glaciers in northern Iceland were merged into one processing unit. Available glacier automated weather stations are shown with grey dots. Further details of these stations are given in Table 1. A shaded relief representation of a glacier DEM is from Jóhannesson et al. (2013) and catchment delineation from Magnússon et al. (2016), for Drangajökull, Björnsson (1988) and ~~(Björnsson et al., 2000)~~ Björnsson et al. (2000) for Hofsjökull and Mýrdalsjökull, and ~~??~~ Pálsson et al. (2015, 2020a) for Langjökull and Vatnajökull.

2 Data and Methods

Figure 1 shows ~~the~~ a location map of ~~Icelandic glaciers used~~ the Icelandic glaciers referred to in the study. These ~~are glaciers that were~~ were glaciers that are at least 2 km^2 or eight unmixed MODIS pixels. For the larger glaciers, Vatnajökull, Langjökull, Hofsjökull, Mýrdalsjökull and Drangajökull, smaller areas were defined to represent the main ice flow basins of the glaciers for more detailed analysis.

2.1 MODIS products

Daily snow cover data products calculated from the MODIS spectroradiometer on the NASA ~~TERRA~~ Terra (MOD10A1 V006) and ~~AQUA~~ Aqua (MYD10A1 V006) platforms were obtained from the National Snow and Ice Data Center (NSIDC). The products provide daily estimates of snow cover, blue-sky albedo and a quality assessment at 500 m spatial resolution for ~~cloud free~~

cloud-free conditions at the satellite platform overpass (Hall and Riggs, 2016a, b). Daily albedo calculations use reflectances of the first seven visible and near-infrared bands of the MODIS spectroradiometer (459–2155 μm) which have been corrected for atmospheric effects. To correct for anisotropic scattering effects of snow and ice, the DIScrete Ordinates Radiative Transfer model (DISORT) is applied. The daily estimated blue-sky albedo corresponds to the broadband albedo for actual direct and diffusive illumination ~~.~~ (Klein and Stroeve, 2002), and is therefore ~~,~~ directly comparable to field observations with broadband radiometers (Stroeve et al., 2013). For comparison and validation purposes, the multi-look MCD43A3 albedo product V006 was obtained as well from LP DAAC (Schaaf and Wang, 2015). MCD43A3 provides daily albedo using 16 days of Terra and Aqua MODIS data at 500 ~~meter (m)~~ m resolution. Data are temporally weighted to the ninth ~~day~~ of the 16 ~~day~~days. The MCD43A3 product provides black-sky albedo (directional hemispherical reflectance) and white-sky albedo (bihemispherical reflectance) data at local solar noon for the same bands as used in M*D10A1 albedo products.

The quality of remotely-sensed albedo retrievals decreases during fall and winter as the incoming solar irradiance and solar incidence angle decreases. With an increase in solar zenith angles (SZA) and especially beyond 70° the accuracy of satellite- and ground-based instruments declines for albedo retrievals. This results in cases where unrealistic and unexpected values are observed and often exceed expected maximum clear-sky snow albedo. Due to polar darkness (SZA > 85°), MODIS data are generally not available from mid-November until mid-January each year over Iceland (Dietz et al., 2012). Cloud cover in Iceland also poses a challenge ~~in~~ when using optical remote sensing as average cloud cover ranges from ~~70–90~~70 to 90% with little inter-annual variability (Gunnarsson et al., 2019).

The scope of this study was limited to the melt season of Icelandic glaciers, when SZA are low and incoming solar irradiance high (~~May, June, July and August~~MJJA). Every granule from MODIS tile h17v02 was used in this project as it covered all the central highlands in Iceland and left out only a small portion of the western Snæfellsnes peninsula and the Westfjords.

2.2 Meteorological in-situ data

The Icelandic Glacier Automatic ~~Weater~~ Weather Stations network (ICE-GAWS) provided automatic weather-station observations from Vatnajökull, Langjökull, Hofsjökull and Mýrdalsjökull since 1994, 2001, 2016 and 2015, respectively. Most stations in the network were operated during the extended melt season (MJJASO) annually, while a few sites were operated all year around. All sensors were tested and validated annually before deployment in the field in spring. ~~Location~~ Locations of the sites are shown in Figure 1 and location, elevation, observation period and radiometer instrumentation in Table 1.

Radiation was measured with a net radiometer equipped with two pyranometers facing upward and downward, respectively, used to measure the incident (SW↓) and reflected shortwave radiation (SW↑) as ~~an~~ a 10 minute average. The ratio of both quantities allowed the bi-hemisperical albedo of the surface to be estimated. For comparison purposes in this study, daily integrated albedo is used instead of selecting the hourly-mean albedo measured closest in time to the satellite overpasses. Daily integrated albedo was calculated as the running 24-hour sum of upward shortwave divided by the running 24-hour sum of the downward shortwave. This method minimizes the effect of solar zenith angle on the accuracy of the albedo estimation and is less sensitive to radiometer level and cosine response errors since it integrates errors that partly cancel each other (Box et al., 2012). Daily integrated albedo has been shown to represent the daily variability of the glacier surface but only partially represent diurnal variability, such as onset of melt (Stroeve et al., 2005).

Most sites in the GAWS network used Kipp and Zone Zonen CM14, CNR1 and CNR4 radiation sensors which have relatively uniform spectral response ranging from 0.3 – to 2.8 μm with uncertainty that has been reported to be 3 — 10to 10% for daily totals over ice- and snow-covered surfaces (?Guðmundsson et al., 2009; Kipp and Zonen, 2019)(Van den Broeke et al., 2004b, a; Guðmunds . The LI-COR 200 SZ pyranometers were used at a few sites. They have reduced spectral response (0.4 — 1.1 to 1.1 μm) compared with the Kipp and Zone Zonen instruments. Tilting of the instruments with respect to the glacier surface was not monitored and could add further to the uncertainty, especially in the ablation zone of the glaciers (Van den Broeke et al., 2004b). The incoming and reflected shortwave measurements from 20 AWSs during the period 2000–2018 were used to validate the MODIS remotely-sensed albedo products.

Manual quality control of the data was done by screening shortwave and albedo data and remove removing obvious errors, periods when stations are buried in snow and calibration periods prior to site installment instalment in spring. Obvious cases of instrument failure were also rejected. Observations of upward solar irradiance exceeding downward solar irradiance were also removed. Quality control was carried out on the data at an hourly time step prior to aggregating to daily and monthly time steps. 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.

2.3 Data processing

2.4 MODIS data processing

From the MOD10A1 and MYD10A1 daily data tiles, the *MOD Grid Snow 500 m* grid and the grid variable *Snow Albedo Daily Tile* were used for the albedo analysis. Snow albedo is reported in the range 0–100 where the snow/ice-cover mask in the M*D10A1 product identifies whether a pixel is snow covered snow-covered or not. A processing pipeline for MODIS snow-albedo data was partly adopted from Box et al. (2012), with modifications and adoptions for Icelandic glaciers.
Temporal aggregation was applied to the MOD10A1 and MYD10A1 data to reduce the number of unclassified daily pixels due to clouds at the overpass time. The temporal aggregation range was set as the number of days backwards and forwards at each center centre date (t = 0) to merge to a single stack for further processing. A temporal aggregation range as of 5 days backward/forward (t = ±5 d) was selected; i.e., in total 11 days can contribute data to the temporally aggregated product. A total of 22 values are potentially available for each pixel (i.e. 11 days of MOD10A1 and 11 days of MYD10A1). This reduces by 66% the number of pixels classified as no data (cloud cover, detector saturation, etc.)by 66%. From the 22 potentially available values, the mean is calculated to represent the surface-albedo, after median based statistical rejection of outliers. Extremly . Extremely high MODIS albedo values from the original products (MOD10A1 and MYD10A1) (α > 90%) are excluded as

Table 1. Overview of average location, elevation, average operating period and radiometer instrument of the GAWS network used for validation. All stations have temperature probes while GV (Grímsvötn) and GF (Grímsfjall) only observe temperature and incoming shortwave irradiation. Location and elevation are based on the average location of the site for the observation period, i.e. mean location values for multi–year installations which might not be the exact same location from one year to another

Site	Glacier outlet	Latitude	Longitude	m a.s.l.	Operation	Radiometer
Kokv	Vatnajökull SW	64.589	-17.860	1096	MJJAS	LiC
BRE	Vatnajökull SE	64.094	-16.325	210	MJJAS	CNR1
B10	Vatnajökull NE	64.728	-16.112	779	All year	CNR1/CNR4
B13	Vatnajökull NE	64.576	-16.328	1216	MJJASO	CM14/CNR4
B16	Vatnajökull NE	64.402	-16.681	1526	MJJASO	CNR1
BRE1	Vatnajökull SE	64.097	-16.329	116	All year	CNR1
BRE4	Vatnajökull SE	64.183	-16.335	529	MJJASO	CNR1
BRE7	Vatnajökull SE	64.369	-16.282	1243	MJJASO	CNR1
T01	Vatnajökull SW	64.326	-18.118	772	All year	CNR4
T03	Vatnajökull SW	64.337	-17.977	1069	MJJASO	CNR1
T06	Vatnajökull SW	64.404	-17.609	1466	MJJASO	CNR1
K06	Vatnajökull SW	64.639	-17.523	1946	MJJASO	CM14
MYRA	Mýrdalsjökull	63.612	-19.158	1346	MJJAS	CM14
HSA09	Hofsjökull SE	64.770	-18.543	840	MJJASO	CNR1
HSA13	Hofsjökull SE	64.814	-18.648	1235	MJJASO	CNR1
L05	Langjökull S	64.595	-20.375	1103	MJJASO	CNR1
SKE02	Vatnajökull SW	64.303	-17.153	1208	MJJASO	CNR1
L01	Langjökull S	64.514	-20.450	589	All year*	CNR1
Hof01	Vatnajökull SE	64.539	-15.597	1142	All year	LiC
Hosp	Vatnajökull SE	64.431	-15.478	76	MJJASO	LiC

these are considered unrealistic values under clear skies (Konzelmann and Ohmura, 1995; Box et al., 2012) .

Cloud cover is known to be a major challenge in optical remote sensing of the Earth surface, especially for snow- and ice-covered surfaces~~(Davaze et al., 2018; Gunnarsson et al., 2019)~~. Various methods exist to differentiate between clouds and snow- and ~~ice covered~~ ice-covered surfaces (Ackerman et al., 1998; Sirguey, 2009) but omission errors are ~~challenging~~ difficult to avoid completely, leading to misclassification of surface albedo and clouds. Manual inspection of the raw MODIS albedo data for Icelandic glaciers revealed misclassified pixels due to various artefacts such as ~~clouds~~ cloud boundaries, cloud shadows, contrails, cirrus clouds and fog, especially in the glacier terminus area. These artefacts create abrupt changes in the surface-albedo time series, making it possible to reject them based on the temporally aggregated data statistics. On a pixel-by-pixel basis~~the method by~~ , the method Box et al. (2012) was applied to reject values ~~that exceed~~ exceeding 2 standard deviations from the 11 day temporally aggregated data stack. The method is only applied if 4 or more pixels in the data stack have valid albedo data. To prevent rejection of valid data, values ~~that were~~ within a certain threshold ~~from~~ of the median were not rejected. The outlier thresholds were manually adjusted, mostly related to the elevation of the glaciers, ranging from 1 ~~-~~ to 4%, for higher to lower elevation, respectively. From the 22 potentially available values, the mean is calculated to represent the surface-albedo, after median-based statistical rejection of outliers. During periods effected volcanic eruptions the outlier thresholds are not applied, allowing a greater range of expected values, especially lower values at higher elevations where tephra deposits were observed. In this study, this applies in melt seasons 2010 and 2011.

Finally, after temporal aggregation, outlier removal and statistical filtering, the ~~still remaining unclassified pixels~~ remaining pixels classified as clouds were classified statistically with four predicting variables, location (easting, northing), elevation (Z) and aspect, with a daily trained random ~~forrest~~ forest model (Matlab, 2017). Topographic and masking data for ice-covered surfaces were obtained from the National Land Survey of Iceland. The original digital elevation model was a raster with a 10 m spatial resolution which is resampled to match the grid of the MODIS pixels using bilinear sampling (GDAL/OGR contributors, 2019). ~~Correspondingly~~ Aspect was then calculated for each pixel~~aspect was calculated~~. To evaluate the model classification performance, 25% of the classified data from the temporal aggregation were withheld for comparisons purposes. The average RMS error of the classified data was 3.49~~with an~~ %, with a standard deviation of 0.80%, for the period from May to August. On a monthly ~~,~~ basis the lowest RMS error was observed in May (μ : 3.17%, σ : 0.80~~) and the~~ %) and highest in August (μ : 4.03%, σ : 0.83%) while June and July fall in between. For individual years the ~~RMS errors were the~~ RMSE values were highest in 2010, (μ : 4.02%, σ : 1.42%) and 2011, (μ : 4.73%, σ : 1.32%) for MJJA averages. This was most likely due to the volcanic eruptions in Eyjafjallajökull in 2010 and Grímsvötn in 2011. This resulted in volcanic tephra depositions on Icelandic glaciers that poorly correlate to topographic patterns of albedo as the random forest model was trained on location, elevation and aspect. The final output, a daily gap-filled albedo grid, which was used for further processing, is hereafter refereed to as MCD11.

For MCD43A3 multi-look data to be comparable with GAWS data, the ~~blue sky~~ blue-sky albedo was calculated as the average between the black-sky albedo and the white-sky albedo tiles in the product, assuming a constant fraction of diffuse illumination as done by Möller et al. (2014) and Gascoin et al. (2017) in previous studies ~~at~~ of Icelandic glaciers. For cloud cover estimations, daily valid pixels in MOD10A1 (AM overpass) and MYD10A1 (PM overpass) were merged ~~to~~ into a single daily product, representing average daily cloud cover.

To quantify the changes in albedo over time, trends were calculated. The calculations are pixel-based from annual MJJA averages for the period 2000–2019. Significance of ~~data~~ the estimated trends were calculated using the ~~Mann–Kendall test. The Mann–Kendall test is a~~ non-parametric ~~test,~~ Mann–Kendall test that detects the presence of a monotonic tendency in chronological data, and identifies trends in data over time without an assumption of normality (Helsel and Hirsch, 2002). Trends are considered statistically ~~significance then the p-value~~ significant when then the p-value is lower than 0.05. For this study, glacier boundaries delineated in 2010 and 2012 were used for Vatnajökull, and boundaries in 2007 and 2008 for Langjökull and Hofsjökull, respectively. This was selected as a midpoint representing an average glacier area during the period 2000–2019. This needs to be considered when ~~discussing~~ interpreting rapid changes at the glacier terminus, as some areas in 2000 ~~where~~ were part of an active glacier but might in 2019 be ~~dead ice~~ dead-ice or land.

3 Results and discussion

3.1 MODIS albedo validation

~~The MODIS albedo data was validated by a pixel-based comparison, i.e. the nearest pixel to the GAWS station locations was extracted to a time series. In total 20 GAWS sites have SW↓ and SW↑, enabling albedo calculations during the period 2000–2019 spanning elevations from 100 to 1850 m a.s.l., ensuring validation data over a wide elevation range at Vatnajökull, Hofsjökull, Langjökull and Mýrdalsjökull. Months with less than 26 days of GAWS data were excluded from the comparison and daily averages were not calculated unless 22 hours of data within a day were available. MODIS provides only albedo estimation for clear sky conditions.~~

Figure 2 shows the comparison results for ~~May, June, July and August~~ MJJA for MCD11. Overall good visual and statistical agreement is found between the MODIS MCD11 data and ~~the~~ in-situ albedo from GAWS observations. For the whole period from ~~May–August~~May to August, the RMS error is 7.2% with an R^2 of 0.9. The GAWS observation network captures a wide range of melt-season variability of albedo ranging from ~~6–90~~6 to 90% which is well captured with the MODIS MCD11 product as demonstrated ~~with~~ by the overall high correlation coefficients. Based on linear regression (red lines in Figure 2) for all months, albedo was slightly underestimated for higher values (albedo $> \sim 55$) and slightly overestimated at lower values by the MODIS MCD11 product. Various reasons could contribute to these differences, such as sensor accuracy and instrument installation configuration (i.e. tilting, riming on the sensor dome). In the ablation zone, where the lowest albedo values were observed, high melt rates (surface lowering of 3–7 m) can contribute to ~~progressing~~ progressive tilting of the instruments over the ablation period. Large sand, dust and tephra-covered areas have been observed in the instrument footprint during field visits, as well as melt channels and small melt water ponds offsetting the spectral properties of the surface compared with the spectral response of snow and ice, inducing errors in the comparison between in-situ and remotely-sensed albedo. The temporal aggregation of the remotely-sensed data includes a dampening effect on the MCD11 data compared ~~to~~ with the GAWS observations, which ~~could possibly~~ may partially explain outliers in July and August when the in-situ observations are higher than the MCD11. Extensive snowfall events, occurring under cloud cover and limiting accurate data retrievals by the satellites, will lead to albedo that is not correctly represented in the MCD11 reconstruction due to the 11 day temporal aggregation.

Table 2 shows a comparison of MCD11 with other albedo products from MODIS, i.e. MOD10A1, MYD10A1 and MCD43A3. In most cases, the MCD11 product had lower ~~RMS errors~~ RMSE values and higher correlation coefficients~~indicating the success in removing~~ , indicating successful removal of spurious values such as misclassified clouds, image stripes and other ~~artifacts~~ artefacts in the original MODIS products. No correlation was found between RMS error and GAWS location (eleva-

Table 2. Comparison of MODIS albedo products (MOD10A1, MYD10A1, MCD43A1 and MCD11) with GAWS in-situ albedo on a monthly timescale.

	MOD10A1		MYD10A1		MCD43A3		MCD11	
Month	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2
May	8.66	0.82	8.34	0.84	8.28	0.84	7.9	0.86
June	7.07	0.91	7.20	0.91	7.49	0.91	6.59	0.92
July	7.08	0.92	6.30	0.93	7.09	0.91	6.49	0.93
August	8.24	0.88	7.52	0.90	11.0	0.75	7.79	0.89

tion or glacier/location). No further adjustments or calibrations are applied to the MCD11 product in the ~~further use in~~ rest of this study. Table B1 shows validation results for individual stations for MOD10A1, MYD10A1, MCD43A3 and MCD11.

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%~~RMSE values ranging from 8 to 21%, although the results from Gascoin et al. (2017) are based on daily values. Various studies in Greenland using in-situ AWS report lower ~~RMS errors~~RMSE values, ranging from 2.8 ~~–5.4~~to 5.4% on a monthly basis for MOD10A1 using 17 stations for validation by Box et al. (2012) and a total RMSE of 6.7% in a study by Stroeve et al. (2013) using MCD43A3 ~~high quality~~ high-quality retrievals. It is important to consider how representative point-based in-situ observations are (observing ~120–180 m^2 (Kipp and Zonen, 2019)), compared with the spatial footprint of the MODIS data (0.25 km^2), especially in glaciated areas with high spatial albedo variability and MODIS sub-pixel variability as is observed in the bare-ice areas of the Icelandic glaciers.

Sub-pixel variability has been investigated by Reijmer et al. (1999), Pope et al. (2016) and Gascoin et al. (2017) for ~~the Icelandic glaciersindicating high sub-pixel albedovariability.~~ Icelandic glaciers. The study by Reijmer et al. (1999) using AVHRR and Landsat TM data at Vatnajökull reported large systematic differences for some of the automatic weather stations on the ice, attributed to sub-pixel-scale variations in the albedo. Results implied that the scale of the albedo variations was smaller than the scale of the AVHRR and TM pixels. Pope et al. (2016) studied high-resolution (5 m) airborne multi-spectral data collected over Langjökull in 2007, with comparison to near-contemporaneous Landsat ETM+ and MODIS imagery showing albedo to be highly variable at small spatial scales. Work by Gascoin et al. (2017) suggested that the RMSE of the difference between the in-situ automatic weather station data and MODIS data tends to increase when the corresponding Landsat sub-pixel spatial variability is higher. Lower standard deviation values were consistently obtained where the surface was less heterogeneous (accumulation areas).

3.2 Gap-filled albedo

Figure 3 shows the average cloud cover for the main Icelandic glaciers from April to ~~October~~September, based on daily MODIS data from ~~AQUA and TERRA~~Aqua and Terra. This highlights the challenges for optical satellite remote sensing in Iceland due

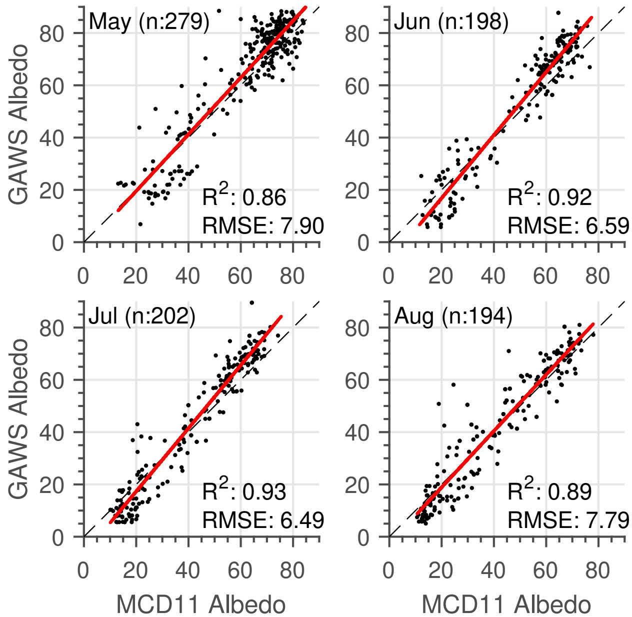

Figure 2. Comparison of monthly averaged monthly-averaged MODIS albedo with in-situ GAWS albedo observations for May, June, July and August for the period from 2000–2019 where data were available for the MCD11 data product.

to cloud obscurity problems. The average cloud cover for glaciers was 73.8% for MJJA and slightly higher for AMJJAS, or at 74.4%. Monthly variability within the melt season was low, with the highest values seen in April, July and September (78, 76 and 75%, respectively) and lower values in May, June, August and October (73, 73.5, 72.8 and 72.8% respectively, respectivel; individual months are shown in Fig. B1–B3). The average highest highest average cloud cover was observed for Eyjafjallajökull (80.3%), Drangajökull (79.6%) , and Mýrdalsjökull (77%) for melt-season averages while the other glaciers have lower average cloud cover ranging from 71–7471 to 74%.

The average daily cloud cover in MOD10A1 data was 79% and slightly lower for MYD10A1, or at 78%, based on data from April to October each year for the period from 2000–2019. By joining these two products on a daily basis, cloud-obscured pixels were reduced to 74%. Temporal aggregation (11 days) of the products had an exponential decaying shape of unclassified pixel reduction, with the highest benefit for aggregating 1 day. For this study, data were aggregated 5 days forward and backward allowing 11 days of both AQUA and TERRA Aqua and Terra MODIS albedo data to contribute to a daily average. This resulted in an average unclassified pixel reduction down to 12%.

The main advantage of the temporal aggregation of the data was the reduction of cloud-obscured pixels, which provides a more spatially continuous product in a simple and computationally efficient way. This comes with the primary disadvantages of response dampening of rapid changes, experienced as an a smoothing effect on the albedo time series. This could pose

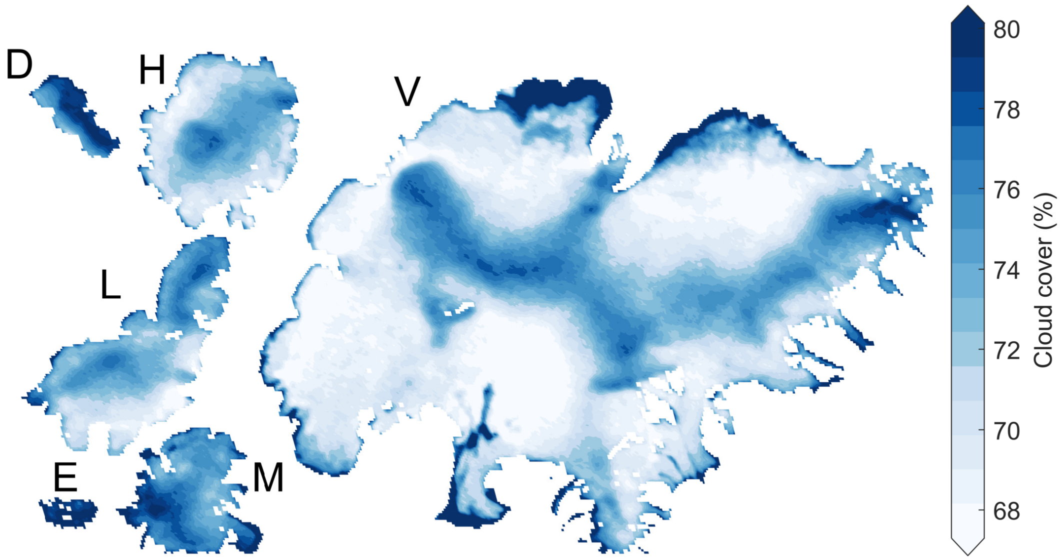

Figure 3. Average cloud cover for the main Icelandic ice caps for the extended melt season from May to September each year from 2000–2019 (average: 73.8%).

a limitation on daily ~~near real-time flow forecasting~~near-real-time flow forecasting, while for weekly to monthly time scale applications, the product should be representative. Cloud detection in the MODIS products is based on the M*D35−L2 cloud mask providing four categories for discrimination of clouds, i.e. cloudy, uncertain, probably clear and confident clear. Cloud and snow confusion is known ~~for~~ to be present in MODIS data for many reasons, such as cold clouds with ice content, very similar spectral responses to snow of some cloud types~~as snow~~, and cirrus clouds that are not detected (Sirguey et al., 2009; Box et al., 2012). The approach in this study to reduce cloud ~~artifacts~~ artefacts is based on robust statistics with a median-based outlier removal. The drawback of this approach is that with a too strict criterion for rejection, valid data could be rejected, with loss of good quality data, especially in cases where surface albedo changes rapidly.

3.3 Annual and inter-annual variability of albedo

Inter-annual albedo variations for Icelandic glaciers were generally high. Figure 4 shows spatial patterns for melt-season mean albedo for the investigated glaciers for the period ~~from~~ 2000–2019 (MJJA). The lowest albedo values (<35%) were found in bare-ice areas where the winter snow cover generally is completely ablated during summer, revealing dirty and impurity-rich bare ice. Higher albedo values (> 45–50%) were found in the accumulation areas associated with higher elevations and a shorter period of positive surface-energy balance during the melt season.

Figure 5 shows the average albedo distribution and relations to elevation in 100 m bands for the six largest ice caps and their sub-areas defined in Fig. 1. Above 1500 m a.s.l. at Vatnajökull there ~~were~~ was limited regional variability while more distinctive patterns were seen between the northern ~~(NW and NE) and~~ and southern parts, especially in the southeast at lower elevations. In the southeast, the elevation of the glacier ranges all the way down to sea level while the glacier terminus was at a much higher elevation in the north (600–700 m a.s.l.). The ~~average-albedo-elevation~~ average albedo-elevation relationship for Vatnajökull, exhibits three elevation gradients. For elevations below 700 m a.s.l. the linear albedo gradient was ∼2.3%/100 m, ∼5.1%/100 m between 700–1300 and ∼0.5%/100 m for elevations above 1300 m. For Hofsjökull, the albedo was generally lower in the southeast than in the northern and southwest parts~~,~~; the average albedo elevation gradient below 1400 m a.s.l. was 4%/100 m and 1.5%/100 m above 1400 m a.s.l. For Langjökull, the south and northeast areas had overall lower average albedo values compared with the northwestern part of the glacier. At Langjökull, the albedo elevation gradient was 3.5%/100 m for the whole elevation range, which was similar ~~as for~~ to elevations below 1400 m a.s.l. at Hofsjökull, but note the start of a change towards a lower gradient at the higher elevations. The northwest part of Mýrdalsjökull had generally higher albedo compared to the southern part. The albedo gradient is 3%/100 m ~~while~~ for the whole elevation range. Distinctive patterns were observed for the ~~eastern and southern part~~ east and south parts of Drangajökull, with lower average values for the south region. A very strong east/south ~~cloud cover gradient was as well~~ cloud-cover gradient also observed at Drangajökull (Fig. 3) ~~that~~ could explain these differences, indicating that less SW↓ reaches the surface, accelerating the snow metamorphism and resulting in lower albedo. The average albedo elevation gradient was 3.0%/100 m for Drangajökull and 2.7%/100 m for Eyjafjallajökull. In general for Eyjafjallajökull, the southern parts of the main ice caps had lower albedo. This was most likely controlled or strongly influenced by orographic generation of precipitation in the dominating ~~SE-SW~~ SW–SE wind providing more energy from rain and warmer temperatures at the surface, accelerating the snow metamorphism (Einarsson, 1984; Crochet et al., 2007; Björnsson et al., 2018). Local lower albedo gradients at Hofsjökull (SE), Langjökull (S) and Mýrdalsjökull (S) coincide with documented locations of severe or extremely severe dust source areas described in Arnalds et al. (2016).

Figure 6 shows the average distribution of albedo as a function of elevation bands (100 m intervals) and time for the period ~~from~~ 2000–2019. The annual maximum albedo value for all elevation bands was generally observed in early April, associated with the last major ~~snowfalls of winter~~ winter snowfall. The lowest average albedo values were observed from ~~mid July to mid August~~mid-July to mid-August. For higher elevations (accumulation areas), the minimum values were associated with first snowfall which increases albedo. For bare-ice areas with impurity-rich ice, these impurities can be washed away from the glacier surface by rain which lead, to higher albedo without fresh snow, i.e. cleaner ice, with less impurities, in late summer.

Figure 7 shows average melt-season mean albedo for the glaciers and sub-areas defined in Fig. 1. Glaciers were sorted from the highest to the lowest melt-season mean albedo for the whole analysis period (highest at the top of the figure), revealing certain spatial, temporal and feature position patterns.The lowest albedo values were observed for Mýrdalsjökull, Eyjafjallajökull and Torfajökull, which ~~all~~ cluster together at the south coast of Iceland (Fig 1, box M). They were also all close to widespread unstable sandy surfaces subject to frequent high-velocity winds, driving numerous wind erosion events and dust production. These unstable erosive surfaces do not sustain seasonal snow cover far into the spring and summer, making them accessible for erosion earlier in the spring than similar areas in the north and east highlands near to Langjökull, Hofsjökull and Vatnajökull.

These glaciers were relatively smallas wellDagsson-Waldhauserova et al. (2014, 2015, 2019) have also shown that dust events can occur frequently in southern parts of Iceland during winter given the right surface and meteorological conditions for dust transport. The Mýrdalsjökull, Eyjafjallajökul and Torfajökull glaciers are also relatively small, indicating that dust producing dust-producing events can influence larger areas of the glaciers with dust deposits. Following these glaciers on the south coast were smaller glaciers, with the exception of northwest Langjökull, with slightly Slightly higher annual average albedo . These were was seen for small alpine and valley glaciers with less smaller elevation range and surface area compared with the large ice caps.The main ice-caps

The main ice caps in Iceland, Vatnajökull, Hofsjökull and Langjökull, had relatively high average albedo compared with the other glaciers, with the exception of the northwestern part of Langjökull which was close to the Flosaskarð area known for extremely severer severe erosion (Arnalds et al., 2016). Drangajökull had the highest observed albedo, its location was ; its location is far from unstable surfaces that produce airborne dust, and volcanic eruptions (2010, 2011) seem to have a minimal effect compared with other Icelandic glaciers. Albedo development at Drangajökull was is likely mostly driven by snow metamorphism where snow grain size increases with time and energy input, resulting in lowering of albedo.

On the temporal scale, various events influencing the melt-season mean albedo were are observed in Fig. 7. For the south coast glaciers (Fig 1, box M), the influence of the 2010 volcanic eruption in Eyjafjallajökull and the post-eruption influence in 2011 and 2012 were obvious, and there were also influence influences on other Icelandic glaciers, with the possible exception of Drangajökull, Hofsjökull Eystri, Snæfell and Norðurlandsjöklar in the north. The influence on albedo due to the 2011 volcanic eruption in Grímsvötn was seen in south west south-west Vatnajökull isolating the glacier surface, constricting surface melt in about 420 km^2. Generally albedo was lower for most glaciers in that year, excluding Drangajökull. In 2015, a cold spring and summer, with prolonged snow cover in the highlands, delayed the onset of melt, as well as limiting the capabilities for airborne dust and tephra to be transported to the glacier surface. The highest melt-season mean albedo observed during the study period was in 2015 for all glacierglaciers, while the lowest albedo was seen in 2010. The melt season in 2019 2019 melt season was furthermore seen to be quite unique. Due to an early winter snow cover melt in the highlands in late April, the earliest and most extensive snow cover depletion for 20 years (MODIS period) (Gunnarsson et al., 2019), followed by a prolonged period with limited precipitation, great amounts of dust and sand from unstable sandy surfaces were transported to the glaciers, providing Light Absorbing Particles LAP that further enhance surface melt. Although similar singular events had been observed historically during the MODIS period, this development was observed at all Icelandic glaciers. Note must be taken when melt season melt-season average values are interpreted that they are influenced by the areal elevation distribution of each glacier or sub-area.

Seasonal variability of albedo for Icelandic glaciers was generally high. Figure 8 shows glacier average seasonal albedo distribution for 2000–2019 plotted together with selected years for Vatnajökull, Hofsjökull, Langjökull, Mýrdalsjökull, Eyjafjallajökull and Drangajökull. The average albedo generally declines from the maximum observed in the first two weeks of April each year (70–80%) to an annual minimum in August. The average minimum observed value is 40–45% for Vatnajökull,

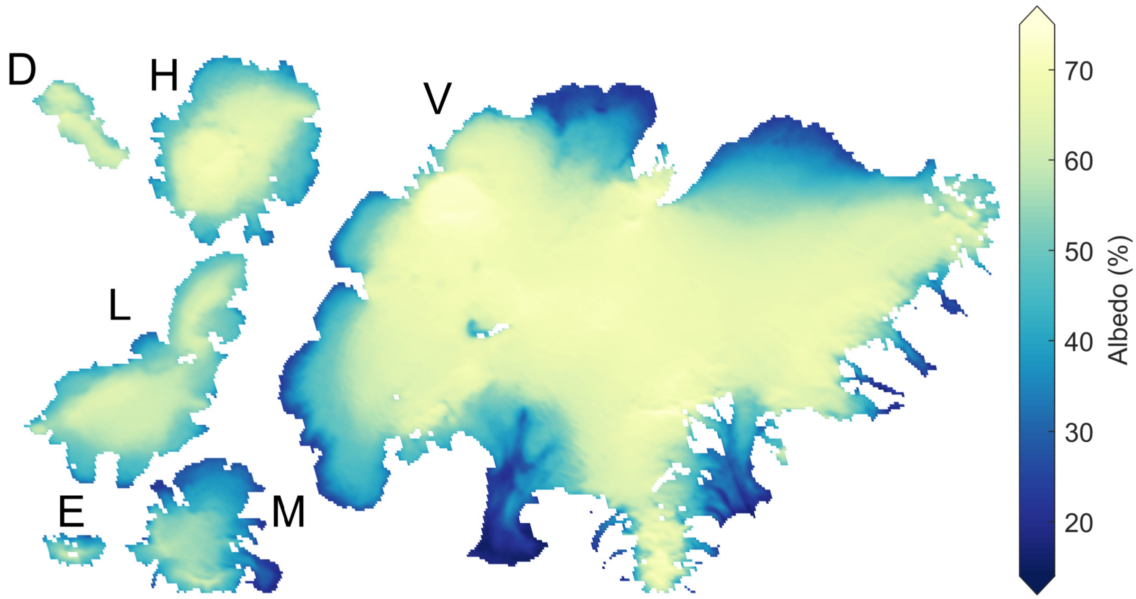

Figure 4. Spatial patterns of mean albedo for the period ~~from~~ 2000–2019 (MJJA). **D:** Drangajökull, **H:** Hofsjökull, **V:** Vatnajökull, **L:** Langjökull, **E:** Eyjafjallajökull and **M:** Mýrdalsjökull.

Hofsjökull, Langjökull and Drangajökull but reaches lower values at Mýrdals- and Eyjafjallajökull (~~>~~<30%). Glacier runoff generally peaks in late June and July (midsummer) (Schmidt et al., 2018), with low albedo and maximum incoming shortwave irradinace near the summer solstice. The variability similarly gradually increased in June, July and August and was generally highest in August. In the fall, seasonal weather patterns in Iceland shift with lowering temperatures and an increase in precipitation following shorter days due to a gradual increase in solar zenith angles (Einarsson, 1984; Hanna et al., 2004; Björnsson et al., 2007, 2018). Frequently in the latter half of August and beginning of September, the first snowfall is observed to increase albedo with fresh highly reflective snow. It was not uncommon to see the albedo lower again after the first snowfall due to liquid precipitation or other events that melt the fresh snow cover over the bare glacier ice. This affects the ~~variance~~ variation of albedo in August and September.

Figure 8 also shows how albedo develops through the melt season for selected abnormal years. The influence of explosive volcanic eruptions in Grímsvötn in Vatnajökull ~~are~~ is shown in 2005 (~~erupted~~ the eruption took place in November 2004) and 2011 and the Eyjafjallajökull eruption in 2010. These events generally influence the albedo of Icelandic glaciers as tephra is discharged into the atmosphere and transported by wind over wide areas. In 2015, seasonal mass balance ~~programs~~ programmes for Vatnajökull, Langjökull and Hofsjökull reported unusually thick winter snow cover followed by a cold and cloudy spring and summer which resulted in a positive net surface mass balance, for the first time in 20 years ~~(???)~~ (Pálsson et al., 2020a, b; Þorsteinsson et al., 2017). Figure 8 shows the development of albedo in 2015 ~~as~~ to the highest aver-

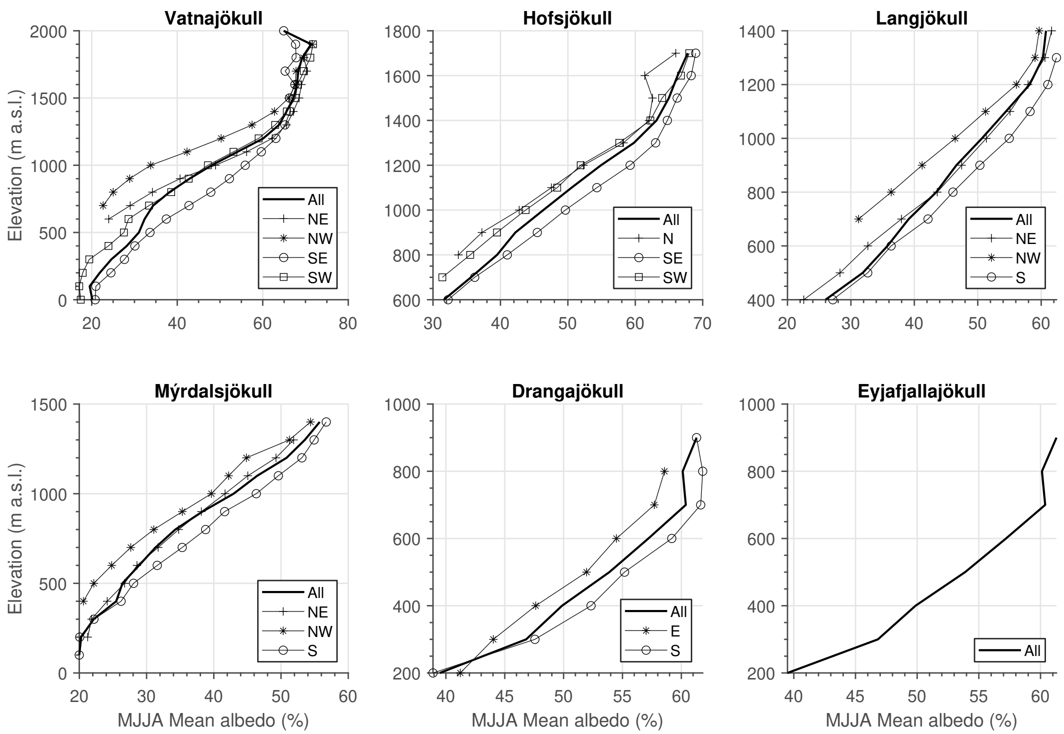

Figure 5. Average albedo for the period as function of elevation for the period 2000–2019. Data are shown for the six largest ice caps for the whole glaciers (All) as well as for the sub-areas defined in Fig. 1. Note: the elevation range varies between figure axes (y-axis).

age values for the study period.

Figure 9 shows the spatial distribution of seasonal average albedo as anomalies from the mean. Blue ~~colors~~ colours represent anomalies above the mean, i.e. higher albedo values, while red areas represent values below the mean. Decisive negative patterns were observed in 2010 and 2011. These relate to the volcanic eruptions in Eyjafjallajökull (2010) and Grímsvötn (2011) as tephra dispersal from explosive eruptions produces high volumes of airborne tephra ~~(Gudmundsson et al., 1997; Guðmundsson et al., 2012;~~ (Gudmundsson et al., 1997; Guðmundsson et al., 2012; Tesche et al., 2012). Airborne tephra and dust can be transported by high plumes that can extend several kilometres into the atmosphere and be transported great distances, up to several hundred kilometers ~~(Guðmundsson et al., 2012; Watson et al., 2016)~~(Guðmundsson et al., 2012; Watson et al., 2016; Đorđević et al., 2019; Dagsso . Tephra dispersal and fallout patterns from explosive eruptions depend on ~~multiple~~ many factors, including plume height, particle size distribution, and wind direction and velocity~~among various geological factors~~. No eruption occurred in 2012 but residual effects were observed as ash deposits from previous eruptions were carried with the prevailing wind directions and high dust storm activity reported in the area, enhancing melt due to the lowering of albedo (Möller et al., 2019; Butwin et al., 2019) . These effects were most clear for Eyjafjallajökull and Mýrdalsjökull but also contribute to negative anomalies for Vatnajökull. The impact of dust deposition on albedo in 2012 for Vatnajökull was investigated by ~~?~~ Wittmann et al. (2017) using

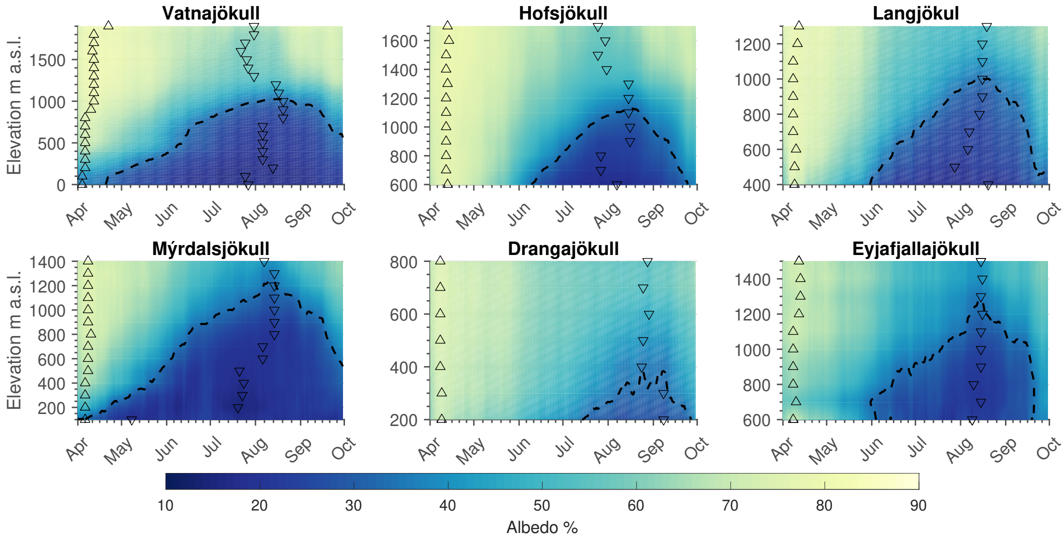

Figure 6. Albedo as a function of elevation and time for the period 2000–2019. Triangles show the max/min values associated with each elevation band, and the dotted black line shows the isoline for 34% albedo, as defined by Cuffey and Paterson (2010) for bare glacier ice.

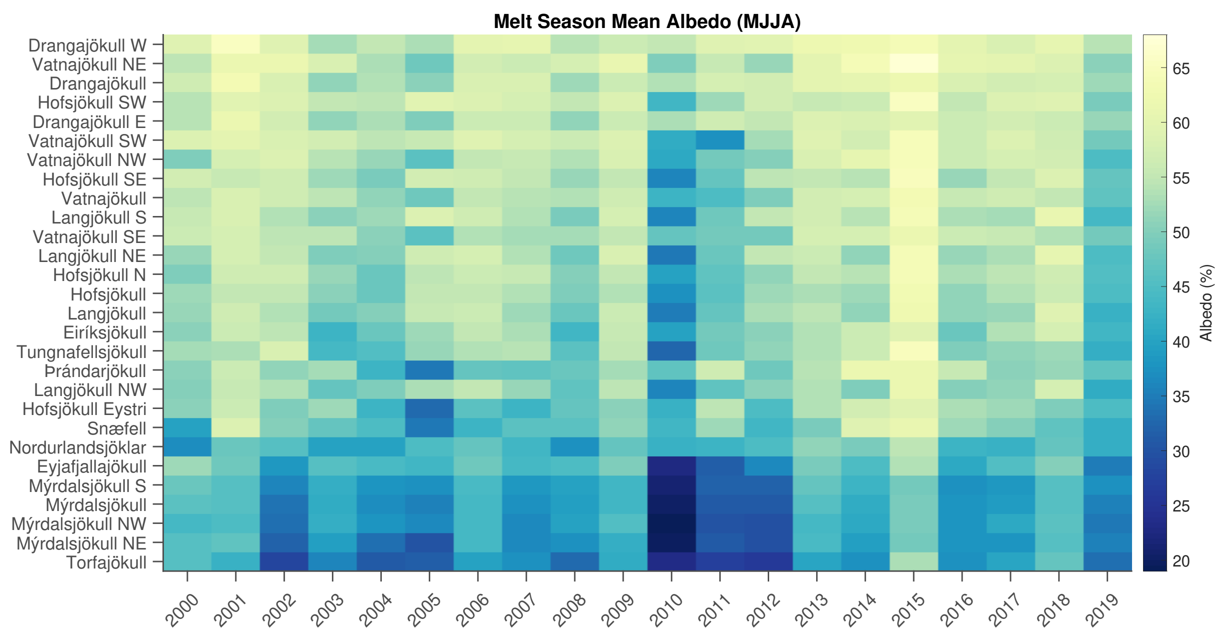

Figure 7. Average melt-season albedo for the studied glaciers. The glaciers are sorted from the lowest 2000–2019 melt season average albedo to the highest. For the larger glaciers, data are provided for individual ice-flow basins, see Figure 1.

dust-mobilization models to calculate dust emission and a dispersion model to simulate atmospheric dust dispersion and deposition on the glacier surface. The main conclusion was that the influence of dust on albedo could lead to up to 40% ~~melt~~

~~increase~~ increase in melt, which confirms the influence of these events on seasonal glacier melt.

Another influencing factor for negative albedo anomalies was dust, sand and other ~~Light Absorbing Particles (LAP)~~ LAP transported from the proglacial areas and sandy deserts which cover more than 22% of Iceland ~~(Arnalds et al., 2016; ?). Plume shape~~ (Arnalds et al., 2016; Wittmann et al., 2017). Plume-shaped patterns could be identified especially for the northern part of Vatnajökull, indicating airborne LAP deposits on the glacier surface. ~~As an~~ For example, in 2001, 2003, 2007, 2008 and 2013, such patterns were observed in the northern part of Vatnajökull (Brúarjökull glacier outlet) extending from the Kverkfjöll mountain range high in the accumulation area as local negative albedo anomalies. These were unlikely to be linked to local climatology resulting in such distinctive anomalies, as such events or dominating patterns would influence larger areas. In 2014–15, the lava flow field of the Holuhraun non-explosive eruption covered about 84 km^2 of volcaniclastic sandy desert and proglacial areas north of Vatnajökull. Since then, similar ~~plume shaped albedo anomalies were not~~ plume-shaped albedo anomalies have not been observed in the data. It is probable that the extent of the lava flow field reduces the dust production of this area significantly, although this cannot be quantified at this point in time~~,~~ ; more data over a range of climatologies are needed to fully understand the impact of the Holuhraun eruption on dust production. Figure 9 also shows an interesting anomaly pattern for 2019. All the major ice caps had largely negative anomalies driven by dust and mineral deposits with an early onset in the spring. The events leading up to these anomalies have already been discussed above. In 2000, large negative anomalies were seen in Dyngjujökull and Brúarjökull (Northern Vatnajökull). These are unlikely to be linked to the ~~1999~~ 2000 Hekla eruption and are presumed a combination of residual effects from the Gjálp eruption in 1996 and dust transported from the ~~pro glacial~~ proglacial areas near the glacier terminus. Landsat images from ~~the summer in~~ summer 2000 show the ~~surroundings near~~ tephra-covered surroundings of Gjálp ~~covered in tephra as~~ to be a possible dust source in ~~a combination with pro glacial~~ combination with proglacial areas.

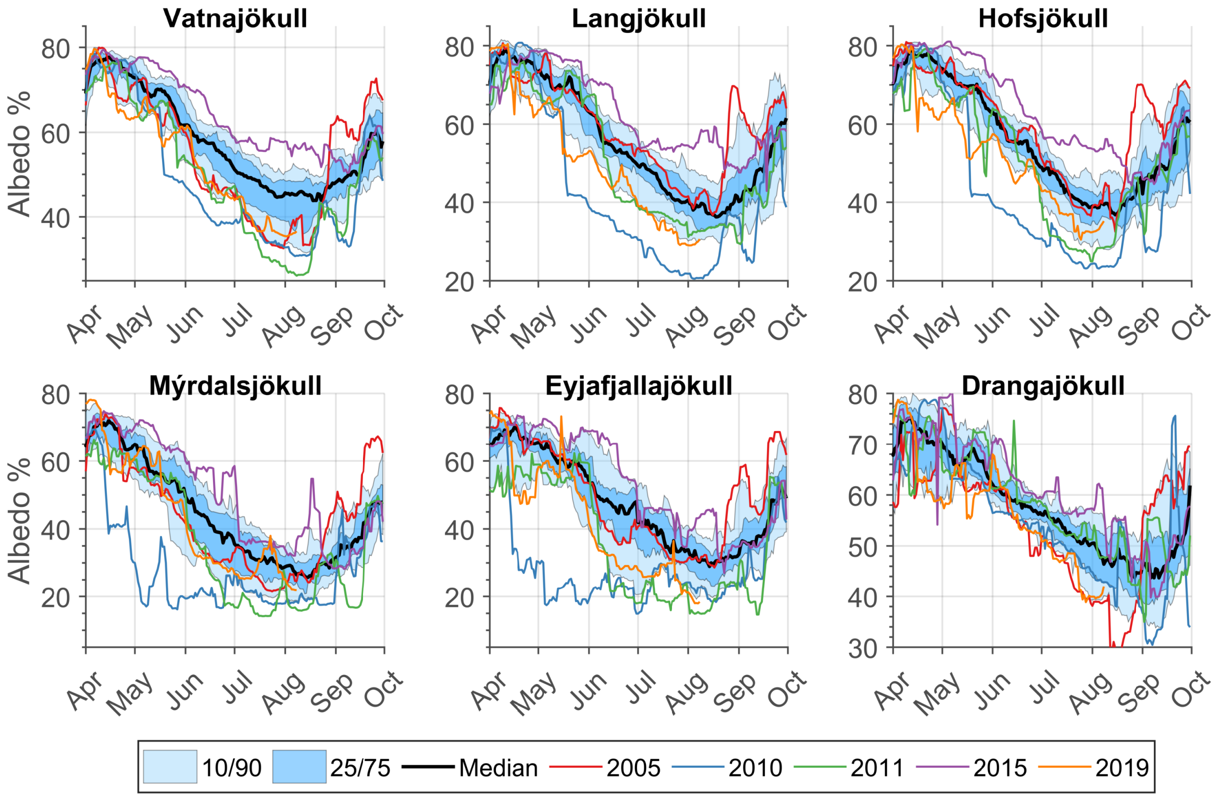

Figure 8. Seasonal variations of average albedo for selected Icelandic glaciers from the MCD11 product for April to October ~~for the from~~ 2000–2019.

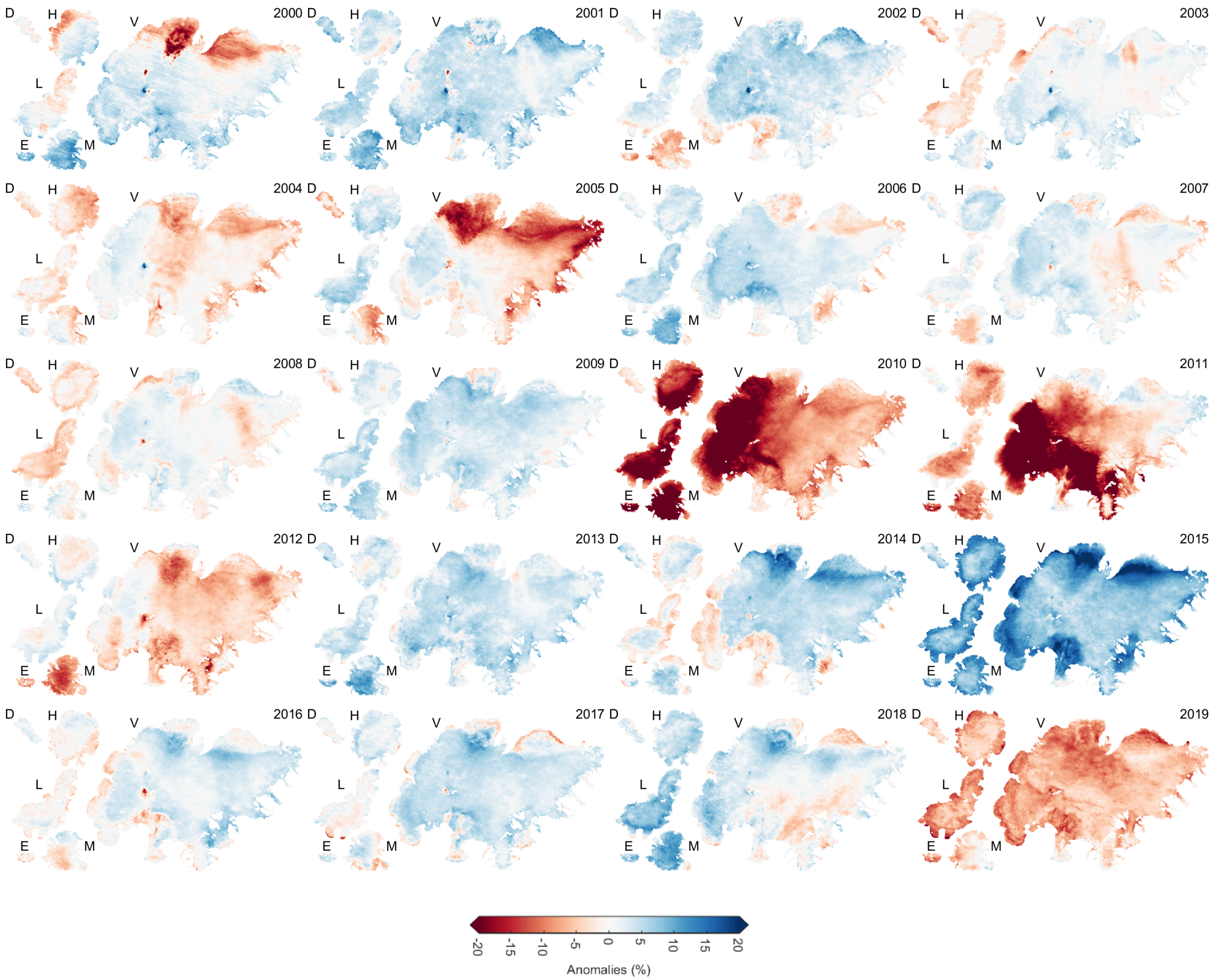

Figure 9. ~~Spatial~~ Annual spatial patterns for melt season (MJJA) albedo anomalies for the ~~period from~~ 2000–2019.

3.4 Trends of albedo

Figure 10 shows ~~annual spatial patterns of albedo trends~~ the spatial pattern of melt season (MJJA) trends in terms of the total change of a least square fit to the albedo during 2000–2019. For Vatnajökull, negative albedo melt season trends were found in the lowest areas of the glacier with the exception of the northwestern part (Dyngjujökull). Negative trends at the terminus of glaciers were expected due to ~~steady glacier retreat for the past decadeswith an~~ glacier retreat in recent decades, with associated debris deposits on dead-ice ~~(Einarsson, 2018)~~(Einarsson, 2018; Hannesdóttir et al., 2020). In general, negative trends extend farther into the accumulation area in the southwest while a growing positive trend was observed in the upper part of the ablation area in the northern part with the exception of the terminus area of Brúarjökull~~termini area~~. Positive trends in the upper part of the ablation area in the northern part (Brúarjökull and Dyngjujökull) of the ice-cap are significant over most of the area. ~~These positive~~ Positive melt season trends were ~~seen for the area~~ also seen near the equilibrium line elevation at Hofsjökull, for most of ~~the extent of~~ Drangajökull, in the northern ~~area~~ part of Mýrdalsjökull and distributed parts of Langjökull~~with the exception of Eyjafjallajökull~~, suggesting a trend towards either increased snowfall or ~~increased~~ decreased snow melt at these glacier outlets. As a melt-season average trend (Fig. 10) these positive trends are only significant in the ablation area in the northern part ~~while negative~~ of Vatnajökull. Negative trends were identified at many glacier termini ~~,~~ due to the steady glacier retreat in ~~the past decades,~~ recent decades, with reduction in the duration of snow cover over low-albedo bare ice, while for the accumulation area in southwest Vatnajökull ~~,~~ the trend is strongly controlled by volcanic ash fallout in 2010 and 2011.

Figure 11 shows average monthly-mean albedo for the main ice caps for the study period, the associated linear trends and the average linear slope of the trend. For all the glaciers with the exception of Drangajökull in June, the average linear slope for May and June was negative, i.e. lower average albedo earlier in the spring. For Vatnajökull, Hofsjökull and Langjökull, the trend was strongly influenced by low May and June albedo in 2017 and 2019. These trends indicate that ~~an~~ more incoming shortwave energy is absorbed at the surface during these months with lower albedo. In July and August, the trend was in general positive, trending towards higher mean albedo. The trends ~~were only statistically significant~~ in July and August were only statistically significant for Drangajökull and in July for Hofsjökull. Positive trends could indicate more extensive or earlier snowfall in July and August, with fresh highly reflecting snow. Extensive dust transport to the glacier surface, as seen in 2019 melt season, had similar overall albedo lowering effect to that in the eruption years 2010 and 2011 for Vatnajökull, Langjökull, Eyjafjallajökull and Drangajökull specifically. It is, however, noted that following volcanic eruptions albedo lowering is generally more localized while extensive dust transport tends to affect larger areas.

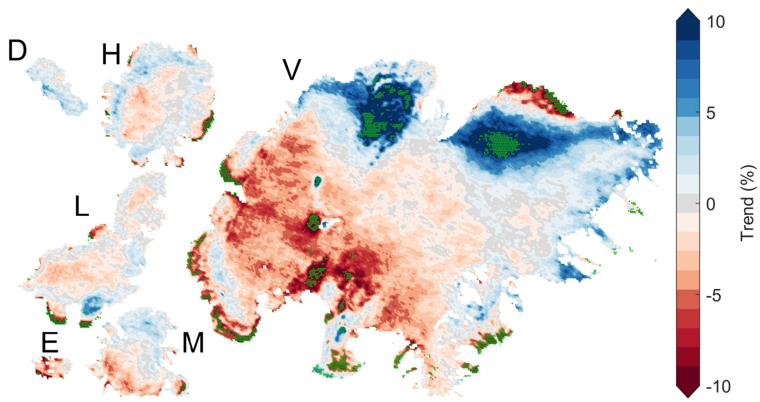

Figure 10. Spatial patterns for albedo trends during the melt season (MJJA) for the period ~~from~~ 2000–2019 in terms of the total change of a least square fit to the albedo over the period. Green stipples indicate areas where significant changes were found.

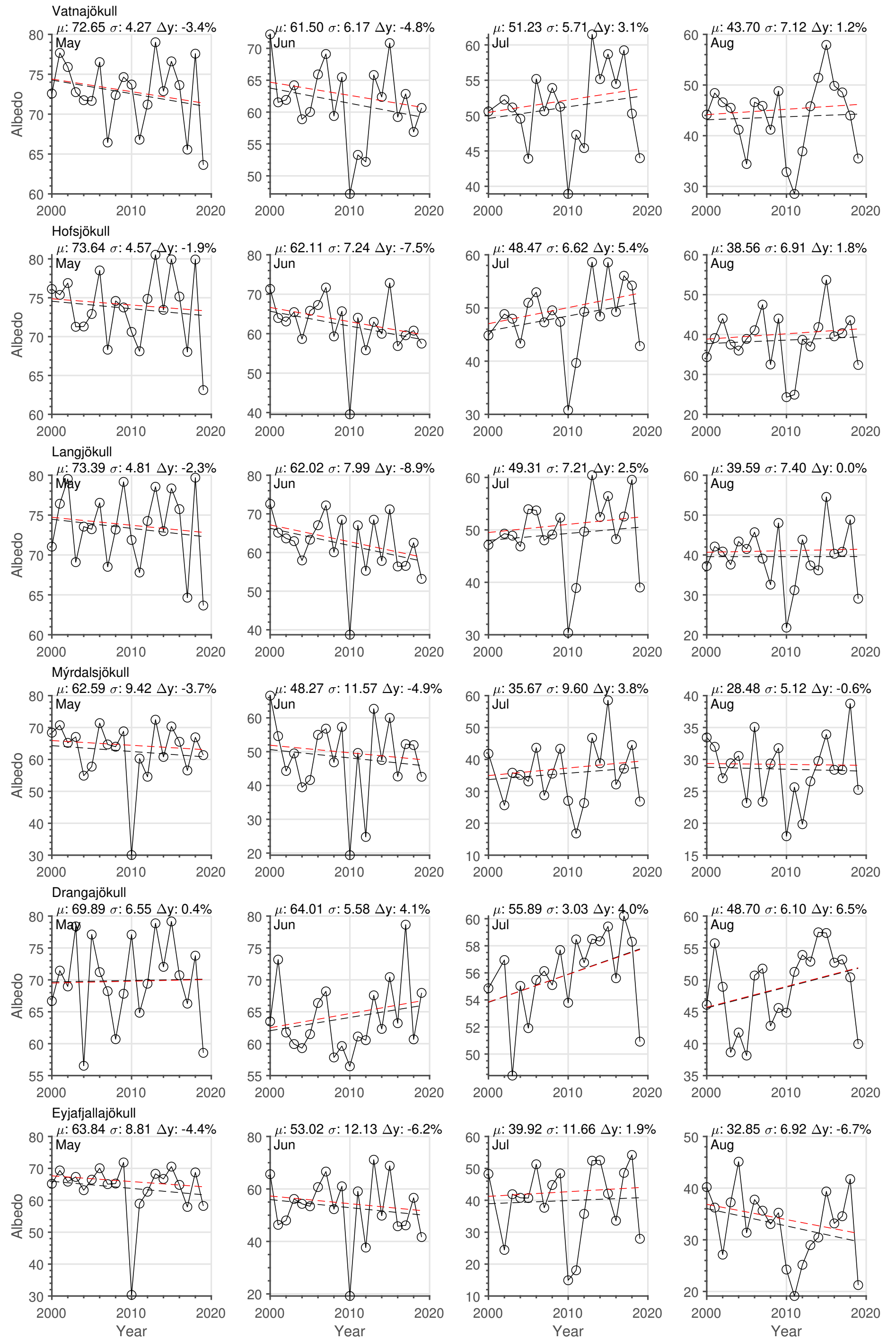

Figure 11. Average monthly mean albedo for the main ice caps in Figure 8. The mean, standard deviation and trend (Δy) are shown. Linear trend ~~detremined~~ determined from all years is shown with black lines while red lines exclude the 2010 and 2011 data to omit the influence of volcanic tephra and ash.

4 Conclusions

In this study, a gap-filled satellite-observed albedo dataset for Icelandic glaciers (MCD11) was produced from daily MODIS Aqua and Terra observations from early 2000 until 2019 at a 500 m spatial resolution. Overall, good visual and statistical agreement was found between the MCD11 data and in-situ albedo from GAWS observations over a range of elevations and glacier locations. Overall, higher ~~RMS errors~~ RMSE values were found in the ablation zone, which could be related to higher albedo variability within a MODIS pixel for impurity-rich bare ice in the ablation zone, indicating that care must be taken when comparing point-based in-situ observations with data with larger spatial footprint.

The main results show that the large seasonal and inter-annual variability in surface albedo for Icelandic glaciers was captured by the MCD11 data although limited in-situ data were available for the smaller glaciers. Icelandic glacier albedo was observed to be influenced by variability in climate, tephra deposits from volcanic eruptions, and airborne dust from widespread unstable sandy surfaces which are subject to frequent wind erosion and dust production. Details are provided regarding spatial patterns and temporal trends, relations to elevation and monthly statistics adding to previous work by Gascoin et al. (2017) for 2000 to 2012.

~~Although not directly quantified in this study, it was clear that Light Absorbing Particles were a major contributor to annual glacier melt through additional radiative forcing at the surface. Light Absorbing Particles originate both from airborne dust sourced outside of the glacier, from volcanic eruptions, as well as from residual effects several years after eruptions. This illustrates the importance of a correct representation of surface albedo for glaciers in Iceland, as surface albedo is a dominating control on mass balance. Therefore, caution must be exercised in applying conventional albedo parametrization in hydro- and glaciological model, which often estimate albedo based on temperature, precipitation and time, especially for short and seasonal forecasting on catchment scales.~~

~~Significant negative~~

Significant positive albedo trends over the study period were found in northern Vatnajökull while other areas and glaciers have a ~~glacier wide~~ glacier-wide non-significant trend. Average linear trends for monthly data indicate that albedo generally decreased over the study period in May and June whereas a general albedo increase was observed in July and August, although, statistically non-significant in all cases with the exception of Hofsjökull in July and Drangajökull in July and August.

The incorporation of the MCD11 albedo product provides capabilities to improve surface mass balance and ~~streamflow~~ runoff forecasting from glaciers. In the case of future volcanic eruptions, the presented methodology allows for rapid assessment of glacier albedo changes in near-real-time and the associated influence on melt which has a direct impact on hydropower production in Iceland and possibly civil infrastructure in some cases. A limitation related to estimating the impact of tephra fallout on a glacier surface from optical data is the assessment of tephra thickness, as very low observed albedo could indicate melt increase due to more surface energy absorbed by the surface but could as well indicate an isolating layer limiting melt due to a thick tephra layer.

The methodology allows for predictive and retrospective modes (Dozier et al., 2008), depending on the application. To use the albedo data for runoff forecasting for example, surface albedo estimations using only data until the present (newest MODIS data) can be provided by applying the statistical filtering and gap-filling routines from today and backwards. Alternatively, in retrospective mode, best estimations can be provided for every day in a period.

Finally, it is noted that the methodology applied in the study, based on MODIS data, can be applied to other satellite albedo products, such as ~~Sentinel 3~~VIIRS and Sentinel-3 as well as future missions, to extend the temporal range beyond the MODIS mission, allowing for short-term as well as long-term monitoring of albedo variations for glaciers in Iceland.

Code and data availability. Code used in the project to process data is available at https://github.com/andrigunn/aig2. MODIS data are available from https://nsidc.org/data. Geospatial data for Iceland are available from the National Land Survey of Iceland at https://atlas.lmi.is. Glacier automatic weather station data are available upon request.

Author contributions. AG conceived and designed the study, performed the analyses, and prepared the manuscript. SMG contributed to the study design, interpretation of the results, and writing of the manuscript. FP, TJ and ÓGBS contributed to the interpretation of the results and writing and reviewing of the manuscript.

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

Acknowledgements. TEXT

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Appendix B: Supplement material

Supplement material. Will be processed to a separate file during final processing

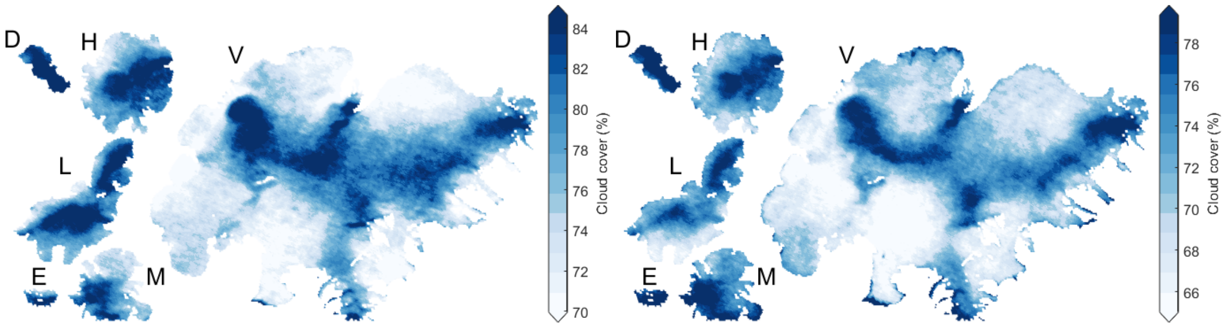

Figure B1. Monthly average cloud cover for selected glaciers in Iceland in April (left) and May (rigth).

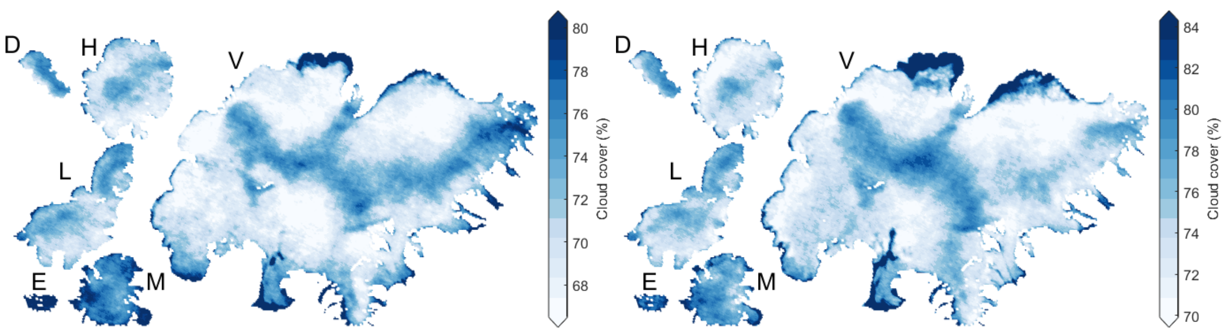

Figure B2. Monthly average cloud cover for selected glaciers in Iceland in June (left) and July (right).

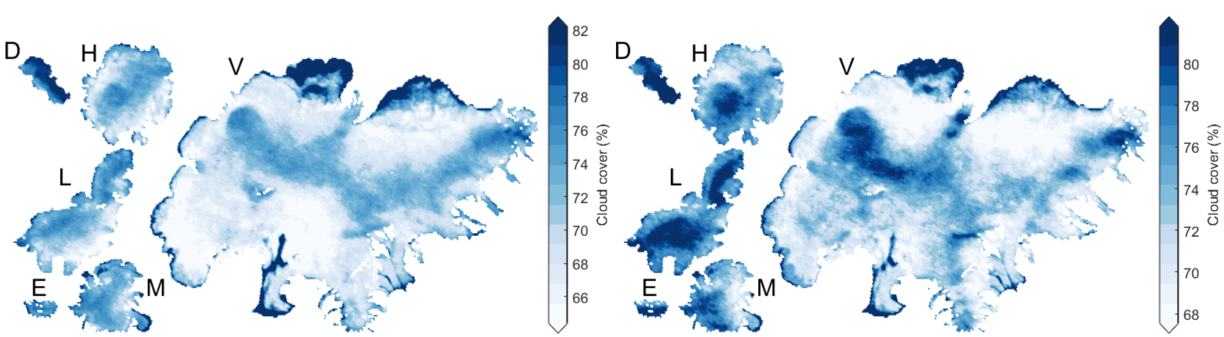

Figure B3. Monthly average cloud cover for selected glaciers in Iceland in August (left) and September (right).

Table B1. RMS error, R^2 values and number of months of overlapping data (n) for individual station comparison on a monthly time scale for MOD10A1, MYD10A1, MCD43A and MCD11.

	MOD10A1			MYD10A1			MCD43A3			MCD11		
Station	RMSE	R2	n	RMSE	R2	n	RMSE	R2	n	RMSE	R2	n
Kokv	9.78	0.74	5	0	-	0	9.25	0.77	5	9.42	0.77	6
BRE	10.02	0.31	101	9.84	0.37	93	10.95	0.31	80	10.54	0.40	109
B10	10.67	0.21	102	11.30	0.17	93	11.56	0.12	84	11.69	0.26	109
B13	13.24	0.37	107	11.59	0.48	93	9.83	0.61	76	13.69	0.36	108
B16	8.02	0.39	102	5.14	0.62	94	5.46	0.59	26	10.63	0.13	105
BRE1	9.16	0.42	102	9.39	0.43	93	10.49	0.34	97	9.90	0.47	109
BRE4	7.68	0.85	33	9.87	0.76	34	10.90	0.75	34	8.50	0.85	36
BRE7	7.58	0.20	17	6.63	0.39	17	7.23	0.23	11	6.16	0.47	17
T01	16.76	0.45	18	13.92	0.59	12	12.60	0.76	20	9.53	0.86	20
T03	11.84	0.67	99	10.54	0.73	86	13.55	0.59	98	12.67	0.64	102
T06	10.27	0.53	98	14.69	0.26	87	7.11	0.73	69	13.91	0.26	100
L01	12.41	0.73	95	13.26	0.69	87	10.24	0.84	99	11.43	0.80	103
L05	8.35	0.71	100	8.58	0.69	92	7.93	0.75	106	9.83	0.65	114
K06	18.06	0.003	35	17.85	0.02	35	21.57	0.03	11	19.37	0.08	36
MYRA	9.08	0.55	20	9.56	0.51	20	18.68	0.02	16	18.53	0.019	21
HSA09	5.75	0.93	11	9.27	0.83	11	5.67	0.94	12	5.18	0.96	13
HSA13	5.81	0.74	11	4.05	0.87	11	5.59	0.78	11	5.47	0.79	13
SKE02	6.00	0.0004	3	0.25	0.99	3	2.07	0.90	3	0.12	0.99	3
Hof01	14.99	0.14	63	15.31	0.12	61	5.21	0.82	24	19.18	0.2	66
Hosp	10.56	0.27	53	10.59	0.26	53	10.96	0.27	56	11.39	0.22	58

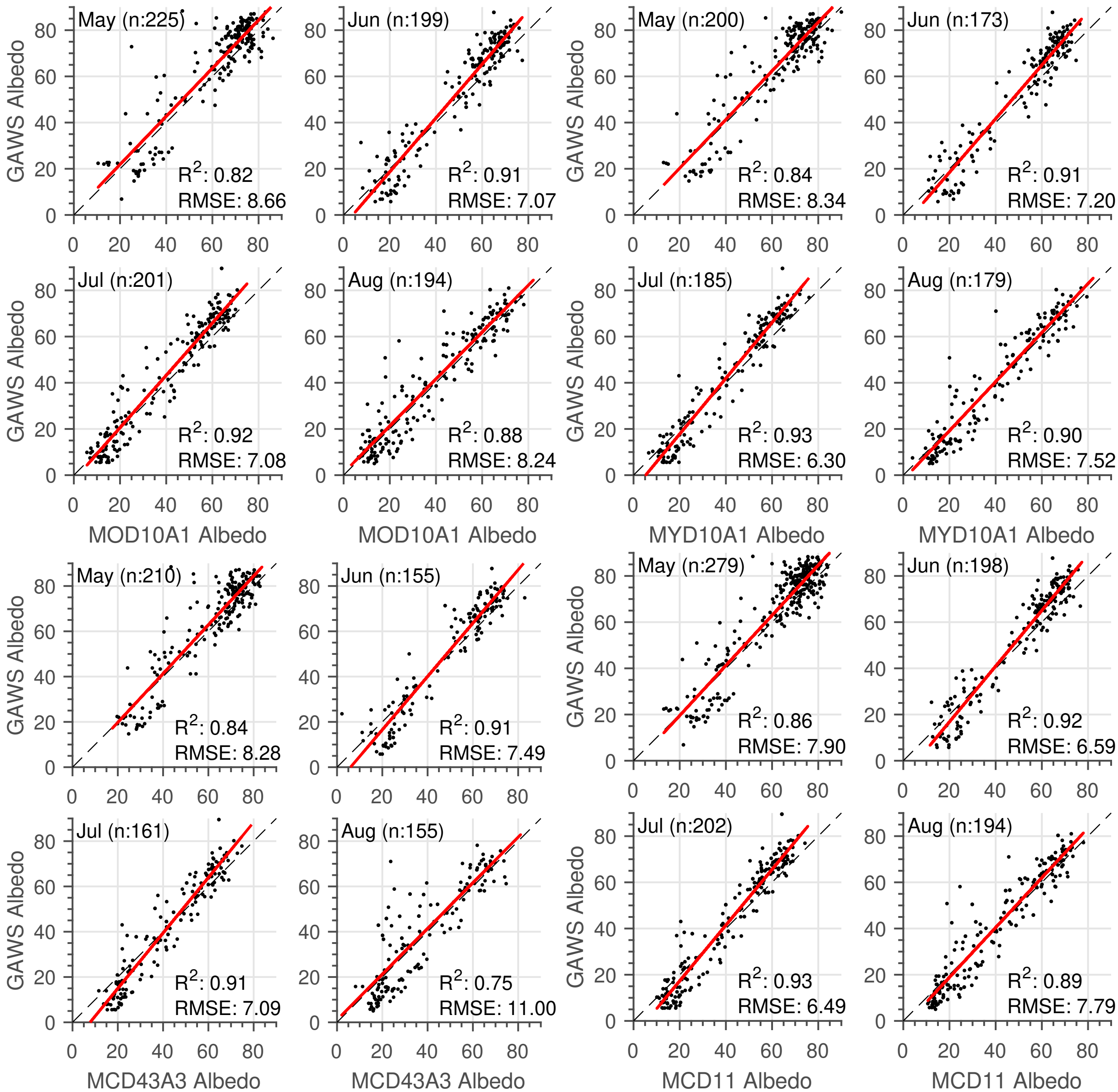

Figure B4. Albedo comparison results from monthly averaged MODIS data for May, June, July and August for the period from 2000 - 2019 2000–2019 where data were available for MOD10A1, MYD10A1, MCD43 and MCD11 data products.