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

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Author response: 12.06.2020

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:
We will incorporate these suggested references into the introduction part of the paper as they are highly relevant and will improve the manuscript.

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

Author response:
References will be updated accordingly

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

Author response:
Will be changed accordingly

L44-45 – ..but it IS limited. . .

Author response:
Will be updated accordingly

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

Author response:
References will be updated accordingly

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

Author response:

Sentence is:
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:
To confirm this hypothesis, Reijmer et al. (1999) compared in-situ data and higher spatial resolution remote sensing data from Landsat 5 Thematic Mapper (TM) sensor. The result showed greater variability in surface albedo implying that the scale of the albedo variations is larger than the AVHHR pixel (1.1 km) could resolve.

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

Author response:
References will be updated accordingly

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.

We will add a sentence in the caption of the table explained the meaning.

L192-193 – opening brackets are missing

Author response:
Will be added

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 is:
Large sand and tephra covered areas have been observed…

Suggested rewrite:
Large sand, dust and tephra covered areas have been observed…

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:
Will be added as a reference

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, adding the following sentence:

Local lower albedo gradients at Hofsjökull (SE), Langjökull (S) and Mýrdalsjökull (S) coincide well 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 refers to (South coast glaciers) there is no significant trend in annual values, especially if the influence of the volcanic eruptions in 2010, 2011 and the residual effect in 2012 is removed.

However we will add long-term dust storm frequency studies in Iceland as a discussion point in Chapter 3.4 Trends of albedo

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 will add these as references to further support our discussion in L322-323

L329 – delete 'r' in severer

Author response:
Yes

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

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

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 is:
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:

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:
Typographical error, will be fixed

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

Author response:
Typographical error, will be fixed

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

Author response:
Yes, 1999 should be 2000, will be 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:
We will incorporate this to the manuscript. *Volcanic ash and dust…*

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.

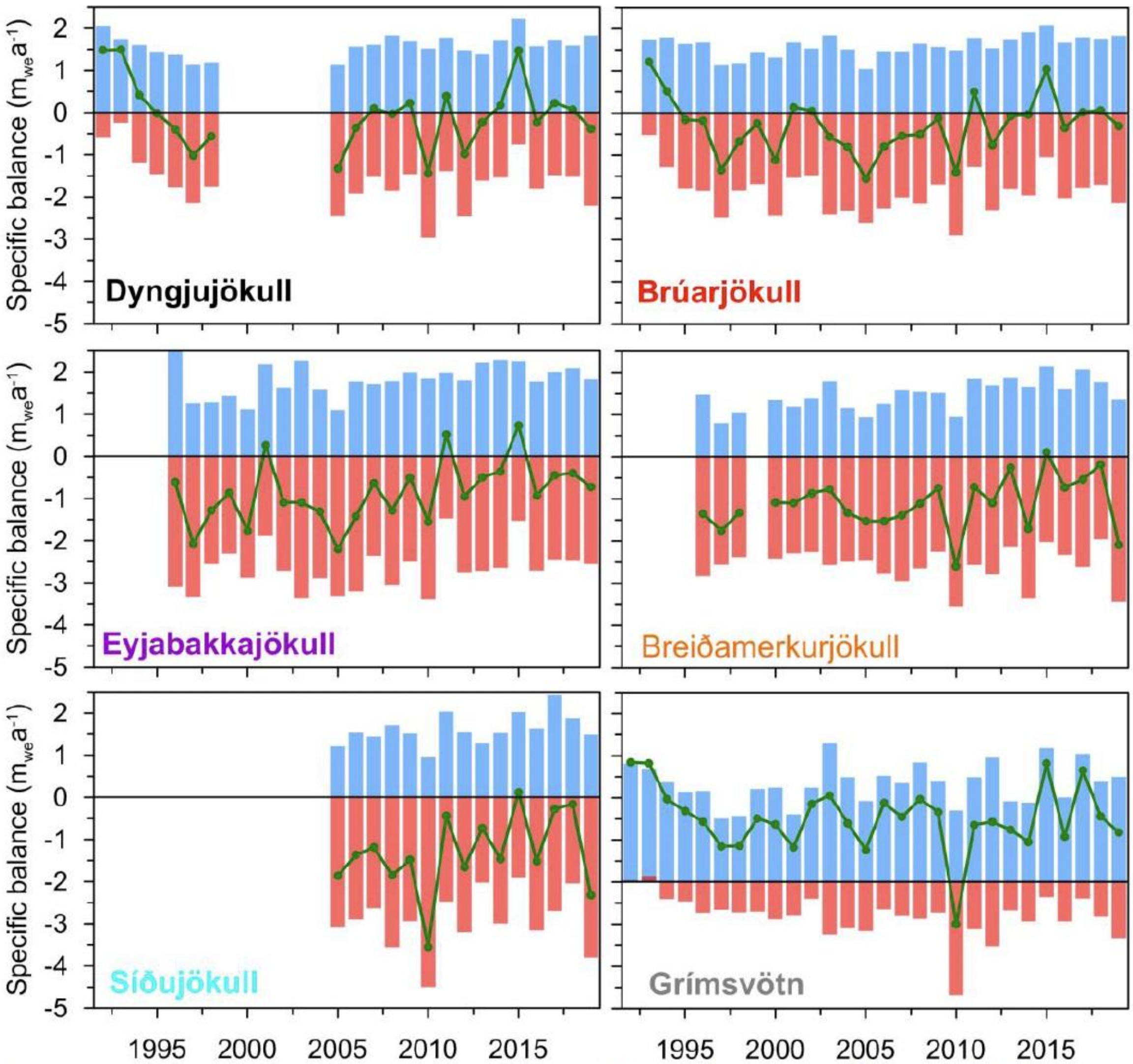

Figure 16. Specific mass balance record for Vatnajökull outlets 1991_92-2018_19.

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.

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 L426 with the discussion about Figure 11:

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

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

Author response:
Yes

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:
We will correct this.

L554 – remove 'a' in Matlab, 2017a

Author response:
We will correct this.

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

Author response:
We will correct this.