AC1_Reply to the comments of Suryanarayanan Balasubramanian

General Comments This paper is well written and provides good scientific evidence on the impact of artificial precipitation on glacial mass balance. Although, the experiment setup being novel, requires further context in the paper. Even though the paper provides compelling evidence by quantifying the impact of 2 artificial precipitation events, the 13-day measurement duration is too short to provide sufficient evidence for the hypothesis suggested.

Re: We thank the referee for the valuable comments which are believed to be greatly helpful for improving the quality of the manuscript. The work itself is preliminary and needs more data to consolidate the current knowledge in future. We have plan to apply for funding for carrying out more intensive experiments in this glacier and/or other glaciers. We also include these concerns in the revised manuscript.

Specific Comments

1. Given that the premise of the paper is to measure the effect of artificial precipitation, little effort has been taken to distinguish or categorize precipitation events as artificial and natural. There needs to be a control experiment without igniting the smog generators to compare the difference in precipitation quantities. References are also lacking to categorize the precipitation events as "artificial".

Re: Thanks. We added the description including a new figure on how we operated the AgI smoke generators and when the AWS recorded the consequent snowfalls in the revised manuscript. There were significant snowfall amounts recorded by the AWS every single time after we ignited the smoke generators. We could not completely distinguish the artificial snowfalls from the natural one if they were mixed in all these events. However, the co-occurring of the snow falling with the AgI smoke allows us to affirm that we were producing some artificial snowfall. The reply has been integrated into and underlined in the revised manuscript.

2. The albedo decay of the artificial precipitation and the snow quality data is required to claim a long-term glacier mass balance impact. These need to be factored in the hypothesis mechanism. Particularly, the variation in likelihood of a precipitation event occurring with or without a smog generator needs to be quantified or referenced.

Re: Yes, thanks. These concerns have been added into the relevant context. As we addressed in the aforementioned reply, this is a very preliminary experiment and need further studies to validate our method and theory. However, we include these new ingredients in our revised manuscript.

Technical Corrections

1. Lines 126 to 137 which describe the AWS instruments can be better presented in the form of a table.

Re: Thanks. We made a new table (Table 1) for the advice.

AC2_Reply to the comments of Samuel Morin

In their manuscript entitled "Applying artificial precipitations to mitigate the melting of the Muz Taw Glacier, Sawir Mountains", Wang et al. report on an experiment where artificial precipitation was produced downstream a mountain glacier in Northern China, and lead to accumulation on the glacier above. The results are discussed in the context of how artificial precipitation could be used to reduce the pace of glacier melt in the context of ongoing climate change. Artificial modifications of the functioning of mountain glaciers is an emerging field, contributing to a larger move of the scientific community towards assessing the potential of geoengineering – which proceeds through various mechanisms and approaches – to reduce the magnitude and impact of climate change at various time scales. Such studies are probably unavoidable, and they are rendered necessary by the push from some societal compartments to apply geoengineering, there is thus a need to carefully assess the impacts, implications, potentials benefits and risks, of such approaches, and this study contributes to this activity. Overall, I think that the data acquired for this study are appropriate to address whether artificial precipitation has a significant impact – or not, on glacier mass balance, but the manuscript suffers from many shortcomings (including a general lack of clarity in how the results are presented and the data compared and interpreted), which I hope that the authors can address before the manuscript can be recommended for publication. I have several major concerns, see below, and series of other editorial comments and suggestions.
Re: The authors thank the reviewer for describing the general impression on our manuscript here. We will address our corrections and improvements in the replies to the specific comments.

Major concerns
Reduction in mass loss: For this study, it seems that the artificial precipitation was applied in summertime, at time of glacier ablation and melt (August 2018). However, it is unclear, whether the decrease in mass loss, reported to be 17% in the abstract, accounts for the amount of precipitation added by the artificial precipitation, or not. Indeed, by adding mass to the glacier, the mass lass can only by lower than without artificial precipitation. The impact can be considered significant if the reduction in mass loss exceeds the gain corresponding to the deposition of artificial precipitation. I think this should be clarified.
Re: I think there was misunderstanding in the statement of the original abstract. We would like to express that "the average mass loss decreased by 41 mm w.e. during and after the APs (i.e. 18 – 24 Aug), accounting for 17% of the mass loss prior to the APs (i.e. 12 – 18 Aug)". We rephrased the sentence and underlined it in the revision. In the revised manuscript, we made two comparisons separately. One is the aforementioned, and the other is comparing the snowfall recorded by the AWS due to the experiments with the total melt after the experiments.

Environmental footprint of artificial precipitation: It is absolutely necessary that geoengineering methods, applied at various scales, undergo an assessment of their effectiveness and potential side effects. Even if a full assessment of the potential side effect of artificial precipitation may fall beyond the scope of this manuscript, I think that it would be worth mentioning that this is a requirement to be undertaken if this experiment is to be repeated or scaled up. In particular, it would be interesting to be able to know, from reading

the article, why is artificial precipitation implemented in these valleys (what is the context for setting up these artificial precipitation units?), what is the energy and water cost associated to these activities, and, therefore, move towards an attempt to quantify the cost and benefit of the method, i.e. contrast the avoided glacier mass loss with the corresponding effort to reach this goal. I think this it is absolutely necessary that side effects and environmental and economic costs associated to this approach, are mentioned, and even better, quantified in a revised version of the manuscript.
Re: Yes, the comment arises an important issue which was not mentioned by the original manuscript. We added some text with references in the revision to address the comment. The environmental side effects are very low according to a review report released by the WMO in 2018. The power used in the smog generators is solar and no extra water is costed. The valley-developed glaciers are ideal sites to perform the experiment due to the prevailing winds helping carry the smog up over the glacier surface. We have plans to scale up the present study to other glaciers in future. These concerns have been integrated into the introduction and conclusion parts of the revision and underlined.

Mechanism: I have major reservations about some aspects of the “possible mechanism” introduced by the authors. It seems clear for me that by adding artificial precipitation, in the form of snow, the albedo of the surface increases, without invoking the influence of cloud cover on surface albedo. See detailed comments below.
Re: Yes, this part has been significantly simplified according to the specific comment in below. We only keep the concern of snowfall – increasing mass and albedo – mass balance part. We exclude Figure 8 from the manuscript.

Minor comments and suggestions
Title: I think the use of the term “mitigate” in the title of the manuscript is misleading. I think “litigate” could be replaced by “reduce”. Mitigation generally refers, in climate change studies, to the reduction in greenhouse gas emissions, which is not the scope of this manuscript.
Re: We did the replacement to the title as advised by the reviewer.

Page 1, Line 17: Replace “Glaciers” by “glaciers”
Re: We replaced “Glaciers” by “glaciers” in Line 17.

Page 1, Line 18: after “higher latitude and lower elevations”, a qualifier is missing after adding “than”, or the sentence needs to be rephrased.
Re: We add “than those in the adjacent areas” after “higher latitude and lower elevations”.

Page 1, Line 20: replace “in presence” by “observed”
Re: Replaced as advised.

Page 1, Line 21: add “additional” or “artificial” before “precipitation”
Re: Yes, we added “artificial”.

Page 1, Line 24: replace “MB” by “Mass Balance”
Re: We replaced “MB” by “mass balance”.

Page 1, Line 25: delete “AWS”, no need to introduce acronyms in the abstract. Page 1, Line 26 : delete “EL”, no need to introduce acronyms in the abstract.
Re: We deleted them in the revision.

Page 1, Line 29: I suggest “decreased by 17%” is clarified, as indicated in my major comment. Also, it should be made more explicit what is the time scale over which the mass balance values are compared. At present, it is unclear whether the reduction applies to annual, monthly, weekly etc. mass balance values.
Re: Yes, we clarified the statement in the abstract and the method. The stick scales for measuring mass balance was read thrice, on 12, 18 and 24 Aug, respectively. We compared the mass varying between the two periods (12-18 Aug and 18-24 Aug). These have been clarified in the revision.

Page 1, Line 30: I suggest rephrasing the “possible mechanism” and replacing it with a more concrete statement about the mechanism, see below for further comments on the mechanism as it is introduced in this manuscript.
Re: Yes, we rephrased it and simplified the mechanism part in the revision. We included more discussion in the reply to the following comments.

Page 1, Line 34: I suggest replacing « MB » by « Glacier mass balance » in the keywords. « Melting mitigation » does not seem a fully appropriate keyword (see above).
Re: Yes, we replaced the keywords as suggested.

Page 2, line 37: Immerzeel et al. (2010) is a solid reference, but there have been more recent and exhaustive and compelling studies published recently on this topic (e.g. Immerzeel et al., 2010, in press, https://doi.org/10.1038/s41586-019-1822-y).
Re: We added the new reference into the revised.

Page 2, line 42 : same here, Zemp et al. (2015) could be replaced by Zemp et al. (2019) for a more up-to-date introduction.
Re: We replaced the old literature with the new one.

Page 2, line 43 : « more intense » : this needs clarification, currently the text does not state than what the ablation is more intense.
Re: Yes, clarified. “For the Sawir Mountains, the ablation of the glaciers is more intense than the global average, and the total area of the glaciers reduced by 46% from 23 km2 in 1977 to 12.5 km2 in 2017 (Wang et al., 2019)”.

Page 2, line 43 and 44: total glacier length and total glacier surface are should be provided, and not only the change, so as to provide better context.
Re: Yes, the information provided in the revision. “For the Sawir Mountains, the ablation of the glaciers is more intense than the global average, and the total area of the glaciers reduced by 46% from 23 km2 in 1977 to 12.5 km2 in 2017 (Wang et al., 2019)”.

Page 2, lines 45 to 49: Thess sentences are not supported by references; maybe refer to the Hock et al. IPCC SROCC Chapter (in press)?

Re: The advised reference was added into the revision. “The accelerated retreat of glaciers not only causes spatial and temporal changes in water resources but also has a significant impact on sea-level rise, regional water cycles, ecosystems and socio-economic systems (such as agriculture, hydropower and tourism); the melting of glaciers also increases the occurrence of glacial disasters, such as glacial lake outburst flooding, icefalls and glacial debris flows (Hock et al., 2019)”.

Page 2, lines 51 to 59. I think this paragraph requires major clarifications. First of all, starting on the first sentence, there are not so many approaches used in practice for reducing the rate of glacier ablation. Covering glaciers with insulating material has been described in detail by Fischer et al. (The Cryosphere, 2016), I think it’s finding should be quoted in this paper. Also, it is surprising to see « scientists and governments » together acting on « taking measures », and later on, on page 59, that « scientists plan to use artificial snow ». In fact, scientists can assess the impact of various approaches, but I don’t think that it can be stated that scientists are « planning » or « taking measures » to reduce glacier mass loss. I think this paragraph should be clarified, in order to better position the respective role of scientists and governing bodies (at local or national scale). I also think that, if the term « geoengineering » is retained (line 55), a definition should be provided, in order to frame this particular article within the climate change geoengineering literature.
Re: Yes, we rephrased the paragraph. The item “geoengineering” was removed from the original manuscript for the small scale of the study against the definition of the word. We clarified the statements involving the roles played by scientists and governments. The reference of Fischer et al. (2016) was added into the revision.

Page 2, line 62 to 63: it should be made clear whether the artificial precipitation devices were installed on purpose for this particular study, or not, and if this is the case, what is the motivation for installing these equipments in a broader context. Maybe, some more context statements should be given about artificial precipitation technology, its typical context and scope, and why it is potentially interesting to apply it for attempting to reduce glacier mass loss.
Re: We addressed their purpose in the revision. “These smog generators were set up there by the local meteorological service for artificial-precipitation tasks”. Some more technic features of these generators are included in the experiment section.

Page 3, line 88 : The first statement needs a reference.
Re: We added a reference. “The Muz Taw Glacier has been in constant recession since 1959 (Wang et al., 2019)”.

Page 3, line 91 : add « surface » before « previous » and « area ».
Re: We added.

Page 3, line 92 : I strongly suggest not using acronyms such as « MB ». It does not save much space, and leads to poorer readability.
Re: We replaced the acronyms, MB and AP with their full-length glossaries throughout the manuscript.

Page 4, line 93: It is very unclear what the values « -975 ~ -1286 mm w.e. » mean. Are these annual mass balance values ? What is the range corresponding to ? Is this an uncertainty on glacier- averaged values ? Or a range representing the spatial variability on the glacier? This should be rephrased for better clarity.
Re: We clarified the mass balance of the glacier measured in separate years in the revised manuscript.

Page 4, line 106 : « When we realized » : this needs to be clarified
Re: We monitored the distribution and structural developing of clouds and identified the orientation, height and distance of the clouds approaching the glacier at the radar station. Associated with observing the moving of the potentially target clouds and the receiving of the reflection of the radar transmission, we ignited the smog generators for seeding artificial precipitations, when we realized the possibility is high enough to potentially form precipitation (Figure 2). The detailed operation of conducting artificial precipitations in the study glacier has been described in Xu et al. (2017).

Page 4, line 107 : « 14 silver-iodide smog generators » : again, it would be useful to know whether this is the usual purpose of such generators ? Or whether they were installed for other purposes ? This could be added to the introduction, but more technical details can also be provided here.
Re: This purpose of the generators has been included in the revision and addressed in the reply to the aforementioned comment.

Page 4, line 109 : is « AP » representing « artificial precipitation » ? If so, I strongly suggest that the plain words are used, and not the acronym. This can be applied throughout the entire manuscript (including figure captions).
Re: Corrected as advised.

Page 6, line 135 : suggestion to replace « the accuracy » by « an accuracy »
Re: Corrected as advised.

Page 6, line 136 : « CR6 » is not very informative. Maybe better to either provide more information to identify the data logger, or drop the information if it is not critically important.
Re: Yes, we supplemented some more relevant information about CR6.

Page 7, line 157 to 164 : I couldn't find if an average value for broadband albedo was computed for the entire glacier, or not. If so, then the method used should be provided.
Re: We averaged the broadband albedo based on the site measurements representing an average for the entire glacier. We clarified the statement in the revision.

Page 7, line 166: I strongly suggest replacing « MB » by « mass balance ».
Re: Corrected as advised.

Page 8, line 184: I suggest starting this paragraph with several sentences providing more background about the meteorological conditions during the experiment, in particular on what days there was some natural precipitation (or not). It should also be provided, whether it is expected that the intensity of the melt would be the same before and after the days when artificial precipitation was applied (in order to make the comparison meaningful).

Re: There are some added text (underlined) in the revised manuscript.

- There was some natural precipitation during 12 – 14 August, while except this and that in the experiment days, the whole period of 12 – 24 August were sparse in precipitation.
- We could not completely distinguish the artificial snowfalls from the natural ones if they were simultaneously mixed in all these events. However, the co-occurring of the significantly snow falling with the AgI smoke allows to suppose that we were producing artificial snowfalls.

Page 8, lines 200 to 202: this sentence is very hard to understand, I suggest it is revised for better clarity.

Re: We replaced this statement by "We would compare the intensity of the melt would be the same or not before and after the days when artificial precipitation was applied".

Page 10, line 233: the use of the symbol « ~ » is deprecated, I suggest using a more appropriate symbol (or use « approx. » for example).

Re: Corrected as advised.

Page 10, line 233: even though it was stated earlier that mass balance measurements are taken since August 12, I think this should be mentioned along with the values provided, for better clarity, and perhaps provided in mm w.e. per day. It is unclear, in the context, what it means « -300 mm w.e. to - 100 mm w.e. after the artificial precipitation » : are the values reset on August 18 ? This is hard to follow. Maybe a table with the mass balance values for various locations, and average over the glacier, and corresponding degree day sums, could help provide a less ambiguous description of the data.

Re: We only have three readings from the scales of the stakes, which were read on 12, 18 and 24 August, respectively (Section 3.4). To study the effects of the artificial precipitations on the mass balance of the glacier, we calculated the mass balance measured by the stakes during the two periods, i.e. 12 – 18 Aug and 18 – 24 Aug, respectively. We do not have the data for mass balance on a daily basis.

Page 10, line 236. « The APs gained the mass » : this needs revision, it is not clear. Page 10, line 242 : add « in °C » after « temperature »

Re: Yes, revised as per the advice.

Page 10, lines 241 to 250: Although this is where the key results are provided, it is unclear. I understand that the sum of positive degree days is provided for the two periods before and after the artificial precipitation, along with the mass balance for the entire glacier. To me, this is not enough to assess the efficiency of the artificial precipitation process. Indeed, to provide a more informative comparison, I believe that the authors could compare the simulated melt rare (or mass balance) during the period after artificial precipitation, and compare this value with the value measured, accounting for artificial precipitation. This comparison should also explicitly account for the amount of snow added through the artificial precipitation, because adding snow precipitation can indeed only increase the

mass. At present, there is no evidence that adding more precipitation leads to lesser mass loss, specifically. This needs to be analyzed in a more in-depth manner, I think. I also think that it would be critical, if the information can be made available, what is the actual deposition rate due to artificial precipitation, on the glacier. With this data at hand, I believe that the authors could make a more compelling case.
Re: Yes, we added some further analysis. The accumulation at the equilibrium line altitude (ELA) of a glacier is approximately equal to the area average of accumulation over the whole glacier (Braithwaite, 2008). We can presume that the snowfall amount measured by the AWS near the ELA of the Muz Taw glacier during t2 was the average received mass of the whole glacier after implementing the artificial precipitatons. The melt amount from the original glacier during t2 would be the difference between the calculated mass balance and the snowfall measured by the gauge on the AWS, i.e. 17.3 mm w.e. Therefore, artificial precipitations may significantly save the melt of the glacier by 53.5%, simply calculated as the percentage of the snowfall divided by the estimated mass balance during t2.

Page 11, Table 1: This table could fill the gap indicated above, but it does not provide sufficiently clear information. One single albedo value is given. Is this an average over the glacier? If so, what is the methodology? Same for the mass balance. Is the value applicable since August 12 in both cases, or only applies to the time periods t1 and t2? I also don't understand the precipitation value. It seems that natural precipitation occurred during t1. If so, how is it possible to assess the impact of artificial precipitation during t2? Only some modelling could be used, I think, to assess the impact of artificial precipitation.
Re: Yes, we clarified the content in Table 2 (original Table 1). Please refer to the reply to the previous comment and the revised manuscript.

Page 11, line 259 to Page 11, line 285. The entire section 4.4 is very confusing, and I recommend that more work is spent on revising it in light of available scientific evidence. It is quite obvious that adding artificial solid precipitation (snow) to a glacier will (1) increase the mass and (2) increase the albedo. There is no need to develop a theory about this. Adding rain may increase the mass. I doubt that the influence of clouds on snow albedo plays a major rôle here (clouds drastically reduce incoming shortwave radiation, which is the #1 factor most certainly in this case). I suggest that this section should be considerably simplified. Instead of these questionable speculations, I encourage the authors to perform some simple mass balance modelling (e.g. based on degree days values), in order to contrast the mass loss values with and without artificial precipitation. This would make the case more compelling and its results could be more useful to the scientific community.
Re: We largely simplified this part. We input some new discussion in the last paragraph of Section 4.3, contrasting the mass loss with and without artificial precipitation.

Page 13, line 292: I understand that in some parts of the glacier, artificial precipitation did not fall as snow but rather rain. Could this be clarified? Here we have the impression that artificial precipitation leads to snow precipitation everywhere on the glacier.
Re: In Section 4.1, we have discussed when the precipitation is snow or rain under some circumstances. In our experiments, the glacier received snow as observed. We clarified the statement in the sentence, avoiding further confusion.

Page 13, lines 296 to 303: this is very confusing. I don't understand what numbers are compared to what, for what periods of time, and what conclusions could be made. I suggest making a thorough revision of this part, because it affects how the efficiency of the artificial precipitation approach can be computed. I strongly suggest making comparisons pertaining to the same time periods, and not comparing different time periods. Again, modelling could be used to place the artificial precipitation experiment in a clearer context.
Re: We did two comparisons for the mass-balance variation of the Muz Taw glacier with or without the artificial-snowfall experiments. One is comparing the mass balance during the period before the experiments (12 – 18 Aug) with that after (18 – 24 Aug). The difference of the mass balances between the two periods was 41 ± 15 mm w.e., suggesting that artificial snow added the mass to the glacier. Another is comparing the total melt of the glacier during the period after the experiments (18 – 24 Aug) with the mass added from the artificial snowfall to the glacier, implying that artificial snow significantly saved the mass loss during the period after the experiments.

Page 13, line 305 to 311: see above my comments about the « physical mechanism ». I think much simpler statements are sufficient to explain the observations. However, as indicated in my major comments, I think that the reader expects, at the end of the conclusion, a broader perspective on this work, a discussion on the efficiency of this « geoengineering » approach (including an assessment of the energy costs for artificial precipitation, to be compared to the benefit of reducing mass loss). It could also be discussed whether the authors have recommendations on future research, in particular in the (possible) context where such a method could be implemented at a wider scale or more regularly. All these questions should be at least mentioned by the authors.
Re: As shown in the reply to the previous comments, the mechanism has been largely simplified. And an additional paragraph has been added into the revised manuscript to address the future perspective on the study.
"The approach in our work uses solar power to ignite the seeding material for forming clouds and uses no extra water but redistributes natural water in the local atmosphere at a small spatial scale. The energy-and-water saving techniques of the approach with reasonably mass-loss-reducing efficiency from the Muz Taw glacier validates its efficiency to possibly be applied in more Central-Asian glaciers to reduce their rapid melting. Especially in summer when the melting is drastic in the Central-Asian glaciers, applying the approach suggested by our study on a much broader scale might reduce the melting significantly. Of course, the period of our experiment is preliminary and short, and the approach would sophisticate itself when being implemented more regularly in future repeated and longer-term, or scaled-up experiments.".

Figures:
Figure 2: replace « Ladar » by « Radar »
Re: Corrected.

Figure 4: onset picture is not readable. If the content is useful to the reader, then it should be provided as clearly readable image. Also, what is « contour line » as indicated in the legend? I also couldn't find the « equilibrium line » on the figure, because several lines have almost the same style. Some editing is required.
Re: We have redesigned the figure. The submitted file has a larger resolution.

Figure 5: I suggest adding vertical shaded areas to indicate the periods when artificial precipitation was applied. Also, the figure quality should be improved, on the pdf provided for review the image quality is quite bad.
Re: We improved the quality of Figure 5 as advised by the reviewer.

Figure 6: the albedo values in the various onset figures is very hard to read. I suggest using a more classical design, with numbers referring to the measurement sites, and larger plots on the side of the map. The information will be better conveyed.
Re: Yes, we redesigned the layout of the figure complying with the comment.

Figure 7: this figure is very confusing. Is « gained mass » the direct consequence of artificial precipitation? Or is it the difference between the two « mass balance » time series (which is confusing, because it is indicated that the reference is on August 12 for all values), which would then combine not only artificial precipitation but also melt after the precipitation. Better clarity and, probably better language to describe what is displayed on the graphs, are needed.
Re: Yes, the gained mass meant to be the difference between two periods and has been clarified. We have clarified the statement including the text and figure in the revision.

List of major changes

Changed Points to RC 1

1. We added a new figure (Figure 5b) in the revision to describe the cause-consequence between the AgI smoke and the consequent snowfalls in the revised manuscript. There were significant snowfall amounts recorded by the AWS every single time after we ignited the smoke generators. We could not completely distinguish the artificial snowfalls from the natural one if they were mixed in all these events. However, the co-occurring of the snow falling with the AgI smoke allows us to affirm that we were producing some artificial snowfall. The change has been underlined in the revised manuscript.
2. The variation in likelihood of a precipitation event occurring with or without a smog generator has been referenced in the revision, also supplemented by the Changed Point 1. We added additional explanation in the end of Section 4.4, “This is a very preliminary theory based on the limited data derived from the short-term experiments, and we need further studies to validate the theory. The albedo decay of artificial snowfall and snow physics are required to claim a long-term impact on the mass balance of glaciers. Particularly, the variation in the likelihood of a snowfall event occurring with or without smoke generators needs to be quantified in future studies.”.
3. A new Table 1 was added into the revision.

Changed Points to RC 2

1. We changed the manuscript title from “…precipitations…” to “…snowfalls…”, in the wake of the main purpose of our study to add artificial snow onto glacier and largely simplifying the hypothesis excluding rainfall and other cases.
2. In the abstract, we clarified some unclear statements. For example, we would like to express that “the average mass loss decreased by 41 mm w.e. during and after the APs (i.e. 18 – 24 Aug), accounting for 17% of the mass loss prior to the APs (i.e. 12 – 18 Aug)”. We rephrased the sentence and underlined it in the revision. In the revised manuscript, we made two comparisons separately. One is the aforementioned, and the other is comparing the snowfall recorded by the AWS due to the experiments

with the total melt after the experiments. Some other typo and grammatical errors are also corrected and underlined in the revision.

3. New keywords: artificial snowfall, Muz Taw Glacier, Sawir Mountains, glacier mass balance, reduce melting
4. We outlook the environmental side effects in the conclusion part, which are very low according to a review report released by the WMO in 2018. The power used in the smog generators is solar and no extra water is costed. The valley-developed glaciers are ideal sites to perform the experiment due to the prevailing winds helping carry the smog up over the glacier surface. We have plans to scale up the present study to other glaciers in future. These concerns have been integrated into the introduction and conclusion parts of the revision and underlined.
5. We largely simplified the mechanism part, with only keeping the “snowfall – increasing mass and albedo – mass balance” part. We also exclude Figure 8 from the manuscript according to the simplification.
6. We supplemented some necessary references and integrated some useful information into the revision. For example,
    i. Zemp, M., Huss, M., Thibert, E., Eckert, N., et al.: Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016, Nature, 568, 382-386, 2019.
    ii. Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., et al.: Importance and vulnerability of the world’s water towers, Nature, doi: 10.1038/s41586-019-1822-y, 2019. 2019.
    iii. Hock, R., Rasul, G., Adler, C., et al.: High Mountain Areas. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, IPCC, New York, 2019.
    iv. Fischer, A., Helfricht, K., and Stocker-Waldhuber, M.: Local reduction of decadal glacier thickness loss through mass balance management in ski resorts, The Cryosphere, 10, 2941-2952, 2016.
    v. Flossmann, A. I., Manton, M. J., Abshaev, A., et al.: Peer Review Report on Global Precipitation Enhancement Activities, 2018. 2018.
7. We rephrased the the second paragraph of the Introduction part. The item “geoengineering” was removed from the original manuscript for the small scale of

the study against the definition of the word. We clarified the statements involving the roles played by scientists and governments. The reference of Fischer et al. (2016) was added into the revision.

8. We addressed their purpose in the revision. “These smog generators were set up there by the local meteorological service for artificial-precipitation tasks”. Some more technic features of these generators are included in the experiment section.
9. Some acronyms, such as “MB”, “AP”, etc. have been changed to their full-length glossaries throughout the manuscript.
10. In the revision, we addressed the time-window capture to operate the artificial-precipitation experiments. We monitored the distribution and structural developing of clouds and identified the orientation, height and distance of the clouds approaching the glacier at the radar station. Associated with observing the moving of the potentially target clouds and the receiving of the reflection of the radar transmission, we ignited the smog generators for seeding artificial precipitations, when we realized the possibility is high enough to potentially form precipitation (Figure 2). The detailed operation of conducting artificial precipitations in the study glacier has been described in Xu et al. (2017). See from line 125 to 141 in the revision.
11. The background about the meteorological conditions during the experiment, in particular on what days there was some natural precipitation. There are some added text (underlined) in the revised manuscript.
    - There was some natural precipitation during 12 – 14 August, while except this and that in the experiment days, the whole period of 12 – 24 August were sparse in precipitation.
    - We could not completely distinguish the artificial snowfalls from the natural ones if they were simultaneously mixed in all these events. However, the co-occurring of the significantly snow falling with the AgI smoke allows to suppose that we were producing artificial snowfalls.
12. In the revised manuscript, we clarified how the mass balance was measured by the stick scales at each site and how the comparison was made between different periods. We only have three readings from the scales of the stakes, which were read on 12, 18 and 24 August, respectively (Section 3.4). To study the effects of the

artificial precipitations on the mass balance of the glacier, we calculated the mass balance measured by the stakes during the two periods, i.e. 12 – 18 Aug and 18 – 24 Aug, respectively. We do not have the data for mass balance on a daily basis.

13. We did two comparisons for the mass-balance variation of the Muz Taw glacier with or without the artificial-snowfall experiments. One is comparing the mass balance during the period before the experiments (12 – 18 Aug) with that after (18 – 24 Aug). The difference of the mass balances between the two periods was 41 ± 15 mm w.e., suggesting that artificial snow added the mass to the glacier. Another is comparing the total melt of the glacier during the period after the experiments (18 – 24 Aug) with the mass added from the artificial snowfall to the glacier, implying that artificial snow significantly saved the mass loss during the period after the experiments.
14. Especially for the side effect and promising perspective of broader application of the artificial snow adding mass to glacier, we have added some text to explain the issue in the revision. See the last paragraph in the conclusion (underlined) in the revision.
15. All the issues of the figures has been accordingly addressed in the revision.

Applying artificial snowfalls to reduce the melting of the Muz Taw Glacier, Sawir Mountains

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ABSTRACT

The glaciers in the Sawir Mountains, Altai area, are characterized by higher latitudes and lower elevations than those in adjacent areas. Influenced by the westerly circulation and the polar air mass, the snowfall is abundant and evenly distributed over the year in this area. However, a continuing and accelerating mass loss of glaciers has been observed since 1959. We carried out two artificial-snowfall experiments on the Muz Taw Glacier of the Sawir Mountains during 19 – 22 Aug 2018, to study the significance of artificial snowfalls in reducing the glacier's melting. We measured the albedo and mass balance at different sites along the glacier before and after the experiments. The records of the automatic weather station set up at the equilibrium line altitude (3400 m) shows that the amounts of snowfall were 7.5 mm and 12.4 mm water equivalent in solid form by the two experiments, respectively. Because of the artificial solid snowfalls, the glacier's surface albedo significantly increased in the mid-upper area; the average mass loss decreased by 41 mm w.e. during and after the artificial snowfalls (i.e. 18 – 24 Aug) comparing to that prior to the artificial snowfalls (i.e. 12 – 18 Aug); and the mass received from the artificial snowfall accounted for over a half of the total melt during 18 – 24 Aug. We also propose a mechanism involving artificial snowfall, albedo and mass balance and the feedbacks, describing the role of snowfall in reducing the melting of the glacier.

Keywords

artificial snowfall, Muz Taw Glacier, Sawir Mountains, glacier mass balance, reduce melting

1 Introduction

Mountain glaciers are an essential part of the cryosphere. As high-altitude reservoirs, they are vital solid-water resources (Immerzeel et al., 2019; Immerzeel et al., 2010). Glacier fluctuations represent an integration of changes in the mass and energy balance and are well recognized as high-confidence indicators of climate change (Bojinski et al., 2014). Satellite and in-situ observations of changes in the glacial area, length and mass show a global coherence of continued mountain-glacier recession in the last three decades with only a few exceptions (Zemp et al., 2019). For the Sawir Mountains, the ablation of the glaciers is more intense than the global average, and the total area of the glaciers reduced by 46% from 23 km^2 in 1977 to 12.5 km^2 in 2017 (Wang et al., 2019). The accelerated retreat of glaciers not only causes spatial and temporal changes in water resources but also has a significant impact on sea-level rise, regional water cycles, ecosystems and socio-economic systems (such as agriculture, hydropower and tourism); the melting of glaciers also increases the occurrence of glacial disasters, such as glacial lake outburst flooding, icefalls and glacial debris flows (Hock et al., 2019).

So far, there are not so many approaches used in practice for reducing the rate of glacier ablation. Some administrative measures, including energy conservation, temperature-increase control and establishing glacial reserves, have been taken to reduce the ice melting on Earth. In recent years, new ideas and techniques have emerged for slowing the melting of glaciers. For example, in the Rhone glacier of the Swiss Alps, white blankets are used to shelter the glacier and slow down its melting (Dyer, 2019). In the Morteratsch Glacier of the Alps, artificial snow was expected to be applied for slowing down the glacier melting (Oerlemans et al., 2017). In Austrian glacier ski resorts, over 20-m thickness of the ice was preserved on mass balance managed areas compared to non-maintained areas during 1997 – 2006 (Fischer et al., 2016).

A peer review report on global artificial-snowfall activities by the World Meteorological Organization suggests that the toxicity of the seeding material (majorly AgI) is unlikely to trigger environmental hazards (Flossmann et al., 2018). A potential concern is that artificial-precipitation activities might redistribute the natural precipitation over a region; however, applying cloud seeding over the mountain glaciers usually up to 5 km in length in Central Asia, is presumably acceptable.

We select the Muz Tau glacier in the Sawir Mountains as the investigated glacier. During the glacier's ablation period, we introduced artificial precipitations by the ground AgI smog generators set at the glacial area. These smog generators were set up there by the local meteorological service for artificial-precipitation tasks. We also combined the precipitation amounts and type, time and frequency recorded by the rainfall gauge and the mass balance and albedo of the glacier measured to study the role of artificial snowfall in reducing the mass loss of the glacier.

2 The Sawir Mountains and the Muz Taw Glacier

The Sawir Mountains span the border shared by China and Kazakhstan and are the transitional section between the Tianshan Mountains and the central Altay Mountains. The Muz Taw Glacier (47°04′N, 85°34′E) is a northeast-orientated valley glacier with an area of 3.13 km^2 and a length of 3.2 km in 2016, located on the northern side of the Sawir Mountains (Figure 1). Its elevation from the terminus to the highest point ranges from 3137 m to 3818 m a.s.l. and its ice volume is 0.28 km^3, with an average ice thickness of 66 m (Wang et al., 2018).

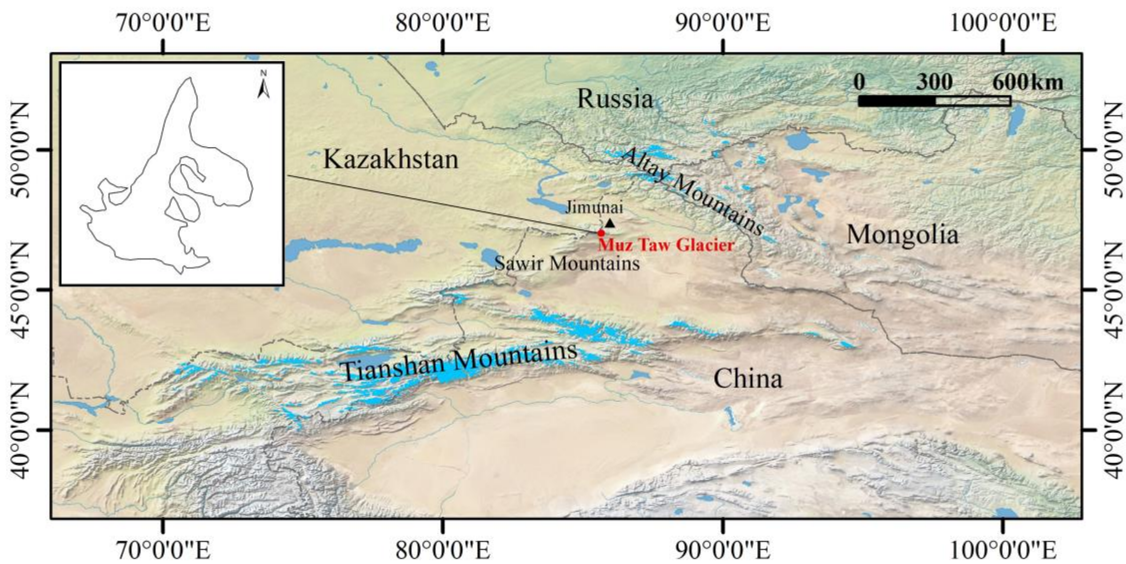

Figure 1 Location of the Muz Taw glacier and the Sawir Mountains, where the map in the background is downloaded from the website https://www.naturalearthdata.com/ and the outline of the glacier is sourced in Guo et al. (2015).

The general circulation over the study area is featured by the prevailing westerlies interacting with the Asian anticyclone and polar air mass in winter (Panagiotopoulos et al., 2005). At the Jimunai Meteorological Station (984 m a.s.l.), 46 km northeast of the Muz Taw Glacier, the annual mean air temperature measured was 4.27 °C; the annual mean precipitation was 212 mm during 1961–2016, and the winter precipitation accounted for 10% - 30% of the annual total.

The Muz Taw Glacier has been in constant recession since 1959 (Wang et al., 2019). Especially for the past 20 years, it has been experiencing a rapid and accelerated shrinkage. From 1977 to 2017, the glacier area decreased by 10.51 km^2, accounting for 45.72 % of its previous surface area (Wang et al., 2019). The average retreat rate of the glacier terminus was 11.5 m a^{-1} during 1989 – 2017. The latest measurements show the mass balance of the Muz Taw Glacier was – 975 mm w.e. in 2016, – 1192 mm w.e. in 2017 and – 1286 mm w.e. in 2018, respectively; and the annual equilibrium line of the glacier was approximately 3400 m a.s.l. (Song, 2019).

3 Field Experiments and measurements

3.1 Artificial-precipitation experiment

We used a WR-08X digital radar system (Wuxi Leyoung Electronics Technology Co., Ltd) built up at the Jimunai Meteorological station to identify the precipitation clouds around the Sawir Mountains. The radar is a new X-band digital weather radar capable of detecting meteorological targets within 300 km. The radar can quantitatively detect the spatial distribution of intensity of cloud rain targets below 20 km distanced from 5 km to 150 km and their motions (e.g., developing height, moving direction and speed.). It can also provide real-time meteorological information. A more detailed description of its application in this area can be referred to in Xu et al. (2017).

The Muz Taw glacier is developing along the valley, and the terminal is the heading source of the Ulequin Urastu River and Ulast River. We distributed 14 silver-iodide (AgI) smog generators along the rivers. These smog generators use solar power to light and are remotely controlled. The AgI sticks used in the generators allow to generate 10^{14} AgI-contained ice nuclei per gram at – 7.5 °C ~ – 20 °C (Kong et al., 2016). In the daytime, valley winds prevail along the valley up to the glacier due to intense radiation and the heating-and-lifting effect for air over the snow surface. It is ideal for generating AgI smogs and carrying them by the upwards air stream over the glacier surface to form precipitations. No extra water is needed to form precipitations in our experiments. We monitored the distribution and structural developing of clouds and identified the orientation, height and distance of the clouds approaching the glacier at the radar station. Associated with observing the moving of the potential target clouds and the receiving of the reflection of the radar transmission, we ignited the smog generators for seeding artificial precipitations, when we realized the possibility is high enough to form precipitation potentially (Figure 2). The detailed operation of conducting artificial precipitations in the studied glacier has been described in Xu et al. (2017).

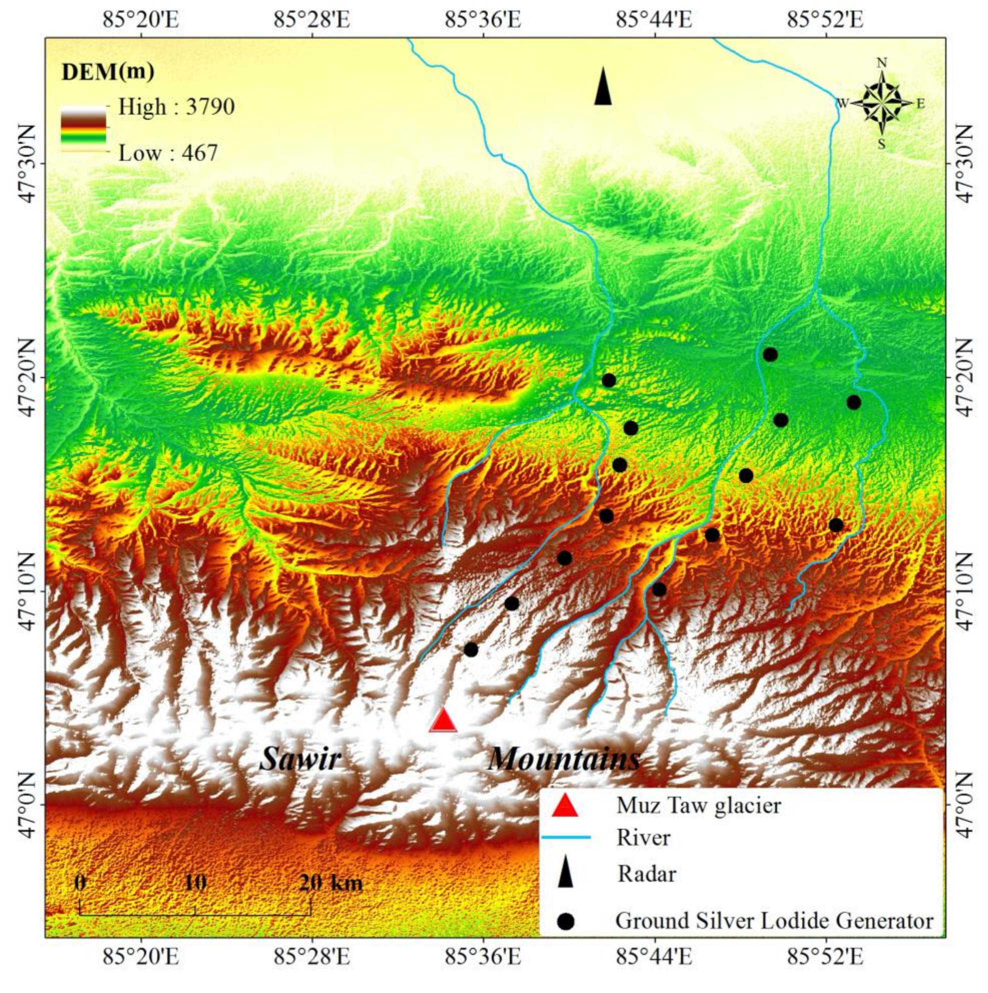

Figure 2 The distribution of the silver-iodide-smog generators along the Ulequin Urastu River and Ulast River in the Sawir Mountains for seeding artificial precipitations.

First, we used the radar to identify local convective clouds in the background synoptic clouds and measured the orientation, height and distance of the convections for determining the time and area for performing artificial precipitation seeding. And then we chose most favourable timing to ignite the silver-iodide smog generators (Figure 3a) and let the silver-iodide (AgI) particles as catalyzer help forming amounts of artificial ice nuclei (Figure 3b) to absorb more water vapour and promote to form precipitations.

Figure 3 a) Igniting the AgI smog generators along the terminal river when the cloud accumulated late on the afternoon of 19 and 22 Aug 2018, and b) the accumulating of clouds in the valley of the Muz Taw Glacier favoured by the AgI particles moved up towards the summit of the glacier.

3.2 Measurement by the automatic weather station (AWS)

We set up an automatic weather station (AWS) on a relatively flat surface near the equilibrium line of the Muz Taw glacier since 8 Aug 2018 (47°03′36″N, 85°33′43″E, 3430 m a. s. l.; Figure 4). The AWS has various sensors to fulfil the requirement of our study (Table 1). A thermometer (Pt100 RTD, ± 0.1 K) was mounted horizontally 1.5 m above the surface to measure air temperature. The measurement of albedo was calculated by measuring incoming and reflected shortwave radiation with the CNR4 pyranometer mounted on the AWS at the height of 1.5 m. The error of pyranometer is smaller than 1% in the wavelength from 0.3 μm to 2.8 μm. Precipitation was measured by an auto-weighing gauge (T-200B, Geonor Inc.) with an accuracy of about ± 0.1%. All sensors were connected to a data logger (CR6, Campbell) which is able to work in low temperature (-55 °C) and record the hourly means every ten seconds.

Table 1 The sensors mounted on the AWS and their technic features

Sensor	Measurement	Model	Accuracy or features
Thermometer	temperature	Pt100 RTC	± 0.1 K
Pyranometer	radiation	CNR4	< 1% in 0.3 - 2.8 μm
Auto-weighing gauge	precipitation	T-200B, Geonor Inc.	± 0.1%
Data logger	data recording	CR6, Campbell	working in low temperature

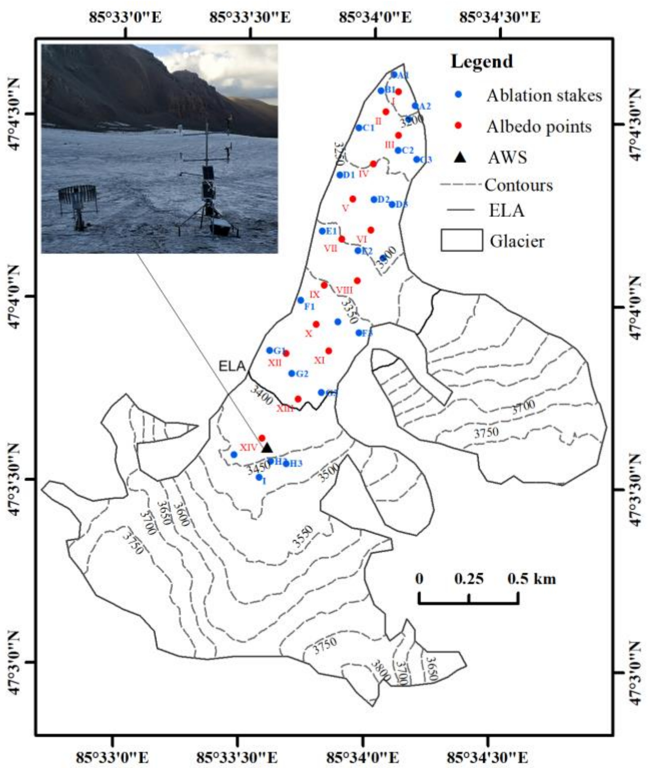

Figure 4 The location of the AWS and the measuring sites for surface albedo and mass balance on the Muz Taw glacier, where a picture of the AWS is in the up left. ELA denotes the equilibrium-line altitude in the map.

3.3 Measurement of the surface spectral reflectance

We used an ASD Fieldspec HandHeld 2 Spectroradiometer to measure the reflectance data at 325-1075 nm by with a resolution of 3 nm and an error of less than 4%. The measurement sensor fitted with a bare fibre was mounted on a tripod at 0.5 m above the surface and had a 25° field of view to a spot sized ~0.225 m in diameter. The spectroradiometer was calibrated to hemispherical atmospheric conditions at the time, by viewing white-reference panel and then viewing the glacier surface. We recalibrated the instrument on occasion when the sky radiation conditions changed. To minimize the influence of slope and solar zenith angle on albedo, we conducted the measurements in a water-level plane within 12:00-16:00 local time. At each sampling site, three consecutive spectra consisting of ten dark currents per scan and ten white reference measurements were recorded and averaged. Meanwhile, cloud cover and surface type were noted for each measurement.

We measured spectral reflectance at fourteen sites across the glacier, on 18, 20, 22 and 24 Aug 2018 (Figure 4). In house, the spectrum data were exported from the instrument by the Spectral Analysis and Management System software (HH2 Sync). The broadband albedo was calculated as a weighted average based on the spectral reflectance and the incoming solar radiation across the entire spectral wavelengths at each site (Ming et al., 2016; Moustafa et al., 2015; Wright et al., 2014; Yue et al., 2017). The period-mean albedo averaged for the 14 sites before and after conducting artificial-precipitation experiments (12 – 18 Aug and 18 – 24 Aug) are shown in Table 2. We excluded the apparent outliers (higher than 0.98) of the albedo data which are physically unrealistic.

3.4 Measurement of the mass balance

We have measured the mass balance of the Muz Taw Glacier annually since 2014 with the method introduced in Østrem and Brugman (1991). Metal stakes for mass-balance measurements were fixed into the ice with a portable steam drill. The stake network consisted of 23 stakes evenly distributed in different altitudes, where three stakes in every row roughly (Figure 4). The stick scale for measuring balance was read thrice, 12, 18 and 24 Aug, respectively. We compared the mass varying between the two periods (12-18 Aug and 18-24 Aug). The snow depth at each stake was measured by reading the scale, and the density of snow was measured by weighing the mass of snow with a given volume. We used the depth and density data of snow to calculate the mass balance at the stake sites. The mass balance was obtained on 1 May and 31 Aug annually. For verifying the effect of artificial snowfalls on the mass balance of the glacier, in particular, we conducted three additional measurements for the mass balance on 12, 18 and 24 Aug 2018, respectively. The baseline of all the mass balance data in this study is the mass balance measured by the stakes on 12 Aug. The calculation of the mass balance of the whole glacier is following an interpolated method based on singular-point measurements introduced by Wang et al. (2014).

4 Results and discussion

4.1 The amounts and form of the artificial precipitations

Figure 5a shows the hourly temperature and precipitations recorded by the AWS from 12 to 24 Aug 2018. There were some natural precipitations during 12 – 14 Aug, while except this and that in the experiment days, the whole period of 12 – 24 Aug was sparse in precipitations. Artificial-precipitation experiments were carried out on 19, 22 and 23 Aug. The amounts of precipitations were 6.2 mm on 19th, 1.3 mm on 20th, 1.8 mm on 22nd and 10.6 mm on 23rd, respectively. Most snowfalls were observed during midnights and early mornings. There were significant precipitation amounts recorded by the AWS every single time after we ignited the smoke generators (Figure 5b). We could not completely distinguish the artificial precipitations from the natural ones if they were simultaneously mixed in all these events. However, the co-occurring of the significant snow falling with the AgI smoke allows supposing that we were producing artificial precipitations.

To determine the amount of solid precipitations that accumulates on the glacier surface, we apply a sinusoidal function (Möller et al., 2007) on the total precipitation. The function describes the transition between solid and liquid precipitations in a temperature range between +2 °C and +4 °C (Fujita and Ageta, 2000; Mölg et al., 2012). When the air temperature is lower than 2 °C, solid precipitations (snow) will occur, and between 2 – 4 °C rain would fall with snow. During our experiments, the air temperatures were below 2 °C when precipitations occur, implying that the precipitations in the two experiments were solid.

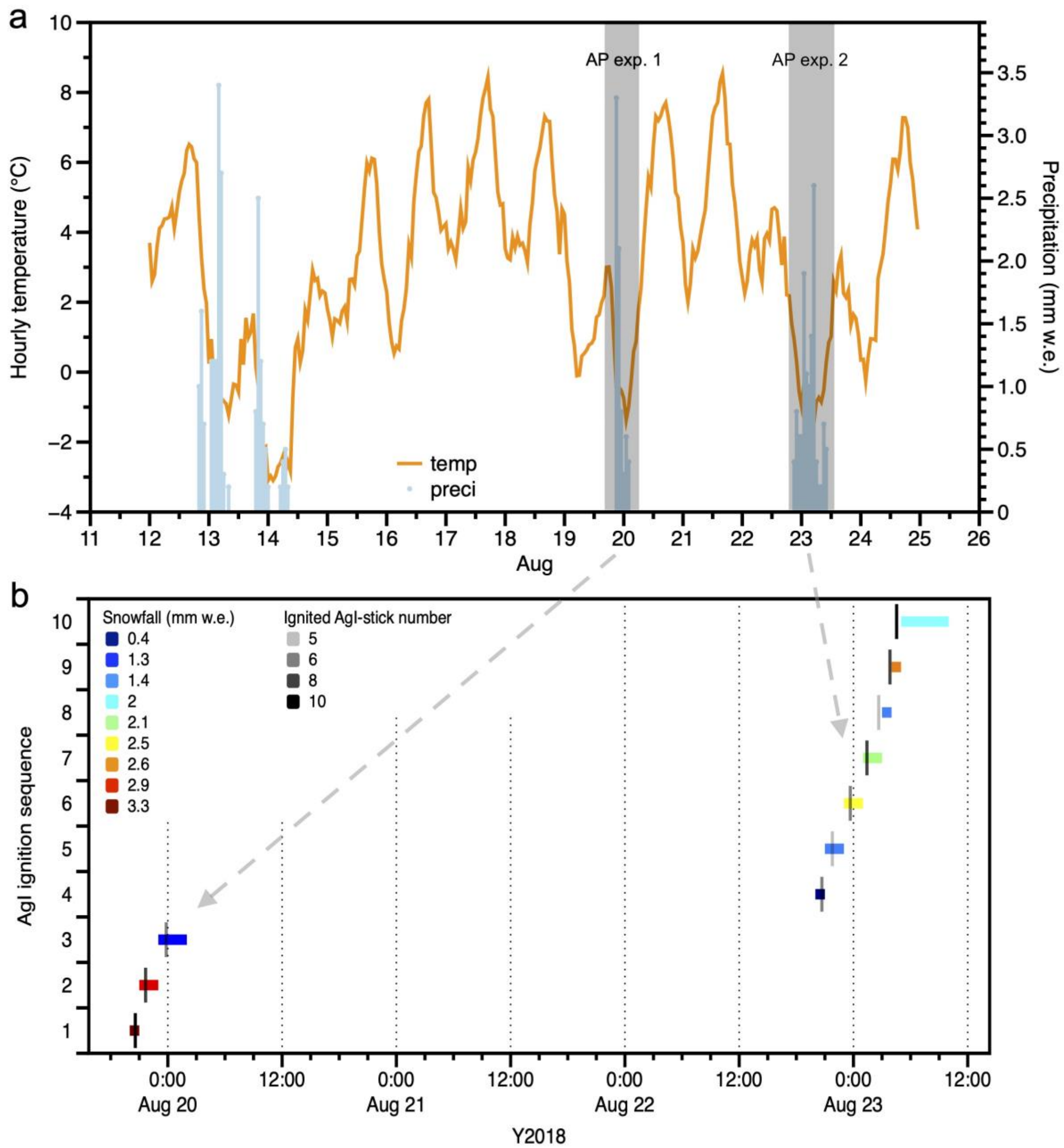

Figure 5 a) The daily snowfalls and hourly averaged temperature recorded by the AWS from 12 to 24 Aug 2018, where the two artificial-snowfall experiments (AP exp. 1 and 2) are marked, and b) the hourly snowfall amounts (indicated by color) and time periods (indicated by length) recorded by the AWS and the ignited AgI-stick number (indicated by color) and time during the two experiments.

4.2 The effects of artificial snowfall on surface albedo

Glacier albedo is highly sensitive to snowfall. Once a snowfall occurs, it will quickly whiten the surface of the glacier and increase the albedo. Figure 6 shows the surface albedo of the Muz Taw Glacier at different locations before and after the artificial-snowfall experiments. We observed that the surface albedo at the sites varied from relative flatness (e.g., at site I and site III) to more significant fluctuations (e.g., at site XII and site VII) between 18 and 24 Aug.

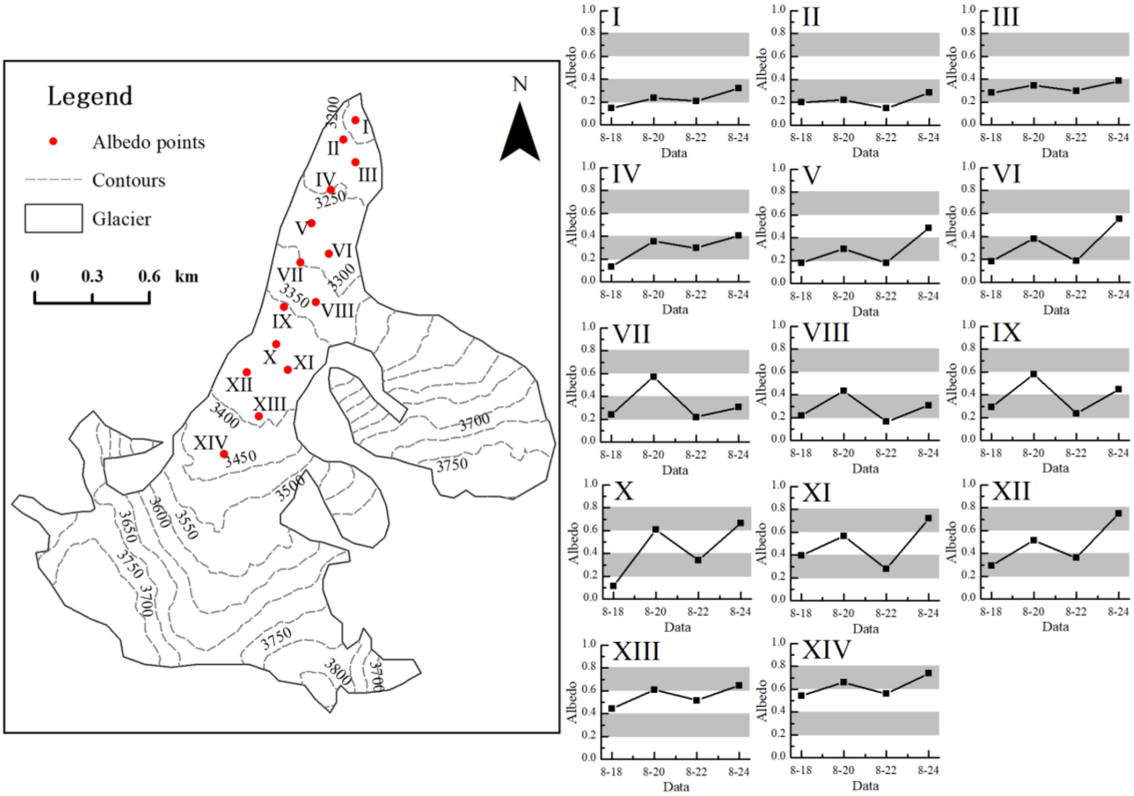

Figure 6 The surface albedo at the fourteen sites (I - XIV) of the Muz Taw Glacier, where the red points denote the sites and the top-left chart as the reference of the fourteen charts (site I to XIV) marks the albedo scale and date with the highlighted grey shades.

Below 3250 m, the surface albedo (at sites I, II, III and IV) was generally smaller than 0.4 (typical albedo of ice with debris) with mild fluctuations as shown in Figure 6. From 3250 to 3350 m a.s.l. (at sites V, VI, VII and VIII), significant variations in albedo were observed, ranging from 0.2 to 0.6. In the area of 3350-3400 m a.s.l., more significant variations in albedo were observed between 0.1 and 0.7. Because this area was located near the equilibrium line, it was highly sensitive to air temperature and snowfall. Artificial snowfall frequently transited the surface from ice to snow, and air temperature turned the surface inversely from snow to ice, and thus dramatic changes in albedo occurred. At sites XIII and XIV, which are much higher than the equilibrium line, the overall albedo exceeded 0.4 and rose up to 0.8. We observed a slightly increasing trend in albedo at these two sites (XIII and XIV), suggesting that the surface was covered by relatively lasting snow owing to artificial snowfalls.

4.3 The varying mass balance responding to the artificial snowfalls

As mentioned in Section 3.4, the stick scale for measuring balance was read thrice at each site, on 12, 18 and 24 Aug, respectively. To study the effects of the artificial snowfalls on the mass balance of the glacier, we calculated the mass balance measured by the stakes during the two periods, i.e. before the artificial snowfalls (12 – 18 Aug) and after the artificial snowfalls (18 – 24 Aug), respectively. The stakes in a group (A to I) were roughly along the altitude contour (Figure 4), and the correspondingly measured mass balance of the same group was averaged (Figure 7). The mass balance decrease with altitude from approx. – 400 mm w.e. at 3100 m to approx. – 100 mm w.e. at the equilibrium line measured by the stakes before the artificial snowfalls, and decrease from approx. – 300 mm w.e. at 3100 m to approx. – 100 mm w.e. at the equilibrium line after the artificial snowfalls. The difference of the mass balances measured at the sites between the two periods was 41 ± 15 mm w.e. on average for the Muz Taw Glacier. This difference resulting from the artificial snowfalls accounted for 17% of the total mass balance before the artificial snowfalls and is more significant in part lower than the equilibrium line.

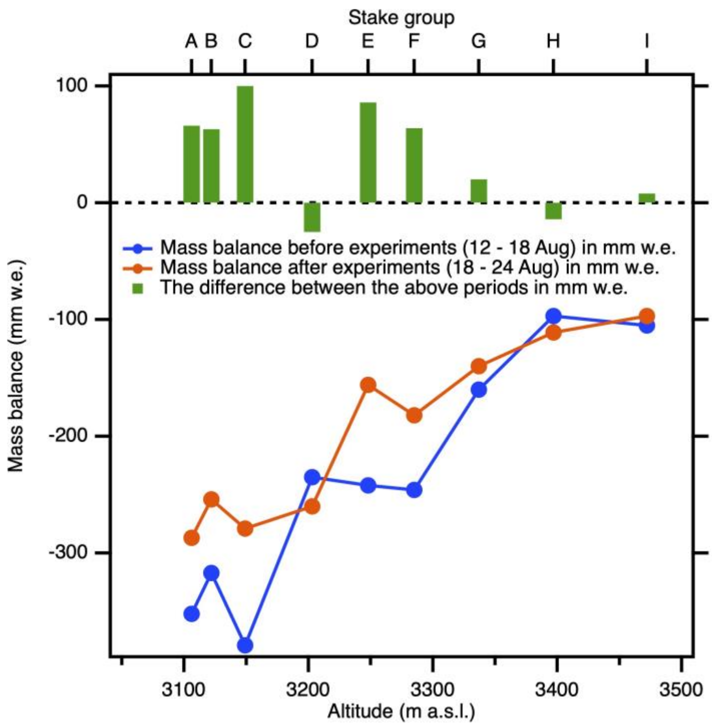

Figure 7 The averaged mass balance measured at the sites (Stake A - I) before (blue) and after (orange) the artificial snowfalls on 18 and 20 Aug compared with that on 12 Aug (The zero line), and the gained mass (green = orange - blue) due to the artificial snowfalls.

We compare the positively accumulative temperatures (in brief PAT = $\sum_{i=1}^{n} T_i$, n is the number of days, and T is the daily averaged temperature in °C), the amounts of snowfalls, and the surface albedo of the measurements from 12 to 18 Aug (t_1) and from 18 to 24 Aug (t_2) (Table 2), respectively. The two periods represent the same time-length span before and after the artificial snowfalls, respectively. The temperature, snowfall and albedo data in this comparison are all from the measurements of the AWS. The estimated mass balance after interpolating the measured mass balance by the stakes to the whole glacier during t_1 and t_2 were – 61.4 mm w.e. and – 37.2 mm w.e., respectively. Although the PAT was higher during t_2 than during t_1, the mass loss of the glacier was 40% lower than t_1. More snowfall and higher albedo resulting from the artificial snowfalls can explain the less mass loss during t_2.

Table 2 The positive accumulated temperatures, snowfalls and albedo measured by the instruments on the AWS, and the calculated mass balance of the Muz Taw glacier during the two artificial-snowfall experiments (t_1 = 12 – 18 Aug, and t_2 = 18 – 24 Aug).

Period	Positively accumulated temperature (°C)	Snowfall (mm)	Albedo	Mass balance (mm)
t_1	17.0	17.4	0.24	- 61.4
t_2	18.2	19.9	0.33	- 37.2

The accumulation at the equilibrium line altitude (ELA) of a glacier is approximately equal to the area average of accumulation over the whole glacier (Braithwaite, 2008). We can presume that the snowfall amount measured by the AWS near the ELA of the Muz Taw glacier during t_2 was the average received mass of the whole glacier after implementing the artificial precipitations. The melt amount from the original glacier during t_2 would be the difference between the calculated mass balance and the snowfall measured by the gauge on the AWS, i.e. 17.3 mm w.e. Therefore, artificial snowfalls may significantly save the melt of the glacier without conducting artificial snowfall by 53.5%, calculated as the percentage of the snowfall divided by the estimated mass balance during t_2.

4.4 The mechanism: how artificial snowfalls reduce the melting of a glacier

In the air temperature lower than 2 °C, the artificial snowfall promotes the form of snow which directly adds mass onto the glacier and increases the mass balance of the glacier and thereby albedo; the snow cools the surface and increases the surface albedo; the increased albedo will decrease the solar radiation absorption in the surface and favour retaining the mass balance which will, in turn, save the albedo; and eventually the whole process forms a positive feedback.

This is a very preliminary theory based on the limited data derived from the short-term experiments, and we need further studies to validate the theory. The albedo decay of artificial snowfall and snow physics are required to claim a long-term impact on the mass balance of glaciers. Particularly, the variation in the likelihood of a snowfall event occurring with or without smoke generators needs to be quantified in future studies.

5 Conclusions

We carried out artificial-snow experiments on the Muz Taw Glacier in Sawir Mountains on 19 and 22 Aug 2018. The albedo and mass balance were measured at the stakes evenly distributed along the altitude contours of the glacier before and after the artificial snowfall experiments. The glacier received a total snow amount of ~ 20 mm w.e. by two artificial-snow experiments. The snow increased the surface albedo of the glacier, and larger fluctuations in albedo were measured at higher sites than lower sites.

By interpolating the measurements of mass balance by the stakes to the whole glacier, we get a mass balance of – 61 mm w.e. for the period of 12 – 18 Aug and – 37 mm w.e. for the period of 18 – 24 Aug, respectively. The artificial-snowfall experiments reduced the mass loss of the glacier by ~ 40% due to more snowfall and higher albedo, although the positively accumulated temperature during the latter period was higher than the former.

We made two comparisons for the mass-balance variation of the Muz Taw glacier with or without the artificial-snowfall experiments. One is comparing the mass balance during the period before the experiments (12 – 18 Aug) with that after (18 – 24 Aug). The difference of the mass balances between the two periods was 41 ± 15 mm w.e., suggesting that artificial snow added the mass to the glacier. Another is comparing the total melt of the glacier during the period after the experiments (18 – 24 Aug) with the mass added from the artificial snowfall to the glacier, implying that artificial snow significantly saved the mass loss during the period after the experiments.

We also propose a theory describing the role of snowfall in reducing the melting of the glacier. The mechanism determines that the environmental temperature and the form of snowfall, and clouds are the two main factors resulting in the mass gain and loss of a glacier. Mechanical erosion, energy exchange (thermal-dynamic) and albedo-induced radiation absorption play major roles in the process of mass varying. This hypothesized mechanism is preliminary and needs more measurements to consolidate.

The approach in our work uses solar power to ignite the seeding material for forming clouds and uses no extra water but redistributes natural water in the local atmosphere at a small spatial scale. The energy-and-water saving techniques of the approach with reasonably mass-loss-reducing efficiency from the Muz Taw glacier validates its efficiency to possibly be applied in more Central-Asian glaciers to reduce their rapid melting. Especially in summer when the melting is drastic in the Central-Asian glaciers, applying the approach suggested by our study on a much broader scale might reduce the melting significantly. Of course, the period of our experiment is preliminary and short, and the approach would sophisticate itself when being implemented more regularly in future repeated and longer-term, or scaled-up experiments.

Code/Data availability

All data involved in the study can be requested by correspondence to the corresponding author in the presence of publication.

Author contribution

F.W. conceived the main ideas, designed the experiment and drafted the manuscript. X.Y., L.W., H.L. and Z.D. helped to design the experiment and collect the data. J.M. helped to sophisticate the work and edit the manuscript.

Competing interests

All contributors declare no competing interests in this work.

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